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A practical assessment of spraying and welding processes for the hard-facing of grey cast iron

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A PRACTICAL ASSESSMENT OF SPRAYING AND
WELDING PROCESSES FOR THE HARDFACING
OF GREY CAST IRON

by

D. WOMERSLEY

A thesis submitted in partial fulfilment of
the requirements for the award of the degree
of Master of Philosophy of the Loughborough
University of Technology

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ACKNOWLEDGEMENTS

Acknowledgements

The author wishes to thank the following:

Dr. N. P. Fletcher, acting Director of the Centre for Industrial Studies, for his permission to undertake the investigation, also for his help and encouragement.

Dr. A. J. Clegg, for his guidance, advice and encouragement.

Mr. R. E. Phelps, for his continual support.

Technical Tutors in the Centre for Industrial Studies especially Mr. C. Wood and Mr. G. Corliss for their expertise in casting and grinding.

Technicians Mr. D. Hurrell and Mr. T. Smith for their help with the photography.

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SYNOPSIS

SYNOPSIS

Billions of pounds are lost every year in industry through worn parts and wastage of materials. By applying hardfaced coatings to parts or components most subjected to breakdown through wear, their working lifetime can be extended. The literature survey on hardfacing showed that very little work has been conducted on the hardfacing of cast iron despite the fact that this is the most widely used cast material. For this reason a grey cast iron conforming to BS 1452 : 1977 and in general use in: Agriculture, Aircraft, Automotive, Construction, Foundry, General Engineering, Mining, Nuclear, Oil, Power Stations and Railways, was selected for the investigation.

In many of the applications for which cast iron is used wear may result in the need to replace the casting. The cost of replacing a single component which has failed can be high for several reasons. To minimise costs, the component user would wish to hold minimum or no stocks. The foundry would charge a higher cost for a one-off casting to recover set-up costs and potential scrap, costs which would be absorbed over longer production runs. In addition there would be a delay factor in obtaining a replacement casting which would lead to a down time cost. For these reasons and those related to the more efficient use of materials, it was considered that the methods for producing hardfaced coatings on cast iron, and their characteristics, was worthy of investigation.

The thesis reports the results of an investigation into the potential-assessment of spraying and welding processes for the hardfacing of grey cast iron to resist abrasive wear. With grey cast irons having a relatively low melting temperature it

was necessary to find a low melting temperature hardfacing alloy to avoid certain constituents, such as graphite, from being burned out of the cast iron. The hardfacing alloy chosen to meet these requirements was a nickel-chromium-boron alloy which is commercially available in powder and "as cast" rod form and offers good hardness and abrasion resistance. It was also necessary to find the appropriate spraying and welding processes to deposit the hardfacing alloy onto the cast iron. The processes finally selected for consideration were:

1. Thermal spraying
2. Powder spray welding
3. Oxy-acetylene welding
4. Tungsten inert gas welding (TIG)

The programme for the research was divided into two stages:

1. The assessment of the procedures and technique for spraying and welding.
2. The assessment of the deposited hardfacing alloy for abrasion resistance and hardness.

The thesis reports in detail the application procedures and techniques considered to be the most suitable for spraying and welding the Ni - Cr - B alloy onto a grey cast iron. In addition the thesis reports the assessment of the quality of one layer and two layer deposits for abrasion resistance and hardness. The abrasion resistance was determined using a reciprocating diamond scratch testing machine. The results were obtained in the form of "wear volume" which is proportional to the width of the scratch. A statistical analysis, based on the standard error of the mean, was carried out on the wear test results to show if any significant differences occurred when each of the four processes were compared one with-another.

The hardness of the coating can be affected if the alloy is diluted by the substrate, consequently it was necessary to measure the hardness of the coating with the following tests:

1. Surface hardness
2. Macro hardness across the interface of the hardfaced deposits, bond area and substrate.

The surface hardness results were also tested by statistical analysis to see if any significant differences occurred when each of the four processes were compared one with another.

The above hardness tests were complemented by Electron Probe Microanalysis (EPMA) which measured the percentage of elements across the deposit/substrate interface and provided an indication of the presence and degree of dilution of the hardfacing alloy by the substrate.

It was also considered that an optical microscopy study of the interface should be conducted to provide information about the integrity of the interface.

From the overall results of the investigation it would appear that the Powder spray welding process provided the best wear resistance closely followed by the Thermal spraying process, Oxy-acetylene welding process and the TIG welding process.

The spraying processes provided a more controlled, thinner coating with a smoother surface finish and low to negligible dilution of the hardfacing alloy with the cast iron substrate. The coatings required very little surface grinding to provide a smooth surface and would be particularly suited to close tolerance engineering applications. The wear resistance and hardness of the coatings appeared to be good on both one layer and two layer deposits.

The welding processes showed a thicker, rougher surface

finish with a minimum of dilution and distortion on the two layer deposits. Heavy surface grinding was required to provide a smooth finish. The wear resistance and hardnesses of the coatings were not good especially on the one layer deposits, the reason for this appeared to be dilution of the hardfacing alloy with the cast iron substrate.

The welding processes would be particularly suited to where thicker coatings are required.

INTRODUCTION

INTRODUCTION

This investigation has the objective of establishing the practical procedures for optimising the abrasion resistance of hardfacing coatings on grey cast iron. Grey cast iron, conforming to BS 1452 (1), was chosen because it is the single most important cast material and a survey of the literature showed that, although work has been conducted on steel substrates, little research has been conducted into the hardfacing of cast irons. Cast iron has many fields of application such as:

Agriculture, Aircraft, Automotive, Construction, Foundry, Mining, Nuclear, Oil, Power Stations and Railways.

In many of these applications wear may be a problem which requires the replacement of castings or where possible, the reclamation of these castings. The cost of replacing a single component which has failed can be high for several reasons. To minimise costs, the component user would wish to hold minimum or no stocks. The foundry would charge a higher cost for a one-off casting to recover set-up costs and potential scrap, costs which would be amortized over longer production runs. In addition there would be a delay factor in obtaining a replacement casting which would lead to a down time cost. For these reasons and those related to the more efficient use of materials, it was considered that the methods for producing hardfaced coatings on cast iron, and their characteristics, was worthy of investigation.

Grey cast irons are available in seven grades, these are: 10, 12, 14, 17, 20, 23 and 26.

The cast iron used in the investigation had a composition within the following range: (2)

C 3.22% - 3.32%, Si 1.97% - 2.08%, Mn 1.56% - 1.66%,
P 0.104% - 0.137%, S 0.036% - 0.038%.

This composition produces a grey cast iron between grades 14 and 17 which have a tensile strength between 220 N/mm^2 and 260 N/mm^2 . Grey cast iron components can be seen in use in all the major industries such as:

Automotive Engineering, Chemical Engineering, Civil Engineering, Electrical Engineering, General Engineering, Iron and Steel industry, Marine Engineering, Mining and Textiles.

With grey cast irons having a melting temperature range of 1130°C - 1250°C , it was necessary to find a low melting temperature hardfacing alloy, to avoid certain constituents, such as graphite from being burnt out of the cast iron.

The hardfacing alloy to meet the above requirements was chosen from a list of Nickel-base alloys, which are commercially available in powder, as cast rod, tubular wire and flux coated electrode form. The alloy is a Nickel - Chromium - Boron alloy which has a relatively low melting temperature 964°C - 1003°C (3), compared to the grey cast iron substrate.

The Ni - Cr - B alloy also offers good hardness and abrasion resistance. It is easy to apply because it contains "self fluxing" agents, (4) and it is less expensive than its alternatives, for example Cobalt - base alloys (5 - 8).

After carrying out a literature survey on spraying and welding processes, it was found that the processes most suitable for depositing the Ni - Cr - B hardfacing alloy would be:

Plasma arc spraying

Thermal spraying

Powder spray welding

Manual Metal arc welding (MMA)

Tungsten Inert Gas Welding (TIG)

Oxy-acetylene welding

Metallic Inert Gas welding (MIG)

Plasma arc spraying is the most modern of all the spraying processes and is mainly favoured for the high melting temperature metals and alloys. (9) It has a fast deposition rate but the equipment is extremely expensive.

Thermal spraying is less expensive than the Plasma arc spraying and can be used to apply a variety of metal and alloyed powders at fast speeds. The process can also be made portable.

Powder spray welding equipment is portable and inexpensive. It uses a conventional oxy-acetylene welding blowpipe with a special powder feed attachment. The deposition rate is slower than the other two processes mentioned.

Manual metal arc welding (MMA) is a fast deposition process which uses flux coated electrodes and is mainly suited to building up heavy deposits. The process involves melting the parent metal in the fusion zone. The equipment depending on its size can be expensive and can be made portable.

Tungsten inert gas welding (TIG) is an alternative to the MMA process, with the advantage that the arc is not as forceful, therefore less severe compared with the MMA process. An "as cast" rod is deposited in an argon gas shield to prevent oxidation. The equipment is expensive but the process can be used for other welding applications. The equipment can also be made portable.

Oxy-acetylene welding deposits an "as cast" rod, like the TIG process. The process is sometimes described as braze welding (10), rather than fusion welding, because the parent metal does not become molten. The equipment is inexpensive and can gener-

ally be found in most welding workshops. It is portable and can easily be adapted to carry out spraying, welding, pre-heating and flame cutting.

Metallic inert gas welding (MIG) deposits a continuous tubular wire (7), with the alloy forming the core, which is shrouded in a gas shield. The deposition rate is very fast and involves melting the parent metal in the fusion zone. The equipment is expensive but by changing the wire and gas shield, it can be adapted to other welding applications. The equipment can also be made portable.

A major problem that occurs when depositing hardfacing alloys by spraying or welding is dilution, that is, of the hardfacing alloy by the substrate material. The dilution problem is greater with the arc processes because they melt the parent metal at the fusion zone. There are many factors that affect dilution. Evidently single layers of alloy will have a greater dilution than will multi-layers. The technique used to deposit the alloy can also affect the dilution for example, the greater the amount of weaving the greater the dilution (11). Dilution with the substrate material can cause a significant decrease in the hardness and wear resistance of the deposited coating.

The spraying and welding processes decided upon to deposit the Ni - Cr - B alloy in the investigation were:

Thermal spraying

Powder spray welding

Oxy-acetylene welding

Tungsten inert gas welding (TIG)

They were all selected for the following reasons:

1. The processes can be normally found in most welding workshops.

2. The equipment is not too expensive.
3. Dilution of the hardfacing alloy by the substrate can be kept to a minimum.
4. All the processes are or can be made portable.

Different application procedures and techniques, involving different levels of operator skills, are required for the deposition of hardfacing alloys by each of the above processes.

To take into account both the requirements for application procedures and the assessment of the wear characteristics of the coatings the experimental programme was divided into two sections.

1. The application procedures and techniques of the spraying and welding processes.
2. The assessment of the hardness and wear resistance (abrasion) of the Ni - Cr - B hardfacing alloy after deposition.

CHAPTER 1

LITERATURE SURVEY

CHAPTER 1

LITERATURE SURVEY

1.1 Hardfacing

Hardfacing is a process in which a layer of alloyed metal is deposited onto a softer and cheaper material, or substrate, to improve the wear resistance of the base metal (12).

Hardfacing extends the working lifetime of parts or components most subjected to wear and breakdown and hard faced surfaces can last up to five times longer (13) than unprotected surfaces, depending on the alloy used.

The use of surfacing materials to improve the wear resistance of parts against abrasion, impact and corrosion dates back to about 1906 (14).

1.1.1 Reasons for Hardfacing

The main reasons for hardfacing can be considered under three headings:

1. Economics
2. Reclamation
3. Coating new parts

Economics

In most circumstances, economic considerations dominate the justification for hardfacing. Ellis and Garrett (15) expressed surprise therefore, that economic criteria appeared to be the least well documented and most confusing aspect of hardfacing technology.

In 1966 a Government inquiry under Professor Jost (16) estimated that industry was losing more than £500 million per annum in worn parts because of its failure to appreciate

the problem and how it could be overcome. Twenty years later the estimates now exceed £2 billion (17). The total world costs for maintenance are enormous, to say nothing of the wastage of materials and energy and the depletion of metal and fossil fuel reserves, some of which will, by the year 2000, be in short supply (18, 19).

In view of the need for energy and materials conservation it seems more than likely that in the future composite materials, including those produced by welding, will be utilised increasingly to save on expensive and scarce metals (20).

Reclamation

The most common use of hardfacing is to build up worn areas on used components to improve their service life. This will enable production to be maintained for longer periods without shut down and, additionally, will improve the rate of production and the quality of the product (10).

Often the time taken to obtain a spare part is extended, so replacements must be ordered far in advance. If the life of the machine component is indeterminate, the spare may be in store for many years. Not only is working capital tied up, the related interest may be high and aggravated by the cost of space, stores handling, insurance etc. . A relatively small investment in surfacing equipment may make possible the repair of a vast array of production machines at short notice (17).

According to Shailles (21) it is possible to show in some cases a saving of as much as 50% for a part that has had its surface refurbished when compared to buying or manufacturing a new part.

Coating New Parts

Increasingly components are being hardfaced before being

put into service. Consequently, hardfacing may be considered as a production process, from the design stage, rather than merely a reclamation process (22). Many mechanical parts are made from costly sophisticated base metals, for example aluminium bronze gear box selector forks(23, 24) although only certain areas require specialised properties. By applying coatings, such as hardfacing alloys of superior wear resistance, to these areas, many such parts could be produced from inexpensive metals at a fraction of the cost (25) and without the need for heat treatment.

Design engineers must be educated in the need for materials conservation and the potential for improving component life by specifying techniques such as hardfacing.

1.2 Nickel - Base Alloys

Alloys containing about 75% nickel and 20% chromium, together with a few per cent of boron, have good corrosion and wear resistance (26). The hardness values of the deposited alloys generally range from 350 HV - 790 HV (27). They have extremely good hot hardness up to about 650°C, after which the hardness falls off rapidly due to their low melting temperature which ranges from 964°C - 1152°C (3).

Since their development the Nickel-base alloys have been manufactured in powder, "as cast" rod, tubular wire and flux coated electrode form. The powder, "as cast" rod and tubular wire can be bought commercially but the coated electrodes normally have to be made to order and bought in large quantities for them to be economical to manufacture.

Recently in Britain the alloys have been manufactured by continuous casting (5, 6) producing a close tolerance hardfacing rod in any length. This opens up for the first time

the use of the materials in mechanised welding processes.

Nickel-base alloys are mostly suited to powder and "as cast" rod, because they are the "self fluxing" type (4). The fluxing agents which are added to the alloy are boron and silicon. These fluxing agents have the ability to dissolve oxides of iron, nickel or chromium and form a hard, smooth protective film which prevents atmospheric oxidation.

All the Nickel-base "self fluxing" alloys are very low in ductility and they also have high thermal expansion coefficients. Consequently, in base materials having a low thermal expansion coefficient there is always a chance of cracking. During cooling, if the coating shrinks appreciably more or faster than the base material, high stresses develop and the ductility and elasticity of the coatings may not be enough to prevent cracking (28).

1.2.1 Applications of the Nickel-base Alloys

Because the alloys exhibit: good metal to metal wear; good low stress scratch abrasion; abrasion and corrosion resistance; and a retention of hardness at elevated temperatures (29); they are used for numerous applications. Typical applications for nickel-base hardfacing alloys are: (30)

Agriculture:- Bean and cane knives, drill shoes and scraper knives, plough shares and potato diggers.

Automotive and Aircraft:- Arrestor hooks, jigs and fixtures, cams, bearing surfaces, exhaust valves (diesel), rocker arms, water pump shafts.

Construction:- Cable drums, dredger pinion shafts, tractor sprockets.

Foundry:- Conveyor parts, mill guides, sand dredgers, shot blast equipment.

Mining:- Coal washers, pump impellers and spider rings.

Railways:- Flange tracks, shackle pins, ball joints, track frogs and wagon couplers.

Also, according to Allnat and Bell (8), extensive experience has shown that a number of traditional nickel-base alloys offer good surface protection for engineering components in Nuclear environments.

1.2.2 Nickel - Chromium - Boron Hardfacing Alloys

The Ni - Cr - B alloy to be deposited in the investigation was chosen from the list of nickel-base alloys which are commercially available. The alloy was chosen because it offers good abrasion resistance and its low melting temperature, relative to the other hardfacing alloys available, was an essential requirement with grey cast iron being used as the substrate.

In 1937 Cole and Edmonds (31) were granted a patent for a nickel - chromium - boron hardfacing alloy named COLMONOY* after their names (COL from COLE, MON from EDMONDS and OY from ALLOY). They found that Ni - Cr alloys could be hardened by the introduction of boron. Subsequently a whole range of Ni - Cr - B alloys has been developed to meet the demand for a variety of mechanical properties.

The typical composition of the alloy chosen is (3):

Chromium - 15%, Boron - 3%, Silicon - 4% - 5%, Iron - 4% - 5%, Nickel - Balance.

The nickel provides corrosion resistance whereas chromium improves high temperature oxidation resistance and increases

* COLMONOY is the registered trademark of WALL COLMONOY CORPORATION

strength and wear resistance. Boron is present mainly in the form of nickel or chromium boride particles. These are dispersed throughout the Ni - Cr alloy matrix and are responsible for much of the hardness and abrasion resistance. Boron, together with silicon, lowers the melting point of the eutectic/solid solution matrix and this reduces the application temperature required (32). The melting temperature of the alloy is between 964°C - 1003°C (3).

The hardness of the deposited alloy is usually between 710 HV - 790 HV (27) but hardness of up to 4600 HV have been recorded (33, 34). However, it should be emphasized that hardness alone is known to be a poor guide to abrasion life (35), which derives principally from the structure.

Ni - Cr - B alloys exhibit a complex structure containing chromium carbide and chromium boride particles, which exhibit the characteristic of extremely high hardness. The alloy has a long freezing range, some 100°C between liquidus and solidus temperatures. This permits the alloy to retain its shape and rigidity during fusing, reducing the chance of sagging or running (34). The low melting of the nickel eutectic matrix limits the use of the alloy to below 950°C (29).

1.2.3 Expansion and Contraction of Ni - Cr - B Alloys

Ni - Cr - B alloys have a high coefficient of expansion and have a tendency to crack during application. On surfaces which are flat, cylindrical or curved, shear and tensile stresses can be developed as the coating is applied.

Slow cooling of the alloys after deposition is essential as they have a tendency to crack when cooled too rapidly. Cooling can be carried out in a furnace or by covering the component with sand or insulating powder.

1.3 Grey Cast iron BS 1452 : 1977 (1)

Cast iron is an alloy of several elements but according to BS 1452 the composition of the iron should be left to the discretion of the manufacturer.

In grey cast iron the majority of the carbon present is in the free state, as graphite and this graphite is normally in flake form. The melting temperature of grey cast iron is in the range of 1130°C - 1250°C .

There are seven grades of grey iron castings:

10, 12, 14, 17, 20, 23 and 26 which correspond to the following tensile strengths:

150, 180, 220, 260, 300, 350 and 400 N/mm^2 .

1.3.1 Expansion and Contraction of Grey Cast Iron

The fraction of its length which a metal will expand when heated through one degree rise in temperature is termed its coefficient of linear expansion (this also applies to contraction when the metal is cooled). The coefficient of linear expansion of cast iron is 0.000010 per degree Celcius (36).

The expansion and contraction of cast iron is of great importance to the welding operator. This is because of the large forces or stresses that can be generated during welding. The low ductility of grey cast irons and their inability to relieve plastically can cause the castings to fracture.

During some welding processes, such as Oxy-acetylene welding, the workpiece normally absorbs a considerable amount of heat and this can be advantageous since it eliminates the steep thermal gradients that create the internal stresses (13).

1.3.2 Applications of Grey Cast Iron

A grey cast iron, with a tensile strength between 220 N/mm^2 and 260 N/mm^2 , was used for the investigation. From the literature survey it would appear that this grey cast iron is the most commonly used by such industries as the following (37):

Automotive, Chemical Engineering, Civil Engineering, Electrical Engineering, General Engineering, Iron and Steel Industry, Marine Engineering, Mining and Textiles. Typical components produced in grey cast iron include: Bottle moulds, chain and gear wheels, crane drums, crankshafts, fly wheels, general pumps and machine tools. Components of grey cast iron can also be found in plant such as: Compressors, diesel engines, earthmoving plant, general engineering machines, quarry machinery, tractors and transmissions.

In view of its wide usage, grey cast iron is likely to encounter a variety of wear mechanisms. Provided below are three examples of grey cast iron components subjected to abrasive conditions which have been coated with a Ni - Cr - B hardfacing alloy.

1. Reclaiming the drive rolls on a barrel painting machine. The cost of the reclamation was a quarter of the price of new rolls and increased the service life from two months to eighteen months. This resulted in a cost saving of over 90% (32).
2. Worn cable grooves in crane drums were rebuilt and then remachined to their original profile, with great cost savings.

3. Glass bottle moulds were clad to extend their service life with consequent economic advantages (24).

1.3.3 Preparation of Grey Cast Iron prior to Hardfacing

The success of any hardfacing operation depends on the preparation of the substrate surface. If the surface is not prepared correctly then the coating will not bond to the substrate (33). Several methods can be used to prepare the surface and the most common methods are:

1. Pre-cleaning (38) must be carried out if the surfaces have oil, grease or other foreign matter on them. It is good practice to use a solvent wash or degreasing fluid and then heat to approximately 290°C to drive out any oil from the pores of the cast iron.
2. Undercutting (38) is carried out on cylindrical components by machining and the depth of the undercut is usually determined by the service conditions. Shoulders at the ends of the undercut sections should be opened at about a $40^{\circ} - 50^{\circ}$ angle, with respect to the axis of the component, see FIG. 1.1

FIG. 1.1 UNDERCUTTING

3. Rough threading (37, 38) of some cylindrical components can be accomplished by using a 60° - 70° pointed tool with a negative back rake. A full depth thread should be cut in a single pass, see FIG. 1.2

FIG. 1.2 ROUGH THREADING

4. Grit blasting (38 - 40) is generally considered to be the most satisfactory and versatile method, although this is contested by Ballard (41). The amount that the surface needs roughening by the grit depends on the type and thickness of the coating being deposited.

1.3.4 Preheating of Grey Cast Iron prior to Hardfacing

Preheating may be necessary for the following reasons:

1. To prevent cracking;
2. To reduce residual stresses;
3. To reduce distortion

The entire part to be hardfaced may be preheated or it may be preheated locally if only part of the surface is to be coated. When local preheating is applied to grey cast iron extreme care is required in the initial stages to avoid

cracking due to thermal shock (24).

The preheating temperature for grey cast iron is between 400°C - 500°C (except for Thermal spraying process, see 2.1.1) and correct control of the temperature is important (42). Furnace preheating is the best method but if a furnace is not available then either a propane burner or oxy-acetylene torch may be used and the temperature measured using a surface contact pyrometer or heat sensitive crayons.

1.4 Spraying and Welding Processes

There is a large number of spraying and welding processes available for depositing hardfacing alloys. From the literature survey it was found that the following processes appear to be the most suitable for depositing the nickel-base alloys:

1. Plasma arc spraying
2. Thermal spraying
3. Powder spray welding
4. Manual metal arc welding (MMA)
5. Tungsten inert gas welding (TIG)
6. Oxy-acetylene welding
7. Metallic inert gas welding (MIG)

Plasma arc spraying

Plasma arc spraying is the most modern of all the spraying processes but the equipment cost is very expensive and, according to Matting (9), the process is mainly favoured when high temperature metals, carbides, oxides or cermets are to be sprayed. Up to 4.5 kg/hr of hardfacing powder can be deposited using a 40 kW Plasma arc spraying head (43).

Thermal spraying

Thermal spraying is an alternative to the Plasma arc spraying, it is less expensive and can apply an infinite

variety of metals, alloys, ceramics and cermets at speeds and costs which are economically feasible (44). The process can be made portable.

Powder spray welding

Powder spray welding is an extension to the Oxy-acetylene welding process. It involves using the same blowpipe but with the addition of a special powder feed attachment. The equipment is portable and inexpensive. When not used for spraying the equipment can be quickly changed over for the conventional gas welding process.

Manual metal arc (MMA) welding

Manual metal arc (MMA) welding is a fast deposition process using flux coated electrodes. It is a popular hardfacing method and is well suited to building up heavy deposits on large areas (26). The process involves melting the parent metal in the fusion zone. The fusion zone then becomes mixed or diluted in with the hardfacing alloy. If cast iron is used as the substrate it is probable that essential constituents, such as graphite, would be burnt out. The equipment is inexpensive and is usually portable.

Tungsten inert gas (TIG) welding

Tungsten inert gas (TIG) welding is an alternative to the MMA process with the advantage that the arc is much softer and therefore does not melt the surface area quite so severely. A tungsten electrode initiates the arc which is shrouded by an argon gas shield to reduce oxidation. An as cast rod is used as the depositing alloy. The deposition rate is slower than the MMA process and equipment costs are expensive but the process can be used for other welding operations, mainly for aluminium and its alloys. The process can

be made portable.

Oxy-acetylene welding

Oxy-acetylene welding can generally be found in all welding workshops. The process deposits an as cast rod, like TIG, and is sometimes described as brazing (10) rather than welding because the parent metal does not become molten. The equipment is portable, inexpensive and versatile because it can be used for spraying, welding, preheating or flame cutting operations at low costs, virtually anywhere.

Metallic inert gas (MIG) welding

Metallic inert gas (MIG) welding uses a continuous tubular wire (7) with the alloyed powder forming the core which is shrouded in a gas shield. Like MMA, dilution caused through melting the parent material is high. The deposition rate is fast and the process is mainly used for building up heavy deposits over large areas. The equipment is expensive but can be easily converted for other applications just by changing the wire and gas shield. The equipment is also portable.

The spraying and welding processes chosen to deposit the Ni - Cr - B alloy in the investigation are:

Thermal spraying, Powder spray welding, Oxy-acetylene welding and TIG welding.

The processes were selected from the seven processes for the following reasons:

1. The processes can be generally found in most welding workshops.
2. The equipment costs are not too expensive, compared to some of their alternatives.
3. Dilution with the parent metal can be kept to a minimum.

4. All the processes are or can be made portable.

The processes selected for the investigation are discussed in greater detail in CHAPTER 2.

1.5 Dilution

Dilution is defined by Davies (11) in the following way: "When two metals are fusion welded together, the final composition consists of an admixture of parent plate and welding wire. The parent plate has melted in with the filler and has diluted it".

Dilution by the substrate during hardfacing appears to be a greater problem with arc processes than it does with the Oxy-acetylene or Powder spraying processes. A comparison of dilution effects is provided in Table 1 (21). It can be seen that in the case of the open arc process, dilution could cause a significant decrease in the hardness of the coating.

Table 1

Process	Deposit thickness	Dilution Single layer
TIG	1.6 mm - 5.0 mm	5% - 10%
Thermal spraying	0.5 mm - 2.4 mm	NIL
Powder spray welding	0.5 mm - 3.0 mm	Up to 5%
Oxy-acetylene	1.6 mm - 5.0 mm	Up to 5%
Open arc	2.5 mm	Up to 30%

Deposit Thicknesses and Dilution (21)

To minimise the dilution in arc processes the current must be kept as low as possible, consistent with the production of a sound bead of alloy (32) and this must be combined with a two layer deposit (45).

The wide range of dilution exhibited by the welding processes does not imply lack of control. However, it reflects the wide variations that can occur depending on the welding conditions i.e. current, travel speed and the welding technique. One technique includes a degree of overlapping of adjacent weld beads. By overlapping, the alloy is being mixed with the adjacent alloyed bead so less alloy is actually being diluted with the substrate, see FIG. 1.3.

Mixing of a proportion of parent metal with deposited alloy can affect the composition and the microstructure, and hence the wear resistance (46).

FIG. 1.3 OVERLAPPING TECHNIQUE

1.6 Wear

Wear, in the general sense, has been known to man since his earliest days, however, only since the mechanical age has it been specially studied with a view to its prevention or minimization. It was not until the beginning of the Twentieth Century that any considerable attention was paid to the improvement of surfaces for the prevention of wear. Faced with, for examples, higher working speeds of machinery, artificial abrasives, the rise of the internal combustion engine and the replacement of the old self-hardened steels by high speed

cutting-tool steels, Engineers found the need for a greater understanding of surfaces and their susceptibility to wear (47).

Wear may be defined as the deterioration of a surface during use (48) and it occurs in a wide variety of operations. No general rule holds for all manifestations of wear. It is affected by a variety of conditions such as: the type of lubricant; temperature; hardness; surface finish; presence of foreign materials and the chemical nature of the environment (49). In many wear situations a combination of these variables makes it very difficult to determine the precise type of wear which has occurred.

Wear (17, 50, 51) encountered in industrial situations can be broken down into various categories and the frequency with which the various main types of wear occur is estimated to be as follows:

Abrasion 50%; Adhesion 15%; Erosion 8%; Fretting 8%;
Chemical 5%; Miscellaneous 14%.

1.6.1 Abrasive Wear

Abrasive wear is usually caused by particles, often non-metallic, present in one or both of the mating materials or in the environment in which they operate. These particles score the metal and tear away elongated chips or slivers from the surface (18, 50). The rate of abrasion is governed largely by the hardness of the surface, its strength and possibly its toughness (47). Because hardness is a major factor this explains why materials hardened on the surface are used wherever possible for wearing surfaces.

1.6.2 Classification of Abrasive Wear

Abrasive wear can be classified according to one of three causes (42): gouging; grinding; or scratching, although

there may be some overlap between them.

Gouging abrasion involves high stresses on a large scale, usually associated with impact in service, this leads to a plastic flow in the metal base (52) and usually occurs when the abrading agent is anchored or well supported in some way. If the surface is too soft for the application, prominent grooves are cut into the wearing surface under the gouging action of the abrasive material.

Grinding abrasion results from extremely high compressive or shear stresses which occur when small hard particles are crushed or nipped between metallic faces. The broken abrasive grains are sharp and score the metal.

Scratching abrasion is often known as erosion and the low stresses produced are the result of sharp particles travelling at speed (42). The contact between the surfaces is slight and the abrasive material is composed of extremely sharp particles of high abrasive power, not usually broken up by the stresses involved.

1.6.3 Abrasive Wear of Ni - Cr - B Hardfacing Alloys

Relatively little information is available on the abrasive wear of Ni - Cr - B alloys. However, in the literature it is assumed by researchers that these alloys have an excellent wear resistance (7, 29, 53).

1.7 Safety

1.7.1 Fume Extraction and Ventilation

Welding processes produce fumes and the degree of hazard to the welding operator depends on the composition of the fumes and gases and their concentration in the air inhaled. Fumes may contain ozone and oxides of nitrogen along with other compounds. To avoid the toxic and noxious effects of

these fumes, suitable ventilation or extraction systems are required when carrying out spraying and welding operations.

1.7.2 Respiratory Hazards

Materials in finely divided form may be damaging to the respiratory system to a varying degree. Grit blasting and spraying (54) both produce dusts which should be considered as hazardous, especially when grit blasting or spraying toxic materials.

Chromium alloys are extremely hazardous. When spraying or welding these metals complete respiratory protection must be used by the operator.

1.7.3 Equipment Safety

All oxy-acetylene equipment must conform to British Standards and a booklet by the Health and Safety at work Executive Committee (55) refers to these British Standards and provides general guidance on the safe use of compressed gases for welding, heating and deposition of metals.

For the construction and use of electric arc welding equipment BS 638 (56) must be followed. A booklet by the Department of Employment and Productivity (57) on electric arc welding gives general guidance on safety, construction and use of electric arc welding equipment in industrial and other employments.

1.7.4 Personal Protection

Welding processes have a high heat output and produce infra red and ultra violet light. Exposure to these hazards requires the following protection for the welding operator:

1. Eye protection regulations came into operation on the 10th April 1975 (58) and must be followed.

For arc welding and gas welding processes, shields

and goggles must be used that conform to BS 1542 and the filters or lens shall conform to BS 679.

2. Protective clothing for welding operators should conform to BS 2653 and requires clothing such as:
 - (a) Leather aprons to shield the body from heat given off from the welding process and to prevent burns as a result of small globules of metal falling onto thighs and legs.
 - (b) Leather gloves are necessary to shield hands and forearms from heat, sparks and radiation from the electric arc.
 - (c) Boots and leggings to protect the feet and legs in the same way as the hands and forearms.

1.8 Summary of Literature Survey

1.8.1 Grey Cast Iron Substrate

A grey cast iron, with a tensile strength of between 220 N/mm^2 and 260 N/mm^2 was chosen as the substrate for the investigation. From the literature survey it would appear that this type of grey cast iron is in common use by such industries as the following:

Automotive, Chemical Engineering, Civil Engineering, Electrical Engineering, General Engineering, Iron and Steel Industry, Marine Engineering, Mining and Textiles.

With the grey cast iron having a melting temperature range of 1130°C - 1250°C a hardfacing alloy with a lower melting temperature had to be selected to avoid certain constituents such as, graphite from being burnt out of the cast iron. However, the alloy must still provide good hardness and abrasion resistance.

1.8.2 Ni - Cr - B Hardfacing Alloy

A Ni - Cr - B alloy with a typical composition of Cr - 15%, B - 3%, Si - 4% - 5%, Fe - 4% - 5%, Ni - Balance was chosen from the list of commercially available nickel-base alloys to meet the above objectives. The Ni - Cr - B alloy has a low melting temperature 964°C - 1003°C ; a hardness range of 710 HV - 790 HV and it also provides good abrasion resistance. The alloy is available in powder, "as cast" rod, tubular wire and flux coated electrode form. The alloy is the "self fluxing" type and provides ease of application and the ability to dissolve oxides of iron, nickel or chromium and form a hard smooth protective film which prevents atmospheric oxidation.

1.8.3 Spraying and Welding Processes

The spraying and welding processes were chosen from a list of seven processes that appeared from the literature survey to be the most suitable for depositing the Ni - Cr - B alloy, these were:

Thermal spraying; Powder spray welding; Oxy-acetylene welding; TIG welding.

The processes were selected for the following reasons:

1. Dilution with the substrate is a problem when hardfacing because it can reduce the hardness and wear resistance of the deposit, so the processes had to produce minimal dilution.
2. The processes can generally be found in most welding workshops.
3. The equipment costs are minimal compared to some of their alternatives.

4. All the processes can be made portable, so deposition of the alloy can be carried out virtually anywhere.
5. Various levels of welding operator skills are required to use the processes.

1.8.4 Safety

When setting up and using the equipment for spraying or welding, good safety practice is essential and British Standards must be followed, especially in the following areas:

Extraction and ventilation; Respiratory protection;
Personal protection; and Construction of equipment.

CHAPTER 2

SPRAYING AND WELDING PROCESSES

CHAPTER 2

SPRAYING AND WELDING PROCESSES

2.1 Thermal Spraying

Thermal spraying (59) is the term developed from the original process known as metal spraying or metallizing. However, because non metallic materials are also sprayed, the process of metal spraying is more aptly described as Thermal spraying. The spraying process was invented in 1910 by Dr. Schoop (30, 60) in Switzerland. His first work was carried out by spraying heated metal powder, but he later developed an automatic wire feed pistol or gun for metal spraying.

About 1945 a process to spray hardfacing alloys in powder form onto a surface to provide a deposit, which could be subsequently heated and welded, was discovered and the spray weld process was born (29). In the last twenty five years techniques involving the use of Plasma arc (59) and Electron beam (61) for spraying coatings have been developed, but the equipment is expensive.

The most economic process used is Thermal spraying (powder process) using acetylene as the fuel gas. As two operations are used in this process, spraying followed by fusing, the process is sometimes described as the Spray Fused process (26).

2.1.1 Operating Technique

The powdered alloy is fed by a trigger mechanism, see FIG. 2.1 (62), from a hopper or canister which is attached to the gun and passes through the heating zone of the flame.

FIG 2.1 Metco Type 2P Thermospray Gun(62)

The powder melts to produce fine particles which are then projected by the flame, the energy is provided by the expanding fuel gas mixtures (8), onto the prepared substrate.

The chart figures supplied by the spray gun manufacturers should be followed as closely as possible for the gas flow, powder feed and nozzle distances, see Table 2 (62).

After preheating the substrate to 93°C (38) the flow control valve is set to the required number of clicks, see Table 2. The powder is then sprayed onto the substrate and, depending on the substrate being stationary or rotated in a lathe, the travel speeds provided in Table 3 should be used.

During application of the powder the substrate temperature should be kept below 260°C otherwise the substrate may overheat and coating stresses are increased. This may cause cracking or separation of the coating as shown in Plate 2.1.

PLATE 2.1 Separation of Deposited Coating

Table 2

METCO Powder No.	NOZZLE	Metering Valve No.	No. Flow Control Valve Clicks Open (2)	Lighting Pressure PSI			Flow Meter Readings			Consumption Per Hour (3)				Sq. ft. Covered Per Hr., .001" Thick (3)	Powder Weight 1 Sq. Ft., .001" Thick (3)	Deposit Efficiency % (4)
				Oxygen	Acetylene	Hydrogen	Oxygen	Acetylene	Hydrogen	Cu. Ft. Oxygen	Cu. Ft. Acetylene	Cu. Ft. Hydrogen	Powder lbs.			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
(7)	12C	P7	1	8-16	12	10	24	28		35	25		11	250	.044	95
	*15E	P7	1	8-16	12	10	24	28		35	25		11	270	.041	95
	15F	P7	2	12-16	15	15	20		40	30		148	9	215	.042	95
	†16C	P7	1	8-16	12	10	24	28		35	25		12	280	.043	95
	18C	P7	1	8-16	12	10	24	28		35	25		10	230	.043	95
(6)	31C	P7	2	8-16	12	10	24	28		35	25		7½	160	.046	95
	32C	P7	2	8-16	12	10	24	28		35	25		7	165	.043	95
	(7) 34F	P7	2	8-14	15	15	20		40	30		148	7	120	.057	90
(8)	41C	P7	2	8-16	12	10	24	28		35	25		6	145	.041	90
	42C	P7	2	8-16	12	10	24	28		35	25		6½	175	.037	95
	43C	P7	2	8-16	12	10	24	28		35	25		7	170	.041	90
	(9) 54	P7	2	12-14	15	15	20		40	30		148	4½	320	.014	85
	(8) 55	P7-B	5	13-15	15	15	20		40	30		148	6	145	.042	95
(11)	101	P7-C	5	6-12	14	12	30	30		47	28		2¼	125	.018	90
(11)	105	P7-C	5	6-12	14	12	30	30		47	28		2	105	.019	80
(11)	201	P7-C	5	6-12	14	12	30	30		47	28		2¼	80	.028	80
(10)†	404	P7-B	5	12-14	17	15	28	28		46	28		8	185	.043	75

† Patents Pending.

‡ Covered by U.S. Patent 2,875,043.

* Meets Requirements of Specifications AMS 4775 and AMS 4775A.

Spray distance (nozzle to work) unless otherwise noted: Spraying metals with acetylene as fuel gas—9" to 10". Spraying metals with hydrogen as fuel gas—6" to 7". Spraying ceramics—2" to 3".

Thermal Spraying Tables for Metco Type 2P Thermospray Gun(62)

Because Ni - Cr - B alloys are porous, as sprayed, and will shrink by approximately 20% when fused, an allowance for this shrinkage must be made when applying the coating.

Table 3

Surface speed metres/min.	Traverse per revolution
5	13 mm
8	9 mm
13	6 mm

Travel Speeds

When using hand held guns on stationary work a traverse of 300 mm should be made within 2 - 6 seconds. The width of the strip aimed for at each pass should be between 13 mm and 18 mm.

2.1.2 Fusing Technique

The object of the fusing operation is to convert the porous deposit into a sound, homogeneous coating securely bonded to the substrate. This operation is best carried out while the substrate is still warm from the spraying operation as this will reduce cracking or separation of the unfused coating.

Fusing is carried out by using a conventional oxy-acetylene blowpipe with a large multi-jet nozzle. However, depending on the size of the component being coated, a furnace or induction heating can be used. The flame technique is the most flexible method and can be applied to a wide variety of components. When using a blowpipe for heating, a carburizing

flame is used, see FIG. 2.2, because this is a soft flame and will stop the surface coating flowing unevenly:

The substrate and unfused coating should be heated uniformly to 350°C keeping the nozzle a distance of between 100 mm - 150 mm away. If the coating is heated too rapidly the coating will expand and separate from the substrate see Plate 2.2.

The nozzle is brought to within 40 mm of the coating and about 25 mm from the edge of the workpiece, the flame is oscillated slightly as the melting point is approached. For the Ni - Cr - B alloy being used, this is between 964°C - 1003°C (26). Once fusion has been initiated, which is shown by a glazing or glassy shine, the torch is moved slowly along the workpiece so that the glazing traverses the whole surface.

The fusing operation should not be interrupted once started. On completion of the fusing operation, the flame is moved back along the surface to ensure that the fused coating has bonded. The thickness of the deposit can be from 0.05 mm to 2.5 mm, with a deposition rate of up to 4 kg/hr.

Slow cooling after depositing the coating is essential to avoid any cracking taking place.

FIG. 2.2 CARBURIZING FLAME

PLATE 2.2 Separation of Fused Coating

2.2 Powder Spray Welding

Powder spray welding is not really a welding process because bonding takes place by diffusion (46) and the substrate is not melted.

The principle of the Powder welding process is that the powders are induced into a special oxy-acetylene blowpipe FIG. 2.3 and deposited onto the substrate.

The powder spray blowpipe consists of a standard oxy-acetylene blowpipe, with a powder feed attachment which has been introduced between the gas control valves and the welding nozzle. The attachment consists of a gas mixing chamber, powder hopper and powder control mechanism.

When the oxygen and acetylene flows through the blowpipe they are mixed in the normal manner in the gas mixing chamber and the mixed gases then flow through into the powder mixing chamber. On depressing the powder control lever the powder is fed into the mixing chamber and is mixed with the

FIG 2.3 Powder spray welding blowpipe

gas stream. It then passes through a further orifice into the welding nozzle. The powder is preheated in the inner cone of the flame FIG. 2.2 and, depending on its size and shape, the powder is molten by the time it reaches the substrate to be surfaced.

2.2.1 Operating Technique

The regulator pressure settings and nozzle sizes that should be used are shown in Table 4 (63).

Table 4

Nozzle Size	Oxygen p.s.i.	Acetylene p.s.i.	Average Consumption ft ³ /h	
			Oxygen	Acetylene
7	8 - 10	8 - 10	11	10
10	10 - 12	10 - 12	12	11
13	12 - 15	12 - 15	13.5	12.5

Regulator Pressure Settings and Nozzle Sizes

The flame is set to the carburizing condition, see FIG. 2.2. After preheating the substrate to 500°C it is then brought to its fusing temperature. To avoid oxidation and to help minimize dilution, an initial layer is sprayed lightly and rapidly over the substrate surface. This is an effective way of securing the coating to the substrate during fusing. Otherwise oxidation has a tendency to prevent proper diffusion, leaving the coating still separate from the substrate (34).

The facing runs are carried out with the travel direction from right to left, leftward technique (64, 65). A small area of the substrate surface is heated until it begins

to show signs of melting. At this time a small amount of powder is sprayed onto the surface and the flame is held there until the alloy fuses. This procedure is repeated until the whole surface is covered.

On large surfaces a slight weaving action, with a travel distance of between 20 mm - 25 mm is used. Powder is introduced on the outward weaving motion and heat alone is applied on the inward motion. This method appears to be more suitable than using straight narrow beads.

The thickness of the deposit is governed by the rate of flow of powder and movement of the blowpipe. This can be from 0.05 mm to 3.0 mm thickness, with a deposition rate of up to 5 kg/hr (46).

After depositing the alloy to avoid the possibility of cracking slow cooling is essential.

2.3 Oxy-acetylene Welding

The Oxy-acetylene welding consists essentially of melting the "as cast" hardfacing rod, by means of a conventional oxy-acetylene blowpipe and depositing it onto the substrate, whose surface is kept just above the hardfacing alloy's melting point. The process is sometimes described as brazed welding (9) rather than fusion welding. As the substrate does not become molten, dilution is kept to a minimum.

2.3.1 Operating Technique

The regulator pressure settings and nozzle sizes are the same as those for Powder spray welding, see Table 4. The flame is adjusted to the carburizing condition, see FIG. 2.2.

After preheating the substrate to 500°C the surface is brought to its fusing temperature. Care must be taken with grey cast iron because its surface does not "sweat" to indicate

that the fusing temperature is being reached and the iron may easily sag or melt. It is advantageous therefore, when coating grey cast iron with this process, to rapidly deposit a very thin layer on the surface. This will practically eliminate dilution in the second layer and stop the substrate from sagging or melting.

The direction of travel is the leftward technique (64, 65) with the angle of the blowpipe at 60° - 70° to the workpiece and the angle of the hardfacing rod at 60° , see FIG. 2.4.

A slight weaving action of the blowpipe, to produce deposits of approximately 25 mm wide, appears to be more successful when coating large areas than using straight narrow beads.

The deposit thickness can be from 1.0 mm up to 5.0 mm depending on the diameter of the hardfacing rod used and the number of layers deposited. The deposition rate is slow with a maximum of 1 kg/hr (46). Due to the high heat input to the workpiece distortion or warping can occur.

After depositing the coating slow cooling is essential to avoid any cracking taking place.

FIG. 2.4 ANGLE OF HARDFACING ROD AND BLOWPIPE

2.4 Tungsten Inert Gas Welding

The tungsten arc process was introduced after the Second World War and has since found its place supplementing the other surfacing methods (13).

The process uses a thoriated tungsten electrode (66) shrouded by an inert gas shield, which is usually argon. An arc is struck between the tungsten electrode and the work and argon is fed around the tungsten electrode which is only slowly consumed.

The hardfacing alloy is deposited from an "as cast" rod in the same way as Oxy-acetylene welding but the heat is more concentrated. Usually the process is operated manually but it can easily be mechanised (46).

2.4.1 Operating Technique

The tungsten electrode is connected to the negative (-) pole of a Direct Current (D.C.) welding transformer. The welding current must be kept as low as possible (and the voltage as high as possible) because increasing the current by 33% will cause a mean increase of 90% in the depth of penetration into the substrate. The voltage should be as high as possible because the higher the voltage the less agitated the weld pool will be and the smaller will be the depth of penetration achieved. Depths of penetration of 0.6 mm - 0.8 mm can be achieved in this way (67).

The largest diameter of hardfacing rod, acceptable for the operation being carried out, should be used because it will reduce some of the contamination from the tungsten electrode.

A D.C. current of between 100 A and 200 A should be used and the tip of the electrode should be ground to an angle of

60° - 90° with the end rounded off, see FIG. 2.5.

The direction of travel is the leftward technique and the angle of the welding torch should be held between 60° - 70° to the workpiece. The hardfacing rod should be held at an angle of 60° , see FIG. 2.4. The weld pool must not be puddled as this will increase the dilution. Straight, narrow beads are deposited quickly and overlapping each other as shown in FIG. 1.3. This technique limits the dilution with the substrate.

At the end of each bead the arc should not be lengthened quickly because the crater that is formed becomes oxidised due to the lack of shielding gas.

The deposit thickness can be from 1.6 mm up to 5.0 mm and the deposition rate up to 2 kg/hr. With the heat input being concentrated only minimal distortion or warping of the substrate occurs. After depositing the alloy, slow cooling is essential to avoid cracking taking place.

FIG. 2.5 PREPARATION OF THE TUNGSTEN ELECTRODE

CHAPTER 3

EXPERIMENTAL WORK

CHAPTER 3

EXPERIMENTAL WORK

As the main objective of the investigation was to establish the most effective method for depositing a hardfacing alloy onto a grey cast iron substrate, it was necessary to establish a procedure for assessing the quality of the coating. The principal attribute of the hardfacing alloy is its ability to withstand abrasive wear and consequently wear testing of the applied coating was considered to be the most appropriate method of assessment. Hardfaced coatings are extremely hard, but this hardness may be adversely affected if the alloy is diluted by the substrate. It was therefore considered that the measurement of hardness, both surface and macro, should be complemented by Electron probe micro analysis (EPMA) which would measure the percentage of the elements across the deposit/substrate interface area and could provide an indication of the presence and degree of dilution of the hardfacing alloy by the substrate. The integrity of the bond between the substrate and hardfacing alloy is clearly an important consideration. In extreme cases it is possible for separation of the coating to occur.

It was considered that an optical microscopy study of the specimens sectioned through the hardfacing/substrate interface should be conducted to provide information about the integrity of the interface.

3.1 Abrasive Wear Testing

Reddy and Nau (68), in their review of wear tests, classify wear test conditions under the following headings.

1. Rolling Contact
2. Simultaneous Rolling and Sliding
3. Localised Sliding Contact
4. Extended Sliding Contact
5. Abrasion
6. Oscillatory

An abrasive wear test will be used in this investigation and abrasion was discussed earlier in 1.6.1.

Abrasion resistant coatings create unique structures. These structures are comprised of at least one coating material bonded to a substrate. The testing problem, therefore, is much more complex than the testing of solid materials because in addition to the combined properties of the coating and the substrate involved the bond conditions between the two must be considered. In addition internal stresses, which result from the differences in physical properties of the materials, must be considered.

Ideally, wear tests should reproduce as closely as possible the fundamental conditions of actual service. A scratch test is usually employed to simulate abrasion and give a more complete understanding of the mechanisms of abrasive wear (69).

The abrasive wear tests in the investigation were carried out on a reciprocating diamond scratch testing machine (70), Plate 3.1 and FIG. 3.1 in which a right circular cone of diamond with a circular tip radius (0.2 ± 0.01 mm) and an inclined angle of 120° was the abrasive element.

To carry out the scratch tests five specimens from each of the 1 layer deposits, 2 layer deposits and control samples, measuring 76 mm x 55 mm, were cut from surface ground blanks, FIG. 3.2. These were then individually clamped onto the

reciprocating carriage and set to the required stroke length. The load required was placed onto the load plate to apply load to the diamond. The number of strokes required were set on a counter with an automatic-stop device. This facility ensured that the tests were stopped automatically when the preset number of reciprocations had been reached. A perspex cover was placed over the top of the testing machine to isolate the wear tests from the ambient environment.

The literature survey showed no comparable scratch testing conditions on hardfacing alloys so the test parameters used, closely followed those of Gibson (70) and Razavizdeh and Davies (71) these were:

Stroke length	:	40 mm
Loads	:	2.5 kg, 5 kg, 10 kg
Average linear speed	:	3.33 cm/sec
No. of strokes	:	10, 50, 100, 500

The results were obtained in the form of a "wear volume" which was proportional to the width of the scratch.

The formula used was: (70, 71)

Wear volume = $(0.144W^2 - 1.63 \times 10^{-3}) \times L$ where

W = Scratch width and

L = Stroke length

The formula was derived as shown in FIG. 3.3 and Appendix 1.

Scratch widths (W) were measured at 8 mm intervals along the length of the scratch using an Engineer's microscope at the position shown in FIG. 3.4 in order to avoid erroneous results due to the measurement from the peaks of the piled up edges.

The diamond was thoroughly cleaned with industrial spirit prior to each test.

PLATE 3.1 Reciprocating Diamond Scratch Testing Machine

FIG 3.1 Detail of Diamond Scratch Testing

3.2 Hardness Testing

Hardness is the property possessed by a metal resisting scratching or indentation. It is measured on various scales, the most common of which are: Brinell, Rockwell and Vickers. When these hardness tests are used on hardfaced coatings, they are influenced by the hardness of the alloy particles, the bond between particles, the porosity of the deposit and the oxide content. The surface hardness is a poor guide to abrasive life which depends directly on the structure of the alloy. For this reason the following tests were selected so that the overall hardness characteristics of the alloy could be measured:

1. Surface hardness
2. Macro hardness

3.2.1 Surface Hardness

Five specimens from each of the control samples, 1 layer deposits and 2 layer deposits were surface ground to provide a uniform finish and then tested for their surface hardness. In the absence of a Brinell Hardness Testing machine a Rockwell Hardness machine, with a ball indenter, was used. Each specimen was tested five times. The control samples were tested on the B scale but because of the hardness of the hardfaced specimens it was necessary to use the C scale. So that a comparison could be made with the other hardness tests being undertaken the hardnesses were converted into equivalent Vickers Hardness (HV).

3.2.2 Macro Hardness

In order to give an indication of the total hardness of the deposited coating, five specimens from each of the 1 layer deposits and 2 layer deposits were tested to measure the

hardness profile across the interface. The tests were carried out using a Vickers Pyramid hardness testing machine, with a 1 kg load and a 2/3" objective.

To prepare the specimens for the macro hardness tests, each specimen was mounted in a bakelite material. The specimens were then ground successively through wet and dry silicon carbide papers, grades 220 μm - 600 μm to eliminate any scratches. The specimens were then washed with water and dried with methanol. To give the specimens a highly polished finish they were polished on a rotating pad which was impregnated with a 3 μm diamond compound. After polishing the difference between the deposited coating and the substrate could be clearly seen, so no etching of the surface was required.

Ideally for comparison purposes the hardness measurements should be made at similar distances from the starting point for each of the specimens, but some difficulty was encountered in setting the testing machine, so the measurements were taken as near equal as practicable for comparability.

3.3 Optical Microscopy

Spraying and welding processes provide difference deposition methods, heat inputs and cooling rates which affect the structure of the deposited alloy, the integrity of the bond between the hardfacing alloy and the substrate, also burning out of essential elements from the cast iron substrate is possible. To provide information on these aspects it was considered necessary to produce photomicrographs. The photomicrographs were produced at a magnification of 200X, using a Nikon microscope.

Preparation of the specimens followed the same order as for the macro hardness test specimens, except that after the final

polishing the specimens were etched by immersion in solutions of Murakamis reagent and mixed acids for a period of 2 minutes in each solution.

Murakamis reagent

10 gms $K_3Fe(CN)_6$, 10 gms Na OH, 100 ml H_2O

Mixed acids

15 ml Acetic acid, 15 ml HNO_3 , 60 ml glycerol

The etchants were chosen because Okada and Maruo (72) had used them on a Ni - Cr - B alloy to show similar structures. The Murakamis reagent was used to show the carbide particles in the alloy and the mixed acids to show the boride particles and the matrix of the alloy.

3.4 Electron Probe Microanalysis (EPMA)

Five specimens from each of the 1 layer and 2 layer deposits produced by each process were selected for EPMA. However, because of the operator's work load, only 1 specimen from each of the 1 layer and 2 layer deposits, for each process, were examined.

The specimens were examined to measure approximate percentages of the elements: Ni; Cr; Si and Fe across the interface area and provide an indication of the presence or degree of dilution of the hardfacing alloy by the substrate.

Preparation of the specimens followed a procedure similar to that for macro hardness test specimens 3.2.2. The bakelite material used for mounting the specimens is usually suitable for EPMA, but it was found to be non-conductive, and the specimens had to be coated with carbon to conduct the electrons away during analysis in order to stop charging.

Because of the difference in coating thicknesses produced by the different processes the EPMA probe travelled

varying distances across the interface. For all the specimens the readings on the chart started at 240 μm below the fusion line into the substrate and then the average peak measurements were taken every 120 μm until the peaks showed a constant level.

The chart speed was 10 mm/min and the specimen speed was 10 $\mu\text{m}/\text{min}$.

The formula used to establish the approximate element percentage was:

$$\begin{array}{c}
 \text{Readings off chart} \\
 \swarrow \quad \searrow \\
 \frac{(\text{Peak} - \text{Background})}{(\text{Standard} - \text{Background})} \times \frac{\text{Full scale deflection counts/sec}}{100} \\
 \swarrow \quad \searrow \\
 \text{Counts per 100 sec}
 \end{array}$$

3.5 Preparation of Specimens for the Hardfacing Experiments

3.5.1 Production of the Substrate

Cast iron blanks were produced by the green sand moulding process using cast iron melted in an oil-fired Morgan tilting crucible furnace. The as-cast size of these blanks was: 152 mm x 76 mm x 13 mm. The analysis of the cast iron was(2): C 3.22% - 3.32%, Si 1.97% - 2.08%, Mn 1.56% - 1.66%, P 0.104% - 0.137%, S 0.036% - 0.038%.

3.5.2 Preparation of the Substrate Surface

The as-cast surface of the cast iron blanks was removed by surface grinding to produce a standardized surface. In all cases this required the removal of 0.5 mm off the material.

The surface grinding was carried out using a grinding wheel number WA 60 - J6 - V and a speed of 3500 surface feet per minute, and the coolant used was a 1:40 soluble oil emulsion.

After surface grinding, the blanks were dried and then grit blasted for 4 minutes on the surface where the alloy was to be deposited, using G39 grit in a Tilghman Wheelabrator machine. At this stage the blanks were then ready for the hardfacing operations.

3.6 Hardfacing Operations

BS 1295 : 1959 (73), for building up surfaces by Oxy-acetylene and Manual metal arc welding processes, was followed as closely as possible.

3.6.1 Thermal Spraying

The conditions used for the setting up procedure for the spraying operation followed the guide lines recommended by the spray gun manufacturer given in Table 2 these were:

Flow meter pressure settings

Oxygen : 24 p.s.i. (1.80 bar)

Acetylene : 28 p.s.i. (2.10 bar)

Lighting pressure settings

Oxygen : 12 p.s.i. (0.90 bar)

Acetylene : 10 p.s.i. (0.75 bar)

Flow control valve setting

14 clicks

Nozzle size

P 7

The cast iron blank, which had been surface ground and then grit blasted, was placed in an upright position on the work bench for ease of spraying and surrounded on three sides with fire bricks to contain the heat. The Ni - Cr - B powder Deloro* 60s was poured into the canister on the thermal spray

* Deloro is a registered trade mark of Deloro Stellite (UK) Ltd.

gun FIG. 2.1. Using the flowmeter and lighting pressure settings given, the flame was ignited. This flame was used to preheat the cast iron blank to 93°C , a digital surface contact thermometer was used to check the temperature. Once the preheating temperature had been reached the flow control valve was set to 14 clicks. The powder was then sprayed horizontally across the blank to form a strip width of approximately 18 mm this was continued by overlapping the strips until the whole surface had been covered. The travel speed for each strip was approximately 3 seconds and the whole surface required approximately 30 seconds to cover. This procedure was repeated, for the 2 layer deposit.

After spraying, the blank was placed in the flat position, so that when fusing occurred it would avoid sagging or running of the alloy.

A conventional blowpipe with a multi jet nozzle was used for the fusing operation and used the same lighting pressure settings as the flame spray gun. The flame was set to the carburizing condition FIG. 2.2 to stop the surface coating flowing unevenly. To stop the coating cracking or separating, the fusing operation was carried out while the blank was still warm. The nozzle was kept at a distance of approximately 100 mm away from the blank to stop the coating heating up too rapidly. The coating was then brought to a uniform temperature of 350°C , this temperature was checked using the digital surface contact thermometer and then the nozzle was brought to within 40 mm distance from the coating and 25 mm in from the edge of the blank. As the melting point of the alloy was being approached the flame was oscillated slightly. When the melting temperature was reached, visible by a glassy

shine, the flame was moved along the blank until all the surface was fused.

After deposition the blank was placed in a container, covered with sand and allowed to cool slowly for 5 hours.

3.6.2 Powder Spray Welding

The setting up procedure for the spraying operation, followed the guide lines set down by the spraying equipment manufacturers, Table 4, these were:

Regulator pressure settings

Oxygen : 12 p.s.i (0.90 bar)

Acetylene : 12 p.s.i (0.90 bar)

Nozzle size

13 (swaged type)

The cast iron blank, which has been surface ground and then grit blasted, was placed flat on the work bench and surrounded on three sides by fire bricks to contain the heat. The Ni - Cr - B powder Deloro 60s was poured into the hopper FIG. 2.3. The flame was ignited and adjusted to the carburizing condition and used to preheat the cast iron blank to 500°C. A digital surface contact thermometer was used to check the temperature.

After preheating, the cast iron was brought to its fusing temperature with the inner cone of the flame, FIG. 2.2, approximately 6 mm away from the cast iron. At this stage the powder control lever was depressed to release the powder and a very light layer was rapidly sprayed onto the cast iron surface to prevent oxidation. A small area of the cast iron was then heated until it showed signs of melting. At this point a small amount of powder was released and sprayed onto the cast iron surface and the flame was held there until the powdered

alloy melted and fused. Travelling from right to left, and using a slight weaving action to produce a deposit width of approximately 20 mm, the powder was introduced on the outward weaving motion and the heat alone on the inward motion. This procedure was carried out until all the surface had been covered. For the 2 layer deposits the whole procedure of covering the surface was repeated.

After deposition the blank was placed in a container, covered with sand and allowed to cool slowly for 5 hours.

3.6.3 Oxy-acetylene Welding

The procedure for setting up the equipment followed that of the Powder spray welding, except that the powder hopper attachment was replaced with a conventional welding blowpipe.

The cast iron blank was placed in the flat position on top of a fire brick on the work bench, no other fire bricks were used to surround the blank, because easy access was required for the welding blowpipe and feeding in of the filler rod. The flame was ignited, then set to the carburizing condition and used to preheat the cast iron blank to 500°C , a digital surface contact thermometer was used to check the temperature. After preheating, the surface of the blank was brought near to its fusing temperature. Care had to be exercised because cast iron does not sweat to indicate its fusion temperature is being reached, instead it starts to sag or melt away.

The blowpipe was traversed in a direction from right to left at an angle of 60° to the cast iron, FIG. 2.4. At this point the 5.0 mm diameter Ni - Cr - B as cast rod, which was held at an angle of 60° , was fed into the flame and melted onto the cast iron surface. A slight weaving motion with the

blowpipe produced a fused deposit of approximately 25 mm width. This procedure was repeated until all the surface had been covered. For the 2 layer deposits the method used for the 1 layer deposit was repeated.

After deposition the blank was placed in a container, covered with sand and allowed to cool slowly for 5 hours.

3.6.4 Tungsten Inert Gas Welding

The conditions for this process were found by preliminary experiments to be:

ADR 200 AC/DC welding transformer

Set to Direct Current (DC)

Welding current

120 Amperes

Voltage

75 Volts

Tungsten electrode

3.0 mm diameter: Thoriated with the tip ground to an angle of 60° with the end rounded, see FIG. 2.5.

Gas shield

Argon : Set to a flow rate of 30 litres per minute

The cast iron blank was placed in the flat position on a metal work bench so that the arc could be initiated. No fire bricks were used to surround the blank because easy access was required for the welding torch and feeding in of the filler rod. Using a multi jet nozzle on the oxy-acetylene welding blowpipe the flame was ignited and adjusted to the carburizing condition. The cast iron blank was then preheated to 500°C , a digital surface contact thermometer was used to check the temperature.

After preheating, an arc was struck between the tungsten

electrode and the cast iron. The angle of the welding torch was held at 60° to the cast iron and a weld pool was formed. The 5.0 mm diameter Ni - Cr - B as cast rod was dipped into the weld pool, the angle of rod was held at 60° . The travel direction was from right to left and straight narrow beads were deposited. The beads were overlapped into each other, see FIG. 1.3, and at the end of each bead the arc was lengthened slowly to avoid oxidation of the weld pool. This procedure was repeated until all the surface had been covered. For the 2 layer deposits the cast iron blank was turned 180° and the method repeated as for the 1 layer deposit. The blank is turned 180° because at the end of the weld bead a crater or flat area forms and if all the layers were deposited in the same direction the surface build up would be unequal.

After deposition the blank was placed in a container, covered with sand and allowed to cool slowly for 5 hours.

3.7 Surface Grinding after Deposition

After the hardfacing alloy had been deposited and cooled the coating was surface ground to provide a smooth uniform finish. It was not possible to surface grind the blanks to an equal thickness because of the different thicknesses of the deposited coatings. The 1 layer Thermal sprayed deposits were too thin to surface grind so the wear and hardness tests were carried out on the as-deposited coating.

The surface grinding was carried out using a grinding wheel number C60-K6-VE with a wheel speed of 3500 surface feet per minute and the coolant used was a 1:40 soluble oil emulsion.

After surface grinding the blanks the specimens for the tests were cut to size, see FIG. 3.2. This was carried out

on a power hacksaw, cutting from the cast iron down to the hardfaced coating and then snapping off the test specimens. The rough edges were surface ground smooth. Following preparation, the specimens were ready for the subsequent test procedures and the results of these experiments are provided in the next chapter.

CHAPTER 4

RESULTS

CHAPTER 4

RESULTS

4.1 Abrasive Wear Test Results

The wear testing programme, the procedure for which was described in section 3.1, generated a very large amount of data. To aid interpretation the data has been treated in the following way:

The data for the control and the four hardfacing processes has been separated according to the number of scratches in the abrasive wear test procedure, namely: 10; 50; 100 and 500.

After each abrasive wear test the scratch width was measured at 8.0 mm intervals along the 40 mm scratch length and from this information an average wear volume value was determined. Each test was repeated five times and the average wear volume obtained from the five tests was used to produce graphs relating wear volume to wear test load.

4.1.1 Control Data

The average wear volume values for the cast iron substrate material are provided in tabular form in Tables 5 to 8 for 10, 50, 100 and 500 scratches respectively. This information is summarised graphically in FIG. 4.1 and the detailed results are provided in Tables 1 to 4 in Appendix 2.

For comparison purposes the appropriate wear volume versus load relationship for the cast iron substrate is included in the graphical results for the hardfacing processes.

4.1.2 Hardfacing Processes

For each process the average wear volume values for the 1 layer and 2 layer deposits are provided in tabular form with

the detailed results presented in Appendix 2. The information for both deposits is also summarised graphically. The relevant Table and Figure numbers are presented below:

Number of Scratches	Average Wear Volumes Table Numbers		Detailed Results Appendix 2 Table Numbers		Graphical Summarisation Figure Number
	1 Layer	2 Layers	1 Layer	2 Layers	
10	9	10	5	6	4.2
50	11	12	7	8	4.3
100	13	14	9	10	4.4
500	15	16	11	12	4.5

Thermal Spraying Process

Number of Scratches	Average Wear Volumes Table Numbers		Detailed Results Appendix 2 Table Numbers		Graphical Summarisation Figure Number
	1 Layer	2 Layers	1 Layer	2 Layers	
10	17	18	13	14	4.6
50	19	20	15	16	4.7
100	21	22	17	18	4.8
500	23	24	19	20	4.9

Powder Spray Welding Process

Number of Scratches	Average Wear Volumes Table Numbers		Detailed Results Appendix 2 Table Numbers		Graphical Summarisation Figure Number
	1 Layer	2 Layers	1 Layer	2 Layers	
10	25	26	21	22	4.10
50	27	28	23	24	4.11
100	29	30	25	26	4.12
500	31	32	27	28	4.13

Oxy-acetylene Welding Process

Number of Scratches	Average Wear Volumes Table Numbers		Detailed Results Appendix 2 Table Numbers		Graphical Summarisation Figure Number
	1 Layer	2 Layers	1 Layer	2 Layers	
10	33	34	29	30	4.14
50	35	36	31	32	4.15
100	37	38	33	34	4.16
500	39	40	35	36	4.17

Tungsten Inert Gas Welding Process

4.1.3 Comparative Results Presentation

In order to provide a direct comparison between the wear test results for each process according to the number of scratches and the number of deposited layers the following figures were prepared:

Number of Scratches	Number of Deposited Layers	Figure Number
10	1 Layer	4.18
	2 Layers	4.19
50	1 Layer	4.20
	2 Layers	4.21
100	1 Layer	4.22
	2 Layers	4.23
500	1 Layer	4.24
	2 Layers	4.25

4.2 Surface Hardness Test Results

In the absence of a Brinell Hardness Testing machine a Rockwell machine, with a ball indenter, was used to measure the hardness of the grey cast iron substrate material. For reasons of standardisation this test was also used to measure the surface hardness of the hardfaced coatings, although the C scale was necessary for these harder materials. To enable a comparison

to be made between the surface hardness and other hardness tests the former were converted into equivalent Vickers Hardness Numbers.

The results of the surface hardness tests by process are shown in Tables 41 to 44.

Table 41 : Thermal Spraying

Table 42 : Powder Spray Welding

Table 43 : Oxy-acetylene Welding

Table 44 : Tungsten Inert Gas Welding

4.3 Macro Hardness Profile Results

Ideally for comparison purposes the hardness measurements should have been made at similar distances from the starting point for each of the specimens. However, this proved to be impracticable as some difficulty was encountered in setting the testing machine. The measurements were taken as near equal as practicable for comparability. As each test was repeated five times the data has been processed for ease of analysis. The average values of hardness for distance from the starting point are presented in separate tables for the one layer and two layer tests with both sets of tests being shown together graphically in the same figure. The detailed results are presented in tabular form in Appendix 3.

The relevant Table and Figure numbers are presented below:

Process	Macro Hardness Profiles Average Values Table Numbers		Detailed Results Appendix 3 Table Numbers		Graphical Summarisation Figure Number
	1 Layer	2 Layers	1 Layer	2 Layers	
Thermal Spraying	45	46	37	38	4.26
Powder Spray Welding	47	48	39	40	4.27
Oxy-acetylene Welding	49	50	41	42	4.28
T.I.G.	51	52	43	44	4.29

4.4 Electron Probe Microanalysis (EPMA)

Hardfaced coatings are extremely hard but this hardness may be adversely affected by the alloy being diluted by the substrate. To provide an indication of the presence and degree of dilution Electron Probe Microanalysis was conducted to establish the percentage of the elements Ni, Cr, Si and Fe across the interface between the deposit and the substrate.

The approximate percentages of these elements, for both the one and two layer deposits, are shown respectively in Tables 53, 54, 55 and 56. More details of the EPMA readings are given in Appendix 4.

4.5 Optical Microscopy

Spraying and welding processes provide deposition methods which differ significantly, in particular with respect to the heat input and cooling rate experienced by the substrate. This can affect the structure of the alloy deposited and the integrity of the bond between the alloy and the substrate. This latter possibility is of particular concern in the case of cast iron because graphite may be removed. Optical microscopy was used to assess these factors and the results obtained are presented in the form of photomicrographs.

For each process five photomicrographs are presented. In each case these have been prepared as follows:

- (a) Etched with Murakami's reagent to show the carbide particles.
- (b) Etched with mixed acids to show the boride particles.
- (c) Etched with both Murakami's reagent and mixed acids
to show carbides, borides and alloy matrix
- (d) Unetched to identify the graphite in relation to the coating, bond and substrate regions.

(e) Etched with both Murakami's reagent and mixed acids to show the integrity of the bond.

Process.	Preparation Procedure				
	Plate Numbers				
	(a)	(b)	(c)	(d)	(e)
Thermal Spraying	4.1a	4.1b	4.2	4.3	4.4
Powder Spray Welding	4.5a	4.5b	4.6	4.7	4.8
Oxy-acetylene Welding	4.9a	4.9b	4.10	4.11	4.12
T.I.G.	4.13a	4.13b	4.14	4.15	4.16

Table 5

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.745
	2	1.705
	3	2.499
	4	1.586
	5	2.042
		<u>1.915</u>
5	1	2.798
	2	3.130
	3	3.695
	4	3.135
	5	3.295
		<u>3.210</u>
10	1	4.166
	2	5.880
	3	5.959
	4	5.300
	5	5.959
		<u>5.452</u>

Grey Cast Iron 10 ScratchesTable 6

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.935
	2	3.295
	3	3.695
	4	2.768
	5	3.560
		<u>3.050</u>
5	1	4.137
	2	5.959
	3	6.321
	4	4.867
	5	4.771
		<u>5.211</u>
10	1	7.846
	2	8.529
	3	8.857
	4	6.318
	5	8.081
		<u>7.926</u>

Grey Cast Iron 50 Scratches

Table 7

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	3.295	4.360
	2	3.695	
	3	4.391	
	4	4.542	
	5	5.880	
5	1	5.481	<u>6.301</u>
	2	5.959	
	3	6.318	
	4	6.749	
	5	6.999	
10	1	8.698	<u>9.450</u>
	2	9.529	
	3	9.634	
	4	9.529	
	5	9.861	

Grey Cast Iron 100 Scratches

Table 8

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	5.880	<u>6.132</u>
	2	5.959	
	3	6.321	
	4	6.318	
	5	6.185	
5	1	8.571	<u>9.130</u>
	2	9.529	
	3	8.529	
	4	9.634	
	5	9.387	
10	1	16.638	<u>15.993</u>
	2	15.510	
	3	16.638	
	4	14.049	
	5	17.131	

Grey Cast Iron 500 Scratches

FIG 4.1 Wear Volume Vs Load
Grey Cast Iron

Table 9

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.073	<u>0.111</u>
	2	0.108	
	3	0.184	
	4	0.068	
	5	0.122	
5	1	0.249	<u>0.264</u>
	2	0.263	
	3	0.263	
	4	0.209	
	5	0.340	
10	1	0.402	<u>0.395</u>
	2	0.385	
	3	0.438	
	4	0.329	
	5	0.422	

Thermal Spraying 1 Layer Deposit 10 Scratches

Table 10

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.064	<u>0.040</u>
	2	0.068	
	3	ZERO	
	4	0.068	
	5	ZERO	
5	1	0.209	<u>0.137</u>
	2	0.151	
	3	0.027	
	4	0.235	
	5	0.064	
10	1	0.306	<u>0.315</u>
	2	0.337	
	3	0.300	
	4	0.329	
	5	0.306	

Thermal Spraying 2 Layer Deposits 10 Scratches

FIG 4.2 Wear Volume Vs Load
THERMAL SPRAYING 10 Scratches

- x = Cast Iron
- = 1 Layer Deposit
- = 2 Layer Deposits

Table 11

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.340	<u>0.459</u>
	2	0.613	
	3	0.389	
	4	0.586	
	5	0.368	
5	1	0.586	<u>0.655</u>
	2	0.870	
	3	0.522	
	4	0.716	
	5	0.582	
10	1	0.959	<u>1.039</u>
	2	1.283	
	3	0.925	
	4	1.099	
	5	0.931	

Thermal Spraying 1 Layer Deposit 50 Scratches

Table 12

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.384	<u>0.359</u>
	2	0.291	
	3	0.353	
	4	0.384	
	5	0.385	
5	1	0.582	<u>0.577</u>
	2	0.611	
	3	0.583	
	4	0.565	
	5	0.545	
10	1	0.819	<u>0.826</u>
	2	0.771	
	3	0.899	
	4	0.911	
	5	0.730	

Thermal Spraying 2 Layer Deposits 50 Scratches

FIG 4.3 Wear Volume Vs Load
THERMAL SPRAYING 50 Scratches

x = Cast Iron "

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 13

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.630	<u>0.487</u>
	2	0.419	
	3	0.565	
	4	0.438	
	5	0.384	
5	1	1.020	<u>0.817</u>
	2	0.730	
	3	0.873	
	4	0.821	
	5	0.645	
10	1	1.116	<u>1.104</u>
	2	0.911	
	3	1.293	
	4	1.193	
	5	1.008	

Thermal Spraying 1 Layer Deposit 100 Scratches

Table 14

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.340	<u>0.372</u>
	2	0.492	
	3	0.155	
	4	0.384	
	5	0.492	
5	1	0.673	<u>0.652</u>
	2	0.863	
	3	0.340	
	4	0.565	
	5	0.819	
10	1	0.873	<u>0.966</u>
	2	1.026	
	3	0.794	
	4	0.873	
	5	1.267	

Thermal Spraying 2 Layer Deposits 100 Scratches

FIG 4.4 Wear Volume Vs Load
THERMAL SPRAYING 100 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 15

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.923	<u>1.591</u>
	2	1.972	
	3	1.887	
	4	1.623	
	5	1.551	
5	1	2.037	<u>2.647</u>
	2	3.154	
	3	2.968	
	4	2.582	
	5	2.497	
10	1	2.903	<u>3.758</u>
	2	4.720	
	3	3.763	
	4	3.831	
	5	3.575	

Thermal Spraying 1 Layer Deposit 500 Scratches

Table 16

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.988	<u>1.121</u>
	2	0.728	
	3	1.887	
	4	1.382	
	5	0.620	
5	1	2.042	<u>1.870</u>
	2	1.586	
	3	2.499	
	4	2.182	
	5	1.043	
10	1	2.768	<u>2.868</u>
	2	3.560	
	3	3.135	
	4	2.798	
	5	2.080	

Thermal Spraying 2 Layer Deposits 500 Scratches

FIG 4.5 Wear Volume Vs Load

THERMAL SPRAYING 500 Scratches

x= Cast Iron

■= 1 Layer Deposit

□= 2 Layer Deposits

Table 17

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.108
	2	0.279
	3	0.184
	4	0.108
	5	0.108
		<u>0.157</u>
5	1	0.263
	2	0.459
	3	0.263
	4	0.235
	5	0.263
		<u>0.296</u>
10	1	0.459
	2	0.874
	3	0.688
	4	0.384
	5	0.438
		<u>0.568</u>

Powder Spray Welding 1 Layer Deposit 10 Scratches

Table 18

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	ZERO
	2	0.054
	3	0.068
	4	0.068
	5	ZERO
		<u>0.038</u>
5	1	0.085
	2	0.151
	3	0.116
	4	0.209
	5	0.172
		<u>0.146</u>
10	1	0.136
	2	0.330
	3	0.256
	4	0.337
	5	0.306
		<u>0.273</u>

Powder Spray Welding 2 Layer Deposits 10 Scratches

FIG 4.6 Wear Volume Vs Load
POWDER SPRAYING 10 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 19

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.389
	2	0.235
	3	0.279
	4	0.384
	5	0.321
		<u>0.321</u>
5	1	0.622
	2	0.419
	3	0.459
	4	0.733
	5	0.663
		<u>0.579</u>
10	1	1.199
	2	0.876
	3	0.874
	4	1.276
	5	1.100
		<u>1.065</u>

Powder Spray Welding 1 Layer Deposit 50 Scratches

Table 20

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.224
	2	0.353
	3	0.249
	4	0.308
	5	0.419
		<u>0.310</u>
5	1	0.534
	2	0.583
	3	0.545
	4	0.583
	5	0.630
		<u>0.575</u>
10	1	0.854
	2	0.847
	3	0.821
	4	0.890
	5	0.997
		<u>0.881</u>

Powder Spray Welding 2 Layer Deposits 50 Scratches

FIG 4.7 Wear Volume Vs Load
POWDER SPRAYING 50 Scratches

x = Cast Iron "
 ■ = 1 Layer Deposit
 □ = 2 Layer Deposits

Table 21

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.608	<u>0.410</u>
	2	0.404	
	3	0.249	
	4	0.504	
	5	0.285	
5	1	0.877	<u>0.627</u>
	2	0.608	
	3	0.395	
	4	0.917	
	5	0.340	
10	1	1.257	<u>1.064</u>
	2	1.055	
	3	0.964	
	4	1.086	
	5	0.959	

Powder Spray Welding 1 Layer Deposit 100 Scratches

Table 22

Load Kgs	Test No	Average Wear Volume mm ³	
2.5	1	0.492	<u>0.305</u>
	2	0.249	
	3	0.155	
	4	0.384	
	5	0.249	
5	1	0.623	<u>0.559</u>
	2	0.582	
	3	0.357	
	4	0.630	
	5	0.624	
10	1	1.099	<u>0.955</u>
	2	0.819	
	3	0.720	
	4	1.220	
	5	0.917	

Powder Spray Welding 2 Layer Deposits 100 Scratches

FIG 4.8 Wear Volume Vs Load

POWDER SPRAYING 100 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 23

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.296
	2	1.573
	3	1.554
	4	1.542
	5	1.723
		<u>1.455</u>
5	1	2.268
	2	2.302
	3	1.496
	4	1.887
	5	2.499
		<u>2.090</u>
10	1	3.655
	2	3.653
	3	2.268
	4	3.154
	5	4.467
		<u>3.439</u>

Powder Spray Welding 1 Layer Deposit 500 Scratches

Table 24

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.401
	2	0.821
	3	0.750
	4	0.611
	5	0.473
		<u>0.611</u>
5	1	0.624
	2	1.193
	3	0.990
	4	0.893
	5	0.890
		<u>0.918</u>
10	1	1.055
	2	1.880
	3	1.442
	4	1.327
	5	1.769
		<u>1.494</u>

Powder Spray Welding 2 Layer Deposits 500 Scratches

FIG 4.9 Wear Volume Vs Load
POWDER SPRAYING 500 Scratches

x= Cast Iron

■= 1 Layer Deposit

□= 2 Layer Deposits

Table 25

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.477
	2	0.307
	3	0.178
	4	0.172
	5	0.162
		<u>0.259</u>
5	1	0.978
	2	0.453
	3	0.430
	4	0.341
	5	0.477
		<u>0.535</u>
10	1	1.040
	2	0.759
	3	0.776
	4	0.509
	5	0.730
		<u>0.762</u>

Oxy - Acetylene 1 Layer Deposit 10 Scratches

Table 26

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.251
	2	0.116
	3	0.152
	4	0.197
	5	0.172
		<u>0.177</u>
5	1	0.263
	2	0.213
	3	0.244
	4	0.209
	5	0.297
		<u>0.245</u>
10	1	0.456
	2	0.418
	3	0.431
	4	0.477
	5	0.384
		<u>0.433</u>

Oxy - Acetylene 2 Layer Deposits 10 Scratches

FIG 4.10 Wear Volume Vs Load
OXY - ACETYLENE 10 Scratches

x = Cast Iron
 ■ = 1 Layer Deposit
 □ = 2 Layer Deposits

Table 27

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.477
	2	0.509
	3	0.308
	4	0.291
	5	0.345
		<u>0.426</u>
5	1	0.978
	2	0.776
	3	0.623
	4	0.419
	5	0.917
		<u>0.742</u>
10	1	1.040
	2	0.978
	3	1.099
	4	1.040
	5	1.292
		<u>1.089</u>

Oxy - Acetylene 1 Layer Deposit 50 Scratches

Table 28

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.137
	2	0.329
	3	0.263
	4	0.308
	5	0.352
		<u>0.277</u>
5	1	0.545
	2	0.668
	3	0.402
	4	0.611
	5	0.750
		<u>0.595</u>
10	1	0.845
	2	1.434
	3	1.043
	4	0.902
	5	1.327
		<u>1.110</u>

Oxy - Acetylene 2 Layer Deposits 50 Scratches

FIG 4.11 Wear Volume Vs Load
OXY - ACETYLENE 50 Scratches

x = Cast Iron "
 ■ = 1 Layer Deposit
 □ = 2 Layer Deposits

Table 29

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.644
	2	0.664
	3	0.664
	4	0.623
	5	0.864
		<u>0.691</u>
5	1	0.864
	2	1.067
	3	0.734
	4	0.839
	5	1.376
		<u>0.976</u>
10	1	2.229
	2	1.185
	3	1.423
	4	1.667
	5	1.086
		<u>1.518</u>

Oxy - Acetylene 1 Layer Deposit 100 Scratches

Table 30

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.694
	2	0.711
	3	0.545
	4	0.582
	5	0.546
		<u>0.615</u>
5	1	0.864
	2	0.789
	3	0.882
	4	0.726
	5	0.839
		<u>0.820</u>
10	1	1.594
	2	1.122
	3	1.122
	4	1.790
	5	1.667
		<u>1.459</u>

Oxy - Acetylene 2 Layer Deposits 100 Scratches

FIG 4.12 Wear Volume Vs Load

OXY - ACETYLENE 100 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 31

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.213
	2	1.496
	3	1.375
	4	1.464
	5	1.833
5	1	2.497
	2	3.655
	3	3.245
	4	3.777
	5	3.463
10	1	5.759
	2	5.963
	3	4.547
	4	5.901
	5	5.759

Oxy - Acetylene 1 Layer Deposit 500 Scratches

Table 32

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.438
	2	1.623
	3	0.645
	4	0.822
	5	1.040
5	1	1.342
	2	3.554
	3	1.335
	4	1.584
	5	2.093
10	1	2.870
	2	5.929
	3	4.515
	4	2.735
	5	5.158

Oxy - Acetylene 2 Layer Deposits 500 Scratches

FIG 4.13 Wear Volume Vs Load

OXY - ACETYLENE 500 Scratches

x= Cast Iron

■= 1 Layer Deposit

□= 2 Layer Deposits

Table 33

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.263
	2	0.279
	3	0.394
	4	0.266
	5	0.241
		<u>0.238</u>
5	1	0.668
	2	0.622
	3	0.673
	4	0.663
	5	0.623
		<u>0.653</u>
10	1	1.078
	2	1.199
	3	0.966
	4	1.213
	5	1.026
		<u>1.096</u>

Tungsten Inert Gas 1 Layer Deposit 10 Scratches

Table 34

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.087
	2	0.250
	3	0.152
	4	0.213
	5	0.117
		<u>0.163</u>
5	1	0.283
	2	0.384
	3	0.330
	4	0.330
	5	0.368
		<u>0.339</u>
10	1	0.489
	2	1.037
	3	0.773
	4	0.663
	5	0.604
		<u>0.713</u>

Tungsten Inert Gas 2 Layer Deposits 10 Scratches

FIG 4.14 Wear Volume Vs Load
TUNGSTEN INERT GAS 10 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 35

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.545
	2	0.563
	3	0.509
	4	0.660
	5	0.522
		<u>0.559</u>
5	1	0.917
	2	0.917
	3	0.626
	4	0.858
	5	0.925
		<u>0.848</u>
10	1	1.292
	2	1.861
	3	1.382
	4	1.339
	5	1.283
		<u>1.431</u>

Tungsten Inert Gas 1 Layer Deposit 50 Scratches

Table 36

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.422
	2	0.399
	3	0.368
	4	0.384
	5	0.491
		<u>0.412</u>
5	1	0.663
	2	0.847
	3	0.752
	4	0.604
	5	0.779
		<u>0.729</u>
10	1	1.220
	2	1.434
	3	1.382
	4	1.327
	5	1.267
		<u>1.326</u>

Tungsten Inert Gas 2 Layer Deposits 50 Scratches

FIG 4.15 Wear Volume Vs Load
TUNGSTEN INERT GAS 50 Scratches

x = Cast Iron
 ■ = 1 Layer Deposit
 □ = 2 Layer Deposits

Table 37

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.720
	2	0.623
	3	1.249
	4	1.496
	5	0.663
		<u>0.930</u>
5	1	1.383
	2	1.099
	3	1.951
	4	2.582
	5	1.591
		<u>1.721</u>
10	1	2.743
	2	1.667
	3	3.580
	4	4.160
	5	2.479
		<u>2.925</u>

Tungsten Inert Gas 1 Layer Deposit 100 Scratches

Table 38

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	0.931
	2	1.055
	3	0.964
	4	0.752
	5	0.931
		<u>0.926</u>
5	1	1.464
	2	1.551
	3	1.655
	4	0.819
	5	1.382
		<u>1.374</u>
10	1	2.109
	2	2.725
	3	2.596
	4	1.824
	5	2.182
		<u>2.297</u>

Tungsten Inert Gas 2 Layer Deposits 100 Scratches

FIG 4.16 Wear Volume Vs Load
TUNGSTEN INERT GAS 100 Scratches

x = Cast Iron

■ = 1 Layer Deposit

□ = 2 Layer Deposits

Table 39

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.614
	2	2.963
	3	2.037
	4	3.655
	5	2.133
		<u>2.481</u>
5	1	3.831
	2	4.025
	3	4.121
	4	5.963
	5	6.818
		<u>4.951</u>
10	1	6.695
	2	6.611
	3	6.427
	4	7.485
	5	7.058
		<u>6.855</u>

Tungsten Inert Gas 1 Layer Deposit 500 ScratchesTable 40

Load Kgs	Test No	Average Wear Volume mm ³
2.5	1	1.255
	2	1.560
	3	0.989
	4	1.383
	5	1.667
		<u>1.370</u>
5	1	2.741
	2	2.618
	3	1.880
	4	2.968
	5	2.743
		<u>2.590</u>
10	1	3.655
	2	4.109
	3	3.132
	4	3.831
	5	4.025
		<u>3.750</u>

Tungsten Inert Gas 2 Layer Deposits 500 Scratches

FIG 4.17 Wear Volume Vs Load
TUNGSTEN INERT GAS 500 Scratches

x= Cast Iron

■= 1 Layer Deposit

□= 2 Layer Deposits

Table 41

	Grey Cast Iron		1 Layer Deposit		2 Layer Deposits	
Test No	R b	*EQ HV	R c	*EQ HV	R c	*EQ HV
1	99	230	52	570	56	648
	99	230	50	543	54	608
	98	224	54	608	52	570
	99	230	52	570	52	570
	99	230	50	543	52	570
Average	99	228	51	567	53	593
2	97	218	54	608	62	792
	96	212	54	608	60	736
	98	224	56	648	60	736
	98	224	56	648	62	792
	98	224	56	648	60	736
Average	97	220	55	632	61	758
3	97	218	50	543	56	648
	97	218	50	543	56	648
	96	212	52	570	56	648
	98	224	54	608	60	736
	98	224	54	608	60	736
Average	97	219	52	574	57	683
4	98	224	58	685	58	685
	98	224	58	685	56	648
	98	224	56	648	62	792
	98	224	56	648	63	833
	98	224	56	648	62	792
Average	98	224	57	662	60	750
5	99	230	52	570	63	833
	99	230	54	608	63	833
	99	230	54	608	63	833
	98	224	52	570	62	792
	99	230	52	570	62	792
Average	99	228	53	585	62	816
Total Average	98	223	53	604	58	720

Thermal Spraying

Surface Hardness

* EQ HV = Equivalent Vickers Hardness

Table 42

	Grey Cast Iron		1 Layer Deposit		2 Layer Deposits	
Test No	R _b	*EQ HV	R _c	*EQ HV	R _c	*EQ HV
1	99	230	62	792	54	608
	99	230	56	648	62	792
	98	224	53	598	64	870
	99	230	53	598	64	870
	99	230	53	598	64	870
Average	99	228	53	647	61	802
2	97	218	54	608	56	648
	96	212	54	608	62	792
	98	224	56	648	58	685
	98	224	56	648	65	900
	98	224	56	648	64	870
Average	97	220	55	632	61	779
3	97	218	54	608	54	608
	97	218	54	608	52	570
	96	212	54	608	60	736
	98	224	54	608	64	870
	98	224	54	608	64	870
Average	97	219	54	608	58	730
4	98	224	56	648	57	666
	98	224	53	598	63	833
	98	224	53	598	65	900
	98	224	54	608	66	940
	98	224	54	608	65	900
Average	98	224	54	612	63	848
5	99	230	58	685	62	792
	99	230	58	685	58	685
	99	230	58	685	63	833
	98	224	56	648	58	685
	99	230	56	648	62	792
Average	99	228	57	670	60	757
Total Average	98	223	55	634	60	783

Powder Spray Welding

Surface Hardness

* EQ HV = Equivalent Vickers Hardness

Table 43

	Grey Cast Iron		1 Layer Deposit		2 Layer Deposits	
Test No	R b	*EQ HV	R c	*EQ HV	R c	*EQ HV
1	99	230	47	481	55	629
	99	230	50	543	55	629
	98	224	49	518	55	629
	99	230	47	481	54	608
	99	230	49	518	55	629
Average	99	228	48	508	55	625
2	97	218	47	481	46	467
	96	212	47	481	46	467
	98	224	45	454	52	570
	98	224	47	481	46	467
	98	224	47	481	34	339
Average	97	220	46	475	44	462
3	97	218	50	543	55	629
	97	218	49	518	55	629
	96	212	49	518	55	629
	98	224	45	454	54	608
	98	224	49	518	54	608
Average	97	219	48	510	54	620
4	98	224	39	371	54	608
	98	224	47	481	54	608
	98	224	53	598	52	570
	98	224	53	598	54	608
	98	224	53	598	54	608
Average	98	224	49	529	53	600
5	99	230	44	441	54	608
	99	230	44	441	52	570
	99	230	45	454	53	598
	98	224	45	454	55	629
	99	230	45	454	57	666
Average	99	228	44	448	54	614
Total Average	98	223	47	494	52	584

Oxy - Acetylene Welding Surface Hardness

* EQ HV = Equivalent Vickers Hardness

Table 44

	Grey Cast Iron		1 Layer Deposit		2 Layer Deposits	
Test No	R _b	*EQ HV	R _c	*EQ HV	R _c	*EQ HV
1	99	230	49	518	49	518
	99	230	49	518	53	629
	98	224	50	543	54	608
	99	230	50	543	53	629
	99	230	50	543	53	629
	99	230	50	543	53	629
Average	99	228	49	533	53	602
2	97	218	49	518	50	535
	96	212	45	454	50	535
	98	224	45	454	52	570
	98	224	45	454	52	570
	98	224	44	441	52	570
	98	224	44	441	52	570
Average	97	220	45	464	51	556
3	97	218	44	441	54	608
	97	218	49	518	54	608
	96	212	45	454	54	608
	98	224	49	518	54	608
	98	224	44	441	54	608
	98	224	44	441	54	608
Average	97	219	46	474	54	608
4	98	224	50	543	52	570
	98	224	54	608	48	501
	98	224	54	608	52	570
	98	224	52	570	52	570
	98	224	52	570	50	535
	98	224	52	570	50	535
Average	98	224	52	580	51	549
5	99	230	49	518	49	518
	99	230	45	454	49	518
	99	230	45	454	50	535
	98	224	49	518	49	518
	99	230	49	518	49	518
	99	230	49	518	49	518
Average	99	228	47	492	49	521
Total Average	98	223	48	508	51	567

Tungsten Inert Gas Welding Surface Hardness

* EQ HV= Equivalent Vickers Hardness

Table 45

Average Depth mm	Average HV
0.085	675
0.140	742
0.225	736
0.327	719
0.411	666
0.481	473
0.563	330
0.679	265
0.816	231
1.035	224

Thermal Spraying 1 Layer Deposit Macro Hardness

Table 46

Average Depth mm	Average HV
0.089	665
0.146	638
0.218	631
0.334	700
0.436	497
0.548	324
0.685	287
0.893	264
1.086	238
1.418	220

Thermal Spraying 2 Layer Deposits Macro Hardness

FIG 4.26 HV Vs Depth of Coating
Thermal Spraying Macro Hardness

● = 1 Layer Deposit

x = 2 Layer Deposits

Table 47

Average Depth mm	Average HV
0.157	768
0.260	775
0.407	751
0.547	638
0.695	626
1.046	456
1.203	408
1.427	266
1.549	250
1.946	229

Powder Spray Welding 1 Layer Deposit Macro Hardness

Table 48

Average Depth mm	Average HV
0.136	848
0.283	881
0.393	797
0.497	715
0.756	635
1.025	498
1.253	423
1.737	283
2.335	252
2.631	224

Powder Spray Welding 2 Layer Deposits Macro Hardness

FIG 4.27 HV Vs Depth of Coating
Powder Spray Welding Macro Hardness

● = 1 Layer Deposit

x = 2 Layer Deposits

Table 49

Average Depth mm	Average HV
0.213	536
0.329	518
0.538	511
0.756	507
1.188	468
1.549	420
1.843	344
2.325	276
3.048	248
3.401	231

Oxy - Acetylene 1 Layer Deposit. Macro Hardness

Table 50

Average Depth mm	Average HV
0.152	578
0.269	554
0.518	620
0.858	658
1.315	592
1.843	534
2.611	452
2.949	354
3.505	271
4.166	236

Oxy - Acetylene 2 Layer Deposits Macro Hardness

FIG 4.28 HV Vs Depth of Coating
Oxy- Acetylene Welding Macro Hardness

● = 1 Layer Deposit

x = 2 Layer Deposits

Table 51

Average Depth mm	Average HV
0.210	509
0.289	499
0.642	469
0.929	476
1.378	440
1.656	402
1.964	385
2.449	290
2.816	237
3.149	222

Tungsten Inert Gas 1 Layer Deposit Macro Hardness

Table 52

Average Depth mm	Average HV
0.192	611
0.340	599
0.741	574
1.137	558
1.630	523
2.221	467
2.667	365
3.047	276
3.454	242
4.013	224

Tungsten Inert Gas 2 Layer Deposits Macro Hardness

FIG 4.29 HV Vs Depth of Coating
Tungsten Inert Gas Welding Macro Hardness

● = 1 Layer Deposit

x = 2 Layer Deposits

Table 53

Process	1 Layer Deposits		2 Layer Deposits	
	Interface	Alloy	Interface	Alloy
Thermal Spraying	0.009%	52% - 56%	0.009%	78%
Powder Spray Welding	0.009%	53%	0.009%	77%
Oxy-acetylene Welding	0.02%	43% - 48%	0.02%	53% - 58%
TIG	0.04%	38% - 44%	0.04%	49% - 53%

Electron Probe Microanalysis (EPMA)

Approximate Percentages Ni

Table 54

Process	1 Layer Deposits		2 Layer Deposits	
	Interface	Alloy	Interface	Alloy
Thermal Spraying	Zero	5% - 13%	Zero	13% - 17%
Powder Spray Welding	Zero	5% - 14%	Zero	11% - 20%
Oxy-acetylene Welding	1%	4% - 11%	1%	7% - 13%
TIG	2%	3% - 7%	2%	4% - 11%

Electron Probe Microanalysis (EPMA)

Approximate Percentages Cr

Table 55

Process	1 Layer Deposits		2 Layer Deposits	
	Interface	Alloy	Interface	Alloy
Thermal Spraying	1%	1%	1%	2%
Powder Spray Welding	0.009%	1%	0.009%	2%
Oxy-acetylene Welding	0.008%	1%	0.008%	2%
TIG	1%	1%	1%	2%

Electron Probe Microanalysis (EPMA)

Approximate Percentages Si

Table 56

Process	1 Layer Deposits		2 Layer Deposits	
	Interface	Alloy	Interface	Alloy
Thermal Spraying	4%	4%	4%	3%
Powder Spray Welding	5%	4%	4%	3%
Oxy-acetylene Welding	10%	8%	6%	5%
TIG	17%	11%	10%	8%

Electron Probe Microanalysis (EPMA)

Approximate Percentages Fe

(a)

(b)

PLATE 4.1 Thermal Spraying Microstructure

PLATE 4.2 Thermal Spraying Microstructure

PLATE 4.3 Thermal Spraying Interface (Unetched)

PLATE 4.4 Thermal Spraying Interface (Etched)

(a)

(b)

PLATE 4.5 Powder Spray Welding Microstructure

PLATE 4.6 Powder Spray Welding Microstructure

PLATE 4.7 Powder Spray Welding Interface (Unetched)

PLATE 4.8 Powder Spray Welding Interface (Etched)

(a)

(b)

PLATE 4·9 Oxy-Acetylene Welding Microstructure

PLATE 4·10 Oxy-Acetylene Welding Microstructure

PLATE 4-11 Oxy-Acetylene Welding Interface (Unetched)

PLATE 4-12 Oxy-Acetylene Welding Interface (Etched)

(a)

(b)

PLATE 4-13 Tungsten Inert Gas Welding Microstructure

PLATE 4-14 Tungsten Inert Gas Welding Microstructure

PLATE 4.15 Tungsten Inert Gas Welding Interface (Unetched)

PLATE 4.16 Tungsten Inert Gas Welding Interface (Etched)

CHAPTER 5

DISCUSSION OF RESULTS

CHAPTER 5

DISCUSSION OF THE RESULTS

5.1 Abrasive Wear Testing

The abrasive wear tests were carried out according to the standard procedures outlined in Section 3.1. By conducting tests at different loads for different durations, light and heavy abrasion conditions could be simulated and the performance of the coatings under these conditions could be assessed.

In this section the results are discussed in the sequence that they were presented in the results section. Each group of results is first discussed independently but the correlation between the results from the different tests is drawn out within the Discussion Summary section.

5.1.1 Control Specimens

Figure 4.1 shows the relationship between wear volume, wear load and wear test duration (number of scratches). The general form of the graphs is as expected in that wear volume increases both with load and test duration.

Although the wear volume increases with increasing load and number of scratches, as expected, there is proportionally more wear at the lower loads of 2.5 kg and 5 kg than at the higher load 10 kg, for the 10, 50 and 100 scratch tests. However, in the case of the 500 scratch test the wear volume increases with increasing load to a much greater extent.

This wear pattern is apparently caused by the formation of a hard-layer. According to Eyre and Wilson (74), during running-in under both unlubricated and lubricated conditions, a hard layer may be formed on the surface as a result of surface

interaction. These layers have been referred to as "hard", "white" or "non-etching" and have been reported to form in most ferrous metals under a wide range of conditions.

During running-in the wear rate is initially high with a severe form of wear, and surface topographical and microstructural changes take place, producing a surface-hardened layer which eventually becomes covered with an oxide layer as the equilibrium mild wear condition is established. A transition from a mild form of wear to a severe form of wear takes place suddenly at some critical load or sliding speed and the wear rate increases by at least an order of magnitude. At the higher load the wear rate shows a marked increase with a change from mild to severe wear and then decreases again as it crosses back from the severe to mild wear region.

5.1.2 Hardfaced Surfaces

When the wear test results for the coated surfaces are compared with those for the cast iron substrate, Figures 4.2 to 4.25, it can be seen that the wear volume is markedly reduced for the same loads and test durations. The wear test results for the four hardfacing processes show consistent similarities in that for every process the wear volume increases with both increasing load and test duration. Furthermore, the one layer coatings consistently demonstrated a higher level of wear than the two layer coatings.

The wear test data for each process has been tabulated in a way which aids comparison. In each table the average wear volumes for: the 1 layer deposit (B) relative to the cast iron substrate (A); the 2 layer deposit (C) relative to the cast iron substrate (A); and the 2 layer deposit (C) relative to the 1 layer deposit (B) are presented as follows:

- Table 57 : Thermal Spraying
 Table 58 : Powder Spray Welding
 Table 59 : Oxy-acetylene Welding
 Table 60 : Tungsten Inert Gas Welding

Table 57

Average Wear Volume mm ³				Relative Percentage Wear		
Load Kg	A	B	C	B to A	C to A	C to B
	Cast Iron	1 Layer	2 Layer	$B \div A \times 100\%$	$C \div A \times 100\%$	$C \div B \times 100\%$
2.5	1.915	0.111	0.040	5.8	2	36.0
5	3.210	0.264	0.137	8.2	4.3	52.4
10	5.452	0.395	0.135	7.3	2.5	34.2
<u>10 Scratches</u>						
2.5	3.050	0.459	0.359	15	11.7	78.2
5	5.211	0.655	0.577	12.5	11	88
10	7.926	1.039	0.826	12.6	10.4	79.4
<u>50 Scratches</u>						
2.5	4.360	0.487	0.372	11	8.5	76.3
5	6.301	0.817	0.652	12.9	10.3	79.8
10	9.450	1.104	0.966	11.6	10.2	87.5
<u>100 Scratches</u>						
2.5	6.132	1.591	1.121	25.9	18.2	70.4
5	9.130	2.647	1.870	28.9	20.4	70.6
10	15.993	3.758	2.863	23.4	17.9	76.3
<u>500 Scratches</u>						

Table 58

Average Wear Volume mm ³				Relative Percentage Wear		
Load Kg	A	B	C	B to A	C to A	C to B
	Cast Iron	1 Layer	2 Layer	$B \div A \times 100\%$	$C \div A \times 100\%$	$C \div B \times 100\%$
2.5	1.915	0.157	0.038	8.1	2	24.2
5	3.210	0.296	0.146	9.2	4.5	49.3
10	5.452	0.568	0.273	10.4	5	48
<u>10 Scratches</u>						
2.5	3.050	0.321	0.310	10.5	10.1	96.5
5	5.211	0.579	0.570	11	10.9	98.4
10	7.926	1.065	0.881	13.4	11	82.7
<u>50 Scratches</u>						
2.5	4.360	0.410	0.305	9.4	6.8	74.3
5	6.301	0.627	0.559	9.9	8.8	89
10	9.450	1.064	0.955	11.2	10.1	89.7
<u>100 Scratches</u>						
2.5	6.132	1.453	0.611	23.6	9.9	42
5	9.130	2.090	0.918	22.8	10	43.9
10	15.993	3.439	1.494	21.5	8.3	43.4
<u>500 Scratches</u>						

Table 59

Average Wear Volume mm ³				Relative Percentage Wear		
Load Kg	A	B	C	B to A	C to A	C to B
	Cast Iron	1 Layer	2 Layer	$B \div A \times 100\%$	$C \div A \times 100\%$	$C \div B \times 100\%$
2.5	1.915	0.259	0.177	13.5	9.2	68.3
5	3.210	0.535	0.245	16.6	7.6	45.7
10	5.452	0.762	0.435	13.9	7.9	56.8
<u>10 Scratches</u>						
2.5	3.050	0.426	0.277	13.9	9	65
5	5.211	0.742	0.595	14.2	11.4	80
10	7.926	1.089	1.110	13.7	14	101.9
<u>50 Scratches</u>						
2.5	4.360	0.691	0.615	15.8	14.1	89
5	6.301	0.976	0.820	15.4	13	84
10	9.450	1.518	1.459	16	15.4	96.1
<u>100 Scratches</u>						
2.5	6.132	1.476	0.913	24	14.8	64
5	9.130	3.327	1.901	36.4	21.6	59.5
10	15.953	5.585	4.244	34.9	26.5	75.9
<u>500 Scratches</u>						

Table 60

Average Wear Volume mm ³				Relative Percentage Wear		
Load Kg	A	B	C	B to A	C to A	C to B
	Cast Iron	1 Layer	2 Layer	$B \div A \times 100\%$	$C \div A \times 100\%$	$C \div B \times 100\%$
2.5	1.915	0.238	0.163	15	8.5	56.5
5	3.210	0.653	0.339	20.3	10.5	51.9
10	5.452	1.096	0.713	20.1	13	65
<u>10 Scratches</u>						
2.5	3.050	0.559	0.412	18.3	13.5	73.7
5	5.211	0.848	0.729	16.2	13.9	85.9
10	7.926	1.431	1.326	18	16.7	92.6
<u>50 Scratches</u>						
2.5	4.360	0.950	0.926	21.7	21.2	97.4
5	6.301	1.721	1.374	27.3	21.8	79.8
10	9.450	2.925	2.287	30.9	24.2	78.1
<u>100 Scratches</u>						
2.5	6.132	2.481	1.370	40.4	22.3	55.2
5	9.130	4.951	2.590	54.2	28.3	52.3
10	15.993	6.855	3.750	42.8	23.4	54.7
<u>500 Scratches</u>						

From these tables the extent of the improvement in wear resistance provided by a hard coating can clearly be seen, whether with 1 or 2 layers. With only one exception the 2 layer coatings provide the better wear resistance although, in relative terms, the difference between the 1 and 2 layers is small in comparison with the difference between either the 1 or 2 layer results and the cast iron substrate.

These results apparently confirm expectations. The 1 layer deposits were thinner than the 2 layer deposits for each of the four processes. With the exception of the Thermal Spraying process, some dilution of the coating by the substrate could be expected and this would be manifested most clearly in the 1 layer coating resulting in poorer wear resistance. In the case of the Oxy-acetylene process the porous nature of the deposit could be expected to impair wear resistance and this could have a more significant effect on the 1 layer deposit results. However, these results require a more rigorous examination before firm conclusions can be stated.

These comments relate to the processes in isolation and there is a need to compare them in a way which will permit ranking and enable a recommendation of the best process to be made. To aid this comparison the data in Tables 57 to 60 inclusive has been retabulated so that for each combination of test conditions the processes can be ranked in order of best to worst performance. For ease of comparison the data is separated into two tables. In Table 61 the results for the 1 and 2 layer deposits are compared with the cast iron substrate whereas in Table 62 the 2 layer results are compared directly with the 1 layer results.

Table 61

Number of Scratches	2.5 Kg		5 Kg		10 Kg	
	1 Layer	2 Layers	1 Layer	2 Layers	1 Layer	2 Layers
10	TS > PS > OA > TIG	TS > PS > TIG > OA	TS > PS > OA > TIG	TS > PS > OA > TIG	TS > PS > OA > TIG	TS > PS > OA > TIG
50	PS > OA > TS > TIG	OA > PA > TS > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	TS > PS > OA > TIG	TS > PS > OA > TIG
100	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG
500	PS > OA > TS > TIG	PS > OA > TS > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > OA > TIG	PS > TS > TIG > OA

1 Layer and 2 Layer Deposits Relative To The Cast Iron Substrate

Table 62

Number of Scratches	2.5 Kg	5 Kg	10 Kg
10	PS > TS > TIG > OA	OA > PS > TIG > TS	TS > PS > OA > TIG
50	OA > TIG > TS > PS	OA > TIG > TS > PS	TS > PS > TIG > OA
100	PS > TIG > TS > OA	TS > TIG > OA > PS	TIG > TS > PS > OA
500	PS > TIG > OA > TS	PS > TIG > OA > TS	PS > TIG > OA > TS

2 Layers Relative To 1 Layer Deposits

Key	Process	Table 61	Table 62
PS =	Powder Spray Welding	15	5
TS =	Thermal Spraying	8	3
OA =	Oxy-acetylene Welding	1	3
TIG =	Tungsten Inert Gas Welding	0	1

League Table to Show Top Processes

Examination of Table 61 shows that there is no overall consistency within the ranking although there are a number of interesting features. For example in the case of the 100 scratch test the order of ranking (PS>TS>OA>TIG) occurs in each of the six combinations. In the 500 scratch tests Powder Spray Welding (PS) is the best in all the combinations and in the 50 scratch tests Powder Spray Welding (PS) is best in three of the six combinations. In the case of the 10 scratch tests Thermal Spraying (TS) proves the best in all combinations with the ranking order (TS>PS>OA>TIG) occurring in five out of the six combinations. Perhaps the most striking and consistent feature is that Tungsten Inert Gas Welding (TIG) is bottom in twenty two of the twenty four rankings. A simple league table shows that Powder Spray Welding was top of the rankings in fifteen cases, Thermal Spraying in eight cases, Oxy-acetylene Welding in one case and Tungsten Inert Gas Welding not at all.

Examination of Table 62 reveals even less consistency, although for the 500 scratch test the ranking order (PS>TIG>OA>TS) is the same for each of the three loads. Once again the simple league table showed Powder Spray Welding to be top of the rankings on the most occasions, five cases in comparison with three each for Thermal Spraying and Oxy-acetylene Welding, and one for Tungsten Inert Gas Welding.

From this consideration of the wear test results it would be possible to conclude that, on balance: the Powder Spray Welding process is the best and Tungsten Inert Gas Welding the worst; and two layers provide better wear resistance than one layer. However, these intuitive conclusions require testing against a more rigorous appraisal. For this purpose a statistical analysis of the results was performed.

5.1.3 Statistical Analysis of Wear Test Results (76)

The test chosen for the analysis was based on the standard error of the mean and the procedure is described in Appendix 5. The tests were applied to each of the ranking groups and to ensure that each of the four processes was compared one with another, six tests were required. With a total of twenty four ranking groups in Table 61 and twelve in Table 62 a total of 192 comparisons were necessary. The results of these comparisons are summarised in Tables 63 to 65.

Table 63

Number of Layers	Load Kgs	Number of Scratches	Statistically Significant Differences
1	2.5	10	Powder Spray Welding Vs TIG Thermal Spraying Vs TIG
1	5	10	
1	10	10	
1	2.5	50	
1	5	50	
1	10	50	
1	2.5	100	
1	5	100	
1	10	100	
1	2.5	500	Powder Spray Welding Vs TIG Thermal Spraying
1	5	500	
1	10	500	

One layer comparisons:

Inspection of Table 63 shows that statistically significant differences occurred in only 4 of the possible 72 comparisons.

Table 64

Number of Layers	Load Kgs	Number of Scratches	Statistically Significant Differences
2	2.5	10	Thermal Spraying Vs. Oxy-acetylene Welding
2	5	10	
2	10	10	
2	2.5	50	Powder Spray Welding Vs. TIG Thermal Spraying
2	5	50	
2	10	50	
2	2.5	100	Powder Spray Welding Vs TIG Thermal Spraying
2	5	100	
2	10	100	
2	2.5	500	Powder Spray Welding Vs TIG
2	5	500	
2	10	500	

Two layer comparisons:

Inspection of Table 64 shows that statistically significant differences occurred in 9 out of the possible 72 comparisons.

Table 65

Number of Layers	Load Kgs	Number of Scratches	Statistically Significant Differences
1 Vs 2	2.5	10	TIG
1 Vs 2	5	10	
1 Vs 2	10	10	
1 Vs 2	2.5	50	
1 Vs 2	5	50	
1 Vs 2	10	50	
1 Vs 2	2.5	100	
1 Vs 2	5	100	
1 Vs 2	10	100	
1 Vs 2	2.5	500	Powder Spray Welding
1 Vs 2	5	500	
1 Vs 2	10	500	

One layer Vs Two layer comparisons:

Inspection of Table 65 shows that statistically significant differences occurred in 2 out of the possible 48 comparisons.

The statistical analysis enables the results to be considered more objectively. It is clear from the results of the wear tests that the application of a hardfaced coating by any of the four processes significantly improves the wear resistance when compared with the results for the cast iron substrate. However, it is not possible to state categorically that, with one layer deposited, any one process provides better results than another. There is some indication that the TIG process may be the least satisfactory as it is shown to be significantly poorer in 4 comparisons.

Intuitively one might expect that the deposition of two layers of hardfacing might provide a better basis for comparison. Any influence of weak bonding or dilution should be diminished by the deposition of the additional layer of hardfacing alloy. The fact that statistically significant differences occurred in 9 of the comparisons could be considered to bear this expectation out.

However these results do not provide a clear cut 'best process' although TIG is once more seen as significantly a poorer process.

Although the wear test results show, with one exception, that the two layer deposits provide better wear resistance than the one layer deposits the improvement is not shown to be significantly better except in 2 of the 48 comparisons. As indicated earlier, the relative difference in wear resistance between the one and two layer deposits is small in comparison with either the one or two layer results and the cast iron substrate.

The implications of this analysis are clearly important to the selection of a hardfacing process. This aspect will be considered more fully in the Discussion Summary section.

5.2 Surface Hardness Testing

From the results presented in Tables 41 - 44 it can be seen that the average hardness of the hardfaced coatings is considerably higher than the average hardness of the grey cast iron substrate which is 223 HV. It can also be seen that the 1 layer deposits show a lower hardness than the 2 layer deposits.

To aid the comparison of the 1 layer and 2 layer deposits the data in Tables 41 - 44 inclusive has been summarised in the simple league tables shown below:

1 Layer Deposits

Powder Spray Welding	634 HV
Thermal Spraying	604 HV
TIG	508 HV
Oxy-acetylene Welding	494 HV

2 Layer Deposits

Powder Spray Welding	783 HV
Thermal Spraying	720 HV
Oxy-acetylene Welding	584 HV
TIG	567 HV

Inspection of these tables shows that for each process a higher hardness is obtained with a 2 layer deposit. Furthermore, the Powder Spray Welding process displays the highest hardness for both the 1 and 2 layer deposits followed by the Thermal Spraying process. The hardness values for the Oxy-acetylene and TIG Welding processes are similar but each is appreciably lower than those for the two spraying processes. These results appear to be quite conclusive. However, they can be tested more rigorously by a statistical analysis.

5.2.1 Statistical Analysis of Surface Hardness Results

The test chosen for the analysis follows the same procedure as in 5.1.3. The tests were applied to ensure that each of the four processes was compared one with another.

The results of these comparisons are summarised in Table 66.

Table 66

Number of Layers	Statistically Significant Differences
1	Powder Spray Welding Vs Oxy-acetylene Welding
2	Powder Spray Welding Vs TIG
2 Vs 1	Powder Spray Welding

One layer and two layer comparisons:

Inspection of Table 66 shows that statistically significant differences occurred only once in each of the two groups of six comparisons.

Two layer Vs one layer comparisons:

Inspection of Table 66 shows that a statistically significant difference occurred in only one of the four comparisons.

It is clear from the results of the surface hardness tests in Tables 41 - 44 that the application of a hardfaced coating by any of the four processes significantly increases the surface hardness when compared to the results for the cast iron substrate.

However, it is not possible from the statistical analysis to state categorically that, with one layer deposited, any one process provides better results than another. There is some indication that the Powder Spray Welding process may be the most satisfactory as it is shown to be significantly better in one of the comparisons.

It might be expected that the deposition of a second layer

of hardfacing alloy would provide a better basis for comparison. Any influence of dilution by the substrate should be diminished by the deposition of the second layer.

Although the surface hardness test results show, that the 2 layer deposits provide a better surface hardness than the 1 layer deposits, this was only shown to be statistically significant with the Powder Spray Welding process.

5.3 Macro Hardness Profile Tests

The average macro-hardness results presented in Tables 45 - 52 were used to produce graphs which are shown in Figures 4.26 to 4.29.

From the figures it can be seen that, as could be expected, a general form of hardness profile was obtained. A high macro-hardness was obtained at the surface zone and this decreased with increasing distance from the surface until the hardness level of the substrate was reached.

In all the processes the starting hardness was generally higher for the 2 layer deposits than for the 1 layer deposits. It can also be seen that the rate of decline is more pronounced for the Thermal Spraying and Powder Spray Welding processes than the other two welding processes. The reason for this is that the welding processes provide a thicker coating and, although the hardness values are not as high as the spraying processes, due to dilution, this hardness is maintained for a greater depth.

5.4 Electron Probe Microanalysis (EPMA)

The approximate percentages of Ni, Cr, Si and Fe presented in Tables 53 - 56 were used to provide an indication of the presence and degree of dilution of the hardfacing alloy by the cast iron substrate.

From the results it can be seen that dilution occurs in

all the deposits but is most evident in the welded deposits.

In the 1 layer and 2 layer deposits the percentage of Ni present in the interface area was 0.009% for both the Thermal Sprayed and Powder Spray Welded deposits, 2% in the Oxy-acetylene Welded deposits and 4% with the TIG welded deposits. The percentage of Ni then increased rapidly into the alloy until a constant level was reached. For the 1 layer deposits this was: Thermal Sprayed 56%; Powder Spray Welded 53%; Oxy-acetylene welding 45%; and TIG welding 44%. For the 2 layer deposits the percentage of Ni was: Thermal Spraying 78%; Powder Spray Welding 77%; Oxy-acetylene Welding 58% and TIG welding 53%. The 2 layer deposits showed a higher percentage of Ni in the alloy than did the 1 layer deposits. This was true for all the processes but the sprayed deposits showed a higher Ni percentage in the alloy than the welded deposits.

There was no evidence of the presence of Cr in the bond layer of either the 1 layer or 2 layer deposits produced by Thermal spraying or Powder Spray Welding. However, 1% Cr was detected in the bond area of the Oxy-acetylene deposit and 2% Cr in the TIG welded deposit. The Cr content then increased gradually from the interface to the body of the deposit finally reaching a constant value which was, for the 1 layer deposits: Powder spray welding 14%, Thermal spraying 13%, Oxy-acetylene welding 11% and TIG welding 7%, and for the 2 layer deposits: Powder spray welding 20%, Thermal spraying 17%, Oxy-acetylene welding 13% and TIG welding 11%. The 2 layer deposits showed a higher percentage of Cr in the alloy than the 1 layer deposits for all the processes and the sprayed deposits showed a higher percentage of Cr in the alloy than the welded deposits.

The percentage of Si present in the interface area for

both the 1 layer and 2 layer deposits was: Oxy-acetylene welding 0.003%; Powder spray welding 0.009%; and for both Thermal spraying and TIG welding 1%. The amount of Si present in the body of the deposit was 1% for the 1 layer deposits produced by each of the four methods and 2% for the 2 layer deposits.

The percentage of Fe present in the interface area was different for the 1 layer and 2 layer deposits. In the 1 layer deposits the percentage of Fe present was: Thermal spraying 4%; Powder spray welding 5%; Oxy-acetylene welding 10% and TIG welding 17%. In the 2 layer deposits the percentage of Fe present was: Thermal spraying and Powder spray welding 4%; Oxy-acetylene welding 6% and TIG welding 10%. There was a gradual decrease in Fe with distance from the interface until a constant percentage was reached in the body of the deposit. For the 1 layer deposits this was: Thermal spraying and Powder spray welding 4%; Oxy-acetylene welding 8% and TIG welding 11%. In the 2 layer deposits the percentage of Fe was: Thermal spraying and Powder spray welding 3%; Oxy-acetylene welding 5% and TIG welding 8%. The 2 layer deposits showed a lower percentage of Fe in the alloy than did the 1 layer deposits and the sprayed deposits showed a lower percentage of Fe than did the welded deposits.

From these results it can be seen that the sprayed deposits show less dilution of the hardfacing alloy by the substrate than the welded deposits. Furthermore, the amount of dilution is less for the 2 layer deposits in both the sprayed and welded deposits.

5.5 Optical Microscopy

The photomicrographs for the coatings produced by Thermal

spraying and Powder spray welding and shown in Plates 4.1, 4.2, 4.5 and 4.6 display a fine structure consisting of boride and carbide particles uniformly distributed throughout the matrix of the alloy. The boride and carbide particles are responsible for most of the hardness and abrasion resistance of the hardfaced coatings. The fine structure can be attributed to the minimum heat input associated with the processes which results in a fast cooling rate in the coating.

An excellent metallurgical bond appears to exist between the hardfaced coatings and grey cast iron substrate and none of the graphite, in the grey cast iron matrix, appears to have been burned out. The degree of dilution is seen to be low as is indicated by the narrow band representing the interface between the coating and matrix of the cast iron.

In the Thermal sprayed deposit some spherical non-metallic inclusions are visible, these appear to be isolated slag particles which could have formed through the action of the boron and silicon fluxing agents producing oxides and/or borates during the Thermal spraying process. The reason for their presence could be due to the relatively low temperature of the Thermal spraying process being insufficient to disperse away all these materials.

The photomicrographs for the coatings produced by Oxy-acetylene welding and TIG welding and shown in Plates 4.9, 4.10, 4.13 and 4.14 display a coarse structure which is made up of boride and carbide particles which have been distributed unevenly throughout the matrix of the alloy. The boride and carbide particles are responsible for most of the hardness and abrasion resistance of the hardfaced coating.

The coarse structure can be attributed to the high heat

input associated with these processes which produces a slow cooling rate in the coating.

An excellent metallurgical bond appears to have been achieved between the hardfaced coating and the grey cast iron substrate. Despite the higher heat input of these processes very little graphite, if any appears to have been burned out of the cast iron. The degree of dilution in the Oxy-acetylene welding deposit appears to be lower than that in the TIG process. The higher dilution of the TIG process is indicated by a broader and more uneven band representing the interface between the coating and matrix of the cast iron, Plate 4.16. This unevenness or irregular band could also be caused by grit blasting prior to hardfacing. (45)

Some voids are visible in the Oxy-acetylene welding deposits and because of their shape and size would appear to be gas holes, possibly caused by entrapped gases during the deposition process.

5.6 Operator Factor

The different procedures required for each of the processes were described in section 3.5. These procedures require various degrees of operator input and skill and this may influence the quality of the coatings deposited and, consequently, the results of this investigation. In this section some attempt, whilst inevitably subjective, is made to quantify and comment on these factors.

5.6.1 Thermal Spraying

The Thermal Spraying process required a good knowledge of welding to set up the equipment but only minimal operator skills to deposit the alloy. The speed of alloy deposition was very fast and large areas could be covered quickly.

The surface finish was extremely smooth, clean, free of porosity and specimen preparation required a minimum of surface grinding. The thickness of the deposited coatings ranged from 1.0 mm, for the 1 layer deposit, to 1.5 mm for the 2 layer deposit.

5.6.2 Powder Spray Welding

This process required a good knowledge of welding to set up the equipment but only minimal operator skills to deposit the alloy. The speed of alloy deposition was fast and large areas could be covered quickly.

The surface finish was smooth, clean, free of porosity and specimen preparation required a minimum of surface grinding. The thickness of the deposited coatings ranged from 2.0 mm, for the 1 layer deposit, to 2.8 mm for the 2 layer deposit.

5.6.3 Oxy-acetylene Welding

The Oxy-acetylene process required a good knowledge of welding to set up the equipment and a high level of operator skills to deposit the alloy. The speed of alloy deposition was slow although a large area could be covered.

The surface finish was porous, rough and dirty in appearance. The specimen was distorted by the high heat input and slow travel speed and required considerable surface grinding to achieve a smooth finish. The thickness of the deposited coatings ranged from 3.0 mm, for the 1 layer deposit, to 4.0 mm for the 2 layer deposit.

5.6.4 Tungsten Inert Gas Welding

Like the Oxy-acetylene process a good knowledge of welding is required to set up the equipment and a high level of operator skills to deposit the alloy. The speed of alloy deposition was slow although a large area could be covered.

The surface finish was reasonably smooth, clean and free of porosity. The specimen was slightly distorted by the high heat input and slow travel speed, but preparation of the specimen required only minimal surface grinding. The thickness of the deposited coatings ranged from 3.0 mm, for the 1 layer deposit, to 4.0 mm for the 2 layer deposit.

5.7 Discussion Summary

After deposition by all four processes of the hardfacing alloy, an excellent metallurgical bond existed between the hardfaced coatings and the grey cast iron substrate. None of the graphite in the matrix of the grey cast iron appeared to have been burned out, despite the high heat input from the welding processes. The heat input from the processes determined the structure of the alloy by influencing the cooling rate. The spraying processes produced a lesser heat input which produced a fast cooling rate and gave a fine structure, whereas the welding processes provided a high heat input which produced a slow cooling rate resulting in a coarse structure.

These structures consist of boride and carbide particles which are distributed throughout the matrix of the alloy and are responsible for most of the hardness and abrasion resistance. The fine structure of the sprayed coatings showed a uniform distribution of these particles in the matrix, whereas the coarse structure of the welded coatings showed an uneven distribution of the particles in the matrix.

The surface hardness tests showed the hardness of the hardfaced coatings to be between 2.25 and 3.5 times higher than the grey cast iron substrate. This hardness decreased with increasing distance from the surface until the hardness of the substrate was reached. Dilution of the coating by the substrate

was expected to occur, especially in the one layer coatings deposited by the welding processes. This was shown to be the case by the EPMA results. Although it might be expected that the deposition of a second layer of coating would be beneficial in overcoming the problem of dilution, statistical significance testing showed this only to be so in the case of Powder Spray Welding.

Although surface hardness is said to be a poor guide to abrasion life (35), which derives principally from the structure, hardness is a major factor and this explains why materials hardened on the surface are used wherever possible for wearing surfaces. It is clear from the results that the application of a hardfaced coating by any of the four processes significantly improves the wear resistance when compared with the results for the grey cast iron substrate.

Inspection of the wear test results suggests that the processes can be ranked in order of performance and that 2 layer deposits provide better wear resistance. However, statistical analysis did not identify an obvious best overall process, although there were good indications that the Powder Spray Welding process was a strong candidate for the best process and TIG welding was the worst.

From the practical and economic viewpoints the spraying processes produced a controlled, thinner coating with a smoother surface finish with minimal dilution by the substrate. These coatings required less surface grinding to produce a uniform finish and would therefore be particularly suitable for close tolerance engineering applications. Minimal operator welding skills are required by the spraying processes, when compared with the welding processes, and the training of personnel would

not be difficult. The statistical analysis showed that the deposition of 2 layers of coating did not significantly improve wear resistance and this is an important finding from the economic viewpoint.

The Powder Spray Welding process is based on the use of Oxy-acetylene welding equipment and both processes are inexpensive, versatile and portable. In comparison the Thermal Spraying and TIG Welding processes and equipment are more expensive and less versatile.

On the basis of the results of the investigation and the ease of use the Powder Spray Welding process could be most strongly recommended. However, the use of the other processes should not be excluded as the choice of a process depends on the job specifications and consideration must be given to the following:

1. Cost
2. Component design (shape, size, thickness etc.)
3. Thickness of coating required
4. Type of surface finish required

CHAPTER 6

CONCLUSIONS

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CONCLUSIONS

1. The investigation proved that a Ni - Cr - B hardfacing alloy could be successfully deposited, by each of the four processes considered, onto grey cast iron substrate without burning out essential elements, such as graphite, from the cast iron.
2. The application of a hardfacing alloy coating reduced abrasive wear to between 2% and 55% of that experienced by the cast iron substrate. The actual improvement depending upon the coating process, the number of layers and the wear test conditions (load and number of scratches).
3. The results of the wear test programme were consistent in showing that wear volume increased with both increased load and increased test duration.
4. Statistical analysis of the wear test results did not show a clear and consistent ranking of processes with respect to wear resistance. However, there was some evidence to show that the best results were achieved with the Powder Spray Welding process and the worst with the Tungsten Inert Gas Welding process.
5. Statistical analysis of the wear test results showed that there was in general no benefit to be gained by applying two layers of hardfacing alloy rather than one layer.
6. The surface hardness of the hardfaced coatings was between 2.25 and 3.5 times greater than that of the cast iron substrate, depending on the process and the number of layers deposited.

7. Statistical analysis of the surface hardness tests did not show that any one of the processes was consistently the best. However, there was some evidence to show that the Powder Spray Welding process produced the better results. The improvement in surface hardness obtained when two layers rather than one layer were applied by the Powder Spray Welding process was shown to be statistically significant.

8. The macro hardness profile tests showed that the highest values were obtained in the surface zone and that hardness decreased with increasing distance from the surface until the hardness level of the substrate was reached. The rate of decline in hardness was more pronounced in the Powder Spray Welding and Thermal Spraying processes than it was in the Oxy-acetylene and TIG welding processes.

9. The EPMA results provided evidence that there was some dilution of the hardfacing coating by the substrate and that this was most pronounced in the Oxy-acetylene and TIG welded deposits.

10. From the optical microscopy evidence each of the processes produced an excellent bond between the hardfacing coating and the substrate. There was no evidence of graphite having being burned out of the substrate.

11. A fine metallurgical structure was observed in the coatings deposited by the Powder Spray Welding and Thermal Spraying processes whereas a coarse structure was observed in the coatings deposited by the Oxy-acetylene and TIG welding processes. The difference can be attributed to the higher heat input and slower solidification rates associated with the latter two processes.

12. Each of the processes required a good knowledge of welding ...

procedures to set up the equipment. However, minimum operator skills were required by either the Powder Spray Welding or Thermal Spraying processes to produce a fast rate of deposition and a smooth, clean, pore-free deposit. A higher level of operator skill was required for the Oxy-acetylene and TIG welding processes and the Oxy-acetylene process produced the least satisfactory deposit with associated distortion.

CHAPTER 7

SUGGESTIONS FOR FURTHER WORK

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SUGGESTIONS FOR FURTHER WORK

Suggestions for further work can be made from the investigation, these are:

1. The requirement for mechanical strength of hardfaced coatings vary widely according to the particular service conditions of the component. Further work could be carried out in testing the Tensile strength of the bond and internal strength of the deposit. These tests would add a valuable extension of knowledge to the work already discussed in the investigation.

The tests would consist of depositing the hardfaced coatings onto one face of a purposely designed specimen. This coating would then be joined by a recommended adhesive (75) to the face of a second purposely designed specimen and then measuring the force required to pull the two specimens apart. A device for holding the specimens would have to be designed and manufactured to fit a standard Tensile testing machine.

2. In the investigation only one grade of cast iron was used as the substrate. Further work could be carried out using other grades and types of cast irons especially the alloyed and unalloyed white cast irons, which have a problem with cracking during repair by welding.

The main causes of cracking are due to:

1. Expansion and contraction caused by localized heat input which exceeds a threshold limit.
2. The contracting weld bead creating high tensile strains on the Heat Affected Zone, during cooling.

Further work carried out by using the same or similar

processes to those in the investigation, especially the spraying processes which are relatively cold processes and a low melting temperature hardfacing alloy could help to overcome problems when repairing or reclaiming cast irons to resist abrasive wear.

REFERENCES

References

1. BS 1452 : 1977, British Standards Institute
2. Analytical Report, Fosco International Ltd.
3. Deloro Stellite Ltd., Booklet No. B39, 1968, December, p 8
4. Metco Bulletin 126, E8500/6/60, 1957 January
5. Wall Colmonoy Ltd. Report, Surface Engineering, 1985, V1, 3, pp 167-168
6. Wall Colmonoy Ltd. Report, Metals and Materials, 1985, July V1, 7, p 443
7. D. Ellis and R. L. Squires, Metal Construction, 1983, July, 15, 7, pp 388-393
8. N. J. Allnat and G. R. Bell, International Colloquium on Hardfacing Materials in Nuclear Power Plants, Avignon, France, 1980, September 25th-26th pp 57-64
9. A. Matting, British Welding Journal, 1966, September, V13, 9, pp 526-532
10. M. Riddiough, Metal Construction and British Welding Journal, 1969, March, V1, 3, pp 126-129
11. A. C. Davies, The Science and Practice of Welding, Cambridge University Press, 1984, V2, pp 56-62
12. E. Wallace, Welding and Metal Fabrication, 1959, January, V27, 1, pp 5-13
13. R. L. Baker, Welding Journal, 1982, July, V61, pp 42-44
14. K. H. Koopman and R. S. Zuchowski, Welding Journal, 1956, July, V35, pp 665-671
15. T. Ellis and G. G. Garrett, Surface Engineering, 1986, V2, 1, pp 55-66
16. A Welding Institute Seminar, Metal Construction, 1975, December, V7, 12, p 616

17. G. R. Bell, Materials and Design, 1983, June/July, V4, pp 785-790
18. T. S. Eyre, Powder Metallurgy, 1961, 2, pp 57-63
19. W. O. Alexander, The Metallurgist and Materials Technologist 1960, September, V12, pp 505-507
20. J. Stromberg, Welding and Metal Fabrication, 1982, June, V50, 6, pp 212-215
21. T. H. Shalles, Chartered Mechanical Engineer, 1983, September, V50, 9, pp 56-58
22. E. N. Gregory, Welding and Metal Fabrication, 1954, July, V27, 7, pp 272-273
23. I. Hoff, Finishing, 1962, October, V6, 10, pp 26-28
24. H. L. Morgan, Joining of Iron Castings BCIRA, Conference at Loughborough University of Technology, 1970, April, pp 403-413
25. M. L. Page, Metal Construction and British Welding Journal 1969, August, V1, 8, pp 392-393
26. F. E. Bonner and R. A. Cresswell, British Welding Journal, 1963, May, V10, pp 205-211
27. Deloro Stellite Ltd., B43/E, 1974, March, p 7
28. H. S. Ingham and A. P. Shepard, Metco Metallizing Handbook, V11, Powder process, p B33
29. L. F. Spencer, Welding Engineer, 1970, November, pp 39-48
30. G. R. Bell, Corrosion Technology, 1961, March, V8, pp 65-76
31. W. P. Clarke, Welding Journal, 1961, July, V60, pp 27-29
32. G. R. Bell, British Welding Journal, 1963, April, V10, 4, pp 150-158
33. W. J. Burling-Smith, Welding and Metal Fabrication, 1959, February, V27, 2, pp 54-60
34. G. R. Bell, Chemical Processing, 1964, September, VX, 9, pp 80-85

35. J. G. Barrington-Stiles, British Welding Journal, 1963, April, V10, 4, pp 111-116
36. A. C. Davies, The Science and Practice of Welding, Cambridge University Press, 1984, V1, p 13
37. Council of Iron Foundry Association, Booklet 14, Pall Mall, London
38. H. S. Ingham and A. P. Shepard, Metco Metallizing Handbook, p B29
39. R. L. Apps, British Welding Journal, 1967, December, V14, p 627
40. J. G. Barrington-Stiles, British Welding Journal, 1962, June, V9, pp 367-370
41. W. E. Ballard, British Welding Journal, 1962, June, V9, 6, pp 363-364
42. The Commonwealth Industrial Gases Ltd., Process Information, No. 1, pp 1-16
43. C. E. Jones and H. Griffiths, British Welding Journal, 1963, November, V10, 11, pp 546-551
44. H. S. Ingham and A. P. Shepard, Metco Metallizing Handbook, p B3
45. M. Riddiough, British Welding Journal, 1962, May, V9, pp 285-290
46. E. N. Gregory, Metal Construction, 1980, December, V12, pp 685-690
47. E. N. Simons, Metal Wear a Brief Outline, Fredrick Muller Ltd., 1972
48. C. Lipson, Wear Considerations in Design, Prentice Hall, 1967
49. A. J. Clegg, M.Sc Thesis, Loughborough University of Technology, 1976

50. T. S. Eyre, Metals Technology, 1984, March, V11, pp 81-90
51. J. K. Lancaster, Institute of Metal Finishing, 1978, February, V56, pp 145-153
52. C. Sharpe, Design Engineering, 1983, December, pp 41-44
53. C. R. Weymueller, Welding Design and Fabrication, 1983, February, pp 37-46
54. H. S. Ingham and A. P. Shepard, Metco Flame Spray Handbook, V1, p A213
55. Health and Safety Executive, Booklet 50, 1977
56. BS 638 : 1966 British Standards Institute
57. Department of Employment and Productivity, Booklet 38, 1970
58. Protection of Eyes Regulations, 1974, H.M.S.O. No. 1681
59. J. R. Franklin, Welding Review, 1983, February, V2, 1, pp 13-15
60. H. S. Ingham and A. P. Shepard, The Flame Spray Handbook 1964, pp A3-A5
61. B. E. Paton, British Welding Journal, 1966, April, V13, 4, pp 201-206
62. Metco Type 2P Thermospray Gun, Instruction Manual, Cat. No. P777, 1965
63. The Commonwealth Industrial Gases Ltd., Form No. 1270492, 1984, March, pp 26-29
64. F. Koenigsberger and R. Adair, Welding Technology, Macmillan and Company Ltd., London, 1965
65. A. C. Davies, The Science and Practice of Welding, Cambridge University Press, 1984, V2, pp 261-262
66. A. C. Davies, The Science and Practice of Welding, Cambridge University Press, 1984, V2, pp 154-155
67. M. S. Polyak, Welding Production, 1963, V10, pp 41-42

68. D. Reddy and B. S. Nau, Wear Testing, The British Hydromechanics Research Association, T.N. 940, 1968, March, p 28
69. H. R. Shetty, T. H. Kosel and N. F. Fiore, Wear, 1982, 80, pp 347-376
70. P. R. Gibson, Ph.D Thesis, Loughborough University of Technology, 1984
71. Razavizadeh and B. L. Davies, Wear, 1981, 69, pp 355-367
72. Minoru Okada and Hiroshi Maruo, British Welding Journal, 1968, August, V15, 8, p 373
73. BS 1295 : 1959, British Standard Institute
74. T. S. Eyre and F. Wilson, Lubrication Engineering, 1973, February, V2, pp 65-72
75. Metco Research Laboratory Report 106, 1973, p 9 3
76. W. E. Duckworth, Statistical Techniques in Technological Research: An Aid to Research Productivity, Methuen, London, 1968, p 27

APPENDIX 1

APPENDIX 1

WEAR VOLUME FOR RECIPROCATING DIAMOND TEST

Derivation: (Ref. FIG. 13)

The wear tract was assumed to be a similar form to the diamond, i.e. 120° inc. angle

0.2 mm tip radius

$$\tan 60 = \frac{\frac{1}{2} w/h}{1} = w/2h$$

$$2h = \frac{w}{\tan 60}$$

$$\text{Hence } h = \frac{w}{2\sqrt{3}}$$

$$\begin{aligned}\text{Area } \triangle ABC &= \frac{1}{2} w \times \frac{w}{2\sqrt{3}} \\ &= 0.144w^2 \text{ mm}^2\end{aligned}$$

$$\text{Area } \triangle EFC = 0.069 \times DC$$

$$\tan 60 = \frac{0.069}{DC}$$

$$\text{Hence } DC = \frac{0.069}{\sqrt{3}} = 3.98 \times 10^{-2}$$

$$\begin{aligned}\text{Area } \triangle EFC &= 0.069 \times 3.98 \times 10^{-2} \\ &= 2.75 \times 10^{-3} \text{ mm}^2\end{aligned}$$

$$\sin \frac{\theta}{2} = \frac{0.069}{0.2} \quad \frac{\theta}{2} = 20.18^\circ$$

$$\theta = 40.36^\circ$$

$$\begin{aligned}
 \text{Area Segment GEHF} &= \frac{40.36}{360} \times \pi \times 0.2^2 \\
 &= 1.41 \text{ mm}^2 \times 10^{-2} \\
 x &= \sqrt{(0.2^2 - 0.069^2)} \\
 &= 0.188 \text{ mm}^2
 \end{aligned}$$

$$\begin{aligned}
 \text{Area } \Delta \text{ GEF} &= 0.069 \times 0.188 \\
 &= 1.297 \times 10^{-2} \text{ mm}^2
 \end{aligned}$$

$$\begin{aligned}
 \text{Area EDHF} &= 1.41 \times 10^{-2} - 1.297 \times 10^{-2} \\
 &= 1.12 \times 10^{-3} \text{ mm}^2
 \end{aligned}$$

Volume of scratch

$$\begin{aligned}
 &= (\text{Area } \Delta \text{ ABC} - \text{Area } \Delta \text{ EFC} + \text{Area} \\
 &\quad \text{EDHF}) \times \text{stroke length} \\
 &= (0.144w^2 - 2.75 \times 10^{-3} + 1.12 \\
 &\quad \times 10^{-3}) \times \text{stroke length} \\
 &= (0.144w^2 - 1.63 \times 10^{-3}) \times L
 \end{aligned}$$

APPENDIX 2

Table 1

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.5080	1.421	1.745	0.8382	3.981	2.798	0.7366	3.060	4.166
	0.5080	1.421		0.6604	2.446		0.8128	3.740	
	0.5588	1.733		0.6096	2.075		0.9652	5.300	
	0.6096	2.075		0.6858	2.643		0.9144	4.750	
	0.6096	2.075		0.7112	2.848		0.8382	3.981	
2	0.6096	2.075	1.705	0.6096	2.075	3.130	1.0922	6.805	5.880
	0.5588	1.733		0.7366	3.060		0.9652	5.300	
	0.5334	1.573		0.7112	2.848		1.1430	7.459	
	0.5334	1.573		0.8636	4.230		0.9144	4.750	
	0.5334	1.573		0.8128	3.740		1.0160	5.088	
3	0.6858	2.643	2.499	0.7874	3.505	3.695	1.1176	7.129	5.959
	0.6604	2.446		0.7874	3.505		1.0160	5.880	
	0.6350	2.272		0.8382	3.981		1.0414	6.181	
	0.6096	2.075		0.8382	3.981		0.9906	5.587	
	0.7366	3.060		0.7874	3.505		0.9398	5.022	
4	0.4826	1.276	1.586	0.7874	3.505	3.250	0.9652	5.300	5.300
	0.6096	2.075		0.7620	3.279		0.9652	5.300	
	0.5588	1.733		0.7366	3.060		0.9652	5.300	
	0.5334	1.573		0.7366	3.060		0.9652	5.300	
	0.4826	1.276		0.7112	2.848		0.9652	5.300	
5	0.5080	1.421	2.042	0.6858	2.643	3.295	1.1176	7.129	5.959
	0.6096	2.075		0.7112	2.848		1.0160	5.880	
	0.5080	1.421		0.8128	3.740		1.0414	6.181	
	0.7112	2.848		0.8128	3.740		0.9906	5.587	
	0.6604	2.446		0.7874	3.505		0.9398	5.022	

Grey Cast Iron

10 Scratches

Table 2

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4572	1.138	1.935	0.6858	2.643	4.137	1.1430	7.459	7.846
	0.6604	2.446		0.9906	5.587		1.3208	9.983	
	0.5334	1.573		0.8128	3.740		1.2192	8.496	
	0.6604	2.446		0.8890	4.487		1.0922	6.805	
	0.6096	2.075		0.8636	4.230		1.0668	6.490	
2	0.6658	2.643	3.295	1.1176	7.129	5.959	1.1938	8.143	8.529
	0.7112	2.848		1.0160	5.880		1.0922	6.805	
	0.8128	3.740		0.9398	5.022		1.2446	8.857	
	0.8128	3.740		1.0414	6.181		1.2446	8.857	
	0.7874	3.505		0.9906	5.587		1.3208	9.983	
3	0.7874	3.505	5.695	0.9906	5.587	6.321	1.2446	8.857	8.857
	0.7874	3.505		1.1176	7.129		1.2446	8.857	
	0.8582	3.981		1.1176	7.129		1.2446	8.857	
	1.8382	3.981		1.0160	5.880		1.2446	8.857	
	0.7874	3.505		1.0160	5.880		1.2446	8.857	
4	0.6350	2.272	2.788	0.8636	4.230	4.487	1.0414	6.181	6.318
	0.7112	2.848		0.9398	5.022		1.1176	7.129	
	0.6858	2.643		0.8890	4.487		1.0668	6.490	
	0.6858	2.643		0.9652	5.300		1.0668	6.490	
	0.7874	3.437		0.9652	5.300		0.9652	5.300	
5	0.7366	3.060	3.560	0.8382	3.981	4.771	1.1430	7.459	8.081
	0.8128	3.740		1.0160	5.880		1.1430	7.459	
	0.9144	4.750		0.9398	5.022		1.2192	8.496	
	0.8382	3.981		0.8890	4.487		1.2192	8.496	
	0.6350	2.272		0.8890	4.487		1.2192	8.496	

Grey Cast Iron

50 Scratches

Table 3

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.7874	3.505	3.295	0.8636	4.023	5.481	1.2700	9.225	8.695
	0.7112	2.848		0.9398	5.022		1.3716	10.771	
	0.8128	3.740		1.0922	6.805		1.3716	10.771	
	0.8128	3.740		1.0922	6.805		0.8636	4.230	
	0.6358	2.643		0.9144	4.750		1.2192	8.496	
2	0.7874	3.505	3.695	1.1176	7.129	5.959	1.3208	9.983	
	0.7874	3.505		1.0160	5.880		1.2446	8.857	
	0.8382	3.981		0.9398	5.022		1.2700	9.225	
	0.8382	3.981		1.0414	6.181		1.2954	9.600	
	0.7874	3.505		0.9906	5.587		1.3208	9.983	
3	0.8128	3.740	4.391	1.0414	6.181	6.318	1.2700	9.225	
	0.8636	4.230		1.1176	7.129		1.3970	11.176	
	0.9144	4.750		1.0668	6.490		1.2446	8.857	
	0.8890	4.487		1.0668	6.490		1.1938	8.143	
	0.9144	4.750		0.9652	5.300		1.3716	10.771	
4	0.8636	4.230	4.542	1.1176	7.129	6.749	1.3208	9.983	9.529
	0.8636	4.230		1.1176	7.129		1.3208	9.983	
	0.9144	4.750		1.1176	7.129		1.2446	8.857	
	0.9144	4.750		1.0414	6.181		1.2954	9.600	
	0.9144	4.750		1.0414	6.181		1.2700	9.225	
5	1.0160	5.880	5.880	1.1176	7.129	6.999	1.3716	10.771	9.861
	1.0160	5.880		1.1176	7.129		1.3716	10.771	
	1.0160	5.880		1.1176	7.129		1.3716	10.771	
	1.0160	5.880		1.0922	6.805		1.2192	8.496	
	1.0160	5.880		1.0922	6.805		1.2192	8.496	

Grey Cast Iron

100 Scratches

Table 4

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	1.0922	6.805	5.830	1.1938	8.143	8.571	1.7526	17.627	16.638
	0.9652	5.300		1.2446	8.857		1.7526	17.627	
	1.1430	7.459		1.2446	8.857		1.7526	17.627	
	0.9144	4.750		1.1936	8.143		1.6256	15.156	
	1.0160	5.880		1.2446	8.857		1.6256	15.156	
2	1.1176	7.129	5.959	1.3208	9.983	9.529	1.7018	16.616	15.510
	1.0160	5.880		1.2446	8.857		1.4986	12.870	
	0.9398	5.022		1.2700	9.225		1.8034	18.667	
	1.0414	6.181		1.2954	9.600		1.5494	13.762	
	0.9906	5.587		1.3208	9.983		1.6510	15.635	
3	0.9906	5.587	6.321	1.1938	8.143	8.529	1.6256	15.156	16.638
	1.1176	7.129		1.0922	6.805		1.6256	15.156	
	1.1176	7.129		1.2446	8.857		1.7526	17.627	
	1.0160	5.880		1.2446	8.857		1.7526	17.627	
	1.0160	5.880		1.3208	9.983		1.7526	17.627	
4	1.0414	6.181	6.318	1.2700	9.225	9.634	1.5748	14.219	14.049
	1.1176	7.129		1.3970	11.176		1.6256	15.156	
	1.0668	6.490		1.2446	8.857		1.5748	14.219	
	1.0668	6.490		1.1938	8.143		1.5748	14.219	
	0.9652	5.300		1.3716	10.771		1.4732	12.435	
5	0.9906	5.587	6.185	1.3208	9.983	9.387	1.7780	18.143	17.131
	1.0414	6.181		1.2700	9.225		1.6784	16.160	
	1.0414	6.181		1.2954	9.600		1.7272	17.118	
	1.0668	6.490		1.1938	8.143		1.7272	17.118	
	1.0668	6.490		1.3208	9.983		1.7272	17.118	

Grey Cast Iron

500 Scratches

Table 5

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.1778	0.116		0.2286	0.235		0.2794	0.384	
	1.524	0.068		0.2286	0.235		0.2794	0.384	
	1.524	0.068	0.073	0.2540	0.306	0.249	0.2540	0.306	0.402
	1.270	Zero.		0.2286	0.235		0.3048	0.469	
	1.778	0.116		0.2286	0.235		0.3048	0.469	
2	0.1524	0.068		0.2540	0.306		0.3048	0.469	
	0.1778	0.116		0.2286	0.235		0.2794	0.384	
	0.2032	0.172	0.108	0.2540	0.306	0.263	0.2794	0.384	0.385
	0.1778	0.116		0.2286	0.235		0.2540	0.306	
	0.1524	0.068		0.2286	0.235		0.2794	0.384	
3	0.2032	0.172		0.2286	0.235		0.3302	0.562	
	0.2032	0.172		0.2286	0.235		0.2540	0.306	
	0.2286	0.235	0.184	0.2286	0.235	0.263	0.2794	0.384	0.184
	0.2032	0.172		0.2540	0.306		0.3048	0.469	
	0.2032	0.172		0.2540	0.306		0.3048	0.469	
4	0.1524	0.068		0.2032	0.172		0.2286	0.235	
	0.1524	0.068		0.2032	0.172		0.2032	0.172	
	0.1524	0.068	0.068	0.2286	0.235	0.209	0.2794	0.384	0.329
	0.1524	0.068		0.2286	0.235		0.2794	0.384	
	0.1524	0.068		0.2286	0.235		0.3048	0.469	
5	0.1524	0.068		0.2540	0.306		0.2794	0.284	
	0.1524	0.068		0.3048	0.469		0.2540	0.306	
	0.1524	0.068	0.122	0.2540	0.306	0.340	0.2794	0.384	0.422
	0.2032	0.172		0.2794	0.384		0.2794	0.384	
	0.2286	0.235		0.2286	0.235		0.3556	0.663	

Thermal Spraying 1 Layer Deposit 10 Scratches

Table 6

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.1524	0.068		0.2032	0.172		0.2540	0.306	
	0.1524	0.068		0.2032	0.172		0.2540	0.306	
	0.1778	0.116	0.064	0.2286	0.235	0.209	0.2540	0.306	0.306
	1.270	Zero		0.2286	0.235		0.2540	0.306	
	1.524	0.068		0.2286	0.235		0.2540	0.306	
2	0.1524	0.068		0.2032	0.172		0.2794	0.384	
	0.1524	0.068		0.1778	0.116		0.2794	0.384	
	0.1524	0.068	0.068	0.2286	0.235	0.151	0.2540	0.306	0.337
	0.1524	0.068		0.1778	0.116		0.2540	0.306	
	0.1524	0.068		0.1778	0.116		0.2540	0.306	
3	0.1016	Zero		0.1270	Zero		0.2794	0.384	
	0.1270	Zero		0.1016	Zero		0.3048	0.469	
	0.1016	Zero	Zero	0.1524	0.068	0.027	0.2032	0.172	0.300
	0.0762	Zero		0.1524	0.068		0.2032	0.172	
	0.1270	Zero		0.0162	Zero		0.2540	0.306	
4	0.1524	0.068		0.2286	0.235		0.2286	0.235	
	0.1524	0.068		0.2286	0.235		0.2032	0.172	
	0.1524	0.068	0.068	0.2286	0.235	0.235	0.3048	0.462	0.329
	0.1524	0.068		0.2286	0.235		0.3556	0.663	
	0.1524	0.068		0.2286	0.235		0.1778	0.116	
5	0.1016	Zero		0.1524	0.068		0.2540	0.306	
	0.1270	Zero		0.1524	0.068		0.2540	0.306	
	1.1016	Zero	Zero	0.1778	0.116	0.064	0.2540	0.306	0.306
	1.1016	Zero		0.1270	Zero		0.2540	0.306	
	1.1016	Zero		0.1524	0.068		0.2540	0.306	

Thermal Spraying

2 Layer Deposits

10 Scratches

Table 7

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2794	0.384	0.340	0.3048	0.469	0.586	0.4318	1.008	0.959
	0.3048	0.469		0.3048	0.469		0.4318	1.008	
	0.2540	0.306		0.3302	0.562		0.4318	1.008	
	0.2286	0.235		0.3810	0.770		0.4064	0.886	
	0.2540	0.306		0.3556	0.663		0.4064	0.886	
2	0.4064	0.886	0.613	0.3048	0.469	0.870	0.4572	1.138	1.283
	0.3556	0.663		0.3556	0.663		0.4318	1.008	
	0.3048	0.469		0.3556	0.663		0.4826	1.276	
	0.3556	0.663		0.4572	1.138		0.5334	1.573	
	0.2794	0.384		0.5080	1.421		0.5080	1.421	
3	0.2540	0.306	0.389	0.3302	0.562	0.522	0.3810	0.770	0.925
	0.3048	0.469		0.2540	0.306		0.5080	1.421	
	0.2286	0.235		0.2032	0.172		0.3556	0.663	
	0.3048	0.469		0.3302	0.562		0.4064	0.886	
	0.3048	0.469		0.4318	1.008		0.4064	0.886	
4	0.3048	0.469	0.586	0.3556	0.663	0.716	0.3810	0.770	1.099
	0.3048	0.469		0.5080	1.421		0.3556	0.663	
	0.3556	0.663		0.3556	0.663		0.4826	1.270	
	0.3810	0.770		0.3556	0.663		0.5842	1.900	
	0.3302	0.562		0.2032	0.172		0.4064	0.886	
5	0.2794	0.384	0.368	0.3556	0.663	0.582	0.4064	0.886	0.931
	0.2794	0.384		0.3556	0.663		0.4064	0.886	
	0.2540	0.306		0.3302	0.562		0.3048	0.469	
	0.2540	0.306		0.3302	0.562		0.4862	1.276	
	0.3048	0.462		0.3048	0.462		0.4572	1.138	

Thermal Spraying

1 Layer Deposit

50 Scratches

Table 8

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2450	0.306	0.384	0.3556	0.663	0.582	0.3810	0.770	0.819
	0.2540	0.306		0.3048	0.462		0.4064	0.886	
	0.3048	0.462		0.3556	0.663		0.3556	0.663	
	0.2794	0.384		0.3302	0.562		0.3810	0.770	
	0.3048	0.462		0.3302	0.562		0.4318	1.008	
2	0.2540	0.306	0.291	0.3810	0.886	0.611	0.3556	0.663	0.771
	0.2540	0.306		0.3302	0.562		0.3810	0.770	
	0.2540	0.306		0.3556	0.663		0.3810	0.770	
	0.2236	0.235		0.3302	0.562		0.4064	0.886	
	0.2540	0.306		0.2794	0.384		0.3810	0.770	
3	0.2794	0.384	0.353	0.3556	0.663	0.583	0.3556	0.663	0.899
	0.2794	0.384		0.3810	0.770		0.3556	0.663	
	0.2540	0.306		0.3302	0.562		0.4318	1.008	
	0.2540	0.306		0.3048	0.462		0.4626	1.276	
	0.2794	0.384		0.3048	0.462		0.4064	0.886	
4	0.2540	0.306	0.384	0.3048	0.469	0.565	0.4318	1.008	0.911
	0.2540	0.306		0.3048	0.469		0.3810	0.770	
	0.2794	0.384		0.3302	0.562		0.4318	1.008	
	0.3048	0.462		0.3556	0.663		0.4064	0.886	
	0.3048	0.462		0.3556	0.663		0.4064	0.886	
5	0.2540	0.306	0.385	0.3302	0.562	0.545	0.3556	0.663	0.730
	0.2794	0.384		0.3302	0.562		0.3810	0.770	
	0.2794	0.384		0.3048	0.469		0.3810	0.770	
	0.2794	0.384		0.3048	0.469		0.3302	0.562	
	0.3048	0.469		0.3556	0.663		0.4064	0.886	

Thermal Spraying 2 Layer Deposits 50 Scratches

Table 9

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3556	0.663		0.4572	1.138		0.4318	1.008	
	0.3556	0.663		0.4064	0.886		0.4318	1.008	
	0.4064	0.886	0.630	0.3810	0.770	1.020	0.4318	1.008	1.116
	0.3048	0.469		0.4064	0.886		0.4572	1.138	
	0.3048	0.469		0.5080	1.421		0.5080	1.421	
2	0.2540	0.306		0.3556	0.663		0.4318	1.008	
	0.2794	0.384		0.4064	0.886		0.3810	0.770	
	0.3048	0.469	0.419	0.3810	0.770	0.730	0.4318	1.008	0.911
	0.3048	0.469		0.3810	0.770		0.4064	0.886	
	0.3048	0.469		0.3302	0.562		0.4064	0.886	
3	0.3048	0.469		0.4064	0.886		0.4318	1.008	
	0.3556	0.663		0.4318	1.008		0.4064	0.886	
	0.3302	0.562	0.565	0.4572	1.138	0.873	0.5588	1.733	1.293
	0.3556	0.663		0.3810	0.770		0.5080	1.421	
	0.3048	0.469		0.3302	0.562		0.5080	1.421	
4	0.2794	0.384		0.4064	0.886		0.4826	1.276	
	0.3302	0.562		0.4318	1.008		0.4572	1.138	
	0.3048	0.469	0.438	0.4064	0.886	0.821	0.4826	1.276	1.193
	0.3048	0.469		0.3556	0.663		0.4572	1.138	
	0.2540	0.306		0.3556	0.663		0.5472	1.138	
5	0.2794	0.384		0.3810	0.770		0.4318	1.008	
	0.2794	0.384		0.3810	0.770		0.4318	1.008	
	0.2794	0.384	0.384	0.3302	0.562	0.645	0.4318	1.008	1.008
	0.2784	0.384		0.3302	0.562		0.4318	1.008	
	0.2794	0.384		0.3302	0.562		0.4318	1.008	

Thermal Spraying 1 Layer Deposit 100 Scratches

Table 10

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306	0.340	0.3302	0.562	0.673	0.4064	0.586	0.873
	0.3048	0.469		0.3556	0.663		0.3556	0.663	
	0.2794	0.384		0.4318	1.008		0.3810	0.770	
	0.2540	0.306		0.3556	0.663		0.4826	1.276	
	0.2286	0.235		0.3048	0.469		0.3810	0.770	
2	0.2794	0.384	0.492	0.4572	1.138	0.863	0.3556	0.663	1.026
	0.3302	0.562		0.4826	1.276		0.3810	0.770	
	0.3048	0.469		0.3810	0.770		0.4572	1.138	
	0.2794	0.384		0.3556	0.663		0.4572	1.138	
	0.3556	0.663		0.3048	0.469		0.5080	1.421	
3	0.1524	0.068	0.155	0.2540	0.306	0.340	0.3302	0.562	0.794
	0.2540	0.306		0.3048	0.469		0.3048	0.469	
	0.1778	0.116		0.2286	0.235		0.4572	1.138	
	0.1778	0.116		0.2540	0.306		0.4572	1.138	
	0.2032	0.172		0.2794	0.384		0.3556	0.663	
4	0.2540	0.306	0.384	0.3048	0.469	0.565	0.4064	0.586	0.873
	0.2540	0.306		0.3556	0.663		0.4318	1.008	
	0.2794	0.384		0.3302	0.562		0.4572	1.138	
	0.3048	0.462		0.3556	0.663		0.3810	0.770	
	0.3048	0.462		0.3048	0.469		0.3302	0.562	
5	0.3048	0.469	0.492	0.4064	0.886	0.819	0.4572	1.138	1.267
	0.3302	0.562		0.4318	1.008		0.4318	1.008	
	0.2794	0.384		0.3810	0.770		0.5334	1.573	
	0.2794	0.384		0.4064	0.886		0.5588	1.733	
	0.3556	0.663		0.3556	0.663		0.4064	0.886	

Thermal Spraying 2 Layer Deposits 100 Scratches

Table 11

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3302	0.562	0.923	0.6858	2.643	2.037	0.6604	2.446	2.903
	0.3810	0.770		0.6096	2.075		0.6604	2.446	
	0.4572	1.138		0.7874	3.437		0.8128	3.740	
	0.4572	1.138		0.7874	3.437		0.7874	3.437	
	0.4318	1.008		0.6858	2.643		0.6604	2.446	
2	0.5334	1.573	1.972	0.5334	1.573	3.154	0.8382	3.981	4.720
	0.7366	3.060		0.7112	2.848		1.0160	5.880	
	0.5588	1.733		1.0922	6.805		0.9398	5.022	
	0.6096	2.075		0.6858	2.643		0.8890	4.487	
	0.5080	1.421		0.5842	1.900		0.8636	4.230	
3	0.5334	1.573	1.887	0.6858	2.643	2.968	0.7874	3.437	3.763
	0.5334	1.573		0.8128	3.740		0.7874	3.437	
	0.5334	1.573		0.7620	3.279		0.8382	3.981	
	0.6350	2.272		0.7620	3.279		0.8382	3.981	
	0.6604	2.446		0.5842	1.900		0.8382	3.981	
4	0.5334	1.573	1.623	0.6350	2.272	2.582	0.7874	3.437	3.851
	0.5334	1.573		0.6350	2.272		0.7620	3.279	
	0.5080	1.421		0.6858	2.643		0.8382	3.981	
	0.4826	1.276		0.6604	2.446		0.8636	4.230	
	0.6350	2.272		0.7620	3.279		0.8636	4.230	
5	0.4826	1.276	1.551	0.7366	3.060	2.497	0.9398	5.022	3.575
	0.4826	1.276		0.5581	1.733		0.6604	2.446	
	0.5588	1.733		0.7366	3.060		0.6604	2.446	
	0.5842	1.900		0.7366	3.060		0.8382	3.981	
	0.5334	1.573		0.5334	1.573		0.8382	3.981	

Thermal Spraying

1 Layer Deposit

500 Scratches

Table 12

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4064	0.886	0.988	0.5080	1.421	2.042	0.6350	2.272	2.768
	0.4826	1.276		0.6096	2.075		0.7112	2.848	
	0.4064	0.886		0.5080	1.421		0.6858	2.643	
	0.4064	0.886		0.7112	2.848		0.6858	2.643	
	0.4318	1.008		0.6604	2.446		0.7874	2.437	
2	0.3048	0.469	0.728	0.4826	1.276	1.586	0.7366	3.060	3.560
	0.4826	1.276		0.6096	2.075		0.8128	3.740	
	0.3302	0.562		0.5588	1.733		0.9144	4.750	
	0.3810	0.770		0.5334	1.573		0.8382	3.981	
	0.3302	0.562		0.4826	1.276		0.6350	2.272	
3	0.5334	1.573	1.887	0.6858	2.643	2.499	0.7874	3.437	3.135
	0.6350	2.272		0.7366	3.060		0.7620	3.279	
	0.6604	2.446		0.6604	2.446		0.7112	2.848	
	0.5334	1.573		0.6350	2.272		0.7366	3.060	
	0.5334	1.573		0.6096	2.075		0.7366	3.060	
4	0.4826	1.276	1.382	0.5334	1.573	2.182	0.8382	3.981	2.798
	0.4064	0.886		0.5334	1.573		0.6604	2.446	
	0.5334	1.573		0.6350	2.272		0.6096	2.075	
	0.5842	1.900		0.7112	2.848		0.7112	2.848	
	0.4826	1.276		0.6858	2.643		0.6858	2.643	
5	0.4064	0.886	0.620	0.4572	1.138	1.043	0.5080	1.421	2.080
	0.4064	0.886		0.4572	1.138		0.5080	1.421	
	0.2794	0.384		0.3558	0.663		0.6350	2.272	
	0.2794	0.384		0.4572	1.138		0.6858	2.643	
	0.3302	0.562		0.4572	1.138		0.6858	2.643	

Thermal Spraying 2 Layer Deposits 500 Scratches

Table 13

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.1524	0.068	0.108	0.2286	0.235	0.263	0.3556	0.663	0.459
	0.1524	0.068		0.2286	0.235		0.3302	0.562	
	0.1778	0.116		0.2286	0.235		0.2794	0.384	
	0.1778	0.116		0.2540	0.306		0.2794	0.384	
	0.2032	0.172		0.2540	0.306		0.2540	0.306	
2	0.2286	0.235	0.279	0.3556	0.663	0.459	0.2286	0.235	0.874
	0.2286	0.235		0.3302	0.562		0.2540	0.306	
	0.2286	0.235		0.2794	0.384		0.4826	1.276	
	0.2540	0.306		0.2794	0.384		0.4826	1.276	
	0.2794	0.384		0.2540	0.306		0.4826	1.276	
3	0.2032	0.172	0.184	0.2286	0.235	0.263	0.2794	0.384	0.688
	0.2032	0.172		0.2286	0.235		0.4064	0.886	
	0.2032	0.172		0.2540	0.306		0.3556	0.663	
	0.2032	0.172		0.2540	0.306		0.4318	1.008	
	0.2286	0.235		0.2286	0.235		0.3302	0.502	
4	0.1524	0.068	0.108	0.2286	0.235	0.235	0.2794	0.384	0.384
	0.1524	0.068		0.2286	0.235		0.2794	0.384	
	0.1778	0.116		0.2286	0.235		0.2794	0.384	
	0.1778	0.116		0.2286	0.235		0.2794	0.384	
	0.2032	0.172		0.2286	0.235		0.2794	0.384	
5	0.1524	0.068	0.108	0.2286	0.235	0.263	0.3302	0.562	0.438
	0.1524	0.068		0.2286	0.235		0.3048	0.469	
	0.1778	0.116		0.2286	0.235		0.3048	0.469	
	0.1778	0.116		0.2540	0.306		0.2540	0.306	
	0.2032	0.172		0.2540	0.306		0.2794	0.384	

Powder Spray Welding 1 Layer Deposit 10 Scratches

Table 14

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.1016	Zero	Zero	0.1778	0.116	0.085	0.1778	0.116	0.136
	0.1016	Zero		0.1524	0.068		0.1778	0.116	
	0.1016	Zero		0.1524	0.068		0.2032	0.172	
	0.1016	Zero		0.1778	0.116		0.1778	0.116	
	0.1016	Zero		0.1524	0.068		0.2032	0.172	
2	0.1270	Zero	0.054	0.2032	0.172	0.151	0.2286	0.235	0.330
	0.1524	0.068		0.1778	0.116		0.2540	0.306	
	0.1524	0.068		0.2286	0.235		0.2794	0.384	
	0.1524	0.068		0.1778	0.116		0.3302	0.502	
	0.1524	0.068		0.1778	0.116		0.2286	0.235	
3	0.1524	0.068	0.068	0.1778	0.116	0.116	0.2286	0.235	0.256
	0.1524	0.068		0.1778	0.116		0.2286	0.235	
	0.1524	0.068		0.1778	0.116		0.2286	0.235	
	0.1524	0.068		0.1778	0.116		0.2032	0.172	
	0.1524	0.068		0.1778	0.116		0.2540	0.306	
4	0.1524	0.068	0.068	0.2032	0.172	0.209	0.2794	0.384	0.337
	0.1524	0.068		0.2032	0.172		0.2794	0.384	
	0.1524	0.068		0.2286	0.235		0.2540	0.306	
	0.1524	0.068		0.2286	0.235		0.2540	0.306	
	0.1524	0.068		0.2286	0.235		0.2540	0.306	
5	0.1016	Zero	Zero	0.2032	0.172	0.172	0.2540	0.306	0.306
	0.1016	Zero		0.2032	0.172		0.2540	0.306	
	0.1016	Zero		0.2032	0.172		0.2540	0.306	
	0.1016	Zero		0.2032	0.172		0.2540	0.306	
	0.1016	Zero		0.2032	0.172		0.2540	0.306	

Powder Spray Welding 2 Layer Deposits 10 Scratches

Table 15

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306	0.389	0.3556	0.663	0.622	0.4064	0.886	1.199
	0.2286	0.235		0.3556	0.663		0.4572	1.138	
	0.3048	0.469		0.3556	0.663		0.4826	1.276	
	0.3048	0.469		0.3302	0.562		0.4826	1.276	
	0.3048	0.469		0.3302	0.562		0.5080	1.421	
2	0.2286	0.235	0.235	0.3302	0.562	0.419	0.4064	0.856	0.876
	0.2286	0.235		0.2794	0.384		0.4064	0.856	
	0.2286	0.235		0.2794	0.384		0.3810	0.770	
	0.2286	0.235		0.2794	0.384		0.3302	0.562	
	0.2286	0.235		0.2794	0.384		0.4826	1.276	
3	0.2286	0.235	0.279	0.3556	0.668	0.459	0.2286	0.235	0.874
	0.2286	0.235		0.3302	0.562		0.2540	0.306	
	0.2286	0.235		0.2794	0.384		0.4826	1.276	
	0.2540	0.306		0.2794	0.384		0.4826	1.276	
	0.2794	0.384		0.2540	0.306		0.4826	1.276	
4	0.2794	0.384	0.384	0.3302	0.562	0.733	0.4826	1.276	1.276
	0.2794	0.384		0.3302	0.562		0.4826	1.276	
	0.2794	0.384		0.3810	0.770		0.4826	1.276	
	0.2794	0.384		0.4064	0.886		0.4826	1.276	
	0.2794	0.384		0.4064	0.886		0.4826	1.276	
5	0.2540	0.306	0.321	0.3556	0.663	0.663	0.4064	0.886	1.100
	0.2540	0.306		0.3556	0.663		0.4064	0.886	
	0.2540	0.306		0.3556	0.663		0.5080	1.421	
	0.2540	0.306		0.3556	0.663		0.5080	1.421	
	0.2794	0.384		0.3556	0.663		0.4064	0.886	

Powder Spray Welding 1 Layer Deposit 50 Scratches

Table 16

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2032	0.172	0.224	0.3556	0.663	0.534	0.4064	0.886	0.854
	0.2032	0.172		0.2794	0.384		0.3048	0.469	
	0.2286	0.235		0.3810	0.770		0.3810	0.770	
	0.2286	0.235		0.3048	0.469		0.4318	1.008	
	0.2540	0.306		0.2794	0.384		0.4572	1.138	
2	0.2794	0.384	0.353	0.3556	0.663	0.583	0.4064	0.886	0.847
	0.2540	0.306		0.3302	0.562		0.4064	0.886	
	0.2794	0.384		0.3048	0.462		0.3556	0.663	
	0.2540	0.306		0.3048	0.462		0.3556	0.663	
	0.2794	0.384		0.3810	0.770		0.4572	1.138	
3	0.2032	0.172	0.249	0.3302	0.562	0.545	0.4064	0.886	0.821
	0.2286	0.235		0.3302	0.562		0.4318	1.008	
	0.2286	0.235		0.3556	0.663		0.4064	0.886	
	0.2540	0.306		0.3048	0.469		0.3556	0.663	
	0.2540	0.306		0.3048	0.469		0.3556	0.663	
4	0.2286	0.235	0.308	0.3302	0.562	0.583	0.3810	0.770	0.890
	0.2286	0.235		0.3048	0.462		0.3810	0.770	
	0.2540	0.306		0.3048	0.462		0.4064	0.886	
	0.2794	0.384		0.3556	0.663		0.4064	0.886	
	0.2794	0.384		0.3810	0.770		0.4572	1.138	
5	0.3048	0.469	0.419	0.3556	0.663	0.630	0.3302	0.562	0.997
	0.2540	0.306		0.3556	0.663		0.4318	1.008	
	0.3048	0.469		0.3048	0.469		0.4572	1.138	
	0.2794	0.384		0.4064	0.886		0.4572	1.138	
	0.3048	0.469		0.3048	0.469		0.4572	1.138	

Powder Spray Welding 2 Layer Deposits 50 Scratches

Table 17

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3048	0.469		0.3302	0.562		0.4826	1.276	
	0.4084	0.886		0.4318	1.008		0.4318	1.008	
	0.3302	0.562	0.608	0.4826	1.276	0.877	0.4318	1.008	1.257
	0.3302	0.562		0.3810	0.770		0.5334	1.573	
	0.3302	0.562		0.3810	0.770		0.5080	1.421	
2	0.3302	0.562		0.2794	0.384		0.5080	1.421	
	0.2540	0.306		0.3556	0.663		0.5080	1.421	
	0.2794	0.384	0.404	0.3302	0.562	0.608	0.3556	0.663	1.055
	0.2794	0.384		0.3810	0.770		0.4064	0.886	
	0.2794	0.384		0.3556	0.663		0.4064	0.886	
3	0.2286	0.235		0.2540	0.306		0.3048	0.469	
	0.2286	0.235		0.2540	0.306		0.4826	1.276	
	0.2540	0.306	0.249	0.3048	0.469	0.395	0.5080	1.421	0.964
	0.2286	0.235		0.3048	0.469		0.4064	0.886	
	0.2286	0.235		0.2794	0.384		0.3810	0.770	
4	0.3048	0.469		0.3810	0.770		0.4318	1.008	
	0.3048	0.469		0.3810	0.770		0.4318	1.008	
	0.3048	0.469	0.504	0.3810	0.770	0.917	0.4572	1.138	1.086
	0.3302	0.562		0.4572	1.138		0.4572	1.138	
	0.3302	0.562		0.4572	1.138		0.4572	1.138	
5	0.2794	0.384		0.2540	0.306		0.4318	1.008	
	0.2540	0.306		0.3048	0.469		0.4318	1.008	
	0.2286	0.235	0.285	0.2286	0.235	0.340	0.4318	1.008	0.959
	0.2794	0.384		0.2540	0.306		0.4064	0.886	
	0.1778	0.116		0.2794	0.384		0.4064	0.886	

Powder Spray Welding 1 Layer Deposit 100 Scratches

Table 18

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2794	0.384	0.492	0.3302	0.562	0.623	0.3810	0.770	1.099
	0.2794	0.384		0.4572	1.138		0.3556	0.663	
	0.3048	0.469		0.3302	0.562		0.4826	1.276	
	0.3302	0.562		0.2794	0.384		0.5842	1.900	
	0.3556	0.663		0.3048	0.469		0.4064	0.886	
2	0.2286	0.235	0.249	0.3556	0.663	0.582	0.3810	0.770	0.819
	0.2286	0.235		0.3556	0.663		0.4064	0.886	
	0.2286	0.235		0.3302	0.562		0.3556	0.663	
	0.2286	0.235		0.3302	0.562		0.3810	0.770	
	0.2540	0.306		0.3048	0.462		0.4318	1.008	
3	0.1524	0.068	0.155	0.2794	0.384	0.337	0.3556	0.663	0.720
	0.1778	0.116		0.2794	0.384		0.4318	1.008	
	0.1778	0.116		0.2540	0.306		0.4064	0.886	
	0.2032	0.172		0.2540	0.306		0.2794	0.384	
	0.2540	0.306		0.2540	0.306		0.3556	0.663	
4	0.2540	0.306	0.384	0.3556	0.663	0.630	0.4826	1.276	1.220
	0.2540	0.306		0.3556	0.663		0.4826	1.276	
	0.3048	0.462		0.4064	0.886		0.4826	1.276	
	0.2794	0.384		0.3048	0.469		0.4572	1.138	
	0.3048	0.462		0.3048	0.469		0.4572	1.138	
5	0.2032	0.172	0.249	0.3048	0.469	0.624	0.3810	0.770	0.917
	0.2286	0.235		0.3556	0.663		0.3810	0.770	
	0.2286	0.235		0.3556	0.663		0.4064	0.886	
	0.2540	0.306		0.3556	0.663		0.4064	0.886	
	0.2540	0.306		0.3556	0.663		0.4826	1.276	

Powder Spray Welding 2 Layer Deposits 100 Scratches

Table 19

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.5334	1.573		0.4064	0.886		0.9398	5.022	
	0.5334	1.573		0.8636	4.230		0.6604	2.446	
	0.5842	1.900	1.296	0.6096	2.075	2.268	0.8890	4.487	3.655
	0.3810	0.770		0.6096	2.075		0.9144	4.750	
	0.3556	0.663		0.6096	2.075		0.5334	1.573	
2	0.5334	1.573		0.6858	2.643		0.3556	0.663	
	0.5334	1.573		0.6096	2.075		0.7874	3.437	
	0.5334	1.573	1.573	0.6096	2.075	2.302	0.9652	5.300	3.653
	0.5334	1.573		0.6858	2.643		0.9906	5.587	
	0.5334	1.573		0.6096	2.075		0.7620	3.279	
3	0.4826	1.276		0.5334	1.573		0.4064	0.886	
	0.4826	1.276		0.5588	1.733		0.8636	4.230	
	0.5080	1.421	1.334	0.5842	1.900	1.496	0.6096	2.075	2.268
	0.5080	1.421		0.4572	1.138		0.6096	2.075	
	0.4826	1.276		0.4572	1.138		0.6096	2.075	
4	0.5080	1.421		0.5334	1.573		0.5334	1.573	
	0.5334	1.573		0.6350	2.272		0.7112	2.848	
	0.5334	1.573	1.342	0.6604	2.446	1.837	1.0922	6.805	3.154
	0.4572	1.138		0.5334	1.573		0.6858	2.643	
	0.4318	1.008		0.5334	1.573		0.5842	1.900	
5	0.5334	1.573		0.6858	2.643		0.8890	4.487	
	0.5334	1.573		0.7366	3.060		0.8890	4.487	
	0.5080	1.421	1.723	0.6604	2.446	2.499	0.8890	4.487	4.467
	0.7620	3.279		0.6096	2.075		0.8890	4.487	
	0.3810	0.770		0.6350	2.272		0.8890	4.487	

Powder Spray Welding 1 Layer Deposit 500 Scratches

Table 20

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2794	0.384	0.401	0.3048	0.469	0.624	0.3810	0.770	1.055
	0.2794	0.384		0.3556	0.663		0.4064	0.886	
	0.3048	0.469		0.3556	0.663		0.4826	1.276	
	0.2794	0.384		0.3556	0.663		0.5334	1.573	
	0.2794	0.384		0.3556	0.663		0.3810	0.770	
2	0.4064	0.886	0.821	0.4826	1.276	1.193	0.6096	2.075	
	0.4318	1.008		0.4572	1.138		0.5082	1.421	
	0.4064	0.886		0.4826	1.276		0.5842	1.900	
	0.3556	0.663		0.4572	1.138		0.5588	1.733	
	0.3556	0.663		0.4572	1.138		0.6350	2.272	
3	0.4064	0.886	0.750	0.3810	0.770	0.990	0.4318	1.008	1.442
	0.3810	0.770		0.3810	0.770		0.4064	0.886	
	0.3810	0.770		0.4572	1.138		0.5588	1.773	
	0.3556	0.663		0.4572	1.138		0.5588	1.773	
	0.3556	0.663		0.4572	1.138		0.5588	1.773	
4	0.3810	0.770	0.611	0.3810	0.770	0.893	0.5080	1.421	1.327
	0.3810	0.770		0.4318	1.008		0.3810	0.770	
	0.3556	0.663		0.3556	0.663		0.4572	1.138	
	0.3048	0.469		0.4572	1.138		0.5334	1.573	
	0.2794	0.384		0.4064	0.886		0.5588	1.733	
5	0.3556	0.663	0.473	0.3810	0.770	0.890	0.4826	1.276	1.769
	0.2794	0.384		0.4064	0.886		0.4826	1.276	
	0.3048	0.469		0.4064	0.886		0.4318	1.008	
	0.2794	0.384		0.3810	0.770		0.6858	2.642	
	0.3048	0.469		0.4572	1.138		0.6858	2.643	

Powder Spray Welding 2 Layer Deposits 500 Scratches

Table 21

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306	0.477	0.3556	0.663	0.978	0.4572	1.136	1.040
	0.2540	0.306		0.5588	1.773		0.3810	0.770	
	0.4318	1.008		0.4318	1.008		0.4318	1.008	
	0.2794	0.384		0.3302	0.562		0.4826	1.276	
	0.2794	0.384		0.4064	0.886		0.4318	1.008	
2	0.2540	0.306	0.307	0.3048	0.469	0.453	0.2794	0.384	0.759
	0.2540	0.306		0.3302	0.562		0.2794	0.384	
	0.2540	0.306		0.2794	0.384		0.3048	0.469	
	0.2286	0.235		0.2794	0.384		0.5080	1.421	
	0.2794	0.384		0.3048	0.469		0.4572	1.138	
3	0.1524	0.068	0.178	0.3302	0.562	0.430	0.4064	0.886	0.776
	0.2032	0.172		0.4064	0.886		0.4064	0.886	
	0.2032	0.172		0.2286	0.235		0.4064	0.886	
	0.2032	0.172		0.2286	0.235		0.3302	0.562	
	0.2540	0.306		0.2286	0.235		0.3556	0.663	
4	0.2032	0.172	0.172	0.3048	0.469	0.341	0.3556	0.663	0.509
	0.2032	0.172		0.2794	0.384		0.2794	0.384	
	0.2032	0.172		0.2794	0.384		0.3048	0.469	
	0.2032	0.172		0.2286	0.235		0.3048	0.562	
	0.2032	0.172		0.2286	0.235		0.3302	0.469	
5	0.2032	0.172	0.162	0.2540	0.306	0.477	0.3810	0.770	0.730
	0.2032	0.172		0.2540	0.306		0.4064	0.886	
	0.2286	0.235		0.2794	0.384		0.3556	0.663	
	0.1778	0.116		0.2794	0.384		0.3302	0.562	
	0.1778	0.116		0.4318	1.008		0.3810	0.770	

Oxy - Acetylene

1 Layer Deposit

10 Scratches

Table 22

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306		0.2286	0.235		0.3556	0.663	
	0.2540	0.306		0.2286	0.235		0.2794	0.384	
	0.2286	0.235	0.251	0.2286	0.235	0.263	0.2794	0.384	0.456
	0.2032	0.172		0.2540	0.306		0.2794	0.384	
	0.2286	0.235		0.2540	0.306		0.3048	0.469	
2	0.1778	0.116		0.2540	0.306		0.2794	0.384	
	0.1778	0.116		0.2286	0.235		0.3048	0.469	
	0.1778	0.116	0.116	0.2286	0.235	0.213	0.2794	0.384	0.418
	0.1778	0.116		0.2032	0.172		0.3038	0.469	
	0.1778	0.116		0.1778	0.116		0.2794	0.384	
3	0.2032	0.172		0.2032	0.172		0.3302	0.562	
	0.2286	0.235		0.2286	0.235		0.2286	0.285	
	0.2032	0.172	0.152	0.3048	0.469	0.244	0.3302	0.562	0.431
	0.1524	0.668		0.2032	0.172		0.2286	0.235	
	0.1778	0.116		0.2032	0.172		0.3302	0.562	
4	0.2032	0.172		0.2032	0.172		0.2540	0.306	
	0.2032	0.172		0.2032	0.172		0.2540	0.306	
	0.2032	0.172	0.197	0.2286	0.235	0.209	0.2794	0.384	0.477
	0.2286	0.235		0.2286	0.235		0.2794	0.384	
	0.2286	0.235		0.2286	0.235		0.4318	1.008	
5	0.2032	0.172		0.2540	0.306		0.2794	0.384	
	0.2032	0.172		0.2540	0.306		0.2794	0.384	
	0.2032	0.172	0.172	0.2286	0.235	0.297	0.2794	0.384	0.384
	0.2032	0.172		0.2032	0.172		0.2794	0.384	
	0.2032	0.172		0.3048	0.469		0.2794	0.384	

Oxy - Acetylene

2 Layer Deposits

10 Scratches

Table 23

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306		0.3556	0.663	0	0.4572	1.138	
	0.2540	0.306		0.5588	1.773		0.3810	0.770	
	0.4318	1.008	0.477	0.4318	1.008	0.978	0.4318	1.008	1.040
	0.2794	0.384		0.3302	0.562		0.4826	1.276	
	0.2794	0.384		0.4064	0.886		0.4318	1.008	
2	0.3556	0.663		0.4064	0.886		0.3556	0.663	
	0.2794	0.384		0.4064	0.886		0.4318	1.008	
	0.3048	0.469	0.509	0.3302	0.562	0.776	0.5588	1.773	0.978
	0.3302	0.562		0.3556	0.663		0.3302	0.562	
	0.3048	0.469		0.4064	0.886		0.4064	0.886	
3	0.2286	0.235		0.3048	0.469		0.3810	0.770	
	0.2286	0.235		0.4572	1.138		0.3556	0.663	
	0.2794	0.384	0.308	0.3302	0.562	0.623	0.4064	0.886	1.099
	0.2794	0.384		0.3302	0.562		0.4826	1.276	
	0.2540	0.306		0.2794	0.384		0.5842	1.900	
4	0.2540	0.306		0.2540	0.306		0.6096	2.075	
	0.2540	0.306		0.2794	0.384		0.4572	1.138	
	0.2540	0.306	0.291	0.3048	0.469	0.419	0.3556	0.663	1.040
	0.2286	0.235		0.3048	0.469		0.3556	0.663	
	0.2540	0.306		0.3048	0.469		0.3556	0.663	
5	0.3556	0.663		0.3556	0.663		0.5080	1.421	
	0.3302	0.562		0.4318	1.008		0.4064	0.886	
	0.3048	0.469	0.545	0.4318	1.008	0.917	0.5334	1.573	1.292
	0.3048	0.469		0.4572	1.138		0.5334	1.573	
	0.3302	0.562		0.3810	0.770		0.4318	1.008	

Oxy - Acetylene

1 Layer Deposit

50 Scratches

Table 24

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2540	0.306		0.3302	0.562		0.3556	0.663	
	0.2540	0.306		0.3556	0.663		0.3556	0.663	
	0.2794	0.384	0.137	0.3302	0.562	0.545	0.4318	1.008	0.845
	0.2794	0.384		0.3048	0.469		0.4318	1.008	
	0.2540	0.306		0.3048	0.469		0.4064	0.886	
2	0.2286	0.235		0.3048	0.469		0.5588	1.733	
	0.2032	0.172		0.3810	0.770		0.5080	1.421	
	0.2794	0.384	0.329	0.3810	0.770	0.668	0.4318	1.008	1.434
	0.2794	0.384		0.3302	0.562		0.5588	1.733	
	0.3048	0.469		0.3810	0.770		0.4826	1.276	
3	0.2286	0.235		0.2794	0.384		0.5080	1.421	
	0.2540	0.306		0.2794	0.384		0.4572	1.138	
	0.2286	0.235	0.263	0.3048	0.469	0.402	0.4572	1.138	1.043
	0.2540	0.306		0.2540	0.306		0.4064	0.886	
	0.2286	0.235		0.3048	0.469		0.3556	0.663	
4	0.2286	0.235		0.3810	0.770		0.4572	1.138	
	0.2286	0.235		0.3048	0.469		0.3810	0.770	
	0.2794	0.384	0.308	0.2794	0.384	0.611	0.5334	1.573	0.902
	0.2794	0.384		0.3810	0.770		0.3048	0.469	
	0.2540	0.306		0.3556	0.663		0.3302	0.562	
5	0.2540	0.306		0.3810	0.770		0.5080	1.421	
	0.2794	0.384		0.3810	0.770		0.5588	1.733	
	0.2540	0.306	0.352	0.3556	0.663	0.750	0.5334	1.573	1.327
	0.2794	0.384		0.3556	0.663		0.4572	1.138	
	0.2794	0.384		0.4064	0.886		0.3810	0.770	

Oxy - Acetylene

2 Layer Deposits

50 Scratches

Table 25

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3556	0.663		0.3810	0.770		0.6350	2.272	
	0.3302	0.562		0.3810	0.770		0.9144	4.750	
	0.3810	0.770	0.644	0.4064	0.886	0.864	0.5334	1.573	2.229
	0.3302	0.562		0.4064	0.886		0.4826	1.276	
	0.3556	0.663		0.4318	1.008		0.4826	1.276	
2	0.3556	0.663		0.5080	1.421		0.3048	0.469	
	0.3302	0.562		0.4318	1.008		0.3810	0.770	
	0.3556	0.663	0.664	0.4064	0.886	1.067	0.4872	1.138	1.185
	0.3556	0.663		0.4064	0.886		0.4826	1.276	
	0.3810	0.770		0.4572	1.138		0.6350	2.272	
3	0.3556	0.663		0.3302	0.562		0.5080	1.421	
	0.3556	0.663		0.3810	0.770		0.4572	1.138	
	0.3302	0.562	0.664	0.3302	0.562	0.734	0.4318	1.008	1.423
	0.3556	0.663		0.3810	0.770		0.4826	1.276	
	0.3810	0.770		0.4318	1.008		0.6350	2.272	
4	0.2794	0.384		0.4064	0.886		0.5842	1.900	
	0.3302	0.562		0.4064	0.886		0.8128	3.740	
	0.3302	0.562	0.623	0.3810	0.770	0.839	0.5080	1.421	1.667
	0.3048	0.469		0.3810	0.770		0.4572	1.138	
	0.4572	1.138		0.4064	0.886		0.4572	1.138	
5	0.3810	0.770		0.4572	1.138		0.5080	1.421	
	0.3810	0.770		0.4572	1.138		0.4318	1.008	
	0.4318	1.008	0.864	0.4572	1.138	1.376	0.4572	1.138	1.086
	0.4064	0.886		0.5580	1.733		0.4572	1.138	
	0.4064	0.886		0.5580	1.733		0.4572	1.138	

Oxy - Acetylene

1 Layer Deposit

100 Scratches

Table 26

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3556	0.663		0.3810	0.770		0.6350	2.272	
	0.3302	0.562		0.3810	0.770		0.5334	1.573	
	0.3810	0.770	0.644	0.4064	0.886	0.864	0.5334	1.573	1.594
	0.3302	0.562		0.4064	0.886		0.4826	1.276	
	0.3556	0.663		0.4318	1.008		0.4826	1.276	
2	0.4064	0.886		0.4318	1.008		0.4826	1.276	
	0.3810	0.770		0.3810	0.770		0.5080	1.421	
	0.3556	0.663	0.711	0.4572	1.138	0.789	0.4572	1.138	1.122
	0.3810	0.770		0.3302	0.562		0.3810	0.770	
	0.3048	0.469		0.3048	0.469		0.4318	1.008	
3	0.3302	0.562		0.3810	0.770		0.4318	1.008	
	0.3556	0.663		0.4572	1.138		0.4826	1.276	
	0.3302	0.562	0.545	0.3556	0.663	0.882	0.4572	1.138	1.122
	0.3048	0.469		0.3810	0.770		0.5080	1.421	
	0.3048	0.469		0.3810	0.770		0.3810	0.770	
4	0.3556	0.663		0.3556	0.663		0.6350	2.272	
	0.3048	0.469		0.3048	0.469		0.3810	0.770	
	0.3556	0.663	0.562	0.4826	1.276	0.726	0.7366	3.060	1.790
	0.3302	0.562		0.3556	0.663		0.4826	1.276	
	0.3302	0.562		0.3302	0.562		0.5334	1.573	
5	0.3556	0.663		0.3810	0.770		0.5842	1.900	
	0.3556	0.663		0.3810	0.770		0.8128	3.740	
	0.3048	0.469	0.546	0.4064	0.886	0.839	0.5080	1.421	1.667
	0.3048	0.469		0.4064	0.886		0.4572	1.138	
	0.3048	0.469		0.4064	0.886		0.4572	1.138	

Oxy - Acetylene 2 Layer Deposits 100 Scratches

Table 27

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4064	0.886		0.7366	3.060		0.8636	4.230	
	0.4064	0.886		0.5588	1.733		0.8128	3.740	
	0.4572	1.138	1.213	0.7366	3.060	2.497	0.9398	5.022	5.759
	0.5588	1.733		0.7366	3.060		1.2446	9.000	
	0.5080	1.421		0.5334	1.573		1.0922	6.805	
2	0.5334	1.573		0.9398	5.022		0.7874	3.437	
	0.5588	1.733		0.6604	2.446		0.9398	5.022	
	0.5842	1.900	1.496	0.8890	4.487	3.655	1.0414	6.000	5.963
	0.4572	1.138		0.9144	4.750		1.1684	7.900	
	0.4572	1.138		0.5334	1.573		1.1430	7.459	
3	0.4064	0.886		0.6858	2.643		0.8636	4.230	
	0.5334	1.573		0.8128	3.740		0.8636	4.230	
	0.5334	1.573	1.375	0.7620	3.279	3.245	0.8636	4.230	4.547
	0.5080	1.421		0.7620	3.279		0.9398	5.022	
	0.5080	1.421		0.7620	3.279		0.9398	5.022	
4	0.5588	1.733		0.9398	5.022		0.9398	5.022	
	0.4572	1.138		0.8890	4.487		0.9398	5.022	
	0.5842	1.900	1.464	0.8890	4.487	3.777	1.0414	6.000	5.901
	0.4826	1.276		0.6604	2.446		1.0414	6.000	
	0.4826	1.276		0.6604	2.446		1.1430	7.459	
5	0.5588	1.733		0.7620	3.279		0.8636	4.230	
	0.5588	1.733		0.7620	3.279		0.9398	5.022	
	0.5842	1.900	1.833	0.7620	3.279	3.463	0.8128	3.740	5.759
	0.5842	1.900		0.8128	3.740		1.0922	6.805	
	0.5842	1.900		0.8128	3.740		1.2446	9.000	

Oxy - Acetylene

1 Layer Deposit

500 Scratches

Table 28

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2794	0.384	0.438	0.4318	1.008	1.342	0.7620	3.279	2.870
	0.3302	0.562		0.5080	1.421		0.7620	3.279	
	0.3048	0.469		0.5334	1.573		0.7112	2.848	
	0.3048	0.469		0.5334	1.573		0.6350	2.272	
	0.2540	0.306		0.4572	1.138		0.6858	2.643	
2	0.5080	1.421	1.623	0.6350	2.272	3.554	1.0160	5.880	5.929
	0.6350	2.272		0.8382	3.981		1.1430	7.459	
	0.4826	1.276		0.7368	3.060		1.0160	5.880	
	0.5334	1.573		0.8636	4.230		0.9398	5.022	
	0.5334	1.573		0.8636	4.230		0.9906	5.587	
3	0.4318	1.008	0.645	0.4318	1.008	1.335	0.8128	3.740	4.515
	0.3302	0.562		0.4318	1.008		0.8890	4.487	
	0.4064	0.886		0.6858	2.643		0.9398	5.022	
	0.2794	0.384		0.4318	1.008		0.8128	3.740	
	0.2794	0.384		0.4318	1.008		0.9906	5.587	
4	0.4318	1.008	0.822	0.7368	3.060	1.584	0.7620	3.279	2.735
	0.4318	1.008		0.5080	1.421		0.6350	2.272	
	0.3810	0.770		0.4064	0.886		0.7112	2.848	
	0.3556	0.663		0.4826	1.276		0.6858	2.643	
	0.3556	0.663		0.4826	1.276		0.6858	2.643	
5	0.6096	2.075	1.040	0.6096	2.075	2.093	0.9398	5.022	5.158
	0.4572	1.138		0.5080	1.421		0.9398	5.022	
	0.3556	0.663		0.6350	2.272		0.9652	5.300	
	0.3556	0.663		0.5080	1.421		1.0414	6.000	
	0.3556	0.663		0.7620	3.279		0.8890	4.487	

Oxy - Acetylene

2 Layer Deposits

500 Scratches

Table 29

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2286	0.235		0.2794	0.384		0.3810	0.770	
	0.2286	0.235		0.4064	0.886		0.4064	0.886	
	0.2286	0.235	0.263	0.3556	0.663	0.688	0.5080	1.421	1.078
	0.2540	0.306		0.4318	1.008		0.5334	1.573	
	0.2540	0.306		0.3302	0.562		0.3810	0.770	
2	0.2286	0.235		0.3556	0.663		0.4064	0.886	
	0.2286	0.235		0.3556	0.663		0.4572	1.138	
	0.2286	0.235	0.279	0.3556	0.663	0.622	0.4826	1.276	1.199
	0.2794	0.384		0.3302	0.562		0.4826	1.276	
	0.2540	0.306		0.3302	0.562		0.5080	1.421	
3	0.3302	0.562		0.3302	0.562		0.4064	0.886	
	0.3302	0.562		0.3556	0.663		0.4572	1.138	
	0.2540	0.306	0.394	0.4318	1.008	0.673	0.3556	0.663	0.966
	0.2540	0.306		0.3556	0.663		0.4318	1.008	
	0.2286	0.235		0.3048	0.469		0.4572	1.138	
4	0.2286	0.235		0.3556	0.663		0.4064	0.886	
	0.2032	0.172		0.3556	0.663		0.4064	0.886	
	0.2540	0.306	0.266	0.3556	0.663	0.663	0.4572	1.138	1.213
	0.2794	0.384		0.3556	0.663		0.5080	1.421	
	0.2286	0.235		0.3556	0.663		0.5588	1.733	
5	0.2540	0.306		0.3302	0.562		0.3556	0.663	
	0.2794	0.384		0.3302	0.562		0.3810	0.770	
	0.2032	0.172	0.241	0.3048	0.469	0.623	0.5080	1.421	1.026
	0.2032	0.172		0.2794	0.384		0.4572	1.138	
	0.2032	0.172		0.4572	1.138		0.4572	1.138	

Tungsten Inert Gas 1 Layer Deposit 10 Scratches

Table 30

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.1524	0.068	0.087	0.1778	0.116	0.283	0.3048	0.469	0.489
	0.1778	0.116		0.3048	0.469		0.3302	0.562	
	0.1778	0.116		0.2540	0.306		0.2794	0.384	
	0.1524	0.068		0.2286	0.235		0.3302	0.562	
	0.1524	0.068		0.2286	0.235		0.3048	0.469	
2	0.2540	0.306	0.250	0.3048	0.462	0.384	0.4826	1.276	1.037
	0.2540	0.306		0.2540	0.306		0.4318	1.008	
	0.2286	0.235		0.2794	0.384		0.4318	1.008	
	0.2286	0.235		0.2794	0.384		0.4064	0.886	
	0.2032	0.172		0.2794	0.384		0.4318	1.008	
3	0.2032	0.172	0.152	0.2286	0.235	0.330	0.4064	0.886	0.773
	0.2286	0.172		0.2540	0.306		0.4064	0.886	
	0.2032	0.172		0.2794	0.384		0.3556	0.663	
	0.1778	0.116		0.3302	0.562		0.3556	0.663	
	0.1524	0.068		0.2286	0.235		0.3810	0.770	
4	0.2540	0.306	0.213	0.2286	0.235	0.330	0.3556	0.663	0.663
	0.2286	0.235		0.2286	0.235		0.3556	0.663	
	0.2286	0.235		0.2540	0.306		0.3556	0.663	
	0.2032	0.172		0.2794	0.384		0.3556	0.663	
	0.1778	0.116		0.3302	0.562		0.3556	0.663	
5	0.1778	0.116	0.117	0.2794	0.384	0.368	0.3556	0.663	0.604
	0.1524	0.068		0.2794	0.384		0.3810	0.770	
	0.1778	0.116		0.2540	0.306		0.3302	0.562	
	0.2032	0.172		0.2540	0.306		0.3048	0.462	
	0.1778	0.116		0.3048	0.462		0.3302	0.562	

Tungsten Inert Gas 2 Layer Deposits 10 Scratches

Table 31

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3556	0.663		0.3556	0.663		0.5080	1.421	
	0.3302	0.562		0.4318	1.008		0.4064	0.886	
	0.3048	0.469	0.545	0.4318	1.008	0.917	0.5334	1.573	1.292
	0.3048	0.469		0.4572	1.138		0.5334	1.573	
	0.3302	0.562		0.3810	0.770		0.4318	1.008	
2	0.3048	0.469		0.3556	0.663		0.6096	2.075	
	0.3302	0.562		0.4318	1.008		0.5080	1.421	
	0.3302	0.562	0.563	0.4318	1.008	0.917	0.6096	2.075	1.861
	0.3302	0.562		0.4572	1.138		0.7112	2.848	
	0.3556	0.663		0.3810	0.770		0.4064	0.886	
3	0.3048	0.469		0.3048	0.469		0.4826	1.276	
	0.3048	0.469		0.3810	0.770		0.4826	1.276	
	0.3302	0.562	0.509	0.3302	0.562	0.626	0.4826	1.276	1.382
	0.3556	0.663		0.3302	0.562		0.6096	2.075	
	0.2794	0.384		0.3810	0.770		0.4318	1.008	
4	0.4064	0.886		0.3810	0.770		0.5334	1.573	
	0.4064	0.886		0.3302	0.562		0.6350	2.272	
	0.3302	0.562	0.660	0.3810	0.770	0.858	0.3810	0.770	1.339
	0.2540	0.306		0.5080	1.421		0.3556	0.663	
	0.3556	0.663		0.3810	0.770		0.5080	1.421	
5	0.3302	0.562		0.3810	0.770		0.4572	1.138	
	0.2540	0.306		0.5080	1.421		0.5334	1.573	
	0.2032	0.172	0.522	0.3556	0.663	0.925	0.4318	1.008	1.283
	0.3302	0.562		0.4064	0.886		0.5080	1.421	
	0.4318	1.008		0.4064	0.886		0.4826	1.276	

Tungsten Inert Gas 1 Layer Deposit 50 Scratches

Table 32

Wear Volume Vs Load

Test No	2.5 Kgs			5 Kgs			10 Kgs		
	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.2794	0.384	0.422	0.3556	0.663	0.663	0.4826	1.276	1.220
	0.2794	0.384		0.3556	0.663		0.4826	1.276	
	0.2794	0.384		0.3556	0.663		0.4826	1.276	
	0.2540	0.306		0.3556	0.663		0.4572	1.138	
	0.3556	0.663		0.3556	0.663		0.4572	1.138	
2	0.3048	0.462	0.399	0.4064	0.886	0.847	0.5588	1.733	1.434
	0.3048	0.462		0.4064	0.886		0.5588	1.733	
	0.3048	0.462		0.3556	0.663		0.4318	1.008	
	0.2540	0.306		0.3556	0.663		0.4826	1.276	
	0.2540	0.306		0.4572	1.138		0.5080	1.421	
3	0.2794	0.384	0.368	0.3556	0.663	0.752	0.4826	1.276	1.382
	0.2794	0.384		0.4064	0.886		0.4826	1.276	
	0.2540	0.306		0.3556	0.663		0.5334	1.573	
	0.2540	0.306		0.4064	0.886		0.4064	0.886	
	0.3048	0.462		0.3556	0.663		0.5842	1.900	
4	0.2540	0.306	0.384	0.3556	0.663	0.604	0.5588	1.733	1.327
	0.2540	0.306		0.3302	0.562		0.5334	1.573	
	0.2794	0.384		0.3302	0.562		0.5080	1.421	
	0.3048	0.462		0.3048	0.462		0.4572	1.138	
	0.3048	0.462		0.3810	0.770		0.3810	0.770	
5	0.3048	0.462	0.491	0.4572	1.138	0.779	0.4572	1.138	1.267
	0.2794	0.384		0.3810	0.770		0.4064	0.886	
	0.2794	0.384		0.3556	0.633		0.4318	1.008	
	0.3302	0.562		0.3556	0.663		0.5334	1.573	
	0.3556	0.663		0.3556	0.663		0.5588	1.733	

Tungsten Inert Gas

2 Layer Deposits

50 Scratches

Table 33

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.3556	0.663	0.720	0.4064	0.886	1.383	0.6096	2.075	2.743
	0.4318	1.008		0.5534	1.573		0.9398	5.022	
	0.4064	0.886		0.5842	1.900		0.5842	1.900	
	0.2794	0.384		0.5080	1.421		0.6096	2.075	
	0.3556	0.663		0.4572	1.138		0.6858	2.643	
2	0.3302	0.562	0.623	0.3810	0.770	1.099	0.5842	1.900	1.667
	0.3302	0.562		0.3556	0.663		0.8128	3.740	
	0.4572	1.138		0.4826	1.276		0.5080	1.421	
	0.2794	0.384		0.5842	1.900		0.4572	1.138	
	0.3048	0.469		0.4064	0.886		0.4572	1.138	
3	0.5080	1.421	1.249	0.5334	1.573	1.951	0.8382	3.981	3.580
	0.4826	1.276		0.5588	1.733		0.8128	3.740	
	0.4572	1.138		0.5588	1.733		0.8128	3.740	
	0.4828	1.276		0.6604	2.446		0.9398	5.022	
	0.4572	1.138		0.6350	2.272		0.5080	1.421	
4	0.5588	1.733	1.496	0.6350	2.272	2.582	0.8890	4.487	4.160
	0.5842	1.900		0.6350	2.272		0.8636	4.230	
	0.6096	2.075		0.6858	2.643		0.9906	5.587	
	0.4064	0.886		0.6604	2.446		0.7874	3.437	
	0.4064	0.886		0.7620	3.279		0.7360	3.060	
5	0.3556	0.663	0.663	0.4572	1.138	1.591	0.5080	1.421	2.479
	0.3556	0.663		0.5588	1.733		0.7620	3.279	
	0.3556	0.663		0.5588	1.733		0.6858	2.643	
	0.3556	0.663		0.4826	1.276		0.7620	3.279	
	0.3556	0.663		0.6096	2.075		0.5588	1.773	

Tungsten Inert Gas 1 Layer Deposit 100 Scratches

Table 34

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4064	0.886	0.931	0.5588	1.733	1.464	0.5588	1.733	2.109
	0.3048	0.469		0.4572	1.138		0.5334	1.573	
	0.4064	0.886		0.5842	1.900		0.6604	2.446	
	0.4826	1.276		0.4826	1.276		0.7366	3.060	
	0.4572	1.138		0.4826	1.276		0.5588	1.733	
2	0.5080	1.421	1.055	0.4826	1.276	1.551	0.6858	2.643	2.725
	0.5080	1.421		0.4826	1.276		0.6858	2.643	
	0.3556	0.663		0.5588	1.733		0.6858	2.643	
	0.4064	0.886		0.5842	1.900		0.7112	2.848	
	0.4064	0.886		0.5334	1.573		0.7112	2.848	
3	0.3048	0.469	0.964	0.4826	1.276	1.655	0.5842	1.900	2.596
	0.4826	1.276		0.5334	1.573		0.7620	3.279	
	0.5080	1.421		0.6096	2.075		0.6858	2.643	
	0.4064	0.886		0.6096	2.075		0.8128	3.740	
	0.3810	0.770		0.4826	1.276		0.5080	1.421	
4	0.3556	0.663	0.752	0.3810	0.770	0.819	0.4318	1.008	1.824
	0.3556	0.663		0.4064	0.886		0.5080	1.421	
	0.3556	0.663		0.3556	0.663		0.5842	1.900	
	0.4064	0.886		0.3810	0.770		0.5588	1.733	
	0.4064	0.886		0.4318	1.008		0.7366	3.060	
5	0.4064	0.886	0.931	0.4826	1.276	1.382	0.5334	1.573	2.182
	0.4064	0.886		0.4826	1.276		0.5334	1.573	
	0.4064	0.886		0.4064	0.886		0.6350	2.272	
	0.4318	1.008		0.5334	1.573		0.6858	2.643	
	0.4318	1.008		0.5842	1.900		0.7112	2.848	

Tungsten Inert Gas 2 Layer Deposits 100 Scratches

Table 35

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4826	1.276	1.614	0.7874	3.437	3.831	0.9906	5.587	6.695
	0.7366	3.060		0.7620	3.279		1.2192	8.496	
	0.5334	1.573		0.8382	3.981		0.9906	5.587	
	0.4826	1.276		0.8636	4.230		1.0922	6.805	
	0.4064	0.886		0.8636	4.230		1.1684	7.000	
2	0.6858	2.643	2.968	0.7824	3.437	4.025	1.0922	6.805	6.611
	0.8128	3.740		0.8382	3.981		1.2446	9.000	
	0.7620	3.279		0.7112	2.848		0.8636	4.230	
	0.7620	3.279		1.0160	5.880		0.9398	5.022	
	0.5842	1.900		0.8382	3.981		1.1938	8.000	
3	0.6858	2.643	2.037	0.8128	3.174	4.121	0.9144	4.750	6.427
	0.6096	2.075		0.8890	4.487		0.8890	4.487	
	0.7874	3.437		0.9398	5.022		1.2446	9.000	
	0.7874	3.437		0.7874	3.437		1.1684	7.000	
	0.6858	2.643		0.8890	4.487		1.1176	6.900	
4	0.9398	5.022	3.655	0.7874	3.437	5.963	1.2192	8.496	7.485
	0.6604	2.446		0.9398	5.022		1.2954	9.600	
	0.8890	4.487		1.0414	6.000		1.1430	7.459	
	0.9144	4.750		1.1684	7.900		1.0414	6.000	
	0.5334	1.573		1.1430	7.459		1.0160	5.880	
5	0.6096	2.075	2.133	0.9906	5.587	6.818	0.7874	3.437	7.058
	0.6858	2.643		1.1684	8.000		1.2192	8.496	
	0.5588	1.733		1.1430	7.459		1.2446	9.000	
	0.6858	2.643		1.1430	7.459		1.1176	6.900	
	0.5334	1.573		0.9906	5.587		1.1430	7.459	

Tungsten Inert Gas1 Layer Deposit500 Scratches

Table 36

Wear Volume Vs Load

	2.5 Kgs			5 Kgs			10 Kgs		
Test No	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average	Scratch Width mm	Wear Volume mm ³	Wear Volume Average
1	0.4572	1.138		0.6604	2.446		0.6858	2.643	
	0.4572	1.138		0.7874	3.437		0.8128	3.740	
	0.5334	1.573	1.255	0.5842	1.900	2.741	0.8382	3.981	3.655
	0.5080	1.421		0.6858	2.643		0.8890	4.487	
	0.4318	1.008		0.7620	3.279		0.7874	3.437	
2	0.4826	1.276		0.5334	1.573		0.9144	4.750	
	0.5842	1.900		0.5588	1.733		0.9144	4.750	
	0.6096	2.075	1.560	0.6858	2.643	2.618	0.8890	4.487	4.109
	0.4826	1.276		0.8382	3.981		0.7620	3.279	
	0.4826	1.276		0.7366	3.060		0.7620	3.279	
3	0.3810	0.770		0.4572	1.138		0.7874	3.437	
	0.4064	0.886		0.7112	2.848		0.7620	3.279	
	0.4318	1.008	0.989	0.6350	2.272	1.880	0.6096	2.075	3.132
	0.4826	1.276		0.5334	1.573		0.8636	4.230	
	0.4318	1.008		0.5334	1.573		0.6858	2.643	
4	0.4064	0.886		0.6858	2.643		0.7874	3.437	
	0.5334	1.573		0.8128	3.740		0.7620	3.279	
	0.5842	1.900	1.383	0.7620	3.279	2.968	0.8382	3.981	3.831
	0.5080	1.421		0.7620	3.279		0.8636	4.230	
	0.4572	1.138		0.5842	1.900		0.8636	4.230	
5	0.5842	1.900		0.6096	2.075		0.7824	3.437	
	0.8128	3.740		0.9398	5.022		0.8382	3.981	
	0.5080	1.421	1.667	0.5842	1.900	2.743	0.7112	2.848	4.025
	0.4572	1.138		0.6096	2.075		1.0160	5.880	
	0.4572	1.138		0.6858	2.643		0.8382	3.981	

Tungsten Inert Gas 2 Layer Deposits 500 Scratches

APPENDIX 3

Table 37

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.076	660	.076	660	.096	686	.101	686	.076	686
.123	742	.152	772	.152	772	.123	686	.152	742
.203	742	.203	742	.228	772	.254	686	.228	742
.340	686	.254	742	.330	742	.330	686	.381	742
.381	600	.330	686	.381	742	.482	660	.482	686
.482	467	.406	482	.431	482	.505	467	.584	467
.558	245	.558	230	.482	245	.558	467	.660	467
.736	214	.660	224	.558	297	.660	297	.785	297
.787	214	.785	224	.787	245	.787	230	.938	245
1.041	214	.938	224	1.041	224	1.114	230	1.041	230

Thermal Spraying 1 Layer Deposit Macro Hardness

Table 38

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.076	772	.076	836	.098	876	.101	876	.098	839
.123	895	.136	831	.142	876	.152	876	.177	713
.203	861	.203	772	.228	772	.228	876	.228	876
.330	772	.340	742	.330	772	.381	742	.290	772
.482	496	.482	572	.431	482	.406	453	.381	482
.660	321	.558	283	.558	321	.482	321	.482	378
.785	263	.787	257	.711	263	.584	276	.558	276
.965	234	.938	234	1.041	234	.736	321	.787	297
1.041	234	1.041	234	1.270	234	1.041	245	1.041	245
1.422	224	1.401	214	1.422	224	1.401	214	1.444	224

Thermal Spraying 2 Layer Deposits Macro Hardness

Table 39

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.152	686	.152	772	.152	839	.177	772	.152	772
.228	686	.228	839	.221	839	.346	742	.281	772
.381	686	.346	839	.290	772	.381	686	.381	772
.508	453	.660	686	.482	686	.505	533	.584	686
.863	453	.787	686	.508	772	.660	533	.660	686
.965	378	1.219	390	1.016	686	.965	297	1.066	533
1.219	378	1.346	378	1.117	533	1.114	269	1.219	482
1.472	251	1.549	269	1.346	269	1.346	269	1.422	276
1.600	229	1.600	251	1.422	251	1.549	245	1.574	276
2.108	224	1.959	219	1.600	245	1.959	229	2.108	229

Powder Spray Welding 1 Layer Deposit Macro Hardness

Table 40

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.101	772	.152	916	.177	876	.152	839	.101	839
.228	772	.281	1003	.281	876	.346	839	.281	916
.381	742	.381	839	.381	686	.444	805	.381	916
.482	686	.508	713	.482	686	.508	686	.508	805
.508	685	.990	636	.508	533	.914	636	.863	686
.965	533	1.066	571	.990	453	.990	453	1.117	482
1.346	378	1.214	378	1.219	453	1.117	453	1.371	453
1.549	305	1.498	313	1.498	305	1.778	239	2.362	257
2.108	251	2.362	239	2.306	313	2.362	229	2.540	230
2.489	229	2.540	224	2.794	224	2.540	229	2.794	218

Powder Spray Welding 2 Layer Deposit Macro Hardness

Table 41

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.203	482	.152	533	.279	551	.203	533	.228	591
.355	482	.303	563	.355	498	.279	551	.355	498
.584	467	.584	563	.584	498	.355	563	.584	467
.787	467	.812	600	.685	498	.685	533	.812	439
1.244	439	1.295	467	.990	439	1.168	533	1.244	462
1.355	425	1.794	439	1.676	348	1.244	498	1.676	390
1.676	305	2.032	251	1.955	348	1.600	467	1.955	348
2.032	297	2.540	251	2.302	263	1.955	305	2.794	263
2.540	245	3.303	229	3.302	251	2.794	263	3.302	251
2.794	229	3.556	224	3.556	229	3.302	251	3.799	224

Oxy-acetylene Welding 1 Layer Deposit Macro Hardness

Table 42

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.101	591	.101	591	.203	571	.203	453	.152	686
.228	533	.203	571	.301	515	.257	515	.279	636
.508	660	.381	591	.508	613	.687	551	.508	686
.812	660	.685	686	.736	660	1.219	515	.838	772
1.295	660	1.143	613	1.193	636	1.676	439	1.270	613
1.955	498	1.676	613	1.955	636	2.032	498	1.600	426
2.794	467	2.413	453	2.514	401	2.540	551	2.794	390
3.048	297	2.794	297	3.048	305	2.794	515	3.064	358
3.302	251	3.302	257	3.556	269	3.556	269	3.810	313
4.064	229	4.064	224	4.064	251	4.318	234	4.318	245

Oxy-acetylene Welding 2 Layer Deposit Macro Hardness

Table 43

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.203	482	.228	515	.152	551	.254	533	.257	467
.355	467	.279	482	.254	533	.279	533	.279	482
.498	467	.584	482	.685	533	.787	482	.660	482
.812	482	.685	467	.812	482	1.524	467	.812	482
1.168	439	1.244	467	1.279	482	1.676	467	1.524	348
1.325	439	1.752	439	1.524	482	2.082	305	1.600	348
1.752	425	1.900	434	1.676	467	2.540	313	1.955	290
2.032	297	2.082	305	2.540	313	2.799	313	2.794	224
2.794	214	2.540	313	2.799	214	3.048	224	2.900	224
3.048	214	2.794	245	3.302	214	3.556	224	3.048	214

Tungsten Inert Gas Welding 1 Layer Deposit Macro Hardness

Table 44

Test No 1		Test No 2		Test No 3		Test No 4		Test No 5	
Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV	Depth mm	HV
.228	636	.203	571	.152	591	.152	571	.228	636
.355	636	.584	551	.228	591	.254	533	.279	636
.736	666	.965	551	.584	571	.685	533	.736	533
1.244	551	1.397	636	.736	533	1.168	482	1.143	591
1.676	482	1.828	551	1.524	518	1.600	515	1.524	551
2.082	482	2.260	482	2.068	426	2.438	467	2.260	482
2.413	467	2.540	467	2.794	234	3.048	313	2.540	348
2.794	339	3.043	305	3.048	218	3.556	229	2.794	290
3.048	251	3.556	239	3.556	216	4.064	224	3.048	283
3.302	245	4.064	218	4.318	216	4.318	219	4.064	224

Tungsten Inert Gas Welding 2 Layer Deposit Macro Hardness

APPENDIX 4

APPENDIX B

EPMA RESULTS

Thermal Spraying

Ni 1 Layer

Background	4073	)	
		)	
Standard	1055107	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds.

Peaks average

0.020 at 240 μm

- 0.650 from 240 μm - 480 μm

- 0.700 from 480 μm - 720 μm

Peak	-	0.010	x	10000	
1055107	-	4073	$\div$	100	10510.34

240 μm

0.0095144

= 0.009%

240 μm - 480 μm

0.5232942

= 0.52%

480 μm - 720 μm

0.5698498

= 0.56%

Thermal Spraying

Ni 2 Layers

Background	4174	)	
		)	
Standard	1057083	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.020 at 240 μm

0.833 from 240 μm - 720 μm

Peak	-	0.010	x	10000	
1057083	-	4174	$\div$	100	10529.09

240 μm

0.0094974

= 0.009%

240 μm - 720 μm

0.7816439

= 0.78%

Powder Spray Welding

W1 1 Layer

Background	3968	)	
		)	
Standard	1025183	)	counts/seconds
		)	
Full scale deflection	10 ⁴	)	

Readings off chart

Background 0.010 counts/seconds.

Peaks average

0.020 at 240 μ m

0.561 from 240 μ m - 960 μ m

Peak	-	0.010	x	10000	
1025183	-	3968	$\div$	100	10212.15

240 μ m

0.0097922

= 0.009%

240 μ m - 960 μ m

0.5395533

= 0.53%

Powder Spray Welding

Ni 2 Layers

Background	3933	)	
		)	
Standard	1027518	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.020 at 240 μm

0.800 from 240 μm - 960 μm

Peak	-	0.010	x	10000	
1027518	-	3933	$\div$	100	10235.85

240 μm

0.0097695

= 0.009%

240 μm - 960 μm

0.7717971

= 0.77%

Oxy-acetylene Welding

Ni 1 Layer

Background	5749	)	
		)	
Standard	1034364	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.050 counts/seconds

Peaks average

0.075 at 240 μm

0.500 from 240 μm - 480 μm

0.550 from 480 μm - 960 μm

Peak	-	0.050	x	10000	
1034364	-	5749	$\div$	100	<u>10306.15</u>

240 μm

0.0242573

= 0.02%

240 μm - 480 μm

0.4366324

= 0.43%

430 μm - 960 μm

0.4851472

= 0.48%

Oxy-acetylene Welding

Ni 2 Layers

Background	4402	)	
		)	
Standard	1151205	)	counts/seconds
		)	
Full scale deflection	0.050	)	

Readings off chart

Background 10^4 counts/seconds

Peaks average

0.075 at 240 μm

0.667 from 240 μm - 480 μm

0.720 from 480 μm - 960 μm

Peak	-	0.050	x	10000	
1151205	-	4402	÷	100	11468.03

240 μm

0.0217997

= 0.02%

240 μm - 480 μm

0.5380174

= 0.53%

480 μm - 960 μm

0.5842328

= 0.58%

TIG Welding

Ni 1 Layer

Background	4011	)	
		)	
Standard	1025021	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.056 at 240 μm

0.450 from 240 μm - 480 μm

0.500 from 480 μm - 960 μm

Peak	-	0.010	x	10000	
1025021	-	4011	$\div$	100	10210.1

240 μm

0.0450534

= 0.04%

240 μm - 480 μm

0.3863718

= 0.38%

480 μm - 960 μm

0.44074

= 0.44%

TIG Welding

Ni 2 Layers

Background	3934	)	
		)	
Standard	987132	)	counts/seconds
		)	
Full scale deflection	10 ⁷	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.055 at 240 μm

0.500 from 240 μm - 480 μm

0.540 from 480 μm - 960 μm

Peak	-	0.010	x	10000	
987132	-	3934	$\div$	100	9831.98

240 μm

0.045769

= 0.04%

240 μm - 480 μm

0.4983736

= 0.49%

480 μm - 960 μm

0.5390572

= 0.53%

Thermal Spraying

Cr 1 Layer

Background	1266	)	
		)	
Standard	515788	)	counts/seconds
		)	
Full scale deflection	5×10^3	)	

Readings off chart

Background 0.010 counts/seconds.

Peaks average

0.010 at 240 μm

0.100 from 240 μm - 480 μm

0.250 from 480 μm - 720 μm

Peak	-	0.010	x	3000	
515788	-	1266	$\div$	100	<u>5145.22</u>

240 μm

Zero

240 μm - 480 μm

0.0524758

= 0.05%

480 μm - 720 μm

0.1399357

= 0.13%

Thermal Spraying

Cr 2 Layers

Background	1220	)	
Standard	517572	)	
Full scale deflection	3×10^5	)	counts/seconds

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.010 at 240 μm

0.250 from 240 μm - 480 μm

0.350 from 480 μm - 720 μm

Peak	-	0.010	x	3000	
517572	-	1220	$\div$	100	5163.52

240 μm

Zero

240 μm - 480 μm

0.1394397

= 0.13%

480 μm - 720 μm

0.1742997

= 0.17%

Powder Spray Welding

Cr 1 Layer

Background	1171	)	
		)	
Standard	501440	)	counts/seconds
		)	
Full scale deflection	5×10^3	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.010 at 240 μm

0.100 from 240 μm - 480 μm

0.250 from 480 μm - 960 μm

Peak	-	0.010	x	3000	
501440	-	1171	$\div$	100	<u>5002.69</u>

240 μm

Zero

240 μm - 480 μm

0.0539709

= 0.05%

480 μm - 960 μm

0.1439225

= 0.14%

Powder Spray Welding

Cr 2 Layers

Background	1197	)	
		)	
Standard	503138	)	counts/seconds
		)	
Full scale deflection	5×10^3	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.010 at 240 μm

0.200 from 240 μm - 480 μm

0.350 from 480 μm - 960 μm

Peak	-	0.010	x	3000	
503138	-	1197	$\div$	100	<u>5019.41</u>

240 μm

Zero

240 μm - 480 μm

0.1135591

= 0.11%

480 μm - 960 μm

0.2032111

= 0.20%

Oxy-acetylene Welding

Cr 1 Layer

Background	1444	)	
		)	
Standard	635750	)	counts/seconds
		)	
Full scale deflection	5×10^3	)	

Readings off chart

Background 0.050 counts/seconds

Peaks average

0.075 at 240 μm

0.150 from 240 μm - 480 μm

0.300 from 480 μm - 960 μm

Peak	-	0.050	x	3000	
635750	-	1444	$\div$	100	<u>6343.06</u>

240 μm

0.0118239

= 0.01%

240 μm - 480 μm

0.0472957

= 0.04%

480 μm - 960 μm

0.1182394

= 0.11%

Oxy-acetylene Welding

Cr 2 Layers

Background	1304	)	
		)	
Standard	574094	)	counts/seconds
		)	
Full scale deflection	5×10^5	)	

Readings off chart

Background 0.050 counts/seconds

Peaks average

0.075 at 240 μm

0.200 from 240 μm - 480 μm

0.310 from 480 μm - 960 μm

Peak	-	0.050	x	3000	
574094	-	1304	$\div$	100	<u>5727.9</u>

240 μm

0.0130938

= 0.01%

240 μm - 480 μm

0.0785628

= 0.07%

480 μm - 960 μm

0.1361755

= 0.13%

TIG Welding

Cr 1 Layer

Background	1347	)	
		)	
Standard	634647	)	counts/seconds
		)	
Full scale deflection	10^5	)	

Readings off chart

Background 0.050 counts/seconds

Peaks average

0.200 at 240 μm

0.250 from 240 μm - 480 μm

0.500 from 480 μm - 960 μm

Peak	-	0.050	x	1000	
634647	-	1347	$\div$	100	<u>6333.0</u>

240 μm

0.0236854

= 0.02%

240 μm - 480 μm

0.0515806

= 0.03%

480 μm - 960 μm

0.0710563

= 0.07%

TIG Welding

Cr 2 Layers

Background	1161	)	
		)	
Standard	534912	)	counts/seconds
		)	
Full scale deflection	10^5	)	

Readings off chart

Background 0.050 counts/seconds

Peaks average

0.200 at 240 μm

0.300 from 240 μm - 480 μm

0.650 from 480 μm - 960 μm

Peak	-	0.050	x	1000	
534912	-	1161	$\div$	100	<u>5337.51</u>

240 μm

0.0281029

= 0.02%

240 μm - 480 μm

0.0468383

= 0.04%

480 μm - 960 μm

0.1124119

= 0.11%

Thermal Spraying

Si 1 Layer

Background	764	)	
		)	
Standard	304823	)	counts/seconds
		)	
Full scale reflection	10^2	)	

Readings off chart

Background 0.120 counts/seconds

Peaks average

0.455 at 240 μm

0.600 from 240 μm - 480 μm

0.710 from 480 μm - 720 μm

Peak	-	0.120	x	100	
---	304823	-	764	$\div$	100
					<u>3040.59</u>

240 μm

0.0110175

= 0.01%

240 μm - 480 μm

0.0157864

= 0.01%

480 μm - 720 μm

0.0194041

= 0.01%

Thermal Spraying

Si 2 Layers

Background	753	)	
		)	
Standard	300590	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.120 counts/seconds

Peaks average

0.465 at 240 μm

0.928 from 240 μm - 480 μm

0.720 from 480 μm - 720 μm

Peak	-	0.120	x	100	
300590	-	758	$\div$	100	2998.32

240 μm

0.0115064

= 0.01%

240 μm - 480 μm

0.0269484

= 0.02%

480 μm - 720 μm

0.0200112

= 0.02%

Powder Spray Welding

Si 1 Layer

Background	659	)	
		)	
Standard	305938	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.120 counts/seconds

Peaks average

0.400 at 240 μm

0.500 from 240 μm - 480 μm

0.650 from 480 μm - 720 μm

Peak	-	0.120	x	100	
305938	-	659	$\div$	100	<u>3052.79</u>

240 μm

0.0091719

= 0.009%

240 μm - 480 μm

0.0124476

= 0.01%

480 μm - 720 μm

0.0173611

= 0.01%

Powder Spray Welding

Si 2 Layers

Background	749	)	
		)	
Standard	306847	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.120 counts/seconds

Peaks average

0.400 at 240 μm

0.740 from 240 μm - 480 μm

0.740 from 480 μm - 960 μm

Peak	-	0.120	x	100	
306847	-	749	$\div$	100	<u>3060.98</u>

240 μm

0.0091473

= 0.009%

240 μm - 480 μm

0.0202549

= 0.02%

480 μm - 960 μm

0.0202549

= 0.02%

Oxy-acetylene Welding

Si 1 Layer

Background	925	)	
		)	
Standard	339507	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.140 counts/seconds

Peaks average

0.420 at 240 μm

0.567 from 240 μm - 480 μm

0.800 from 480 μm - 960 μm

Peak	-	0.140	x	100	
339507	-	925	÷	100	<u>3385.82</u>

240 μm

0.0082697

= 0.008%

240 μm - 480 μm

0.0126114

= 0.01%

480 μm - 960 μm

0.019493

= 0.01%

Oxy-acetylene Welding

Si 2 Layers

Background	964	)	
		)	
Standard	427831	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.120 counts/seconds

Peaks average

0.500 at 240 μm

0.980 from 240 μm - 480 μm

0.980 from 480 μm - 960 μm

Peak	-	0.120	x	100	
427831	-	964	$\div$	100	<u>4268.67</u>

240 μm

0.008902

240 μm - 480 μm

0.0201467

= 0.02%

480 μm - 960 μm

0.0201467

= 0.02%

TIG Welding

Si 1 Layer

Background	809	)	
Standard	295322	)	counts/seconds
Full scale deflection	10^2	)	

Readings off chart

Background 0.140 counts/seconds

Peaks average

0.520 at 240 μm

0.531 from 240 μm - 480 μm

0.580 from 480 μm - 960 μm

Peak	-	0.140	x	100	
293822	-	809	÷	100	<u>2930.13</u>

240 μm

0.0129692

= 0.01%

240 μm - 480 μm

0.0133441

= 0.01%

480 μm - 960 μm

0.0150163

= 0.01%

TIG Welding

Si 2 Layers

Background	817	)	
		)	
Standard	293784	)	counts/seconds
		)	
Full scale deflection	10^2	)	

Readings off chart

Background 0.140 counts/seconds

Peaks average

0.520 at 240 μm

0.800 from 240 μm - 480 μm

0.800 from 480 μm - 960 μm

Peak	-	0.140	x	100	
293784	-	817	$\div$	100	<u>2929.67</u>

240 μm

0.0129707

= 0.01%

240 μm - 480 μm

0.0225281

= 0.02%

480 μm - 960 μm

0.0225281

= 0.02%

Thermal Spraying

Fe 1 Layer

Background	2463	)	
		)	
Standard	847385	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.835 at 240 μm

0.050 from 240 μm - 720 μm

<u>Peak</u>	<u>-</u>	<u>0.010</u>	<u>x</u>	<u>10000</u>	
847385	-	2463	$\div$	100	8449.22

240 μm

0.9764214

= 0.97%

240 μm - 720 μm

0.0473416

= 0.04%

Thermal Spraying

Fe 2 Layers

Background	2318	)	
		)	
Standard	828581	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.793 at 240 μm

0.050 from 240 μm - 480 μm

0.038 from 480 μm - 720 μm

Peak	-	0.010	x	10000	
828581	-	2318	$\div$	100	8262.63

240 μm

0.9476401

= 0.94%

240 μm - 480 μm

0.0484107

= 0.04%

480 μm - 720 μm

0.0338875

= 0.03%

Powder Spray Welding

Fe 1 Layer

Background	2517	)	
		)	
Standard	832765	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.800 at 240 μm

0.055 from 240 μm - 480 μm

0.050 from 480 μm - 960 μm

Peak	-	0.010	x	10000	
832765	-	2517	$\div$	100	8302.48

240 μm

0.9515229

= 0.95%

240 μm - 480 μm

0.0542006

= 0.05%

480 μm - 960 μm

0.0431783

= 0.04%

Powder Spray Welding

Fe 2 Layers

Background	2396	)	
		)	
Standard	840077	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.810 at 240 μm

0.050 from 240 μm - 480 μm

0.040 from 480 μm - 960 μm

Peak	-	0.010	$\times$	10000	
840077	-	2396	$\div$	100	<u>8376.81</u>

240 μm

0.9550174

= 0.95%

240 μm - 480 μm

0.0477508

= 0.04%

480 μm - 960 μm

0.0358131

= 0.03%

Oxy-acetylene Welding

Fe 1 Layer

Background	22589	)	
		)	
Standard	1088886	)	counts/seconds
		)	
Full scale deflection	1.5×10^4	)	

Readings off chart

Background 0.060 counts/seconds

Peaks average

0.745 at 240 μm

0.135 from 240 μm - 480 μm

0.120 from 480 μm - 960 μm

Peak	-	0.060	x	15000	
1088886	-	22589	$\div$	100	<u>10662.97</u>

240 μm

0.9636152

= 0.96%

240 μm - 480 μm .

0.1055053

= 0.10%

480 μm - 960 μm

0.0844042

= 0.08%

Oxy-acetylene Welding

Fe 2 Layers

Background	2318	)	
		)	
Standard	823323	)	counts/seconds
		)	
Full scale deflection	10^4	)	

Readings off chart

Background 0.010 counts/seconds

Peaks average

0.300 at 240 μm

0.065 from 240 μm - 480 μm

0.055 from 480 μm - 960 μm

Peak	-	0.010	$\times$	10000	
823323	-	2318	$\div$	100	<u>8210.05</u>

240 μm

0.9622353

= 0.96%

240 μm - 480 μm

0.066991

= 0.06%

480 μm - 960 μm

0.0548108

= 0.05%

TIG Welding

Fe 1 Layer

Background	25798	)	
		)	
Standard	1206138	)	counts/seconds
		)	
Full scale deflection	1.5×10^7	)	

Readings off chart

Background 0.060 counts/seconds

Peaks average

0.810 at 240 μm

0.200 from 240 μm - 480 μm

0.150 from 480 μm - 960 μm

Peak	-	0.060	x 15000	
1206138	-	25798	- $\div$ 100	11803.4

240 μm

0.9531152

= 0.95%

240 μm - 480 μm

0.1779148

= 0.17%

480 μm - 960 μm

0.1143738

= 0.11%

TIG Welding

Fe 2 Layers

Background	25988	)	
Standard	1222574	)	
Full scale deflection	1.5×10^4	)	counts/seconds

Readings off chart

Background 0.065 counts/seconds

Peaks average

0.838 at 240 μm

0.150 from 240 μm - 480 μm

0.130 from 480 μm - 960 μm

Peak	-	0.065	x	15000	
1222574	-	25988	$\div$	100	<u>11965.86</u>

240 μm

0.9690068

= 0.96%

240 μm - 480 μm

0.1065531

= 0.10%

480 μm - 960 μm

0.0814818

= 0.08%

APPENDIX 5

APPENDIX 5

STATISTICAL ANALYSIS OF WEAR AND SURFACE HARDNESS TEST RESULTS

Method: The Standard Error of the Difference between Sample Means

The research worker can tell whether the difference between two experiments is a chance difference, arising merely from the random selection of samples from the same population, or whether the difference signifies a real difference between the populations represented by the samples by calculating the standard error of the mean.

Just as the standard error of the mean is the standard deviation of the distribution of sample means, so the standard error of the difference is the standard deviation of the distribution of the differences between sample means.

To calculate the standard error, first calculate the variance of the distribution of the differences.

$$\text{Var} = \sigma^2$$

Similarly, the variance of the distribution of sample means may be expressed:

$$\text{Var}_{\bar{x}} = \frac{\sigma^2}{n}$$

It may also be shown mathematically that the variance of the difference of two independent variables is equal to the sum of their individual variances. Thus:

$$\text{Var} (\bar{x}_1 - \bar{x}_2) = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}$$

The standard deviation for the distribution of the differences is equal to the square root of the variance

$$= \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

and this is known as the standard error of the mean.

The difference between the two sample means is then measured against the standard error. If the difference between the means exceeds three times the standard error of the difference, such a difference would indicate that there is a significant difference between the populations from which the samples were drawn.