Tribology International 121 (2018) 139–147

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Wear and friction performance under lubricated reciprocating tests of steel powder mixtures sintered by Spark Plasma Sintering

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A B S T R A C T

Literature indicates that porosity in sintered materials decreases mechanical properties and fatigue resistance. However, given porosity shape and distribution on a surface, it is possible that these small cavities could improve surface lubrication conditions. This work aims to evaluate the effects of porosity, surface finishing, oil viscosity and heat treatment on wear and friction of two sintered carbon steels during lubricated high contact pressure tests. Samples were characterized prior and after tests by SEM, optical profilometry and hardness measurements. Main results showed that surface hardness and porosity controlled wear behavior of sintered material in high load conditions. Rougher material seemed to activate anti-wear additives contained on the lubricant, promoting less worn volume than polished samples.

1. Introduction

Powder metallurgy (PM) permits the production of a large range of materials with reduced costs, optimized weight and complex geometries. The minimization of material residues and finishing operation promotes the utilization of this near-net-shape technique in many industrial applications [1]. Nevertheless, PM materials present porosity, which influences mechanical and tribological behavior.

Pores have significant influence on mechanical properties, since they are volume defects and stress concentrator regions [2,3]. The porosity usually reduces tensile strength, Young's modulus, corrosion resistance, elongation and fatigue resistance [3–5]. Mechanical properties of PM material are widely explored [6–10], however pores tribological effect is a relative new issue in the literature [11–14].

The tribological effect of porosity is still under discussion because it can be either beneficial or detrimental. Surface pores can enhance debris trapping and load support capacity, increase film thickness and act as oil reservoirs [15,16]. However, surface porosity reduces real contact area between two bodies, so it alters local strain and stress distribution, promoting wear and fatigue crack nucleation [17].

Reciprocating tests were not usually performed in sintered materials [14–16]. In this configuration different velocities and regimes of lubrications could be reached during counter body movement [18]. Furthermore, these types of tests were used to study lubricant additives [19,20], especially in high contact conditions. In this situation, extreme pressure based additives could be activated and produce a tribofilm that protects and prevents surface wear [21].

Porosity volume fraction influences morphological and geometrical characteristic of pores. High porosity leads to more connected pores that decrease material load support capacity and could promote plastic deformation and failure [15,16]. Martin, García, and Blanco [16] explained that not only total porosity, but also pore geometries and dimensions had significant effects on tribological behavior. In PM, it is possible to control pore dimensions through particle characteristics as well as sintering and compaction parameters.

PM materials can be produced in different ways and a promising sintering method is the process of Pulsed Electric Current Sintering (PECS) or also known as Spark Plasma Sintering (SPS), developed in Japan in the early 1990s [22]. The high heating rate – up to 100 °C/min – allows the production of materials with lower porosity with lower time and temperature compared to those required for conventional sintering processes [23]. The phenomena related to the SPS process has been studied [24,25], contributing to understanding the influence of sintering parameters on the different materials and on pore features. Besides providing the rapid manufacture of a large material range, the flexibility of SPS cycle permits obtaining different density and porosity features.

The need of new mechanical components with high resistance and fatigue requirements, complex geometry and low cost demand a deeper tribological study of sintered material behavior in critical conditions, such as boundary lubrication condition with high contact pressures.

On this basis, this work aims to evaluate porosity, oil viscosity, surface finishing and heat treatment effects on steel powder mixtures sintered by SPS during reciprocating high contact pressure tests (2.4 GPa).

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https://doi.org/10.1016/j.triboint.2018.01.032
Received 10 October 2017; Received in revised form 23 December 2017; Accepted 15 January 2018
Available online 31 January 2018

2. Material and methodology

2.1. Test sample materials

Two steel powder mixtures were sintered by Spark Plasma Sintering technique (SPS) using the DR. SINTER® SPS1050 made using SPS Syntex Inc. Powder mixtures were based on FeCCr (1.85% Cr, 0.2 %C, 97.95% Fe wt%) and FeCMo (0.85% Mo, 0.3% C, 98.85% Fe wt%). Both mixtures had an average particle size between 45 μm and 150 μm. Low carbon steels are known to present low wear resistance, being a choice to evaluate the influence of porosity on wear behavior, since these pores could act as oil reservoirs in critical lubrication conditions and promote better wear resistance [15,16].

The sintering process, carried on under vacuum, was based on two different thermal cycles: sintering temperatures of 900 and 1000 °C which were held for 5 min with a constant compaction pressure of 70 MPa. The heating rate was maintained at 100 °C/min up to 650 °C, 50 °C/min up to 900 °C and then it was decreased up to 20 °C/min. Thermal and pressure cycles are presented in Fig. 1. Different sintering conditions were chosen to vary porosity in the samples. After sintering process, each sample was heated at 850 °C for 30 min, water quenched and then tempered at 200 °C for 60 min (Q+T). In order to obtain higher hardness values some samples were not tempered (Q).

The sintered samples were disk-shaped and had dimensions of about 20 mm in diameter and 9 mm in thickness. After sintering and heat treatment, the samples were ground to ensure face parallelism and obtain a standard thickness for wear tests. Ground finishing was applied to disk samples as to reach the roughness parameter S_a values of approximately 0.3 μm (rough surfaces), whereas some samples were polished to minimize the influence of micro-irregularities (smooth surfaces).

Commercially available chromium-steel balls (AISI 52100) were used as counter-body in tribological tests. These balls were 10 mm in diameter and had hardness values approximately of HV 750 ± 5 HV.

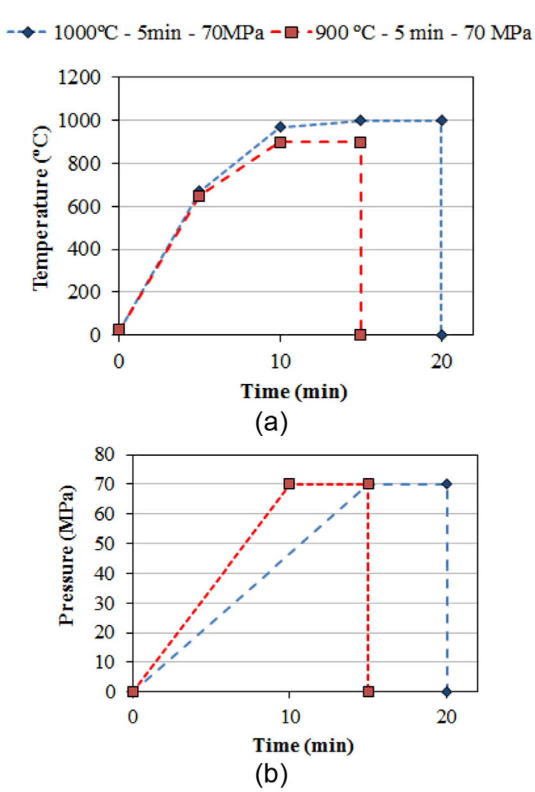

Fig. 1. (a) Thermal and (b) pressure cycles utilized in the sintering processes.

2.2. Oil lubricant characteristics

Two synthetic transmission oils were used during tribological tests. Both lubricants had extreme pressure (EP) and anti-wear (AW) additives, but different viscosity. Oil A presented lower viscosity at all temperatures compared to oil B. Oil characteristics were summarized in Table 1. These additives interact chemically and modify the surface to prevent wear. AW additives normally acts on mixed and EP additives in boundary lubrication regime [21]. EP contains different chemical elements, anyhow sulfur is predominant. High contact pressures and temperatures promote sulfur decomposition and the formation of metal sulfide layers which improve surface wear resistance [21,26,27]. For this reason, EPs were especially utilized in metalworking and gears fluids.

2.3. Tribological test conditions

Wear tests were carried out at room temperature using an SRV 4® from Optimol Instruments Inc. in the configuration of lubricated ball on disk reciprocating tests. The ball, fixed on a support, had a reciprocating movement against the disk, fixed on the base, Fig. 2. A vertical load was applied to the ball and a fixed quantity of oil was spread on the disk before the test begins to prevent starvation. Vertical load, chamber temperature, test time and counter body movement (stroke and frequency) could be controlled.

The reciprocating movement is characterized by acceleration and deceleration along the counter body stroke, reaching maximum speed in the middle stroke. The tribometer registers for each second a single value of COF, which represents the average between COF values in the stroke reversing regions [28]. This default procedure of the tribometer does not capture COF variations along the stroke and, in this work, the values of COF were also acquired along the stroke position to capture the influence of different velocities, evaluated by 51,200 measurement points per second.

Tests were carried out during 30 min with 160 N of normal load, frequency of 50 Hz and 1 mm stroke. Material, lubricant, surface finishing, porosity and heat treatment were evaluated in different tribological tests, presented in Table 2. Porosity was expressed in terms of sintering temperature, since different thermal cycles promote changes in porosity features [16]. Each test condition in Table 2 was repeated three times in order to generate reliable data.

Tribological tests were divided in three conditions, allowing the comparison of two variables in each condition. In **condition I**, **material** (FeCCr/FeCMo) and **oil** characteristics (A/B) were studied (tests 1, 2, 3, 4). In **Condition II**, **surface finishing** (ground/polished) and **porosity** (900 °C/1000 °C) were investigated (tests 1, 5, 6, 7). **Condition III** focused on **porosity** (900 °C/1000 °C) and **heat treatment** (Q+T/Q), analyzed by tests 6, 7, 8 and 9.

The macroscopic lubrication regime was defined as boundary for all test conditions, given by the selection of frequency, normal load and stroke. Also, normal load of 160 N was chosen in order to achieve high Hertzian contact pressure values (approximately 2.4 GPa) on the test.

2.4. Specimens characterization

The material microstructural characterization was carried out by scanning electron microscopy (SEM) using a Jeol JSM – 6010LA, light optical microscopy using a Leika DCM3D (LOM), energy-dispersive X-ray spectroscopy (EDS-SEM) and Vickers hardness measurements. Surface

Table 1
Properties of the oils.

PROPRIETIES	Oil A	Oil B
Viscosity class	SAE 75W	SAE 75W-85
Density at 15 °C (g/cm^3)	0.850	0.863
Viscosity at 30 °C (cSt)	50	180