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Development of a nanodiamond-based lubricant for a versatile use in the beverage industry conveyor systems

Abstract

Purpose: This paper proposes the formulation of a nanodiamond particle-loaded food-grade lubricating oil, a nanolubricant, that can be used over a broad range of loads within the factory (low load applications: conveyor systems; and heavy machinery within the factory where high loads are applied)

Design/Methodology: Tribological performance of the nanolubricant at both load levels was studied. A factory-sized conveyor was employed for the low load range using typical beverage packaging (aluminium cans, glass and PET bottles). Coefficients of friction and wear scars were measured and the lubricating performance quantified. A four-ball tester was used to characterise the performance of the nanolubricant as per ASTM D2783/D4172. A comparison between the nanolubricant and the baseline oils was established.

Findings: The results show an overall decrease of the coefficients of friction and wear scars for all packages at low pressures when the nanolubricant is used. It also shows a better friction-reduction performance in the high loads. The results indicate that the nanolubricant is versatile at both ranges of loading.

Practical/Environmental implications: The current protocols for lubrication in the food and drink factories involve the use of water-based detergents for the conveyor lines, and industry-grade oils for the machinery. The use of a single and versatile lubricant for both ranges of application loads may carry a positive impact on the sustainability and environmental performance of the sector.

Originality/value: Beverage processing and packing factories need their mechanised conveyor systems suitably lubricated to avoid excessive friction between the containers and the load bearing surface of the conveyors (e.g. belts or chains). Other areas of the conveying systems, such as motors, gears, rollers and bearings, are also in need of suitable lubrication to prevent failure and lengthen their working life. There is a myriad of lubricants and lubricating solutions for each of these areas independently, but no existing availability of commercial lubricating fluids that could be used on both successfully.

Keywords – Nanodiamond, poly alpha olefin oil, mineral oil, beverage conveyor system, lubrication

Paper type – research paper

1. Introduction

Filling, capping, labelling, sealing, packing and discharge stations on beverage processing lines are areas in the factory where cans, plastic and glass bottles and jars remain stationary while the belts and chains move linearly underneath. Damages (e.g. scaring, scratches, scuffing, peeling off) to the packages result in production loss and waste. Packaged food and drink compete in the very crowded market of fast moving consumer goods, so any defect on the packaging or label is perceived as detrimental to the brand. In order to avoid undesirable flaws caused by the transport in the filling/packaging lines, lubrication solutions are applied. These can consist of solid (e.g. graphite, PTFE and metal dichalcogenides [1] (i.e. MX_2 , where M is, for instance, molybdenum (Mo) or tungsten (W) and X is sulphur (S) or selenium (Se)) particles scattered or sprayed onto the surfaces subject to friction [2]) and liquid lubrication approaches. The most sought after specifications in the liquid lubricating system are (i) good lubricity to reduce coefficient of friction and wear, (ii) low viscosity which allows easy application (via spraying or pumping), and (iii) compatibility between the lubricant and the beverage packaging material to avoid damage or cracking in transit or in storage, or to inhibit solid precipitates when content and lubricant come into contact in the event of spillage.

The application of concentrated liquid lubricants (typically <50% of dispersant [3] and called 'dry' lubrication to distinguish from 'wet' lubrication where the dispersant, typically water, is the main component) has become very popular in the recent years in industries that utilise conveyor systems (e.g. assembly, packaging, sorting, warehousing). However, most of the lubricants applied in the 'dry' regime still suffer from being specific to each application. For example, silicone-based [3] and fluorine-containing lubricants [4] are good performers with PET bottles (i.e. containers made of ethylene terephthalate homopolymers, copolymers and mixtures) but less effective on glass and metal containers, particularly on a metal surface [3]. Silicone with fatty amines are recommended for glass on stainless-steel [5]. Lubricants that contain amines, alcohols, potassium hydroxide, ammonium salts or mixtures are incompatible with PET containers causing them to crack in transit or storage [6-8]. Applied by brushes and nozzles, PTFE adheres very strongly to the chains and this soiling curb the performance profile of the lubricant gradually [9]. In addition, PTFE has also been shown to produce stress-cracking in PET bottles [4].

The lubricants formulated for use in the food industry conveying systems perform well as long as low load conditions exist and are not necessarily specified for harsher environments. The lubricants available for application in high load conditions are typically mineral oils with anti-corrosion, anti-wear, anti-friction additives in different proportions [10]. In the food industry machinery these oils are used as hydraulic, circulating, cable, chain, spindle, gear and compressor oils for equipment in the service industry. In the most recent years the nanoparticle-containing suspensions in oils have surged as the most promising of the lubricants for high pressure mechanical applications, in particular when the boundary lubrication is the dominant

regime (i.e. the lubricating fluid film thickness is small and asperities from rubbing surfaces come into contact and wear is high). Although the majority of examples are oil-based, there are also examples of water-based lubricants [11]. The nanometre scale of the particles improves solubility into the oils, compared to the micro scales [12] and there is a voluminous body of work published in the areas of metal nanoparticles [12-15], non-metal nanoparticles dispersed in mineral oils [16-19], in polymeric oils [20, 21], in natural oils [22, 23], in paraffin [24, 25], and with extra additives to improve their anti-wear, anti-friction features [26-29]. The lubrication mechanisms promoted by nanoparticles have been described and can be classified into two [30]: (i) Direct effects on lubrication (physical effect): the nanoparticles act as spacers and produce ball [31] and sliding effects [32] via mechanical entrapment of the particles between the rubbing surfaces (e.g. exfoliation and third body transfers [33]). They may also adhere onto the rubbing surfaces creating a protective film preventing them from direct contact, resulting in a decrease in friction and wear [34]; and (ii) Secondary effect on surface enhancement (chemical effect): there may exist tribo-chemical reactions [35] in which the nanoparticles may react with the material(s) they are rubbing against creating new chemical components that promote a mending or polished effect on the surfaces [18, 36, 37].

One of the nanoparticles already reported which shows a promising future as a lubricant component for the food technology use is the nanodiamond. Its carbon chemistry biodegradability, non-toxicity [38], bearing-like shape promoting sliding rolling as lubrication mechanism [39], solubility in both mineral oil and others ([25, 40] and feasible production into de-agglomerated [41, 42] and stable dispersions [43] (via the detonation method [44-47]) makes it a suitable candidate for formulations designed for the use in the mechanical services in the food factory and for the occasional contact with food materials and containers (namely H1 USDA approved).

In the search of a versatile lubricating fluid which can be used successfully on both ranges (low and high pressure applications) and on typical beverage packaging, a nanodiamond particle-loaded lubricating commercial and food grade oil, a nanolubricant, has been formulated, characterised and tested to show that the dual performance is achievable. Factory conditions were replicated for the low load values so that these results can faithfully characterise the nanolubricant in its most realistic working conditions. This is a novel way of assessing lubrication features that satisfies both industrialists as well as applied research scientists. Traditional tests performed on lubricants, in accordance with International Standards, were also considered in this study and therefore allowed comparison with the work carried out by others in this area.

2. Experimental

Materials

The nanodiamond particles used in this study were purchased from Adámas Nanotechnologies (USA). The particle population in the slurry was characterized using a Nanosight LM-10 instrument (Malvern Instruments Ltd, UK) and its stability (i.e. zeta-potential and conductivity) measured using a Zetasizer Nano ZS (Malvern, UK). Figure 1 shows the results from this analysis in which the majority of the particles are <30nm. The zeta-potential was -116mV, conductivity 4.12μS/cm and electrophoretic mobility of -6.83e-3μm.cm/Vs, values that confirmed full stability of the dispersions. Two commercial oils (Kristol M24, a white mineral oil (Petrochem Carless Ltd, United Kingdom) and a polyalphaolefin oil, SpectraSyn™ 6 (ExxonMobil, USA) were used as the base oils without further treatment. The properties of the oils are listed in Table 1. Samples for tribological tests were prepared by dispersing 0.01%wt ratio of nanodiamonds in the base oil. This concentration was informed by previous studies [48]. As a comparison, the tribological properties of the base oils without carrying the nanodiamonds or additives, in their pure form, were also evaluated. The rheological characteristics of the nanolubricants were measured using a Brookfield Rheometer DV-II+ Pro with a RV-1 spindle at a spindle speed of 60rpm. For the low load 'factory-like' conditions, the friction force was measured by means of the sliding force of the conveyor when the packages were under motion-restricted mode. A digital force gauge (Mecmesin Ltd, UK) collected sliding forces at a 10Hz sampling rate as shown in Figure 2. This allowed the calculation of the coefficient of friction (COF) under low load schemes using equation (1), with force F being the load (N) registered by the force gauge, 'i' the number of packs, g the gravitational constant (m/s^2) and mass m the average value (kg) of the packs used in each run.

$$COF = \frac{F}{i \cdot g \cdot m} \quad (1)$$

The wear scar surfaces were inspected by high resolution scanning (2400dpi) on and EPSON Perfection Scanner 1640SU and the results analysed with ImageJ (W. Rasband, 1997, National Institutes of Health, USA). For the high load schemes, the lubricants load-carry capacity – and more specifically the load wear index (LWI) and the weld load (P_D) - were measured in a four ball tribometer according to ASTM D2783. Measurements of the wear-preventing characteristics of the lubricants were assessed as per ASTM D4172.

Table 1: Rheological properties of the base oils

	Mineral oil	PAO oil
Commercial name	Kristol M24	SpectraSyn 6
Kinematic viscosity (mm ² /s) 40°C	36.0	30.0
Pour point (°C)	-6	-57
Flash point (°C)	180	249
Specific gravity (at 15°C)	0.859	0.827
pH	6.5	5.5
Colour /Odour	Colourless / Odourless	Colourless / Odourless

Figure 1: Particle size distribution of the nanodiamonds as received

3. Results and Discussion
A) Tribological performance under low load schemes - on the conveyor belts

An industrial-size stainless steel belt conveyor was used for testing friction and scaring (or scuffing) on the bottom of three types of beverage packaging (aluminium cans, glass bottles and PET bottles) typically found in the bottling and filling food industries. The belt travelled at a speed of 20m/min and the tests were run for 60min (Figure 2). A test was run without any lubrication (labelled as ‘blank’). When lubricants were present, these were deposited onto the conveyor belts in ‘dry-regime’ conditions on top of the chain on the wear strips. The lubricants tested were mineral base oil (labelled ‘Min’), nanolubricant comprising the dispersion of nanodiamonds 30nm in the mineral oil (Min30) and nanolubricant comprising the dispersion of the nanodiamonds 30nm in the PAO oil (PAO30). Results from the friction using only base oil PAO are similar to those of mineral only and therefore not shown.

Figure 2: Experimental set up for the low load scheme (on the conveyor belt)

Figure 3: Representative scars and scuffing on packages used on the conveyors: (left) aluminium cans, (middle) glass bottles, (right) PET bottles

Boundary was the regime of lubrication observed and it remained stable throughout the duration of the friction test in all cases. Examination to the bottom of the packages revealed scratches due to the abrasion (Figure 3). The coefficient of friction (COF) for each of the packages as a function of time and the wear scar area for each of the lubricating fluids including the 'blank' are plotted in Figure 4 and Figure 5. The results of the measurements are summarised in Table 2. As it can be seen in Figure 4, maximum COF values (within the range 0.16-0.25) were reached when there was no lubricating fluid present (i.e., in 'blank' conditions). In the presence of lubrication, COF values were reduced generally for all the beverage packages, as per Table 2. The COF reduction is 35% in the aluminium cans, ~27% in the glass bottles, and 63% in the PET bottles. The wear print decreases ~43% in

the glass bottles. The aluminium cans with nanolubricant fabricated using PAO oil and 30nm nanodiamond presents the most remarkable drop (52%) compared to the use of the plain oil (17%). This effect is also observed in the PET bottles, with a better performance of the nanodiamond-loaded oils compared to the plain oil. It can be hypothesised therefore that the nanoparticles are agglomerates that allow higher probability for the ‘ball bearing’ effect to develop between the two surfaces in contact, in that way protecting from solid-to-solid abrasion. Similar reduction values for the COF and wear scars have been reported by other authors working in the same oil-nanodiamond system [48-50], the paraffin-nanodiamond system [25], and an oil-non nanodiamond system [18].

It is worth noting the difference between the aluminium cans and the PET bottles: the latter ones exhibit lower COFs. Further investigation on the scars and scuffing on the bottles revealed a plastic deformation on the materials (i.e. pilling) along with heavy scratches which could have contributed to lowering the friction between the bottles (soft material) against the conveyor belt (harder material) (Figure 3, right, see arrows). This mixed abrasive-plastic deformation mechanism has been observed in other studies [51]. On the other hand, this event cannot be observed on the aluminium cans, whose worn area is characterised by linear scratches only (i.e. hard on hard materials) (Figure 3, left).

Figure 4: COF values for low load scheme

Figure 5: COF and Wear Scar Area per package and lubricant type

Table 2: Coefficient of friction and wear scar area values for each of the packages when using the lubricating fluids on the conveyors

	Aluminium cans		Glass bottles		PET bottles	
Mass (average)	0.530kg		1.131kg		0.543kg	
Dimensions	6.63cm diameter		8.2cm diameter		6.76cm diameter	
Contact surface	Circular lip, OD 5.26cm, ID 4.7cm		Circular lip, OD 8.2cm, ID 7.1cm		Pentalobe base, each lobe 0.71cmx0.8cm	
	COF(std) (Δ%)	Wear, cm ² (std) (Δ%)	COF(std) (Δ%)	Wear, cm ² (std) (Δ%)	COF(std) (Δ%)	Wear, cm ² (std) (Δ%)
Blank	0.199(0.009) (-)	0.81(0.12) (-)	0.171(0.013) (-)	0.13(0.03) (-)	0.216(0.016) (-)	2.01(0.58) (-)
Min	0.131(0.014) (-34%)	0.67(0.13) (-17%)	0.121(0.011) (-29%)	0.07(0.02) (-47%)	0.080(0.010) (-63%)	1.66(0.38) (-18%)
Min30	0.128(0.014) (-35%)	0.57(0.05) (-30%)	0.125(0.022) (-27%)	0.08(0.01) (-39%)	0.080(0.014) (-63%)	1.22(0.56) (-40%)
PAO30	0.129(0.016) (-35%)	0.39(0.10) (-52%)	0.129(0.014) (-25%)	0.08(0.02) (-43%)	0.084(0.013) (-61%)	1.27(0.29) (-37%)

*note: Coefficient of friction (COF) and Wear Scar Area are averaged values with a standard deviation (std). Δ% is the percentage of reduction (negative scalar) or increment (positive scalar) with respect to the blank tests with no lubricating fluid.

B) Tribological performance under high load schemes

The load-carrying and anti-wear properties of the nanolubricants in high pressure conditions were compared to those of the base oil without the particles. As per ASTM D2783, three chrome alloy steel balls (of 12.7mm diam, with a Rockwell C hardness in the range 64-66 and a surface roughness grade 25 EP(extra polish)) were locked in a tribometer test cup. The under-test lubricant was poured over them. A fourth steel ball was held in place in a rotating clamp and placed on top of the 3 balls. It was then made to spin at 1,760 rpm and subjected to a 10sec long series at increasing loads until welding of the balls occurred. The load was recorded. This test allowed the finding of the load wear index (LWI) which quantifies the wear protection at high loads, and of the weld point, i.e. lowest applied load at which sliding surfaces of the balls seize and therefore weld. The results for LWI as a function of the lubricant used can be shown in Figure 6. No significant difference was exhibited for the four lubricating fluids. Similarly, a 4 ball tribometer was used for measuring wear preventing characteristics of a lubricant as per ASTM D4172. Three new steel balls (features as above) were locked in the test cup and a fourth ball placed on top of the cavity formed by the 3 clamped balls for 3point contact. At a lubricant temperature of 75°C the top ball was rotated at 1,200 rpm while applying a force of 392N. After 60min the top ball was discarded, the 3 remaining balls cleaned and inspected for wear damage under optical microscope, and the wear scar diameter (WSD) measured. Results are shown in Figure 7. Both the ASTM D2783 and the ASTM D4172 tests were performed at standard ambient conditions (1 atm, 25C, 45%RH)

Figure 6: Results for the ASTM D2783 extreme pressure tests

Figure 7: Results for the ASTM D4172 on wear preventing characteristics tests

It can be extracted from the LWI results that the nanolubricants present an increment in anti-wear properties (58.8% and 44.4%) with respect to the base oils alone (mineral and PAO). This result is consistent with results obtained on other oil-nanoparticle systems [15, 18]. A large value of LWI indicates a larger ability of the lubricant to prevent wear at applied loads. The four lubricants seized at 1236.06N, being that their weld point. This suggests that the nanodiamonds do not display significant load-carrying improvements when compared to the base oils. In the results from the WSDs the nanolubricants present a 19% smaller diameter of wear scar with respect to the plain oil, which indicates a significant anti-wear protection improvement provided by the nanoparticles.

4. Conclusions

In this study the tribological performance of a nanolubricant prepared with nanodiamonds dispersed in commercial oils (mineral and polyalphaolefin) was studied. As a lubricant to be used on beverage conveyor systems and in contact with food packages, a factory-sized set-up was considered for the friction and wear tests under low load conditions, in accordance with the conditions in industry. The characterisation of load-bearing, anti-friction and anti-wear (e.g. scratching or scuffing) capacity of the lubricant at large pressures and high loads was also of interest since the purpose is to develop a versatile lubricant that can be used also on mechanical machinery within the factory.

- With the prolonged low pressure friction process, wear scar was reduced in the presence of the nanolubricant comprising nanodiamonds of <30nm dispersed in the base oils.
- The predominant regime of lubrication was boundary film and the solid-solid friction mechanisms observed were abrasion (cans and glass bottles) and plastic deformation (PET bottles).

- The results at high pressure conditions show that the friction occurred in the presence of nanolubricating fluids was lower than that of the pure oils, which suggests that the nanodiamonds have good friction-reduction properties.

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Colour /Odour	Colourless / Odourless	Colourless / Odourless

Table 2: Coefficient of friction and wear scar area values for each of the packages when using the lubricating fluids on the conveyors

	Aluminium cans		Glass bottles		PET bottles	
Mass (average)	0.530kg		1.131kg		0.543kg	
Dimensions	6.63cm diameter		8.2cm diameter		6.76cm diameter	
Contact surface	Circular lip, OD 5.26cm, ID 4.7cm		Circular lip, OD 8.2cm, ID 7.1cm		Pentalobe base, each lobe 0.71cmx0.8cm	
	COF(std) (Δ%)	Wear, cm² (std) (Δ%)	COF(std) (Δ%)	Wear, cm² (std) (Δ%)	COF(std) (Δ%)	Wear, cm² (std) (Δ%)
Blank	0.199(0.009) (-)	0.81(0.12) (-)	0.171(0.013) (-)	0.13(0.03) (-)	0.216(0.016) (-)	2.01(0.58) (-)
Min	0.131(0.014) (-34%)	0.67(0.13) (-17%)	0.121(0.011) (-29%)	0.07(0.02) (-47%)	0.080(0.010) (-63%)	1.66(0.38) (-18%)
Min30	0.128(0.014) (-35%)	0.57(0.05) (-30%)	0.125(0.022) (-27%)	0.08(0.01) (-39%)	0.080(0.014) (-63%)	1.22(0.56) (-40%)
PAO30	0.129(0.016) (-35%)	0.39(0.10) (-52%)	0.129(0.014) (-25%)	0.08(0.02) (-43%)	0.084(0.013) (-61%)	1.27(0.29) (-37%)

*note: Coefficient of friction (COF) and Wear Scar Area are averaged values with a standard deviation (std). Δ% is the percentage of reduction (negative scalar) or increment (positive scalar) with respect to the blank tests with no lubricating fluid.

78x59mm (96 x 96 DPI)

cation and Tribology

121x166mm (96 x 96 DPI)

146x156mm (96 x 96 DPI)

tribology

195x166mm (96 x 96 DPI)

238x200mm (96 x 96 DPI)

160x181mm (96 x 96 DPI)