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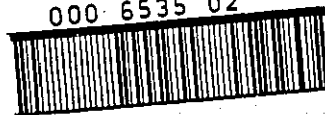
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PRECISION CAST TOOLING

by

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A Doctoral Thesis submitted in partial fulfilment of the
requirements for the award of Doctor of Philosophy of the
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SYNOPSIS

The thesis reports an investigation concerned with the optimisation of materials and methods in the production of precision cast H13 die steel tooling. The investigation was conducted in four stages:

mould material evaluation

metallurgical processing

test casting production and evaluation

finishing procedures

The mould material evaluation considered the properties and performance of materials used in the production of composite moulds. These moulds were produced using a molochite backing material bonded with sodium silicate and a facing material of mullite bonded with ethyl silicate. An appropriate mould processing procedure was established based on the results of the mould material evaluation.

In the stage concerned with metallurgical processing, the principal objective was to establish the most suitable method of suppressing the pitting defect associated with the production of cast H13 die steel. The effects of: mould atmosphere; mould material additions; mould and metal temperature; and melt additions on the severity of the pitting defect were assessed. The results enabled recommended procedures to be established.

The results from the first two stages were used to formulate the programme for test casting production and evaluation. The objectives of this stage of the investigation were the confirmation, or otherwise, of the findings and recommendations of the previous stages and the establishment of the attainable precision in test castings, which included industrial components. The castings were assessed using dimensional metrology and surface finish measurements.

In the final stage of the investigation the effect of heat treatment on the dimensions of the test castings was established. An attempt was also made to quantify the effects of electrical discharge machining (EDM) on the surface composition of the as-cast material using electron probe microanalysis.

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CHAPTER ONE

INTRODUCTION AND STATEMENT OF THE PROBLEM

Impression moulds and dies are used for a variety of applications in the field of manufacturing technology. They are tools which contain the workpiece shape totally or partly as a negative shape. This negative shape will either be impressed on the workpiece as a positive shape, or it is used to hold a component for a secondary operation. The dies usually consist of two, three and sometimes more parts for more complex workpieces. Toolset components with internal contours are usually termed 'die', while parts with external features may be considered punches. The working surface of impression dies lies between a few mm² and a few m², the mass ranging from less than 0.1 kg to more than 50 tonnes (1).

Some of the principal applications of dies and moulds are:

Casting:	gravity die casting pressure die casting foundry pattern tooling
Forming and forging:	drop forging extrusion and wire drawing stamping powder metallurgy
Plastics and rubbers:	low pressure moulding high pressure moulding extrusion blow moulding tyre moulds
Glass:	glass moulds

From this list it may be seen that dies and moulds play an important role in the economy of an industrial society such as that of the UK. An efficient toolmaking industry is of fundamental importance to the metal and plastics processing industry and, in turn, final product manufacture (2).

1.1 DIE MATERIALS

The range of materials used in tool and die manufacture is extensive and dependent on many factors. Non-ferrous alloys may be used for foundry tooling, gravity diecasting dies and plastic tooling. However, in the majority of applications ferrous alloys are preferred. Although cast iron is used in foundry tooling and press tooling, die steels predominate. Die steels are characterised by high hardness and resistance to abrasion coupled with, in many instances, resistance to softening at elevated temperature (3). Generally, these attributes are attained with high carbon and alloy content. Each manufacturing process places different requirements on die material selection. In the case of forging, die steels are selected on the basis of the following characteristics (4):

- 1 Ability to harden uniformly.
- 2 Ability to resist the abrasive action of the metal while it is being forged.
- 3 Ability to withstand high pressures and heavy shock loads.
- 4 Ability to resist cracking and checking caused by heat.

Furthermore, selection of the most suitable combination of steel and hardness for die blocks and die inserts is influenced by:

- (i) Shape and size of the forging.
- (ii) Composition of the metal to be forged.
- (iii) Temperature at which the metal is to be forged.
- (iv) Number of forgings to be made.
- (v) Type of forging equipment (hammer or press).
- (vi) Cost of the die steel.
- (vii) Sequence of machining the die impressions (before or after hardening).
- (viii) Forging tolerances (including those specified for draft angles).
- (ix) Established plant practice and previous experience with similar applications.
- (x) Availability of auxiliary equipment.

As the various properties desired to meet specific forging conditions are frequently incompatible with each other, compromises are necessary in the selection of tool material and hardness.

A detailed consideration of die steel selection may be obtained from the Metals Handbook (3,4).

1.2 DIE MANUFACTURE

The majority of dies and moulds start life on a one-off basis (5). The conventional approach to manufacture involves the construction of a model which is then used for copy milling the required cavity in a forged die block. Even when, as in forging or glass making, several moulds may be required this approach is still used. The nature of conventional machining processes is such that considerable skilled hand finishing work, termed benching, is usually required to complete the die.

The UK die and mould report showed that in 1968 there were 250 independent and 1000 tied die and mould making concerns responsible for the production of tooling (6). For the year, independent toolrooms produced dies and moulds to the value of £13M, tied toolrooms £60M worth and a further £2M worth was imported. At that time it was predicted that there would be a growth of 8% and 15% pa respectively for tools for diecasting and plastics. However, the skilled labour force was growing at a rate of only 4% pa. By 1975 it was estimated that approximately 6000 skilled mould and die makers were employed in the UK industry (7).

During the past decades there has been an increasing trend towards the reduction of the amount of machining that is required of engineering components (8). This has increased the importance of the processes capable of producing more accurate components. Two factors are involved: firstly an increasing requirement for tooling for these accurate processes, and secondly an increasing requirement for these tools to be more accurate.

Die and mould costs represent a substantial proportion of the component cost. It has been reported that in the USA the cost of making or replacing dies for drop, upset, or press forgings can be as low as a few hundred dollars, or as much as 100,000 dollars or more (9). Depending on the type of forging and the material used, the cost of repairing and replacing dies can add anything between 6% and 20% to the cost of a finished forging.

Eventually, dies must be withdrawn from service because of wear. The factors influencing die wear have been the subject of numerous investigations and reports. Forging handbooks list the following factors as influencing the life of dies used in closed die forging: die material and hardness; flow stress and temperature of workpiece; scale; workpiece design; tolerances of the workpiece; and rapidity and intensity of the blow. The same handbooks mention the following factors as the main causes for die failures: overloading; overheating; abrasive wear; heat checking and cold dies (10). Diecasting dies are subject to two principal modes of failure: heat checking and die erosion.

In the more demanding field of forging, die life is a particular cause of concern. The life of dies used for the same product can vary from a few hundred to 50,000 plus (11). Although there is considerable effort to control these die life variations by controlling process parameters, the problem is still serious.

All these factors place considerable pressure on tool and die makers, who often face criticism that they are unable to meet delivery schedules. These pressures can be summarised as:

- (a) need to find faster methods of sinking dies.
- (b) need to find cheaper methods of sinking dies.
- (c) need to put impressions into dies with greater accuracy.
- (d) need to use materials with improved strength and also wear resistance.

To help meet these requirements toolmakers have adopted new technology: NC machine tools; computer aided manufacture; and electro-discharge machining (EDM).

A survey by Coates (12) which considered forging die sinking by ten different methods in eight different firms concluded: the lowest quoted times were obtained for completion of impression sinking and benchwork operations and were associated with the employment of spark erosion for the moulder and finisher impressions. When repeated orders for dies are involved, as in forging, this is reflected still further. The advantages of EDM include: reduction of skilled labour requirements for process operation since the machines, once set, operate automatically; reduction of skilled labour requirements in

bench finishing, since a better standard of machine finish can generally be obtained by EDM.

1.3 CAST DIES AND MOULDS

An alternative to using metal removal processes to produce an impression in a die is that of casting the required impression in a die material. The casting process provides the designer with increased scope and freedom for his ideas. Casting is the cheapest and most convenient method of producing intricate detail and complex shapes in a wide variety of metals and alloys, without a weight limitation. A range of casting processes is available, the choice of process depending upon such factors as size, number required and dimensional accuracy.

Two groups of processes may be considered:

- (I) Sand casting: green sand; dry sand; cold setting processes; full mould.
- (II) Precision casting: plaster casting; shell moulding; investment casting; Shaw process.

The processes in group I may be used to cast a component to shape, but machining is generally required to produce a die of the required dimensions. With the exception of the green sand process, the processes are suitable for the production of large press tools.

The processes in group II may, with the exercise of careful quality control at all stages of production, be capable of producing cast to size components. Under ideal conditions machining may not be required, however, in most cases some finish machining may be necessary. Plaster casting is limited to non-ferrous alloys, principally aluminium-base alloys. Shell moulding and investment casting, although suitable for a broader range of alloys, are restricted to the production of small castings. The Shaw process is perhaps the most versatile, being suitable for a broad range of alloys and casting weights.

Some indication of the scope of cast tooling and the range of materials can be seen by reference to Table One.

Table 1: Cast Tooling Materials and Applications

Production Process	Cast Tooling Material	Typical Cast Tooling Application
Forging	H12, H13 and other hot work tool steels.	Drop forging dies, hot die forging, press forging, roll forging.
Extrusion	Tool steel.	Aluminium extrusion.
Pressing	Cast iron, SG iron, tool steel.	Automobile pressings.
Diecasting	H13 tool steel.	Aluminium-base, copper-base, magnesium-base, zinc-base alloys.
Plastics Moulding	Aluminium-base alloys, beryllium-copper alloys, cast iron, tool steel.	Shoe moulds, injection moulding, blow moulding, rubber moulding.
Glass Moulds	Cast iron, SG iron, tool steel.	Glass bottles, ovenware.
Foundry Tooling	Aluminium-base alloys, cast iron, alloy irons, SG irons, tool steel.	Mass production patterns and coreboxes. Shell core and hot box core-boxes.

1.4 PRECISION CAST TOOLING

Although there are many articles published in the technical press describing the manufacture and applications for precision cast tooling, relatively few provide qualitative data. From those papers which do contain relevant data there are three aspects of cast dies which are of importance:

Die Life

Metallurgical Quality

Dimensional Accuracy

1.5 DIE LIFE

The initial industrial enthusiasm for precision cast dies arose from the publication of a Czechoslovakian book on the production of cast cutting tools (13). In this book the authors also described the production of cast forging dies by the Shaw process. They produced several cast dies and compared their performance with dies machined from wrought steel. The cast dies were reported to show an average improvement in die life of 78.5%. The authors concluded that cast dies gave better service performance at a lower production cost.

In the UK a Shaw process foundry and a forge co-operated in a programme of work to investigate the use of precision cast die inserts for the production of drop forgings. In a report issued by the forge (14) die life figures were provided for five forging dies, comparing the performance of wrought dies and cast dies, produced in two different steels (see Table Two).

Table 2: Improvement in Die Life when Changing from Wrought to Cast Forging Dies

Forging Die	% Improvement in Die Life	
	No 5 Steel	5% Cr steel
Hub Flange	50	80
Coal Pick	31	69
Connecting Rod	71	136
Coal Pick	116	280
Coal Pick	54	71

The average improvement in die life performance when changing from wrought to cast dies was:

70% for No 5 die steel (BS 224)
116% for 5% Cr die steel (0.3% C; 1% W; 5% Cr; 2% Mo; 0.25% V)

A substantial investigation into the use of cast dies for forging applications was undertaken by a French team of investigators (15). Several evaluations, using different die steels and die configurations, were conducted at different forges. Some of the results are presented overleaf.

Spider Transmission Forging:

Two sets of cast dies provided die lives of 22,150 and 19,900 respectively, compared with the average wrought die life of 9500.

Hub Forging:

Three sets of cast dies were used in service and provided die lives of 5000; 6200 and 8600 (an average of 6600) in comparison with the average wrought die life of 5800.

One of the trials conducted compared die lives for cast dies with as-cast impressions, cast die blocks with machined impressions, and wrought die blocks with machined impressions. Results were reported for two forgings:

Large Wheel Hub:	average die life
wrought die	3500
cast die - machined impression	7500
cast die - as-cast impression	8122

Wheel Hub:

wrought die	3500
cast die - machined impression	6932
cast die - as-cast impression	4356

Trials at the Simca forge were conducted using cast dies produced by the shell mould and Shaw process. In these trials all the die impressions were finished to size by EDM.

Synchronisation Ring:

wrought dies	5000
cast dies	5541

Fixing Plate:

wrought dies	5000
cast dies	4556

The French investigation concluded that improvements in die life figures of from 30% to 100% were possible if cast dies were used in preference to wrought dies.

Many papers have been published on the use of precision cast dies in the forging industry in the USA. Typical of these is one by Stutzman (16) which provides twelve case studies on the successful introduction of cast dies in place of wrought dies. Die life improvements gained by using cast dies ranged from 20% to 150% when the cast and wrought dies had been produced from similar steels and had similar heat treatment.

Work conducted in Japan at the Riken Piston Ring Co (17) indicated that cast forging dies produced by the Shaw process were at least as good as wrought dies, and in some cases better. The service life of cast dies was on average 50% longer than for wrought dies. In work carried out at the Toyo Kogyo Co in Japan and reported by Murao and Mino (18), the Shaw process was used in the manufacture of diecasting dies. The cast dies were used to produce a range of automobile components in aluminium alloys and included a transmission cover, clutch housing, and a timing gear case. Comparative figures for wrought die lives were not included in the report. The performance of cast dies, as reported, is presented in Table Three.

Table 3: Die Life Figures for Cast Diecasting Dies

Diecasting Die	Die Weight (kgs)	Die Life (no of shots)
Master Cylinder Piston	45	134,115
Rocker Arm Shaft Supporter	18	111,988
Transmission Top Cover	105	33,332
Clutch Housing	100	65,000
Timing Gear Case	96	19,500

1.6 METALLURGICAL QUALITY

The reported improvements in die lives when cast dies have been used to replace wrought dies indicate the high degree of surface integrity in these cast components. The production of high quality precision castings in die steels requires careful control of metal processing. Casting temperatures need to be firmly established to avoid adversely affecting dimensional accuracy (19) and casting soundness. Feeding requirements and gating techniques need to be determined to ensure

that sound castings, free from inclusions, are produced. Grain refining additions may be used to improve strength and reduce the severity of subsequent heat checking of the die in service (20). Die steels containing chromium must be processed correctly to ensure that surface defects associated with high chromium contents are eliminated and that surface decarburisation, which can result in early die wear, is controlled (21). The application of non-destructive testing techniques enables the founder to guarantee the integrity of the castings produced.

However, the production of a high integrity cast die, although guaranteed free from defects, is not in itself a sufficient reason for the improved die lives reported. Die life has been the subject of investigation and a number of metallurgical reasons for the improved performance of cast dies have been suggested. An investigation of factors affecting heat checking revealed that, although heat checks propagate in a similar manner in both cast and wrought dies, in cast dies they extend into the casting to a shallow depth and then stop. It is suggested that the lack of directionality in the grain structure of castings is a significant factor (22). The non-directional grain structure of the cast die material is also claimed to reduce residual stresses within the die and, as a result, castings do not warp or distort during heat treatment to the extent that wrought dies do (20).

Metallurgical investigations comparing the properties of cast and wrought H12 and H13 die steels have been reported in papers by Stutzman (16,23,24). Extensive tests were undertaken on precision cast and wrought material at room and elevated temperatures. The room temperature results of ultimate tensile strength and yield strength were similar for both materials, but the reduction in area and % elongation test results were significantly lower for the cast material. The difference in values of ductility was less pronounced in the tests carried out at temperatures of 480°C and 590°C, and negligible at temperatures of 650°C and 705°C. At these latter temperatures the ultimate tensile strength and yield strength values for the cast material were slightly higher than those for the wrought material. Of note was the existence of a true yield point in the cast samples, which showed that the heat treated precision cast tool steel was not brittle.

The impact strength, measured by the Charpy V notch test, of the cast material was appreciably lower than the wrought material when tested at both room and elevated temperatures, but there was no evidence of a brittle fracture. Fatigue tests indicated that wrought steels were inferior to the cast material when notched specimens were used. However, with unnotched specimens the wrought specimens were much superior.

Hot hardness tests conducted on material which had been heat treated to give a hardness value of Rockwell C40 and C52 indicated that the cast structure was superior to the wrought structure:

At 315°C to 425°C the cast material was 1 RC harder

At 540°C the cast material was 2-4 RC harder

At 590°C to 650°C the cast material was 8 RC harder

It was considered that alloy segregation inherent in the interdendritic regions of cast structures might be beneficial in resisting tempering effects at higher temperatures. In order to assess this, specimens heat treated to RC50 were tempered for 100 hours at various temperatures. After tempering, the specimens were cooled to room temperature for hardness determination. The results are shown in Table Four, from which it can be seen that the cast specimens were consistently harder.

Table 4: The Effect on Hardness of Prolonged Exposure at High Temperature (23)

Exposure Temperature for 100 hours (°C)	Hardness RC		Difference (cast-wrought)
	Wrought	Cast	
Room Temperature	50.2	50.8	0.6
540	45.3	48.5	3.2
590	29.0	31.8	2.8
650	22.7	24.5	1.8
705	20.1	21.3	1.2
760	13.9	16.8	2.9

The comparison of wrought and cast H12 microstructures at a magnification of x500 did not reveal any significant differences (16). However, at a magnification of x7600 it was apparent that the cast structure had

carbides more evenly dispersed throughout the material, whereas in the wrought material the carbides were larger and situated at grain boundaries. It was considered that the structure of the cast material reduces wear at service temperatures and therefore contributed to the improved die life of cast dies.

1.7 DIMENSIONAL ACCURACY

Detailed information about the dimensional accuracy of precision cast dies is not readily available and one must assume when reading the literature that, because cast dies were used in production, their dimensional accuracy must have been satisfactory. The Czechoslovakian work (13) indicated that as-cast dimensions were produced to within 0.3 mm (0.012 ins) without detailing actual dimensions. Jones (14) gave very little specific detail, although some details were specified for a hub flange forging cast die insert. This insert had external dimensions of 133 mm (5.25 ins) diameter and was 76 mm (3 ins) thick. The cavity dimensions of 46 mm (1.8125 ins), 57 mm (2.25 ins) deep with a 76 mm (3 ins) square base were produced with a maximum dimensional discrepancy of 0.08 mm (0.003 ins) which, as it was undersize, was easily corrected.

The report of the work at Toyo Kogyo (18) concluded that precision casting of diecasting dies to close tolerances is a technically demanding process, in particular with regard to an accurate prediction of contraction allowance. This is especially so in the case of larger dies, although small dies can be cast very precisely. Dimensions were quoted for a four impression die having external dimensions of 360 mm x 270 mm x 70 mm (14 ins x 10.5 ins x 2.75 ins) in which the cavity dimensions were within 0.05 mm to 0.18 mm (0.002 ins to 0.007 ins). The Riken report (17) suggested that a finishing allowance of 0.05 mm/25 mm (0.002 ins/1 in) should be sufficient for the impressions in forging dies, providing that the contraction allowance was accurately predicted.

The French team (15) did not provide many details about dimensional accuracy. They concluded that it was preferable, from an economic viewpoint, to produce a casting of the impression with an acceptable precision. The impression could then be finished by means of an orthodox process, removing 0.1 mm to 1.0 mm (0.004 ins to 0.040 ins)

at different points of the impression, rather than try to produce a precision casting to exact dimensions. American workers appear similarly reluctant to quote actual dimensions and prefer to quote general process tolerances. Typical values for Shaw process castings are given below (25):

For dimensions up to 25 mm	(1 in)	± 0.08 mm (± 0.003 ins)
" " between 25 - 75 mm	(1 - 3 ins)	± 0.13 mm (± 0.005 ins)
" " " 75 - 200 mm	(3 - 8 ins)	± 0.38 mm (± 0.015 ins)
" " " 200 - 375 mm	(8 - 15 ins)	± 0.76 mm (± 0.030 ins)
" " over 375 mm	(15 ins)	± 1.14 mm (± 0.045 ins)

For dimensions across the parting line of the mould an additional tolerance of between ± 0.25 mm and 0.50 mm (0.010 ins and 0.020 ins) must be provided. Surface finish values of 2 micrometres (80 micro-inches) can be obtained, compared with values of 5 to 10 micrometres (200 to 400 micro-inches) for sand moulded castings.

In the UK die users have been reluctant to use cast dies because of defects traditionally associated with castings, such as porosity, blow holes, surface imperfections and variations in metallurgical structure. The obtainable precision and reproducibility of tolerances have also been questioned in many instances. The criticisms applied, to some extent, to precision cast dies produced using the Shaw process during the late 1950's and early 1960's. It is possible that, at this time, the UK foundry industry was not in a position to develop the production of precision cast tooling. Certainly, the initial enthusiasm in the UK did not result in the development of cast tooling to the extent that it was developed in other European countries, Japan and the USA.

With this in mind the Science and Engineering Research Council has provided funding for research into the optimisation of materials and methods in the preparation of cast dies. This project is one of several initiated by the SERC in the field of die and mould technology. Other areas selected for investigation include: EDM; ECM; surface coatings; heat treatment; heat transfer; CAD; manufacturing economics; costing and estimating.

CHAPTER TWO

2.1 THE SHAW PROCESS

2.1.1 Introduction

The Shaw Process is a precision casting process capable of the production of accurate castings with excellent surface finish and metallurgical integrity. Moulds are produced using highly refractory aggregates bonded with silica provided by a liquid ethyl silicate binder. A high temperature firing treatment is a feature of the production sequence and this produces an inert mould into which the majority of commercial ferrous and non-ferrous alloys can be cast with confidence.

The process has been used commercially for many years, it was known before the Second World War that silicon esters could be used as refractory aggregate binders (26). As with most processes there has been a continuous development, in particular with respect to the binder system and the methods of mould production. Many of these developments are the subject of patents and much of the technical information has been restricted to Shaw Process licensees.

2.1.2 Outline of the Process

The mould material is prepared by blending refractory powders, containing a high proportion of fine material, with a liquid ethyl silicate binder and a gelling agent. Careful selection of the refractory material results in two particular advantages:

- (i) The fine grains of refractory material provide a smooth surface finish on the resultant casting.
- (ii) The selection of a thermally stable refractory material ensures that the mould is not subject to unpredictable dimensional changes in contact with the molten metal during pouring, thus enabling an accurate estimate of casting contraction to be made.

The blended, mobile liquid slurry is poured into the moulding box and around the pattern. Within a short period of time, controlled by the amount of gelling agent, the mould material gels to a rubbery

consistency and the pattern can be separated from the mould. The nature of the process permits certain benefits to be gained at this stage:

- (a) Pouring a liquid slurry around the pattern ensures a high degree of contact and therefore accuracy and intricacy in the final casting.
- (b) The mould material sets in contact with the pattern and consequently produces a mould which accurately reproduces the pattern detail.
- (c) The rubbery nature of the mould allows the pattern to be withdrawn without distortion to the mould, thus maintaining the dimensional accuracy of the mould cavity.

On removal of the pattern the moulds are either torched immediately to remove evolved alcohol (Shaw Process) or immersed in a stabilising bath prior to torching (Unicast Process) (27). Torching produces a very fine crazed surface and interior structure which does not affect the casting surface, ie there is no metal penetration into the fine cracks, but may improve permeability to allow the escape of air/gases during casting. After torching the moulds are fired in a furnace at a temperature up to 1000°C , which ensures that there are no combustible materials in the mould and that a strong, rigid, inert, accurate and stable mould is produced. The stages in the production of a casting by the Shaw Process are outlined in the flow diagram presented on page 222.

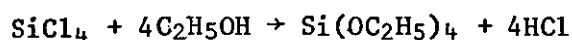
The advantages claimed for moulds manufactured by the Shaw Process include the following (28):

- 1 Good pattern stripping characteristics: the rubbery nature of the gelled mould provides flexibility to the mould which enables the pattern and mould to be separated without damage to the mould when intricate detail or even straight draws are required.
- 2 Dimensional stability: the excellent reproduction of pattern detail and dimensions is retained by the mould to a great extent after firing and during casting, thus enabling accurate dimensional allowances to be made.
- 3 Mould strength: is sufficient to allow moulds to be cast without the need for moulding boxes.
- 4 Collapsibility and resistance to tears: the characteristic internal structure of the mould material improves its breakdown properties and there is less constraint of the casting during contraction.

- 5 Resistance to thermal shock: the characteristic internal structure permits expansion of the mould material to occur readily, as a result moulds can safely be poured cold.
- 6 Resistance to spalling and washing: the nature of the silica bond prevents the generation of inclusions during mould filling.
- 7 Permeability and inertness: as the mould is inert after firing the only gas to be displaced is that occupying the mould cavity. The characteristic structure provides sufficient permeability to enable the metal to readily displace the gas through the mould.

2.1.3 The Binder

Ethyl silicate is an organic based silica binder that is free of those alkaline salts which reduce the refractoriness of mould materials. It is produced by reacting silicon tetrachloride (SiCl_4) with ethyl alcohol (29):



and it is important to remove the hydrochloric acid so that subsequent gelling characteristics may be easily controlled. If industrial ethanol, which invariably contains some water, is used as an alternative to pure ethyl alcohol, the product obtained is a mixture of tetraethoxysilane and ethoxypolysiloxanes. Tetraethoxysilane contains approximately 28% silica by weight, whereas the ethoxypolysiloxanes, which contain an average of up to five silicon atoms/molecule, contain 40% silica (30). This product is known as technical ethyl silicate and, because of its higher silica content, is generally preferred for use in the foundry industry (31).

2.1.4 Hydrolysis

Ethyl silicate is a stable substance with no binding ability. It is necessary to hydrolyse the solution and cause it to react with water in order to produce a solution which will deposit the adhesive form of silica desirable for bonding refractory aggregates (32). Ethyl silicate and water are immiscible unless a mutual solvent such as ethanol is used (33), and it also serves to dilute the solution to the desired silica content. The hydrolysis may be carried out under either acid or alkaline conditions (29). However, alkaline conditions usually result in fairly rapid gelation and, consequently, acid hydrolysis is preferred for foundry requirements. The preferred acid is hydrochloric

acid, although sulphuric or phosphoric acid are suitable (33). The acid hydrolysates prepared in this manner have a very good storage life and are marketed as prehydrolysed ethyl silicates, which are ready for direct use in the foundry.

2.1.5 Gelation

In order to bind the refractory aggregate the ethyl silicate hydrolysate must be made to gel. It is the gel which provides the bonding action by two methods (33):

- (i) Air drying bond = $3\text{H}_4\text{SiO}_4 \rightarrow \text{H}_2\text{SiO}_5 + \text{H}_2\text{SiO}_3 + 4\text{H}_2\text{O}$
- (ii) Precipitation bond = $3\text{H}_4\text{SiO}_4(\text{gel}) + 6\text{H}_2\text{O}$

Upon heating, the silicic acid or silica gel binders condense to form a refractory silica cement. It is this silica form which provides the high strength developed by firing.

There are many ways of promoting the gelling of an acid hydrolysed ethyl silicate using the principle of pH control (32). Hydrolysed ethyl silicate solutions are usually prepared with a pH value of between 1.5 and 3.0, at which they are relatively stable, they are also stable at pH values above 7.0. They are inherently unstable at pH values between 5.0 and 7.0. By adding an alkaline agent to the hydrolysed ethyl silicate solution the pH value of the solution can be increased to a value of 5.0, when the binder becomes unstable and gels. Ammonia, ammonia salts - acetate, carbonate, hydroxide, or organic ammonia salts - piperidine, morpholemar, triethylamine, may be used for this purpose. The actual time for gelation will depend on the particular application and can be varied by adjusting the amount of gelling agent addition.

If accurate control of setting time or a very long setting time is required, use may be made of organotin catalysts (30). The organotin catalysts enable hydrolysis and gelation to proceed readily in the absence of either acid or base. By a special heat treatment process the gelation characteristics can be altered to change the gel time when water is added.

2.1.6 Refractory Aggregates

Many refractory materials may be used in association with ethyl silicate to produce Shaw Process moulds, the list in Table Five includes many of the possible materials but is not exhaustive.

Table 5: Refractory Materials Suitable for Use in the Shaw Process

Material	Chemical Notation	Melting Point °C
Magnesia	MgO	2800
Zirconia	ZrO ₂	2677
Calcia	CaO	2600
Zircon	ZrO ₂ .SiO ₂	2420
Calcium Zirconite	CaO.ZrO ₂	2345
Magnesia Spinel	MgO.Al ₂ O ₃	2135
Alumina	Al ₂ O ₃	2015
Mullite	3Al ₂ O ₃ .2SiO ₂	1830
Fused Silica	SiO ₂	1723

In the selection of a suitable material for a particular application the following factors must be considered:

- 1 Purity
- 2 Refractoriness
- 3 Stability
- 4 Thermal Expansion
- 5 Thermal Conductivity
- 6 Particle Size and Distribution
- 7 Cost

The mould material must be sufficiently refractory to withstand the pouring temperature of the particular metal being cast, without either melting or softening. The melting point value is a good guide to refractoriness, providing the material is pure, as very small amounts of alkali metal salts or iron oxide can reduce melting points severely. The refractory selected should exhibit stability, it should not be susceptible to hydration, or reactions with other materials in the mould or the metal. Thermal stability is also important, expansion is

inevitable, however, providing that it is predictable, ie constant and reproducible it can be taken into account when estimating contraction allowance.

Thermal conductivity is in part a property of the material selected, but it is also a function of particle size and distribution when that material is used to produce a porous, particulate mould. The property does influence the rate of solidification and heat transfer through a mould, which may have an influence on metallurgical integrity.

Cost is a major factor in refractory material selection and is affected by such factors as availability, purity and particle size requirement.

2.1.7 Moulding Mix Specification

The secret of successful mould production and quality castings lies in the mould material mix specification. It is essential to balance the grades of refractory material with the volume of binder and amount of gelling agent in order to produce moulds of consistently high quality. Shaw Process slurry preparation is critical (34), if it is too thin mould cracking will occur on firing, and if it is too thick detail is lost and air bubbles are trapped at the pattern surface.

When selecting the grades of refractory material to be used the principles which apply to sand moulding can be used as a guide. Surface finish will be improved when finer material is used, however, permeability will decrease and binder requirement increase as a consequence. The strength, measured conventionally by AFS compression and tensile strength, will also be affected by grade selection. Strength will be at a maximum when refractory grades are selected on the basis of using several size gradings, which permit infilling of the voids between larger grains by the smaller (32), this is also the most economic way of using the binder. Mix specification is inevitably a compromise between theoretical considerations and practical requirements, but a reading of standard ceramic texts (35,36) can be invaluable.

2.1.8 Mould Production and Processing

As a principal advantage of the process is its ability to produce castings to consistent and close dimensional tolerances, it is essential that patterns and mould locating equipment be produced to a high standard of accuracy.

2.1.9 Pattern Equipment

As a casting cannot contain more detail or be more accurate than the pattern from which it was made, it follows that particular attention must be paid to pattern construction and quality. The Shaw Process utilises permanent pattern equipment and, in principle, a wide range of materials may be used (37): wood, plaster, graphite, epoxy resin, metal, for examples. However, in practice the requirement for high standards of accuracy reduces the choice. Wood patterns are affected by heat and moisture and their dimensions can vary by as much as 3%, which would severely affect accuracy (37). Plastic resin patterns may also be subject to distortion when used in conjunction with the Shaw Process (34). To achieve good dimensional accuracy polished metal patterns are preferred, for which aluminium alloys are particularly suitable.

Patterns are normally coated with a release agent, for example a 10% solution of paraffin wax in benzene (38), or similar proprietary products, and if sparingly applied and well buffed, pattern release from the mould presents no problem.

2.1.10 Mould Production

Shaw Process moulds may be produced by one of several alternative methods: for small components a ceramic shell is quite acceptable, for larger components a boxless block mould is suitable. If the mould is very large, or if demand for a particular casting is great and it is desirable that mould material costs be reduced, a composite mould can be produced. In this case the facing material is Shaw based, but the backing material might be sodium silicate bonded. For mass production applications the process, in each of these forms, lends itself to mechanisation and rapid output of moulds.

In the production of composite moulds additional pattern requirements in the form of a pre-form pattern may be necessary. These may be produced in wood as their purpose is only to produce an oversize cavity in the backing mould. This mould is then positioned over the precision pattern and the gap filled by introducing the mobile Shaw slurry.

Permanent pre-form patterns are not essential, the required effect can be obtained by covering the precision pattern with a thickness of material such as oil sand, CO₂ sand, felt, etc (38-41), which will permit the oversize backing mould to be produced. To ensure that

separation of the backing and facing layers does not become a problem, the mould materials selected for the backing and facing layers should have similar thermal expansion characteristics. Permanent metal backing moulds are also suitable (42).

2.1.11 Mould Processing

When the mould has been separated from the pattern it must pass through several stages which can exert a significant influence on the quality of the finished mould. The craze cracking effect in Shaw Process mould material is only produced when ignition follows immediately after pattern stripping. When the mould material is allowed to air-dry for a substantial period the craze cracking does not develop.

Coarse cracking may be a problem at internal corners in a mould cavity, particularly if pools of alcohol are allowed to form. Sharp corners are unsuitable in most casting designs and a minimum radius of 3 mm is recommended where practicable. The evolved alcohol usually ignites readily, but ignition can be encouraged by the use of a gas/air torch, in either case the moulds should stand on a grid to provide free access of air during ignition.

A further variation in practice exists in the Unicast Process when the separated mould is immersed in a bath of stabilising liquid before torching and subsequent firing (27). It is claimed that stabilisation for a period of one hour in a bath containing ethyl alcohol, for example, will improve the dimensional stability and strength of the mould. Small moulds can be enclosed within sealed plastic bags to enable stabilisation to occur (43).

After torching moulds are fired for two reasons:

- (i) To burn off any residual organic material and remove any moisture, in order to produce an inert mould.
- (ii) To improve mould strength through a sintering effect.

A considerable range of baking or firing temperatures, from 300°C to 1300°C, is suggested in the literature. Whereas the first objective should be met by 'firing' at 500°C, it is unlikely that any substantial improvement in strength will be obtained with a sintering temperature below 1000°C. Slightly oxidising conditions are recommended (44) when

firing moulds to encourage the burning of residual volatiles. Composite moulds present their own difficulties, with radiant heating in tunnel furnaces being preferred to fire the facing material without excessively heating the backing material (45).

Moulds may subsequently be cast whilst still hot or allowed to cool, depending on section thickness and metallurgical requirements. Mould part location in boxless moulds is most easily obtained by across-the-joint dowels seating in moulded dowel prints. Mould joints may be sealed externally with a refractory luting compound. Sealing compounds should not be used on the joint face as they reduce the accuracy of dimensions perpendicular to the joint line. Moulds may be weighted, or clamped using metal bands, before casting.

2.2 METALLURGICAL PROCESSING OF DIE STEELS

2.2.1 Introduction

The 5% chromium die steels, AISI specifications H11, H12 and H13 (BS4659:1971 specifications BH11, BH12 and BH13) have good red hardness and will maintain hardness even after prolonged exposure at 540°C (56). They are very popular in the field of diecasting and forging die production. The carbon content of these steels confers high hardenability and carbides are produced when chromium, molybdenum, vanadium and tungsten are present. The effect of the main alloying elements present may be summarised as follows:

Chromium:	oxidation resistance; deep air hardening when molybdenum is also present..
Manganese:	increases hardenability.
Molybdenum:	improves toughness, wear and thermal shock resistance, and hot hardness.
Silicon:	provides oxidation resistance when present above 1%.
Vanadium:	grain refinement, improved hot hardness, very hard alloy carbides, increases resistance to metal erosion and heat checking.

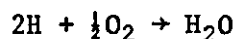
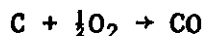
To ensure that a high standard of metallurgical integrity is obtained in cast dies the following should be observed: high purity melting stock should be used; alloy analysis should be carefully controlled; grain size control must be exercised; and the metal should be free from dissolved gases.

2.2.2 Melting

Metal melting should be carried out rapidly to the minimum superheat necessary and the metal should be cast quickly. This procedure minimises the opportunity for the melt to pick up gas. High temperatures may also cause grain coarsening and increase the tendency for refractory inclusions to occur (46). To minimise oxidation during melting a slag cover is beneficial (47). The metal must be skimmed to remove the slag before casting, and pouring ladles and gating systems which minimise slag retention by the metal are to be preferred.

2.2.3 Deoxidation

The hydrogen content of steels is generally below the limit of solid solubility and gross porosity due to hydrogen is rare. However, gas unsoundness in steel can arise from the following reactions which occur as the steel solidifies:



In these reactions carbon and hydrogen are acting as deoxidisers. A prime function of deoxidation in steel is to inhibit these reactions by treating the melt with a more potent deoxidiser prior to pouring (48).

Deoxidation can be defined as a reaction in which the oxygen concentration in the liquid melt is reduced and a deoxidiser as the element which promotes the removal of oxygen. Elements with the highest negative free energy for oxide formation will form oxides preferentially. For steel, silicon is a suitable deoxidiser and may also improve fluidity when present in excess. However, aluminium is a more potent deoxidiser and is generally preferred. Effective deoxidation improves the properties of cast steel by: the formation of oxides which are more stable than FeO, thus preventing the reactions which cause gas porosity; promoting globular rather than stringer type sulphide inclusions; and by a grain refining effect.

An element effective as a deoxidiser may also form other stable compounds such as sulphides, carbides and nitrides. In steels of relatively high oxygen content, sulphides are large and globular. As the oxygen content is reduced by using a strong deoxidiser such as aluminium, the large globular sulphides (Type I) are changed to the eutectic type (Type II) with resulting detriment to the steel's ductility. Increasing the aluminium content beyond that required for complete ^{de}oxidation can cause a further change in the form of the sulphides (Type III) with a beneficial effect on the ductility. However, should the steel contain nitrogen, excess aluminium forms aluminium nitride which can precipitate on slow cooling as a film at the grain boundaries, with resulting brittleness and poor ductility.

A review has shown that 80-90% of micro-inclusions in steel are entrapped products of deoxidation (49). Deoxidation products trapped in steel are either (a) primary products which are formed immediately

on addition of the deoxidiser, or (b) secondary products which are formed during cooling and solidification. Ideally, deoxidation products should be insoluble in steel and separate out rapidly, and neither the residual deoxidiser or the deoxidation products should be detrimental to steel properties. It is suggested that not all the requirements can be fulfilled by any single deoxidising agent and it has been suggested that improved performance may be obtained by combination additions.

For the correct deoxidation of low carbon steels, much higher residual aluminium contents are necessary than for the deoxidation of high carbon steels (50). The formation of Type II sulphides in low carbon steel may be avoided by a complex deoxidation addition of aluminium with silicon-calcium-manganese. However, the use of these strong deoxidants may result in surface pitting and corner shrinks (46). Cope surface defects in steel castings have been identified as arising from deoxidation products (51). The problem is due to alumina formation in the melt and this may react with iron oxide and/or with silica and iron oxide. It is suggested that melts be held before casting to allow inclusions to float out.

2.2.4 Grain Refinement

In cast steels grain refinement is used to cover: (i) refinement in size of the as-cast grains consisting of dendrites, (ii) refinement of the internal structure of each grain, and (iii) change or conversion of columnar to equiaxed structure (52). The main variables in casting which control the grain structure are: (1) pouring temperature, (2) rate of pouring, (3) degree of turbulence, (4) size of casting, (5) thermal conductivity of the solidified metal, and (6) composition of the metal as it affects the range of solidification.

Refinement of cast metals can be accomplished by: rapid solidification; vibration; moving electromagnetic fields; and by the addition of small quantities of selected alloying elements. This latter procedure, commonly termed inoculation, is the most popular because of its simplicity. The addition of inoculants to the molten metal can produce grain refinement by restricting grain growth through constitutional supercooling and/or providing heterogeneous nuclei for the solidification of fine equiaxed grains. In a comprehensive investigation which considered alternative materials and methods, it was concluded that a

0.1% titanium addition to the melt was suitable for a medium alloy steel, providing that metal superheat and mould design were suitable (53).

2.2.5 Pouring

The use of a ceramic mould which is both strong and inert permits the use of top gating through an open riser and this method is practised. However, this form of pouring can result in defects which include: slag inclusions; shots from splashing; and local hot spots with associated shrinkage defects (47). For quiet and progressive mould filling bottom gating is usually preferred with, in some cases, moulds poured at an uphill angle of 30° (17). The use of vents at the end of the mould remote from the ingate may also be useful. Pouring temperature is an important parameter in the production of good castings and should be carefully controlled.

2.2.6 Metal Contraction

The value of the allowance to be added to a pattern dimension, to account for metal contraction, cannot be based on the coefficient of expansion value alone. Many factors exert an influence and include: melting method; gating method; cooling rate; casting configuration and size; mould temperature; and pouring temperature (47). The latter two are particularly important and should preferably be standardised (54). A pouring temperature between 1520°C - 1560°C has been suggested for H13 die steel. The dimensions of a casting were found to increase with an increase in the pouring temperature and this became significant at pouring temperatures above 1560°C (19). Evidence that section size and casting size exert an influence on dimensional accuracy is given respectively by Paterson (34) and Madono (17). The value of contraction allowance recommended in the literature varies between 1% and 2% (55,56).

2.2.7 Surface Characteristics

The quality of the surface of a precision casting is particularly important. The surface finish of a casting produced using the Shaw Process is affected by several factors, which include refractory grading, mould and metal temperature, and metal/mould reactions. Scale formation is of particular concern in precision castings where exact dimensions, sharp delineation of relatively small details and smoothness of surface finish are of utmost importance. In order to reduce the

severity of this problem several alternative procedures may be adopted. These include vacuum casting or inert gas flushing of the mould to remove gaseous oxygen (57). Alternatively reducing agents may be used, either as an addition to the mould, eg graphite (44), or added to the surface of the riser after casting, eg hexamethylenetetramine, in which case the mould must be enclosed within a suitable container (58).

Die steel surface chemistry must be maintained to ensure maximum die life. Carbon at the die surface can be depleted by air, water vapour and carbon dioxide. Steels containing chromium are also subject to a form of surface defect known as pitting. Surface reactions in precision cast steels have been the subject of several investigations.

In an investigation of the mechanism by which decarburisation occurs in steel castings made in ceramic moulds, it was established that decarburisation occurs rapidly and is a function of the time that the casting remains at an elevated temperature, ie above 870°C (44). Doremus and Loper (57) examined two low alloy steels: one containing 0.24% carbon and 0.60% chromium; the second 0.93% carbon and 1.49% chromium; cast in Shaw Process moulds. They found that decarburisation increased with an increase in mould temperature and that, because slow cooling produced a larger grain size, there was considerable penetration of decarburisation along the prior austenite boundaries. Decarburisation was also greater for the steel with the higher initial carbon content.

The problem of surface pitting has been associated primarily with those steels containing chromium and particularly those steels containing chromium in excess of 10% chromium and between 1% and 10% nickel. A report of work carried out at IIT* suggested that, between narrow limits, chromium was the primary element causing the defect. The defect occurred after solidification and between 1090°C and 1425°C in an oxidising atmosphere and was augmented by super-heat and mass (21).

That pitting occurs after solidification, and could be avoided by preventing oxygen from coming into contact with the solidified skin until it had been cooled below a definite temperature, is supported by Duffen (59). The mechanism proposed was one of simple cell corrosion

(* Illinois Institute of Technology)

by a liquid iron oxide/silica reaction product. Interface temperature measurements indicated that no pitting occurred below 1150°C. Below this temperature no liquid is present in the system. Of concern is the rate and degree of reaction of the oxide skin with the silica of the refractory. It was thought likely that silica reacts with the oxides rather than the metal, particularly iron oxide.

In a more recent investigation of pitting and decarburisation in a range of steels, casting modulus was shown to be an important factor. Decarburisation increased linearly with an increase in casting modulus in a stepped block casting. Similarly, the extent of pitting increased with an increase in modulus. The researchers concluded from their investigation that there was a relationship between pitting and decarburisation. The two phenomena are based on carbon monoxide formation. The carbon monoxide results from a chemical decarburisation reaction between the steel and the silica in the mould material and pitting is a physical effect caused by the carbon monoxide bubbles deforming the metal surface (60).

The foregoing investigations were undertaken using alumino-silicate mould materials. In an empirical study of pitting in cast H13 dies, reported in Portuguese, the problem also occurred with zirconite-base mould materials. It was suggested that a reaction between the metal oxide and the zirconite was the cause of the problem (61).

The presence of oxygen is clearly significant in the problems of decarburisation and surface pitting. Under normal conditions oxygen is present in the atmosphere; in the interstices of the mould; in combined form as the refractory aggregate; and in the silica bond. The techniques mentioned previously to deal with scale formation are also used to minimise the problems of decarburisation and pitting. The effect of these techniques and other methods has been considered in several investigations (57-63) and is briefly summarised in the following paragraphs.

Pouring, and cooling the filled mould, under vacuum or the protection of an inert atmosphere of argon or nitrogen, eliminates the defects. The addition of material to the mould which creates a reducing atmosphere at the moment of casting, such as graphite, diminishes or

eliminates the problem. Certain deoxidiser material additions to the mould material may also reduce or prevent decarburisation (57). Post casting reducing atmospheres may prove suitable for eliminating or reducing the severity of the defects.

Although these procedures may prove effective, silica-free moulds might prove an even better solution. As silica provides the bond this may appear impracticable, however, free silica can be avoided. A patented method of overcoming metal/mould reactions is based on the addition of free alumina to the mould material. The alumina reacts with the silica bond at the firing temperature to produce mullite (63). The replacement of zirconite by mullite was suggested by de Oliveira Pinto, as a way of reducing the seriousness of pitting. Using alumina-based mould material completely eliminated the problem. In a paper advocating the use of organo-tin compounds in ethyl silicate binders, Emblem suggests that they act as mineralising agents promoting the formation of mullite when tabular alumina is bonded with ethyl silicate. Microscopy indicated that the alumina particles were cemented together by the aluminosilicate phase, mullite (30).

The surface characteristics of cast dies and tools produced by the Shaw Process may be deliberately altered. A resistant layer can be produced on the castings by feeding a suitable gaseous or liquid substance into the moulds, eg ammonia. The nitrided castings also retain a bright, scale-free appearance. It was found that the thickness of the diffused layer was directly related to the thickness of the casting (64).

CHAPTER THREE

ELECTRICAL DISCHARGE MACHINING

3.1 INTRODUCTION

Electrical discharge machining (EDM) is a controlled method of metal removal using rapid electrical discharges in the presence of a dielectric. A source of pulsating electrical energy is connected to a tool or electrode and a workpiece. The power source must be precisely controlled to emit the desired current, frequency and overcut (65).

The commercial development of EDM is credited to Lazarenko who, in 1943, used a machine with a relaxation circuit. Subsequently Kohlschutter observed that, when a spark occurs, less metal is removed from the negative rather than the positive electrode. A cathodic tool is required for the relaxation circuit machine and, as the duration of the discharge becomes larger, there is more likelihood of the spark assuming arc discharge characteristics culminating in greater cathode erosion, and tool and workpiece damage. Relaxation circuitry has been superseded by rotary impulse generators and, more recently, by static electronic switching (66).

In toolmaking, EDM can be regarded as combining the accuracy of a jig borer with the forming variety of a copy miller (67). The average EDM machine is not unduly expensive, particularly in relation to the versatility of form generation which it offers. EDM is basically a "forming" process, the tool electrode imposes its complementary shape upon the workpiece with a small amount of overcut. The electrode does not contact the workpiece as a machining gap of from 0.005" (0.013 mm) to 0.010" (0.025 mm) is automatically maintained. The process is at its best producing internal shapes, traditionally the more difficult type of operation. It remains for the user to produce the easier male electrode.

Three mechanisms have been proposed to explain the way in which the tool material is eroded: thermal, electromechanical and thermomechanical (68). In the pure thermal theory it is proposed that material is wholly removed by evaporation. The electromechanical theory proposes that the high current density generated in the spark-

impingement area creates a large potential gradient between the impact area and the bulk of the workpiece. This leads to an electrostatic repulsive force greater than the yield point, which causes material in the impact area to break away. The thermomechanical theory suggests that some metal is removed by vaporisation, but that the bulk is ejected as a liquid from the crater by a combination of many factors, including electrostatic and electromagnetic forces.

Significant and widespread evidence is available to suggest the predominance of the thermal basis of metal removal (69). The energy of the spark is converted into heat and a local temperature of $10,000^{\circ}\text{C}$ to $20,000^{\circ}\text{C}$ can be reached (70). The ejected electrode material appears as resolidified spherical metal debris in the dielectric fluid, and it is widely observed that a resolidified layer and thermally affected material occurs at the workpiece surface.

The main sequence of events and the mechanism of metal removal can be briefly stated as occurring within three distinguishable stages (69):

- (i) The ignition phase, leading to ionisation and arc formation at some discrete and localised area between the electrodes, following the application of a voltage.
- (ii) The main discharge - an electron "avalanche" which strikes the anode and takes place at very high current density, due partly to the low electrical resistance in the discharge channel following phase (i) and also to the hydraulic restriction of the dielectric fluid and to the magnetic "pinch" effect. Later, ions strike the cathode, which is heated less rapidly than the anode.
- (iii) Local melting and even vaporisation of the electrode metal occurs in the region of the spark strike, followed by its expulsion. Under relatively long pulses, the discharge will tend to assume the characteristics of an arc and current density will fall.

3.2 ADVANTAGES OF EDM

Many advantages are claimed for the use of EDM in preference to conventional die sinking procedures. The following is a comprehensive list of the advantages claimed (71):

- 1 Materials may be machined in the hardened condition, thereby avoiding distortion and cracking of intricate shapes.

- 2 Complex shapes may be produced in a single die block rather than separate sections, which improves dimensional accuracy.
- 3 Accurate alignment and uniform die clearance produced by EDM means longer die life.
- 4 EDM finish has been found to be more desirable than conventionally produced finish for many applications.
- 5 The crater (matte) surface produced by EDM requires less bench time in mould making.
- 6 Dies and moulds are easily modified for engineering changes.
- 7 Carbide dies are produced at lower cost.
- 8 Procurement time is reduced by using EDM for tooling production.
- 9 Die repair is simplified.
- 10 Close tolerances can be realised.
- 11 Mating die halves can be bedded in by using one half as the electrode and the other as the workpiece.
- 12 Die life may be increased.

As with any list of advantages they may not all apply to one specific case and there are disadvantages, these are considered in later sections.

3.3 EDM EQUIPMENT

An EDM machine must combine four functions: mechanical - holding and moving the tool and workpiece; spark gap control; spark generation; and dielectric control - circulation and filtration of the dielectric fluid (68).

In the early machines relaxation type generators were used, and still persist in the low energy (finishing) range. In these generators a capacitor is charged from a dc power supply. The pulse form and time depends upon the impedance of the discharge circuit and little control can be exercised. Generally the peak currents are high, up to 100 A (68).

The introduction of transistorised generators, which produce voltage with accurately controlled characteristics, has enabled the main spark-erosion parameters to be controlled with reasonable accuracy (72). The amount of power released by the spark is controlled by the generator, thus a range of surface finishes can be produced by variation of the

generator parameters. By careful choice of the electrode material wear can be kept to below 1%, although this varies with spark duration, being a minimum for long discharges and maximum for short ones.

To attain stable machining conditions and to protect the electrode surfaces against arc damage, penetration of the tool into the workpiece must be accomplished whilst maintaining a controlled gap size. This is achieved using an adaptive control system with a sensitive servo-mechanism incorporated in the machining head (66).

Reciprocation of the machining head has been shown to enhance metal removal rates, improve surface finish and resultant microstructures by assisting flushing by the dielectric (73). More recently electrode orbiting techniques have been introduced to aid the removal of debris from the spark gap and to increase the metal removal rate (74).

To ensure accuracy of dimensions in the workpiece the machine tool must be rigid to resist the dielectric pressure (75). In particular, the machining head must be rigid over the full length of travel. Most machines are of standard vertical motion with machine tables up to 1 m x 2 m being most common. The table design must have jig bore accuracy and repeatability and accurate location of the tool and workpiece is essential to precision.

3.4 EDM MATERIALS

3.4.1 Electrodes

The economic use of the EDM process is almost entirely controlled by the cost of making electrodes (76). In most cases, to obtain the accuracy and finish, more than one electrode is required to finish each cavity. In standard EDM work the manufacturing of electrodes represents an estimated 40% to 60% of the total EDM cost (77). Hence the selection of the electrode material and the method of manufacture is most important. The decision is based on many factors, including: workpiece material; production requirements; power supply; machining variables; electrode geometry; dielectric; and flushing technique (78). Although electrodes are expensive, hand finishing or benching requirements may be eliminated or at least substantially reduced.

The electrode should not normally be made of the same material as the workpiece (79). When making an electrode, provision must be made for what is commonly called "overcut". The electrode must be smaller than the cavity being sunk so that a flow of dielectric may take place between the electrode and workpiece, otherwise poor cutting or arcing will occur. The electrode material must be dense and homogeneous to ensure even discharge. It must resist corrosion during storage and temperature effects during sparking. It should be easy to fabricate and reasonably cheap. The methods of electrode production include: moulding, stamping, casting, spraying, orthodox machining, and total form machining. Materials used include: copper, brass, aluminium, zinc, copper-tungsten, tungsten-copper, tungsten carbide, and graphite.

Graphite is probably the best electrode material, followed by copper; and is generally considered to have the best metal removal characteristics both for bulk metal removal and in the production of intricate shapes. Further reasons for its use include good thermal and electrical conductivity, good machinability and relatively low cost.

Graphite electrode material is produced by moulding a mixture of petroleum coke and coal tar pitch and heating it in a non-oxidising atmosphere to about 1000°C to form a carbon, which is then transformed to graphite by heating to between 2500°C and 3000°C (80). It is manufactured in various grades that differ in density, grain size and porosity. Because these factors affect both wear rate of the electrode and surface finish of the workpiece, they must be considered carefully to assure the best possible job at the lowest possible cost. Fine grained material should be used where intricate detail is required.

Electrodes must be straight, parallel and proper size to allow for the correct overcut, and inspection before use is essential. Surface finish should be as good or better than the requirement for the finished part (75).

3.4.2 Dielectrics

The dielectric acts as a barrier between the tool electrode and the workpiece and its functions in EDM are (81):

- (I) To remove machining debris from the small gap-spacing between the electrode and workpiece.

- (II) To remove some of the heat caused by the repetitive transient electrical discharges from the sparking region.
- (III) To provide a containment action for each individual discharge.

The requirements of a dielectric include: relatively high flash point; low viscosity; chemical neutrality; non-toxicity; cheapness and availability (69). Dielectric fluids used in EDM equipment have been petroleum products, usually treated to remove odour and inhibit bubble formation. Silicone fluids and mixtures of silicones with petroleum fluids are also used, but are expensive.

In the role of aiding the electrical breakdown process, the contamination of the fluid can cause a more stable EDM operation, although accompanied by a lower machining rate (81). An increase in debris concentration has been shown to increase the tool/workpiece erosion rate when machining die steel (82). For improved precision it is necessary to have a particularly efficient filter system and an oscillating mechanism to assist flushing.

3.5 MACHINING CONDITIONS

In determining the optimum machining conditions the following factors must first be considered: desired accuracy of the workpiece; roughness of the workpiece; and metal removal rate. These parameters are inter-related. The material parameters comprise those physical constants of the workpiece material which influence the thermal erosion process and comprise: thermal conductivity; specific heat; melting and boiling temperature; melting and evaporation heat. These parameters underlie the machining conditions which should be used. Following the choice of tool electrode material and the provisions for flushing, appropriate machine adjustments must be decided. A machine equipped with a controlled pulse generator must be set for: pulse duration, pulse cycle time, generator open voltage, polarity of the electrode, servo conditions, and flushing conditions (69).

Accuracy and efficiency of machining result only when a constant and reliable gap-distance is maintained (83). This is assured by a servo-mechanism which advances or retracts the tool by sensing deviations in the gap voltage. Removal rate of material depends on the machining area, the shape and composition of the workpiece to be eroded, and

electrical parameters such as current, frequency, duration of discharge, and properties of the electrode material.

Low frequency and high current produce the fastest cutting and the roughest finish on the workpiece but, at the same time, the lowest electrode wear. As frequencies increase metal removal rate decreases, but finish is finer. Reverse polarity, when the workpiece is negative in respect to the electrode, works best with graphite electrodes and the more popular tool steels to provide no-wear conditions. However, standard polarity works best, as a general rule, with the metallic electrodes and for finishing with graphite (79).

Finishing EDM passes should be undertaken at low amperage to produce a surface finish of 0.625 to 0.750 micrometres (25 to 30 microinches) CLA and to minimise surface damage caused by the heating effect (84). With extreme care and control, a finish of 0.200 to 0.250 micrometres (8 to 10 microinches) CLA can be obtained (85).

The electro-discharge machined surface is composed of many hemispherical craters of microscopic size which give a matte appearance. Whilst satisfactory for some applications, this may be unsuitable for others and some conventional finishing may be necessary (69).

3.6 METALLURGICAL TRANSFORMATIONS

Complex surface changes are observed when ferrous and non-ferrous materials are subjected to EDM. The most commonly observed phenomena are: slip and twinning; cleavage; lattice defects; residual stresses; and phase changes. In general, pure non-ferrous metals do not exhibit phase changes, whereas ferrous metals and alloys: pure iron, carbon steel and alloy steels, exhibit changes of increasing complexity. These phase changes can significantly affect the surface hardness and wear resistance of the material being machined (86).

After erosion the surface of nearly all materials is covered by shallow overlapping craters, whose diameter to depth ratio varies from 5 to 50. The surface of each crater has been melted and refrozen, usually epitaxially, and this layer frequently undergoes chemical and structural changes. The depth of the frozen layer ranges from 500 to < 1 micrometre (20,000 to < 40 microinches), depending on the spark and

the material, this layer may be highly strained and contain cracks. Immediately beneath the frozen surface is a macro-strained zone that may show evidence of mechanical deformation (eg slip or phase changes); cracks in the frozen layer continue into this zone, which may be much deeper than the melted layer (in long pulse machines) or of about the same depth (lower energies in relaxation circuit machines) (68).

The metallurgical examination of various tool materials machined by EDM shows that some exhibit a shallow "white layer". This condition is apparent in heat-treated material subsequently cut by EDM, but does not appear on tools which are annealed before cutting and heat treated subsequently. The "white layer" has been identified as a rehardened zone produced by the heat generated from the sparks in EDM (87). The heat generated in EDM is sufficient for austenitisation to occur and a quench effect is provided by the dielectric fluid and bulk of tool material (88).

Quite complex changes are likely at the surface of eroded material. The molten surface of a spark crater suddenly becomes charged with alloying material which arises from the opposite electrode and from the cracking of the dielectric (70).

In an investigation to determine the effect of EDM on the surface of pure iron, low carbon steel (0.1%), high carbon steel (0.7%) and low carbon stainless steel, it was found that the white layer consists of superimposed strata derived from melted and then re-frozen material. The carbon content of the white layer increased up to a maximum of about 3.40% when machining under carburising conditions. This was independent of the carbon content of the matrix, for material whose carbon content was between 0% and 0.8%. The increase in carbon content in the white layer depends mainly on the pyrolysis products following cracking of the dielectric and was chiefly confined to the melted and refrozen zone. The structure of the white layer which was formed on pure iron and low carbon steels consisted mainly of carbides in acicular or globular form, distributed in an austenite matrix, independent of the composition of the base metal or the electrode (graphite or copper) (89).

3.7 SURFACE INTEGRITY

In the production of a manufactured component surface integrity has been defined as (90):

"Surface integrity is the unimpaired or enhanced surface condition and/or properties of a material resulting from the impact of a controlled manufacturing process. Surface integrity has two ingredients: those which relate to the characteristics immediately below the surface; and surface texture."

Surface integrity consists of some twenty five elements, which include cracks (micro and macro), phase transformations and residual stresses. Data developed in recent years has brought into critical focus many situations where component performance is dependent upon the characteristics of machined surfaces. Material removal methods can exhibit a strong influence on the fatigue strength and other mechanical properties exhibited by machined surfaces. The higher strength materials, which are also of higher hardness, show a greater sensitivity to surface strength characteristics, especially fatigue resistance (91).

Tool and die steels sustain surface damage during EDM (92). High thermal stresses are generated by the EDM process and these may give rise to large residual tensile stresses, microcracking and other effects. The depth of the damaged layer is related to the machining conditions and can be minimised by careful selection of finishing cut parameters.

Spark machined surfaces have been found to produce lower fatigue values than ground and polished surfaces. When the damaged layer is removed by lapping some improvement in fatigue life is possible. Impact tests also confirm the surface damage produced by EDM (93). The problem can be eliminated by completely removing the surface layer. The influence of spark machining on the tensile fatigue properties of steel will depend greatly on the sensitivity of the material to spark damage.

Conflicting evidence exists about the way in which these surface changes affect the life of a die. In a recent investigation no evidence was found to suggest that spark erosion reduces die life in brass stamping (94).

CHAPTER FOUR

EXPERIMENTAL APPROACH AND DESIGN OF EQUIPMENT

4.1 INTRODUCTION

The remit for the project was to consider the optimisation of materials and methods used in the manufacture of cast dies. Such a remit requires a comprehensive approach in which all aspects of manufacture must be considered. In order to prepare a programme of experimental work for the investigation, the project was divided into four phases:

- I Evaluation of Mould Materials
- II Mould and Casting Production
- III Metal Melting and Treatment
- IV Requirements for Finishing

The following sections describe the experimental approach and methods, and the design and manufacture of special equipment for each of the phases of the investigation. However, detailed consideration of refractory material selection, mix specification and quality control procedures is presented in Appendix One. Similarly, information relevant to the CO₂/sodium silicate process is presented in Appendix Two.

4.2 EVALUATION OF MOULD MATERIALS

For the reasons outlined in Section 1.3, the Shaw Process was selected as the method of mould manufacture and details of the process are given in Section 2.1. The refractory aggregates and binder used for the Shaw Process are relatively expensive, and moulding costs are high if the whole mould is produced by the process. The benefits conferred by the Shaw Process are only required where the mould and metal are in contact. Costs may be reduced by using a Shaw Process facing in conjunction with a cheaper backing material. It was decided from the outset to use this composite moulding approach.

The evaluation consisted of two stages. Firstly there was the requirement to determine suitable mix compositions for both the facing and backing materials. Secondly a programme of experiments was required to determine the properties of the mould materials. In particular: strength, permeability and expansion characteristics are important for the satisfactory performance of the mould. As the moulds must be fired at a high temperature, the influence of firing temperature on these properties was of interest. When using a composite moulding technique it is essential that the materials be compatible with regard to expansion characteristics. It was necessary, therefore, to establish some information about the characteristics of the bond between the facing and the backing materials.

4.2.1 Backing Material

The requirements of the backing material are that it should be sufficiently strong to act as a support for the mould, permeable to gases and be relatively cheap. Silica sand is excluded primarily because of its high and non-linear expansion characteristic. An alternative cheap material suggested in the literature is chamotte, a crushed used firebrick material. Although readily available in the UK, it is not supplied in graded form and this results in inconsistent moulding mix properties. For the material supplied, the high proportion of coarse particles resulted in poor strength characteristics even when using between 6% and 10% of sodium silicate. At an early stage it was necessary to reject chamotte as being unsuitable for the investigation.

To obtain consistent properties, material of consistent grading is required. Molochite meets this requirement and, although more expensive than chamotte, it is cheaper than mullite which was the material chosen for the facing material. Molochite was available in three principal grades: -8 + 16; 30/80; and -120 (BSS), although other grades can be obtained. The coarse grade is the cheapest but single grades provide poor strength, even with high binder additions. To minimise binder requirement, whilst still providing adequate strength and permeability, admixture of the grades was necessary.

A satisfactory mix specification based on 60% -8 + 16; 20% 30/80 and 20% -120 mesh grades, to which 6% by weight of C125 sodium silicate was added, was developed. The optimum gassing conditions for this mix were determined by varying gassing time and gas flow rate. This established that a flow rate of 5 litres/minute for two minutes produced the best results for standard AFS compression specimens. A compression strength of 500 lbf/in² (3450 kN/m²) was obtained on standing for 24 hours after gassing. Permeability values for the material were in the region of 100.

Having established a mix specification it was then necessary to determine the influence of firing temperature and time on the properties of the backing material. The properties which are of interest include: dimensional stability; retained strength on cooling; hot strength; gas evolution and permeability. To evaluate these properties standard tests were used, details of which are given in Appendix Three. The tests included the preparation of standard AFS compression and tensile strength specimens which were fired to different temperatures for predetermined times. These tests provided information about permeability changes and retained strength on cooling. In addition, by using a simple gauge, an indication of dimensional stability was obtained by measuring the length of the compression strength specimens at room temperature before and after firing. Further experiments were undertaken to establish hot strength, hot deformation and gas evolution characteristics.

4.2.2 Facing Material

The preparation of the facing slurry is one of the most important aspects in the production of a precision casting by the Shaw Process. The quality of the facing slurry determines the quality of the casting surface finish. The slurry must have the correct viscosity to ensure replication of detail, air bubbles must be excluded and the material must set without cracks if faults are not to show on the casting surface.

Many factors are involved in the establishment of a mix specification. The refractory material and grading, the proportion of binder to refractory, and the type and quantity of gelling agent used all exert an influence on the properties of the slurry. In addition the quality, as supplied, of the refractory and the binder, the ambient temperature and relative humidity during processing are influencing factors. A detailed programme of experiments was therefore conducted to establish a suitable mix specification. For reasons which will be considered elsewhere, it was not possible to maintain a standard mix specification for the facing slurry throughout the investigation.

A comprehensive series of experiments, similar to those conducted on the backing material, was also used to evaluate the properties of the facing material.

4.2.3 Backing/Facing Interface

When using the composite moulding method, the extent of bond development at the interface between the backing and facing materials is important. In practice, when moulds are being produced, the facing slurry is poured into contact with the pattern and the backing material and is gelled in this position. The strength of the bond is important at two stages. Firstly, there must be sufficient green bond to ensure that the whole mould separates from the pattern without separation at the interface. Secondly, firing should promote bonding at the interface; providing that differential expansion does not cause separation at the interface.

To simulate this procedure and provide data about the strength of the interface bond, a modified AFS tensile specimen was adopted. Half-tensile test specimens were produced from the backing material (see

Figure 4.1) and gassed in the mould. The other half of the specimen was then produced by pouring the slurry into the mould containing the backing material half-tensile specimen. After gelation, the whole specimen was separated from the mould. A series of experiments to determine the retained tensile strength after firing was undertaken using specimens produced in this way.

4.2.4 Special Equipment Manufacture

Although conventional sand testing procedures and equipment were used, there was a requirement for certain specialist equipment to be manufactured. To accommodate the testing of high strength refractory material, a Hounsfield tensometer was used because existing sand testing equipment was unsuitable. A compression fixture was available for this equipment and a pair of specimen holders were manufactured to make it suitable for standard AFS compression strength tests (see Figure 4.2). However, to enable the necessary tensile strength tests to be conducted, a complete set of special equipment was required. This included:

Tensile testing fixture	(see Figure 4.3)
Tensile specimen mould holder with gassing facility	(see Figure 4.4)
Split specimen rammer	(see Figure 4.5)
Tensile specimen moulds	(see Figure 4.6)
Tensile and compression specimen slurry pouring plates	(see Figure 4.7)

Compression strength specimens in facing slurry were produced using wooden moulds (see Figure 4.8) and a pouring plate (see Figure 4.7). The gauge manufactured to enable the length of AFS compression specimens to be measured before and after firing is shown in Figure 4.9. Specimens for hot distortion tests were produced using the equipment shown in Figure 4.10 (i-iv) and those for high temperature tests in Figure 4.10 (v).

4.3 MOULD MANUFACTURE

4.3.1 Ingot Castings

The dimensions of the ingot casting pattern are shown in Figure 4.11. A circular cross section was chosen in preference to rectangular to reduce the number of corner effects. Two patterns were produced, one in an aluminium alloy and the second in graphite to enable a comparison of the two materials' performance to be made. The patterns were mounted on an aluminium pattern plate, Figure 4.12, and provision was included for an air supply to assist pattern separation from the mould. The moulding box was a simple plywood frame, Figure 4.13, which was suitable for composite mould or block Shaw mould production. For composite mould production an aluminium alloy preform pattern was also required, Figure 4.14.

4.3.2 Composite Moulds for Ingot Castings

In the manufacture of composite moulds the following procedure was adopted. The backing material was mixed in 5 kg batches in a laboratory paddle mixer to the following specification:

3 kg	-8 + 16 mesh	Molochite
1 kg	-30 + 80 mesh	Molochite
1 kg	-120 mesh	Molochite
300 gm	C125	sodium silicate

The materials were mixed for three minutes before discharging into a container which was sealed before the material was used for moulding.

The preform pattern, plate and moulding frame were coated with a wax polish before the backing material was introduced and compacted using a peg rammer. The top was strickled level and a vent wire used to make a hole in each corner of the mould. A probe was inserted and carbon dioxide introduced into each vent for 30 seconds at a flow rate of 5 litres/minute. After gassing the backing mould was separated from the pattern and frame. The procedure was repeated until the required number of backing moulds had been produced.

The ingot pattern was attached to the pattern plate and the assembly was coated with a thin layer of warmed Trenn Mittel W70 release agent,

which was lightly buffed with a soft cloth. A backing mould was placed in the moulding frame and these were located on the pattern plate. A facing slurry mix was then prepared to the following typical specification:

500 gm	-100	mesh Mullite.	.
250 gm	-30	mesh Mullite	
250 gm	-8 + 16	mesh Mullite	
225 gm		Ethyl Silicate	
10 gm	10% NH ₃	Solution (gelling agent)	

The gelling agent was added to the ethyl silicate first and the two were stirred together for 15 seconds. At this point the refractory aggregate was stirred in and mixing continued for a further 45 seconds. The slurry was then poured quickly but carefully into the mould cavity around the pattern. The pattern plate was tapped lightly with a soft mallet to release air bubbles trapped at the pattern surface.

After gelation, which occurred within 2½ to 3 minutes, the moulds were allowed to harden further. Mould stripping was performed between 7½ and 9 minutes after slurry mixing commenced. Immediately after separation the moulds were ignited to burn off the evolved alcohol and then fired in an electrically heated kiln to a maximum temperature of 750°C for two hours.

The mould was separated manually from the pattern. This operation presented some difficulty initially and the moulds were damaged during the separation. To overcome the problem, the pattern was provided with a vent, as mentioned earlier (see Figure 4.11). Before pouring the slurry into the mould this vent was sealed with a thin wire inserted through the pattern plate base. After the slurry had set the wire was withdrawn and an air line was attached to the pattern plate base. To aid mould separation from the pattern air, at a pressure of 0.1 bar, was introduced using a foot-pedal operated valve at the moment manual separation was effected.

4.3.3 Test Castings

To enable a realistic evaluation of the capabilities of the Shaw Process to be obtained, four test castings were used. The first of these was a stepped block designed to provide basic information on the

influence of section thickness on dimensional accuracy. The other three castings were suggested by companies liaising with the investigation. The four castings were:

- (i) Stepped Block
- (ii) Spider Forging Die
- (iii) Flange Yoke Die
- (iv) Retractable Die Core for a Gravity Die Casting Die

4.3.4 Pattern Equipment

In order to obtain a precision casting it is a prerequisite that the pattern and moulding equipment are produced to a high standard of accuracy. To enable a composite moulding technique to be employed, preform and precision patterns were required. For simplicity in use and ease of handling, wood preform patterns were preferred instead of layers of sand or felt, etc, interposed between the precision pattern and backing material. The preform patterns were manufactured to provide a 10 to 13 mm gap between the backing mould and the precision pattern. With one exception the precision patterns were produced in aluminium alloy. The pattern for the retractable die core was produced in graphite to enable further evaluation of its suitability as a pattern material.

Patterns were mounted on precision machined aluminium alloy pattern plates, 12.5 mm thick, and the location of the moulding box and pattern plate was by conventional precision ground hardened steel bushes and pins. The pattern plates also incorporated precision tapered location dowels to permit mould to mould location without the need for boxes. Pattern faces vertical to the plane of the pattern plate were machined with 1° taper to facilitate pattern removal from the mould. The accurate location of patterns and other items on the pattern plate, particularly when accurate matching across the mould joint was required, was achieved by jig boring.

The manufacture of the pattern equipment was undertaken by a skilled engineer and the exact details of manufacture are not included in the thesis. However, the pattern layout drawings are provided and include most of the relevant dimensional information. For the sake of clarity on these small drawings, details of fasteners are omitted as these followed standard practice.

The pattern equipment is shown in the following Figures:

Figure 4.15

Pattern equipment layouts for the stepped block test casting.

4.15 (i): This drawing shows the standard pattern plate layout used for all the patterns. The location pin centres, together with the position of the inside of the moulding box, are shown. Superimposed on this are the positions of the preform and precision cope patterns for the stepped block.

4.15 (ii): The drawing shows the layout for the preform cope pattern.

4.15 (iii): The drawing shows the layout for the precision cope pattern.

4.15 (iv): This drawing shows the dimensions of the precision pattern for the stepped block.

4.15 (v): The drawing shows the preform drag pattern and precision drag pattern layout. The precision drag pattern plate incorporates two location dowels only as all the mould cavity is contained in the cope mould. The preform drag pattern locates onto the location dowels so that the single pattern plate can be used in place of two.

Figure 4.16

The dimensions and construction of the feeder head pattern are shown in this Figure. The calculations for the feeder heads and gating systems are presented in Appendix Four. Where applicable, the same components were used in the gating and feeding systems for all four test castings.

Figure 4.17

The dimensions for the sprue used for each of the test castings are shown in this Figure.

Figure 4.18

The ingate for the stepped block was formed by a Washburn Core and the dimensions of the core box to produce this are shown in the Figure.

Photographs showing the preform and precision cope and drag pattern assemblies are shown in Figures 4.19 and 4.20 respectively.

Figure 4.21

Pattern equipment layout for the spider forging die casting.

4.21 (i): The drawing shows the layout for the preform cope pattern. The dotted lines represent the position of location dowels, gating system and feeder head.

4.21 (ii): Only the working face of the die (produced in the drag) was produced with a precision pattern and facing slurry. The die block was produced in backing material coated with a suitable mould wash. However, the gating and feeding system were moulded in the facing slurry and these dimensions are shown in the Figure.

4.21 (iii): The drawing shows the layout for the drag preform pattern.

4.21 (iv): The drawing shows the layout for the drag precision pattern.

4.21 (v): The dimensions of the working die face and cavity are shown in this Figure. The impression in the pattern was produced by EDM. Photographs of the preform and precision cope and drag pattern assemblies are presented in Figures 4.21 (vi) and 4.21 (vii) respectively.

Figures 4.22

Pattern equipment layouts for the flange yoke die casting.

4.22 (i): The drawing shows the layout for the cope preform pattern. As for the spider forging die, only the working face of the die (produced in the drag) was produced with a precision pattern and facing slurry. However, the gating system and mould location dowels were moulded in the facing slurry. NB The \varnothing 152 mm dimension provides a location point for an exothermic sleeve.

4.22 (ii): The drawing shows the location of precision components for the cope layout.

4.22 (iii): The drawing shows the layout for the drag preform pattern.

4.22 (iv): The drawing shows the layout for the drag precision pattern.

4.22 (v): The dimensions of the working die face and cavity are shown in this Figure. The impression in the pattern was produced by EDM.

Photographs of the preform and precision cope and drag pattern assemblies are shown in Figures 4.22 (vi) and 4.22 (vii) respectively.

Figure 4.23

Pattern equipment layouts for the retractable die core.

4.23 (i): The drawing shows the layout for the cope preform pattern.

4.23 (ii): The drawing shows the layout for the cope precision pattern, but with a cylindrical envelope representing the actual pattern.

4.23 (iii): The drawing shows the layout for the drag preform pattern.

4.23 (iv): The drawing shows the layout for the drag precision pattern, but with a cylindrical envelope representing the actual pattern.

4.23 (v): This drawing shows the dimensions of the precision pattern.

Photographs of the preform and precision cope and drag pattern assemblies are shown in Figures 4.23 (vi) and 4.23 (vii) respectively.

Figure 4.24

The drawing shows the locating pins:

- (1) Cope box to pattern plate.
- (2) Mould to mould dowel.
- (3) Precision pattern dowel.
- (4) Drag box to pattern plate.

4.3.5 Moulding Boxes

Considerable attention was given to the design of the moulding box which was fabricated from mild steel. The design enabled each of the four pattern assemblies to be accommodated. The moulding box halves were machined on their mating surfaces and their internal surfaces. A 5° taper was used in conjunction with four spring-loaded retaining pins to enable the mould to be separated from the box for firing and be accurately relocated in the box subsequently.

Details of the moulding boxes are shown in Figure 4.25.

4.25 (i): The drawing shows the design of the cope moulding box.

4.25 (ii): The drawing shows the design of the drag moulding box.

4.25 (iii): This drawing shows the details for the mould retaining pins (four per box half).

4.3.6 Mould and Pattern Separation

The separation of the pattern from the mould is a source of dimensional inaccuracy in most moulding processes. It is an aspect which requires particular care and attention in a precision moulding process. To provide consistent pattern stripping a simple, gravity action stripping machine was manufactured, details of which are shown in Figure 4.26.

4.26 (i): The Figure shows a single end elevation view of the pattern stripping machine.

4.26 (ii) and 4.26 (iii): These Figures provide details of the parts comprising the pattern stripping machine. Not shown in detail is the toggle clamp which was a bought-out item.

4.3.7 Composite Moulds for Test Castings

The procedure for composite mould manufacture commenced with the production of the backing mould. The backing material was prepared in 24 kg batches in a batch, screw-type mixer. The mix specification was:

13.6 kg	-8 + 16 mesh	Molochite
4.5 kg	-30 + 80 mesh	Molochite
4.5 kg	-120	mesh Molochite
1.4 kg	Cl25	sodium silicate

The refractory grades were mixed dry for one minute prior to adding the sodium silicate, when mixing continued for a further two minutes. The mixed material was discharged into containers which were sealed until the material was required for moulding.

The preform pattern, pattern plate and the inside faces of the moulding box were coated with a thin layer of wax polish to aid separation of the mould. The whole assembly was then clamped in position on the pattern stripping machine. See Figure 4.27.

The backing material was placed in the moulding box and hand rammed in layers until the box was full, when the material was flat-backed and the excess strickled off. The mould was then vented and gassed using a probe arrangement with a carbon dioxide flow rate of 5 litres/minute. After gassing the pattern was mechanically separated from the mould. See Figure 4.28.

4.3.8 Precision Mould Production

The precision pattern plate assembly was prepared by careful cleaning to remove any surface dirt or wax. A thin coating of Trenn Mittell W70 pattern release agent was then applied and buffed with a soft cloth. To ensure that a thin and even coating of release agent was obtained it was preheated in a water bath at a temperature of 50°C. The precision pattern plate assembly was then located onto the moulding box containing the backing mould and the whole assembly transferred to the pattern stripping machine and clamped in position.

To prevent air bubbles from being trapped at the pattern surface, a vibrator unit was incorporated in the pattern stripping machine. A Ling Dynamic Systems 400 series unit, operating at a frequency of 10 Hz and an amplitude level setting of 3, was employed. See Figure 4.29.

The facing slurry was prepared by mixing accurately weighed amounts of ethyl silicate, refractory and gelling agent. In principle the

procedure was similar to that described in the production of the ingot casting mould. The vibrator was switched on before the slurry was mixed so that vibration of the pattern plate was continuous during mould filling and gelation. As soon as gelation occurred, the vibrator was switched off and the vibrator unit removed from the pattern stripping machine.

After separation from the pattern, the mould was immediately transferred to a heat resistant metal grid and ignited to burn off the excess alcohol, see Figure 4.30. When the burn off was complete, the mould retaining pins were released and the moulding box separated from the mould. The mould, standing on the heat resistant grid, was then transferred to the kiln for firing.

The moulds were heated at a rate of 100°C/hour to a maximum temperature of 750°C, at which they were held for a period of two hours. The mould was then allowed to cool to room temperature in the kiln. There was no significant difference in the preparation of cope and drag moulds. See Figures 4.31 and 4.32.

4.3.9 Preparation for Casting

The moulds were prepared for casting by first cleaning to ensure that no mould debris was present. Mould halves were located using tapered conical dowels (see Figures 4.24 (2) and 4.31). This method was used in preference to relocating the mould in the box and using the box pins to locate the two mould halves.

The mould joint was sealed externally with a refractory luting compound and the mould halves were clamped together using two simple clamps, Figure 4.33. A separately prepared refractory pouring cup was positioned over the sprue and sealed in position. The corebox for the manufacture of the pouring cup is shown in Figure 4.34. The sealing compound, although air drying, was torched using an oxy-propane burner to eliminate moisture. The mould was then ready for casting, see Figure 4.35.

4.4 METAL MELTING AND TREATMENT

Steels containing chromium require special consideration during processing when castings of good surface finish are required. Some of the problems which may be encountered, such as: surface scale caused by oxidation; chemical reaction between the mould and metal resulting in decarburisation; or surface pitting; were considered in section 2.2. Several methods for the elimination of these defects are suggested in the literature. To evaluate these and to establish correct procedures for metallurgical processing of the melt, a series of experiments was conducted.

4.4.1 Ingot Castings

For economic reasons the initial work to establish the influence of mould and melt conditions on the surface finish and quality of castings was undertaken using small ingot castings of 1 kg weight. The metal was melted using a 10 kW radio frequency power unit. A furnace unit was designed and manufactured especially for this work and is shown in Figure 4.36.

After preheating the crucible using a graphite susceptor (Figure 4.37), melting was accomplished in less than 20 minutes using a charge consisting of billets of 25 mm \varnothing x 25 mm long cut from virgin bar stock. The billets were preheated to a temperature of 300°C before charging them into the furnace. The temperature of the melt was monitored with a platinum-platinum/13% rhodium thermocouple, enclosed in a silica sheath, which was inserted vertically in the melt to a point 25 mm below the surface. When the metal was at the required temperature the slag was removed, additions were made and the metal poured directly into the mould.

4.4.2 Test Castings

The melts were prepared using virgin bar stock supplied in cast bars of 25 mm \varnothing x 250 mm long to the analysis shown in Appendix Five. Each melt weighed between 20 and 25 kg and the metal was melted using a 40 kW GWB medium frequency induction furnace and sillimanite crucibles. The metal temperature in the furnace was measured using a platinum-platinum/13% rhodium immersion thermocouple linked to a chart recorder.

The metal was tapped into a teapot ladle manufactured in sillimanite refractory. The ladle was preheated using an oxy-propane burner. Deoxidation additions wrapped in aluminium foil were plunged into the metal. The slag was skimmed from the surface of the metal, the metal temperature was determined using a Leeds and Northrup meter dipstick and the metal poured.

4.4.3 Metal/Mould Reactions

A series of ingot castings was produced to investigate the influence of variables such as: mould material; mould preheat temperature; metal temperature; metal treatment; and mould atmosphere. More specifically, these variables were:

mould materials	mullite facing mullite facing with graphite addition zircon facing machined graphite mould
mould preheat temperature	ambient 500°C 800°C
metal pouring temperature	1600°C 1650°C 1700°C
metal treatment	nickel addition deoxidiser addition grain refiner addition
mould atmosphere	air nitrogen argon

The variation in practice from that described in previous sections and the requirement for special equipment are detailed below.

Mould Production:

In the preparation of the mullite facing slurry containing graphite the following procedure was adopted. The graphite, which was of -100

mesh, was added as a direct substitute for the fine mullite. As the addition was made on a weight basis and graphite is less dense than mullite, additional ethyl silicate was required to produce a fluid slurry. Although mould ignition was carried out in the manner described previously, mould firing procedure was modified. As mould firing was carried out under oxidising conditions, some graphite was burnt out from the surface. To minimise this effect the mould cavities were covered with a refractory slab.

For the purpose of evaluating a semi-permanent moulding process, a machined graphite mould was produced. The dimensions of this mould are shown in Figure 4.38. This mould was preheated to 150°C before casting to ensure the absence of moisture absorbed from the atmosphere.

The refractory moulds were preheated in a muffle furnace to the required temperature. Moulds containing graphite being covered during preheating. When the metal was at the required temperature the mould was removed from the furnace and casting accomplished within a minute of the transfer.

Metal Treatment:

All additions to the melt were made on a weight basis, as a percentage of the metal weight. The additions were wrapped in aluminium foil and plunged into the melt. The nickel addition was made in the form of 3 mm shot and the packets were preheated to 150°C before plunging into the metal. The grain refining additions were crushed to -100 mesh before use.

Mould Atmosphere:

The procedure for atmosphere control was based on the use of closed containers which could be flushed with an inert gas. Air removal by vacuum followed by back-filling with an inert gas was not practical. The containers used for the ingot castings and test castings are shown in Figures 4.39 and 4.40 respectively. The containers were lined with kaowool fibre. Only moulds at ambient temperature were processed in an inert atmosphere. The ingot moulds were enclosed in the container for 30 minutes before casting. During this period dry nitrogen was passed through the container at the rate of 2 litres/minute. Just before casting the flow rate was increased to 10 litres/minute to

maintain a nitrogen curtain during casting. After casting the container was sealed and the nitrogen flow rate reduced to 2 litres/minute. This flow was maintained for three hours until the casting had cooled well below 500°C.

The procedure adopted for the test casting moulds was as follows. A plastic sheet with a cut out for the pouring cup was taped in position to seal the top of the box. Nitrogen was introduced through the manifold at a flow rate of 10 litres/minute for at least one hour before the mould was poured. After casting, the top cover was clamped in position on the box and the nitrogen flow rate was reduced to 5 litres/minute. This flow rate was maintained for a period of six hours after casting had taken place.

After separation from the moulds the castings were shotblasted in a Tilghman hand chamber type, shotblast cabinet using No 3 Blastite abrasive. No other operation was performed on the ingot castings. Grinding and chipping operations were necessary to remove the clearance flash on the spider dies and flange yoke dies. These operations did not affect the as-cast surface of the working die surfaces.

The ingot castings were examined visually to assess the influence of mould and metal processing variables on the quality of the cast surface. The visual examination was supported by metallographic examination, including grain size measurement, and microhardness measurements. The test castings were examined visually, to identify the presence of surface defects, and subjected to dimensional metrology and surface finish assessment. Further details of these examination procedures are provided in the relevant results sections.

4.4.4 Determination of Contraction Allowance for H13 Die Steel

A comparison of the test casting dimensions with those of the pattern will show a deviation which is the result of two factors. Firstly there will be the effect due to contraction, and secondly the effect due to process variations. In order to separate the effects, experiments were conducted to establish the coefficient of linear expansion for the H13 die steel. Details in the literature were imprecise, with contraction allowances between 1% and 2% being recommended (55,56).

In order to establish the contraction allowance for the alloy, it was necessary to establish its melting point (solidus) and its coefficient of linear expansion.

Melting Point Determination:

Two ingot moulds were prepared with a silica sheath positioned centrally through the base to enable a platinum-platinum/13% rhodium thermocouple to be positioned at the casting's heat centre. These moulds were preheated to 500°C before casting from alloy heated to 1650°C in the medium frequency furnace. Cooling curves were plotted using a Linseis TYP 2041 chart recorder.

Coefficient of Linear Expansion:

The coefficient of linear expansion was established by dilatometry using a Linseis L76/01 dilatometer recommended for the range 0°C to 1200°C. The equipment was calibrated using a sample of nominally pure copper (high conductivity/oxygen free) as the standard. By assuming the coefficient of linear expansion of copper to be $16.6 \times 10^{-6}/^{\circ}\text{C}$ and measuring the maximum change in length after heating to a given temperature, the recording charts could be accurately calibrated.

Tests were conducted on three specimens of cast H13 die steel. The dilatometer controller was set to heat the specimen at a rate of 20°C/minute to a maximum temperature of 1000°C and then cool, at a similar rate, to room temperature. However, problems were experienced in obtaining the same maximum temperature for each test. As a result, the coefficient of linear expansion was determined for the temperature range from room temperature to the arrest point associated with the lower boundary of the austenite phase field.

4.5 REQUIREMENTS FOR FINISHING

Two aspects were considered under the heading of finishing, these were the requirements for machining and heat treatment. Whilst the objective of producing precision cast dies was to cast them to size, it was accepted from the outset that this objective was ambitious and might not be achieved. However, because the dies would be cast to shape and the dimensions would be close to size, the requirement for material removal would be minimal. Under these circumstances it was considered that EDM would be the most appropriate finishing method. The castings would also require heat treatment to develop the alloy's optimum hardness for service conditions.

4.5.1 Heat Treatment

The heat treatment procedure recommended for H13 die steel (94,95) is presented below:

- 1 Heat slowly to 815°C (heating rate: 50°C to 300°C/hour, depending on part complexity) and soak for 1 hour/inch (24 minutes/cm). An inert atmosphere is recommended to prevent scaling.
- 2 Transfer to a salt bath maintained at a temperature of 1020°C and soak for 20 minutes/inch (8 minutes/cm).
- 3 Remove and quench into a salt bath at 575°C, holding until the temperature equalises. Quickly withdraw and cool in air.
- 4 A double temper is mandatory. Do not temper until temperature is below 50°C but do not allow to cool to room temperature. First temper at 540°C minimum, soaking at 2 hours/inch (48 minutes/cm). Remove and cool in air. The second temper should be at 570°C minimum. An inert atmosphere is recommended to prevent scaling.

After carefully considering the facilities available within the University, it was decided to sub-contract the heat treatment to a specialist company. The company guaranteed to heat treat the castings to a specified hardness of 52 Rc and to use procedures which would minimise distortion and oxidation of the casting surface. Eight test castings were heat treated, four stepped block castings and four retractable die core castings. Whilst the ability of the cast material

to meet the hardness specification was of interest, so too was the effect of the heat treatment procedure on the dimensions of the test castings. Hardness tests were conducted on the castings before and after heat treatment, and the dimensions of the test castings after heat treatment were compared with the measurements obtained as part of the test casting evaluation procedure.

4.5.2 Electrical Discharge Machining

It has been suggested that cast die impressions might possess superior wear characteristics to those obtained from machined impressions. Removing the as-cast surface of a cast die impression could therefore eliminate this advantage. If the as-cast surface layer is removed by EDM, the metallurgical structure of the machined surface layer may be altered significantly. This, in turn, may have a direct influence on the service characteristics of the cast die. A comprehensive evaluation of the significance of these variables in die life would require trials using a simulation technique or industrial operation of the dies. This aspect was considered to be outside the scope of the current project.

However, it was considered appropriate that the influence of EDM on the cast surface and sub-surface structure of the H13 die steel should be investigated. A limited programme of experiments was conducted using samples cut from the bottom step of the stepped block castings. Three stepped block castings were used:

Number 1: moulded in mullite, cast in a nitrogen atmosphere.

Number 2: moulded in mullite, cast in air.

Number 13: moulded in mullite + 10% graphite, cast in air.

Four samples were prepared from each casting, see Figure 4.41, one of which was used as a control. The three remaining samples from each casting had their cast surface layer removed by EDM. For each set of three samples the amount of material removed was: 0.25 mm; 1.25 mm and 2.50 mm respectively.

After machining the samples were prepared by conventional metallographic techniques to enable electron probe microanalysis to be conducted. The objective of this analysis was to establish elemental concentration and distribution within the surface layers and at specified depths below

the surface. The analysis would be complemented by metallographic examination and microhardness measurements. Further details are provided in the relevant results section.

CHAPTER FIVE

RESULTS

5.1 INTRODUCTION

The results are presented in four sections:

5.2 Mould Material Evaluation

5.3 Metallurgical Processing

5.4 Test Castings Evaluation

5.5 Finishing Procedures

The results are arranged in a logical sequence, in that the results in sections 5.2 and 5.3 were required to formulate the programme of experiments reported in section 5.4. The results reported in section 5.3 concern the programme of experiments conducted, using small ingot castings, to evaluate the influence of mould materials, mould atmospheres and metal additions, etc, on casting quality. Section 5.4 reports the results of the trials using the test castings and includes information on the surface finish and dimensional accuracy of these castings. The final section, 5.5, reports the experiments to evaluate the influence of heat treatment and EDM on the characteristics of the cast H13 die material.

5.2 MOULD MATERIAL EVALUATION

5.2.1 Backing Material

Fireclay Grog (Chamotte) A supply of crushed fireclay grog was located but the supplier was unable to control the grading of the material. Samples of the material were mixed with 4% and 6% sodium silicate and gassed with carbon dioxide, and produced the strength values shown in Tables 5.1 and 5.2 respectively. The gassing curves are shown in Figures 5.1 and 5.2. Even after standing for a period of 24 hours, gassed samples of material bonded with 6% sodium silicate did not develop very high strength, Table 5.3 and Figure 5.3.

Molochite As an alternative to fireclay grog, a blend of three grades of molochite was used to provide a backing material with consistent properties. The effect of gassing time and flow rate on the compression strength of samples of the blend bonded with 6% sodium silicate is shown in Tables 5.4 to 5.7 and graphically in Figure 5.4. The effect of standing time on the strength of gassed samples of the molochite blend is shown in Table 5.8 and Figure 5.5.

Effect of Firing Time and Temperature The influence of firing time and temperature on the compression strength and tensile strength of sodium silicate bonded molochite backing material is shown in Tables 5.9 and 5.10 and Figures 5.6 and 5.7 respectively. The influence of firing temperature on the change in length of the standard AFS compression specimens is shown in Table 5.11 and Figure 5.8. The information presented represents the average values obtained from five separate measurements on each of three specimens. This exercise was carried out for only those samples held at the firing temperature for two hours. For the same group of specimens the permeability before and after firing was determined, and the results are shown in Table 5.12.

High Temperature Tests The equipment available for high temperature tests included: a BCIRA/Ridsdale gas determinator; a BCIRA hot distortion tester; and a George Fischer high temperature testing accessory, type PHT. The recommended test procedures are described in Appendix Three. Samples of backing material were fired at two temperatures, 750°C and 1000°C, and held at the maximum temperature for two hours. The conditions represented respectively the temperature

at which all the test casting moulds had been fired and the temperature recommended in the literature to ensure a sintered silica bond.

Gas Evolution:

The equipment was calibrated according to the operating instructions. Samples of approximately 1 gm were weighed from backing material which had been crushed to granular form using a pestle and mortar. The gas evolution tests were conducted at the recommended temperature of 850°C. The results of the tests are shown in Table 5.13.

Hot Distortion:

Attempts to produce test pieces by core shooting, hand ramming and a combination of the two techniques were unsuccessful. The presence of 60% -8 + 16 mesh material in such a thin section test piece (6 mm) prevented ideal compaction. Although gassing conditions were varied in an attempt to optimise strength, all the test pieces broke during removal from the mould.

Unimpeded Linear Expansion:

The tests were carried out at the recommended temperature of 1000°C. The expansion of the test pieces was noted at half minute intervals and the expansion vs time curves are shown in Figure 5.9 for the samples fired at 750°C and 1000°C. Details are presented in Table 5.14, which also shows the maximum expansion expressed as a percentage of the original specimen length.

Hot Strength:

The hot strength of the backing material exceeded the measuring capability of the equipment and therefore no results were recorded.

5.2.2 Facing Material

Effect of Firing Time and Temperature The tests conducted on the ceramic facing slurry were similar to those conducted on the backing material. The influence of firing time and temperature on the compression strength and tensile strength of the material is shown in Tables 5.15 and 5.16 and Figures 5.10 and 5.11 respectively. The influence of firing temperature on the change in length of the standard

AFS compression specimens, held at the firing temperature for two hours, is shown in Table 5.17 and graphically in Figure 5.8. Similarly, the permeability of the specimens determined before and after firing is recorded in Table 5.18.

High Temperature Tests A similar programme of tests to those conducted on the backing material was conducted on the ceramic facing material.

Gas Evolution:

Samples of approximately 1 gm were prepared from facing material crushed to granular form in a pestle and mortar. The tests were conducted at a temperature of 850°C and the results are recorded in Table 5.19.

Hot Distortion:

The tests were performed according to the recommended procedure. Each test was continued for a period of 10 minutes. The results of the tests on facing material fired to 750°C are shown in Figures 5.12a to 5.12c. Those for the material fired at 1000°C are shown in Figures 5.13a to 5.13c.

Unimpeded Linear Expansion:

The tests were carried out at the recommended temperature of 1000°C and the results are shown graphically in Figure 5.14 and in tabular form in Table 5.20.

Hot Strength:

The standard test procedure was adopted. The hot strength was determined as soon as the test piece had been heated for one minute at 1000°C. The results are shown in Table 5.21.

5.2.3 Backing/Facing Material Interface

The only test conducted to provide information about the bond between the backing and facing material was the tensile test conducted on the 50:50 composite dog bone specimens. The results obtained from these tests are presented in Table 5.22 and shown graphically in Figure 5.15.

5.3 METALLURGICAL PROCESSING

The main emphasis of the work reported in this section was the establishment of the influence that: mould material and temperature; mould atmosphere; and metal treatment and temperature had on the surface quality and microstructure of the ingot castings. The programme of ingot casting experiments detailing the variables involved is presented in Table 5.23.

5.3.1 Macroexamination

For each of the series detailed in Table 5.23 a photograph is presented and the appropriate figure numbers are presented in Table 5.24. The surface quality of the ingot castings was evaluated visually as the main criterion of quality was the presence of gross surface defects, such as the pitting defect. Visual comparison, whilst inherently subjective, was considered to be more appropriate than quantitative surface finish measurements in view of the size of the defects. The differences in surface quality show very clearly in the photographs and it is considered that the method of assessment enabled a valid ranking of surface quality to be obtained. Brief observations are included in Table 5.23 and a detailed consideration of the results is provided in section 6.3.1.

5.3.2 Microexamination

Samples for metallography were prepared from sections cut from the centre of selected ingots by EDM. The machined surface was removed by grinding before conventional metallographic preparation procedures were adopted. Figure 5.33 shows the shape of the specimens and the position from which they were taken. The specimen dimensions chosen enabled the structure to be examined from the cast surface through to the casting centre using a single specimen.

Microhardness Measurements:

The equipment used for these measurements was a Vickers microhardness attachment, used in conjunction with a Vickers M41 Photoplan metallurgical microscope. Microhardness measurements were obtained from the 17 ingot metallographic specimens. Two sets of readings were taken from each specimen, one set from the ingot centre and the second set from the sub-surface layer. For the latter set, readings were

taken at a point within 0.1 mm of the surface. The microhardness readings are shown in Table 5.25, each recorded value represents the average of three readings.

Grain Size Measurements:

The Schneider-Graf, or intercept method (96) was used to obtain a measurement of grain size. Metallographic specimens from the ingot castings were viewed using a Hitachi monitor screen connected via a Hitachi CCTV camera to a Nikon Optiphot metallurgical microscope. The final magnification was $\times 1265$. Three lines of 161 mm, intersecting in the pattern shown in Figure 5.34, were used as the intercepts along which the number of grains intercepted were counted. Five areas were selected for each specimen, providing 15 intercept readings/specimen. The average values for the intercept readings are presented in Table 5.26.

Microstructures:

Selected photomicrographs of the surface and centre structure of selected ingot castings are presented in Figures 5.35 to 5.49.

5.4 TEST CASTINGS EVALUATION

For the purpose of confirming the results obtained from the investigation phases reported in sections 5.2 and 5.3, and to establish their relevance to actual test casting production, an initial series of 12 test castings was produced. Three castings of each of the four test casting types were produced under different conditions. Whilst the programme did not permit each casting type to be produced using every set of conditions, it was anticipated that the test programme would identify the optimum procedure. Following examination of the 12 test castings, a further three castings were produced to establish the repeatability of the optimum procedure.

5.4.1 Visual Examination

The programme for test casting production showing the sequence of casting, the mould material specification and the mould atmosphere is shown in Table 5.27. A photograph of each test casting, together with details of the melt production, is provided and the relevant Figure numbers (5.50 to 5.64) are presented in Table 5.27. The table also contains observations about the appearance of the castings. Details of the mould material specification are presented in Table 5.28.

5.4.2 Dimensions and Surface Finish

Casting dimensions were established using conventional metrology practice and compared with the pattern dimensions. Surface finish measurements were made using a Rank Taylor Hobson Talydata with computing facility.

Stepped Block A sketch of the stepped block casting showing the dimensions measured, together with their points of measurement, is provided in Figure 5.65. The dimensions of the pattern are shown in Table 5.29 and those of the castings in Tables 5.30 to 5.33. It should be noted that the actual pattern dimensions may differ slightly from the drawing dimensions shown in Figure 4.15(iv). The surface finish measurements for the pattern are shown in Figure 5.66 and those for the castings in Figures 5.67 to 5.70.

Retractable Die Core A sketch of the die core casting showing the dimensions measured is presented in Figure 5.71. The dimensions of the pattern and test castings are shown in Table 5.34 and the pattern

drawing is shown in Figure 4.23(v). The surface finish measurements for the pattern are shown in Figure 5.72 and those for the castings in Figures 5.73 to 5.76.

Spider Forging Die Figure 5.77 shows a sketch of the spider die casting with the measured dimensions indicated. The dimensions of the pattern and test castings are shown in Table 5.35 and the pattern drawing is shown in Figure 4.21(v). The surface finish measurements for the pattern are shown in Figure 5.78 and those for the castings in Figures 5.79 to 5.82.

Flange Yoke Die A sketch of the flange yoke die casting showing the dimensions measured is presented in Figure 5.83. The dimensions of the pattern and test castings are shown in Table 5.36 and the pattern drawing is shown in 4.23(v). The surface finish measurements for the pattern are shown in Figure 5.84 and those for the castings in Figures 5.85 to 5.87.

5.4.3 Contraction Allowance

Melting Point Determination:

Examination of the cooling curves showed the solidus arrest points of the two castings to be 1410°C. Subsequent failure of one of the recording systems prevented further data being obtained from one of the cooling curves. However, it was evident from the second cooling curve that an arrest point occurred at 892°C, which represents the lower boundary of the austenite field (97).

Coefficient of Linear Expansion:

The coefficient of linear expansion, α , is expressed as:

$$\alpha = \frac{\text{measured change in length}}{\text{original specimen length} \times \text{temperature rise}}$$

The calculated values and other experiment details are presented in Table 5.37.

Contraction Allowance:

A value of contraction allowance, representing unimpeded linear contraction, can be estimated from the data obtained. From Table 5.37

the average coefficient of linear expansion is 11.8×10^{-6} . Assuming that the alloy cools from a solidus temperature of 1410°C to an ambient temperature of 20°C , the change in unit length would be:

$$[1390 \times 1 \times 11.8 \times 10^{-6}] \times 100\% = 1.64\%$$

Table 5.1: The Effect of Gassing Time on the Compression Strength of Fireclay Grog Bonded with 4% Cl25 Sodium Silicate
(flow rate 5 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	234	245	251	243
60	276	276	289	280
120	289	313	286	299
240	313	331	331	325

Table 5.2: The Effect of Gassing Time on the Compression Strength of Fireclay Grog Bonded with 6% Cl25 Sodium Silicate
(flow rate 5 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	152	148	162	154
60	248	255	265	256
120	303	289	300	297
240	338	358	327	341

Table 5.3: The Effect of Standing Time on the Gassed Compression Strength of Fireclay Grog Bonded with 6% Cl25 Sodium Silicate (flow rate 5 l/min)

Standing Time (hours)	Compression Strength kN/m ²			
	1	2	3	Average
0	303	289	300	297
1	582	558	586	575
2	562	579	579	573
4	661	661	630	651
24	1047	1089	1068	1068

Table 5.4: The Effect of Gassing Time on the Compression Strength of Blended Molochite Bonded with 6% Cl25 Sodium Silicate
(flow rate 2.5 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	475	503	496	491
60	1137	1102	1068	1102
120	1536	1579	1474	1529
240	1819	1798	1798	1805

Table 5.5: The Effect of Gassing Time on the Compression Strength of Blended Molochite Bonded with 6% Cl25 Sodium Silicate
(flow rate 5 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	696	744	730	723
60	1613	1710	1619	1647
120	1778	1936	1909	1874
240	1909	1971	2060	1980

Table 5.6: The Effect of Gassing Time on the Compression Strength of Blended Molochite Bonded with 6% Cl25 Sodium Silicate
(flow rate 7.5 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	668	668	717	684
60	1137	1185	1233	1185
120	1481	1441	1358	1427
240	1598	1626	1660	1628

Table 5.7: The Effect of Gassing Time on the Compression Strength of Blended Molochite Bonded with 6% C125 Sodium Silicate
(flow rate 10 l/min)

Gassing Time (secs)	Compression Strength kN/m ²			
	1	2	3	Average
30	868	868	854	863
60	1688	1626	1750	1688
120	1826	1922	1929	1892
240	1964	1902	2081	1982

Table 5.8: The Effect of Standing Time on the Gassed Compression Strength of Blended Molochite Bonded with 6% C125 Sodium Silicate (flow rate 5 l/min)

Standing Time (hours)	Compression Strength kN/m ²			
	1	2	3	Average
0	1778	1936	1909	1874
1	3052	2901	3052	3002
2	3149	3094	3280	3174
6	3445	3390	3500	3445
24	3638	3445	3583	3555

Table 5.9: The Effect of Firing Temperature and Time at Firing Temperature on the Retained Compression Strength of Sodium Silicate Bonded Molochite

Firing Temperature °C	Firing Time (hours)	Compression Strength kN/m ²			
		1	2	3	Average
500	1	5220	5108	5290	5206
	2	5578	6033	5654	5755
	3	4756	4661	4399	4605
600	1	6095	5640	5950	5895
	2	6778	6730	6633	6714
	3	5161	5407	5014	5194
700	1	6674	6136	6343	6384
	2	8357	8060	7764	8060
	3	6194	6095	6046	6112
800	1	7371	7419	7764	7518
	2	8114	8114	8062	8100
	3	6564	6950	6343	6619
900	1	8504	8356	8110	8323
	2	9860	9860	9736	9818
	3	8553	8602	8406	8520
1000	1	8012	7767	7570	7693
	2	8996	8946	8651	8864
	3	7365	6750	7177	7097

Table 5.10: The Effect of Firing Temperature and Time at Firing Temperature on the Retained Tensile Strength of Sodium Silicate Bonded Molochite

Firing Temperature °C	Firing Time (hours)	Tensile Strength kN/m ²			
		1	2	3	Average
500	1	386	380	372	379
	2	552	565	579	565
	3	480	462	485	476
600	1	567	580	569	572
	2	746	710	717	724
	3	524	524	565	538
700	1	605	630	608	614
	2	765	779	793	779
	3	581	614	627	607
800	1	660	690	657	669
	2	979	931	1007	972
	3	830	830	884	848
900	1	865	805	865	845
	2	1275	1338	1275	1296
	3	1117	1172	1272	1172
1000	1	810	810	861	827
	2	1137	1120	1197	1151
	3	1020	1075	1048	1048

Table 5.11: The Effect of Firing Temperature on the Dimensional Stability of Sodium Silicate Bonded Molochite

Firing Temperature °C	Average Length Before Firing (mm) - - -	Average Length After Firing (mm)	Average Change in Length (mm)
500	51.04	51.01	-0.03
600	51.41	51.38	-0.03
700	51.14	51.00	-0.14
800	50.84	50.74	-0.10
900	51.12	50.96	-0.16
1000	51.10	50.91	-0.19

Table 5.12: The Effect of Firing Temperature on the Permeability of Sodium Silicate Bonded Molochite

Firing Temperature °C	Average Permeability Before Firing	Average Permeability After Firing	Average Change in Permeability
500	93	-	-
600	95	107	+12
700	87	97	+10
800	90	114	+24
900	93	105	+12
1000	97	117	+20

Table 5.13: Gas Evolution from the Fired Sodium Silicate Bonded Molochite

Firing Temperature °C	Sample Number	Sample Weight gm	Gas Evolution ml/gm
750	1	1.0074	0
750	2	0.9912	0
1000	1	0.9963	0
1000	2	1.0026	0

Table 5.14: Unimpeded Linear Expansion of the Fired Sodium Silicate Bonded Molochite

Firing Temperature °C	Sample Number	Expansion ($\times 10^{-2}$ mm) vs Time (mins)									Maximum Expansion ($\times 10^{-2}$ mm)	Maximum Expansion (%)
		0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4		
750	1	0	+2.6	+4.2	+2.6	-1.8					+4.2	0.210
750	2	0	+1.9	+3.4	+3.6	+2.2	-0.8				+3.6	0.180
750	3	0	+3.2	+4.9	+4.0	+0.5	-2.5				+4.9	0.245
	Average										+4.2	0.212
1000	1	0	+3.0	+5.4	+6.0	+5.8	+4.9	+3.8	+2.8	+2.4	+6.0	0.300
1000	2	0	+3.6	+5.8	+6.2	+5.2	+3.8	+2.7	+1.6	+0.9	+6.2	0.310
1000	3	0	+3.1	+5.4	+5.8	+5.3	+4.0	+3.0	+2.1	+1.4	+5.8	0.290
	Average										+6.0	0.300

Table 5.15: The Effect of Firing Temperature and Time at Firing Temperature on the Retained Compression Strength of the Ceramic Facing Slurry

Firing Temperature °C	Firing Time (hours)	Compression Strength kN/m ²			
		1	2	3	Average
500	1	1081	1131	1180	1131
	2	885	885	860	877
	3	1287	1278	1253	1276
600	1	1401	1352	1499	1417
	2	993	956	998	982
	3	1450	1548	1426	1475
700	1	1622	1499	1647	1580
	2	1081	1081	1032	1065
	3	1573	1596	1622	1597
800	1	1622	1647	1598	1622
	2	1229	1253	1253	1241
	3	1647	1671	1671	1663
900	1	1612	1572	1593	1592
	2	1401	1426	1426	1417
	3	1720	1720	1770	1737
1000	1	1927	1770	1893	1863
	2	1580	1580	1492	1551
	3	1804	1765	1894	1821

Table 5.16: The Effect of Firing Temperature and Time at Firing Temperature on the Retained Tensile Strength of the Ceramic Facing Slurry

Firing Temperature °C	Firing Time (hours)	Tensile Strength kN/m ²			
		1	2	3	Average
500	1	103	103	110	105
	2	62	62	55	60
	3	100	100	107	102
600	1	117	121	131	123
	2	69	69	66	68
	3	128	131	131	130
700	1	145	141	152	146
	2	79	79	83	80
	3	148	148	134	143
800	1	165	165	159	163
	2	90	90	97	92
	3	162	179	159	167
900	1	186	186	179	184
	2	110	110	124	115
	3	179	169	172	173
1000	1	200	221	214	212
	2	131	131	131	131
	3	186	200	200	195

Table 5.17: The Effect of Firing Temperature on the Dimensional Stability of the Ceramic Facing Slurry

Firing Temperature °C	Average Length Before Firing (mm) - -	Average Length After Firing (mm)	Average Change in Length (mm)
500	51.39	51.40	+0.01
600	51.47	51.53	+0.06
700	51.32	51.35	+0.03
800	51.28	51.30	+0.02
900	51.25	51.30	+0.05
1000	51.30	51.32	+0.02

Table 5.18: The Effect of Firing Temperature on the Permeability of the Ceramic Facing Slurry

Firing Temperature °C	Average Permeability Before Firing	Average Permeability After Firing	Average Change in Permeability
500	4.0	-	-
600	3.4	3.7	+0.3
700	4.1	3.8	-0.3
800	4.0	4.6	+0.6
900	5.1	3.9	-1.2
1000	4.7	4.2	-0.5

Table 5.19: Gas Evolution from the Fired Ceramic Facing Material

Firing Temperature °C	Sample Number	Sample Weight gm	Gas Evolution ml/gm
750	1	0.9925	0
750	2	0.9702	0
1000	1	0.9880	0
1000	2	1.0185	0

Table 5.20: Unimpeded Linear Expansion of the Fired Ceramic Facing Material

Firing Temperature °C	Sample Number	Expansion ($\times 10^{-2}$ mm) vs Time (mins)									Maximum Expansion ($\times 10^{-2}$ mm)	Maximum Expansion (%)
		0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4		
750	1	0	+2.8	+4.6	+5.3	+5.3	+4.6	+3.8	+3.2	+2.4	+5.3	0.265
750	2	0	+3.2	+4.8	+5.2	+5.2	+4.2	+2.6	+1.8	+0.6	+5.2	0.260
750	3	0	+2.8	+4.6	+5.4	+5.1	+3.8	+2.8	+1.9	+1.0	+5.4	0.270
	Average										+5.3	0.265
1000	1	0	+3.8	+5.9	+7.0	+7.1	+7.0	+6.8	+6.3	+5.9	+7.1	0.355
1000	2	0	+3.5	+5.5	+6.5	+6.7	+6.7	+6.5	+6.1	+5.8	+6.7	0.335
1000	3	0	+3.2	+5.4	+6.4	+6.5	+6.5	+6.4	+6.1	+5.7	+6.5	0.325
	Average										+6.8	0.338

Table 5.21: Hot Strength of the Fired Ceramic Facing Material

Firing Temperature °C	Sample Number	Hot Strength kN/m ²	Average Hot Strength kN/m ²
750	1	1000	1034
750	2	1069	
750	3	1034	
1000	1	1276	1310
1000	2	1310	
1000	3	1345	

Table 5.22: The Effect of Firing Temperature and Time at Firing Temperature on the Retained Strength of the Sodium Silicate Bonded Molochite/Ceramic Facing Slurry Composite

Firing Temperature °C	Firing Time (hours)	Tensile Strength kN/m ²			
		1	2	3	Average
500	1	48	49	46	48
	2	48	48	48	48
	3	66	66	66	66
600	1	56	56	62	58
	2	52	52	45	50
	3	72	76	79	76
700	1	65	69	72	69
	2	55	55	59	57
	3	76	79	83	79
800	1	72	72	76	73
	2	62	62	62	62
	3	83	79	79	80
900	1	83	90	86	86
	2	66	66	66	66
	3	76	83	90	83
1000	1	90	103	97	97
	2	72	76	79	76
	3	90	90	90	90

Table 5.23: Ingot Casting Programme

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
I	4	mullite	ambient	air	none	1600°C	exhibits pitting defect (but fairly light)
I	3	mullite	ambient	air	none	1650°C	exhibits pitting defect (more severe than 4)
I	2	mullite	ambient	air	none	1700°C	exhibits severe pitting defect (more severe than 3)
II	10	mullite	500°C	air	none	1600°C	exhibits pitting defect (more severe than 4)
II	9	mullite	500°C	air	none	1650°C	exhibits pitting defect (more severe than 3)
II	8	mullite	500°C	air	none	1700°C	exhibits pitting defect (pits are smaller than 2 but cover more of the surface)
III	23	mullite	800°C	air	none	1600°C	exhibits pitting defect (more severe than 10 or 2), surface excrescence defect present
III	36	mullite	800°C	air	none	1650°C	exhibits pitting defect (more severe than 9 or 3), surface excrescence defect present (more severe than 23)

Table 5.23 cont

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
III	39	mullite	800°C	air	none	1700°C	exhibits pitting defect (more severe than 8 or 2), surface excrescence defect present
IV	41	mullite	ambient	nitrogen	none	1600°C	surface free of pitting defect, some surface excrescence
IV	50 + 43	mullite	ambient	nitrogen	none	1650°C	surface free of pitting defect, surface excrescence defect present
IV	46	mullite	ambient	nitrogen	none	1700°C	surface free of pitting defect, surface excrescence defect present
V	42	mullite	ambient	air	deoxidiser 0.25 wt% Stellagen 1	1650°C	pitting defect present
V	34	mullite	ambient	air	deoxidiser 0.50 wt% Stellagen 1	1650°C	areas of pitting defect, some areas free, some areas of surface excrescence
V	37	mullite	ambient	air	deoxidiser 0.75 wt% Stellagen 1	1650°C	surface generally free of pitting defect, but increased surface excrescences

Table 5.23 cont

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
VI	44	mullite	ambient	air	grain refiner 0.025 wt% Fe Ti + 0.0025 wt% Fe Nb	1650°C	pitting defect present, some surface excrescence
VI	35	mullite	ambient	air	grain refiner 0.050 wt% Fe Ti + 0.0050 wt% Fe Nb	1650°C	pitting defect present, some surface excrescence
VI	38	mullite	ambient	air	grain refiner 0.075 wt% Fe Ti + 0.0075 wt% Fe Nb	1650°C	pitting defect present, some surface excrescence
VII	66	mullite	ambient	air	deoxidiser + grain refiner	1600°C	some pitting present, generally poor finish
VII	63	mullite	ambient	air	deoxidiser + grain refiner	1650°C	some pitting present, generally poor finish
VII	62	mullite	ambient	air	deoxidiser + grain refiner	1700°C	some pitting present, generally poor finish
VIII	64	mullite	ambient	nitrogen	deoxidiser + grain refiner	1600°C	pitting suppressed, but poor surface finish
VIII	58	mullite	ambient	nitrogen	deoxidiser + grain refiner	1650°C	pitting suppressed, but poor surface finish

Table 5.23 cont

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
VIII	60	mullite	ambient	nitrogen	deoxidiser + grain refiner	1700°C	pitting suppressed, but poor surface finish, penetration defect present
IX	7	mullite + 10 wt% graphite	ambient	air	none	1600°C	pitting defect absent, small surface excrescences present
IX	6	mullite + 10 wt% graphite	ambient	air	none	1650°C	pitting defect absent, small surface excrescences present
IX	5	mullite + 10 wt% graphite	ambient	air	none	1700°C	pitting defect absent, small surface excrescences present
X	13	mullite + 10 wt% graphite	500°C	air	none	1600°C	pitting defect absent, small surface excrescences present
X	12	mullite + 10 wt% graphite	500°C	air	none	1650°C	pitting defect absent, small surface excrescences present
X	11	mullite + 10 wt% graphite	500°C	air	none	1700°C	pitting defect absent, small surface excrescences present

Table 5.23 cont

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
XI	54	mullite + 10 wt% graphite	800°C	air	none	1600°C	pitting defect absent, surface finish generally poor and small surface excrescences present
XI	53	mullite + 10 wt% graphite	800°C	air	none	1650°C	pitting defect absent, surface finish very poor and metal penetration evident
XI	24	mullite + 10 wt% graphite	800°C	air	none	1700°C	pitting defect absent, surface finish poor with some surface excrescences and penetration
XII	65	mullite + 10 wt% graphite	ambient	air	deoxidiser + grain refiner	1600°C	pitting defect absent, surface finish poor
XII	59	mullite + 10 wt% graphite	ambient	air	deoxidiser + grain refiner	1650°C	pitting defect absent, surface finish poor
XII	61	mullite + 10 wt% graphite	ambient	air	deoxidiser + grain refiner	1700°C	pitting defect absent, surface finish poor
XIII	20	mullite + 10 wt% graphite	ambient	nitrogen	none	1600°C	pitting defect absent, surface finish exhibits a matte effect
XIII	57	mullite + 10 wt% graphite	ambient	nitrogen	none	1700°C	pitting defect absent, very poor surface finish with severe metal penetration

Table 5.23 cont

Series Number	Casting Number	Mould Material	Mould Temperature	Mould Atmosphere	Melt Additions	Furnace Temperature	Observations
XIV	55	mullite + 10 wt% graphite	ambient	argon	none	1550°C	pitting defect absent
XIV	25	mullite + 10 wt% graphite	ambient	argon	none	1650°C	pitting defect absent
XIV	56	mullite + 10 wt% graphite	ambient	argon	none	1700°C	pitting defect absent, very poor surface finish with severe metal penetration
XV	21	zircon	ambient	air	none	1600°C	pitting defect present
XV	15	zircon	ambient	air	none	1650°C	pitting defect present, surface excrescences present
XVI	26	machined graphite	ambient	air	none	1675°C	severe surface gas holes
XVI	27	machined graphite	150°C	air	none	1675°C	not as bad as (26), but still gas defects
XVII	47	mullite	ambient	air	1 wt% nickel	1650°C	pitting defect present
XVII	48	mullite	ambient	air	2 wt% nickel	1650°C	pitting defect present
XVII	52	mullite	ambient	air	3 wt% nickel	1650°C	pitting defect present

Table 5.24: Ingot Casting Series Figure Numbers

Series Number	Figure Number
I	5.16
II	5.17
III	5.18
IV	5.19
V	5.20
VI	5.21
VII	5.22
VIII	5.23
IX	5.24
X	5.25
XI	5.26
XII	5.27
XIII	5.28
XIV	5.29
XV	5.30
XVI	5.31
XVII	5.32

Table 5.25: Average Vickers Microhardness Readings from
Ingot Castings

Ingot Casting Number	Average Vickers Microhardness Values	
	Casting Centre	Casting Subsurface
3	649	584
34	636	622
35	727	733
37	683	610
38	763	582
42	684	603
43	698	627
44	695	630
58	651	550
59	687	591
60	651	664
61	713	633
62	673	632
63	675	628
64	675	630
65	658	625
66	742	674

(200 gramme load, primary magnification x 75)

Table 5.26: Average Grain Size Measurements from the Ingot Castings

Ingot Casting Number	Melt Additions	Average Number of Grains Intercepted
3	no addition	3.54
43	no addition	3.82
42	0.25 wt% Stellagen 1	4.14
34	0.50 wt% Stellagen 1	4.14
37	0.75 wt% Stellagen 1	4.40
44	0.025 wt% Fe Ti + 0.0025 wt% Fe Nb	4.28
35	0.050 wt% Fe Ti + 0.0050 wt% Fe Nb	4.46
38	0.075 wt% Fe Ti + 0.0075 wt% Fe Nb	5.52
62	0.050 wt% Fe Ti + 0.0050 wt% Fe Nb + 0.50 wt% Stellagen 1	5.40
63	0.050 wt% Fe Ti + 0.0050 wt% Fe Nb + 0.50 wt% Stellagen 1	5.34
66	0.050 wt% Fe Ti + 0.0050 wt% Fe Nb + 0.50 wt% Stellagen 1	5.34

Table 5.27: Test Casting Production Sequence

Casting Number	Casting Type	Mould Material	Mould Atmosphere	Observations	Figure Number
1	stepped block	A	nitrogen	rounded casting edges and some slag inclusions	5.50
2	stepped block	A	air	very poor surface finish, cold laps and poor casting edge definition	5.51
3	stepped block	B	air	metal penetration evident and some metal/mould reaction	5.52
4	retractable die core	D	air	some metal penetration and metal/mould reaction, some rounded edges on teeth	5.53
5	retractable die core	C	nitrogen	some evidence of pitting defect, cold laps present	5.54
6	retractable die core	C	air	cold laps present	5.55
7	spider die	C	nitrogen	some cold laps, loss of definition on cavity edges, surface sink and ingate draw	5.56
8	spider die	A	air	slight cold lap defect, some loss of edge definition, some metal penetration, surface sink	5.57
9	flange yoke die	B	air	surface excrescences present	5.58

Table 5.27 cont

Casting Number	Casting Type	Mould Material	Mould Atmosphere	Observations	Figure Number
10	spider die	C	air	some cold laps, loss of definition on cavity edge, slight sink and ingate draw	5.59
11	flange yoke die	A	nitrogen	metal/mould reaction evident and pitting defect, splash laps in cavity	5.60
12	flange yoke die	D	air	some metal penetration evident	5.61
13	stepped block	D	air	some metal penetration evident, thin casting flash, gross mould crack	5.62
14	retractable die core	D	air	some evidence of pitting defect, poor edge definition on teeth, thick flash	5.63
15	spider die	D	air	some metal penetration, mould cavity has poor surface quality	5.64

Table 5.28: Mould Facing Material Specifications

Mould Material and Grade	Mould Facing Material Specification (wt%)			
	A	B	C	D
-8 + 16 mullite	25	25	25	25
-30 mullite	25	25	25	25
-100 mullite	50	40	25	20
-300 mullite			25	20
-100 graphite		10		10

Table 5.29: Dimensions of the Stepped Block Pattern

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.952	(2)	2.951	(3)	2.953
a	mm	(1)	74.98	(2)	74.96	(3)	75.01
a	in	(4)	2.952	(5)	2.951	(6)	2.953
a	mm	(4)	74.98	(5)	74.96	(6)	75.01
b	in	(7)	1.963	(8)	1.964		
b	mm	(7)	49.86	(8)	49.88		
c	in	(9)	0.981	(10)	0.981	(11)	0.982
c	mm	(9)	24.91	(10)	24.91	(11)	24.93
d	in	(12)	1.899	(13)	1.905	(14)	1.901
d	mm	(12)	48.23	(13)	48.38	(14)	48.28
e	in	(15)	2.884	(16)	2.885		
e	mm	(15)	73.25	(16)	73.28		
f	in	(17)	3.870	(18)	3.870	(19)	3.870
f	mm	(17)	98.30	(18)	98.30	(19)	98.30

Table 5.30: Dimensions of Stepped Block Casting 1

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.927	(2)	2.920	(3)	2.926
a	mm	(1)	74.35	(2)	74.17	(3)	74.32
a	in	(4)	2.915	(5)	2.918	(6)	2.915
a	mm	(4)	74.04	(5)	74.12	(6)	74.04
b	in	(7)	1.941	(8)	1.942		
b	mm	(7)	49.30	(8)	49.32		
c	in	(9)	0.971	(10)	0.973	(11)	0.973
c	mm	(9)	24.67	(10)	24.71	(11)	24.72
d	in	(12)	1.874	(13)	1.883	(14)	1.881
d	mm	(12)	47.60	(13)	47.82	(14)	47.77
e	in	(15)	2.839	(16)	2.849		
e	mm	(15)	72.11	(16)	72.36		
f	in	(17)	3.799	(18)	3.791	(19)	3.803
f	mm	(17)	96.49	(18)	96.29	(19)	96.60

Table 5.31: Dimensions of Stepped Block Casting 2

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.911	(2)	-	(3)	2.918
a	mm	(1)	73.94	(2)	-	(3)	74.12
a	in	(4)	2.910	(5)	2.908	(6)	2.915
a	mm	(4)	73.91	(5)	73.86	(6)	74.04
b	in	(7)	1.940	(8)	1.948		
b	mm	(7)	49.27	(8)	49.49		
c	in	(9)	0.974	(10)	0.984	(11)	0.987
c	mm	(9)	24.75	(10)	24.99	(11)	25.06
d	in	(12)	1.869	(13)	1.872	(14)	1.867
d	mm	(12)	47.48	(13)	47.55	(14)	47.43
e	in	(15)	2.837	(16)	2.834		
e	mm	(15)	72.06	(16)	71.98		
f	in	(17)	3.802	(18)	3.794	(19)	3.787
f	mm	(17)	96.57	(18)	96.37	(19)	96.19

Table 5.32: Dimensions of Stepped Block Casting 3

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.923	(2)	-	(3)	2.922
a	mm	(1)	74.24	(2)	-	(3)	74.22
a	in	(4)	2.920	(5)	2.920	(6)	2.922
a	mm	(4)	74.17	(5)	74.17	(6)	74.22
b	in	(7)	1.948	(8)	1.947		
b	mm	(7)	49.49	(8)	49.46		
c	in	(9)	0.982	(10)	0.982	(11)	0.981
c	mm	(9)	24.95	(10)	24.95	(11)	24.93
d	in	(12)	1.891	(13)	-	(14)	-
d	mm	(12)	48.04	(13)	-	(14)	-
e	in	(15)	-	(16)	-		
e	mm	(15)	-	(16)	-		
f	in	(17)	-	(18)	-	(19)	-
f	mm	(17)	-	(18)	-	(19)	-

(Note: Metal penetration defect prevented some dimensions from being measured.)

Table 5.33: Dimensions of Stepped Block Casting 13

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.883	(2)	-	(3)	2.886
a	mm	(1)	73.23	(2)	-	(3)	73.30
a	in	(4)	2.878	(5)	2.897	(6)	2.902
a	mm	(4)	73.10	(5)	73.58	(6)	73.71
b	in	(7)	1.927	(8)	1.930		
b	mm	(7)	48.95	(8)	49.02		
c	in	(9)	0.970	(10)	0.977	(11)	0.970
c	mm	(9)	24.64	(10)	24.82	(11)	24.64
d	in	(12)	1.870	(13)	1.876	(14)	1.874
d	mm	(12)	47.50	(13)	47.65	(14)	47.60
e	in	(15)	2.833	(16)	2.835		
e	mm	(15)	71.96	(16)	72.01		
f	in	(17)	3.803	(18)	3.801	(19)	3.791
f	mm	(17)	96.60	(18)	96.55	(19)	96.29

**Table 5.34: Dimensions of the Retractable Die Core Pattern
and Test Castings**

Dimension		Measured Values				
Code	Unit	Pattern	Casting 4	Casting 5	Casting 6	Casting 14
a	in	3.755	3.684	3.681	3.677	3.682
a	mm	95.38	93.57	93.50	93.40	93.52
a1	in	3.753	3.680	3.682	3.683	3.678
a1	mm	95.33	93.47	93.52	93.55	93.42
a2	in	3.755	3.683	3.681	3.685	3.679
a2	mm	95.38	93.55	93.50	93.60	93.45
b	in	1.003	0.985	0.986	0.984	0.984
b	mm	25.48	25.02	25.04	24.99	24.99
c	in	1.003	0.981	0.989	0.981	0.987
c	mm	25.48	24.92	25.12	24.92	25.07
Ø1	in	2.000	1.970	2.021	1.960	1.973
Ø1	mm	50.80	50.05	51.33	49.88	50.11
Ø2	in	2.000	1.961	1.957	1.964	1.952
Ø2	mm	50.80	49.81	49.71	49.60	49.58
Ø3	in	2.000	1.957	1.963	1.957	1.960
Ø3	mm	50.80	49.70	49.86	49.71	49.78
Ø4	in	1.882	1.879	1.907	1.869	1.868
Ø4	mm	47.80	47.73	48.44	47.47	47.45
Ø5	in	1.632	1.620	1.603	1.616	1.620
Ø5	mm	41.45	41.15	40.72	41.05	41.15
Ø6	in	1.344	1.338	1.344	1.332	1.348
Ø6	mm	34.14	33.99	34.14	33.83	34.24

Table 5.35: Dimensions of the Spider Forging Die Pattern
and Test Castings

Dimension		Measured Values				
Code	Unit	Pattern	Casting 7	Casting 8	Casting 10	Casting 15
a	in	0.435	0.431	0.431	0.428	0.437
a	mm	11.05	10.95	10.95	10.87	11.10
b	in	0.434	0.430	0.429	0.432	0.437
b	mm	11.02	10.92	10.90	10.97	11.10
c	in	0.435	0.430	0.428	0.428	0.431
c	mm	11.05	10.92	10.87	10.87	10.95
d	in	0.435	0.430	0.428	0.427	0.431
d	mm	11.05	10.92	10.87	10.85	10.95
e	in	1.246	1.207	1.212	1.217	1.205
e	mm	31.65	30.66	30.78	30.91	30.61
f	in	1.246	1.206	1.215	1.217	1.206
f	mm	31.65	30.63	30.86	30.91	30.63

Table 5.36: Dimensions of the Flange Yoke Die Pattern
and Test Castings

Dimension		Measured Values			
Code	Unit	Pattern	Casting 9	Casting 11	Casting 12
a	in	1.761	1.718	1.721	1.715
a	mm	44.73	43.64	43.71	43.56
b	in	1.762	1.715	1.728	1.717
b	mm	44.75	43.56	43.89	43.61
c	in	1.421	1.390	1.397	1.382
c	mm	36.09	35.31	35.48	35.10
d	in	1.422	1.385	1.395	1.385
d	mm	36.12	35.18	35.43	35.18
Øe	in	3.793	3.717	3.721	3.711
Øe	mm	96.34	94.41	94.51	94.26
f	in	0.349	0.336	0.341	0.340
f	mm	8.86	8.53	8.66	8.64

Table 5.37: Results of the Dilatometry Experiments

Sample	Specimen Length in (mm)	Austenite Transformation Temperature (°C)	Change in Specimen Length in (mm)	Coefficient of Linear Expansion $\times 10^{-6}$
1 H13	1.378 (35.001)	889	0.0146 (0.371)	11.9
2 H13	1.380 (35.052)	895	0.0145 (0.368)	11.7
3 H13	1.379 (35.027)	886	0.0145 (0.368)	11.8
4 Copper (control)	1.390 (35.306)	-	0.0145 (0.368)	16.6

5.5 FINISHING PROCEDURES

5.5.1 Heat Treatment

The results of the bulk hardness tests conducted on the castings before and after heat treatment are shown in Table 5.38.

The dimensions of the test castings after heat treatment are shown in Tables 5.39 to 5.42 for the stepped block castings and Table 5.34 for the retractable die core castings.

5.5.2 Electrical Discharge Machining

Electrical Discharge Machining was conducted using a Wickman EDM 0 machine with a 30 series power generator. A pure copper electrode was used and a standard cutting voltage between 30 and 80 volts (open circuit 90 volts) was selected according to the manufacturer's recommendations. Details of the significance of machining parameters are included in Chapter Three. Generally, a low frequency and high current produce the fastest cutting speed and the roughest finish on the workpiece - with lowest electrode wear. As frequency is increased, metal removal rate decreases, but the finish produced is finer.

Finishing passes should be undertaken at low amperage to produce a good surface finish. The cutting conditions employed in these experiments were:

Roughing:	frequency	16 kHz
	current	30 A
	capacitance	15 μ F

Finishing:	frequency	65 kHz
	current	15 A
	capacitance	2 μ F

Microhardness Measurements:

Microhardness measurements were conducted in the subsurface zone and central section of the A samples removed from each of the three stepped blocks selected and the average microhardness values are presented in Table 5.44. Microhardness measurements were also conducted on the samples which had their as-cast surface removed by EDM. These measurements were taken from the sub-machined surface zone and are presented in Table 5.45.

Microstructures:

The microstructures of the as-cast surface and centre of the A sample removed from test casting 13 were examined and compared with the microstructures of the surfaces machined by EDM. Selected photomicrographs are presented in Figures 5.88 to 5.95.

5.5.3 Electron Probe Microanalysis (EPMA)

The microanalysis was conducted using a Cambridge Microscan 5 instrument. The samples for analysis were prepared using standard metallographic techniques and mounted in conducting Bakelite. The samples were divided into two groups, with the first group consisting of the A samples on which the analysis would be conducted from the as-cast surface into the bulk of the sample. Examination of these results would be expected to show whether there was any difference attributable to the mould material/mould atmosphere combination employed in the production of the casting.

The second group of samples consisted of those on which analysis would be conducted from the surface machined by EDM into the bulk of the casting. In the light of the results obtained from the first group of samples, the second group consisted only of samples from test casting 13. These were: sample 13C; 13B; and 13D which had, respectively: 250 μm ; 1.25 mm; and 2.85 mm of material removed from the as-cast surface.

The elements of interest were the six principal elements present in the H13 die steel, namely: carbon; silicon; manganese; chromium; molybdenum and vanadium. In addition, because a copper electrode was used during EDM, an analysis for copper was also conducted on selected samples. As it was only possible to conduct an analysis for two elements simultaneously the following pairings were used: carbon and vanadium; silicon and chromium; manganese and molybdenum; and copper and iron. A lithium fluoride crystal was used in the analysis of chromium, copper, manganese and vanadium; a mica crystal for iron, molybdenum and silicon; and mica-stearate for carbon. A 'cold finger' was used to condense out oil vapour in an attempt to eliminate error in the carbon readings.

A continuous scanning mode was used, progressing across the Bakelite/specimen interface and continuing for a nominal distance of 250 μm from the specimen surface. Whilst an attempt was made to conduct the paired

analyses on the same area, precise superposition of the beam could not be guaranteed. The nominal beam diameter was 1 μm , beam voltage 29 kV and beam current between 1 and 2×10^{-8} A. The instrument operated at 100 counts/second and the output was recorded on a chart recorder operating at a chart speed of 10 mm/minute, with 1 mm on the chart corresponding to 1 μm on the specimen. Background levels for each element were monitored and recorded after each scan. Duplicate scans were conducted on several but not all specimens.

Presentation of EPMA Results:

The actual chemical analysis for each test casting was not known, although the melting stock analyses were provided (see Appendix Five). From the melting stock analyses a notional average melt analysis was established:

<u>Element</u>	<u>%</u>
carbon	0.43
silicon	1.55
manganese	0.54
chromium	4.78
molybdenum	1.52
vanadium	1.15

For each specimen and for each of the six principal elements considered, the following procedure was adopted. The element concentration, recorded on the original chart, was measured at steps of 10 μm (10 mm on the chart). From this measurement was deducted the mean element background concentration. This was repeated for the measurements from 10 μm to 250 μm from the interface. The mean of these corrected measurements was calculated and equated to the notional melt analysis value for that element. From this information a graph of % element concentration vs distance from the interface could be drawn. Whilst this approach does not provide a quantitative measure, it does permit trends to be observed and enabled the results for a single specimen to be observed simultaneously. The graphs are presented in Figures 5.96 to 5.101.

The results for the analysis of copper, conducted on specimens 13A, 13C and 13D, could not be presented in the same way because an analysis for

copper in the melting stock was not available. For these specimens a tracing of the actual chart recording is presented in Figures 5.102 to 5.104 respectively.

Table 5.38: Test Casting Hardness Values

Casting Type	Casting Number	Hardness Rc (As-Cast)	Hardness Rc (Heat Treated)
Stepped Blocks	1	50	56
	2	48	55
	3	49	54
	13	47	55
Retractable Die Cores	4	47	52
	5	50	53
	6	47	52
	14	42	48

Table 5.39: Dimensions of Stepped Block Casting 1 After Heat Treatment

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.928	(2)	2.921	(3)	2.927
a	mm	(1)	74.37	(2)	74.19	(3)	74.35
a	in	(4)	2.921	(5)	2.921	(6)	2.920
a	mm	(4)	74.19	(5)	74.19	(6)	74.17
b	in	(7)	1.946	(8)	1.945		
b	mm	(7)	49.43	(8)	49.40		
c	in	(9)	0.977	(10)	-	(11)	0.978
c	mm	(9)	24.82	(10)	-	(11)	24.84
d	in	(12)	1.878	(13)	1.888	(14)	1.881
d	mm	(12)	47.70	(13)	47.96	(14)	47.78
e	in	(15)	2.843	(16)	2.845		
e	mm	(15)	72.21	(16)	72.26		
f	in	(17)	3.802	(18)	3.798	(19)	3.801
f	mm	(17)	96.57	(18)	96.47	(19)	96.55

Table 5.40: Dimensions of Stepped Block Casting 2 After Heat Treatment

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.914	(2)	2.920	(3)	2.926
a	mm	(1)	74.06	(2)	74.17	(3)	74.32
a	in	(4)	2.926	(5)	2.915	(6)	2.921
a	mm	(4)	74.32	(5)	74.04	(6)	74.19
b	in	(7)	1.947	(8)	1.954		
b	mm	(7)	49.45	(8)	49.63		
c	in	(9)	0.986	(10)	-	(11)	0.990
c	mm	(9)	25.04	(10)	-	(11)	25.15
d	in	(12)	1.870	(13)	1.879	(14)	1.879
d	mm	(12)	47.50	(13)	47.73	(14)	47.73
e	in	(15)	2.839	(16)	2.844		
e	mm	(15)	72.11	(16)	72.24		
f	in	(17)	3.804	(18)	3.808	(19)	3.806
f	mm	(17)	96.62	(18)	96.72	(19)	96.67

Table 5.41: Dimensions of Stepped Block Casting 3 After Heat Treatment

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.928	(2)	2.927	(3)	2.930
a	mm	(1)	74.37	(2)	74.35	(3)	74.42
a	in	(4)	2.932	(5)	2.927	(6)	2.927
a	mm	(4)	74.47	(5)	74.35	(6)	74.35
b	in	(7)	1.952	(8)	1.951		
b	mm	(7)	49.58	(8)	49.56		
c	in	(9)	0.983	(10)	0.985	(11)	0.984
c	mm	(9)	24.97	(10)	25.02	(11)	24.99
d	in	(12)	-	(13)	-	(14)	-
d	mm	(12)	-	(13)	-	(14)	-
e	in	(15)	-	(16)	-		
e	mm	(15)	-	(16)	-		
f	in	(17)	-	(18)	-	(19)	-
f	mm	(17)	-	(18)	-	(19)	-

Table 5.42: Dimensions of Stepped Block Casting 13 After Heat Treatment

Dimension		(Point of Measurement) and Measured Value					
Code	Unit						
a	in	(1)	2.893	(2)	2.869	(3)	2.897
a	mm	(1)	73.48	(2)	72.87	(3)	73.58
a	in	(4)	2.908	(5)	2.909	(6)	2.910
a	mm	(4)	73.86	(5)	73.89	(6)	73.91
b	in	(7)	1.933	(8)	1.936		
b	mm	(7)	49.10	(8)	49.17		
c	in	(9)	0.972	(10)	-	(11)	0.974
c	mm	(9)	24.69	(10)	-	(11)	24.74
d	in	(12)	-	(13)	-	(14)	-
d	mm	(12)	-	(13)	-	(14)	-
e	in	(15)	2.844	(16)	2.841		
e	mm	(15)	72.24	(16)	72.16		
f	in	(17)	3.805	(18)	-	(19)	-
f	mm	(17)	96.65	(18)	-	(19)	-

Table 5.43: Dimensions of the Retractable Die Core Castings
After Heat Treatment

Dimension		Measured Values			
Code	Unit	Casting 4	Casting 5	Casting 6	Casting 14
a	in	3.687	3.687	3.681	3.683
a	mm	93.65	93.65	93.50	93.55
a1	in	3.691	3.683	3.682	3.685
a1	mm	93.75	93.62	93.50	93.60
a2	in	3.689	3.686	3.681	3.689
a2	mm	93.70	93.62	93.50	93.70
b	in	0.986	0.988	0.985	0.984
b	mm	25.04	25.10	25.02	24.99
c	in	0.987	0.984	0.992	0.983
c	mm	25.07	24.99	25.20	24.97
Ø1	in	1.975	1.996	1.967	1.976
Ø1	mm	50.17	50.70	49.96	50.19
Ø2	in	1.951	1.964	1.952	1.963
Ø2	mm	49.56	49.89	49.58	49.86
Ø3	in	1.960	1.967	1.964	1.951
Ø3	mm	49.78	49.96	49.89	49.56
Ø4	in	1.873	1.876	1.864	1.875
Ø4	mm	47.57	47.65	47.04	47.63
Ø5	in	1.633	1.629	1.622	1.628
Ø5	mm	41.49	41.38	40.84	41.35
Ø6	in	1.340	1.349	1.334	1.347
Ø6	mm	34.04	34.26	33.63	34.21

Table 5.44: Average Vickers Microhardness Readings for Test Castings

Test Casting and Sample Number	Average Vickers Microhardness Values	
	Casting Centre	Casting Subsurface
1A	658	607
2A	689	651
13A	621	630

Table 5.45: Average Vickers Microhardness Readings for the Machined (EDM) Subsurface Zone of the Test Castings

Test Casting and Sample Number	Amount of Cast Surface Removed by EDM (mm)	Average Vickers Microhardness Values
1D	2.85	644
2B	1.25	711
2C	0.25	677
2D	2.85	653
13B	1.25	569
13C	0.25	584
13D	2.85	592

CHAPTER SIX

OBSERVATIONS AND DISCUSSION

6.1 INTRODUCTION

The results reported in Chapter 5 are discussed by section as follows:

6.2 Mould Material Evaluation

6.3 Metallurgical Processing

6.4 Test Castings Evaluation

6.5 Finishing Procedure

Whilst each section represents a distinct phase of activity and experiments, and therefore justifies a separate discussion section, the whole programme is inter-related. In an attempt to show how this inter-relationship affects the quality of the castings produced a discussion summary, section 6.6, is also included.

In each section observations precede the detailed discussion of the results.

6.2 MOULD MATERIAL EVALUATION

Observations:

6.2.1 Backing Material

As indicated previously, a suitable supply of graded chamotte could not be obtained. The material supplied provided extremely poor strength, even when bonded with 6% by weight of sodium silicate. Figure 5.2 shows the as-gassed strength to be only around 350 kN/m^2 , although on standing for 24 hours the strength increased to around 1000 kN/m^2 , see Figure 5.3. It was decided, therefore, to use molochite as a backing material for the purposes of the investigation, although it was recognised that a cheaper backing material would be preferable for commercial applications.

The backing material was based on a 3:1:1 ratio blend of -8 + 16 : -30 + 80 : -120 mesh grades of molochite. The effect of gassing time and flow rate on the compression strength development of the molochite blend bonded with 6% by weight sodium silicate is shown in Figure 5.4. It can be seen that the as-gassed strengths of the molochite blend are about five times higher than those for the chamotte material. From the information presented in Figure 5.4, a gassing time of 2 minutes and a flow rate of 5 litres/minute were chosen as a compromise to minimise gas consumption whilst providing acceptable as-gassed strength. These conditions were adopted for the production of all standard AFS specimens. Under these conditions, specimens could be expected to develop a compression strength of around 3500 kN/m^2 after standing for 24 hours, as shown in Figure 5.5. This value was considered to be more than adequate for the requirements of the backing material.

Because of the need to fire the moulds, the influence of firing temperature and time at firing temperature on the backing material was of interest. The tests conducted can be considered in two groups: (a) tests carried out on the material at room temperature after it had been heated to a higher temperature; and (b) tests carried out on the material whilst it was at a high temperature.

The retained strength of the backing material after heating to temperature and cooling down to room temperature was established in compression, see Figure 5.6, and tension, see Figure 5.7. In both

cases the graphs follow a similar pattern, strength increases with an increase in firing temperature to a maximum at the nominal firing temperature of 900°C and then falls. In both cases the graphs for the specimens held at firing temperature for two hours show the highest strengths.

Two other tests were conducted on specimens held at firing temperature for two hours, namely change in specimen length and change in permeability. Table 5.11 and Figure 5.8 show that the specimen length decreased with an increase in firing temperature, and Table 5.12 shows that the permeability increased as a result of heating to a high temperature.

The high temperature tests on the backing material were restricted by experimental difficulties to gas evolution and unimpeded linear expansion. In the case of gas evolution, the tests indicated that the material fired at either 750°C or 1000°C did not evolve any gas at the proscribed testing temperature of 850°C, Table 5.13. The results for unimpeded linear expansion, Figure 5.9, show a clear difference between the material fired at 750°C and that fired at 1000°C. Although, in both cases, expansion increases with time to a maximum and then decreases, the effect occurs more quickly in the material fired at 750°C and the maximum expansion figure is lower.

6.2.2 Facing Material

The effect of firing temperature and time at firing temperature on the retained compression and tensile strength of the ceramic facing material is shown in Figures 5.10 and 5.11 respectively. In both cases the trend is similar, with strength increasing with an increase in firing temperature to a maximum at the nominal firing temperature of 1000°C. The results for specimens held at firing temperature for one hour and three hours are very similar, whilst those for specimens held at firing temperature for two hours are much lower. However, this does not demonstrate the significance of firing temperature but an inconsistency in binder quality, as the two hour specimens were prepared from a different batch of prehydrolysed ethyl silicate.

The change in specimen length, measured for those specimens held at firing temperature for two hours, was positive although small for each firing temperature, see Table 5.17 and Figure 5.8. The permeability

values for the ceramic facing material were extremely low and no significant change occurred as the result of firing the material, see Table 5.18.

A full range of high temperature tests was conducted on the ceramic facing material. The gas evolution tests showed the material, whether fired at 750°C or 1000°C, to be inert, see Table 5.19. The results of the hot distortion tests for specimens which had been fired at 750°C and 1000°C were similar, see Figures 5.12 and 5.13 respectively. In all cases there was an expansion within the first 30 seconds, the value of which decreased with time during the remainder of the 10 minute test. Discernible differences do exist between the material fired at the different temperatures. In the case of the material fired at 750°C, the average maximum expansion was about 0.45 mm declining to 0.25 mm after 10 minutes. Whereas, for the material fired at 1000°C, the average maximum expansion was 0.50 mm declining to 0.35 mm after 10 minutes.

The results for unimpeded linear expansion also follow a similar pattern, see Figure 5.14, with expansion rising to a peak and then declining. However, there is a clear difference between the results. In the case of the material fired at 1000°C, the peak is higher and occurs later than for the material fired at 750°C. Furthermore, the peak value does not decline as markedly in the material fired at 1000°C.

It was possible to establish hot strength values for the ceramic facing material and these are shown in Table 5.21. These results show that the hot strength of the material fired at 1000°C was on average about 25% higher than for the material fired at 750°C.

6.2.3 Backing/Facing Material Interface

The strength of the interface bond was assessed by producing AFS tensile specimens consisting of 50% backing material and 50% facing material. The effect of firing temperature and time at firing temperature is shown in Figure 5.15. The graphs show a small but definite increase in strength with an increase in firing temperature up to the maximum nominal firing temperature of 1000°C. The specimens held at firing temperature for two hours show the lowest strength for the reason outlined previously. It was observed that the tensile

specimens did not always break at the interface. A significant number broke within the ceramic facing material, but none broke in the sodium silicate bonded backing material.

Discussion:

The effect of heat on the retained strength of silicate bonded sand was explained by Nicholas (98), as follows:

It is characteristic for the retained strengths of silicate bonded sands to have two maxima, one at approximately 200°-300°C and a second at about 900°C. The highest strength is generally developed at about 900°C.

The strength changes at temperatures up to approximately 500°-600°C are due to dehydration of ungasged sodium silicate followed by softening of the bond. At higher temperatures the retained strengths increase again due to chemical reaction between residual sodium silicate and sodium compounds with grains of quartz sand. In this manner a continuous monolithic structure of high strength is formed as the temperature is raised from 600°-900°C. At higher temperatures the quartz form of silica transforms to tridymite and/or cristobalite. This transformation is accompanied by a large volume increase, which can be as high as 30-40%, and the stresses produced lower the retained strength.

In the case of the sodium silicate bonded molochite used in this investigation, the graph of retained compression strength shown in Figure 5.6 shows a similar trend over the nominal firing temperature range of 500°-1000°C. However, the composition of molochite is different to the silica sand considered by Nicholas. Molochite is an alumino-silicate refractory containing approximately 52% silica and 42% alumina (99). Whilst there is no reason to expect a difference between the two materials' properties up to around 900°C, the fall-off in strength associated with the sodium silicate bonded molochite fired to 1000°C is less easy to explain. Measurements of the change in specimen length do not show the large volume increase associated with the transformation of β quartz in the silica system. As this change is considered to be the cause of the reduction in strength in the silica sands, its absence in the molochite should not be associated with the observed decline in strength.

The actual kiln temperatures were found to deviate from the nominal firing temperatures by the amounts shown in Table 6.1 below. Whilst this deviation affects the slope of the graphs, it does not affect the trend, and the observed fall in strength between the nominal firing temperatures of 900°C and 1000°C is real.

Table 6.1: Deviation of Actual Kiln Temperature from Nominal Firing Temperature

Nominal Temperature °C	Actual Temperature °C
500	542
600	648
700	725
750	779
800	827
900	981
1000	1033

The graphs of retained compression and tensile strength both show the highest strength for the specimens retained at temperature for two hours.

The change in specimen length, which increases with an increase in firing temperature - see Figure 5.8 - is negative, which implies contraction. However, a linear change need not imply that a volume change has occurred and the linear change is in any case small, less than 0.40%. It is suggested that the change is a manifestation of the bond softening, which has resulted in a slight settling of the specimen under its own weight.

The increase in permeability as the result of firing does not appear to be temperature dependent. The improvement in permeability, on average by about 15%, is most probably due to the removal of the water associated with the sodium silicate binder. At the low flow rate used for gassing the specimens, little water would be removed by the CO₂ gas. As all the free water would be removed once the temperature exceeded 100°C, higher firing temperatures would not be expected to further increase the permeability.

The experiments to establish gas evolution showed the material to be inert. If the only volatile ingredient in the backing material was the water associated with the sodium silicate, this result would be expected. Under these circumstances the choice of firing temperature, that is 750°C or 1000°C, would not exert any influence.

The results of the experiments to establish unimpeded linear expansion, Figure 5.9, appear to confirm that there is a softening of the silicate bond at higher temperatures. At the start of each test the specimen was loaded in slight compression to ensure positive contact between the silica discs and rods. The shape of the graphs clearly indicates that softening of the bond occurs, which would account for the contraction phase which follows the initial expansion. Because the material fired at 1000°C has a higher retained strength than that fired to 750°C, the effect of bond softening is delayed.

During early mould firing trials it was noticed that unsupported corners of the backing mould cracked and in some cases broke away. This effect was clearly much worse at the higher firing temperatures. It was determined, empirically, that a nominal firing temperature of 750°C should not be exceeded to maintain the integrity of the backing mould. The effect suggested that collapse occurred due to a softening of the bond at higher temperatures and this appears to be confirmed by the change in specimen length results and those for unimpeded linear expansion.

In selecting 750°C as the nominal firing temperature for the moulds it was necessary to establish the differences, if any, between the mould material fired to 750°C or 1000°C. As the preceding results indicate, there was no significant reason why this choice should not be made.

In the case of the ceramic facing material, the retained strengths after firing are much lower than those obtained for the sodium silicate bonded material. The retained strengths increase progressively up to the maximum nominal firing temperature of 1000°C, which tends to suggest that the reduction in strength of the backing material may be related to the presence of sodium oxide (100). One reason for the lower strength of the facing material is the particle size gradings used. The facing material contains 50% of the fine grade (-100 mesh) mullite and the associated large surface area increases the binder

demand to achieve high strength. Although the results show that a high firing temperature is necessary to develop the highest strength, the rate of strength development is not high. Hence, it can be seen from the graph in Figure 5.10 that if the moulds were fired at 750°C instead of 1000°C, they would still develop about 90% of the strength obtained at 1000°C. Very high strength in the facing material might not be desirable, as it could present hot tearing or distortion problems associated with poor breakdown.

Measurements of the change in specimen length for the facing material suggest it to be quite stable. The very slight expansion recorded for all specimens was, on average, less than 0.1%. The permeability of the facing material containing such a high proportion of fine material was very low. The before firing tests were conducted on samples which had been 'torched' and would therefore show any benefit obtained through 'micro-crazing'. Even though the material is essentially inert, the low permeability could be a problem in resisting the displacement of air or inert gas from the mould cavity by the incoming metal. However, in the test casting moulds the facing layer would not exceed 13 mm, and this layer would be more permeable than the 50.8 mm thickness associated with the AFS sample.

The inertness of the material was confirmed by the gas evolution tests. No gas was evolved, at 850°C, from the material previously fired to either 750°C or 1000°C.

The results of the hot distortion tests were strongly indicative of the stability of the facing material and showed, as expected, that heat has little effect on breakdown.

Similarities exist between the unimpeded linear expansion results for the backing and facing materials. However, the ceramic facing material resists the effect of bond softening for a longer period. The material fired to 1000°C resists softening significantly better than that fired to 750°C. From the graphs it appears that the facing material has a higher coefficient of linear expansion. However, the difference may be due to the better resistance to softening exhibited by the facing material. The hot strength results for the facing material show the material fired at 1000°C to be, on average, 25% stronger than that fired to 750°C. A comparison between the retained compression

strengths after firing and cooling shows the difference to be around 10%. The greater difference in hot strength may reflect the improved resistance to softening exhibited by the material fired to 1000°C.

The strength of the bond between the backing and facing material is very low. For a firing temperature of 750°C the retained tensile strength of the composite test piece, by extrapolation, would be about 80 kN/m², which is around half that expected from the ceramic material and just over 10% of that expected from the sodium silicate bonded material. However, a bond does exist, which suggests that some of the ethyl silicate present in the ceramic slurry penetrates the backing material at the interface during mould production.

From the results obtained, it was considered that an acceptable nominal firing temperature for the test casting moulds would be 750°C and that a holding time of two hours at the maximum temperature would be sufficient. These conditions were a compromise between minimising the damage to the backing material and maximising the strength of the facing material. Whilst the experiments showed that facing material fired to 1000°C had better cold strength and hot strength characteristics, the difference was not considered significant for the production of successful castings.

6.3 METALLURGICAL PROCESSING

Observations:

6.3.1 Macroexamination

Visual examination of the ingot castings enabled certain observations to be made from which important conclusions could be drawn. Although brief details are included in Table 5.23, further observations on each series of experiments are made below.

Series I to III (Figures 5.16 to 5.18):

All nine castings in this group exhibit the pitting defect. However, the severity appears to increase with both an increase in the pouring temperature (furnace temperature) and an increase in the mould preheat temperature. Castings produced in the moulds preheated to the highest temperature (800°C) appear to show an increased number of pits which are smaller in size than those on the castings produced in cooler moulds.

Series IV (Figures 5.19 i and 5.19 ii):

The use of a nitrogen atmosphere has almost completely suppressed the pitting defect. In addition, the nitrogen atmosphere has suppressed the formation of oxide scale, Figure 5.19 ii.

Series V (Figure 5.20):

Increasing the addition level of the deoxidiser, Stellan 1, appears to decrease the severity of the pitting defect.

Series VI (Figure 5.21):

Increasing the addition level of the grain refining agents had no demonstrable effect on the severity of the pitting defect.

Series VII and VIII (Figures 5.22 and 5.23):

The castings produced in air (Series VII) exhibit the pitting defect. However, the severity of the defect appears to have been reduced by the addition of the deoxidiser to the melt. The pitting defect has been suppressed in those castings produced in a nitrogen atmosphere (Series VIII), although the surface quality cannot be described as good. There is evidence of a penetration-like defect.

Series IX to XI (Figures 5.24 to 5.26):

The presence of 10 weight % graphite in the mould facing material has suppressed the formation of the pitting defect. The castings produced from moulds preheated to 800°C have an inferior surface quality with evidence of a penetration-like defect.

Series XII (Figure 5.27):

The presence of graphite in the mould facing material has suppressed the pitting defect. However, the surface quality of the castings is not good and is similar to the equivalent castings in Series VII and VIII (Figures 5.22 and 5.23).

Series XIII and XIV (Figures 5.28 and 5.29):

The combination of a mould material containing graphite and the presence of an inert gas atmosphere during casting and solidification did not produce castings of improved quality. Whilst the pitting defect was suppressed in all cases, the ingot castings produced with the nitrogen atmosphere exhibited poor surface quality. The ingot cast at 1600°C had a matte effect finish, whilst that cast at 1700°C had severe penetration-like defects. Although the ingots produced at lower casting temperatures in an argon atmosphere possessed reasonable surface quality, that cast at 1700°C exhibited severe penetration-like defects.

Series XV (Figures 5.30):

The castings produced using a zircon mould facing material exhibited the pitting defect.

Series XVI (Figures 5.31):

The castings produced in the machined graphite mould had a very poor surface quality as a result of the presence of gross gas defects.

Series XVII (Figures 5.32):

These castings exhibited the pitting defect, indicating that the addition of up to 3 weight % nickel to the melt is ineffective for eliminating the defect.

6.3.2 Microexamination

Microhardness Measurements:

The microhardness measurements were conducted on a transverse section cut from the ingot castings. The subsurface measurements were therefore obtained on a plane perpendicular to the as-cast surface. The proximity of the hardness impression to the as-cast surface was therefore limited by the size of the diamond and the requirement to produce a fully shaped impression. Readings were taken in the subsurface layer and from the centre of the ingot casting, and the average microhardness values are presented in Table 5.25. Examination of these values shows that, for 15 out of the 17 ingot castings tested, the subsurface hardness value was lower than that of the ingot centre.

Grain Size Measurements:

These measurements were performed on a group of 11 ingot casting specimens with the specific aim of assessing the effect of grain refining additions. The average grain size measurements are presented in Table 5.26 and appear at first examination to suggest that grain refining additions do reduce the grain size.

Microstructures:

To provide standardisation all the microstructures presented are taken from ingot castings produced from melts with a furnace temperature of 1650°C. For the purposes of comparison, the structures can be considered in three groups:

Group A, ingot castings 3, 43 and 59 (Figures 5.35/36, 5.41/42 and 5.45/46):

In this group ingot casting 3 was air-cast in a mullite mould, 43 was produced in a mullite mould but cast and solidified in a nitrogen atmosphere, and 59 was air-cast in a mullite mould facing material containing 10 weight % graphite. The microstructures do not reveal any significant differences between the surface structures, although a layer of porosity exists beneath the skin of casting 3.

Group B, ingot castings 3, 34, 35 and 63 (Figures 5.35/36, 5.37/38, 5.39/40 and 5.47/48):

All the castings in this group have been air-cast in a mullite mould. The difference between the castings is that 3 contains no melt

additions, 34 has been deoxidised, 35 has been grain refined, and 63 has been deoxidised and grain refined. The microstructures do not reveal any significant difference between the surface structures.

Group C, ingot castings 63, 58 and 59 (Figures 5.47/48, 5.43/54 and 5.45/46):

All the castings in this group have been deoxidised and grain refined. Casting 63 was air-cast in a mullite mould, 58 was moulded in mullite but cast and solidified in a nitrogen atmosphere, and 59 was air-cast but moulded in mullite containing 10 weight % graphite. The microstructures do not reveal any significant difference between the surface structures.

Figure 5.49 a and b show two magnifications of the centre structure of ingot casting 37. The structure is typical of the whole group of ingot castings.

Discussion:

The ingot castings produced in mullite moulds and cast in air exhibited the pitting defect. The severity of the defect increased with both mould preheat temperature and pouring temperature. The presence of surface pitting was expected and has been observed by other researchers (21, 59, 60). If the pitting defect is the result of a metal/mould reaction which occurs at high temperatures (21) then it would be expected that the slower rate of cooling, produced by higher pouring temperature and/or mould temperature, would exacerbate the problem.

Reducing the effect of oxygen either by casting with an inert gas atmosphere or incorporating graphite in the mould facing material suppressed the formation of the pitting defect. These results conform with the findings and suggestions in the literature (59, 62). The ingot castings produced using a nitrogen atmosphere were almost scale-free, unlike those produced in the moulds containing graphite and cast in air. This has a practical implication in that scale-free castings may not require shotblasting and may therefore possess improved surface finish and dimensional accuracy.

For the series of castings produced from deoxidised melts, both the mould and metal temperatures were maintained at a constant level. The

addition of deoxidiser to the melt reduced but did not eliminate the extent of the pitting defect. Although this effect was not described in the literature, the addition of certain deoxidisers to the mould material (57) has been recommended to reduce or prevent surface decarburisation. The presence of an element which oxidises preferentially to carbon should curtail the mechanism by which the pitting defect occurs (60).

The addition of grain refining additions to the melt had no discernable effect on the extent of the surface pitting defect. In the castings produced from melts which had been treated with both deoxidiser and grain refiners there was evidence that the pitting defect had been reduced. Melts treated with the combined additions were poured at different temperatures, but the mould temperature remained a constant.

Perhaps the most disappointing results were those for the ingot castings produced in moulds containing graphite and cast in either a nitrogen or argon atmosphere. Whilst it would be reasonable to expect that this combination might provide the best possible surface quality, in practice this was not the case. Whilst the pitting defect was absent, other surface defects were present. Although the castings produced at the two lower temperatures using an argon atmosphere had a better surface quality than those produced with a nitrogen atmosphere, they were certainly no better than those cast in air. The very poor surface finish with penetration-like defects, found on the ingots cast at 1700°C in both argon and nitrogen, might be due to the combination of high pouring temperature and the absence of an oxide skin promoting the conditions for metal penetration.

The experiments using machined graphite moulds were performed to evaluate the possibility of using a semi-permanent mould process, as well as to confirm the suitability of graphite as a pitting defect suppressor. Whilst the results were poor, it should be noted that neither a mould coating nor quiescent method of mould filling were used. These features are present in the Griffin process used successfully to produce cast steel wheels for railway requirements.

Zircon moulds have been recommended as suitable for casting die steels (18), but in these experiments the pitting defect was observed on the ingot castings, a feature confirmed by other workers (61). The

addition of nickel to the melt has been suggested as a method of suppressing the pitting defect (18, 61). However, in these experiments the addition of up to 3 weight % nickel was not found to be effective in this respect.

From observations made as a result of the ingot casting programme, the following recommendations are suggested as a means of minimising the extent of the surface pitting defect and maximising the surface quality of castings:

- 1 Moulds produced in mullite should be cast and solidified in an inert gas atmosphere or, alternatively, be produced with an addition of 10 weight % graphite if they are to be cast in air.
- 2 Moulds should not be preheated, unless the presence of thin sections dictates this to ensure mould filling.
- 3 The metal pouring temperature should be kept as low as possible.
- 4 The molten metal should be treated with a suitable deoxidiser.

As indicated previously, the subsurface microhardness was lower than that of the centre in 15 of the 17 ingot castings tested. The mean average microhardness value for the casting subsurfaces was 625, with a range of 550 to 733, and that for the casting centres was 686, with a range of 636 to 763. A simple statistical test (101) suggested that the difference in microhardness values between the subsurface and centre of the ingots was significant. Applying a more discriminating method (102), based on determining the standard error of the mean, confirmed that the differences in microhardness were statistically significant. Details of the statistical tests are presented in Appendix Seven.

The subsurface microhardness readings were all taken within a zone extending 0.1 mm from the surface of the ingots. It was considered that this zone would be representative of the 'casting skin'. The reduced microhardness levels in this surface zone might be due to a lower level of carbon resulting from decarburisation. A lower casting skin hardness was observed by other researchers using a slightly different approach to establish hardness and using a very different steel (103).

To assess the effect of grain refining additions, a statistical comparison was performed on selected ingot castings from the group of eleven detailed in Table 5.26. Castings 3 and 43, to which no additions were made, were considered as one sample (A) and castings 62, 63 and 66, to which had been added a deoxidiser and grain refining additions, as a second sample (B). The statistical tests are detailed in Appendix Seven, where the values used to calculate the average number of grains intercepted, shown in Table 5.26, are shown in full for the ingot castings under consideration. The mean value of sample A was 3.7, with a range of 2.7 to 4.7, and that for sample B was 5.4, with a range of 4.3 to 6.0. A simple statistical test (104) suggested a significant difference and this was confirmed by the more discriminating test (102).

Whilst the addition of grain refining additions clearly decreases grain size, no mechanical tests were performed on the cast H13 die steel and so a quantitative assessment of the benefit of grain refinement was not obtained. However, a correlation could exist between hardness values and grain size. An analysis was conducted for association (105) using the data from Tables 5.25 and 5.26 and is shown in Appendix Seven. However, the analysis did not show any significant association.

The microstructures presented in Figures 5.35 to 5.48 are essentially similar and show the typical features of cast H13 die steel (106). The structures consist of some carbide particles in a matrix of untempered martensite (dark areas) and retained austenite (light areas). Some porosity and non-metallic inclusions are present in most specimens. No visually distinguishable surface layer could be detected in the microstructures. The roughness of the surface was apparent, especially at high magnifications. The rough surface exists on ingot castings produced in a mullite mould and cast in either air or nitrogen and on the castings produced in a mullite mould facing containing graphite. In some cases, surface depressions lead directly into grain boundaries where there is evidence of oxidation (see Figure 5.48). These features could provide initiation points for crack propagation in service if the cast surface was not removed by a finishing operation.

Neither the microhardness readings nor the microstructures provided evidence to suggest that the casting skin possessed qualities which merit retention. The evidence suggests the opposite, with the microhardness of the subsurface layer being generally lower than that

of the casting centre and the microstructures revealing at best an undulating surface, but generally one containing pits and protruberances. Whilst this rough surface layer is generally quite shallow, below 35 μm , its removal would improve the integrity of the surface.

6.4 TEST CASTINGS EVALUATION

Observations:

6.4.1 Visual Examination

Although comments on the visual appearance of the test castings are provided under the heading observations in Table 5.27, they become more meaningful when considered in relation to pouring temperature. In the literature it is recommended that H13 steel castings be poured at between 1520°C and 1560°C (18,19). In this investigation the pouring temperatures ranged between 1483°C and 1586°C, with eleven test castings being poured within the recommended range, see Table 6.2.

Table 6.2: Test Casting Pouring Temperature Ranges

Pouring Temperature Range °C	Number of Test Castings in the Range	Test Casting Numbers
1480 - 1500	2	2,6
1501 - 1520	1	7
1521 - 1540	4	1,5,10,15
1541 - 1560	7	4,8,9,11,12,13,14
1561 - 1580	0	-
1581 - 1600	1	3

Table 6.3 presents the visual observations on test casting quality in order of ascending pouring temperatures.

Table 6.3: Observations on Test Castings Related to
Pouring Temperature

Pouring Temperature °C	Test Casting Number	Observations
1483	2	Cold laps and rounded edges present.
1500	6	Cold laps and rounded edges present, especially in the teeth.
1516	7	Some cold laps present on the cavity edge.
1523	1	Rounded edges with poor definition.
1530	5	Poor definition in the teeth, some pitting evident.
1540	10	Some evidence of cold laps with some poor edge definition.
1540	15	No evidence of cold laps, poor surface quality in the cavity, some evidence of penetration.
1545	9	No evidence of cold laps.
1545	12	No evidence of cold laps, good edge definition.
1550	8	Not perfect but generally good definition, evidence of slight penetration.
1550	11	Cold laps due to overspill down the open head, quite severe pitting defect evident.
1550	14	No evidence of cold laps, imperfect teeth form but better than 5 and 6, some pitting evident.
1555	4	Not perfect but much better edge definition than 5 and 6.
1555	13	No cold laps, good edge definition but penetration defects present.
1586	3	No cold laps, good edge definition, penetration defects worse than 13.

6.4.2 Dimensions and Surface Finish

Whilst the details for casting and pattern dimensions and surface finish are presented in section 5.4, the values by themselves provide little information. In order to establish the influence of such variables as: casting weight; mould material; mould atmosphere and pouring temperature on the accuracy and quality of surface finish of the castings, the data must be suitably processed.

Dimensions The dimensions of each test casting were compared with the equivalent pattern dimensions and the % deviation, of the casting dimension from the pattern dimension, established:

let a = pattern dimension - casting dimension

then, % deviation = $\frac{a}{\text{pattern dimension}} \times 100$

Under normal circumstances it would be expected that the % deviation would be negative because the casting contracts. The % deviation values for each group of test castings are presented in Tables 6.4 to 6.7.

The % deviation values have been used in two ways. Firstly the average % deviation value, compounded for the range of each casting's dimensions, was calculated for each test casting. With this information, and considering the castings by type, it was hoped to identify any relationship between average % deviation and the variables: pouring temperature; casting weight; and mould material/mould atmosphere. Secondly by grouping the average % deviations in bands, according to the original pattern dimensions, it was hoped to identify any relationship between average % deviation and the size of the dimension.

Pouring Temperature:

No meaningful diagrammatic representation could be found to express a relationship between pouring temperature and average % deviation.

Casting Weight:

Figure 6.1 shows the average % deviation values plotted according to the casting type or weight.

Mould Material/Mould Atmosphere:

Figure 6.2 shows the average % deviation values plotted against the different mould material/mould atmosphere combinations.

Effect of Dimension Size:

Figure 6.3 shows the average % deviation values plotted against the nominal pattern dimension for four distinct pattern dimension bands.

Surface Finish The mean Ra and Wa values for the test castings were established from the individual readings conducted on each casting and are presented in Table 6.8. Table 6.9 presents the equivalent values for the patterns. In an attempt to identify any relationship with process variables, the mean Ra and Wa values were treated as follows:

Pouring Temperature:

No meaningful diagrammatic representation could be found to express a relationship between pouring temperature and either Ra or Wa.

Casting Weight:

Figure 6.4 shows the mean Ra values for the test castings plotted according to the casting type or weight. Figure 6.5 shows the equivalent relationship for mean Wa values.

Mould Material/Mould Atmosphere:

Figure 6.6 shows the mean Ra values plotted against the different mould material/mould atmosphere combinations and Figure 6.7 the equivalent relationship for the mean Wa values.

Bearing Ratio The bearing ratio curves are shown in Figures 5.66 to 5.70; 5.72 to 5.76; 5.78 to 5.82; and 5.84 to 5.87. With only a few exceptions, these graphs were very similar. The average values for both patterns and castings are shown in Table 6.10.

6.4.3 Contraction Allowance

The determination of the contraction allowance required experiments to determine the melting point (solidus temperature) of the H13 die steel and its coefficient of linear expansion. The information obtained is considered in the subsequent discussion and no specific observations are presented.

Discussion:

Assuming the liquidus temperature for H13 die steel to be about 1475°C (97,107) it is not surprising that the two castings poured below 1501°C are characterised by very poor surface quality, cold laps and poor edge definition. Although these two castings exhibited the poorest surface quality, cold laps and poor edge definition were generally evident in those castings poured at temperatures between 1501°C and 1540°C . It was not until the pouring temperature exceeded 1541°C that cold laps were no longer evident and good edge definition was obtained. However, even at the highest pouring temperatures, the teeth of the retractable die core were not perfectly formed.

Some evidence of pitting was seen in test castings 5, 11 and 14. Test castings 5 and 11 were poured and cooled under a nitrogen atmosphere and test casting 14 was produced in a mould containing 10 weight % graphite in the facing material. According to the results obtained in the production of ingot castings, these conditions should have produced castings free from the pitting defect. An objective assessment of the methods of processing the moulds during firing and prior to casting may highlight limitations which have resulted in the appearance of the pitting defect.

The moulds were fired in an electrically heated kiln with an air (oxidising) atmosphere. If graphite is to be effective in suppressing the pitting defect it must remain in the facing material. Despite attempts to prevent its loss during mould firing, by using covers, there was evidence to suggest that some loss was occurring. A difference in colour was observed, with the deeper pockets retaining a darker grey colouration after firing than those areas near to the top (joint) face of the moulds. Whilst this may explain the occurrence of the pitting defect on the retractable die core casting 14, it should be noted that several other castings were produced in the same mould material and without the defect. Oxidising conditions are normally recommended when firing Shaw process moulds (44) to ensure the removal of any volatile material. However, on reflection, it would seem appropriate to use either a reducing or inert atmosphere to prevent the loss of graphite.

The use of a nitrogen atmosphere for test casting production was not as successful as it was for ingot casting production. Whereas the ingot

castings showed no sign of the pitting defect and were almost free of oxide scale, two of the four test castings produced using a nitrogen atmosphere exhibited the pitting defect and all four exhibited an oxide scale which required a shotblasting treatment to remove it. In the case of the ingot castings, small castings were produced in small open-top moulds in a small container flushed with relatively high flow rates of nitrogen. The castings cooled down to room temperature within a few hours. In the case of the test castings, much larger castings were produced in large, predominantly sealed, moulds in a large container with a relatively low flow rate of nitrogen. These castings cooled very slowly and were still too hot to handle when broken from the moulds 24 hours later.

The observed metal penetration defect takes the form of small, almost spherical, protrusions on the surface of the test castings. The defect appears to be formed by metal penetrating the mould skin to fill small voids formed by air bubbles present during mould manufacture. The defect is at its worst in the casting poured at the highest temperature of 1586°C. Three of the four castings exhibiting the defect were produced in moulds in which the mould facing contained 10 weight % graphite. It is possible that the increased volume of fine material caused more air to be entrapped in the slurry. Altering the pattern vibration conditions during mould filling and/or careful control of the metal pouring temperature may eliminate this problem.

The laps which spoil the cavity in test casting 11 were the result of careless pouring, which allowed metal to spill over the bush side and down the open head. The defect could have been prevented by covering the open head with a refractory board.

The spider forging dies all exhibited a sink in the top (as-cast) surface and in some cases a draw in the ingate. The calculated head size should have been sufficient to feed the casting and trial castings were produced without apparent shrinkage defects. It is possible that the neck connecting the feeder head to the casting may not have been sufficiently large.

The retractable die core castings all showed imperfections in the teeth form to some extent. The casting is fairly small, cast weight 1.6 kg, and the heat loss during filling with the associated loss of fluidity would be quite high. The gating system design and low mould

permeability may also be contributory factors to poor definition. However, it is possible that the problems experienced may indicate a limit to the shape complexity possible without preheating the mould.

Dimensions:

An examination of Figures 6.1 to 6.3 does not reveal any apparent relationships. In Figure 6.1 the castings are considered by type and weight. The approximate cast weights are as follows:

retractable die core (rack core)	1.6 kg
stepped block	2.9 kg
spider forging die	7.0 kg
flange yoke forging die	18.0 kg

The group means for the % deviation from pattern dimension for each type of casting range from -1.17 to -2.37, compared with the overall average for all fifteen castings of -1.65. If the results for the retractable die core were excluded, there would appear to be a trend with % deviation increasing with casting weight.

When the % deviation values are grouped according to mould material/atmosphere combinations, the group means range from -1.57 to -1.71 and are therefore grouped very much more closely around the overall average of -1.65, see Figure 6.2. This appears to suggest that the mould material/atmosphere combination is not a significant process variable with regard to its influence on dimensional variations.

When the % deviation values are grouped according to the nominal pattern dimensions, there is once more no clear trend. The group mean values range from -1.29 to -1.94, which compares with the overall average of -1.68.

Surface Finish:

The equipment available for measuring surface finish has been developed to accommodate the common conventional machined surfaces in engineering which are produced by grinding, milling or turning (108). Machined surfaces have a definite, regular, repetitive, directional pattern and defining a cross-section of the machined pattern defines the surface. In contrast, cast surfaces have an irregular, random pattern and there can be a wide latitude in the mathematical value within a small area

(109). For this reason conventional stylus measuring machines have been considered inappropriate, especially where sand cast surfaces are considered (110).

The inherently smoother surfaces associated with precision casting permit stylus measuring machines to be used and, if the limitations are accepted, they may still provide a useful method of comparison in the absence of a suitable alternative. In these experiments the three aspects of surface finish measured were:

Roughness Average	Ra
Waviness	Wa
Bearing Ratio	tp

In the case of machined surfaces, roughness refers to the irregularities in the production process left by the actual machining agent (eg cutting tool, grit, spark). Waviness may result from such factors as machine or work deflections, vibrations, chatter, various causes of strain in the material, and extraneous influences (111). Whilst these feature do not apply directly to the production of a cast surface, they are clearly involved in the production of the patterns and may in part be translated to the casting finish. The roughness of the casting surface will be affected by the grain size of the refractory aggregate used in moulding. In these experiments a wide range of particle sizes was used to formulate the facing mix and this would be expected to exert an influence. As Ra and Wa essentially measure surface roughness of different frequencies, it is possible that the results could reflect the presence of fine refractory particles in Ra and large refractory particles in Wa. This interpretation would differ from the definition of waviness in the case of machined surfaces, which defines waviness as that component of surface texture upon which roughness is superimposed.

Mathematically, Ra is the arithmetic average value of the departure of the profile from the centre line throughout the sampling length. Ra gives no information as to the shape of the irregularities or profile and no distinction is made between peaks and valleys. Ra must be quoted in conjunction with the meter cut-off value, for which 0.8 mm is the most universally recommended.

Bearing ratio, t_p , is the ratio (expressed as a percentage) of the length of bearing surface at any specified depth in the profile to the evaluation length. Whilst the value is of interest primarily in bearing or wear applications, it can be used as a measure of consistency in the case of cast surfaces.

Examination of Figure 6.4 reveals an apparent trend in that the mean Ra values increase with an increase in casting weight. This apparent trend is strengthened when the values for the patterns are examined in relation to those for the castings (see Table 6.9). The mean Ra value for the retractable die core pattern is much higher than those for the other three patterns. The die core pattern was produced from graphite, whereas aluminium was used for the other three patterns. Visual examination of the graphite pattern surface revealed an 'open grain' structure which may in part explain the higher pattern Ra value. Even though the pattern was coated with wax before moulding, this apparently did not effectively fill the open pattern surface. When the mean pattern Ra value is subtracted from the group mean value for each casting type the differences are:

	Ra
retractable die core	1.40
stepped block	3.08
spider die	3.87
flange yoke die	4.73

which particularly emphasizes the difference between the die core and stepped block values not apparent in Figure 6.4.

The range for group mean Ra values when considered in relation to casting type is 1.9, ie from 3.16 to 5.06. The overall average Ra value for the fifteen test castings is 3.88. When the mean Ra values are considered in relation to the mould material/atmosphere combination (see Figure 6.6) the group means have a range of only 0.21, ie from 3.79 to 4.00. This relationship is similar to that observed for % deviation from the pattern dimensions.

When the mean Wa values are considered in relation to casting type/weight (see Figure 6.5), the values for the retractable die core appear to break an apparent trend. However, although there was a large difference in mean Ra values between patterns, this was not the case between Wa values (see Table 6.9). The range of casting group mean Wa

values is 2.17, ie from 5.48 to 7.65. The overall average Wa value for the fifteen test castings is 6.50. When the mean Wa values are considered in relation to the mould material/atmosphere combination (see Figure 6.7) the group means have a range of 1.32, ie from 5.70 to 7.02. Once again, this relationship is similar to that observed for % deviation from the pattern dimensions.

The bearing ratio values were computed at the equipment's set condition, which is at the mean of the amplitude distribution, which has the effect of grouping the values around $t_p = 50\%$. To a certain extent this decreases sensitivity and makes comparison between numeric values less fruitful. For this reason it is important to consider the shape of the curves. A high bearing ratio implies that the number of peaks in the surface is lower and/or they are flatter. This is denoted by a convex curve, conversely a low bearing ratio is denoted by a concave curve. Reference to Table 6.10 and the relevant figures between 5.66 and 5.87 shows that, in general, the curves are very similar and convex in form. Deviations from the general trend, such as castings 5 and 8 (Figures 5.73 and 5.80), show a degree of concavity in the bearing ratio curves.

Tests for association were conducted between the measured variables of % deviation, mean Ra, mean Wa and bearing ratio, and the pouring temperature and casting weights, see Appendix Seven. When this was conducted using the sample of all fifteen test castings, two associations were found. These associations were between:

- mean Ra and casting weight
- mean Ra and mean Wa

Because the values of group mean % deviation and group mean Wa for the retractable die core castings appeared to break apparent trends, further tests for association were conducted after excluding values for the retractable die cores. This produced an association between:

- % deviation and casting weight
- mean Ra and casting weight
- mean Ra and mean Wa
- mean Wa and pouring temperature

The tests for association have supported the apparent influence of casting weight on dimensional accuracy and surface finish. This

association is strongest for the relationship between mean Ra and casting weight, which is evident whether the whole group of fifteen castings is considered or just the smaller group of eleven castings. Although the association between mean Ra and mean Wa is equally strong, there was no association between mean Wa and casting weight. This was despite the apparent trend which can be observed in Figure 6.5, if the results for the retractable die core are excluded. However, there is a wide scatter in the values of mean Wa, as may be observed in respect of the spider die castings.

When the results of the retractable die core are excluded, an association exists between % deviation and casting weight, strengthening the significance of this variable. In excluding the retractable die core results, weight is being given to a subjective view that these results appear to be at deviance with those for the other casting types. However, the retractable die core pattern was made with an unconventional pattern material which had produced an inferior Ra value, so there is also an objective reason for considering association in the absence of the retractable die core results.

The reasons for the significance of casting weight have not been quantified in this investigation. Whilst casting weight and the size of dimensions may often be related, the two terms should not be considered as synonymous. Other workers have found that the size of a dimension influences the amount of contraction which occurs, although these findings were not necessarily in agreement. Patterson (34) found that the overall contraction decreased for Nicrosil and HH steel as the size of the casting dimensions increased. Conversely, Madono (17) found that greater contraction allowances were necessary for the length dimensions in H4 steel dies than for the width dimensions.

The attempt to define the relationship between % deviation from pattern dimension and the size of dimension, which would incorporate the effect of contraction, did not provide a conclusive result in this investigation, see Figure 6.3. Furthermore, it did not prove possible to differentiate between the influence of contraction allowance and process variations on the value of % deviation.

The experimentally established value of 1.64% for contraction allowance falls within the range of values suggested in the literature (55,56). However, the experimentally obtained value was determined over the

range of 20°C-900°C and can therefore only be considered as a guide. In addition, the value is a linear one and attempts to use such values as predictors of final shape in complex three dimensional shapes may not provide accurate values. Despite this limitation, it was hoped that the contraction allowance could be used in an attempt to distinguish between the effects of contraction and process variables on dimensional repeatability. However, a major difficulty in this respect is the average value for % deviation from the pattern dimensions for all fifteen test castings which, at 1.65%, is almost identical to the value of 1.64% for contraction allowance.

Returning to the significance of casting weight, its effect may relate to the castings' solidification and cooling times. The heavier castings would have slower solidification and cooling times. The slower solidification time could be equated to there being a longer period during which the liquid alloy was in contact with mould material and able to more closely replicate that surface. This effect would appear as higher numeric values of mean Ra for the heavier castings. Similarly, longer cooling times could permit greater oxidation or scaling of the heavier castings to occur which, after removal by shotblasting, may account for the larger % deviations of cavity dimensions of the spider and flange yoke forging dies.

The results of the test casting evaluation programme have not provided any evidence to show that any of the three mould material/atmosphere combinations produces castings with improved dimensional accuracy or surface finish. When the values for % deviation, mean Ra and mean Wa were considered in groups according to the mould material/atmosphere combination, their group means were close together and well within one standard deviation of the overall means when all fifteen castings were considered as a group. However, it should be emphasized that the variation in practice was directed at eliminating the pitting defect and that this defect is very large in comparison with the irregularities measured by the Talysurf. Any improvement in surface finish as a result of using a particular combination would have been an additional bonus. The use of an inert gas atmosphere had produced scale-free ingot castings and had this effect occurred with the larger test castings, some improvement in surface finish may have been seen.

If the results of this investigation were used as a tolerance guide, incorporating contraction allowance and process variations, the following table could be produced:

For dimensions up to	26 mm	(~ 1 in) \pm 0.32 mm (\pm 0.013 in)
For dimensions between	26- 51 mm	(~ 1-2 in) \pm 0.70 mm (\pm 0.028 in)
For dimensions between	51- 77 mm	(~ 2-3 in) \pm 1.01 mm (\pm 0.040 in)
For dimensions between	77-102 mm	(~ 3-4 in) \pm 1.70 mm (\pm 0.067 in)

The surface finish (Ra) values obtained ranged between 2.5 and 5.75 μ m, which compares with a claimed possible best value of 2.0 μ m for the Shaw Process and the typical 5 to 10 μ m for sand moulded castings (25).

Table 6.4: Deviation from Pattern Dimensions: Stepped Block Test Castings

Dimension	Pattern Dimension	1		2		3		13	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	74.98	74.17	-1.08	73.97	-1.35	74.20	-1.04	-	-
b	49.87	49.31	-1.12	49.38	-0.98	49.48	-0.78	48.99	-1.76
c	24.92	24.70	-0.88	24.93	+0.04	24.94	+0.08	24.70	-0.88
d	48.30	47.73	-1.18	47.49	-1.68	48.04	-0.54	-	-
e	73.27	72.24	-1.41	72.02	-1.71	-	-	71.99	-1.75
f	98.30	96.46	-1.87	96.38	-1.95	-	-	96.48	-1.85
Average % Deviation			-1.26		-1.27		-0.57		-1.56

Table 6.5: Deviation from Pattern Dimensions: Retractable Die Core Test Castings

Dimension	Pattern Dimension	4		5		6		14	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	95.38	93.57	-1.90	93.50	-1.97	93.40	-2.08	93.52	-1.95
a1	95.33	93.47	-1.95	93.52	-1.90	93.55	-1.87	93.42	-2.00
a2	95.38	93.55	-1.92	93.50	-1.97	93.60	-1.87	93.45	-2.02
b	25.48	25.02	-1.81	25.04	-1.73	24.99	-1.92	24.99	-1.92
c	25.48	24.92	-2.20	25.12	-1.41	24.92	-2.20	25.07	-1.61
Ø1	50.80	50.05	-1.48	51.33	+1.04	49.88	-1.81	50.11	-1.36
Ø2	50.80	49.81	-1.95	49.71	-2.15	49.60	-2.36	49.58	-2.40
Ø3	50.80	49.70	-2.17	49.86	-1.85	49.71	-2.15	49.78	-2.01
Ø4	38.27	38.20	-0.18	38.91	+1.67	37.94	-0.86	37.92	-0.91
Ø5	31.92	31.62	-0.94	31.19	-2.29	31.52	-1.25	31.62	-0.94
Ø6	24.61	24.46	-0.61	24.61	0	24.30	-1.26	24.71	+0.41
Average % Deviation*			-1.96		-1.80		-1.99		-1.90

* across the joint dimensions excluded

Table 6.6: Deviation from Pattern Dimensions: Spider Forging Die Test Castings

Dimension	Pattern Dimension	7		8		10		15	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	11.05	10.95	-0.90	10.95	-0.90	10.87	-1.63	11.10	+0.45
b	11.02	10.92	-0.91	10.90	-1.09	10.97	-0.45	11.10	+0.73
c	11.05	10.92	-1.18	10.87	-1.63	10.87	-1.63	10.95	-0.90
d	11.05	10.92	-1.18	10.87	-1.63	10.85	-1.81	10.95	-0.90
e	44.35	43.36	-2.23	43.48	-1.96	43.61	-1.67	43.31	-2.35
f	44.35	43.33	-2.30	43.56	-1.78	43.61	-1.67	43.33	-2.30
Average % Deviation			-1.45		-1.50		-1.48		-0.88

Table 6.7: Deviation from Pattern Dimensions: Flange Yoke Forging Die Test Castings

Dimension	Pattern Dimension	9		11		12	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	44.73	43.64	-2.44	43.71	-2.28	43.56	-2.62
b	44.75	43.56	-2.66	43.89	-1.92	43.61	-2.55
c	36.09	35.31	-2.16	35.48	-1.69	35.10	-2.74
d	36.12	35.18	-2.60	35.43	-1.91	35.18	-2.60
Øe	96.34	94.41	-2.00	94.51	-1.90	94.26	-2.16
f	8.86	8.53	-3.72	8.66	-2.26	8.64	-2.48
Average % Deviation			-2.60		-1.99		-2.53

Table 6.8: Mean Ra and Wa Values for the Test Castings

Test Casting Number	Mean Ra Value	Mean Wa Value
1	2.54	4.38
2	3.45	5.38
3	3.59	7.08
4	3.56	7.45
5	2.91	8.10
6	3.15	4.85
7	3.84	4.13
8	4.76	8.84
9	5.03	7.84
10	5.30	7.93
11	5.63	8.59
12	4.52	6.52
13	3.44	4.99
14	3.02	6.31
15	3.40	4.93

Table 6.9: Mean Ra and Wa Values for the Test Casting Patterns

Pattern	Mean Ra Value	Mean Wa Value
Stepped Block	0.18	0.23
Retractable Die Core	1.76	1.27
Spider Die	0.46	1.32
Flange Yoke Die	0.33	1.03

Table 6.10: Average Bearing Ratio Values for Test Castings
and Patterns

Description	Bearing Ratio tp (%)
<u>Patterns</u>	
Retractable Die Core	51.07
Stepped Block	50.95
Spider Forging Die	49.75
Flange Yoke Die	49.75
Average Value	50.38
<u>Castings</u>	
1	47.97
2	50.80
3	49.40
4	47.37
5	46.30
6	51.90
7	51.25
8	43.80
9	52.35
10	49.00
11	49.85
12	54.65
13	50.17
14	52.20
15	51.75
Average Value	49.92

6.5 FINISHING PROCEDURES

Observations:

6.5.1 Heat Treatment

The hardness of each of the eight test castings which were heat treated increased as a result of the treatment. The average hardness of the group of castings before heat treatment was 47.5 Rc and after heat treatment 53 Rc. The increase in hardness was not uniform, with increases ranging from 3 points to 8 points on the Rc scale.

The dimensions of the castings after heat treatment were processed in a similar manner to those obtained after casting. The % deviations from the pattern dimensions are shown in Table 6.11 for the stepped block castings and Table 6.12 for the retractable die cores. The effect of heat treatment on the dimensions of the castings is shown in Table 6.13, from which it can be seen that all the castings exhibit growth as the result of heat treatment.

6.5.2 Electrical Discharge Machining

Microhardness Measurements:

From the small number of results obtained there was no indication of a significant difference between the hardness of the as-cast subsurface, the machined subsurface or the casting centre.

Microstructures:

Examination of the microstructures shown in Figures 5.90 to 5.95 reveals a distinct recast layer at the surface subjected to electrical discharge machining. Apart from this, the structures are similar to those observed and discussed previously (see section 6.4). During the machining of specimen 13D an excess of material was accidentally removed. Whereas it was intended that 2.5 mm be removed, it was found after roughing that 2.85 mm had been removed. Machining was stopped at this point, although it was intended to complete machining under fine finishing conditions. As a result specimen 13D has a very rough surface and a thicker recast layer than either 13C or 13B.

6.5.3 Electron Probe Microanalysis

Specimen 1A (Figure 5.96):

The main distinguishing feature is the presence of peaks on the graphs for several elements. Such peaks can usually be attributed to the presence, for example, of carbides in the case of chromium, or sulphides in the case of manganese. Whilst repeated scans could not be guaranteed to cover precisely the same area of specimen, it is interesting to note the coincident appearance of peaks in the graphs of several elements. At about $20\mu\text{m}$ from the interface a peak occurs simultaneously in the graphs for chromium, molybdenum and vanadium, and between 60 and $70\mu\text{m}$ from the interface peaks occur simultaneously for chromium, vanadium and manganese. Apart from these features, there are no apparent trends and no indication that the immediate surface layer has a different composition from the deeper layers.

Specimen 2A (Figure 5.97):

The observations for specimen 2A are similar to those for 1A. Simultaneous peaks occur in the respective graphs for chromium and molybdenum.

Specimen 13A (Figure 5.98):

This specimen did not exhibit any peaks in the chromium graph, but small peaks were observed in the molybdenum and vanadium graphs.

Specimen 13C (Figure 5.99):

This specimen had $250\mu\text{m}$ of material removed from the cast surface by EDM. This was equivalent to removing the $250\mu\text{m}$ analysed layer from the as-cast surface of specimen 13A. No observable difference exists between the concentration of elements close to the machined surface and that some distance away.

Specimen 13B (Figure 5.100):

This specimen had 1 mm of material removed from the cast surface by EDM. Once more the only apparent feature is the occurrence of simultaneous peaks in the graphs for chromium, molybdenum and vanadium.

Specimen 13D (Figure 5.101):

As mentioned previously, this specimen had 2.85 mm of material removed from the cast surface by EDM using roughing conditions only. However, this does not appear to have affected the distribution of the six elements considered.

Copper Analyses (Figures 5.102 to 5.104):

Figure 5.102 shows a tracing of the recording chart for the analysis of specimen 13A. The graph for copper shows a constant trace analysis. In Figures 5.103 and 5.104 a significant peak in the copper concentration occurs near to the specimens' machined surfaces. In the case of specimen 13D (Figure 5.104), the peak in the copper concentration is associated with a noticeable trough in the iron concentration. (Note: The scale used for copper in specimen 13A is different to that used for 13C and 13D.)

Discussion:

The expansion of H13 die steel as the result of heat treatment arises because of the transformation of austenite to martensite, which has a higher specific volume. The effect is small representing, on average, a change of 0.19% in the dimensions of the test castings. However, this small change represents a 12% reduction in the average % deviation from the pattern dimensions of the test castings as-cast. It should therefore be taken into consideration when specifying either the contraction allowance or attainable as-cast tolerances. No attempt was made to measure distortion in the test castings. It should be emphasized that the prediction of dimensional changes as the result of heat treatment has similar difficulties to the prediction of dimensional changes as the result of casting.

The expected recast layer at the surface machined by EDM is clearly in evidence in the microstructures of specimens 13B, 13C and 13D.

However, this recast layer is very narrow, in the order of 10 μm in specimens 13B and 13C and 25 μm in specimen 13D. These layers are smaller than the average diagonal length of the microhardness test diamond impression, typically 24-30 μm . Consequently, the microhardness readings were taken outside these layers and could only represent compositional or phase variations within a zone extending 100 μm from the surface (as indicated in section 6.3). As a result the readings in Tables 5.44 and 5.45 do not show any significant variation.

The microstructure of specimen 13D, Figures 5.94 and 5.95, clearly demonstrates the greater surface roughness and thicker recast layer resulting from the higher current used during EDM roughing operations. The associated higher surface temperature is probably responsible for the electrode copper diffusion into the specimen, which has occurred to a far greater extent than that found in specimen 13C. In specimen 13B the peak in the copper concentration occurs within 10 μm of the surface, whereas in specimen 13D the peak occurs at about 25 μm from the surface. The peak concentration of copper in specimen 13D was estimated to be about 7%, which is almost double that in specimen 13C. Copper is not usually added to alloy steels, but its effect in both low and high chromium cast irons is to suppress pearlite, which it does most effectively in the presence of 0.5 to 2.0% molybdenum.

The appearance of copper in the surface layer of the machined specimens was expected as the result of diffusion from the copper electrode and conforms with other findings (112). Apart from this significant feature, no other marked changes were observed in the six principal elements considered. In the case of carbon this was unexpected as, in the case of the as-cast specimens, decarburisation might have been expected (60) and, in the case of machined specimens, carbon migration (112,113) or carbon pick-up from the dielectric (89) might have been expected.

The peaks in concentration level observed in the graphs generally occur in relation to the elements chromium, molybdenum and vanadium, each of which is a strong carbide former. It is reasonable, therefore, to assume that these peaks represent the presence of carbides in the interdendritic spaces scanned by the electron beam. The association between peaks for these elements suggests that complex carbides of these elements were formed. However, no associated peak was observed in the concentration level of carbon.

The Experimental Officer responsible for the EPMA had, from the outset, expressed doubts about the equipment's capability to produce accurate results for low atomic number elements such as carbon. The absence of any detectable trends or changes in carbon level in these results would tend to confirm the Officer's pessimism.

In the absence of reliable data for carbon, any conclusions about the influence of EDM on the as-cast surface structure of the die steel must

be limited. The analysis for the other elements has not revealed any significant difference between the immediate surface zone and the zone underlying it, except in the case of copper. The microstructural evidence shows that the recast layer produced by the EDM operation is quite shallow. As it would be normal practice to finish the surface by polishing, it is highly likely that the recast layer would be removed by this operation.

In this investigation an attempt was made to establish the effects of EDM on the as-cast surface structure. However, it should be noted that the EDM operation could be performed after heat treatment. In view of the changes in dimensions produced by heat treatment, it might be considered preferable to conduct the finishing operation after heat treatment. Under these circumstances, quite different metallurgical changes could occur. Whilst this aspect is clearly of relevance to the production of cast dies, it was not examined in this investigation.

Table 6.11: Deviation from Pattern Dimensions after Heat Treatment: Stepped Block

Dimension	Pattern Dimension	1		2		3		13	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	74.98	74.37	-0.81	74.18	-1.17	74.39	-0.79	-	-
b	49.87	49.42	-0.90	49.54	-0.66	49.57	-0.60	49.14	-1.46
c	24.92	24.83	-0.36	25.10	+0.72	24.99	+0.28	24.72	-0.80
d	48.30	47.81	-1.01	47.65	-1.35	-	-	-	-
e	73.27	72.24	-1.41	72.18	-1.49	-	-	72.20	-1.46
f	98.30	96.53	-1.80	96.67	-1.66	-	-	96.65	-1.68
Average % Deviation			-1.05		-0.94		-0.37		-1.35

Table 6.12: Deviation from Pattern Dimensions after Heat Treatment: Retractable Die Core

Dimension	Pattern Dimension	4		5		6		14	
		Dimension	% Dev	Dimension	% Dev	Dimension	% Dev	Dimension	% Dev
a	95.38	93.65	-1.81	93.65	-1.81	93.50	-1.97	93.55	-1.92
a1	95.33	93.75	-1.66	93.62	-1.79	93.50	-1.92	93.60	-1.81
a2	95.38	93.70	-1.76	93.62	-1.85	93.50	-1.97	93.70	-1.76
b	25.48	25.04	-1.73	25.10	-1.49	25.02	-1.81	24.99	-1.92
c	25.48	25.07	-1.61	24.99	-1.92	25.20	-1.10	24.97	-2.00
Ø1	50.80	50.17	-1.24	50.70	-0.20	49.96	-1.65	50.19	-1.20
Ø2	50.80	49.56	-2.44	49.89	-1.79	49.58	-2.40	49.86	-1.85
Ø3	50.80	49.78	-2.00	49.96	-1.65	49.89	-1.79	49.56	-2.44
Ø4	38.27	38.04	-0.60	38.12	-0.39	37.51	-1.99	38.10	-0.44
Ø5	31.92	31.96	+0.13	31.85	-0.22	31.31	-1.91	31.82	-0.31
Ø6	24.61	24.51	-0.41	24.73	-0.49	24.10	-2.07	24.68	+0.28
Average % Deviation*			-1.71		-1.77		-1.75		-1.88

* across the joint dimensions excluded

Table 6.13: Comparison Between the Deviation from Pattern Dimensions
Before and After Heat Treatment

Test Casting Number	Average % Deviation from Pattern_as-cast	Average % Deviation from Pattern post heat treatment	Difference
1	-1.26	-1.05	0.21
2	-1.27	-0.94	0.34
3	-0.57	-0.37	0.20
13	-1.56	-1.35	0.21
4	-1.96	-1.71	0.25
5	-1.80	-1.77	0.03
6	-1.99	-1.75	0.22
14	-1.90	-1.88	0.02
Average	-1.54	-1.35	0.19

6.6 DISCUSSION SUMMARY

The mould material evaluation programme had as its major objective the establishment of an acceptable mould firing regime for composite mould production. The effect of firing temperature and time at firing temperature on retained strength was demonstrated for both the facing and backing materials. The suggestion that a minimum firing temperature of 1000°C was necessary to develop maximum strength in the facing material was confirmed. However, it was also shown that this strength was not that much higher than that obtained by firing to 750°C . Furthermore, it was established that the high temperature properties and inertness of the material fired at 750°C were acceptable for the requirements of test casting production. A maximum firing temperature of 750°C and time at temperature of two hours were selected as the ideal compromise solution for the production of composite moulds.

The major emphasis of the experimental work on metallurgical processing was the establishment of the most suitable processing conditions for producing castings free from the pitting defect. Whilst the approach adopted for evaluation was inherently subjective, it provided clear recommendations for suppressing this defect. For example, it was established that a high mould temperature and/or metal pouring temperature exacerbated the pitting defect. On the other hand, the problem was reduced when a deoxidiser was added to the melt. However, the defect could only be eliminated from castings produced in mullite moulds when pouring and cooling occurred under an inert gas cover. Alternatively, the moulds could be cast in air providing 10 weight % graphite was incorporated in the mould facing material. The advantage of a scale-free casting was, however, only obtained when using an inert gas atmosphere. The programme of experiments also provided evidence that grain refining additions could be used to reduce the grain size of cast H13 die steel. Finally, evidence was obtained which suggested that the 'casting skin' was softer than the core structure of the ingot castings.

The objectives of the test casting evaluation programme included the confirmation of the findings of the work on mould material evaluation and metallurgical processing. In addition, the programme was directed at providing information about the effect of process variables on the dimensional accuracy and surface quality of the test castings. The

major variable under consideration was the mould material/atmosphere combination. By using four different test casting designs, of different size and weight, the influence of shape and size on the casting quality could be assessed. An attempt was made to standardise other variables. All melts were deoxidised with 0.5% Stellan 1 and with only two exceptions the maximum metal temperature in the furnace was maintained at 1650°C. Whilst an attempt was made to pour the castings at around 1540°C, pouring temperatures varied between 1483°C-1586°C, presenting another variable whose effect could be assessed. The moulds were all maintained at ambient temperature for pouring.

The results of the test casting evaluation were not definitive and did not show clear confirmation of the results obtained from the metallurgical processing programme. It was not possible to show that any one of the mould material/atmosphere combinations produced a superior casting quality. Especially disappointing was the appearance of the pitting defect in test castings which had been processed in a nitrogen atmosphere or a mould facing containing graphite. However, limitations in practice may have caused the problem and were discussed earlier.

Pouring temperature was expected to exert a significant influence on the quality of test castings. However, the expected association between pouring temperature and % deviation and mean Ra did not occur, although association did occur between pouring temperature and mean Wa for the group of castings excluding the retractable die cores. Subjective visual assessment of the test castings suggested that a minimum pouring temperature of 1540°C should be used to prevent cold laps and/or loss of definition. It is more difficult to propose a safe maximum pouring temperature. Metal penetration was observed on two castings poured respectively at 1555°C and 1586°C. However, these castings were produced in mould facing material containing graphite which, as explained earlier, may be the cause of the observed defect. A tentative guide for pouring temperature, in the absence of objective information, could be 1550°C \pm 10°C.

The most significant variable, established by tests for association, was that of casting weight, which was shown to have a direct influence on mean Ra values for the group of fifteen test castings. When the

retractable die core castings were discounted, association existed between casting weight and mean Ra, and between casting weight and % deviation from the pattern dimensions.

Although a value for contraction allowance was determined experimentally, it did not prove possible to use the value to differentiate between the contributions of contraction and process to the % deviation from pattern dimensions. This was because the experimentally determined value of 1.64% for contraction allowance was so close to the mean % deviation from pattern dimension of 1.65%.

In the programme of work to evaluate the effect of finishing procedures, it was established that the adopted heat treatment procedure resulted in growth in the test castings which, on average, represented about 0.19% of the original pattern dimension. The results of the experiments to establish the influence of EDM on cast surface structure were less conclusive. The expected recast layer was present but because it was very shallow, especially when fine finishing conditions were used, it was not possible to establish the micro-hardness of the layer using a sample face perpendicular to the machined surface.

Electron probe microanalysis revealed the pick-up of copper by the die steel from the EDM electrode. However, the scans did not reveal any significant trends in the distribution of the six elements considered between the as-cast surfaces or those machined by EDM. In this respect it was unfortunate that the analysis for carbon could not be considered to be reliable.

No evidence was found to suggest that the as-cast surface possessed special properties which merited retention. In addition, the results did not show any reason why the surface skin should not be removed by EDM if finishing was required. As it would be normal practice to finish the cavities by polishing, the very shallow recast layer would be substantially removed before the die was used in service.

CHAPTER SEVEN

CONCLUSIONS

Mould Material Evaluation:

- 1 A blend of -8 + 16; -30 + 80; and -120 mesh grades of molochite blended in the ratio of 3:1:1 and mixed with 6 weight % C112 sodium silicate provides a suitable backing material for composite mould manufacture. The material possesses good as-gassed strength and after firing to 750°C, and holding at temperature for two hours, has excellent retained strength, good permeability and is inert.
- 2 A blend of -8 + 16; -30; and -100 mesh grades of mullite blended in the ratio of 1:1:2 and mixed in the ratio of 1 kg of mullite blend to 225 gm of ethyl silicate and 12 gm of 10% ammonia in water solution produces a mobile slurry suitable for mould facing material. Whilst this material develops higher retained strength and increased high temperature properties when fired to 1000°C, the properties developed by firing to 750°C are considered to be adequate for the application.
- 3 Although the bond which develops between the backing and facing material has relatively low strength, it is sufficiently strong to prevent separation of the two materials during mould processing.

Metallurgical Processing:

- 4 Ingot castings produced in mullite moulds and cast in air exhibited the pitting defect. The severity of the defect was found to increase with an increase in mould preheat temperature and metal pouring temperature. The severity was found to decrease when the melt was treated with a deoxidiser.
- 5 Ingot castings produced in a mullite mould facing material containing 10 weight % graphite and cast in air were found to be free from the pitting defect.
- 6 Ingot castings produced in a mullite mould, cast in and cooled in an inert gas atmosphere were also found to be free from the pitting defect. In addition, the as-cast surface was substantially free from oxide scaling.

- 7 The addition to the melt of a grain refining agent, based on a mixture of ferro-titanium and ferro-niobium, increased the grain count in treated ingot castings.
- 8 The hardness of the as-cast subsurface layer of the ingot castings was found in general to be lower than that for the casting centres.

Test Castings Evaluation:

- 9 Considering the results for all fifteen test castings a statistically significant association, at the 5% level, was found to exist between: mean Ra and casting weight; and mean Ra and mean Wa.
- 10 When the results for the retractable die core castings were excluded from consideration a statistically significant association, at the 5% level, was found to exist between: mean Ra and casting weight; mean Ra and mean Wa; % deviation from the pattern dimensions and casting weight; and mean Wa and pouring temperature.
- 11 No evidence was found to suggest that any one of the three mould material/atmosphere combinations employed produced significantly different dimensional accuracy or surface finish results. Furthermore, it could not be proven conclusively that the combinations of: a mullite mould and inert gas atmosphere; and a mullite mould facing containing 10 weight % graphite and casting in air; would result in a casting free of the pitting defect.
- 12 An experimentally determined value for contraction allowance of 1.64% was established. However, because this value was so close to the value of 1.65% for the mean % deviation from the pattern dimension value, it was not possible to differentiate between the influence of the contraction allowance and process variables on the overall dimensional accuracy of the test castings.
- 13 A tentative suggestion for pouring temperature range would be 1550°C \pm 10°C.

Finishing Procedures:

- 14 The recommended heat treatment procedure enables the cast H13 die steel to develop an average hardness value of 53 Rc.

- 15 The recommended heat treatment procedure resulted in casting growth equivalent, on average, to a deviation of 0.19% of the original pattern dimension.
- 16 Electrical discharge machining of the cast H13 die steel results in the formation of a shallow recast layer. When fine finishing conditions were employed this layer was approximately 10 μm thick.
- 17 Electron probe microanalysis did not reveal any difference in composition between the as-cast surface material of castings produced using the different mould material/atmosphere combinations. Furthermore, no difference in composition was found between the as-cast surface layer and the machined (EDM) surface layer, other than the pick-up of copper from the EDM electrode. However, it must be stated that the analysis for carbon may be unreliable.

CHAPTER EIGHT

SUGGESTIONS FOR FURTHER WORK

- 1 It must be accepted that the sample size of fifteen castings used for the test casting evaluation programme was small in statistical terms. Where association was shown to exist between variables, it was at the risk of a 1 in 20 chance of being wrong. To reduce this risk and confirm, or otherwise, the associations obtained it would be prudent to produce additional test castings. Whilst the accuracy of interpretation will increase with the number of castings produced, a practical limit to this number must be applied. By producing a second batch of fifteen castings, a sample of thirty test castings would be available and this should markedly improve the validity of the statistical tests.
- 2 The mould material evaluation was restricted to a consideration of the effects of temperature on the properties of a plain aluminosilicate refractory bonded with ethyl silicate. If a facing material incorporating 10 weight % graphite were to be adopted it would be valuable to assess the properties of this material in a similar manner to that reported in this investigation.
- 3 The procedure for producing the composite moulds used in this investigation was time consuming and required significant practical expertise. That the Shaw Process provides superior dimensional accuracy and surface finish to conventional sand practice is not disputed. However, it would be interesting to compare the quality of castings produced using silica free aggregates bonded with cold-set binder systems with those produced in this investigation. Clearly, if the quality of such castings approached that attainable in castings produced by the Shaw Process, there would be little point in paying the cost premium associated with the latter, especially if some machining was in any case going to be necessary.
- 4 No attempts have been made within this investigation to assess the wear characteristics of the cast H13 die steel, either by a simulation technique or industrial trials. A point of interest in such trials would be the attempt to compare the performance of as-cast die impressions with those which have required surface removal

by EDM, rather than to compare the performance of cast material with wrought material. In this respect a comparison of the effect of conducting EDM before and after heat treatment would also be of interest.

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APPENDIX ONE

MATERIALS USED IN THE CERAMIC SLURRY PROCESS

1 Guidelines for Refractory Material Selection

The material should:

be clean and pure - to prevent contamination and metal-mould reaction;
be refractory - to give a good hot strength;
have low thermal expansion - to reduce spalling and improve dimensional accuracy.

In order of decreasing refractoriness, the materials which meet these requirements are:

fused alumina
tabular alumina
calcined alumina
fused silica
mullite
sillimanite
zircon flour
molochite
silica flour
potters flint

Thermal Expansion:

In general, high thermal expansion and large volume changes at inversion points are detrimental. It is desirable to match the expansion of facing and backing mould materials.

Specific Gravity:

In general, the specific heats of these refractory materials are very similar, therefore the specific gravity indicates the amount of heat a given volume of material can absorb for a specified temperature rise. The higher the specific gravity the more heat will be absorbed. Therefore a material such as zircon, with a high specific gravity, may have an effectively higher refractoriness than, say, sillimanite or mullite, despite its lower dissociation temperature/melting point.

Alumina Materials:

Melting Point:	2050°C
Specific Gravity:	3.9
Coefficient of Thermal Expansion:	$9.5 \times 10^{-6}/^{\circ}\text{C}$
Specific Heat:	0.174 cal/g/°C

There are no allotropic changes between ambient temperature and the melting point. The most common form of alumina is the α type (corundum); most commercial aluminas take this form, produced by the calcination temperature, which controls the reactivity and subsequent shrinkage of the alumina, and the soda content. High soda content could give rise to premature gelation of the silica binder.

Mullite:

Melting Point:	$\sim 1810^{\circ}\text{C}$ (decomposes to alumina and liquid silica)
Specific Gravity:	3.14
Coefficient of Thermal Expansion:	$6 \times 10^{-6}/^{\circ}\text{C}$

This is the only stable high temperature compound of alumina and silica - $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. The material is available in the 'sintered' or 'fused' forms; the latter being more refractory and more expensive. It is stable in use up to 1700°C for prolonged periods.

Molochite:

Melting Point:	softens around 1600°C
Specific Gravity:	2.70
Coefficient of Thermal Expansion:	$4.4 \times 10^{-6}/^{\circ}\text{C}$

Molochite is an alumino-silicate material of 42-43% alumina and 1.5-2.0% alkalis, which after calcination at 1500°C , consist of about 57% mullite embedded in an alumino-silicate glass. This mineralogy gives a uniform thermal expansion curve up to at least 1400°C .

Chamotte (Fireclay Grog):

Melting Point:	indeterminate
Specific Gravity:	2.5 to 2.7
Coefficient of Thermal Expansion:	$4 \text{ to } 6 \times 10^{-6}/^{\circ}\text{C}$

This product is made by calcining high alumina clays (38-45% Al_2O_3) or by crushing used fireclay bricks. The product is similar to molochite in many respects but contains many more impurities - oxides of iron, sodium, potassium, calcium and magnesium. Its refractoriness will suffer due to impurities and it will have a refractoriness lower than that of molochite.

Zircon:

Melting Point:	dissociates* around 1600°C
Specific Gravity:	4.2 to 4.6
Coefficient of Thermal Expansion	$4.5 \times 10^{-6}/^\circ\text{C}$

* there is disagreement in the literature on this point; claims are made of melting points as high as 2480°C, whereas counter claims suggest that zircon dissociates around 1600°C into zirconia (ZrO_2) and silica glass. The latter claim is believed to be more correct.

The natural grain or sand have particle sizes all + 200 mesh, zircon flour is ground zircon sand. The high specific gravity of zircon gives it a high heat absorption characteristic.

2 Prehydrolysed Ethyl Silicate

The development of methods of preparing ethyl silicate hydrolysates having a long storage life has made hydrolysed ethyl silicate solutions commercially available. These solutions are referred to as 'prehydrolysed' ethyl silicate. They are supplied as ready to use hydroxylated forms of ethyl silicate in active form capable of forming refractory bonds.

Several types of prehydrolysed ethyl silicate are commercially available and they are generally formulated to cater for the widest possible application in ceramic mould-building operations.

As well as eliminating the need for the foundry to prepare its own hydrolysed solutions they offer the advantages of consistent quality, long shelf life and, in some cases, improved functional performance.

Storage:

Protected from exposure to air and moisture and excessive heat, storage life can be up to nine months. Ideally the material should be stored at or below normal ambient temperatures (20°C), storage above 20°C for prolonged periods should be avoided. Containers should be kept firmly sealed to prevent evaporation of solvent.

Safety:

The material should be used with care. Skin and eye contact should be avoided; if it occurs, remove immediately with water flushing. Vapours inhalation should be avoided. The material is inflammable (flashpoint ~ 11°C) and suitable fire precautions should be taken.

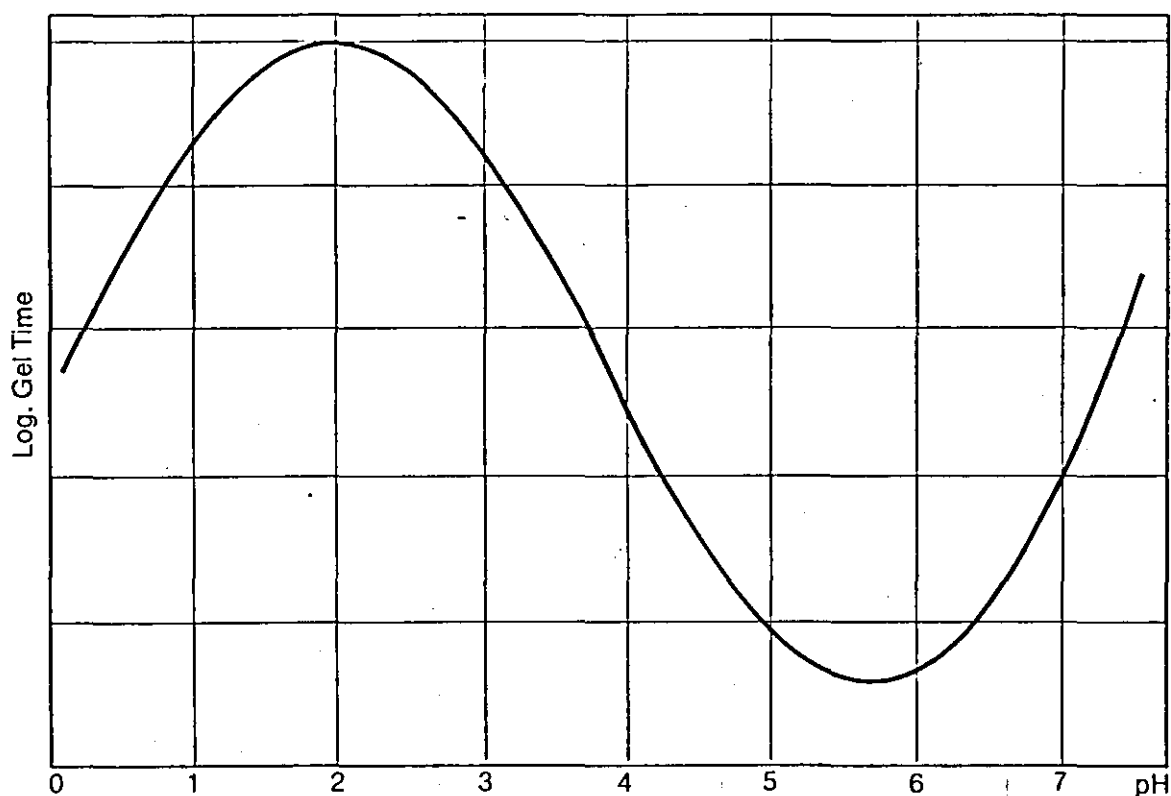
Gelation Methods:

The reactivity of the binder depends upon its formulation - the higher the 'silica' content and degree of hydrolysis, the more reactive the binder. A useful test of the reactivity, and of satisfactory hydrolysis, is to place a drop of the binder on a watch glass and allow time for the alcohol to evaporate. This condenses the binder until it reaches instability and gels. A relatively high silica, reactive solution will form a gel in a few minutes at an ambient temperature of 20°C, and a firm gel within 30 minutes.

Chemically Controlled Gelation:

Silica gels result from the linking-up of molecules of polysilicic acid, or by aggregation of silica particles of colloidal size.

The rate of gelation of these silica systems is associated with a number of factors, a particularly significant one being pH. The general relationship between the logarithm of the gelation time and pH is shown below:



Log Gel Time Versus pH of Binders (reproduced from source 4)

Maximum stability, or longest time to gel, occurs at a pH value between 1.5 and 2: gelling is most rapid at pH 5-6 and the systems set irreversibly. Below 1.5 the stability decreases again, while above pH 6 it increases again up to a pH of 11. These are general trends, actual gelation time depends on other factors too.

Binder Quality Control Procedures

Relevant tests which can be used as quality acceptance tests for the liquid prehydrolysed binders include:

- I Ability to Gel
- II Gel Time
- III Acidity
- IV pH Value

I Ability to Gel:

The purpose of this simple test is to check that the material has been hydrolysed.

II Gelation Time:

The purpose of the test is to determine whether or not the ethyl silicate has been properly hydrolysed. The addition of a predetermined amount of a suitable gelling agent to a fixed quantity of satisfactory binder liquid should, at a constant temperature, result in a gel within certain time limits.

III Acidity:

The range 0.03% to 0.30% is preferred. At very low acid concentrations silica tends slowly to settle out of solution. High acid concentration causes premature gelation of the entire solution.

IV pH Value:

The term pH implies that measurements are taken in an aqueous system. However, the pH of ethyl silicate 40 and its hydrolysates can be measured by the usual means. The simplest method of carrying out pH measurements is by using Universal Indicator Solution, or the narrow range Universal pH papers.

3 Recommended Ceramic Slurry Moulding Mixes

Monsanto:

To form a strong matrix, 30 to 50% of fines must be present in the filler and the remainder should be as coarse as the shape to be cast will permit. A typical filler formulation is:

50% - 30 + 80 mesh sillimanite

50% - 200 mesh sillimanite

This should be mixed in the ratio of 0.45 kg of filler to 90 ml of binder.

Clino Foundry Supplies:

Recommend > 50% fines in the mix. Alternative mix formulations recommended are:

(a) 6 parts - 100 mesh mullite

4 parts - 30 + 80 mesh molochite

1 part - 16 + 30 mesh molochite

- (b) 80% - 100 mesh mullite
 20% - 30 + 80 mesh molochite

Associated Engineering Developments Ltd:

Recommend that only mullite refractories be used for precision casting die steels. Suggested mix formulation:

- 50% - 100 mesh mullite
40% - 16 + 22 mesh mullite
 5% - 22 mesh mullite
 5% - 8 + 16 mesh mullite

Leeds University, Department of Metallurgy:

In a parallel SERC funded research project, the following mix formulation was found to be satisfactory:

- 25% - 8 + 16 mesh molochite
25% - 30 + 60 mesh molochite
25% - 200 mesh molochite

The refractory filler was blended at the rate of 1 kg to 250 ml of ethyl silicate and gelled using a 2% ammonia solution.

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APPENDIX TWO

THE CO₂/SILICATE PROCESS

In the CO₂/Silicate process a refractory aggregate is mixed with an aqueous sodium silicate solution to form a moulding material. After compaction around a pattern, carbon dioxide gas is passed through the material to harden it. Although the process is quite straightforward to use, certain aspects require careful consideration to ensure moulds of consistently high quality. The major aspects of importance are briefly outlined.

Binders:

The production of sodium silicate involves the heating of crushed silica with sodium carbonate to give a silica-sodium oxide compound. By careful control and adjustment a sodium silicate solution with a specific ratio of silica to sodium oxide is produced. In the UK a 2:1 ratio is still most popular, although higher ratio silicates are available. This ratio, in conjunction with the specific gravity, is sufficient to characterise the sodium silicate. The specific gravity of the solution can be altered by adjusting the water content, but the usual range is 100° to 140° Twaddell.

Mixing:

Ideally, the mixing operation should:

produce a uniform distribution of the silicate binder, coating all the grains evenly;

cause the minimum water evaporation and air drying of the aqueous sodium silicate;

cause the least rise in temperature throughout the mix.

Most conventional foundry sand mixers are suitable. It is possible to over mix the silicate bonded material, with the following disadvantages:

evaporation of the water during mixing will reduce the bench life;

the as-gassed strength will be difficult to control;

there is an increased risk of friability and loss of strength during storage.

Bench Life:

Mixtures containing 2:1 ratio silicates possess a relatively long bench life, which permits extended usage without a serious reduction in gassed strengths. When exposed to air a mixture gradually forms a hard crust, due mainly to the evaporation of water from the binder. By storing the mixture in sealed containers, the bench life can be prolonged.

Principles of CO₂ Gassing

A fast bonding reaction occurs when CO₂ gas reacts with sodium silicate exposed as a thin film on the surface of the refractory grains. Several methods for introducing the gas are used in practice and include:

- probe gassing;
- hood gassing;
- hollow pattern incorporating gassing vents;
- vacuum chamber gassing.

CO₂/Silicate Reactions

Time Dependence:

With a constant gas flow rate, the strength increases progressively as the gassing time is extended. In many cases there is an initial period of some seconds at the start of gassing when virtually no strength is developed. Subsequently, a rapid increase in strength occurs as gassing continues.

CO₂ Flow Rate:

Changing the flow rate at which CO₂ gas passes through a refractory mass has important effects on both the strength of bond obtained and the distribution pattern of the gas. Finding the best flow rate for a particular application necessitates a compromise between these two interests and that of gas economy.

The gas flow rate controls both the as-gassed strength and stored strength of the material. At high flow rates, 30 litres/minute, as-gassed strengths are low in comparison with as-gassed strengths

developed with a flow rate of 5 litres/minute. On the other hand, much higher strengths are developed on standing by the material gassed at a high flow rate.

CO₂ Dehydration of Silicates:

The reason for the decrease in as-gassed strength at high CO₂ flow rates is a change in the hardening mechanism. CO₂ gas is very dry (dew point -40°C) and the gas can harden aqueous sodium silicate by two alternative mechanisms:

- (i) A chemical reaction involving the formation of a silica hydrogel bond;
- (ii) A physical process in which a glass-like, high viscosity sodium silicate bond is formed, due to dehydration of the aqueous silicate by the dry CO₂ gas.

At low gas flow rates the former mechanism predominates, whereas at high flow rates it is the latter mechanism which predominates.

Gas Pressure:

The actual pressure of the gas delivered does not appear to have any influence upon the speed of the hardening process.

Sand Temperature:

Hardening reactions between CO₂ gas and sodium silicate are temperature dependent and are greatly retarded by low temperatures. Below 10°C reaction is extremely slow and the process becomes less economic, due to the length of time taken and volume of gas consumed before an adequate bond is obtained.

Another factor influencing the efficient operation of the CO₂ process is the increase in viscosity of sodium silicate binders at low temperatures, which will hinder the uniform distribution of the silicate during mixing.

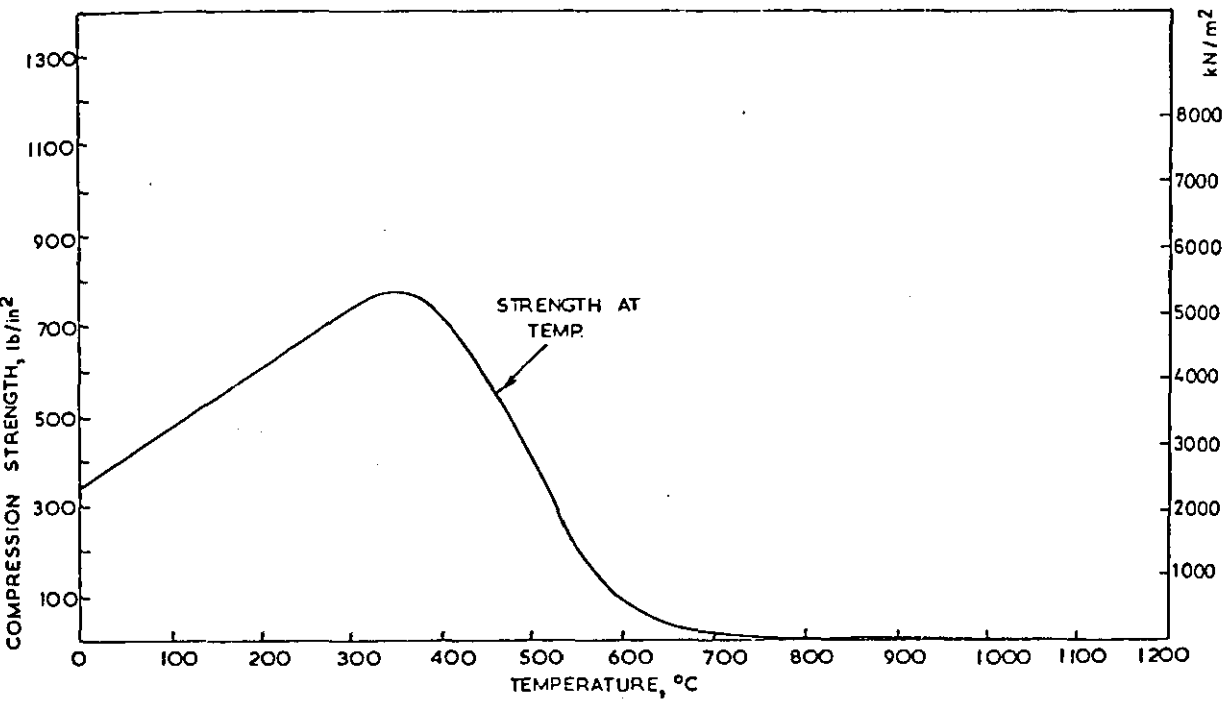
High Temperature Properties

A great deal of attention has been given to the high temperature properties of silicate bonded sands, the main interests being in methods and materials to improve breakdown and simplify knock-out,

especially of CO₂/Silicate process cores. Although the molochite used in this project has an important difference in composition to sand, some of the effects of temperature on sodium silicate bonded sand are included for the purpose of comparison.

Strength at High Temperature:

This property is sometimes referred to as the 'hot strength'. The changes in strength of cores made from a 2:1 ratio silicate gassed for one minute and then heated at temperatures up to 1200°C are shown below:



Variation in High Temperature Strength of CO₂/Silicate Process Cores
(reproduced from source 1)

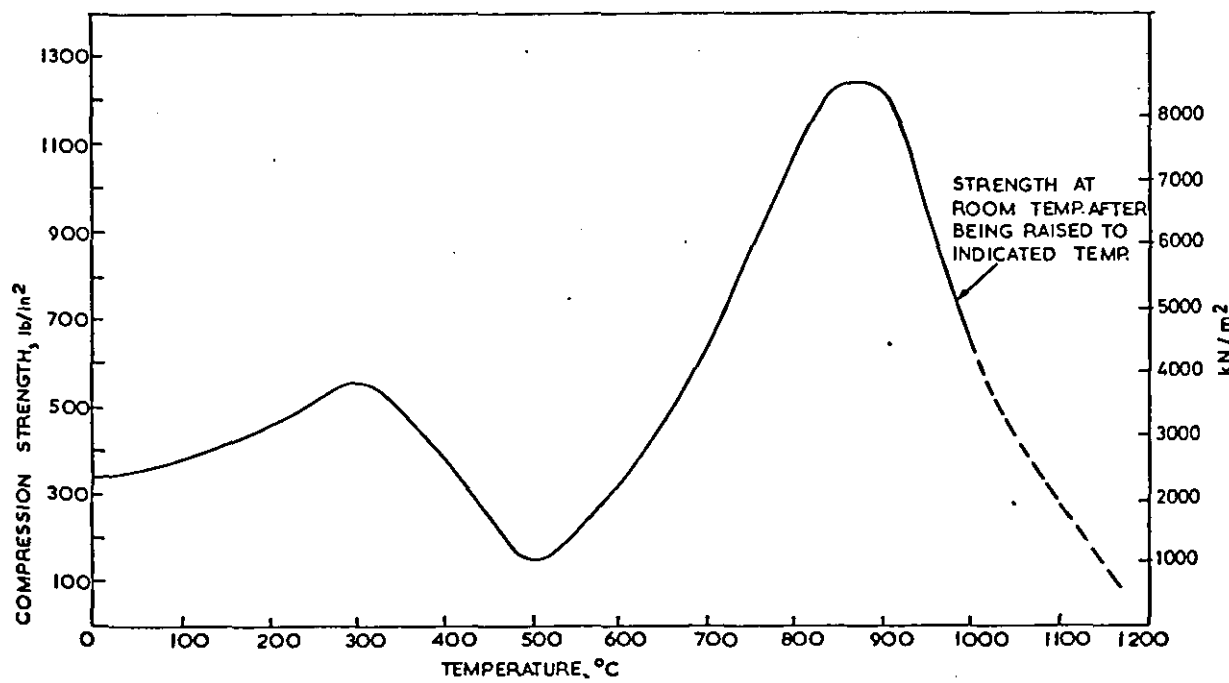
It can be seen that, as the temperature is raised to 400°C, the strength increases gradually to a maximum value and that, at higher temperatures, a drastic reduction in strength occurs until, at temperatures of 700°C and above, the strength is negligible.

The increase in strength up to 400°C is partly governed by the duration of the initial gassing with CO₂. The shorter the gassing period, the greater the subsequent increase in strength on heating to 400°C.

The rise in hot strength at temperatures up to 400°C is due to dehydration of unreacted sodium silicate, whilst at higher temperatures softening of the bond is believed to account for the drastic strength reduction.

Retained Strength After Heating and Cooling to Room Temperature:

If CO₂ process material is heated to a high temperature and then cooled, the retained compression strength can be very high, exceeding 1000 lbf/in² (6895 kN/m²). The nature of the changes in these retained strengths for material heated at temperatures up to 1200°C is shown below:



Variation in Strength of CO₂/Silicate Process Cores after Heating and Cooling to Normal Temperature (reproduced from source 1)

It is characteristic for the retained strengths of silicate bonded sands to have two maxima, one at 200-300°C and a second at about 900°C. The highest strength is generally developed at about 900°C.

The strength changes at temperatures up to about 500-600°C are due to dehydration of ungasged sodium silicate followed by softening of the bond. At higher temperatures the retained strengths increase again, due to chemical reaction between residual sodium silicate and sodium

compounds with grains of quartz sand. In this manner a continuous monolithic structure of high strength is formed as the temperature is raised from 600-900°C.

At higher temperatures the quartz form of silica transforms to tridymite and/or cristobalite. This transformation is accompanied by a large volume increase, which can be as high as 30-40%, and the stresses produced lower the retained strength. In cases where the phase transformation is complete, the specific gravity is reduced from 2.65 to 2.32. The transformation is not reversible to quartz on cooling in these circumstances.

The magnitude of retained strength is affected by the following process variables: duration of CO₂ gassing; concentration of sodium silicate in a mixture; the SiO₂:Na₂O ratio of the silicate binder; and organic or inorganic additions to the sand mixture.

Sources of Information

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APPENDIX THREE

MOULD MATERIAL TESTS

Specimen Preparation

The tests for permeability, compression strength, tensile strength and dimensional stability were carried out using standard American Foundrymen Society (AFS) specimen sizes.

Facing Material:

The preparation of specimens of facing material differed from the recommended AFS procedures because compaction was unnecessary. The equipment for the production of compression strength specimens and dog bone tensile strength specimens was described in section 4.2.4 and is shown in Figures Six, Seven and Eight. The pouring plates ensured that the specimens were produced to the correct height. In the case of the compression strength specimens, it was necessary to carefully remove the pouring pip from the surface.

Backing Material:

The standard compression strength specimens were prepared by first weighing out a quantity of the sodium silicate bonded molochite sufficient to form the specimen. The material was transferred to a cylindrical container with a metal base cup. The specimen was next compacted using the standard procedure to form a specimen of $2" \pm 1/32"$ ($50.8 \text{ mm} \pm 0.79 \text{ mm}$) high. Gassing was carried out immediately after ramming using a Ridsdale cup for gassing with CO_2 . Specimens for as-gassed properties were tested immediately after gassing. Specimens for fired properties were allowed to cool in the kiln before transfer to a dessicator. A minimum of three test results were used to establish the average compression strength.

Tensile specimens were produced using a special moulding box with a gassing facility, shown in Figure Four. A quantity of material sufficient to form the specimen was weighed and transferred to the mould. The specimen was next compacted using the standard procedure to form a specimen $1" \pm 1/64"$ ($25.4 \text{ mm} \pm 0.40 \text{ mm}$) high. The specimen was gassed whilst remaining in the moulding box. Specimens for as-

gassed properties were tested immediately after gassing. Those for fired properties were allowed to cool in the kiln before transfer to a dessicator. A minimum of three test results were used to establish the average tensile strength.

Backing/Facing Composites:

By introducing a distance piece into the moulding box and the rammer head, see Figures Four and Five, the dog bone specimen could be produced in two halves. Each half was gassed in the mould. The half backing material sample was then located in one half of the slurry tensile specimen mould and the mould covered with the slurry pouring plate. Slurry was poured into the vacant half of the tensile mould and allowed to gel. After gelation the composite specimen was ignited and fired to temperature. After cooling in the kiln, the specimens were stored in a dessicator prior to testing. A minimum of three test results were used to establish the average interface tensile strength.

Dimensional Stability:

To provide information on the dimensional stability of the mould materials, a simple test was used. The dimensions of compression strength test pieces were measured before and after firing. Care was taken to ensure that specimens were tested in the correct order. After firing the specimens were cooled in the kiln and transferred to a dessicator before testing. A minimum of five dimensions were measured on each of three test pieces to establish the average change in length value.

Permeability

A Ridsdale-Dietert electric permimeter was used to evaluate the permeability of the facing and backing materials. This permeability meter employs the orifice method for the rapid determination of permeability. Air at a constant pressure is applied to an AFS standard specimen (in a specimen tube) and the drop in pressure is measured on a pressure gauge, which is calibrated directly in AFS permeability numbers. Check jets were used to establish that the instrument was working correctly. A Fischer dry permeability holder was used to hold and seal the vertical surface of the specimens. A minimum of three test results were used to establish the average permeability number.

High Temperature Tests

The tests for hot strength and unimpeded linear expansion were conducted using the George Fischer High Temperature Testing Accessory, Type PHT. Backing material specimens were produced using the GF compacting device and were gassed in the specimen tube before extraction. Facing material specimens were produced using the specially manufactured mould shown in Figure Ten (v). The specimen dimensions for these tests are 11 mm diameter x 20 mm high.

Measurement of Unimpeded Linear Expansion:

The test specimen standing on a flat, round silica disc is placed on the lower silica press rod and raised until the top covering convex silica disc just touches the upper fixed silica press rod. The position of the pointer on the dial gauge is noted. Subsequently, the preheated furnace is lowered and the expansion of the test specimen is continuously noted from the dial gauge. Either the maximum expansion is noted, or the expansion in relation to time at different temperatures is determined. For standard tests it is sufficient to determine the maximum expansion in per cent at 1000°C. A minimum of three test results were used to establish the average linear expansion value.

Determination of Hot Strength:

The initial procedure for the test is similar to that described above. The preheated furnace is lowered and the time measured from this moment on. After a period of time, determined from a reference graph of heating time vs furnace (or test) temperature, the compression strength is tested and read from the scale. For the standard test temperature of 1000°C the specimen must be heated for exactly one minute before testing for compression strength. A minimum of three test results were used to establish the average hot strength.

Hot Distortion Test:

The hot distortion test is designed to assess the expansion, susceptibility to cracking, deformation and bending of bonded sands at high temperatures. The BCIRA Hot Distortion Tester uses a test piece of 1" x 4.5" x 0.25" (25 mm x 114 mm x 6 mm). This test piece, clamped at one end and loaded in cantilever, is heated strongly under controlled conditions at the centre of the underface. A displacement transducer

connected to an XY recorder produces a record of movement of the test piece with time. Interpretation of these records enables the hot properties of the material to be assessed.

The specimen mould permits sodium silicate bonded material to be blown using a core blower. The specimen can be gassed in situ. Facing slurry can be poured into the mould and separated for torching and firing.

Gas Evolution:

A BCIRA-Ridsdale gas determination apparatus was used to determine the amount of gas evolved from the backing and facing mould materials. The test consists of heating a one gramme sample of the mould material in a pressure tight tube furnace containing a nitrogen atmosphere. As gas is evolved from the sample it causes an increase in pressure and this can be recorded against time on a chart recorder. The pressure, in mm water gauge, can be converted to a gas volume, ml/gm, using calibration curves. Calibration curves are prepared for the test temperature using potassium hydrogen^{carbonate} (KH CO₃) which decomposes on heating to release 22.4 litres of gas/mole (100.12 gm).

Sources of Information

- 1 Methods of Testing Prepared Foundry Sands. Third Report of the Joint Committee on Sand Testing. Published by the Institute of British Foundrymen, September 1966.
- 2 Methods of Testing Cold Setting Chemically Bonded Sands. First Report of the Joint Committee on Sand Testing (1973). The British Foundryman, 1976, 69, 9, p 213-221.
- 3 High Temperature Testing Accessory Type PHT. George Fischer Ltd.
- 4 Routine Test Procedures on Chemically Bonded Sands - Determination of Gas Evolution. BCIRA Broadsheet 16-16.
- 5 Hot Distortion Test for Chemically Bonded Sands. BCIRA Broadsheet 177.

APPENDIX FOUR

FEEDING AND GATING CALCULATIONS

To simplify production and minimise manufacturing requirements, it was decided to use common elements in the gating and feeding systems as far as possible. Feeder head sizes were determined using the Modulus approach proposed by Wlodawer (I). The modulus for each casting was determined as shown in the following section.

Casting Modulus Calculations

Stepped Block:

This casting was considered to be a block having the following dimensions:

length	100 mm
width	75 mm
depth	75 mm

Discounting the interface area between the head and the casting, the modulus of the casting is:

$$\begin{aligned}\frac{V}{SA} &= \frac{100 \times 75 \times 75}{4(100 \times 75) + 2(75 \times 75)} \\ &= \frac{562,500}{30,000 + 11,250} \\ &= \frac{562,500}{41,250} \\ &= \underline{13.6}\end{aligned}$$

Spider Forging Die:

This casting was considered to be a block having the following dimensions:

length	135 mm
width	135 mm
depth	70 mm

Discounting the interface area between the head and the casting, the modulus of the casting is:

$$\begin{aligned}
 \frac{V}{SA} &= \frac{135 \times 135 \times 70}{2(135 \times 135) + 4(135 \times 70)} \\
 &= \frac{1,275,750}{36,450 + 37,800} \\
 &= \frac{1,275,750}{74,250} \\
 &= \underline{17.2}
 \end{aligned}$$

Flange Yoke Die:

This casting was considered to be a cylinder with the following dimensions:

diameter 183 mm
height 95 mm

A top head with exothermic lining was required because of the casting shape and limited capacity of the melting furnace. As a result, the interface area was not included in the modulus calculation. The modulus of the casting is:

$$\begin{aligned}
 \frac{V}{SA} &= \frac{\pi r^2 h}{2\pi r h + \pi r^2} \\
 &= \frac{\pi \times 91 \times 5^2 \times 95}{2 \times \pi \times 91.5 \times 95 + \pi \times 91.5^2} \\
 &= \frac{2,499,033}{54,624 + 26,306} \\
 &= \frac{2,499,033}{80,930} \\
 &= \underline{30.9}
 \end{aligned}$$

Retractable Die Core:

This casting was considered to be a cylinder with the following dimensions:

diameter 50 mm
length 165 mm

Discounting the interface area between the head and the casting, the modulus of the casting is:

$$\begin{aligned}
\frac{V}{SA} &= \frac{\pi r^2 h}{2\pi r h + 2\pi r^2} \\
&= \frac{\pi \times 25^2 \times 165}{2 \times \pi \times 25 \times 165 + 2 \times \pi \times 50^2} \\
&= \frac{324,019}{25,922 + 15,710} \\
&= \frac{324,019}{41,632} \\
&= \underline{7.8}
\end{aligned}$$

Feeder Head Calculations

A single feeder head size was proposed for each of the test castings except the flange yoke die. In each case a side head of height: diameter ratio = 1.5 and a domed top was proposed. To ensure effective feeding the dome was pierced by an integrally moulded puncture core. The proposed head dimensions were 100 mm diameter x 150 mm long. If required, this could be supplemented by the use of a hemispherical base in the drag half of the mould.

A domed cylindrical head of 100 mm diameter and height of 150 mm has a modulus as follows:

$$\begin{aligned}
\frac{V}{SA} &= \frac{\pi r^2 h + \frac{1}{2}(4/3 \pi r^3)}{2\pi r h + \pi r^2 + \frac{1}{2}(4\pi r^2)} \\
&= \frac{\pi \times 50^2 \times 100 + \frac{1}{2}(4/3 \times \pi \times 50^3)}{2\pi \times 50 \times 100 + \pi \times 50^2 + \frac{1}{2}(4\pi \times 50^2)} \\
&= \frac{785,500 + 261,833}{31,420 + 7,855 + 15,710} \\
&= \frac{1,047,333}{54,985} \\
&= \underline{19.05}
\end{aligned}$$

The addition of a hemispherical base modifies the modulus calculation as follows:

$$\begin{aligned}
\frac{V}{SA} &= \frac{\pi r^2 h + 4/3 \pi r^3}{2\pi r h + 4\pi r^2} \\
&= \frac{\pi \times 50^2 \times 100 + 4/3 \times \pi \times 50^3}{2 \times \pi \times 50 \times 100 + 4 \times \pi \times 50^2} \\
&= \frac{785,500 + 523,667}{31,420 + 31,420}
\end{aligned}$$

$$= \frac{1,309,167}{62,840}$$

$$= \underline{20.8}$$

According to Wlodawer, the modulus of the head should be at least 1.2 x the modulus of the casting, to ensure that the head solidifies after the casting.

For the stepped block:

$$M_h > 1.2 M_c$$

$$> 1.2 \times 13.6 = 16.3$$

this condition is met by the domed head.

For the spider forging die:

$$M_h > 1.2 M_c$$

$$> 1.2 \times 17.2 = 20.6$$

this condition is met by the domed head with a hemispherical base.

For the retractable die core:

$$M_h > 1.2 M_c$$

$$> 1.2 \times 7.8 = 9.4$$

this condition is met by the domed head.

Flange Yoke Die:

For this casting a top head of 150 mm diameter and 150 mm high was proposed. A Foseco Kalminex exothermic sleeve was used. The nominal modulus of such a head is:

$$\frac{V}{SA} = \frac{\pi r^2 h}{2\pi r h + \pi r^2}$$

$$= \frac{\pi \times 75^2 \times 150}{2\pi \times 75 \times 150 + \pi \times 75^2}$$

$$= \frac{2,651,063}{70,695 + 17,674}$$

$$= \frac{2,651,063}{88,369}$$

$$= \underline{30}$$

The sleeve extends the modulus by a factor of 1.3, \therefore the true modulus of the head is 39.

The modulus of the flange yoke die was calculated as 30.9. For the head to be effective:

$$M_h > 1.2 M_c$$

$$> 1.2 \times 30.9 = 37.1$$

this condition is met by the Foseco sleeved head.

Although the modulus approach produces a feeder head which stays liquid longer than the casting, two further checks are required to ensure that the head sizes calculated are suitable. These are for volume feed capacity and feeding distance.

Volume Feed Capacity

For plain cylindrical heads:

$$V_{\max}(\text{casting}) = V_{\text{head}} \times \frac{14 - S}{S}$$

where S = specific shrinkage of the alloy (%).

For a head lined with exothermic material this expression becomes:

$$V_{\max}(\text{casting}) = V_{\text{head}} \times \frac{67 - S}{S}$$

The specific shrinkage for H13 was assumed to be 5%, in the absence of an available reference source.

The volume of each of the four castings was calculated to be:

(i) stepped block	562,500 mm ³
(ii) spider forging die	1,275,750 mm ³
(iii) flange yoke die	2,499,033 mm ³
(iv) retractable die core	324,019 mm ³

Now, taking only the $\varnothing 100$ mm x 100 mm high section of the proposed head:

$$\begin{aligned} V_{\max}(\text{casting}) &= 785,500 \times \frac{14 - 5}{5} \\ &= \underline{32,873,181 \text{ mm}^3} \end{aligned}$$

\therefore the head has sufficient volume feed capacity for castings (i) to (iii) above.

Feeding Distance

Applying the feeding distance rules developed by Pellini (II):

For a bar the feeding distance is $6/T$.

For a plate the feeding distance is $4.5T$.

(where T is given in inches)-

For each of the castings:

- | | |
|---------------------------|----------------------------|
| (i) stepped block | $T_{\max} = 75 \text{ mm}$ |
| (ii) spider forging die | $T_{\max} = 70 \text{ mm}$ |
| (iii) flange yoke die | (not applicable) |
| (iv) retractable die core | $T_{\max} = 50 \text{ mm}$ |

$$\begin{aligned}\text{For (i), feeding distance} &= 6\sqrt{75/25.4} \\ &= \underline{262 \text{ mm}}\end{aligned}$$

as the casting is 100 mm long, this is more than adequate.

$$\begin{aligned}\text{For (ii), feeding distance} &= 4.5 \times (70/25.4) \\ &= \underline{315 \text{ mm}}\end{aligned}$$

as the casting is 135 mm long, this is more than adequate.

$$\begin{aligned}\text{For (iii), feeding distance} &= 6\sqrt{50/25.4} \\ &= \underline{214 \text{ mm}}\end{aligned}$$

as the casting is 165 mm long, this is adequate.

Gating Systems

The dimensions of a gating system are usually described in terms of the gating ratio $a:b:c$, where:

- a = cross-sectional area of the sprue
- B = cross-sectional area of the runner
- c = cross-sectional area of the ingate

The recommendations for dimensioning gating systems contained in the literature are diverse. However, in a paper on premium quality casting production, Polich et al (III) recommend a ratio of 1:2:2 for steel castings and this proposal has been adopted.

For the stepped block, spider die and die core castings, a side head was used. For such a layout, Wallace (IV) recommends minimum size dimensions for the neck connecting the head and casting. To minimise the tendency for premature solidification in the neck, the dimension of L_n should not exceed 15 mm. A Washburn core was used with the stepped block casting, whereas moulded gates were used for the spider die and the die core.

The arrangement for the flange yoke die casting required gating into the mould cavity from the runner bar and the use of a top head. The arrangement for the other three castings involved running the metal into the head before filling the mould cavity.

With L_n set at 15 mm:

$$\begin{aligned} D_n &= 1.2 \times 15 + 0.1 \times 100 \\ &= \underline{\varnothing 28 \text{ mm}} \end{aligned}$$

\therefore cross-sectional area of ingate $\approx 600 \text{ mm}^2$.

On this basis, the gating ratio becomes:

300:600:600

The runner bar dimensions to provide this cross-sectional area are:

height	25 mm
width	25 mm (base)
	23 mm (top)

The sprue outlet diameter to provide a cross-sectional area of 300 mm^2 is 20 mm. To avoid aspiration a tapered sprue is advised, the dimensions of which can be determined from the expression:

$$\frac{A_o}{A_i} = \frac{h_b}{h_t}$$

\therefore sprue inlet area is:

$$\begin{aligned} A_i &= \frac{A_o}{\sqrt{75/250}} \\ &= \underline{545 \text{ mm}^2} \end{aligned}$$

and the sprue inlet diameter is 26 mm.

To minimise turbulence effects at the base of the sprue, it is recommended that a sprue well be incorporated in the gating system. To meet this requirement, a sprue well diameter of 50 mm was used.

As indicated previously, the stepped block was gated using a \varnothing 28 mm ingate produced using a Washburn core. This permitted gating at the centre of the heaviest section. For the other castings it was necessary to use different ingate shapes, although the ingate area remained constant.

Retractable Die Core:

Although this component is moulded in both the cope and drag, its design is such that an ingate can only be accommodated in the cope. A semicircular ingate with a radius of 20 mm was chosen.

Spider Forging Die:

As the casting is moulded in the cope, the ingate must also be moulded in the cope. In the interest of commonality, the ingate for the retractable die core was used:

Flange Yoke:

A simple tangential runner bar with a rectangular ingate blended into the casting diameter was used.

Pouring Times

The pouring times for each of the casting configurations can be calculated using the following formula (V):

$$t = \frac{W}{d.C.A. \sqrt{2g.H}}$$

where:

- t = pouring time (in seconds)
- w = casting weight (in kg)
- d = density of metal (in kg/m³)
- C = discharge coefficient for system
- A = choke area (in m²)
- G = acceleration due to gravity (9.81 ms)
- H = effective height of metal head (metres)

The value of C has been quoted as 0.5 to 0.9 in the literature. For this calculation an average value of 0.7 was used. The density of the alloy is 6800 kg/m³ and the value of H is 0.275 m.

For the purpose of calculations the estimated weight of metal cast, which includes gating and feeding systems, for each casting is:

- (i) stepped block 13.4 kg
- (ii) spider forging die 21.5 kg
- (iii) flange yoke die 28.1 kg
- (iv) retractable die core 12.2 kg

The value of d.C.A. $\sqrt{2g.H}$ is a constant for these castings and is equal to:

$$6800 \times 0.7 \times 3.142 \times 10^{-4} \sqrt{2 \times 9.81 \times 0.275}$$

$$= \underline{3.46}$$

$$\therefore t = \frac{W}{3.46}$$

Pouring time for each casting:

- (i) $t = \frac{13.4}{3.46} = \underline{3.9 \text{ seconds}}$
- (ii) $t = \frac{21.5}{3.46} = \underline{6.2 \text{ seconds}}$
- (iii) $t = \frac{28.1}{3.46} = \underline{8.1 \text{ seconds}}$
- (iv) $t = \frac{12.2}{3.46} = \underline{3.5 \text{ seconds}}$

References for Appendix Four

- I Wlodawer R; Directional Solidification of Steel Castings, Pergammon Press, Oxford, 1966.
- II Pellini W S; Trans AFS, 1953, 61, 61.
- III Polich R F, Saunders A and Flemings M C; Trans AFS, 1963, 71, 418.
- IV Wallace J F (Editor); Fundamentals of Riser Steel Castings, Steel Founders Society, USA, 1960.
- V Report of IBF Subcommittee TS24, Foundry Trade J, 1955, 99, 691.

APPENDIX FIVE

MELTING STOCK ANALYSES

MELT NUMBER	QUANTITY (kg)	% COMPOSITION							
		C	Si	Mn	P	S	Cr	Mo	V
E398/2	164	0.41	1.41	0.53	0.022	0.023	4.81	1.52	1.16
E404/21	223	0.45	1.61	0.59	0.026	0.028	4.80	1.49	1.13
E435/21	230	0.42	1.62	0.51	0.021	0.018	4.73	1.54	1.15

(Supplier: Ross and Catherall Ltd)

APPENDIX SIX

MATERIALS AND EQUIPMENT SUPPLIERS

Pattern Making

Aluminium alloy for precision patterns (HE30WP) and plates (NP8):

Henry Righton & Co Ltd, Bookyale Road, Witton, Birmingham. B6 7EY

Graphite for patterns and for EDM electrodes, grade CS 'Ucar':

British Acheson Electrodes Ltd, Grange Mill Lane, Wincobank, Sheffield.
S9 1HS

Pattern Coating

Trenn Mittel W70 pattern release agent:

S H Baron & Co Ltd, 35 Russell Hill Road, Purley, Surrey. CR2 2LF

Mould Materials and Binders

Ethyl silicate, Clinosil BS:

Clino Foundry Supplies Ltd, The Mill, Puleston Industrial Estate,
Ruabon Road, Wrexham, Clwyd.

Molochite, various grades:

Whitfield and Sons Ltd, 23 Albert Street, Newcastle, Staffs.

Mullite, various grades:

Cawoods Refractories Ltd, Crabtree Manor Way, Belvedere, Kent.

Sodium Silicate, Cl25 grade:

ICI Ltd, Mond Division, PO Box 7, Northwich, Cheshire. CW8 4DJ

Chamotte (crushed fireclay grog < 1/8"):

Hepworth Refractories Ltd, Hazlehead, Stocksbridge, Sheffield. S30 5HG

Ammonia and Ammonia salts (gelling agents):

Fisons Scientific Apparatus, Loughborough, Leics.

Sairset (mould jointing compound):

Wm Elliot and Sons Ltd, 155 Glaisdale Drive West, Nottingham.

Moldcote 33:

Foseco (FS) Ltd, Drayton Manor, Tamworth, Staffs.

Graphite (- 100 mesh grade):

S & A Blackwell (St Annes) Ltd, 10 Market Square, Lytham, Lytham
St Annes.

Melting Stock

BS 4659 : 1971 BH 13 die steel:

Ross and Catherall Ltd, Forge Lane, Killamarsh, Nr Sheffield. S31 8BA

Melt Treatment

Crucibles and shanking ladle:

Refractory Mouldings and Castings Ltd, Market Place, Kegworth, Derby.
DE7 2EF

Slax 30 slag coagulant and Stellan 1 deoxidiser:

Foseco (FS) Ltd

Ferro alloys - various:

S & A Blackwell (St Annes) Ltd

Feeding Aids

Exothermic sleeves (6" ID) with and without breaker cores:

Foseco (FS) Ltd

Special Equipment

Spermolin mixer (50 lb capacity):

Newport Forge and Engineering Ltd, Pantglas Estate, Bedwas, Gwent.

Bricesco Electrikiln, model SK/705:

British Ceramic Service Co Ltd, Bricesco House, Park Avenue,
Wolstanton, Newcastle, Staffs. ST5 8AT

Digital meter stick:

Leeds and Northrup Ltd, Wharfedale Road, Tyseley, Birmingham. B11 2DJ

Heat resisting mould firing trays:

Wellman Alloys Ltd, Amblecote, Stourbridge, West Midlands. DY8 4HW

Air motor and fittings:

Airtools and Compressors Ltd, Leicester Depot, 102 Catherine Street,
Leicester.

Special toggle clamp fittings for mould stripper:

D H Woolley (Quorn) Ltd, Unit 2, Windmill Road, Loughborough, Leics.

Oxy-propane burner for mould torching and pouring shank preheating:

Z Onions & Sons, Station Avenue, Loughborough. LE11 OEB

Copper tube for induction heating coil (Enots 5/16" OD x 20 g):

Thos P Headlands, 60 Cannock Street, Barkby Thorpe Road Industrial
Estate, Leicester.

APPENDIX SEVEN

STATISTICAL TESTS

Microhardness Measurements:

(i) $2\sqrt{N}$ Test

Considering the results in Table 5.25, a plus sign is placed against those results where the subsurface microhardness value is greater than that for the centre and a minus sign for the converse situation. This gives 15 plus signs and 2 minus signs. The simple rule for testing whether the predominance of plus signs is statistically significant is to compare the difference between the number of plus signs and minus signs with twice the square root of their sum. If the difference is greater than, or equal to, twice the square root of the sum, then the result can be said to be significant. Thus:

15-2 is compared with $2\sqrt{15+2}$

13 is compared with 8.25

as $13 > 8.25$, the result is significant at the 5% level.

(ii) Standard Error of the Mean

By comparing the difference between two sample means with the standard error of the means, it can be shown that a statistically significant difference exists between the two samples when the difference between the means exceeds three times the standard error of the difference.

Subsurface Microhardness

Average Microhardness Readings (x)	(x - \bar{x})	(x - \bar{x}) ²
584	-40.6	1,648.4
622	-2.6	6.8
733	+108.4	11,750.6
610	-14.6	213.2
582	-42.6	1,814.8
603	-21.6	466.6
627	+2.4	5.8
630	+5.4	29.2
550	-74.6	5,565.2
591	-33.6	1,129.0
664	+39.4	1,552.4
633	+8.4	70.6
632	+7.4	54.8
628	+3.4	11.6
630	+5.4	29.2
625	+0.4	0.2
674	+49.4	2,440.4
$\Sigma x = 10,618$	$\Sigma(x - \bar{x}) = -0.2$	$\Sigma(x - \bar{x})^2 = 26,788.8$

$$\bar{x} = \frac{\Sigma x}{n} = \frac{10,618}{17} = 624.6$$

$$s = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n - 1}} = \sqrt{\frac{26,788.8}{16}}$$

$$s = 40.9$$

Centre Microhardness

Average Microhardness Readings (x)	(x - \bar{x})	(x - \bar{x}) ²
649	-36.9	1,361.6
636	-49.9	2,490.0
727	+41.1	1,689.2
683	-2.9	8.4
763	+77.1	5,944.4
684	-1.9	3.6
698	+12.1	146.4
695	+9.1	82.8
651	-34.9	1,218.0
687	+1.1	1.2
651	-34.9	1,218.0
713	+27.1	734.4
673	-12.9	166.4
675	-10.9	118.8
675	-10.9	118.8
658	-27.9	778.4
742	+56.1	3,147.2
$\Sigma x = 11,660$	$\Sigma(x - \bar{x}) = -0.3$	$\Sigma(x - \bar{x})^2 = 19,227.6$

$$\bar{x} = \frac{\Sigma x}{n} = \frac{11,660}{17} = 685.9$$

$$S = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n - 1}} = \sqrt{\frac{19,227.6}{16}}$$

$$S = 34.7$$

The standard error of the means is given by S/\sqrt{n} :

$$\text{for subsurface} = 40.9/\sqrt{17} = 10$$

$$\text{for centre} = 34.7/\sqrt{17} = 8.5$$

The standard error of the difference between the means of the two samples is:

$$\sqrt{[(10)^2 + (8.5)^2]} = \sqrt{[172.3]} = 13.1$$

The difference between the means is $685.9 - 624.6 = 61.3$, which is more than three times the standard error of the difference. The difference is statistically significant at the 5% level.

Grain Size Measurements:

(i) Tukey Test

This test is more flexible than the $2\sqrt{N}$ test because it may be used where there are unequal numbers in the two groups. Let A be the group without grain refining additions and B the group with grain refining additions, see Table 5.26. For group A the highest value is 4.7 and the lowest value is 2.7. For group B the highest value is 6.0 and the lowest value is 4.3. The number of values in the B group which are higher than the highest value in the A group is 12 and the number of values in the A group which are lower than the lowest value in the B group is 8. Adding these two numbers gives a score of 20. If the score is equal to, or greater than, 7 the difference is significant. As 20 is greater than 7 the difference is significant at the 5% level.

(ii) Standard Error of the Mean

Applying the more discriminating test to the data:
without grain refining additions:

Average Number of Grains Intercepted (\bar{x})	$(x - \bar{x})$	$(x - \bar{x})^2$
4.7	-1.0	1.0
2.7	+1.0	1.0
3.3	+0.4	0.16
3.3	+0.4	0.16
3.7	0	0
4.7	-1.0	1.0
3.7	0	0
4.0	-0.3	0.09
3.0	+0.7	0.49
3.7	0	0
$\Sigma x = 36.8$	$\Sigma(x - \bar{x}) = +0.2$	$\Sigma(x - \bar{x})^2 = 3.9$

$$\bar{x} = \frac{\sum x}{n} = \frac{36.8}{10} = 3.7$$

$$s = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}} = \sqrt{\frac{3.9}{9}}$$

$$s = 0.66$$

with grain refining additions:

Average Number of Grains Intercepted (x)	$(x - \bar{x})$	$(x - \bar{x})^2$
4.7	+0.7	0.49
6.0	-0.6	0.36
5.3	+0.1	0.01
5.0	+0.4	0.16
6.0	-0.6	0.36
5.7	-0.3	0.09
6.0	-0.6	0.36
5.3	+0.1	0.01
5.0	+0.4	0.16
4.7	+0.7	0.49
4.3	+1.1	1.21
5.3	+0.1	0.01
5.7	-0.3	0.09
5.7	-0.3	0.09
5.7	-0.3	0.09
$\sum x = 80.4$	$\sum (x - \bar{x}) = +0.6$	$\sum (x - \bar{x})^2 = 3.98$

$$\bar{x} = \frac{\sum x}{n} = \frac{80.4}{15} = 5.4$$

$$s = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}} = \sqrt{\frac{3.98}{14}}$$

$$s = 0.53$$

The standard error of the means is:

$$\text{without grain refining additions} = 0.66/\sqrt{10} = 0.21$$

$$\text{with grain refining additions} = 0.53/\sqrt{15} = 0.14$$

The standard error of the difference between the means of the two samples is:

$$\sqrt{[(0.21)^2 + (0.14)^2]} = \sqrt{[0.044 + 0.020]} = 0.25$$

The difference between the means is $5.4 - 3.7 = 1.7$, which is more than three times the standard error of the difference. The difference is statistically significant at the 5% level.

Association between Microhardness Measurements and Grain Size Measurements:

Ingot Casting Number	Average Number of Grains Intercepted	Average Vickers Microhardness Values (Centre)
3	3.54	649
43	3.82	698
42	4.14	684
34	4.14	636
37	4.40	683
44	4.28	695
35	4.46	727
38	5.52	763
62	5.40	673
63	5.34	675
66	5.34	742
Average Values:	4.58	693

The number of pairs in which both figures are higher and both figures are lower than the respective average is: $2 + 4 = 6$.

The number of pairs in which one figure is higher and the other figure lower than the respective average is 5.

The difference between the two sets of pairs is: $6 - 5 = 1$.

The total number of pairs is 11 and $\therefore 2\sqrt{N} = 6.6$. As $6.6 > 1$ there is no significant association.

Tests for Association between: % Deviation, Ra, Wa, Bearing Ratio, Pouring Temperature and Casting Weight:

Test Casting Number	A % Deviation (mean)	B Ra (mean)	C Wa (mean)	D Bearing Ratio (mean)	E Pouring Temperature °C	F Casting Weight kg
1	-1.26	2.54	4.38	47.97	1523	2.9
2	-1.27	3.45	5.38	50.80	1483	2.9
3	-0.57	3.59	7.08	49.40	1586	2.9
4	-1.96	3.56	7.45	47.37	1555	1.6
5	-1.80	2.91	8.10	46.30	1530	1.6
6	-1.99	3.15	4.85	51.90	1500	1.6
7	-1.45	3.84	4.13	51.25	1516	7.0
8	-1.50	4.76	8.84	43.80	1550	7.0
9	-2.60	5.03	7.84	52.35	1545	18.0
10	-1.48	5.30	7.93	49.00	1540	7.0
11	-1.99	5.63	8.59	49.85	1550	18.0
12	-2.53	4.52	6.52	54.65	1545	18.0
13	-1.56	3.44	4.99	50.17	1555	2.9
14	-1.90	3.02	6.31	52.20	1550	1.6
15	-0.88	3.40	4.93	51.75	1540	7.0
Average I	-1.65	3.88	6.49	49.92	1538	6.7
Average II	-1.55	4.14	6.42	50.09	1540	8.5

Average I values are for all 15 castings. Average II values are for 11 castings, with the retractable die core casting values excluded.

Considering first the whole group of 15 castings, the possible pairings for association are: A + B; A + C; A + D; A + E; A + F; B + C; B + D; B + E; B + F; C + D; C + E; C + F; D + E; D + F. (E + F is not a dependent relationship.)

A + B

The number of pairs in which both figures are higher and both figures are lower than the respective average is: $4 + 4 = 8$. The number of pairs in which one figure is higher and the other lower than the respective average is 7. The difference between the two sets of pairs

is: $8 - 7 = 1$. The total number of pairs is 15 and $\therefore 2\sqrt{N} = 7.75$.
As $1 < 7.75$ there is no association. Expressing this in abbreviated form:

$$A + B : 4 + 4 = 8 ; 7 ; 8 - 7 = 1 ; 1 < 7.75$$

similarly for the other pairings:

$$A + C : 5 + 4 = 9 ; 6 ; 9 - 6 = 3 ; 3 < 7.75$$

$$A + D : 5 + 4 = 9 ; 6 ; 9 - 6 = 3 ; 3 < 7.75$$

$$A + E : 5 + 3 = 8 ; 7 ; 8 - 7 = 1 ; 1 < 7.75$$

$$A + F : 3 + 4 = 7 ; 8 ; 7 - 8 = -1 ; -1 < 7.75$$

$$B + C : 5 + 7 = 12 ; 3 ; 12 - 3 = 9 ; 9 > 7.75$$

$$B + D : 2 + 4 = 6 ; 9 ; 6 - 9 = -3 ; -3 < 7.75$$

$$B + E : 5 + 5 = 10 ; 5 ; 10 - 5 = 5 ; 5 < 7.75$$

$$B + F : 5 + 8 = 13 ; 2 ; 13 - 2 = 11 ; 11 > 7.75$$

$$C + D : 1 + 1 = 2 ; 13 ; 2 - 13 = -11 ; -11 < 7.75$$

$$C + E : 7 + 4 = 11 ; 4 ; 11 - 4 = 7 ; 7 < 7.75$$

$$C + F : 5 + 5 = 10 ; 5 ; 10 - 5 = 5 ; 5 < 7.75$$

$$D + E : 5 + 2 = 7 ; 8 ; 7 - 8 = -1 ; -1 < 7.75$$

Considering the group of 11 castings, which excludes the 4 retractable die core castings. The same pairings can be considered and these are shown below in brackets to differentiate them from the first group. It should be noted that two pouring temperature values of 1540°C coincide with the smaller group average for pouring temperature. Therefore, the pairs of numbers which include these values are excluded.

$$(A + B) : 3 + 5 = 8 ; 3 ; 8 - 3 = 5 ; 5 < 6.63$$

$$(A + C) : 3 + 4 = 7 ; 4 ; 7 - 4 = 3 ; 3 < 6.63$$

$$(A + D) : 3 + 4 = 7 ; 4 ; 7 - 4 = 3 ; 3 < 6.63$$

$$(A + E) : 4 + 3 = 7 ; 2 ; 7 - 2 = 5 ; 5 < 6$$

$$(A + F) : 3 + 7 = 10 ; 1 ; 10 - 1 = 9 ; 9 > 6.63$$

$$(B + C) : 5 + 5 = 10 ; 1 ; 10 - 1 = 9 ; 9 > 6.63$$

$$(B + D) : 2 + 2 = 4 ; 7 ; 4 - 7 = -3 ; -3 < 6.63$$

$$(B + E) : 4 + 3 = 7 ; 2 ; 7 - 2 = 5 ; 5 < 6$$

$$(B + F) : 3 + 6 = 9 ; 2 ; 9 - 2 = 7 ; 7 > 6.63$$

$$(C + D) : 2 + 1 = 3 ; 8 ; 3 - 8 = -5 ; -5 < 6.63$$

$$(C + E) : 5 + 3 = 8 ; 1 ; 8 - 1 = 7 ; 7 > 6$$

$$(C + F) : 3 + 5 = 8 ; 3 ; 8 - 3 = 5 ; 5 < 6.63$$

$$(D + F) : 3 + 1 = 4 ; 5 ; 4 - 5 = -1 ; -1 < 6$$

A statistically significant association at the 5% level exists for the following pairs:

Group I : B + C and B + F

Group II : A + F ; B + C ; B + F ; and C + E

APPENDIX EIGHT

RELATED PUBLICATIONS

The following publications have arisen from the project described in this thesis and copies of the papers are presented:

- 1 Precision Casting for Moulds and Dies. A J Clegg and A A Das, The Production Engineer, 1978, 57, 11, p 17-21.
- 2 Precision Cast Tooling. A J Clegg and A A Das, paper presented to the Engineers' Digest International Conference entitled: New Frontiers in Tool Materials, Cutting Techniques and Metal Forming, London, 1979, 15-16 March, pp 18.
- 3 The Shaw Process - A Review. A J Clegg, Foundry Trade Journal, 1980, 149, 3197, p 429-438 and reprinted in Foundry Technology - A Source Book, edited by P J Mikelonis and published by the American Society for Metals, 1982, Ohio, p 53-58.

Precision casting for moulds and dies

Mr A J Clegg MIProdE and Mr A A Das of the department of engineering production at Loughborough University of Technology take a look at the precision casting processes currently used for producing cast dies and moulds and other tooling. The authors are involved in a Science Research Council sponsored investigation into the production of precision cast tooling.

DIE AND mould supply in the UK is of fundamental importance to the economy because of the key position the toolmaking industry has with respect to the metal and plastics processing industries and, in turn, final product manufacture. The absolute value of the output of dies and moulds can also contribute substantially towards the UK balance of payments¹.

Traditionally, dies and moulds have been produced by machining from wrought material. However, castings have also been used for many years in the production of dies,

particularly iron castings which have been used in the manufacture of automobile press body dies and dies for permanent mould or gravity die casting. These castings have been produced by the traditional sand casting routes and required machining to produce the required final dimensions.

The casting process provides the designer with broad freedom for his ideas. Casting is the cheapest and most convenient method of producing intricate detail and complex shapes in a wide variety of metals and alloys. Die users, however, have with certain exceptions,

been reluctant to use cast dies because of defects traditionally associated with castings such as micro-porosity, blow holes, surface imperfections, and variations in metallurgical structure. The obtainable precision and reproducibility of tolerances have also been questioned in many instances.

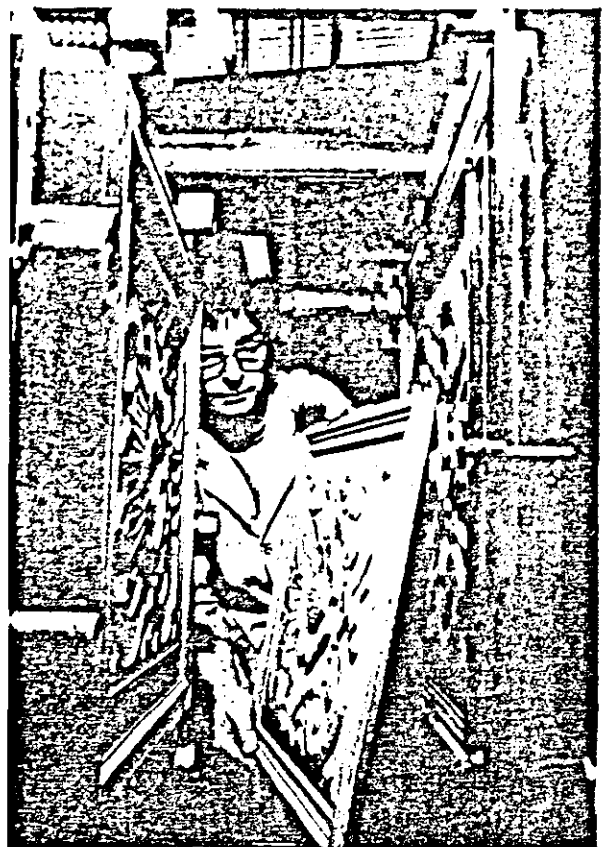
The criticisms also applied, to some extent, to precision cast dies produced by the Shaw process during the late 1950s and early 1960s. It is possible that at this time the British foundry industry was not fully in a position to develop the production of precision cast tooling. Certainly the initial enthusiasm in this country did not result in the development of cast tooling to the extent that it was developed in other European countries, Japan and the USA^{2,3,4}.

Revival

Developments in foundry technology over the past two decades have resulted in a considerable improvement in casting quality and precision. The ability of a precision casting foundry to guarantee casting integrity and the increased costs associated with traditional die making techniques, have resulted in a revival of interest in cast tooling which is now being used in a variety of applications.

This article briefly reviews the precision casting processes currently used for producing cast dies and moulds and outlines some of the materials used for, and the application of, cast tooling.

The terms 'precision cast tooling', 'cast to size' and 'cast to shape' are currently used to describe cast dies and moulds for use in a variety of applications. Each term implies that a precision casting process has been used to produce the die or mould. However, 'cast to size' implies that the casting accurately resembles the part required and that only a minimum amount of bench fitting is necessary to prepare the die or mould for production



Production process	Cast tooling material	Typical cast tooling application
Forging	H12, H13 and other hot work tool steels	Drop forging dies, hot die forging, press forging, roll forging
Extrusion	Tool steel	Aluminium extrusion
Pressing	Cast iron, SG iron, tool steel	Automobile pressings
Diecasting	H13 tool steel	Aluminium-base, copper-base, magnesium-base and zinc-base alloys
Plastics moulding	Aluminium-base alloys, beryllium-copper alloys, cast iron, tool steel	Shoe moulds, injection moulding, blow moulding, rubber moulding
Glass moulds	Cast iron, SG iron, tool steel	Glass bottles, ovenware
Foundry tooling	Aluminium-base alloys, cast iron, alloy irons, SG irons, tool steel	Mass production patterns and coreboxes, shell core and hot box core boxes

Figure 1 Cast tooling materials and applications.

UNIS1 designation	BS4659: 1971 designation	Nominal chemical composition (%)						Remarks
		C	W	Cr	Mo	V	Co	
BA2	BA2	1.00		5.00	1.00	0.20		Air hardening; good balance of abrasion resistance, toughness, and freedom from hardening hazards
BD2	BD2	1.50		12.00	0.80	0.90		Excellent hardness and abrasion resistance
BH12	BH12	0.35	1.50	5.00	1.50	1.00		General purpose; good balance of toughness and wear resistance; can be watercooled in service
BH13	BH13	0.35		5.00	1.50	1.00		Better abrasive wear than H12; can be watercooled in service
BH19	BH19	0.40	4.25	4.25		2.00	4.25	Good resistance to hot abrasive wear
BH21	BH21	0.35	9.50	3.50				Greater resistance to high temperature
BH26	BH26	0.50	18.00	4.00		1.00		High speed steel; optimum resistance to wear in high temperature forging applications
—	—	0.60	6.00	4.00	5.00	2.00		Maintains high hardness at high operating temperatures

re 2 Steels for cast tooling applications — see Reference 7.

'Cast to shape' indicates that the casting closely resembles the required shape of the die mould but the casting incorporates a pre-determined finishing allowance. The quality of precision encompasses not only the accuracy of individual dimensions, surface finish and general appearance⁵. Ideal casting would not only fall within specified dimensional tolerances but its outputs would be crisp and clear cut and its surface smooth. With precision is coupled the ability of intricacy, seen in the reproduction of elaborate features and fine detail.

Ceramic moulding

Although measures taken by the foundry to increase precision can result in increased costs, increased accuracy may reduce the overall costs by the reduction or elimination of machining, particularly where difficult corners, awkward access or tough alloys are involved. The factors which influence dimensional accuracy are:

- Accuracy of the pattern and mould equipment
- Accuracy with which the mould cavity reproduces the pattern shape after pattern withdrawal
- Accuracy with which the casting conforms to the original shape of the mould cavity, depending on the characteristics of the metal/mould combination and the dimensional stability of the mould cavity on cooling
- The contraction factor, which determines the predictability of dimensional

changes during cooling

● Finishing operations.

The precision casting processes almost universally adopted in the production of precision cast tooling are the ceramic moulding methods of the Shaw process or its variant the Unicast process. In either process the essential prerequisites to successful precision castings are accurately produced patterns and mould equipment.

It is clear that a casting cannot be more accurate than the pattern from which it is produced. The mould material is produced by blending a finely ground refractory powder, usually mullite, with ethyl silicate, a liquid binder. By adding a hydrolysing agent and a catalyst, a colloidal silica gel is formed which binds the refractory grains together.

Rubbery nature

Careful selection of the mould material results in two specific benefits. Firstly, the fine grains of the refractory mould material produce a very smooth surface finish on the resultant casting. And secondly, the selection of a thermally stable mould material ensures that the mould is not subject to excessive dimensional changes during metal casting thus enabling an accurate prediction of casting contraction factors.

The blended liquid slurry is poured into the moulding box and around the pattern. Within a short period of time, controlled by the amount of catalyst added, the mould material gels to a rubbery consistency and the mould can be removed from the pattern. One of the

advantages of this process is that pouring the liquid slurry over the pattern ensures a high degree of contact and therefore accuracy and intricacy in the final casting. Also, the mould material sets in contact with the pattern and consequently produces a mould which accurately reproduces the pattern detail.

The rubbery nature of the mould allows it to be withdrawn from the pattern without distortion thus ensuring that the mould retains the pattern shape. When the mould is withdrawn it is either torched immediately to remove evolved alcohol (Shaw process) or immersed in a stabilising bath prior to torching (Unicast process).

The torching procedure introduces a very fine crazed surface to the mould which does not affect the casting surface, but does provide mould permeability to allow the escape of air during casting. After torching the moulds are fired in a furnace to 1000°C which ensures that there are no combustible materials in the mould and that a strong, rigid, inert, accurate and stable mould is produced.

Plaster casting

Metal can be poured into hot or cold moulds and if the mould is contained within an inert atmosphere a clean casting free from oxide scale is produced. Careful control of mould production and metal melting and treatment enables an accurate prediction of casting contraction allowance to be made thus ensuring the accuracy and soundness of the final casting. Thus the Shaw process provides a precision casting which is clean, smooth and accurate and a wide range of ferrous and non-ferrous alloy castings can be produced satisfactorily by the process.

Another method of producing precision castings is to use plaster casting. As the name implies the basic moulding material in this process is plaster of Paris. Moulds can be produced by pouring the plaster slurry around a pattern and allowing it to set prior to separating, which requires considerable care. Plaster mould sections can also be produced from flexible rubber patterns and core boxes. This approach can be particularly useful

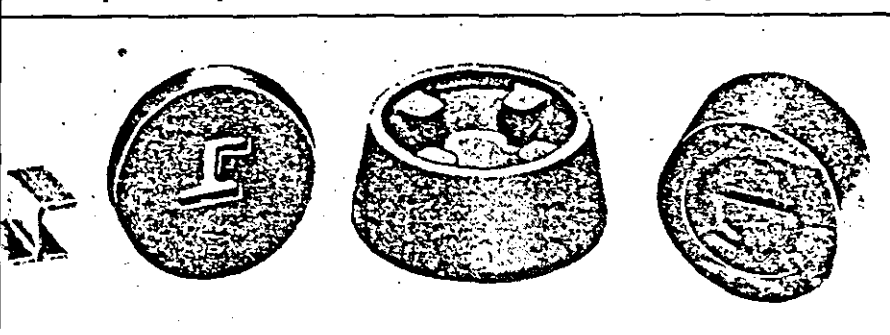


Figure 3 Group of typical extrusion and forging dies, precision cast in hot work tool steel.

When parts cannot be moulded by normal methods as a result of undercuts, and so on.

By careful control of the mould processing conditions an homogeneous grain structure with a high degree of permeability can be achieved whilst still maintaining a smooth, fine skin. The process is generally restricted to the production of castings in aluminium-base alloys, used for foundry tooling and some plastics and rubber moulds.

Liquid hobbing is a process which is particularly suitable for the production of mould cavities in beryllium-copper alloys. Here, a master hob attached to a stripper plate and surrounded by an open-ended steel frame, is placed on a press table. The molten beryllium-copper alloy is poured into the frame and pressure is applied by a plunger during solidification. This process is generally known as squeeze casting.

Wheeldon process

The technique ensures a more faithful reproduction of the form and gives a denser hobbing. The master hob is usually machined from a high grade die steel and the process is capable of producing small, deep cavities of high quality.

A similar process to that of liquid hobbing is the Wheeldon process in which a metal model, or male form, of the die cavity required is produced. This model is then used in a similar manner to the hob in that metal is cast around it, although without the application of pressure. Having produced a die half, this is then used to produce the second die half by casting against it. It is claimed that casting directly onto the first die half in this manner produces the best possible joint line mating. A high degree of precision is claimed for the process and the model can be produced from the same metal which is to be cast around it.

The nominal tolerances obtainable in cast tooling vary from process to process. For instance, with ceramic moulded tooling the casting tolerances are quoted as:

- $\pm 0.08\text{mm}$ on dimensions up to 25mm
- $\pm 0.13\text{mm}$ on dimensions between 25-75mm

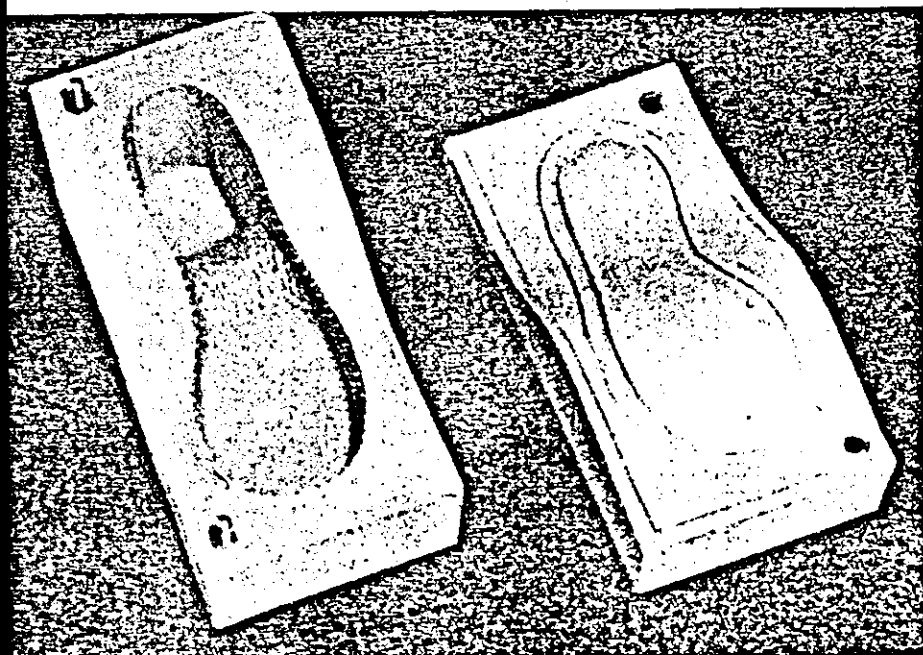


Figure 5 Shoe mould cast to size in an aluminium alloy.

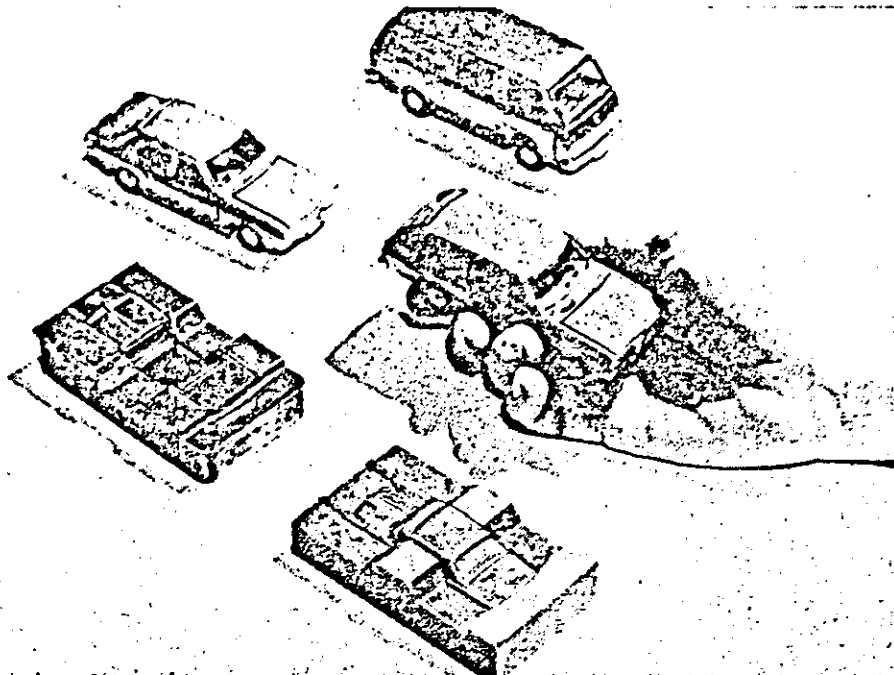


Figure 4 Diecasting dies produced cast to size in heat resistant tool steel.

- $\pm 0.38\text{mm}$ on dimensions between 75-200mm
- $\pm 0.76\text{mm}$ on dimensions between 200-375mm
- $\pm 1.14\text{mm}$ on dimensions over 375mm.

For dimensions across the parting line of the mould an additional tolerance of between $\pm 0.25\text{mm}$ to 0.50mm must be provided. Surface finish values in the region of $2\mu\text{m}$ can be obtained compared with values of $5-10\mu\text{m}$ for normal green-sand practice.

Closer tolerances are readily attainable by experienced suppliers and also by reworking the pattern after a test casting has been compared with the pattern. Reproducibility is excellent, once the pattern has been established subsequent castings will be extremely consistent one to another.

With plaster casting, the casting tolerances quoted are:

- $\pm 0.13\text{mm}$ on dimensions up to 25mm

- ± 0.20 on dimensions between 25-50mm
- $\pm 0.25\text{mm}$ on dimensions between 50-75mm
- $\pm 0.30\text{mm}$ on dimensions between 75-150mm
- $\pm 0.38\text{mm}$ on dimensions between 150-225mm
- $\pm 0.50\text{mm}$ on dimensions between 225-300mm
- $\pm 0.76\text{mm}$ on dimensions between 300-500mm

Surface finish values in the range $2-3\mu\text{m}$ are generally attainable for plaster cast aluminium alloys.

It is claimed for the Wheeldon process that the dimensions of the die are exact to the pattern.

Lateral dimensions on liquid hobbing are controlled mainly by the master hob dimensions and to a certain extent by the hob and melt temperatures. The vertical dimension, between the bottom of the casting and the hob plate, will depend on the accuracy of metering of the liquid metal. Casting tolerances quoted are:

- Aluminium alloys^a
 - $\pm 0.10\text{mm}$ on dimensions up to 25mm
 - $\pm 0.04\text{mm}$ per 25mm on dimensions between 25-300mm
 - $\pm 0.025\text{mm}$ per 25mm on dimensions over 300mm

- Steels^b

(tolerances depend on casting geometry)

 - $\pm 0.10-0.20\text{mm}$ on dimensions up to 25mm
 - $\pm 0.10-0.20\text{mm}$ per 25mm on dimensions between 25-300mm
 - $\pm 0.10-0.20\text{mm}$ per 25mm on dimensions over 300mm

Finishing requirements depend upon the application of the cast die and whether it was produced cast to size or cast to shape. In either case castings are usually supplied in the annealed condition and will have been blast cleaned to remove any refractory, or oxide scale. In the case of ferrous die materials a

y fine aluminium oxide abrasive may be d and for beryllium-copper alloys, glass ds can be used.

For cast to size applications, where the dies to be coated with a refractory material or ease agent, the shot blasted surface may be irable. In other situations bench finishing d polishing will be the only work required. n the case of cast to shape tooling the final chining to size can be conducted by the al methods providing the material is not essively difficult to machine. Depending, casting configuration and degree of chining difficulty, either grinding or trical discharge machining may be the shing process required.

Cast tooling can easily incorporate locat-pads and centre lines, transferred from the tern, which will provide reference points a convenient means of location in all three nes without working from the cavity itself. The range of materials and their applica-in in the field of tool and die manufacture is nsiderable and only a brief review of the ssibilities is given here. A general apprecia-on of the scope of cast tooling can be tained by referring to Figure 1.

The die steels which can be cast cessfully are shown in Figure 2. In terms f vice conditions forging dies have to meet most severe performance requirements. ese include high cold and hot strength, high ar resistance, high mechanical fatigue istance, good thermal fatigue resistance d good brittle fracture resistance. Despite se stringent requirements forging dies were e of the earliest successful applications of ecision cast dies during the early 1960s¹⁰.

Improved die life

Castings have been used in the form of cast e blocks, cast inserts and cast blocks into hich the die cavity is subsequently achined. However, the use of cast inserts her than cast die blocks is recommended r greatest economy. An improved economic vantage is achieved when using cast tooling the pattern cost can be amortised over veral castings. Although a number of cast e steels are used successfully, AISI, H13 die el is particularly popular.

Cast dies have been found to give improved e life over dies produced from wrought aterial. Although comparative figures for e life must be considered with caution, ports of improved output varying from 25%

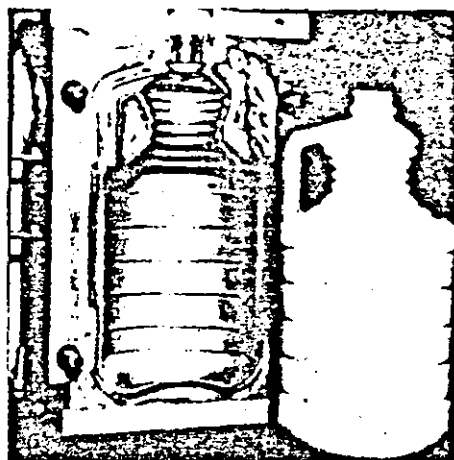


Figure 6 Precision cast beryllium-copper alloy plastics blow mould.

to 150% when using cast dies in a variety of forging applications have been made¹⁰. Some metallurgical evidence has been obtained which substantiates the claim that cast dies provide superior performance because of better high temperature properties¹¹. Figure 3 shows a selection of forging and extrusion dies.

AISI H13 hot work tool steel in wrought form has been used extensively in the production of diecasting dies for aluminium-base, magnesium-base and zinc-base alloys. As the material can easily be cast it has also been the most widely used material for cast diecasting tooling. As a result considerable data is available on the advantages of using cast H13 dies for diecasting applications¹². An example of a diecasting die which has been cast-to-size is shown in Figure 4.

Wrought maraging steels are finding an application as suitable die materials. The relative ease of heat treatment compared with existing die steels is a particular advantage. Although more expensive than die steel, improved material performance may outweigh this disadvantage. Maraging steels are currently being used for diecasting applications in the USA with some considerable success¹³. Research is currently being undertaken at Leeds University to develop a casting material, with carbide dispersions in a tough alloy maraging steel matrix, which may be suitable for precision cast tooling for forging as well as other applications.

Cast irons have a number of applications in such areas as foundry tooling, press dies, glass moulds and some rubber moulds. In the

foundry industry cast iron has been used for many years in gravity die (permanent mould) casting of aluminium-base alloys, copper-base alloys and cast iron. Core boxes for mechanised hot box and shell core production are usually produced in grey irons which perform satisfactorily under the low temperature thermal cycling involved. The glass industry also uses cast iron extensively for tooling purposes.

Beryllium-copper

Aluminium-base alloys have a limited application, although cast tooling produced by plaster casting or Shaw/Unicast methods is used successfully in a number of areas. These areas include moulds for producing expanded polystyrene parts, moulds for producing plastics sole units for footwear (Figure 5), and for foundry pattern equipment used in mass production green-sand moulding. The material may also be used in water cooled gravity die casting dies.

Beryllium-copper alloys have emerged recently as highly suitable alternatives to die steels in the manufacture of moulds for plastics production. The alloys have particularly good thermal conductivity values ranging from two to five times those of die steels. This property may provide improved production rates through improved rates of thermal cycling. In addition the materials have good castability (greatly superior to steel) and provide extremely good reproducibility of textured surfaces and fine details.

Where necessary the material can easily be machined, repair welded and takes a high polish. High production runs, in some cases far in excess of 100 000 parts, are possible as a result of the alloy's properties of high hardness, good abrasion and corrosion resistance. The hardness of the material is developed by a straight-forward heat treatment process.

Intricate detail

Another application for beryllium-copper is in the production of dies for gravity diecasting brass components. In this application the alloy is replacing cast iron and a considerable improvement in die life is obtained primarily as a result of the reduction of heat checking achieved through the higher thermal conductivity of the alloy. Runs of over 150 000 have been reported for a single pair of dies¹⁴.

American alloy designation	Alloying elements (%)			Rockwell Hardness		Remarks
	Be	Co	Si	Aged	ST and aged	
10C	0.45 to 0.75	2.35 to 2.70	—	B40	B96	Good strength and good high temperature properties
20C	1.90 to 2.15	0.35 to 0.65	0.20 to 0.35	B63	C40	High strength and hardness; good castability
165C	1.65 to 1.75	0.20 to 0.30	—	B59	C38	High strength and hardness; good corrosion resistance
245C	2.25 to 2.45	0.35 to 0.65	0.20 to 0.35	B75	C45	High strength, hardness and wear resistance; good castability
275C	2.50 to 2.75	0.35 to 0.65	0.20 to 0.35	B85	C46	High hardness and wear resistance; good castability

Figure 7 Beryllium-copper alloys for cast tooling applications — see Reference 7.

An example of a mould for blow moulding produced in a cast beryllium-copper alloy is shown in figure 6. Cast alloy specifications are given in Figure 7.

Certain compounds of beryllium, notably its oxide, are known to be toxic and detrimental to health if inhaled or otherwise absorbed into the body and adequate protective measures must be taken when processing these alloys.

Casting may be advantageous in the production of dies or moulds for any of the reasons given in the following checklist:¹⁵

- Contoured shapes which would require three dimensional copy pattern in any case for shapes more easily realised in the first instance in the positive form in a more easily worked material.

- Mould or die inserts which have contoured split lines. Matched castings need only light bedding out which can be further reduced, minimising the width of the shut-off and at the pattern-making stage

- Avoiding bulk metal removal which is wasteful in terms of material, machining and labour costs

- The reproduction of intricate details and surface textures such as wood and other natural grains

- Projects where a model or component is already in existence and can provide the basis for pattern-making, thus saving the high costs incurred in model making

- Multiple cavities such as ornate bottle closures and aerosol caps where the model and pattern making costs can be spread

- Moulds which have form in the back, such as watercooling grooves on injection

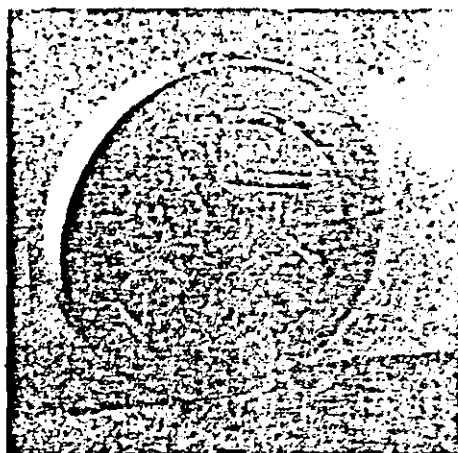


Figure 8 Ceramic moulded spring steel casting for a machine tool application. Picture courtesy Associated Engineering Developments.

moulds, or blow moulds where often the mould takes the form of a 10mm thick shell designed to give maximum heat transfer and consequently minimum cycle times

- Reducing the extent of finishing when compared with the equivalent copy milled cavity.

Acknowledgements

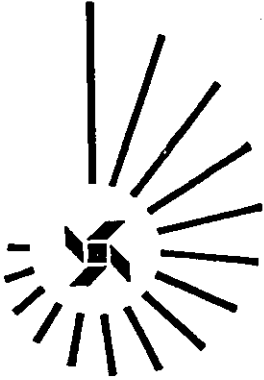
The authors wish to thank Professor R J Sury, head of the department of engineering production, for permission to publish this paper. Thanks are also due to Mr R E Greenwood, president of the Unicast Corp, for his permission to use the photographs in Figures 3, 4, 5, 6.

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**NEW FRONTIERS IN
Tool Materials
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International Conference at Mount Royal Hotel,
London. 15th & 16th March 1978



SESSION V

PAPER 2

PRECISION-CAST TOOLING

by

A. Clegg and Dr. A.A. Das
University of Loughborough

PRECISION CAST TOOLING

by Mr A. J. Clegg and Dr A. A. Das, Department of Engineering Production, Loughborough University of Technology.

SYNOPSIS

The paper includes an introduction which defines the terms associated with precision cast tooling. A brief description of the processes used in the precision casting of dies and moulds follows. Some materials suitable for cast tooling are tabulated and their applications summarised. The review of the important research and development work in the field of precision cast tooling is restricted to tools made of die steels because of the very wide range of application of these materials. The review concentrates on the following:

1. Die Life.
2. Metallurgical Quality.
3. Dimensional Accuracy.

Finally the paper provides a brief outline of the work in progress at Loughborough University of Technology vis-a-vis the co-ordinated die and mould research programme of the Science Research Council (SRC).

INTRODUCTION

The concept of precision cast tooling is not new. The demand for precision cast dies originated from the aircraft industry's requirement for dies made in alloys which are difficult to machine. The die geometry can be relatively complex, e.g. for turbine blades and a high degree of dimensional accuracy is required. Although work had been undertaken in Germany before World War II it was not until the British Aircraft industry initiated research that a casting method - the Shaw process, with real potential for producing precision cast dies, was developed (1).

In spite of the potential of the Shaw process the commercial feasibility of using cast dies was not investigated in the UK until the late 1950's and early 1960's.

Even then cast tooling did not find acceptance in the UK die and mould industry on the scale of acceptance enjoyed in other European countries, Japan and the USA (2, 3, 4).

In the UK, die and mould users have been reluctant to use cast products because of concern that they may contain defects such as: microporosity, blow-holes, segregation, surface imperfections and variations in the metallurgical structure. Additionally die users have questioned the degree of precision obtainable in the dimensions of the die cavity and the reproducibility of tolerances. Developments in foundry technology during the past two decades have resulted in a considerable improvement in casting quality and precision. The ability of a precision casting foundry to guarantee casting integrity and accuracy, and the ever increasing cost of traditional die making techniques, have resulted in a revival of interest in cast tooling which is now being used in a variety of applications. The casting process is often the cheapest and most convenient method of producing intricate detail and complex shapes in a wide variety of alloys. No other process provides such freedom and flexibility for the designer.

DEFINITION OF TERMS

Several terms including: 'precision cast tooling', 'cast to size' and 'cast to shape' are currently used to describe cast dies and moulds for use in a variety of applications. Although each term implies that a precision casting process has been used to produce the die or mould there is a significant difference in the degree of die finishing required. 'Cast to size' implies that the casting accurately resembles the part required and that only a minimum amount of bench fitting is necessary to prepare the die or mould for use in production. On the other hand 'cast to shape' indicates that although the casting closely resembles the required shape of the die or mould it incorporates a pre-determined machining and finishing allowance. The quality of precision (5) encompasses not only the accuracy of individual dimensions but surface finish and general appearance. An ideal casting would not only fall within specified dimensional tolerances but its outlines would be crisp and clear cut and its surfaces smooth. With precision is coupled the quality of intricacy, seen in the reproduction of elaborate features and

fine detail. Although measures taken by the foundry to increase precision can result in increased costs, increased accuracy may reduce the total costs by the reduction or elimination of machining, particularly where difficult contours, awkward access or difficult to machine alloys are involved.

PRECISION CASTING PROCESSES

Although there are several precision casting processes available to the founder the most commonly adopted process for the production of precision cast tooling is the Shaw process or its variant the Unicast process. These processes have the particular advantage that they may be used to produce castings in a wide range of ferrous and non-ferrous alloys. In view of the importance of the process in the successful production of precision castings a brief description will not be out of place. The essential prerequisite to successful precision castings are accurately produced patterns and mould equipment. A casting cannot be more accurate than the pattern from which it is produced. The mould material is prepared by blending refractory powders, containing a high proportion of fine material, with a liquid ethyl silicate binder and a gelling agent. Careful selection of the refractory material results in two particular advantages:

- (i) The fine grains of refractory material provide a smooth surface finish on the resultant casting.
- (ii) The selection of a thermally stable refractory material ensures that the mould is not subject to unpredictable dimensional changes in contact with the molten metal during pouring, thus enabling an accurate estimate of casting contraction to be made.

The blended liquid slurry is poured into the moulding box and around the pattern. Within a short period of time, controlled by the amount of gelling agent, the mould material gels to a rubbery consistency and the pattern can be removed from the mould. Benefits gained at this stage include:

- (a) Pouring a liquid slurry around the pattern ensures a high degree of contact and therefore accuracy and intricacy in the final casting.

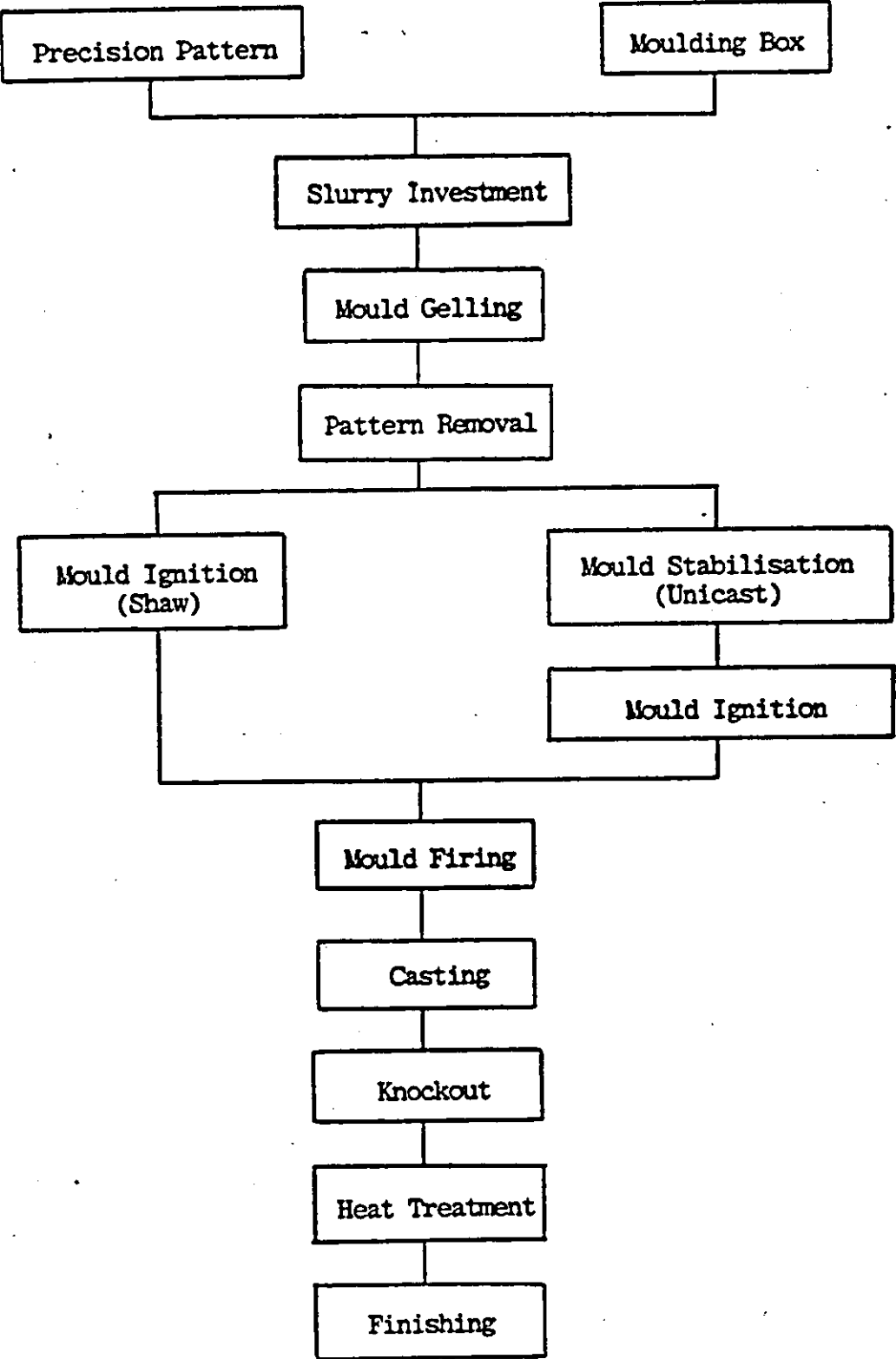
- (b) The mould material sets in contact with the pattern and consequently produces a mould which accurately reproduces the pattern detail.
- (c) The rubbery nature of the mould allows the pattern to be withdrawn without distortion to the mould thus ensuring dimensional accuracy of the mould cavity.

On removal of the pattern the moulds are either torched immediately to remove evolved alcohol (Shaw process) or immersed in a stabilising bath prior to torching (Unicast Process). Torching produces a very fine crazed surface on the mould which does not affect the casting surface i.e. no metal penetration into the fine cracks, but does provide mould permeability to allow the escape of air/gases during casting. After torching the moulds are fired in a furnace to a temperature of 1000°C which ensures that there are no combustible materials in the mould and that a strong, rigid, inert, accurate and stable mould is produced. The stages in the production of a die by the ceramic mould process are outlined in the flow diagram presented in Figure 1.

Metal can be poured into hot or cold moulds and if the mould is contained within an inert atmosphere, for example nitrogen, a clean casting free from oxide scale is produced. Careful control of mould production and metal melting and treatment enables an accurate prediction of casting contraction allowances to be made thus ensuring the accuracy and soundness of the final casting.

Several other precision casting processes are available and are used in the production of cast tooling. Plaster casting is suitable for aluminium-base alloys which can be used for some plastics and rubber moulds. Liquid hobbing or 'squeeze casting' has been used successfully for the production of beryllium-copper tooling. In another process, metal is cast around a male pattern to form a female die cavity and the second die half is cast against the first die half to ensure accurate matching, this process is known as the Wheeldon process. The principle of 'squeeze casting' is shown in Figure 2 and that of the Wheeldon process in Figure 3.

FIGURE 1: Flow diagram representing the stages in the production of a die by the ceramic mould process.



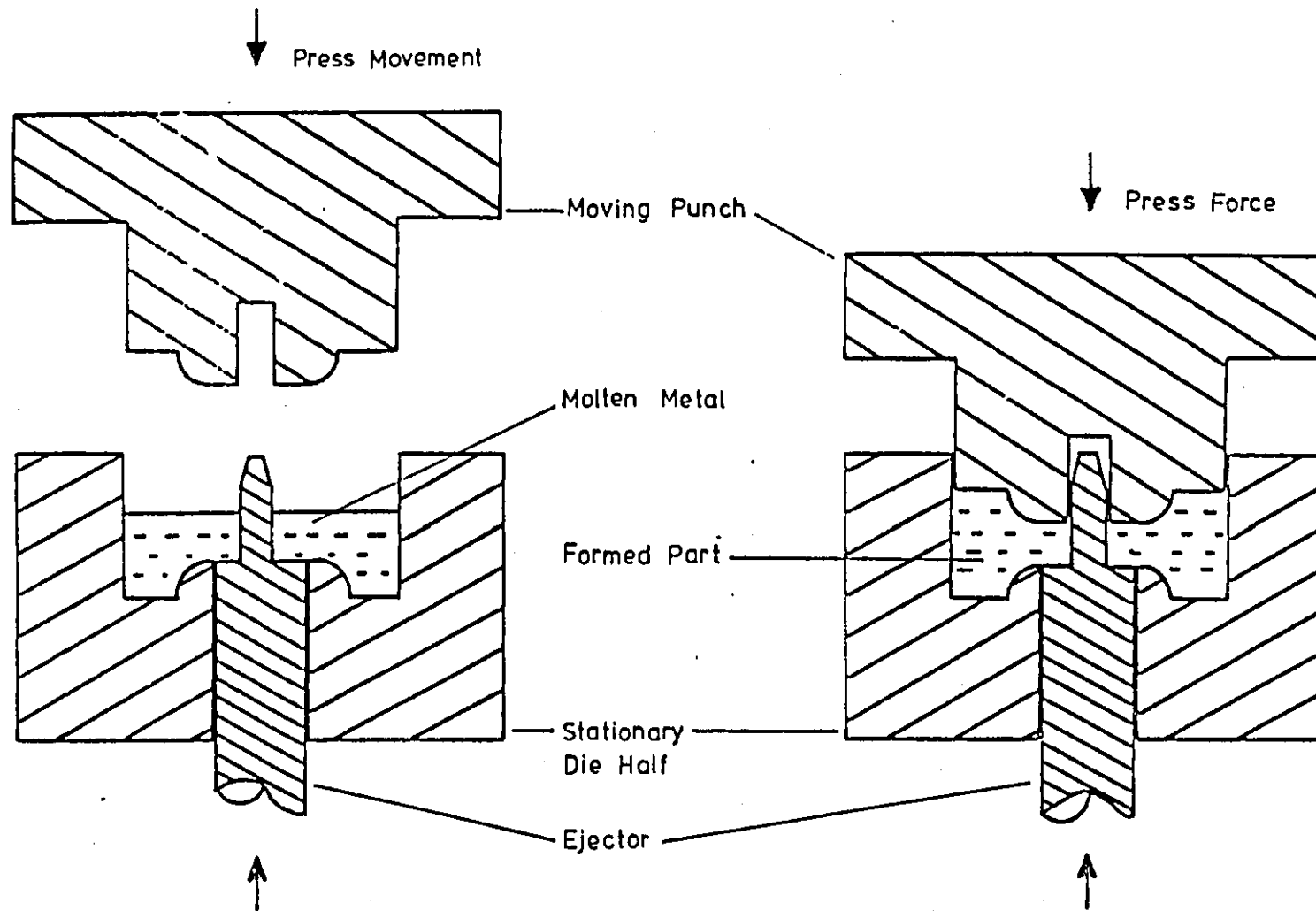
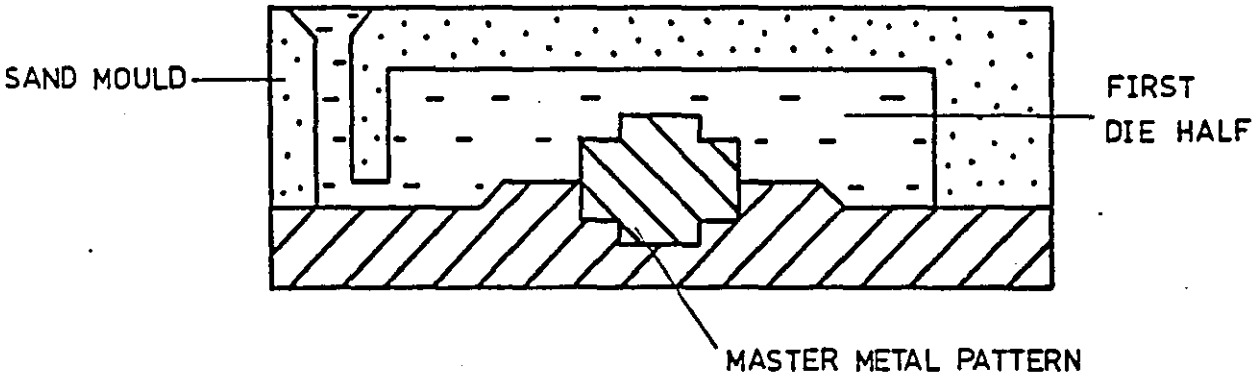


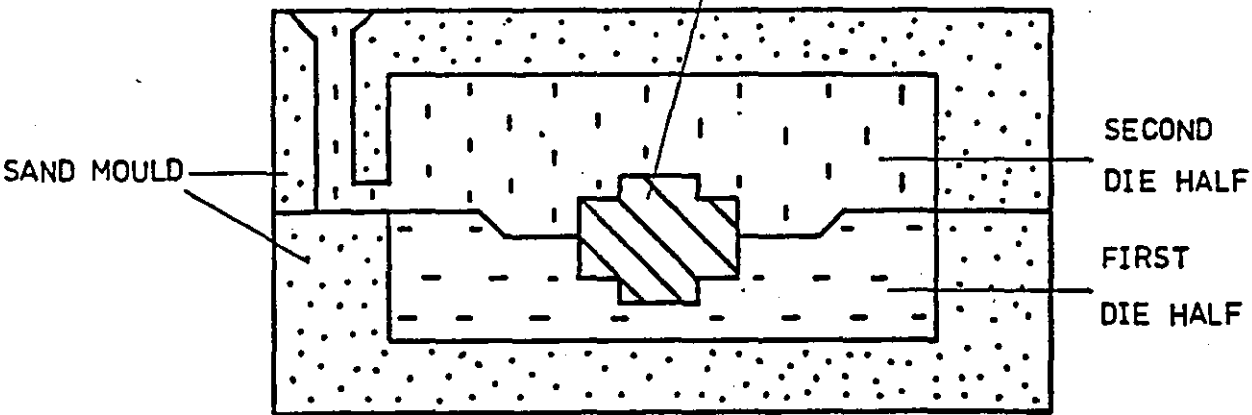
FIGURE 2 PRINCIPLE OF THE SQUEEZE CASTING PROCESS

FIGURE 3 PRODUCTION OF A DIE BY THE WHEELDON PROCESS.

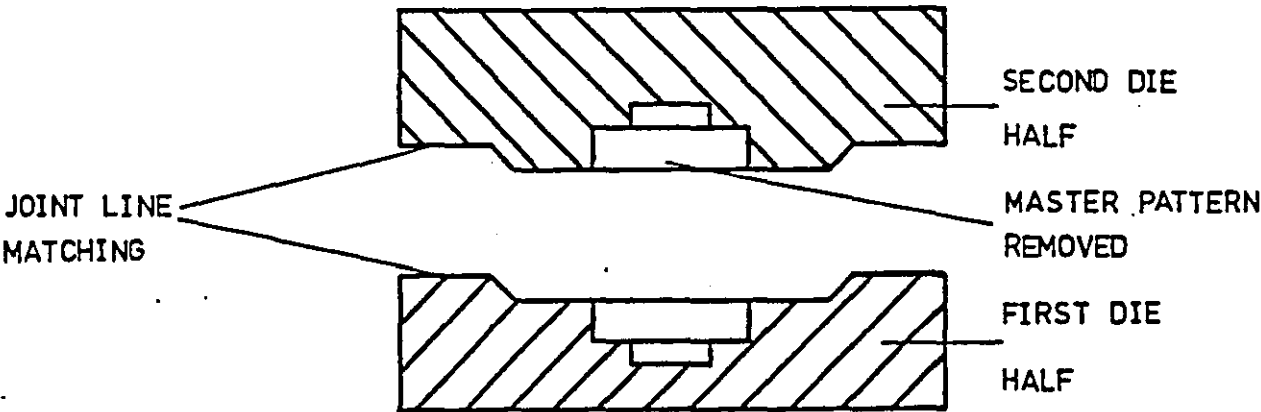
3 A PRODUCTION OF FIRST DIE HALF.



3 B PRODUCTION OF SECOND DIE HALF.



3 C COMPLETED DIE SET.



MATERIALS

The range of materials used in the production of dies and moulds is considerable and some indication of the scope for cast tooling can be gained by reference to Table 1. Further information on the range of materials and the aspects covered so far in this paper may be obtained by reference to a previous article published by the authors (6). Because the range of materials is so wide, the remainder of this paper concentrates on the use of die steels; and in particular AISI H13, (BS 4659 : 1971 BH 13), which is a particularly versatile alloy suitable for dies for forging, for diecasting, and moulds for the manufacture of plastic parts.

REVIEW OF PREVIOUS WORK

The review of published work on the subject of precision cast dies concentrates on three particular aspects:

Die Life

Metallurgical Quality

Dimensional Accuracy

DIE LIFE

The initial industrial enthusiasm for precision cast dies arose from the publication of a Czechoslovakian book on the production of cast cutting tools (7). In this book the authors also described the production of cast forging dies by the Shaw process. They produced several cast dies and compared their performance with dies machined from wrought steel. The cast dies were reported to provide an average improvement in die life of 78.5%. They concluded that cast dies gave better service performance at a lower production cost.

In the UK a Shaw foundry and a forge co-operated on a programme of work to investigate the use of precision cast die inserts for the production of drop forgings. In a report issued by the forge (8) die life figures were provided for five forging dies comparing the performance of wrought dies with dies cast in two different steels (see Table 2). The average improvement in die life performance when changing from wrought to cast dies was:

70% for no. 5 die steel. (BS 224 no. 5 steel)

116% for 5% chromium die steel. (0.3%C; 1% W; 5% Cr; 2% Mo; 0.25% V)

Table 1: Cast Tooling Materials and Applications

Production Process	Cast Tooling Material	Typical Cast Tooling Application
Forging	H12, H13 and other hot work tool steels	Drop forging dies, hot die forging, press forging, roll forging
Extrusion	Tool Steel	Aluminium extrusion
Pressing	Cast Iron, S.G. Iron, Tool Steel	Automobile pressings
Diecasting	H13 tool steel	Aluminium-base, copper-base, magnesium-base and zinc-base alloys.
Plastics Moulding	Aluminium-base alloys, beryllium-copper alloys, cast iron, tool steel	Shoe moulds, injection moulding, blow moulding, rubber moulding.
Glass Moulds	Cast Iron, S.G. Iron, Tool steel.	Glass bottles, ovenware.
Foundry Tooling	Aluminium-base alloys, cast iron, alloy irons, S.G. irons, tool steel.	Mass production patterns and coreboxes. Shell core and hot box core-boxes.

TABLE 2 : IMPROVEMENT IN DIE LIFE WHEN CHANGING FROM WROUGHT TO CAST FORGING DIES

Forging Die	% Improvement in Die Life	
	No. 5 steel	5% Cr. steel
Hub Flange	50	80
Coal Pick	31	69
Connecting Rod	71	136
Coal Pick	116	280
Coal Pick	54	71

A substantial investigation into the use of cast dies for forging applications was undertaken by a French team of investigators (2). Several evaluations using different die steels and die configurations were conducted at different forges. Some of the results are presented below:

SPIDER TRANSMISSION FORGING

Two sets of cast dies provided die lives of 22,150 and 19,900 respectively compared with the average wrought die life of 9,500.

HUB FORGING

Three sets of cast dies were used in service and provided die lives of 5,000, 6,200 and 8,600 (an average of 6,600) in comparison with the average wrought die life of 5,800.

One of the trials conducted compared die lives for cast dies with ascast impressions, cast die blocks with machined impressions, and wrought die blocks with machined impressions. Results were reported for two forgings:

LARGE WHEEL HUB

	average die life
wrought die	3,500
cast die - machined impression	7,500
cast die - ascast impression	8,122

WHEEL HUB

	average die life
wrought die	3,500
cast die - machined impression	6,932
cast die - ascast impression	4,356

Trials at the Simca forge were conducted using cast dies produced by both the Croning (shell mould) and Shaw process. In these trials all the die impressions were finished to size by electric discharge machining (EDM).

SYNCHRONISATION RING

wrought die	5,000
cast dies	5,541

FIXING PLATE

wrought die	5,000
cast dies	4,556

The French investigation concluded that improvements in die life figures of from 30% to 100% were possible if cast dies were used in preference to wrought dies.

Many papers have been published on the use of precision cast dies in the forging industry in the USA. Typical of these is one by Stutzman (9) which provides twelve case studies on the successful introduction of cast dies in place of wrought dies. Die life improvements gained by using cast dies ranged from 20% to 150% when the cast and wrought dies had been produced from similar steels and had similar heat treatment.

Work conducted in Japan at the Riken Piston Ring Co. (10) indicated that cast forging dies produced by the Shaw process were at least as good as wrought dies and in some cases better. The service life of cast dies was on average 50% longer than for wrought dies. In work carried out at the Toyo Kogyo Co. in Japan and reported by Murao and Mino (3) the Shaw process was used in the manufacture of diecasting dies. The cast dies were used to produce a range of

automobile components in aluminium alloys and included a transmission cover, clutch housing, and a timing gear case. Comparative figures for wrought die lives were not included in the report. The performance of cast dies, as reported, is presented in Table 3.

TABLE 3 : DIE LIFE FIGURES FOR CAST DIECASTING DIES

Diecasting Die	Die Weight (kgs)	Die Life (no. of shots)
Master Cylinder Piston	45	134,115
Rocker Arm Shaft Supporter	18	111,988
Transmission Top Cover	105	33,332
Clutch Housing	100	65,000
Timing Gear Case	96	19,500

METALLURGICAL QUALITY

The reported improvements in die lives when cast dies have been used to replace wrought dies indicate the high degree of integrity of the surface available in these cast components. The production of high quality precision castings in die steels requires careful control of metal processing. Casting temperatures need to be firmly established to avoid adversely affecting dimensional accuracy (11) and casting soundness. Feeding requirements; the use of feeding aids, and gating techniques need to be determined to ensure that sound castings, free from inclusions, are produced. Grain refining additions may be used to improve strength and reduce the severity of subsequent heat checking of the die in service (12). Die steels containing chromium must be processed correctly to ensure that surface defects associated with high chromium contents are eliminated and that surface decarburisation, which can result in early die wear, is controlled (13). The application of non-destructive testing techniques enables the founder to guarantee the integrity of the castings produced.

However, the production of a high integrity cast die, although guaranteed free from defects, is not in itself a sufficient reason for the improved die lives reported. Die life has been the subject of investigation and a number of

metallurgical reasons for the improved performance of cast dies have been suggested. An investigation of factors affecting heat checking revealed that although heat checks propagate in a similar manner in both cast and wrought dies, in cast dies they extend into the casting to a shallow depth and then stop. It is suggested that the lack of directionality in the grain structure of castings is a significant factor (14). The non-directional grain structure of the cast die material is also claimed to reduce residual stresses within the die and as a result castings do not warp or distort during heat treatment to the extent that wrought dies do (12).

Metallurgical investigations comparing the properties of cast and wrought H13 die materials have been the subject of papers by Stutzman (9, 15, 16). Extensive tests were undertaken on precision cast and wrought material at room and elevated temperatures. The room temperature results of ultimate tensile strength and yield strength were similar for both materials but the reduction of area and % elongation test results were significantly lower for the cast material. The difference in values of ductility was less pronounced in the tests carried out at temperatures of 480°C and 590°C, and negligible at temperatures of 650°C and 705°C. At these latter temperatures the ultimate tensile strength and yield strength values for the cast material were slightly higher than those for the wrought material. Of note was the existence of a true yield point in the cast samples which shows that heat treated precision cast tool steel is not brittle.

The impact strength, measured by the Charpy V notch test, of the cast material was appreciably lower than the wrought material when tested at both room and elevated temperatures but there was no evidence of a brittle fracture. Fatigue tests indicated that wrought steels were inferior to the cast material when notched specimens were used. However, with unnotched specimens the wrought specimens were much superior.

Hot hardness tests conducted on material which had been heat treated to give a hardness value of Rockwell C40 and C52 indicated that the cast structure is superior to the wrought structure:

At 315°C to 425°C	the cast material was	1 RC harder.
" 540°C	" " " "	2-4 RC harder.
" 590°C to 650°C	" " " "	8 RC harder.

It was considered that alloy segregation inherent in the interdendritic regions of cast structures might be beneficial in resisting tempering effects at higher temperatures. In order to assess this, specimens heat treated to RC 50 were tempered for 100 hours at various temperatures. After tempering, the specimens were cooled to room temperature for hardness determination. The results are shown in Table 4, from which it can be seen that the cast specimens were consistently harder.

TABLE 4 : THE EFFECT ON HARDNESS OF PROLONGED EXPOSURE
AT HIGH TEMPERATURE

Exposure Temperature for 100 hours ($^{\circ}\text{C}$)	Hardness RC		Difference (cast-wrought)
	Wrought	Cast	
room temperature	50.2	50.8	0.6
540	45.3	48.5	3.2
590	29.0	31.8	2.8
650	22.7	24.5	1.8
705	20.1	21.3	1.2
760	13.9	16.8	2.9

The comparison of wrought and cast micro structures at a magnification of X 500 did not reveal any significant differences. However, at a magnification of X 7600 it is apparent that the cast structure has carbides more evenly dispersed throughout the material whereas in the wrought material the carbides are larger and situated at grain boundaries. It is considered that the structure of the cast material reduces wear at service temperatures and therefore contributes to the improved die life of cast dies.

DIMENSIONAL ACCURACY

Detailed information about the dimensional accuracy of precision cast dies is not readily available and one must assume when reading the literature that because cast dies were used in production their dimensional accuracy must have been satisfactory. The Czechoslovakian work (7) indicated that as cast dimensions were produced to within 0.3 mm (0.012 ins) without detailing actual dimensions. Jones (8) gave very little specific detail, although some details were specified for a hub flange forging cast die insert. This insert had external dimensions of 133 mm (5.25 ins) diameter and was 76 mm (3 ins) thick.

The cavity dimensions of 46 mm (1.8125 ins), 57 mm (2.25 ins) deep with a 76 mm (3 ins) square base were produced with a maximum dimensional discrepancy of 0.08 mm (0.003 ins) which, as it was undersize, was easily corrected.

The report of the work at Toyo Kogyo (3) concluded that precision casting of diecasting dies to close tolerances is a technically demanding process, in particular with regard to an accurate prediction of contraction allowance. This is particularly so in the case of larger dies although small dies can be cast very precisely. Dimensions were quoted for a four impression die having external dimensions of 360 mm x 270 mm x 70 mm (14 ins x 10.5 ins x 2.75 ins) in which the cavity dimensions were within 0.05 mm to 0.18 mm (0.002 ins to 0.007 ins). The Riken report (10) suggested that a finishing allowance of 0.05 mm/25 mm (0.002 ins/in) should be sufficient for the impressions in forging dies provided that the contraction allowance was accurately predicted.

The French team (2) did not provide many details of dimensional accuracy and concluded that it was preferable, from an economic viewpoint, to produce a casting of the impression with an acceptable precision, and to finish this impression by means of an orthodox process removing 0.1 mm to 1.0 mm (0.004 ins to 0.040 ins) at different points of the impression, rather than try to produce a precision casting to exact dimensions. American workers appear similarly reluctant to quote actual dimensions and prefer to quote general process tolerances. Typical values for Shaw process castings are given below (17):

For dimensions up to 25 mm	(1 in)	± 0.08 mm (± 0.003 ins)
" " between 25 mm - 75 mm	(1 in-3 ins)	± 0.13 mm (± 0.005 ins)
" " " 75 mm - 200 mm	(3 in-8 ins)	± 0.38 mm (± 0.015 ins)
" " " 200 mm - 375 mm	(8 in-15 ins)	± 0.76 mm (± 0.030 ins)
" " over 375 mm	(15 ins)	± 1.14 mm (± 0.045 ins)

For dimensions across the parting line of the mould an additional tolerance of between ± 0.25 mm to 0.50 mm (0.010 in to 0.020 in) must be provided. Surface finish values of 2 micrometres (80 microinches) c.l.a. can be obtained compared with values of 5 to 10 micrometres (200 to 400 microinches) for sand moulded castings.

SUMMARY

To summarise, the precision casting process is suitable for the production of cast dies of high metallurgical quality and capable of providing die lives as good, or better, than dies machined from wrought material. Dimensional accuracy poses the greatest problem to the founder and producing dies 'cast to size' is a very demanding technical exercise. However, the production of 'cast to shape' dies which incorporate a pre-determined finishing allowance is a task which is easily accomplished by the competent precision foundry. The die user must determine carefully which is the more economical route to a finished die, the precision casting route or the traditional diemaking route. Certainly the precision casting route should be given ample consideration.

RESEARCH AT LOUGHBOROUGH

The authors are currently engaged on a research project on the optimisation of materials and methods in the production of precision cast tooling, which is financed by the SRC under the auspices of the Die and Mould research programme. The SRC programme is not restricted to precision casting. It covers electric discharge machining, electrochemical machining, heat treatment, surface coating, heat transfer, computer aided design, and the economics of die and mould manufacture.

The project at Loughborough is directed towards the establishment of methods and procedures for the production of precision cast tooling and to an independent assessment of the degree of accuracy attainable in the cast product. A comparison of the surface integrity of as cast surfaces and EDM surfaces is also included in the programme. To this end cast tools are being produced to specifications prepared by companies co-operating with the research programme. Casting trials have yet to be completed and involve the production of three tools in H13 die steel:

1. A retractable diecasting die core incorporating a cast thread.
2. A drop forging die for the production of a flange yoke transmission forging.
3. A drop forging die for the production of a spider transmission forging.

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The Shaw Process—a Review

By A. J. Clegg*

The Shaw Process is a precision casting process suitable for the production of castings in a wide range of casting alloys. This article reviews the factors of importance in the production of moulds and castings by the Shaw Process. In particular, the author considers the binder system, refractory aggregates, moulding procedure, and metallurgical and dimensional quality of steel castings produced by the process.

The Shaw Process is a precision casting process capable of the production of accurate castings with excellent surface finish and metallurgical integrity. Moulds are produced using highly refractory aggregates bonded with silica provided by a liquid ethyl silicate binder. A high temperature firing treatment is a feature of the production sequence and this produces an inert mould into which the majority of commercial ferrous and non-ferrous alloys can be cast with confidence.

The process has been used commercially for many years; it was known before the Second World War that silicon esters could be used as refractory aggregate binders¹. As with most processes there has been a continuous development, in particular with respect to the binder system and the methods of mould production. Many of these developments are the subject of patents and much of the technical information has been restricted to Shaw Process licensees. As a result, the process may not have received the interest and support by the UK foundry industry that its qualities deserve.

At a time when there is an increasing demand for castings with guaranteed quality, dimensional accuracy and metallurgical integrity, it may be appropriate to consider the possibilities that the Shaw Process offers.

Outline of the Process

The mould material is prepared by blending refractory powders, containing a high proportion of fine material, with a liquid ethyl silicate binder and a gelling agent. Careful selection of the refractory material results in two particular advantages:

- 1 The fine grains of refractory material provide a smooth surface finish on the resultant casting.
- 2 The selection of a thermally stable refractory material ensures that the mould is not subject to

unpredictable dimensional changes in contact with the molten metal during pouring, thus enabling an accurate estimate of casting contraction to be made.

The blended, mobile liquid slurry is poured into the moulding box and around the pattern. Within a short period of time, controlled by the amount of gelling agent, the mould material gels to a rubbery consistency and the pattern can be separated from the mould. The nature of the process permits certain benefits to be gained at this stage:

a Pouring a liquid slurry around the pattern ensures a high degree of contact and therefore accuracy and intricacy in the final casting.

b The mould material sets in contact with the pattern and consequently produces a mould which accurately reproduces the pattern detail.

c The rubbery nature of the mould allows the pattern to be withdrawn without distortion to the mould, thus maintaining the dimensional accuracy of the mould cavity.

On removal of the pattern the moulds are either torched immediately to remove evolved alcohol (Shaw Process) or immersed in a stabilising bath

Das Shaw-Verfahren—eine Übersicht von A. J. Clegg

Das Shaw-Verfahren ist ein Präzisionsgussverfahren, das für die Herstellung von Teilen in einer grossen Auswahl von Gusslegierungen geeignet ist. In diesem Artikel werden die bei der Herstellung von Formen und Gussteilen nach dem Shaw-Verfahren wichtigen Verfahren beschrieben. Insbesondere betrachtet der Verfasser das Bindesystem, Zuschlagstoffe für das Feuerfestmaterial, Formverfahren und die metallurgische und dimensionale Qualität von Stahlgussteilen, die nach diesem Verfahren hergestellt werden.

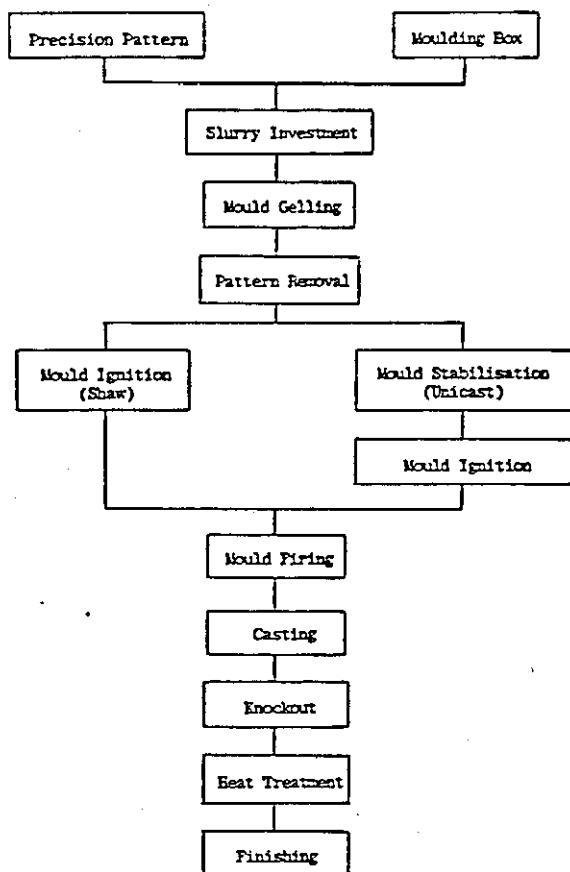
Etude sur le procédé Shaw par A. J. Clegg

Le procédé Shaw est une méthode de moulage de précision convenant à la fabrication de pièces en un grand choix d'alliages. Cet article examine les principaux facteurs qui influencent la fabrication des moules et le moulage des pièces par le procédé Shaw. L'auteur se penche en particulier sur les liants, les agrégats réfractaires, l'opération de moulage et les propriétés métallurgiques et dimensionnelles des pièces réalisées par ce procédé.

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THE SHAW PROCESS—A REVIEW

prior to torching (Unicast Process)². Torching produces a very fine crazed surface and interior structure which does not affect the casting surface, ie there is no metal penetration into the fine cracks, but may improve permeability to allow the escape of air/gases during casting. After torching the moulds are fired in a furnace to a temperature of 1,000°C, which ensures that there are no combustible materials in the mould and that a strong, rigid, inert, accurate and stable mould is produced. The stages in the production of a casting by the Shaw Process are outlined in the flow diagram presented in fig. 1.



1 Stages in the manufacture of a casting by the Shaw Process.

The advantages claimed for moulds manufactured by the Shaw Process include the following³:

- 1 Good pattern stripping characteristics: the rubbery nature of the gelled mould provides flexibility to the mould, which enables the pattern and mould to be separated without damage to the mould when intricate detail, or even straight draws, are required.
- 2 Dimensional stability: the excellent reproduction of pattern detail and dimensions is retained by the mould to a great extent after firing and during casting,

thus enabling accurate dimensional allowances to be made.

- 3 Mould strength: this is sufficient to allow moulds to be cast without the need for moulding boxes.

- 4 Collapsibility and resistance to tears: the characteristic internal structure of the mould material improves its breakdown properties and there is less constraint of the casting during contraction.

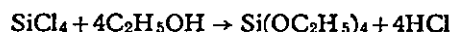
- 5 Resistance to thermal shock: the characteristic internal structure permits expansion of the mould material to occur readily, as a result moulds can safely be poured cold.

- 6 Resistance to spalling and washing: the nature of the silica bond prevents the generation of inclusions during mould filling.

- 7 Permeability and inertness: as the mould is inert after firing the only gas to be displaced is that occupying the mould cavity. The characteristic structure provides sufficient permeability to enable the metal to readily displace the gas through the mould.

The Binder

Ethyl silicate is an organic-based silica binder that is free of those alkaline salts which reduce the refractoriness of mould materials. It is produced by reacting silicon tetrachloride (SiCl₄) with ethyl alcohol⁴:



and it is important to remove the hydrochloric acid so that subsequent gelling characteristics may be easily controlled. If industrial ethanol, which invariably contains some water, is used as an alternative to the pure ethyl alcohol, the product obtained is a mixture of tetraethoxysilane and ethoxypolysiloxanes. Tetraethoxysilane contains approximately 28% silica by weight, whereas the ethoxypolysiloxanes which contain an average of up to five silicon atoms per molecule contain 40% silica⁵. This product is known as technical ethyl silicate and because of its higher silica content is generally preferred for use in the foundry industry⁶.

Hydrolysis

Ethyl silicate is a stable substance with no binding ability. It is necessary to hydrolyse the solution and cause it to react with water in order to produce a solution which will deposit the adhesive form of silica desirable for bonding refractory aggregates⁷. Ethyl silicate and water are immiscible unless a mutual solvent such as ethanol is used⁸ and it also serves to dilute the solution to the desired silica content. The hydrolysis may be carried out under either acid or alkaline conditions⁴. However, alkaline conditions usually result in fairly rapid gelation and consequently acid hydrolysis is preferred for foundry requirements. The preferred acid is hydrochloric acid although sulphuric or phosphoric acid are suitable⁸. The acid hydrolysates prepared in this manner have a very good storage life and are marketed as prehydrolysed ethyl silicates which are ready for direct use in the foundry.

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Gelation

In order to bind the refractory aggregate the ethyl silicate hydrolysate must be made to gel. It is the gel which provides the bonding action by two methods⁸:

a Air drying bond:



b Precipitation bond:



Upon heating, the silicic acid or silica gel binders condense to form a refractory silica cement. It is this silica form which provides the high strength developed by firing.

There are many ways of promoting the gelling of an acid hydrolysed ethyl silicate using the principle of pH control⁷. Hydrolysed ethyl silicate solutions are usually prepared with a pH value of between 1.5 and 3.0, at which they are relatively stable, they are also stable at pH values above 7.0. They are inherently unstable at pH values between 5.0 and 7.0. By adding an alkaline agent to the hydrolysed ethyl silicate solution the pH value of the solution can be increased to a value of 5.0 when the binder becomes unstable and gels. Ammonia, ammonia salts—acetate, carbonate, hydroxide; or organic ammonia salts—piperidine, morpholemar, triethylamine, may be used for this purpose. The actual time for gelation will depend on the particular application and can be varied by adjusting the amount of gelling agent addition.

If accurate control of setting time or a very long setting time is required use may be made of organotin catalysts⁸. The organotin catalysts enable hydrolysis and gelation to proceed readily in the absence of either acid or base. By a special heat treatment process the gelation characteristics can be altered to change the gel time when water is added.

Refractory Aggregates

Many refractory materials may be used in association with ethyl silicate to produce Shaw Process moulds, the list in Table 1 includes many of the possible materials but is not exhaustive. In the selection of a suitable material for a particular application the following factors must be considered:

- 1 Purity
- 2 Refractoriness
- 3 Stability
- 4 Thermal Expansion
- 5 Thermal Conductivity
- 6 Particle Size and Distribution
- 7 Cost

The mould material must be sufficiently refractory to withstand the pouring temperature of the particular metal being cast, without either melting or softening.

TABLE 1: Refractory materials suitable for use in the Shaw Process

Material	Chemical Notation	Melting Point °C
Magnesia	MgO	2,800
Zirconia	ZrO ₂	2,677
Calcia	CaO	2,600
Zircon	ZrO ₂ . SiO ₂	2,420
Calcium zirconite	CaO. ZrO ₂	2,345
Magnesia spinel	MgO. Al ₂ O ₃	2,135
Alumina	Al ₂ O ₃	2,015
Mullite	3Al ₂ O ₃ . 2SiO ₂	1,830
Fused silica	SiO ₂	1,723

The melting point value is a good guide to refractoriness providing the material is pure, as very small amounts of alkali metal salts or iron oxide can reduce melting points severely. The refractory selected should exhibit stability, it should not be susceptible to hydration, or reactions with other materials in the mould or the metal. Thermal stability is also important, expansion is inevitable; however, providing that it is predictable, ie constant and reproducible, it can be taken into account when estimating contraction allowance.

Thermal conductivity is in part a property of the material selected but it is also a function of particle size and distribution when that material is used to produce a porous, particulate mould. The property does influence the rate of solidification and heat transfer through a mould which may have an influence on metallurgical integrity.

Cost is a major factor in refractory material selection and is affected by such factors as availability, purity and particle size requirement.

Moulding Mix Specification

The secret of successful mould production and quality castings lies in the mould material mix specification. It is essential to balance the grades of refractory material with the volume of binder and amount of gelling agent in order to produce moulds of consistently high quality. Shaw Process slurry preparation is critical⁹, too thin and mould cracking will occur on firing, too thick and detail is lost and air bubbles are trapped at the pattern surface.

When selecting the grades of refractory material to be used the principles which apply to sand moulding can be used as a guide. Surface finish will be improved when finer material is used; however, permeability will decrease and binder requirement increase as a consequence. The strength, measured conventionally by AFS compression and tensile strength, will also be affected by grade selection. Strength will be at a maximum when refractory grades are selected on the basis of using several size gradings which permit infilling of the voids between larger grains by the smaller⁷, this is also the most economic way of using the binder. Mix specification is inevitably a compromise between theoretical considerations and practical requirements but a reading of standard ceramic texts^{10,11} can be invaluable.

Experimentally determined values¹² of strength

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TABLE 2: Tensile strengths of mullite mixes bonded with silester AR

Refractory material and size grading	cc. of binder per kg. of refractory	AFS Tensile Strength (lb. per sq. in.)			
		Before firing		After firing at 1,000 C	
		air dried	torched	air dried	torched
1. 100%—300, mesh mullite	456	—	2.0	—	5.6
	422	—	2.7	—	6.0
	400	5.3	2.7	21.0	5.3
	356	—	3.0	—	7.3
	333	9.3	3.2	37.0	8.3
	311	—	3.4	—	11.0
2. 30%—16/30, 30%—30/60, 40%—300, mesh mullite	267	—	9.0	—	16.7
	222	—	10.7	—	22.7
	178	—	11.8	—	28.3
	—	—	—	—	—

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which emphasise some of these points are shown in Table 2.

Mould Production and Processing

As a principal advantage of the process is its ability to produce castings to consistent and close dimensional tolerances it is essential that patterns and mould locating equipment be produced to a high standard of accuracy.

Pattern Equipment

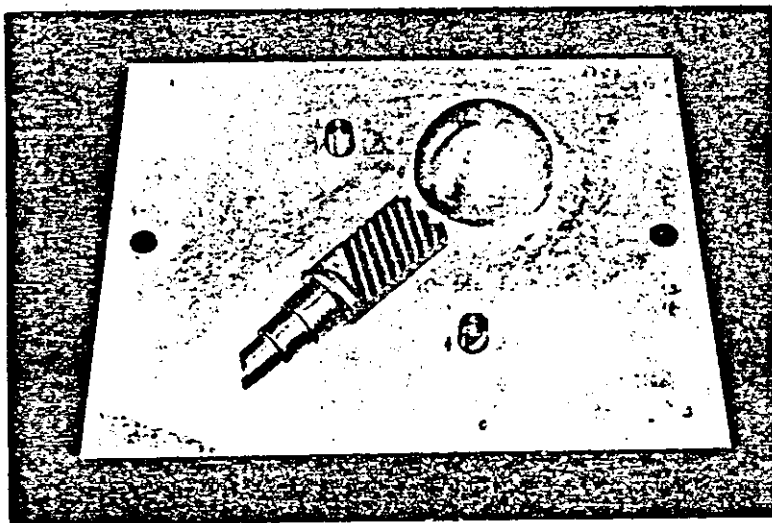
As a casting cannot contain more detail or be more accurate than the pattern from which it was made, it follows that particular attention must be paid to pattern construction and quality. The Shaw Process utilises permanent pattern equipment and in principle a wide range of materials may be used¹³; wood, plaster, graphite, epoxy resin and metal for examples. However, in practice the requirement for high standards of accuracy reduces the choice. Wood patterns are affected by heat and moisture and their

dimensions can vary by as much as 3", which would severely affect accuracy¹³. Plastic resin patterns may also be subject to distortion when used in conjunction with the Shaw Process⁹. To achieve good dimensional accuracy polished metal patterns are preferred for which aluminium alloys are particularly suitable. Fig. 2 shows an example of a precision aluminium pattern plate assembly and a graphite pattern. Patterns are normally coated with a release agent, for example a 10% solution of paraffin wax in benzene¹⁴, or similar proprietary products and, if sparingly applied and well buffed, pattern release from the mould presents no problem.

Mould Production

Shaw Process moulds may be produced by one of several alternative methods: for small components a ceramic shell is quite acceptable, for larger components a boxless block mould is suitable. If the mould is very large or if demand for a particular casting is great and it is desirable that mould material costs be reduced, a composite mould can be produced. In this case the facing material is Shaw-based but the backing material might be sodium silicate bonded. For mass production applications the process, in each of these forms, lends itself to mechanisation and rapid output of moulds.

In the production of composite moulds, an example of which is shown in fig. 3, additional pattern requirements in the form of a pre-form pattern may be necessary. These may be produced in wood as their purpose is only to produce an oversize cavity in the backing mould. This mould is then positioned over the precision pattern and the gap filled by introducing the mobile Shaw slurry. Permanent pre-form patterns are not essential, the required effect can be obtained by covering the precision pattern with a thickness of material such as oil-sand, CO₂ sand, felt, etc.¹⁴⁻¹⁷ which will permit the oversize backing mould to be produced. To ensure that separation of the backing and facing layers does not become a problem the mould materials selected for the backing and facing layers should have similar thermal expansion



2 Precision aluminium pattern plate assembly and graphite pattern.

characteristics. Permanent metal backing moulds are also suitable¹⁸.

Mould Processing

When the mould has been separated from the pattern it must pass through several stages which can exert a significant influence on the quality of the finished mould. The craze cracking effect in Shaw Process mould material is only produced when ignition follows immediately after pattern stripping. When the mould material is allowed to air-dry for a substantial period the craze cracking does not develop. It is interesting to note that the strengths developed by firing are considerably higher in the air-dried material—but at the expense of permeability, thermal shock resistance and breakdown characteristics¹⁹. See Table 2.

Coarse cracking may be a problem at internal corners in a mould cavity, particularly if pools of alcohol are allowed to form. Sharp corners are unsuitable in most casting designs and a minimum radius of three millimetres is recommended where practicable. The evolved alcohol usually ignites readily but ignition can be encouraged by the use of a gas/air torch, in either case the moulds should stand on a grid to provide free access of air during ignition.

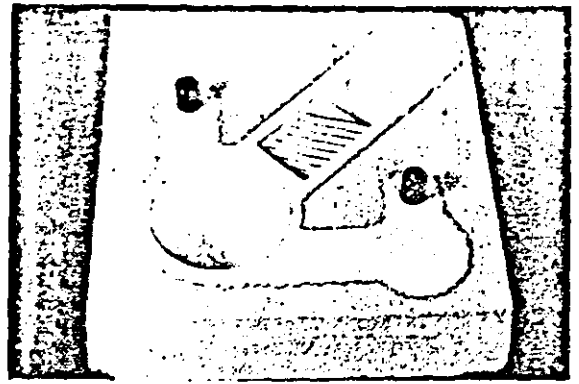
A further variation in practice exists in the Unicast Process when the separated mould is immersed in a bath of stabilising liquid before torching and subsequent firing². It is claimed that stabilisation for a period of one hour in a bath containing ethyl alcohol, for example, will improve the dimensional stability and strength of the mould. Small moulds can be enclosed within sealed plastic bags to enable stabilisation to occur²⁰.

After torching moulds are fired for two reasons:

- a To burn off any residual organic material and remove any moisture in order to produce an inert mould.
- b To improve mould strength through a sintering effect.

A considerable range of baking or firing temperatures, from 300 to 1,300°C, is suggested in the literature. Whereas the first objective should be met by "firing" at 500°C, it is unlikely that any substantial improvement in strength will be obtained with a sintering temperature below 1,000°C. Slightly oxidising conditions are recommended²¹ when firing moulds to encourage the burning of residual volatiles. Composite moulds present their own difficulties, with radiant heating in tunnel furnaces being preferred to fire the facing material without excessively heating the backing material²².

Moulds may subsequently be cast whilst still hot or allowed to cool, depending on section thickness and metallurgical requirements. Mould part location in boxless moulds is most easily obtained by making provision for mould locating pins at the pattern-making stage. This is illustrated in fig. 3 which shows the use of double-ended taper location pins. Mould joints are sealed externally with a luting compound, joint face seals reduce accuracy across the joint, and moulds may be weighted or clamped using metal bands before casting.



3 A composite mould with Shaw Process facing and sodium silicate bonded backing. Note mould location pins.

Casting Quality

The quality of a precision casting is judged using three major parameters:

- 1 Dimensional accuracy.
- 2 Surface finish and appearance.
- 3 Metallurgical integrity.

Dimensional Accuracy

The dimensional accuracy of any casting is determined by the accuracy of the pattern equipment and by the accuracy with which mould parts are located. It is inevitable that closer dimensional tolerances can be maintained within a single mould half than can be held in dimensions across the mould joint. The mould material also exerts an influence on dimensional accuracy, first through its thermal characteristics, and second through permeability. Neither of these factors can be disassociated from metal temperature which has been shown to exert a major influence on dimensional accuracy²³. Variations in melt composition may also result in dimensional variations but with careful melting practice this should be a minor influence. As a safety precaution it has been suggested that matching castings, eg die half castings be cast from the same melt²⁴.

Typical dimensional tolerances suggested for steel castings produced by the Shaw Process are²⁵:

- For dimensions up to 25 mm. (1 in.)
± 0.08 mm. (± 0.003 in.)
 - For dimensions between 25 and 75 mm. (1–3 in.)
± 0.13 mm. (± 0.005 in.)
 - For dimensions between 75 and 200 mm. (3–8 in.)
± 0.38 mm. (± 0.015 in.)
 - For dimensions between 200 and 375 mm. (8–15 in.)
± 0.76 mm. (± 0.030 in.)
 - For dimensions over 375 mm. (15 in.)
± 1.14 mm. (± 0.045 in.)
- For dimensions across the mould joint line an additional tolerance of between ± 0.25 to 0.50 mm. (0.010 to 0.020 in.) should be allowed.

Surface Finish and Appearance

The surface finish of a casting produced using the Shaw Process is influenced by several factors which

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include refractory grading, metal and mould temperature, and metal/mould reactions considered in the following section. The finer the grade of refractory filler used in the refractory aggregate the better should be the surface finish. Preheated moulds and high casting temperature are likely to reduce the quality of surface finish²⁶. It is possible to obtain surface finish values in the region of two micrometres (80 microinches) cla for steel castings, better for non-ferrous alloys, which compares with five to ten micrometres (200–400 microinches) cla for sand castings.

Heavily oxidised surfaces reduce both dimensional accuracy and the quality of surface finish directly and through the requirement for abrasive shot blasting. The use of inert gas atmospheres to minimise these effects can be worthwhile.

Metallurgical Considerations

The nature of the Shaw Process mould material results in relatively slow cooling of the metal in comparison with other casting processes. This can cause a coarse grain structure which may be unacceptable in certain castings' applications; it can be countered by grain refining additions. The slow cooling is in part responsible for decarburisation and surface oxidation in steel castings²⁷. In steels containing chromium the surface may be further affected by pitting²⁸.

Decarburisation has been shown to be a function of the time that the casting remains at an elevated temperature, that is above 875°C²⁷. In practice the severity of the problem can be reduced by one of several methods which include: hexamethylene tetramine placed on the exposed surface of the metal when the mould is enclosed within a container²⁹, a reducing gas atmosphere³⁰, or most effectively by a vacuum treatment to remove air from the mould followed by back filling with an inert gas²⁷. The occurrence of pitting has been shown to be associated with decarburisation²⁸. The two phenomena are caused by carbon monoxide formation. Carbon in the metal reacts with oxygen from the mould atmosphere and the silica which provides the mould bond. This results in decarburisation and the carbon monoxide bubbles deform the casting surface. This implies that it may not be possible to eliminate decarburisation entirely because oxygen will always be present in the silica which provides the bond.

It has been suggested that casting surface characteristics can be altered by passing a gas through the mould material as a steel casting is cooled. By using ammonia³¹ a nitrided surface can be developed and a carburised surface produced by using a carbon rich atmosphere²¹.

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