The Use of Powder Metallurgy for Promoting Friction Reduction under Sliding-Rolling Lubricated Conditions

G. Boidi ^{a,b,c*}, F.J. Profito ^a, A. Kadiric ^b, I.F. Machado ^a, D. Dini ^b

[*Guido.Boidi@ac2t.at](mailto:Guido.Boidi@ac2t.at)

^a Escola Politécnica, University of São Paulo – USP, São Paulo, Brazil

^b Tribology Group, Department of Mechanical Engineering, Imperial College London, South Kensington Campus, Exhibition Road, London, SW7 2AZ, UK

^c AC2T research GmbH, Viktor-Kaplan-Straße 2/C, 2700 Wiener Neustadt, Austria

ABSTRACT

This work exploits the use of different sintering manufacturing techniques for obtaining superior performances in lubricated point contacts. Disc and ball specimens were manufactured varying porosity and pore characteristics. The effect of surface pores in sintered materials was evaluated based on the frictional behaviour under different sliding-rolling conditions and lubrication regimes. Furthermore, lubricant film thicknesses were measured using interferometric technique. Test results showed that the decrease of porosity generally improves tribological performance. Low porosity surfaces can promote friction reduction compared to non-porous reference materials in specific configurations and operating with similar specific lubricant thickness values. This work contributes to an improved understanding of how randomly distributed micro-irregularities could change lubrication conditions, potentially increasing the efficiency of lubricated mechanical systems.

KEYWORDS: Surface pores; Film thickness; Powder metallurgy; Sliding-rolling

1. Introduction

Powder Metallurgy (PM) is a manufacturing technique that allows producing a broad range of materials through sintering. It is possible to make mechanical components with a complex shape avoiding additional machining operations, thus reducing costs and material waste. Furthermore, the sintering temperature is lower than the melting temperature, promoting ceramics, hard-metals and composites [1]. A very positive aspect and part of the great attractiveness of sintering techniques is that surface pores are produced directly by PM manufacturing, and other additional operations are not required. PM production is itself a low cost-manufacturing technique for large scale-production [1]. The extra benefits obtained by the presence of surface features that could potentially improve tribological performances [2–4] make this an even more promising technology. However, it must be taken into account that porosity negatively affects the mechanical properties of materials, since the lack of material between particles has a detrimental effect on the bulk properties [5–8]. Moreover, pores modify tension distribution and could be hot spots for crack propagation and initiation [9,10], potentially decreasing components' fatigue life, especially for heavily loaded machine elements.

The tribological behaviour of sintered materials has been overlooked and not well understood until now, probably due to the detrimental influence of porosity on mechanical properties. Furthermore, open and interconnected surface pores influence material permeability and, consequently, negatively affect lubrication decreasing film thickness and lubricant load support capacity [11–13]. On the contrary, the effect of surface closed porosity could be somehow compared to the texture. Some authors ventured to compare the tribological effects of surface features produced by sintering and laser texturing using machine learning techniques in previous work [14]. Surface cavities could act as oil reservoirs and debris trapping under boundary and mixed lubrication, thus decreasing friction and wear [15]. Under (elasto)-hydrodynamic lubrication regime, surface cavities could promote extra load-carrying capacity by locally increasing the fluid pressure ("micro bearing effect") and reducing friction [16–20]. One of the main differences between the sintered and textured surfaces is that although particles characteristics and sintering parameters control porosity, surface pores are generally randomly distributed spatially within the material in terms of shape and size. On the contrary, surface texture patterns are typically designed for a specific purpose and tightly controlled. The number of studies related to textured materials has increased in the last years [19–22], whereas the tribological effect of porosity in PM materials is still poorly explored and understood.

Few studies attempted to scrutinise the tribological performance of porous materials [23–25], especially for self-lubricating contacts (bearings and gears) under boundary lubrication and sliding conditions. Notably, Martin and co-authors showed how the increase in PM materials' porosity led to wear reduction [26]. The authors showed that surface porosity acted as oil reservoirs and enhanced extra lubrication in harsh conditions (boundary lubrication), thus promoting heat transfer and reducing wear. Li et al. compared the tribological behaviour of wrought and sintered gear materials

under pin-on-disc sliding tests [27–29]. Main results showed that a more porous surface generally reduced friction and wear in the boundary lubrication regime compared to a reference non-porous surface. These findings corroborated by previous studies of Martin et al. [26].

Furthermore, Li et al. verified that non-porous samples (wrought) tested against porous material (PM) performed better than the same pair of materials (wrought × wrought or PM × PM). It was only recently that studies ventured to scrutinise the performance of PM materials under high load EHL conditions [30–33]. Large porosity generally decreases surface load support capacity, leading to high wear rates and pores closure when a heavy load is applied [31,34,35]. The presence of small close porosity could improve the lubricant load-carrying capacity and consequently reduce friction. On the contrary, it was shown that large pore dimensions and open porosity (connected networks of pores) increase surface roughness and friction in mixed and full-film EHL regimes [31–33]. As recently emphasised by Ebner et al. [33] and the authors [32], porous surfaces could potentially decrease friction; however, a right balance between porosity and surface finishing should be selected.

Since the tribological studies related to PM materials were mainly confined to specific aspects (e.g. sliding conditions under boundary lubrication), one of the purposes of this work is to explore the tribological performance of PM material for a wide range of slide-roll ratios and lubrication regimes. Furthermore, the film thickness was measured for rough surfaces by using a novel interferometry technique [36,37] to identify each lubrication regime for different surface conditions (surface porosity and roughness). The possibility of using a less expensive manufacturing technique to promote friction reduction should be better scrutinised since it could bring a reduction in pollutant emissions and cost savings.

In this context, this work aims to evaluate the tribological performances of sintered materials in lubricated point contacts. The variation of sliding-rolling conditions during tests permits to identify in which operating regimes and test conditions sintered materials could promote friction reduction compared to standard non-porous materials. This study contributes to understanding how random micro-irregularities could change lubricant conditions, potentially increasing the efficiency of mechanical systems. This research will also support exploring the use of sintering in large-scale manufacturing processes, aimed at reducing production costs.

2. Material and methodology

2.1. Experimental set-up and procedure

This study involved both the manufacturing of samples and tribological testing. The PM specimens were manufactured using different sintering techniques due to dimensional requirements for tribological tests. After sintering, the material was machined for obtaining disc and ball-shaped samples. PM balls and discs were both sintered using three distinct parameter set-ups to achieve different porosity and pores distribution. PM balls were tested against non-porous discs (defined as **NP**), whereas PM discs against non-porous balls. NP pairs were used as reference material made of standard AISI 52100 through hardened bearing steel. The coefficient of friction (COF) and film thickness were measured using two test rigs using ball-on-disc configuration. Entrainment speed and sliding-rolling conditions were varied during frictional tests obtaining a surface response of COF (3D friction map). All test combinations were run in one test with one set of samples. Therefore, experiments started using less severe conditions (low speed and low sliding rate) up to more severe ones to avoid significant modification of contact conditions and excessive wear. Surface topography was measured before and after tests for evaluating wear mechanisms. The same speed range adopted for frictional experiments was used for film thickness measurements to permit combining the two tribometers' results. For instance, the specific film thickness was calculated for each speed and combined with frictional results to evaluate the effect of porosity on the lubrication conditions. Film thickness was measured using interferometry technique, loading a plain ball against a glass disc; therefore, only PM and NP balls were tested in this configuration. More details about tribological tests, PM manufacture and specimen characterisations could be found in the following sections.

2.2. Preparation of sintered samples

A commercially available steel powder mixture was used to prepare sintered samples. The steel mixture contained 0.85 wt.% of Molybdenum and 0.3 wt.% of Carbon. Ball samples were 19.05 mm ($\frac{3}{4}$ inch) in diameter, whereas discs were 6 mm in thickness and 46 mm in diameter. Bulk and surface properties are presented in the results section (see Table 3).

Test balls were produced using the *Spark Plasma Sintering* (SPS) technique, as illustrated schematically in Figure 1a. Using this technique [38], the high current densities and uneven temperature distribution within the powders only allow the production of smaller sample dimensions (10-30 mm). For this reason, only the test balls could be sintered using SPS.

Again, in order to provide a desired range of porosities on the ball samples, different combinations of compacting pressures, sintering temperatures and holding time were used as detailed in Table 1. As usual, the temperature, time and pressure used for the SPS process were much lower than those used for the conventional sintering process [39,40]. The three different ball samples produced are hereafter denoted as B1, B2 and B3.

The disc specimens were produced using a conventional sintering technique. This consists of mixing, compacting and sintering phases [1] and allows for the production of samples of relatively large dimensions (100-200 mm). The technique is illustrated in Figure 1b. In order to obtain different porosity levels and characteristics of the resulting pores, discs were prepared with three different compacting pressures, 400 MPa, 500 MPa and 600 MPa. The sintering temperature (1280 °C), atmosphere (Ar) and holding time (60 min) were the same in all cases. The three resulting sintered discs are denoted hereafter as D4, D5 and D6. The process parameters are listed in Table 1.

After sintering, the PM material was machined, heat-treated and polished, see Figure 1. For disc-shaped samples, the machining process involved lathe and milling operations to achieve the standard dimensions required for tribological tests. Then, samples were case hardened (Effective Case Depth - ECD 0.9 mm, tempered within 2 hours at 250 °C) and polished before tribological testing. The manufacturing of sintered balls required additional machining operations for shaping balls from cylinders produced by SPS technique. The ball samples were case hardened following the same routine as the discs and then polished. The manufacturing operation is outlined schematically in Figure 1.

Figure 1 – Schematic of the manufacturing process for sintered (a) balls and (b) disc samples.

Table 1 – Sintering parameters used for the manufacture of the ball (SPS technique) and disc samples (conventional sintering)

	Sintered balls			Sintered discs		
	SPS			Conventional Sintering		
	B1	B2	B3	D4	D5	D6
Compacting pressure (MPa)	35	70	70	400	500	600
Sintering temperature (°C)	800	900	1000	1280	1280	1280
Holding time (min)	1	5	5	60	60	60

2.3. Specimen characterisation

Microstructural and surface analyses were carried out using Light Optical and Scanning Electron Microscopy (LOM and SEM, respectively). Furthermore, roughness and wear were evaluated using a White Light Interferometer (WLI) – Veeco Wyco NT9100. Vickers hardness was measured to obtain mechanical properties of samples.

Sintered materials required a specific characterisation due to porosity. The total volume fraction of porosity was estimated using Archimedes' method (density evaluation), and pore characteristics were evaluated through a 2D optical analysis. Principal parameters of size (area) and shape (circularity index) were considered for the characterisation of surface pores [41]. Mechanical properties of sintered materials (elastic modulus E and Poisson's ratio ν) were estimated based on material total porosity, as previously done in [29,32,42,43].

2.4. Experimental apparatus and test conditions

The COF was measured using a Mini-Traction Machine (MTM, PCS Instruments) in the ball-on-disc configuration. This rig allows continuous variation of the ball and disc rotational speeds, thus permitting to achieve a wide range of slide-roll ratios (SRR). The SRR is defined as follows, with U_e being the entrainment (or rolling) and U_s the sliding speeds:

$$SRR = 100 \times \frac{|U_{Disk} - U_{Ball}|}{(U_{Disk} + U_{Ball})/2} = 100 \times \frac{|U_s|}{U_e} \quad (1)$$

The SRR can assume values from pure rolling (SRR 0%) up to pure sliding (SRR 200%). Note that in the MTM, both negative and positive SRR s are used to measure COF at a given speed for removing any offset in the force transducer.

Friction tests were performed by varying both entrainment speed and SRR values (see Table 2) to map friction response in different lubrication conditions. All experiments were conducted at 40 °C and maximum Hertzian contact pressure of 0.6 GPa (see Table 2). Each test was repeated three times to ensure results repeatability. Overall, all test combinations presented good repeatability (variation below 5%). All speeds and SRR s combinations ran in one test for each sample. The experiment consisted in six "Stribeck-like" curves (entrainment speed variation for each SRR), starting from less (SRR 5%) to more severe (SRR 120%) sliding conditions for preventing excessive wear and surface changes.

The film thickness was evaluated through the ultra-thin film interferometry rig (EHD, PCS Instruments). In this configuration, a steel ball is loaded against a glass disc coated with a thin Cr layer and SiO₂ spacer layer for optical interferometry measurements [44–46]. In this study, the film thickness was evaluated for NP and sintered balls, since a plain steel disc could not be used for interferometry measurements. A specific interferometry method developed to study rough surfaces was adopted [36,37] since surface pores alter the specimens' morphological characteristics. This technique was developed by Guegan et al. at Imperial College London during his doctorate [36,37,47]. Two monochromatic LED sources (green and red) were used rather than a white light halogen lamp for increasing fringes intensity and measuring higher film thickness (> 500 nm). A camera with sufficiently fast shutter speed was utilised (shutter speed of 10 μs) for avoiding blurred images at high speeds (> 2000 mm/s). Image capture was triggered of the ball shaft, rather than the standard triggering on the disc shaft, to ensure that each image in a given test corresponds to the same area on the ball and hence the same roughness patch. This allowed for monitoring of film thickness build-up during the test. A custom-made MATLAB® code was then used to process the images and hence evaluate the film thickness of a selected region of the contact. This novel technique was applied to rough surfaces produced by hard turning in [36,37,47], and it is now used for the first time on sintered samples. More details about the interferometry techniques and measurement procedure could be found in [36,37].

It was shown in previous works that film thickness mainly depends on entrainment speed, whereas changes in SRR have negligible effects [36,37,48]. For this reason, only pure rolling (SRR 0%) was evaluated during film thickness measurements, see Table 2.

Table 2 – Test parameters used in the MTM and EHD tests

	MTM rig	EHD rig
Range of entrainment speed, U_e (mm/s)	2000 – 100	2200 – 20
Slide-to-roll ratio, SRR (%)	5, 20, 50, 80, 100 and 120	0
Temperature (°C)	40	40
Maximum contact pressure (GPa)	0.6	0.5
Lubricant	PAO 6	PAO 6

(a)

(b)

(c)

(d)

(e)

(f)

Figure 2 – Ball samples microstructure sintered using SPS technique. (a), (c), (e) LOM image of cross-sections, and (b), (d), (f) filtered images.

Film thickness and friction measurements were obtained using different rigs and contact conditions (materials and load applied). However, the results of film thickness obtained in the EHD rig could be utilised for conditions tested in the MTM rig through a transformation based on the Hamrock-Dowson formula for film thickness calculation [49] following the method used in [50]. In the following equation h , E' and W represent the central film thickness, composite elastic module and load used for the EHD and MTM rigs:

$$\frac{h_{MTM}}{h_{EHD}} = \left(\frac{E'_{EHD}}{E'_{MTM}} \right)^{0.073} \times \left(\frac{W_{EHD}}{W_{MTM}} \right)^{0.067} \quad (2)$$

In this work, the relationship between h_{MTM} and h_{EHD} always remained approximately 0.99 even changing mechanical properties of ball-shaped samples, see section 3.1. Based on the film thickness measurements made on the EHD rig (h_{EHD}), it is possible to estimate the film thickness values of metal-to-metal contact on the MTM (h_{MTM}) at any given speed and thus, to analyse the friction response in terms of specific film thickness values (Λ), see section 4.2. In all tribological tests, pure PAO 6 base oil with a kinematic viscosity of 31 mm²/s at 40 °C and 6 mm²/s at 100 °C was used as the lubricant.

3. Results

3.1. Porosity and microstructural characteristics of sintered specimens

Cross-sections of sintered samples were analysed for each sintering condition to characterise bulk porosity of PM materials. Images of porosity (LOM) for sintered ball specimens are shown in Figure 2. The optical images were filtered and processed to improve the contrast between pores and bulk material.

The increase of sintering temperature using SPS (see Table 1) led to a decrease in porosity, see Figure 2 and Table 3. The open-source image software ImageJ was used to analyse the filtered images of bulk porosity and obtain pores size and circularity index distribution (see Figure 3). Three different regions of each PM samples were studied to achieve statistically reliable results.

The size distribution of pores for PM balls followed similar trends for the three configurations used. The predominant pore size was around 2 µm, and the number of pores decreased with the increase of pore size (see Figure 3a). It is noteworthy that material sintered at a lower temperature (B1) still presented many large pores. A general trend could be found in pores' shape distribution since the increase of pore dimensions promoted the decrease of circularity index values (see Figure 3b). This index ranges from 1 (perfectly circular shape) to 0 (irregular shape).

The same analyses were conducted for sintered discs produced by conventional sintering technique. Similar trends could be found in disc-shaped samples, since the increase of compacting pressure for PM discs and temperature for PM balls reduced the total porosity, see Table 3. Furthermore, similar pores size and shape distribution were found, showing that the increase of pore dimensions generally produces more irregular shapes.

Figure 3 – Pore size (a) and circularity index (b) distributions of ball samples sintered using the SPS technique.

Results of bulk porosity characteristics, mechanical properties (hardness, elastic modulus E and Poisson's ratio ν) and surface roughness of all sintered samples are summarised in Table 3. NP material has been inserted in the same table to improve comparability. The increase of bulk porosity reduced material hardness, E and ν , having a detrimental effect on mechanical properties as expected [6,34]. Furthermore, pores represent surface micro-valleys and, consequently, they negatively affect surface roughness. The presence of higher porosity and pores of larger dimensions generally increases roughness values (Rq), as shown in Table 3. As a result, the NP material presented higher hardness values and lower roughness compared to sintered samples.

Despite presenting different bulk porosities, sintered balls had similar surface roughness ($Rq \sim 180$ nm). Machining operation (from cylinders to ball-shaped specimens, see Figure 1) caused significant plastic deformation on the surface and led to pore closure. Surface pores collapsed in the less porous materials (B2 and B3); however, a residual surface porosity (approximately 2%) was encountered in the more porous sample (B1), see Figure 4. This porosity was mainly composed of small pores (around 2 µm) with regular shape (see Figure 4).

On the contrary, the bulk and surface conditions of sintered discs behaved similarly. The manufacturing processes (grinding) led surface pores to open and, consequently, more porous discs (D4) showed higher roughness values than less porous ones (D5 and D6), see Table 3. Notice that E and ν are 70 GPa and 0.22, respectively, for the glass disc used in the film thickness measurements [43,50].

Table 3 – Porosity characteristics, mechanical properties and surface roughness values of sintered and NP samples.

	Sintered balls			Sintered discs			Discs/balls NP
	B1	B2	B3	D4	D5	D6	
Density (g/cm ³)	6.6	7.4	7.5	6.7	6.9	7.0	7.8
Bulk porosity	16%	6%	4%	14%	12%	11%	NA*
Maximum pores size (μm)	28	13	11	49	40	38	NA
Average pore size (μm)	3.7	2.3	2.3	7.1	6.5	5.4	NA
Average circularity index	0.7 ± 0.3	0.7 ± 0.2	0.8 ± 0.2	0.7 ± 0.3	0.8 ± 0.2	0.8 ± 0.2	NA
Surface hardness (HV1)	600±80	650±75	700±60	520±85	520±75	550±55	750±25
Elastic modulus, E (GPa)	114	169	184	125	137	143	210
Poisson's ratio, ν	0.264	0.280	0.284	0.268	0.272	0.273	0.29
Surface roughness, Rq (nm)	180±50	180±55	180±50	370±85	280±70	190±60	20±5

*NA=not applicable

Figure 4 – SEM surface images of sintered balls (a) B1, (b) B2 and (c) B3. Backscattered electrons.

3.2. Film Thickness

Interferograms were taken at different entrainment speeds for the non-porous smooth (NP) and sintered balls. The images were processed using a custom-made MATLAB® code for obtaining maximum, minimum and average film thickness values of a defined region [36]. For instance, the central flat contact region was selected for avoiding the typical film constriction of EHL point contacts at high speeds (horse-shoe), see Figure 5. Surface pores represent irregular micro-valleys general increasing roughness values, see Table 3. In this case, the average value of film thickness for the central region was used as central film thickness h_c .

Figure 5 – Interferograms at $U_e = 150$ mm/s for (a) NP ball and (b) sintered ball B1.

Central film thickness values h_c at different entrainment speeds are summarised in Table 4. Note that NP material had very low roughness compared to PM balls (see Table 3). Therefore, it was tested at lower entrainment speeds compared to PM materials to achieve similar values of specific film thickness, see section 4.2.

Table 4 – Central film thickness (h_c) for sintered and NP balls measured through the EHD rig at different entrainment speeds (U_e).

Entrainment Speed U_e (mm/s)	Central film thickness h_c (nm)			
	Sintered balls			Balls NP
	B1	B2	B3	
29	-	-	-	14
40	-	-	-	22
57	-	-	-	30
78	-	-	-	35
108	95	92	93	45
151	108	109	107	52
211	120	126	128	66
296	143	149	155	87
414	173	184	191	107
579	207	223	233	137
809	246	261	276	183
1134	288	305	317	211
1588	333	355	363	259
2224	378	400	408	294

3.3. Friction

Figure 6 shows MTM friction results obtained at *SRR* 5% and 120% over a range of entrainment speeds for sintered discs (D4, D5 and D6) against standard non-sintered balls (NP). Colour bands around the solid line represent positive and negative errors calculated over 3 tests for each point. The same trends are evident for low (5%) and high (120 %) *SRR*s. It is immediately apparent that under these conditions the sintered samples have much higher friction than the standard smooth NP samples. Furthermore, the higher the porosity amongst the sintered samples, the higher the measured friction (D4 and D5 had higher friction than the less porous D6).

Figure 6 – MTM COF vs U_e for sintered discs and NP balls (a) *SRR* 5% and (b) *SRR* 120%.

The friction response of NP discs tested against sintered balls is shown in Figure 7. As above, the non-sintered smooth balls had lower COF than all sintered samples across the range of *SRR* and entrainment speeds tested. For the sintered samples themselves, some differences are observed depending on the level of porosity and pore characteristics. For instance, balls with pores closure (B2 and B3) behaved similarly, especially in harsh conditions (*SRR* 120%). Material with residual surface porosity (B1) improved tribological performances when compared to other PM conditions (B2 and B3), both varying *SRR* and entrainment speeds, see Figure 7.

Figure 8 shows surface images of the NP and sintered discs pre- and post-test. No significant wear occurred on the discs during the test as expected, given the short test duration. Only rougher sintered discs (D4, see Table 3) presented some superficial scratches; however, these were less deep than porosity and did not significantly change the contact conditions between the beginning and the end of the test. The surface pores remain open after the test, see Figure 8c. This confirms that the surface conditions remained unchanged so that the measured COF curves can be compared.

Figure 7 – COF vs U_e for NP discs and sintered balls using (a) *SRR* 5% and (b) *SRR* 120%.

Figure 8 – (a,b) Optical images of the disc wear track for sintered material (D4) before and after the test and (c) 2D WLI roughness profiles of the same wear track.

4. Discussion

4.1. Porosity influence on friction response

Surface pores were assumed closed since pore interconnectivity was considered insignificant due to the high-compactness and stiffness of the sintered materials evaluated. Therefore, permeability effects on lubrication [11–13] were assumed to be negligible, also because such effects are recognised to be more pronounced in applications involving large solid deformation (e.g. soft materials). These assumptions allowed the forthcoming comparisons between the friction results found in this work and those obtained in the presence of surface micro-texture reported in the literature.

For **disc** samples (D4, D5 and D6), the increase of compacting pressure (from 400 to 600 MPa, see Table 1) using the conventional sintering technique slightly reduced total porosity (from 14% to 11%, see Table 3) and the average pore dimensions. These porosity differences did not lead to significant differences on the surface hardness (approximately 520 HV for D4, D5 and D6, see Table 3). On the contrary, disc surfaces presented different surface roughness, ranging from $R_q=370$ nm for the most porous (D4) to $R_q=190$ nm for the least porous (D6) surface, see Table 3. The COF reduction obtained by reducing total porosity of disc (D4, D5 and D6 in Figure 6) was probably mainly due to the combination of porosity and roughness reduction. The authors found similar results for conformal contact in some of their previous work [30].

For **ball** samples (B1, B2 and B3), the increase of sintering temperature, compacting pressure and holding time (see Table 1) using the SPS process led to a significant total porosity reduction (from 16% to 4%, see Table 3). Porosity was also much lower than the conventional sintering techniques (4% for B3 and 11% for D6, see Table 3), as expected [40]. The presence of pores slightly decreased material hardness (from 700 HV for B3 to 600 HV for B1, see Table 3);

however, the surface roughness was similar for all conditions (around $Rq=180$ nm, see Table 3) due to the manufacturing process, see Figure 1. Furthermore, surface pores were closed due to plastic deformation during the manufacturing for all balls (B2 and B3) except for the most porous ones (B1), that showed a residual porosity of 2% and small rounded pores. Comparing sintering materials, COF reduction was obtained only for samples with residual porosity (see Figure 7). In this case the beneficial effect was due to residual porosity rather than to roughness. Micro-cavities morphology plays a crucial role in term of tribological response, as reported in [51]. Dimples geometry and the absence of the material pile-up close of texture patterns improves tribological performance [52,53]. These conditions are challenging to control using PM technique. However, it was shown in the present work that pores with regular pore shape (circularity index close to one) could decrease friction when compared to irregular porous materials, see Table 3 and Figure 7. Pore features encountered in ball B1 (2% and rounded shape) can be compared to textured dimples [54,55]. Even if pores are randomly distributed in B1, a reduction of friction was achieved compared to surfaces with pore closure of PM material (B2 and B3), see Figure 7.

It should be noticed that the best surface condition (B1) was obtained by a combination of sintering and mechanical processes. As previously reported by Ebner et al. [33] and the authors [32], it is crucial for PM material to find a good combination between surface porosity, finishing, roughness, and mechanical properties to achieve improvement in the tribological performance. The use of PM materials in real components for improving tribological performance should consider several factors. Overall, it was shown that porosity could bring benefits in some conditions, either in terms of wear [26] or COF reduction [3,32]. Besides that, the sintering technique reduces costs in large-scale production and reduces material waste. Even with small improvements or same performances of wrought material, the use of PM could be interesting for tribological applications, especially for components not operating continuously.

In this study, the presence of random surface irregularities in concentrated contacts seemed to have a negative effect on frictional behaviour compared to non-porous steel. It must be considered that porosity negatively affects mechanical properties and surface roughness since pores represent surface micro-valleys. The increase of porosity led to an increment of surface roughness (see Table 3) and raised the friction response (see Figure 6). NP material presented a much lower value of surface roughness and, consequently, the COF was much smaller than rougher materials (PM samples). To avoid comparing materials with very different surface roughness, friction results must be analysed in terms of specific film thickness values instead of entrainment speed for a fairer comparison.

4.2. Specific film thickness evaluation

The specific film thickness parameter Λ was calculated as:

$$\Lambda = \frac{h_c}{\sqrt{Rq_1^2 + Rq_2^2}} \quad (3)$$

where Rq_1 and Rq_2 are the root mean square roughness of surface 1 and 2, respectively (see Table 3), and h_c is the average value of film thickness for the central region as measured on the EHD rig (see Table 4).

All relevant Λ values were related to the friction results obtained on the MTM rig. Figure 9 shows 3D friction maps containing the measured COF, Λ and SRR . The colour scale was set to be the same for the four maps to allow a better visual comparison. Figure 10 shows selected 2D friction curves with the same dataset.

Figure 9 – 3D friction maps (COF vs Λ vs SRR) for NP and sintered balls tested against NP balls at 40 °C.

It can be observed in Figure 9 and Figure 10 that NP material performed better than PM ones at low SRR for all Λ values. However, balls B1 presented lower COF than NP balls at SRRs of 100% and over. This is particularly evident at low Λ (Figure 10c and d), where balls with residual porosity (B1) performed better than other PM configurations, as previously shown in Figure 7. Nevertheless, the NP material showed interesting results when compared to PM ones for the same Λ . For instance, with low sliding conditions (SRR 5%) wrought samples presented lower COF. The increase of sliding (SRR 80%) led to an increment in COF and NP materials behave similarly to B1. Even harsher conditions showed that NP performed as B2 and B3 and higher values of COF were observed when compared to B1. These findings corroborate with the hypothesis made in the previous section, *i.e.* that residual porosity could act as dimple texture and improve lubrication in harsh conditions.

5. Conclusions

This study assesses the tribological performance of sintered components in terms of the effect of porosity and surface pore characteristics on friction and lubricant film thickness in rolling-sliding non-conformal contacts. Steel powder was sintered using the conventional and the spark plasma sintering technique to promote both porosity and pores dimensions reduction. Friction was measured using a ball on disc tribometer (MTM) under varying slide-roll ratios and lubrication regimes. Corresponding film thickness was measured using a modified optical interferometry technique specifically designed to provide accurate film thickness measurements in rough surface contacts. Based on the obtained results, the following general conclusions can be made:

- A variation on sintering parameters (temperature, holding time and compacting pressure) permitted the manufacture of PM with different porosity (from 16% to 4%) and morphology of pores. The use of spark plasma sintering significantly reduced the overall porosity (4%), when compared to conventional sintering technique (11%). Changes in surface porosity directly affected the surface hardness and roughness;
- The increase of porosity (from 4% to 16%), pores dimensions (average pore size from 2 to 7 μm) and surface roughness (R_q from 180 to 370 nm) led to detrimental tribological results compared to smooth reference surfaces ($R_q = 20 \text{ nm}$);
- The presence of reduced dimensions cavities with regular shape decreased friction compared to materials with similar hardness and surface roughness. In fact, sintered samples with small residual surface pores (B1) performed better than PM surfaces with pores closure (B2 and B3), even presenting similar surface roughness (R_q around 180 μm) and hardness (around 650 HV);
- For the same specific film thickness, PM material with residual surface porosity of 2% (B1) reduced coefficient of friction, especially in harsh conditions (high slide-roll ratios, low entrainment speed and consequently low specific film thickness);
- A mechanical process (*i.e.* calibration or surface rolling) could be used after sintering to reduce surface porosity, roughness and potentially increase tribological performance. However, sintered samples should ideally achieve lower roughness values to bring significant benefits to energy saving.

Figure 10 – 2D friction curves (COF vs Δ) for NP and sintered balls for (a) SRR 5%, (b) SRR 50%, (c) SRR 100% and (d) SRR 120%.

Acknowledgements

The authors acknowledge the support received from the State of São Paulo Research Foundation, Brazil (FAPESP grant N. 2016/25067-9 and 2017/21151-8) and the Brazilian National Council for Scientific and Technological Development (CNPq) for their generous financial support. G.B. thanks the Austrian Research Promotion Agency (FFG) for the funding obtained by the Austrian COMET-Program (Project K2, InTribology, no. 872176) carried out at the “Excellence Centre of Tribology” (AC2T research GmbH). D.D. also acknowledges the support received from the Engineering and Physical Sciences Research Council (EPSRC) via his Established Career Fellowship EP/N025954/1.

References

- [1] A. Upadhyaya, G.S. Upadhyaya, Powder Metallurgy: Science, Technology and Materials, First, CRC Press LLC, Taylor and Francis Group, Boca Raton, FL 33487, USA, 2011.
- [2] A. Babakhani, A. Haerian, M. Ghambri, Effect of heat treatment, lubricant and sintering temperature on dry sliding wear behavior of medium alloyed chromium PM steels, J. Mater. Process. Technol. 204 (2008) 192–198. <https://doi.org/10.1016/j.jmatprotec.2007.11.061>.
- [3] H. Du, J. Qi, Y. Lao, T. Xiong, Oil retaining capability and sliding friction behaviour of porous copper with elongated cylindrical pores, J. Mater. Process. Technol. 212 (2012) 1796–1801. <https://doi.org/10.1016/j.jmatprotec.2012.03.024>.
- [4] S. Król, Z. Zalisz, M. Hepner, Comparison of the friction and wear properties of titanium and oxidised titanium in dry sliding against sintered high speed steel HS18-0-1 and against C45 carbon steel, J. Mater. Process. Technol. 164–165 (2005) 868–875. <https://doi.org/10.1016/j.jmatprotec.2005.02.113>.
- [5] N. Kurgan, Effect of porosity and density on the mechanical and microstructural properties of sintered 316L stainless steel implant materials, Mater. Des. 55 (2014) 235–241. <https://doi.org/10.1016/j.matdes.2013.09.058>.
- [6] N. Chawla, X. Deng, Microstructure and mechanical behavior of porous sintered steels, Mater. Sci. Eng. A. 390

- (2005) 98–112. <https://doi.org/10.1016/j.msea.2004.08.046>.
- [7] G. Straffellini, A. Molinari, H. Danninger, Impact notch toughness of high-strength porous steels, *Mater. Sci. Eng. A*. 272 (1999) 300–309. [https://doi.org/10.1016/S0921-5093\(99\)00491-8](https://doi.org/10.1016/S0921-5093(99)00491-8).
- [8] M.S. Koval'chenko, Mechanical properties of sintered materials, *Sov. Powder Metall. Met. Ceram.* 30 (1991) 257–261. <https://doi.org/10.1007/BF00794920>.
- [9] S. Carabajar, C. Verdu, A. Hamel, R. Fougères, Fatigue behaviour of a nickel alloyed sintered steel, *Mater. Sci. Eng. A*. 257 (1998) 225–234. [https://doi.org/10.1016/S0921-5093\(98\)00846-6](https://doi.org/10.1016/S0921-5093(98)00846-6).
- [10] S. Carabajar, C. Verdu, R. Fougères, Damage mechanisms of a nickel alloyed sintered steel during tensile tests, *Mater. Sci. Eng. A*. 232 (1997) 80–87. [https://doi.org/10.1016/S0921-5093\(97\)00100-7](https://doi.org/10.1016/S0921-5093(97)00100-7).
- [11] S. Boubendir, S. Larbi, R. Bennacer, Numerical study of the thermo-hydrodynamic lubrication phenomena in porous journal bearings, *Tribol. Int.* 44 (2011) 1–8. <https://doi.org/10.1016/j.triboint.2010.09.008>.
- [12] G.K. Kalavathi, P.A. Dinesh, K. Gururajan, Influence of roughness on porous finite journal bearing with heterogeneous slip/no-slip surface, *Tribol. Int.* 102 (2016) 174–181. <https://doi.org/10.1016/j.triboint.2016.05.032>.
- [13] S. Some, S.K. Guha, Steady-state performance analysis of misaligned double-layered porous journal bearings under coupled-stress lubrication with slip flow and additives percolation effect, *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* 233 (2019) 841–858. <https://doi.org/10.1177/1350650118806373>.
- [14] G. Boidi, M.R. da Silva, F.J. Profito, I.F. Machado, Using Machine Learning Radial Basis Function (RBF) Method for Predicting Lubricated Friction on Textured and Porous Surfaces, *Surf. Topogr. Metrol. Prop.* 8 (2020) 044002. <https://doi.org/10.1088/2051-672X/abae13>.
- [15] X.. Wang, H.. Zhang, S.M. Hsu, The Effects of dimple size and depth on friction reduction under boundary lubrication pressure, (2007) 24–26.
- [16] A. Rosenkranz, T. Heib, C. Gachot, F. Mücklich, Oil film lifetime and wear particle analysis of laser-patterned stainless steel surfaces, *Wear*. 334–335 (2015) 1–12. <https://doi.org/10.1016/j.wear.2015.04.006>.
- [17] D. Braun, C. Greiner, J. Schneider, P. Gumbsch, Efficiency of laser surface texturing in the reduction of friction under mixed lubrication, *Tribol. Int.* 77 (2014) 142–147. <https://doi.org/10.1016/j.triboint.2014.04.012>.
- [18] A. Kovalchenko, O. Ajayi, A. Erdemir, G. Fenske, I. Etsion, The Effect of Laser Texturing of Steel Surfaces and Speed-Load Parameters on the Transition of Lubrication Regime from Boundary to Hydrodynamic, *Tribol. Trans.* 47 (2004) 299–307. <https://doi.org/10.1080/05698190490440902>.
- [19] G. Boidi, I.S. Tertuliano, F.J. Profito, W. de Rossi, I.F. Machado, Effect of laser surface texturing on friction behaviour in elastohydrodynamically lubricated point contacts under different sliding-rolling conditions, *Tribol. Int.* 149 (2020) 105613. <https://doi.org/10.1016/j.triboint.2019.02.021>.
- [20] G. Boidi, P.G. Grützmacher, A. Kadiric, F.J. Profito, I.F. Machado, C. Gachot, D. Dini, Fast laser surface texturing of spherical samples to improve the frictional performance of elasto-hydrodynamic lubricated contacts, *Friction*. (2021). <https://doi.org/10.1007/s40544-020-0462-4>.
- [21] D. Gropper, L. Wang, T.J. Harvey, Hydrodynamic lubrication of textured surfaces: A review of modeling techniques and key findings, *Tribol. Int.* 94 (2016) 509–529. <https://doi.org/10.1016/j.triboint.2015.10.009>.
- [22] B. Mao, A. Siddaiah, P.L. Menezes, Y. Liao, Surface texturing by indirect laser shock surface patterning for manipulated friction coefficient, *J. Mater. Process. Technol.* 257 (2018) 227–233. <https://doi.org/10.1016/j.jmatprotec.2018.02.041>.
- [23] M. Kawakame, J.D. Bressan, Study of wear in self-lubricating composites for application in seals of electric motors, *J. Mater. Process. Technol.* 179 (2006) 74–80. <https://doi.org/10.1016/j.jmatprotec.2006.03.078>.
- [24] Y. Zhu, G. Lin, M.M. Khonsari, J. Zhang, H. Yang, Material characterization and lubricating behaviors of porous stainless steel fabricated by selective laser melting, *J. Mater. Process. Technol.* 262 (2018) 41–52. <https://doi.org/10.1016/j.jmatprotec.2018.06.027>.
- [25] H. Torres, M. Rodríguez Ripoll, B. Prakash, Self-lubricating laser claddings for friction control during press hardening of Al-Si-coated boron steel, *J. Mater. Process. Technol.* 269 (2019) 79–90. <https://doi.org/10.1016/j.jmatprotec.2019.02.002>.
- [26] F. Martin, C. García, Y. Blanco, Influence of residual porosity on the dry and lubricated sliding wear of a powder metallurgy austenitic stainless steel, *Wear*. 328–329 (2015) 1–7. <https://doi.org/10.1016/j.wear.2015.01.025>.
- [27] X. Li, U. Olofsson, E. Bergseth, Pin-on-Disc Study of Tribological Performance of Standard and Sintered Gear Materials Treated with Triboconditioning Process: Pretreatment by Pressure-Induced Tribofilm Formation, *Tribol. Trans.* 60 (2017) 47–57. <https://doi.org/10.1080/10402004.2016.1146379>.
- [28] X. Li, U. Olofsson, A study on friction and wear reduction due to porosity in powder metallurgic gear materials, *Tribol. Int.* 110 (2017) 86–95. <https://doi.org/10.1016/j.triboint.2017.02.008>.
- [29] X. Li, M. Sosa, U. Olofsson, A pin-on-disc study of the tribology characteristics of sintered versus standard steel gear materials, *Wear*. 340–341 (2014) 31–40. <https://doi.org/10.1016/j.wear.2015.01.032>.
- [30] G. Boidi, I.S. Tertuliano, M.F. Cano, G.A.A. Machado, R.M. Souza, I.F. Machado, Tribological Evaluation of Sintered and Conventional Gear Materials, in: *SAE Tech. Pap.*, 2017. <https://doi.org/10.4271/2017-36-0153>.

- [31] M. Ebner, T. Lohner, K. Michaelis, B.-R. Höhn, K. Stahl, Self-lubricating gears with oil-impregnated sintered materials, *Forsch. Im Ingenieurwes.* 81 (2017) 175–190. <https://doi.org/10.1007/s10010-017-0227-z>.
- [32] G. Boidi, I.S. Tertuliano, L.G.B.S. Lima, F.J. Profito, I.F. Machado, Porosity Effect of Sintered Steel on the Frictional Performance of Conformal and Nonconformal Lubricated Contacts, *Tribol. Trans.* 62 (2019) 1029–1040. <https://doi.org/10.1080/10402004.2019.1640917>.
- [33] M. Ebner, M. Omasta, T. Lohner, P. Šperka, I. Krupka, M. Hartl, K. Michaelis, B.-R. Höhn, K. Stahl, Local Effects in EHL Contacts with Oil-Impregnated Sintered Materials, *Lubricants*. 7 (2019) 1. <https://doi.org/10.3390/lubricants7010001>.
- [34] G. Boidi, N.K. Fukumasu, I.F. Machado, Wear and friction performance under lubricated reciprocating tests of steel powder mixtures sintered by Spark Plasma Sintering, *Tribol. Int.* 121 (2018) 139–147. <https://doi.org/10.1016/j.triboint.2018.01.032>.
- [35] N.K. Fukumasu, G. Boidi, V. Seriacopi, G.A.A. Machado, R.M. Souza, I.F. Machado, Numerical analyses of stress induced damage during a reciprocating lubricated test of fecmo sps sintered alloy, *Tribol. Int.* 113 (2017) 443–447. <https://doi.org/10.1016/j.triboint.2016.12.025>.
- [36] J. Guegan, A. Kadiric, H. Spikes, A Study of the Lubrication of EHL Point Contact in the Presence of Longitudinal Roughness, *Tribol. Lett.* 59 (2015) 1–18. <https://doi.org/10.1007/s11249-015-0549-7>.
- [37] J. Guegan, A. Kadiric, A. Gabelli, H. Spikes, The Relationship Between Friction and Film Thickness in EHD Point Contacts in the Presence of Longitudinal Roughness, *Tribol. Lett.* 64 (2016) 1–15. <https://doi.org/10.1007/s11249-016-0768-6>.
- [38] W. Chen, U. Anselmi-Tamburini, J.E. Garay, J.R. Groza, Z.A. Munir, Fundamental investigations on the spark plasma sintering/synthesis process, *Mater. Sci. Eng. A*. 407 (2005) 24–30. <https://doi.org/10.1016/j.msea.2005.06.066>.
- [39] R. Orrù, R. Licheri, A.M. Locci, A. Cincotti, G. Cao, Consolidation/synthesis of materials by electric current activated/assisted sintering, *Mater. Sci. Eng. R Reports*. 63 (2009) 127–287. <https://doi.org/10.1016/j.mser.2008.09.003>.
- [40] K. Zarebski, P. Putyra, Iron powder-based graded products sintered by conventional method and by SPS, *Adv. Powder Technol.* 26 (2015) 401–408. <https://doi.org/10.1016/j.appt.2014.11.010>.
- [41] W.C. Seville JPK, Particle Technology and Engineering: an Engineer's Guide to Particles and Powders: Fundamentals and Computational Approaches, 2016.
- [42] J.P. Panakkal, H. Willems, W. Arnold, Nondestructive evaluation of elastic parameters of sintered iron powder compacts, *J. Mater. Sci.* 25 (1990) 1397–1402. <https://doi.org/10.1007/BF00585456>.
- [43] G. Boidi, An experimental assessment of surface micro irregularities (porosity and texture) effects on tribological behaviour under lubricated conditions., Doctorate Thesis, Universidade de São Paulo, 2019. <https://doi.org/10.11606/T.3.2019.tde-22102019-091137>.
- [44] J. Luo, S. Wen, P. Huang, Thin film lubrication. Part I. Study on the transition between EHL and thin film lubrication using a relative optical interference intensity technique, *Wear*. 194 (1996) 107–115. [https://doi.org/10.1016/0043-1648\(95\)06799-X](https://doi.org/10.1016/0043-1648(95)06799-X).
- [45] P.M. Cann, H.A. Spikes, J. Hutchinson, The development of a spacer layer imaging method (slim) for mapping elastohydrodynamic contacts, *Tribol. Trans.* 39 (1996) 915–921. <https://doi.org/10.1080/10402009608983612>.
- [46] G.J. Johnston, R. Wayte, H.A. Spikes, The measurement and study of very thin lubricant films in concentrated contacts, *Tribol. Trans.* 34 (1991) 187–194. <https://doi.org/10.1080/10402009108982026>.
- [47] J. Guégan, Experimental Investigation into the Influence of Roughness on Friction and Film Thickness in EHD Contacts, Imperial College London, 2015. <https://doi.org/10.25560/53388>.
- [48] A. Kadiric, P. Rycerz, Influence of Contact Conditions on the Onset of Micropitting in Rolling-Sliding Contacts Pertinent to Gear Applications, *AGMA Tech. Pap.* (2016). <https://gearsolutions.com/features/influence-of-contact-conditions-on-the-onset-of-micropitting-in-rolling-sliding-contacts-pertinent-to-gear-applications/>.
- [49] B.J. Hamrock, D. Dowson, Elastohydrodynamic Lubrication of Elliptical Contacts for Materials of Low Elastic Modulus I—Fully Flooded Conjunction, *J. Lubr. Technol.* 100 (1978) 236–45. <https://doi.org/10.1115/1.3453284>.
- [50] Y. Kanazawa, N. De Laurentis, A. Kadiric, Studies of Friction in Grease-Lubricated Rolling Bearings Using Ball-on-Disc and Full Bearing Tests, *Tribol. Trans.* 63 (2020) 77–89. <https://doi.org/10.1080/10402004.2019.1662147>.
- [51] S. Li, U. Parmar, The Effects of Microdimple Texture on the Friction and Thermal Behavior of a Point Contact, *J. Tribol.* 140 (2018) 041503. <https://doi.org/10.1115/1.4039228>.
- [52] A.F. Shamsul Baharin, M.J. Ghazali, J. A Wahab, Laser surface texturing and its contribution to friction and wear reduction: A brief review, *Ind. Lubr. Tribol.* 68 (2016) 57–66. <https://doi.org/10.1108/ILT-05-2015-0067>.
- [53] C. Gachot, A. Rosenkranz, S.M. Hsu, H.L. Costa, A critical assessment of surface texturing for friction and wear improvement, *Wear*. 372–373 (2017) 21–41. <https://doi.org/10.1016/j.wear.2016.11.020>.
- [54] L. Mourier, D. Mazuyer, F.P. Ninove, A.A. Lubrecht, Lubrication mechanisms with laser-surface-textured surfaces in elastohydrodynamic regime, *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* 224 (2010) 697–711.

<https://doi.org/10.1243/13506501JET771>.

- [55] I. Krupka, M. Hartl, M. Zimmerman, P. Houska, S. Jang, Effect of surface texturing on elastohydrodynamically lubricated contact under transient speed conditions, *Tribol. Int.* 44 (2011) 1144–1150. <https://doi.org/10.1016/j.triboint.2011.05.005>.