TAPER ROLLER BEARINGS LUBRICATED WITH BIO-GREASES

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ABSTRACT

Taper roller bearings were tested under the same operating conditions, varying the initial amount of grease used to lubricate the bearing. Two biodegradable greases and one reference mineral grease were used to study the influence of grease amount on bearing internal friction, wear and grease degradation. The operating bearing temperatures were monitored (grease, raceways, housing and environment) during each test to evaluate the power loss performance of the grease. At the end of each test the used grease was collected for post-testing analysis using oil analysis techniques (Ferrometry and Analytical Ferrography). Optical Microscopy, Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) techniques were used to complement the analysis of the wear particles, to examine the bearing surface morphology and identify their metallurgical composition.

1. INTRODUTION

Concerns with the environmental issues led to the development of a new generation of lubricating greases that provide similar or higher operating performances and, at the same time, are not harmful to the ecosystem. However, the tribological behaviour of these bio-greases is not yet well understood, mainly in terms of rolling bearing wear and power loss.

The internal friction occurring in rolling bearings is a major concern, since the main function of rolling bearings is to transmit load at very low friction. Thus the importance of understanding internal friction in rolling bearings becomes relevant when the energy savings and the bearing performance optimization are required [Kuhn, 1999].

During operation, rolling bearings generate wear particles due to the contact between rings, rolling elements and cages. These wear particles can be monitored by lubricant analysis and are useful to understand wear mechanisms and quantify bearing wear [Beatriz, 2006].

In this work, the tribological performance of three different greases was evaluated, respectively two ester based biodegradable greases and of one mineral based grease. For that purpose, taper rolling bearings were tested under the same operating conditions, considering two different volumes of grease for the initial bearing lubrication.

During the tests the bearing temperature was continuously recorded and after each test a grease sample was collected for post-testing analysis. Bearing surface analysis complemented the evaluation regarding the wear mechanisms.

2. TAPER ROLLING BEARING TEST

The taper roller bearing tests were performed in a Four-Ball Machine, where the four ball arrangement was replaced by a ***30203 J2*** taper roller bearing mounted in a steel support (see Figure 1). The taper roller bearing dimensions are presented in Figure 2.

The outer race is stationary, the inner race is rotating and the bearing is submitted to a pure axial load. The taper roller bearings were run-in before each test, for about $\boldsymbol{3 \times 10^5}$ cycles. There is no standard available to perform the test.

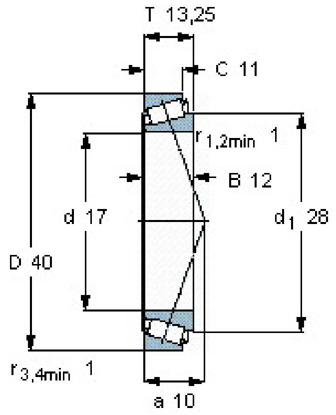

Fig 2 - The 30203 J2 taper roller bearing geometry (dimensions in mm).

2.1 – Lubricating greases

Three different lubricating greases were used in the taper roller bearing tests: BgM3 grease was formulated with mineral base oil, while Eg00 and Eg60 greases contained a biodegradable re-newable ester base fluid. The mineral based grease BgM3, is a non biodegradable and non toxic grease and the ester based greases have pass the biodegradability test (OECD 301F) and eco-toxicity test (OECD 202). Their physical properties are shown in Table 1.

Table 1 – Physical properties of the lubricating greases used on the taper rolling bearing test.

Greases	BgM3	Eg00	Eg60
Type of base oil	Mineral	Ester	Ester
Biodegradability (OECD 301 F)	-	60%	> 60%
ISO Viscosity Grade (base oil)	220	166	166
at 40 °C, mm²/s (cSt), approx.	230	91,8	91,8
at 100 °C, mm²/s (cSt), approx.	17,5	14,5	14,5
LP@60°C (Lube Parameter)	1,77E-09	6,23E-10	6,23E-10
NLGI Number (DIN 51 818)	2	2	2
Dropping Point (°C)	185	> 180	> 180
EP Additives	Yes	Slight	Slight
Thickener	Li	Li/Ca	Li/Ca-Polyurea
Application	Bearings	Multipurpose	

All the greases were thickened with lithium soap (about *12% w/w*), but the thickeners of Eg00 and Eg60 greases also contained calcium and calcium-polyurea, respectively. Figure 3 shows images of the thickener network structures of those greases, obtained through Scanning Electron Microscopy (SEM).

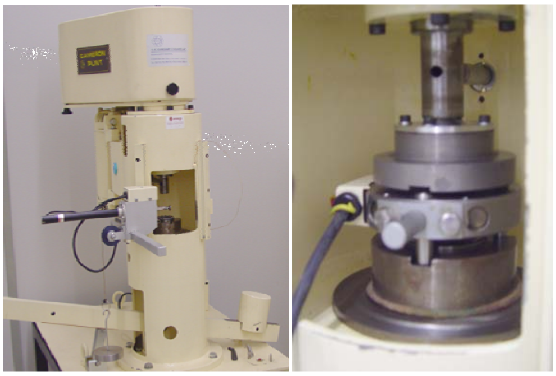

Fig 1 – Taper Roller Bearing Test: Four-Ball machine (left) and bearing holder installed in the Four-Ball machine (right).

The grease base oil type gives a specific shape and form to the thickener fibres. The lithium thickener fibres in the mineral grease BgM3 are significantly larger than those observed in Eg00 and Eg60 ester greases, and, these last two, show additional particles of calcium and polyurea. The thickener - base oil interaction, the base oil viscosity and the constituents in the thickener structure can influence the lubricating performance of the greases, particularly, the film thickness generation and the traction forces [Kaneta, 2000; Couronné, 2003].

An important difference between the thickener structures of Eg00 and Eg60 greases was observed: the Li/Ca polyurea grease (Eg60) presents a more closed network structure than the Li/Ca grease (Eg00), resulting in a different rheological behaviour of the two greases.

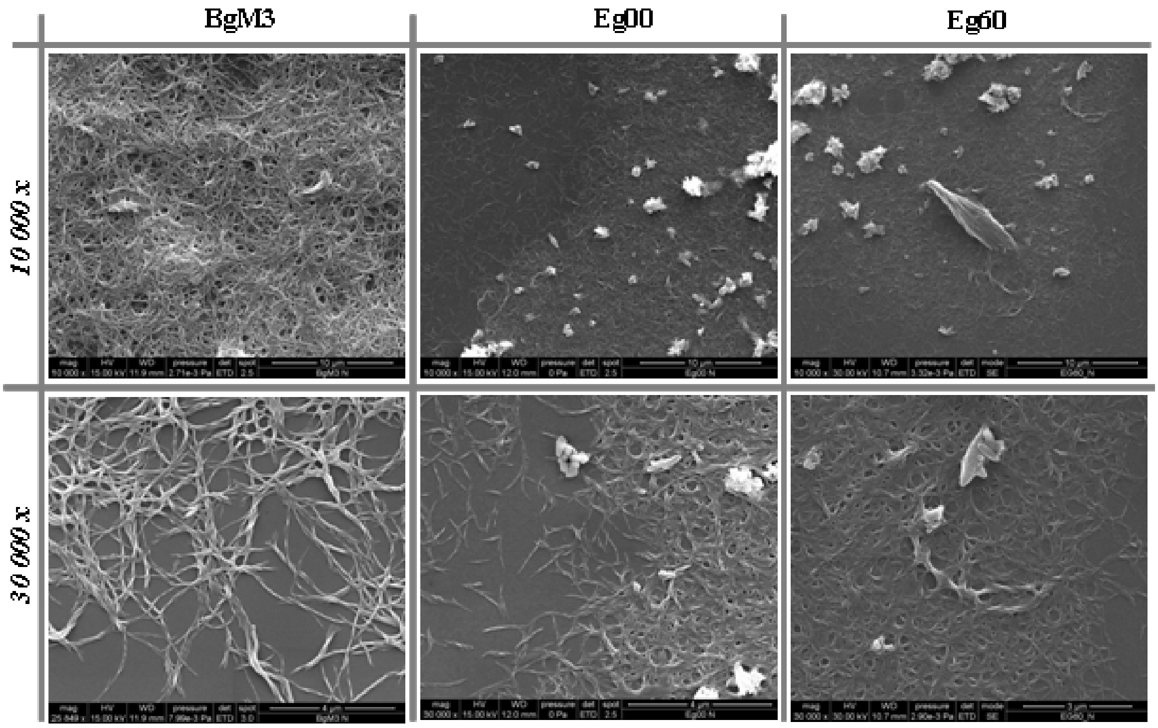

Fig 3 – Thickener network structure in the BgM3, Eg00 and Eg60 greases observed on SEM.

2.2 – Operating conditions

The initial grease volume used in the bearing for the first lubrication was determined by [FAG, 1996]:

$$Q_{initial} = 0,004 \times D \times C$$

where:

Q_{init} = grease quantity for initial fill [cm^3];

D = bearing outside diameter [mm];

C = bearing outer ring width [mm].

A grease volume of *1,76 cm^3* was calculated for the *30203 J2* paper roller bearing. All the bearings were lubricated in the same manner and using pre-defined procedures. A plastic graduated syringe was used to measure the grease volume and to lubricate the bearings.

All the taper rolling bearing tests were performed using the same operating conditions: rotating speed – *1000 rpm*, axial load – *5000 N*, duration - *1x10^6 cycles* (*16 hours and 40 minutes*). The tests were performed with the three greases and with two different initial grease volumes (*1,5 cm^3* and *0,5 cm^3*). Each grease type – grease volume combination was repeated *7* times.

During each test run, the operating grease temperature (T_{lub}), the bearing housing temperature (T_{hs}), the bearing support temperature (T_{sp}) and the surrounding environment temperature (T_{room}), were continuously recorded. Once completed the test set, the taper roller bearing was dismounted and a grease sample was obtained by washing the bearing in an ultrasonic solvent bath. Subsequently, those samples (grease + solvent) were analysed through Ferrometry and Analytical Ferrography.

3. TEST RESULTS

3.1 – Operating temperatures

Figure 4 shows the grease operating temperature (T_{lub}) recorded during each test run (A to G), for the three greases (BgM3, Eg00 and Eg60) and for the two initial grease volumes (1,5 cm^3 and 0,5 cm^3). In general, the grease temperature is more stable during the last 3 test runs (E, F and G), mainly for the ester based greases, which require more time to stabilize the operating temperature.

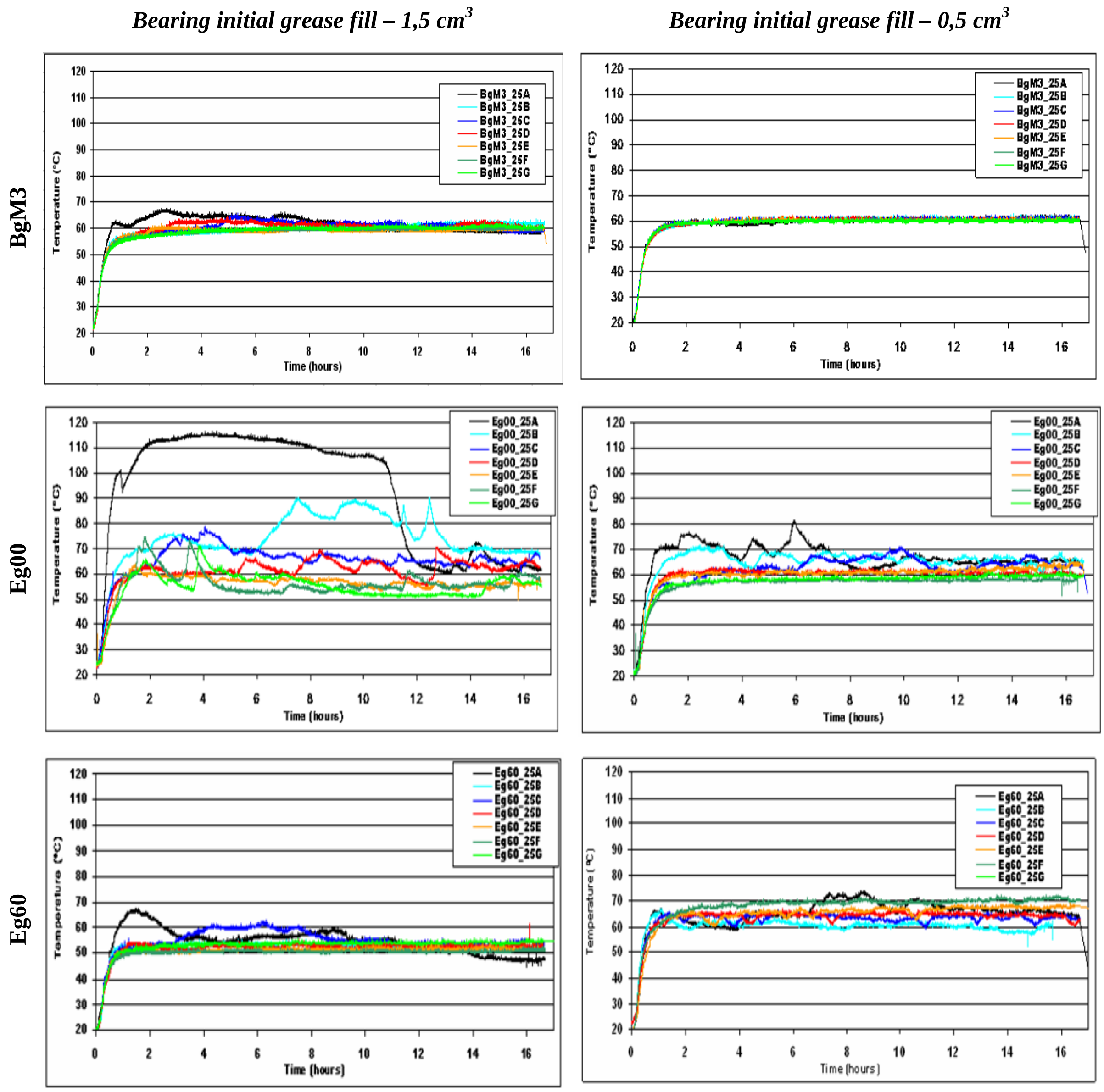

Fig 4 – Evolution of the grease temperature for each of the test run, using a grease volume of 1,5 cm^3 and 0,5 cm^3 for initial bearing lubrication.

When the taper roller bearing is lubricated with 1,5 cm^3 of grease, the mineral grease BgM3 generates more stable operating temperatures. However, the ester based greases (Eg00 and Eg60), show lower stabilized temperatures during the last three test runs.

When the bearing is lubricated with 0,5 cm^3 of grease, the more stable and lower operating temperatures are reached by the mineral grease BgM3.

Analyzing and comparing the evolution of the temperatures recorded in all test runs, showed in Figure 4, it is clear that when the bearing is lubricated with a lower initial grease volume the operating temperature of the grease stabilizes more rapidly.

The difference between the bearing housing temperature (T_{hs}) and room temperature (T_{room}), designated as ΔT ($\Delta T = T_{hs} - T_{room}$), can be related to the heat evacuated from the bearing housing to the surrounding environment, and thus, to the power loss inside the taper roller bearing [Campos, 2007].

Figure 5 shows the average values of ΔT ($\Delta T = T_{hs} - T_{room}$) obtained during each test set, as well as, the lowest and highest values measured. When a lower volume of grease is used, ΔT increases, meaning that the power loss inside the bearing is higher.

Comparing the ester based greases with the mineral one, for an initial grease volume of 1,5 cm^3, the bearing lubricated with mineral grease generates higher power loss than the bearings lubricated with ester based greases.

However, the maximum operating temperatures (T_{max}) generated during each test run were generally lower when a lower grease volume is used, as shown in Figure 6, where the average value of the T_{max}, as well as the corresponding lowest and highest values measured are presented.

3.2 – Wear Particle Analysis

The grease samples collected at the end of each test run were analyzed through Direct Reading Ferrography (also designated as ferrometry) and Analytical Ferrography.

Table 2 shows the ferrometric indexes for large (D_L) and small (D_S) particles measured for each grease sample, which can be used to determine the Wear Particle Concentration CPUC, Wear Severity ISUC and the Percentage of Large Particles PLP, defined by the following equations:

$$CPUC = D_L + D_S\,,$$

$$ISUC = D_L{}^2 - D_S{}^2\,,$$

$$PLP = \frac{100 \times (D_L - D_S)}{CPUC}\,.$$

Table 2 – Ferrometric indexes for each test set and grease

		Grease Lubricant		
	Test Set	BgM3	Eg00	Eg60
DL	1,5 cm^3	32,2	57,6	25,7
	0,5 cm^3	23,3	25,8	41,3
DS	1,5 cm^3	7,4	14,4	7,3
	0,5 cm^3	1,3	5,9	10,7
CPUC	1,5 cm^3	39,6	72	33
	0,5 cm^3	24,6	31,7	52
ISUC	1,5 cm^3	982,1	3110,4	607,2
	0,5 cm^3	541,2	630,8	1591,2
PLP	1,5 cm^3	62,6	60,0	55,8
	0,5 cm^3	89,4	62,8	58,8

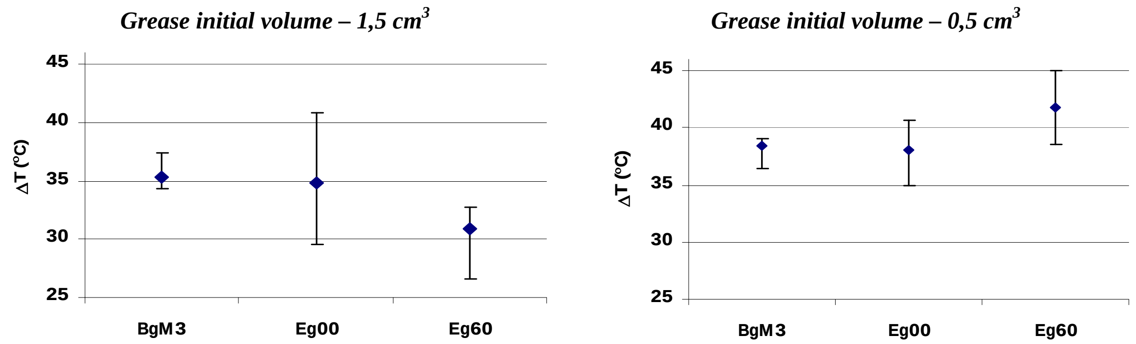

Fig. 5 – Difference between T_{hs} and T_{room} (ΔT) in each test set, for each grease and different grease volumes.

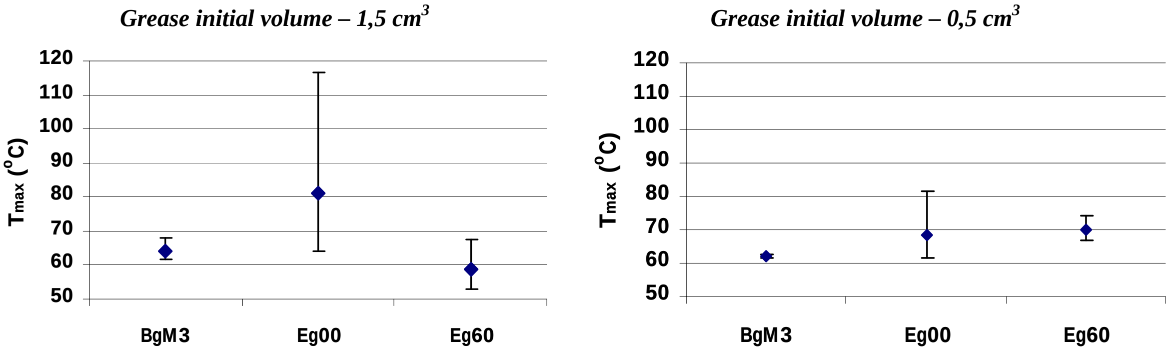

Fig. 6 – Maximum grease operating temperatures T_{max} in each test set, for each grease and different grease volumes.

Figure 7, Figure 8 and Figure 9, show the CPUC, ISUC and PLP values corresponding to the lubricating greases tested and for the two initial grease volumes considered.

Figure 7 and Figure 8 show that the CPUC and ISUC values of BgM3 and Eg00 samples decreased, when the initial grease volume also decreased from 1,5 cm^3 to 0,5 cm^3, while the opposite trend is observed for grease Eg60, indicating that wear behaviour of the taper roller bearings lubricated with greases BgM3 and Eg00 is different from that lubricated with grease Eg60.

Figure 9 shows that the percentage of large particles generated during the roller bearing tests is practically unaffected by the reduction of the initial grease volume from *1,5 cm^3* to *0,5 cm^3*.

The grease samples collected at the end of each test set were analysed by analytical ferrography and the corresponding ferrograms were observed by optical microscopy. Figure 10 shows several microphotographs of the wear particles observed in those ferrograms, indicating that the concentration of wear particles is smaller in the ferrograms corresponding to the test sets performed with a lower initial grease volume (*0,5 cm^3*).

In all test sets, most of the wear particles are laminar, with smooth flat surfaces and irregular contours, suggesting that the main wear mechanism in presence was contact fatigue. Some abrasion wear particles were also found, as well as several black ferrous oxides.

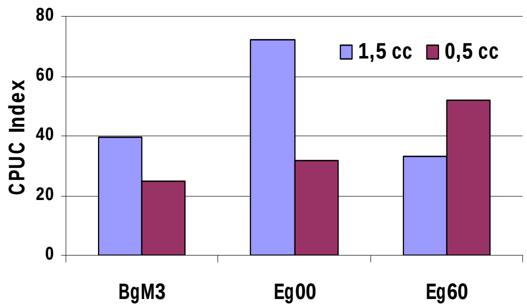

Fig. 7 – Wear Particle Concentration Index (CPUC).

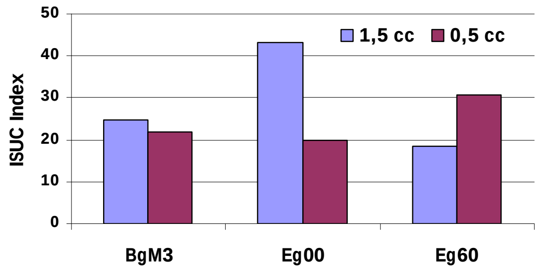

Fig. 8 – Wear Severity Index (ISUC).

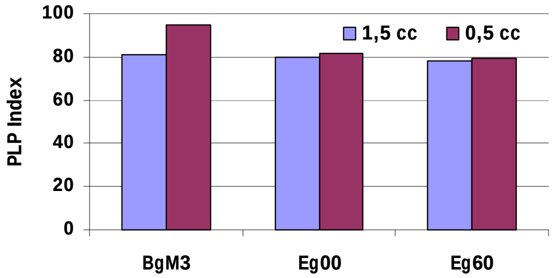

Fig. 9 – Percentage of Large Particles (PLP).

All the ferrograms were heat treated (during 90 seconds at 330 °C in a hot plate) to identify the wear particles metallurgy. Figure 11 shows the colour alterations occurred in the wear particles present in the ferrograms, after being heat treated.

Most of the wear particles changed their appearance colour to blue temper (A1 to A2), indicating they are low alloy and/or carbon steel particles. The taper rolling elements (rollers and races) were made of low alloy steel while the cage is manufactured in carbon steel. However, several particles maintain their colour after this heat treatment at 330 ºC (B1 to B2), indicating they are high alloy steel particles.

Some ferrograms were also observed by Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray technology incorporated (EDX), to verify the metallurgy of the wear particles and confirm their source: bearing races, rollers or cage. The EDX results confirmed the observations of the ferrograms by optical microscopy, indicating that several compositions were found: carbon steel, low alloy steel and high alloy steel (chromium steel). The carbon steel particles are generated by cage wear and the low alloy steel particles are from the bearing rollers

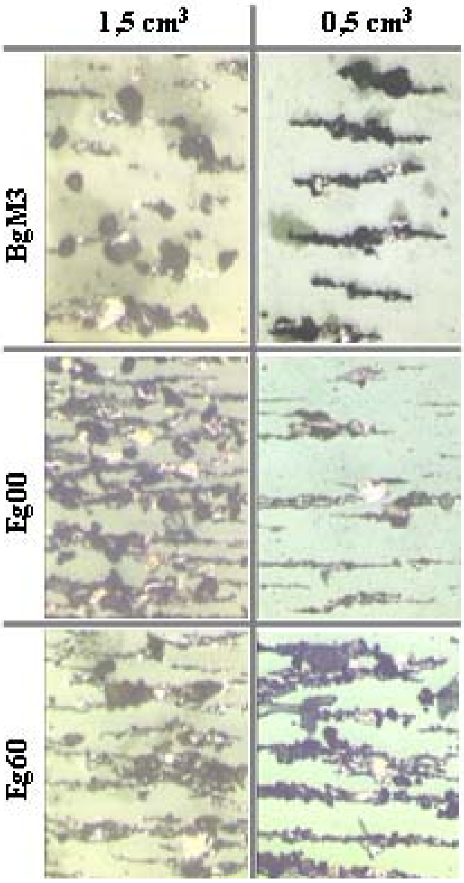

Fig. 10 – Microphotographs (200x) of wear particles observed by optical microscopy in the ferrograms of the grease samples.

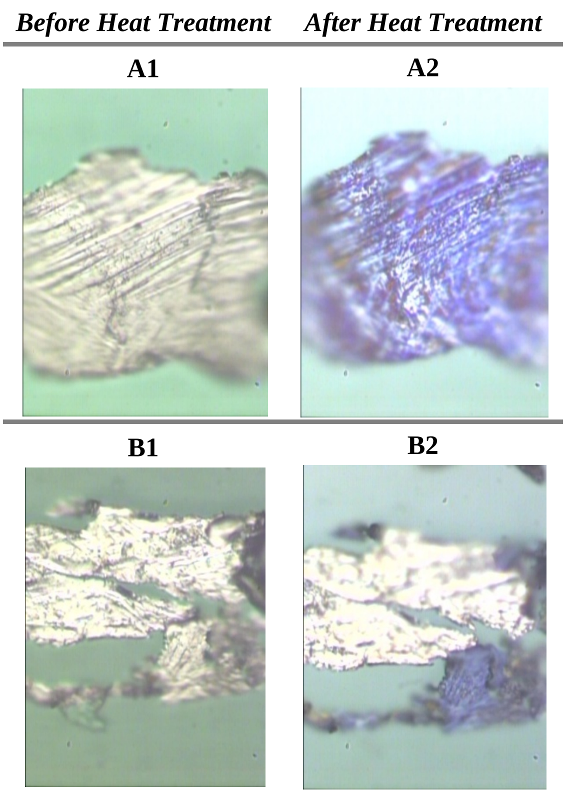

Fig. 11 – Wear particles before and after heat treatment.

and races. The source of the high alloy steel particles is unknown.

Figure 12 shows the wear particle presented on Figure 11 (B), with the corresponding spectrum showing the material composition: iron - *Fe*, chromium - *Cr* and nickel - *Ni*.

Figure 13 shows some of the wear particles observed on the ferrograms through SEM, with the corresponding EDX spectrums. The morphology of these particles clearly indicated that the predominant wear mechanism was contact fatigue wear, although some abrasion particles (cutting wear) were also observed. The EDX spectrums show that the main alloy element is chromium, although some spectrums also indicate the presence of nickel.

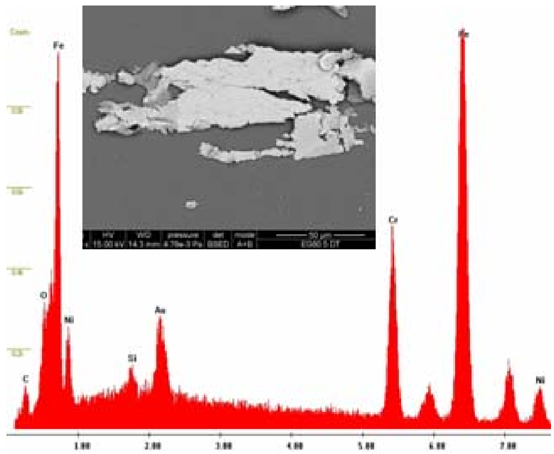

Fig. 12 – Wear particle observed by SEM and the corresponding EDX spectrum.

3.3 - Bearing Surface Analysis

In order to complement the wear debris analysis, the outer races and the taper rollers surfaces were analyzed by optical and electron scanning microscopy. Schematically, the wear mechanisms observed in the rollers and developed for each grease, are presented in Figure 14.

Small surface indentations and circumferential scratches were observed on the rollers surfaces, generated by hard wear particles circulating inside the contact between rollers and races.

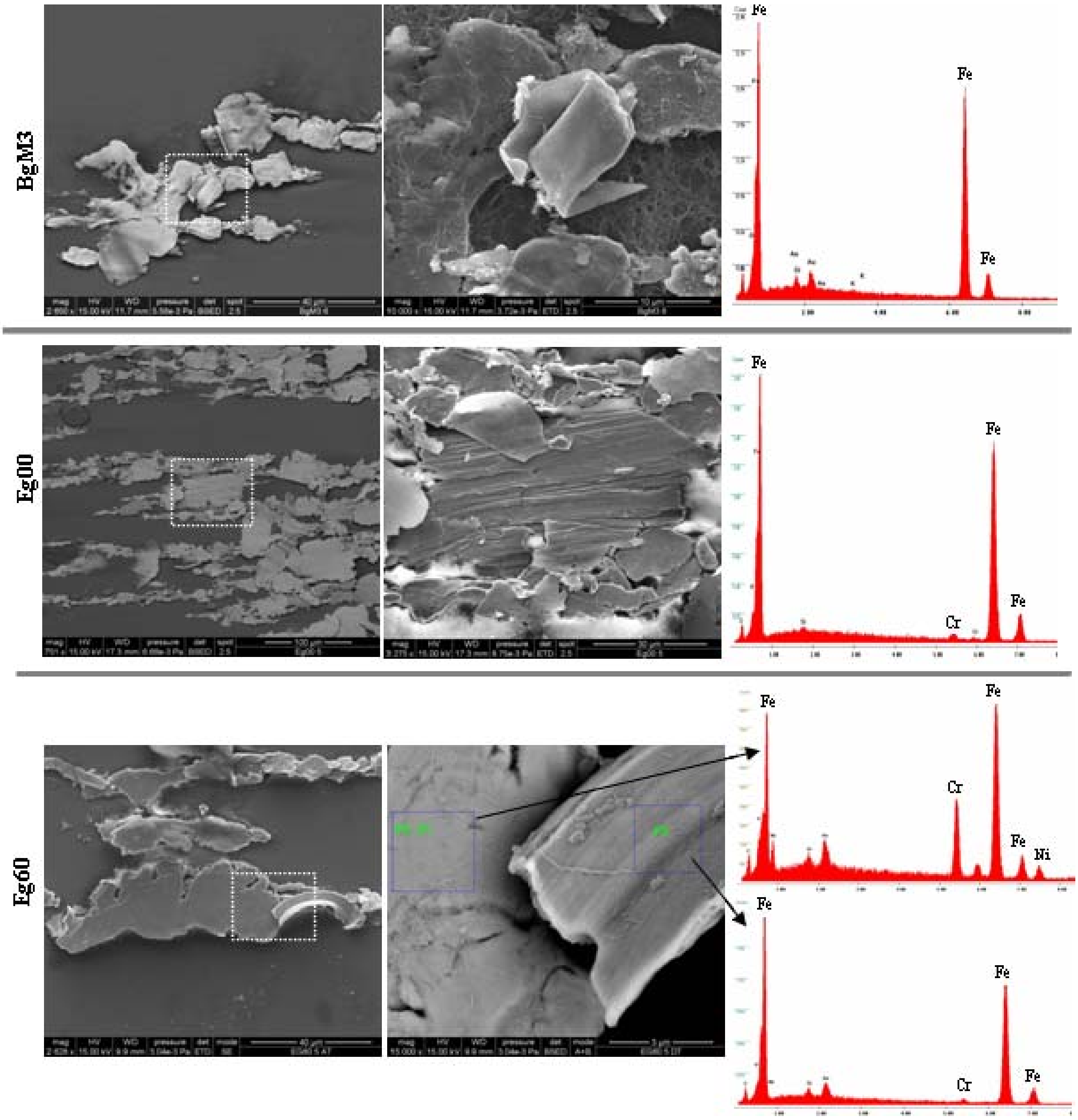

Fig. 13 – SEM and EDX analysis of some particles present on the ferrograms made for BgM3, Eg00 and Eg60 greases tested.

The rollers lubricated with BgM3 grease show a significantly higher concentration of surface indentations, when compared with the other two greases, mainly located in a specific area *3,2 mm* below the roller base,

Circumferential notches were observed in all rollers surfaces, near the rollers face, caused by the plastic deformation of the rollers due to the roller “edge effect” [FAG, 1991]. The surface damage in these circumferential notches is well distinct for the three greases tested.

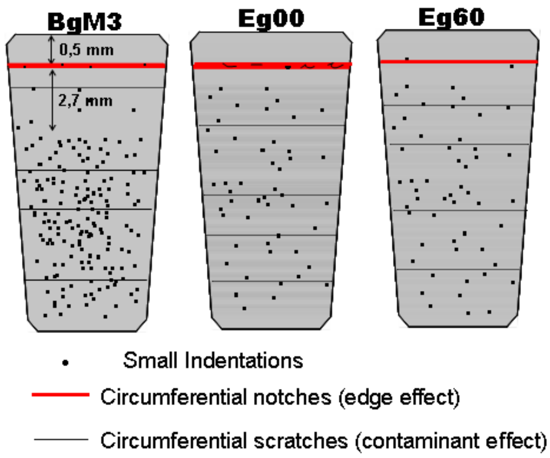

Fig. 14 – Surface wear identification in the taper

As shown in Figure 15, the rollers lubricated with the ester based grease Eg00, presented several micro-pits oriented along the circumferential direction of the roller, with a depth going from *10* to *60 μm*. In the case of the mineral grease BgM3, the circumferential notches observed on the rollers contained a huge amount of micro cracks normal to the rolling direction. The surfaces of the rollers lubricated with ester based grease Eg60 only showed a narrow plastic deformed zone along the circumferential direction.

The cage of the taper rolling bearing lubricated with Eg00 grease, was cut and the bearing dismounted, so that the rollers and races surfaces could be analysed by scanning electron microscopy. In the case of the bearings lubricated with BgM3 and Eg60 greases, only the outer races surfaces were analysed.

In order to identify the source of high alloy steel particles found in several ferrograms, the composition of the bearing surfaces was determined using energy dispersive X-ray (EDX).

Figure 16 shows a micro-pit found inside the circumferential notch observed on the roller surface of the bearing lubricated with Eg00. The micro-pit is about *50 μm* long and the EDX analysis indicated that the composition on the surface of the roller and inside the micro-pit was the same (low alloy steel).

Figure 17 shows the outer race surfaces of the bearings lubricated with greases BgM3, Eg00 and Eg60. In all the microphotographs corresponding to a magnification of *100* and *1000* times, obtained near the border of the raceway, the transition from the contact track to the non contact zone was very clear.

This transition region was located at about *1,2 mm* from the edge, being characterized by a polished lane, where most of the grinding marks disappeared as a consequence of race surface wear. However, the morphology of these polished lanes depended on the grease used to lubricate the bearing.

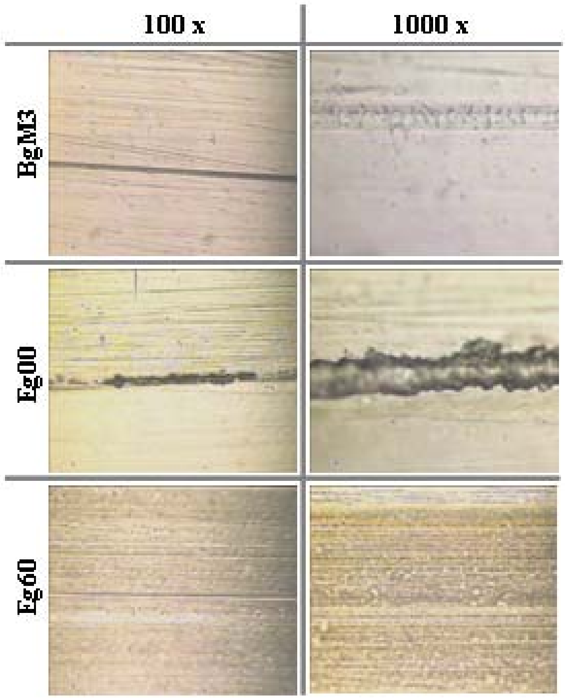

Fig. 15 – Identification of surface wear in the taper rollers observed by optical microscopy.

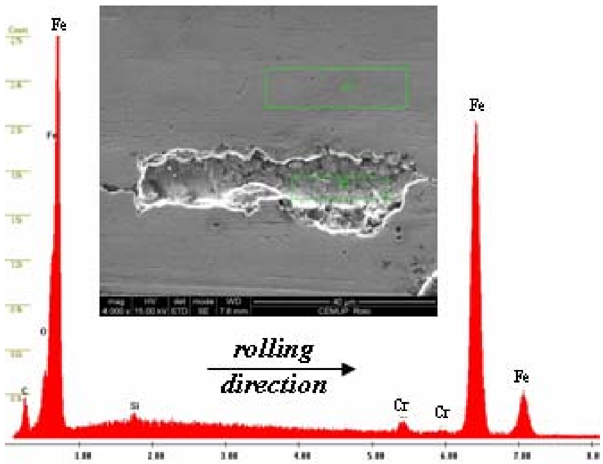

Fig. 16 – SEM and EDX analysis of a micro-pit observed on a roller surface lubricated with Eg00 grease (magnification 10,000 x).

In the case of Eg00 grease, there was a very well defined polish lane. For Eg60 the polish lane contained some scratches, while for BgM3 the lane was slightly polished, and the transition from the wear track to the non-contacting zone was nearly undefined.

The centre of the contact track on each outer raceway was also analysed, and the corresponding microphotographs (with a 15000 times magnification) are also presen-

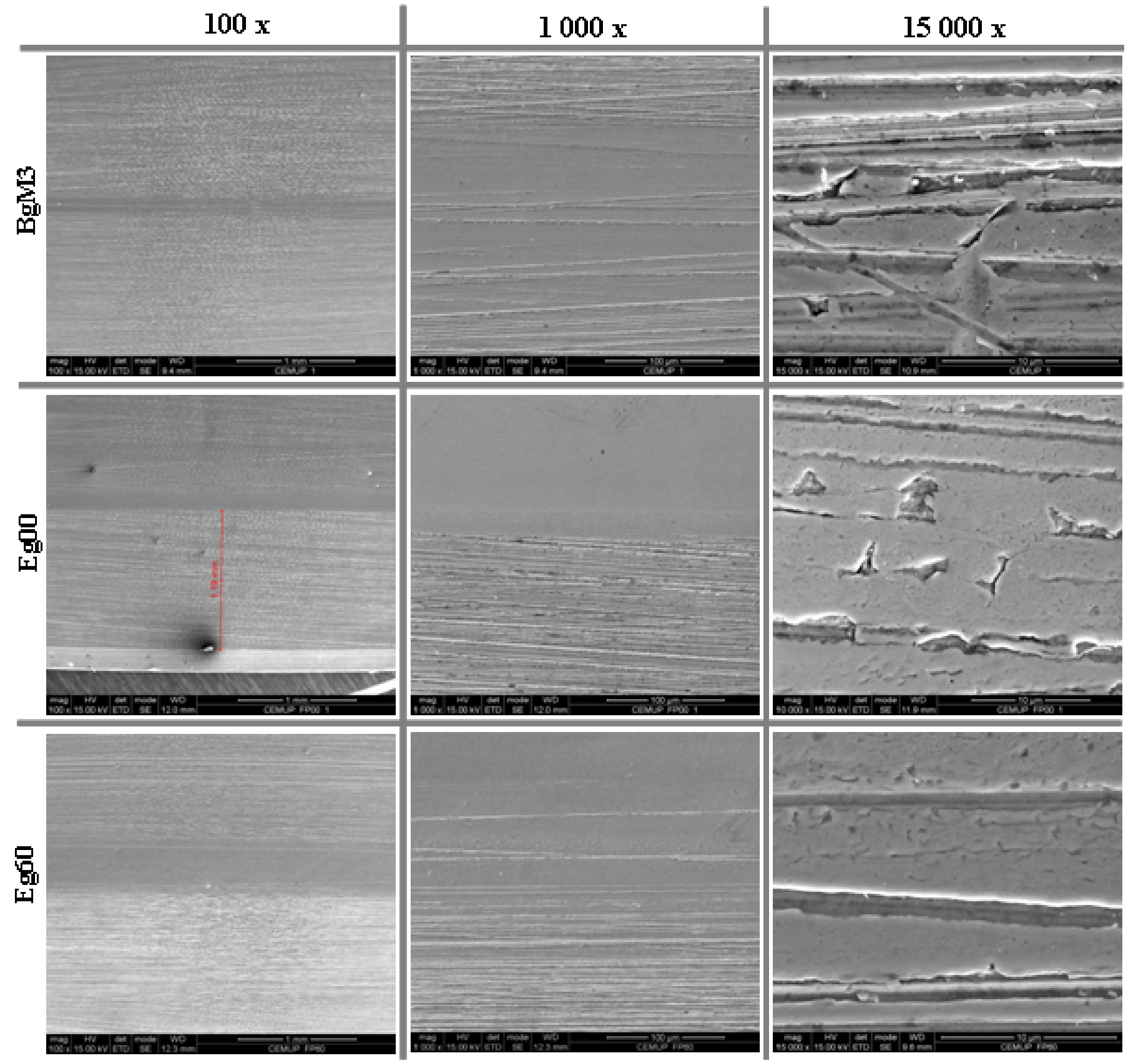

Fig. 17 – SEM analysis of the outer races surfaces observed near the edge (100 x, 1 000 x) and at the center (15 000 x) of the outer races for BgM3, Eg00 and Eg60 greases.

ted in Figure 17. The raceway lubricated with BgM3 grease preserved more grinding marks than the other raceways lubricated with greases Eg00 and Eg60.

In the raceway lubricated with ester based grease Eg00, several micro-pits were observed that propagated along the circumferential direction. These geometrical discontinuities occurred at the bottom end (valleys) of the grinding marks or indent ridges on the top of an undulation are preferential locations for micro-crack initiation [Nelias, 1999].

The EDX analysis made on several points of the raceways identified the raceway material as low alloy steel.

4. DISCUSSION

The experimental results showed that the initial volume of grease used to lubricate the taper roller bearing had a marginal influence on the bearing power loss. Possibly, the lower volume of grease used for initial bearing fill (0,5 cm^3) is as much as necessary to a normal bearing operation, with no occurrence of considerable grease starvation during the testing time period and under the working conditions imposed. However, the grease characteristics, such as, base oil, thickener structure and constituents, seamed to have more influence on the bearing power loss, as well, in the wear characteristics.

The Lubricant Parameter LP (see Table 1) defined by the product of the lubricant dynamic viscosity by the pressure-viscosity coefficient at atmospheric pressure, is directly related to the film thickness (h_0) in an EHD contact. The mineral and the ester base oil of the greases tested have different LP values. Consequently, the ability of the greases to generate a lubricant film is different and can be compared through the following equation:

$$\left(\frac{\boldsymbol{LP^{mineral}}}{\boldsymbol{LP^{ester}}}\right)^{0,727} = \frac{\boldsymbol{h_0^{mineral}}}{\boldsymbol{h_0^{ester}}}$$

The value obtained is 2,135, meaning that the lubricating capacity of the mineral base oil is more that double than the ester base oil. Considering that the lubrication is more efficient when the film thickness is high, the results concerning the wear present in the taper roller bearings tested can be explained:

- the mineral based grease (BgM3), generates higher h_0 and consequently less wear (lower CPUC);
- the ester based bio-greases (Eg00 and Eg60), generates smaller h_0 and thus more wear (higher CPUC). However, the Eg60 grease show lower wear indexes when the roller bearing was tested with 1,5 cm^3 of grease. The thickener structure and, in particular the polyurea particles in this grease, can have an important effect in the wear protection.

The surface analysis results of the rolling elements (rollers and raceways) revealed an initial process of typical contact fatigue wear failure in Taper Rolling Bearings and different plastic deformations, providing additional information about the wear behaviour of the greases tested:

- the mineral based grease (BgM3), containing EP additives in its formulation and operating with higher h_0, showed a good behaviour in terms of operating temperatures. On the raceways surfaces, most of the grinding marks are preserved as the result of lower wear. However, an initial contact fatigue wear, due to edge effect, was detected.
- the ester based bio-greases (Eg00 and Eg60), with low content in EP additives and smaller h_0, perform relatively different in terms of wear. Among the two greases, Eg60 showed the better results in terms of contact fatigue wear, although it seemed to provide higher surface plastic deformation. Again, the thickener structure (in this case a more closed network structure), and the polyurea particles, can contribute to form a surface protective film and, at the same time, generating higher plastic deformations. On the raceways surfaces of the bearings lubricated with these greases, can be observed that most of the grinding marks have been worn out and/or plastic deformed.

To evaluate precisely the fatigue wear protection of these different types of greases, longer bearing tests are necessary.

The lubricant analysis showed the presence of very large wear particles containing chromium and nickel alloys. Such particles were probably generated during the bearing mounting operation. The presence of those particles can have an important effect on bearing wear. Consequently, an improvement on the bearing mounting procedure, as well on the bearing support, should be implemented before restarting the tests on taper roller bearings lubricated with bio-greases.

5. CONCLUSION

The taper roller bearing tests shown that, a reduction in the grease amount for initial bearing lubrication is not a determining factor to diminish internal frictions in a taper roller bearing, at least during limited periods of time. The grease base oil (type and viscosity), the thickener structure and the resultant interactions between then, are very important factors on the grease ability to form a thick lubricant film in a rolling contact, and consequently have a vital effect on the bearing power loss, wear and fatigue life.

The bio-greases evaluated (Eg00 and Eg60), which have the same formulation and manufacturing process, differing only on the presence of polyurea, show distinct behaviors in terms of wear. It should be interesting to continue this study, including on it, the film thickness and friction measurements, as well the knowledge concerning the rheological behavior of the grease base oil and of the grease it self.

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