



World Journal of Engineering

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Menasri Nouredine, Bouchoucha Ali,

Article information:

To cite this document:

Menasri Nouredine, Bouchoucha Ali, (2018) "Experimental investigation of bearing wear of a gear unit DMGH 25.4 of horizontal cement mill", World Journal of Engineering, Vol. 15 Issue: 1, pp.54-61, <https://doi.org/10.1108/WJE-12-2016-0157>

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Experimental investigation of bearing wear of a gear unit DMGH 25.4 of horizontal cement mill

Menasri Noureddine

Mechanical Laboratory, Faculty of Technology, University of M'sila, M'sila, Algeria, and

Bouchoucha Ali

Tribology Laboratory, Faculty of Technology, University of Constantine, Constantine, Algeria

Abstract

Purpose – Rotating machines play a strategic role in the process; it is the case of a gear unit of a cement mill. These machines are composed of tribo-pairs (bearings and gears, etc.) subjected to mechanical stress and harsh industrial environments. This study aims to make an experimental investigation of bearing wear of a gear unit DMGH 25.4 of a horizontal cement mill.

Design/methodology/approach – Several tests were carried out in collaboration with industrial Algerian companies, for example, spectroscopy, micro hardness, X-Ray diffraction analysis and microscopic examination of wear-characterized QJ1244 N2MA bearing.

Findings – Experimental results reveal that there are two types of bearing wear: the first is a continuous mode of damage. The second mode is the wear by a third body (wear debris in suspension in oil). The spalling results from the propagation of cracks through the thickness of the material generally give rise to cracks in the sub-layer depth hertz. An unusual hardening observed suggests that the damage was caused by the dissipation of a large surge of frictional energy lasting several milliseconds. It is found also that heating due to insufficient lubrication of the bearing led to the formation of high-density fine carbides in the microstructure of 100Cr6, which tends to decelerate the movement of dislocations during plastic deformation.

Practical implications – This study allowed the characterization of bearings wear in industrial mechanical systems.

Originality/value – Characterization of the bearings showed that the unusual hardening observed suggests that the damage was caused by the dissipation of a large surge of frictional energy lasting several milliseconds. The microhardness of the worn bearing is very high compared to the beginning wear bearing, which is due to the quantity of carbides formed. The thermo-mechanical stresses do not affect the main phases such as martensite, but they accelerate the fracture propagation at the surface.

Keywords Wear, Bearings, X-ray diffraction, Microhardness, Microstructural

Paper type Research paper

1. Introduction

Bearings are critical components of rotating machines; they ensure the transmission of mechanical forces and the rotation of the shaft, but these are the most fragile. The fabrication technologies of the bearings require precision of micrometer level, and any dimensional variation in time changes the characteristic of the adjustments and free motions, making them either unusable even before the assemblage or with a reduced durability while functioning the process (Bulancea, 2006; Sidiroff, 2002).

The structure represents the base of the evaluation and the appreciation for the success of a thermal process involving steels. It is utilized in the bainitically or martensitically transformed conditions, achieving hardness in the range of 700-800 HV_{0.30} (Barrow and Rivera-Diaz-del-Castillo, 2011). The martensitic transformation in 100Cr6 is facilitated by mechanical twinning that puts the C atoms in the energetically

unfavorable octahedral sites during the transformation (Taylor *et al.*, 1989). The lattice strains associated with the C atoms provide the driving force for the precipitation of transition carbides during tempering (Perez *et al.*, 2009; Taylor *et al.*, 1989).

The tempering of martensitic steels and associated dimensional changes have been extensively studied over the past 50 years (Porter, 1992; Speich and Taylor, 1992; Taylor and Cohen, 1992). Although tempering of martensites has been studied in detail for many alloys, not much has been published concerning the bearing steel 100Cr6.

In fact, the previous studies on tempering of martensite have focused on identifying the transition carbide precipitation during tempering up to 160°C (Olson and Cohen, 1985; Olson, 1984; Olson, 1992; Perez *et al.*, 2009; Taylor *et al.*, 1989). The microstructures developed in 100Cr6 during tempering are complex and consist of nanoscale grains and precipitates, retained austenite, C in solution and large primary carbides that interact to give a complex mechanical response.

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World Journal of Engineering
15/1 (2018) 54–61
© Emerald Publishing Limited [ISSN 1708-5284]
[DOI 10.1108/WJE-12-2016-0157]

This work was supported by Algeria Cement COMPANY A.C.C, Maintenance Equipments Industry (M.E.I) and the central laboratory of spectrometry Arcelor Mittal Annaba Algeria.

Received 13 December 2016

Revised 12 May 2017

Accepted 16 May 2017

The hardness of the martensite and the wear resistance increase sharply with the interstitial C content.

On the other hand, the damage of the type “scuffing” may be the result of insufficient lubrication in terms of throughput. The main damage encountered can be classified into three categories (Stephan, 2009):

- 1 *Profound spalling initiated at depth*: This is the “conventional” deterioration of a bearing operating under normal conditions. The principle of the bearings construction leads to contact between rolling elements and rings that are the site of very strong specific charges. The Hertz pressure at this level results in maximum compressive stress at the surface and the maximum shear stress in under layer. If the charge is sufficient and under conditions of clean environment, alternate constraints faced by the raceways lead to more or less long term to a crack in the material. It starts from inclusions located under layer in the area where the stresses are highest (Hertz). The crack appears in the matrix adjacent to an inclusion. The crack propagates to the surface to cause the detachment of a steel particle, first event of damage by spalling.
- 2 *Superficial spalling initiated at the surface*: In the presence of small hard particles, there is wear of the bearing elements because of metal/metal contact as a result of a heterogeneous lubrication in this sensitive area. This leads to the deterioration of the active surfaces in the form of a very superficial spalling of some tens of microns in depth, affecting a wide area of the raceways. This degradation process is slow. It is the same nature as that caused by an insufficient oil film because of too low viscosity.
- 3 *Profound spalling initiated at the surface*: When pollution is composed of larger particles, the passage of the particle between the rolling bodies and the ring causes a local plastic deformation of the raceway. The effect of this pollution is different according to its hardness. If the particle is sufficiently ductile, it can be deformed plastically in the form of wafer without breaking. The contrary, if pollution is fragile, it breaks through in the contact while plastically deforming the bearing elements. These new fragments then behave according to the second mechanism described above. Then, there is a competition between the degradation caused by local plastic deformation due to indentation and that caused by abrasive wear caused by fragments particle (Skendraoui *et al.*, 2009).

The main damage may be classified as follows (Fin *et al.*, 2013; Bolaers *et al.*, 2004):

- *Damage due to fatigue*: This type of damaged is manifested by the appearance of crack that grows until shucked.
- *Abrasive wear*: This is destruction of an element by removing progressively the surface material and particle formation.
- *Scuffing and adhesive wear*: This is produced at high slip, resulting in localized welding and surface roughness of a material transfer between surfaces.
- *Footprints*: It is related to Hertzian contact. The effect of load produces plastic deformation when a particle is trapped in the contact, causing surface defects.

- *Imbalance heat*: The temperature rise causes destruction of the lubricant.

The wear mechanisms such as abrasion and adhesion can be considered specific responses feeding the third body. Under the effect of mechanical and thermal loads, the first bodies undergo changes in their surface properties, leading to phase transformations and structural changes. The magnitude of these changes depends on the pressure and the deformations induced by temperature (Descartes, 1997). These changes are known as tribological transformed structures (TTS) (Plumet and Dubourg, 1998; Aubert *et al.*, 1990). The appearance of TTS causes a change in the stress field and admissible deformations of the material, leading to a detachment of particles by fragility of the material surfaces (Jullien *et al.*, 1996).

In this article, the bearing wear QJ1244 N2MA of the gear unit DMGH 25.4 has been characterized by identification of the material (chemical analysis) and analysis by X-ray diffraction micro hardness and metallographic examination.

2. Methodology/experimental

2.1 Description of cement mill

The cement mill flender DMGH of the Algerian cement company ACC is a horizontal ball mill, driven by a lateral crown, as shown in Figure 1. It receives the clinker, gypsum and possibly additional materials; loading is performed by a bucket chain to the input of the machine. This mixture is generally pre-crushed with captured material and repressed by the separator using steel balls placed inside the rotating grinder; then the whole is supported by an endless screw, an elevator or another transport device to be processed downstream (Manual, 1999). It consists of a main motor (direct current motor ANGA 315); tacking; gear unit horizontal; two couplings (RWS 800 and gear coupling); and a grinder DMGH.

2.1.1 Gear unit DMGH 25.4

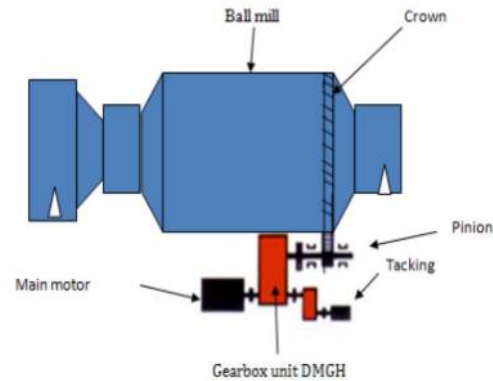
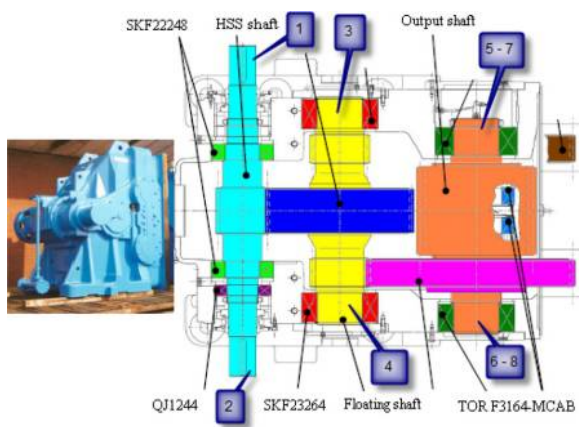
Figure 2 shows the gear unit Flender DMGH25.4, which is driven by a main motor through elastic coupling RUPLEX RLS 800. To move the grinder on a desired position, the gear unit is connected to a tacking with a motor (auxiliary motor) and a brake capable of blocking the grinder on any position. The kinematic characteristics of the gear unit are as follows (Manual, 1999):

- The high-speed shaft (HSS) frequency is 16.57 Hz.
- The intermediate shaft frequency is 7.27 Hz.
- The output shaft frequency is 2.05 Hz.
- G9H grinder frequency is 0.256 Hz.

Technical data of the gear unit are given in Table I.

2.2 Identification of bearing materials

The specimens have been taken from the outer race, inner race, half of the ball of QJ1244 N2MA and a sample of the HSS for analysis of bearing materials (Figure 3). The Chemical analysis of different samples has been done in the spectrometry central laboratory of Arcelor Metal (Annaba) via an optical emission analyzer ARL 3460.

Figure 1 Description of cement mill DMGH25.4**Figure 2** Diagram of the gear unit flender DMGH 25.4

2.3 X-ray diffraction analysis

To identify the existing compounds and their structures, a Bruker D8 Advance X-ray diffractometer has been used. This kind of equipment exists within the crystallographic analysis laboratory at the University of M'sila. It is equipped with a filter made of Ni and a Cu anticathode using the $K\alpha$ radiation of wavelength $\lambda = 1.5406 \text{ \AA}$. The working conditions are as follows: $U = 30 \text{ kV}$, $I = 25 \text{ \mu A}$, the scanning angle $2\theta = (6-90)^\circ$ using a speed rate of $0.05^\circ/\text{s}$.

The specimens have the following dimensions: $8 \times 8 \times 4 \text{ mm}$ (4 mm represents the thickness of the specimens).

The determination of the different phases present in the microstructure has been done using an X'Pert High Score software microcomputer.

2.4 Microhardness test

The specimens are obtained from two types of bearings QJ 1244 N2MA, the first one has undergone a beginning of wear, and the second one is completely worn (spalling). After that, the evolution of the microhardness of the longitudinal profile section has been measured.

The specimens are mounted under compression using an epoxy resin. Then, the mounted specimens undergo polishing. The test specimens have been taken from the bearing (Figure 4). The microhardness tests have been carried out on a Vickers indenter (Microdurometer Tukon 2500 Wilson Hardness). The applied load $P = 10 \text{ g}$, and the holding time = 15 s.

The different measuring points of each zone of the section of the longitudinal profile are carried out at distance points of 0.1 mm.

2.5 Metallographic examination

2.5.1 Macrographic observations

The samples (Figure 4) are observed as received, without any preparation, except cleaning with pure ethanol. These early observations (in its raw state) after wear allow going back to the real conditions of contact between the elements. The observations were made using an optical microscope Zeiss Axio Green 40 MOT assisted by computer.

2.5.2 Micrographic observations

These examinations are intended to characterize the structure of sample elements of bearings studied using an optical microscope Axio reflection green 40 MOT Zeiss. There are two types of observations:

- 1 superficial observations; and
- 2 observations of the heart of the outer race and the inner race.

Table I Technical data of gear unit

Mark	Type	Module (mm)	Power (KW)
Flender	DMGH 25.4	25.4	4551
Speed (T/min)	Weight (Kg)	Ratio input shaft teeth/intermediary	Intermediate shaft teeth/output
990/122.3	35000	25/57	20/71
R teeth drive pinion/crown	Bearings of HSS	Bearings output shaft	Bearings intermediate shaft
31/248	$2 \times 22248 \text{ CC/N1W33C3}$ $QJ1244N2MA$	$2 \times 23264 \text{ CAC/W33}$ $2 \times \text{TOR F3164-MCAB}$	$2 \times \text{TOR F3164 G}$

Figure 3 Image of bearing elements QJ1244 N2MA**Figure 4** Sample of macroscopic observation

2.5.3 Sample preparation.

After cutting, the samples undergo a manual polishing on different abrasive papers in ascending order of grains, final polishing is carried out using 3 μm diamond paste.

Before micrographic observation, the sample underwent an etching with nital 4 per cent. The surface obtained by polishing is dipped for 3-5 s in this solution, again cleaned with ethanol and dried with hot air. This operation is very delicate, because we must leave no trace on the surface.

3. Results and discussion

3.1 Identification of bearing materials

The chemical composition of samples is shown in Tables II and III.

From the results, it is deduced that the shaft is made of 20 NiCrMn6 nuance (AFNOR) equivalent (AISI-SAE 4620) and the bearing is made of 100Cr6 nuance (AFNOR) equivalent (AISI-SAE 52100). The 100Cr6 steel has been heat-treated. It has undergone quenching, followed by tempering. Heating the bearings at a temperature of 830°C will allow them to transform totally in an austenite phase. The C and Cr in cementite will

Table II The chemical composition of HSS

Specimen/element	Spectral analysis (Wt.%)					
	C	Mn	Si	Ni	Cr	Fe
Shaft	0.200	0.51	0.265	1.668	1.5791	95.197

Table III The chemical composition of bearing QJ1244 N2MA

Specimen/element	Spectral analysis (Wt.%)					
	C	Mn	Si	Ni	Cr	Fe
Inner race	1.03	0.97	0.53	0.071	1.420	95.660
Outer race	0.96	0.98	0.50	0.032	1.387	95.970
Ball	0.98	0.26	0.23	0.067	1.370	96.800

dissolve in the gamma phase at 830°C. After quenching, the metal undergoes a tempering at 170°C, which reduces the brittleness of the martensite and eliminates the residual stresses (Bulancea, 2006; Barrow and Rivera-Diaz-del-Castillo, 2011).

The 100Cr6 nuance has a high hardness exceeding 62 HRC (720 Hv) and high dimensional stability, enabling it to withstand high loads and can be used up to +150°C. Its homogeneous structure on a macroscopic and microscopic scale allows responding to the requirements of low torque and high speeds (Bulancea, 2006; Barrow and Rivera-Diaz-del-Castillo, 2011).

3.2 X-ray diffraction analysis

The obtained X-ray diffraction spectra for the bearings steel (100Cr6) are shown in Figure 5:

The diffractograms show the main characteristic peaks of iron α' (martensite) (JCPDS Card No.01-085-1410) with remarkable intensity. In addition to iron peaks α' ; we note that a series of peaks of Hagg carbide (Fe_5C_2) (JCPDS file No. 00-020-0509) and Cr carbide (Cr_7C_3) (JCPDS File No. 00-006-0683). The formation of this carbide is provided by the reaction of Cr atoms with the C atoms of the inner race and ball. However, the peaks Fe_3C have not been noticed.

3.3 Microhardness test

The micro superficial hardness of the ball is 838 $\text{HV}_{0.1}$. Figures 6 and 7 show the evolution of the microhardness of the elements QJ1244 early wear and worn bearings QJ1244 (spalling), respectively.

The results of the microhardness test show that the Vickers hardness of 100Cr6 steel just below the surface of the beginning wear and worn bearing QJ1244, was measured at a much higher value compared to the normal state, it's found that the hardness varies between 720 and 800 HV. The unusual hardening observed suggests that the damage was caused by the dissipation of a large surge of frictional energy lasting several milliseconds (Sigrid and Woydet, 2005). Instead of a surface with pitting or cracks raceway, typical consequences of an overload, the material in the raceway seemed to have been plated or rolled onto the surface.

It has been noticed that the microhardness of the worn bearing is very high relative to the beginning wear bearing, which is due to the quantity of carbides formed.

3.4 Metallographic examination

3.4.1 Macrographic observations

The following figures present the images of macrographic observations of different elements in contact bearings (Figures 8 and 9).

The macrostructure observations show that:

The macrostructure of a portion of the ball has non-parallel grooves and streaks (grid) because of the friction of the ball on the two rings. The bearing QJ1244 beginning wears has a strip macrostructure.

From the obtained results, it's shown that the faces are damaged and are in the form of parallel stripes in the direction of the bearings rotation. This damage is due to the abrasion resulting from the external loads applied on the bearing rings. The spalling are of a small size.

Figure 5 X-ray diffraction spectrums (a) for the outer race of bearing QJ1244 beginning of wear and (b) for the inner race of bearing QJ1244 has worn bearing (spalling)

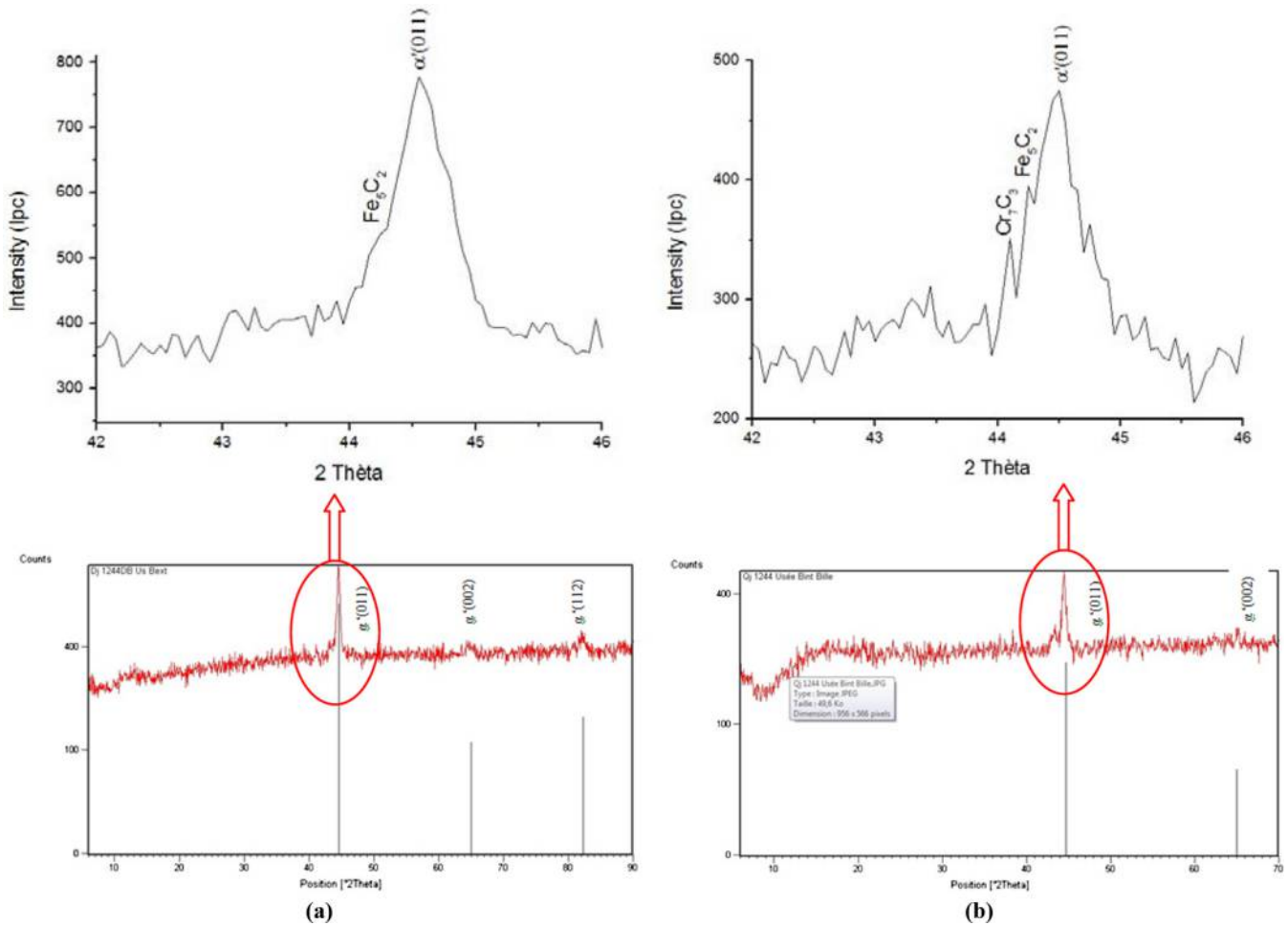
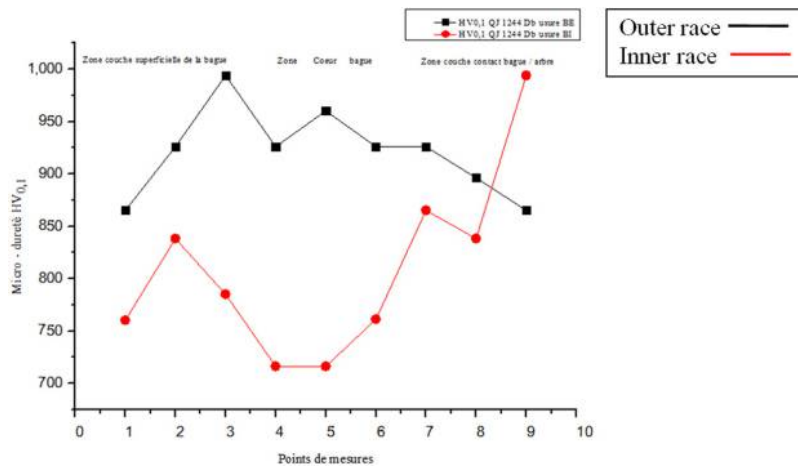
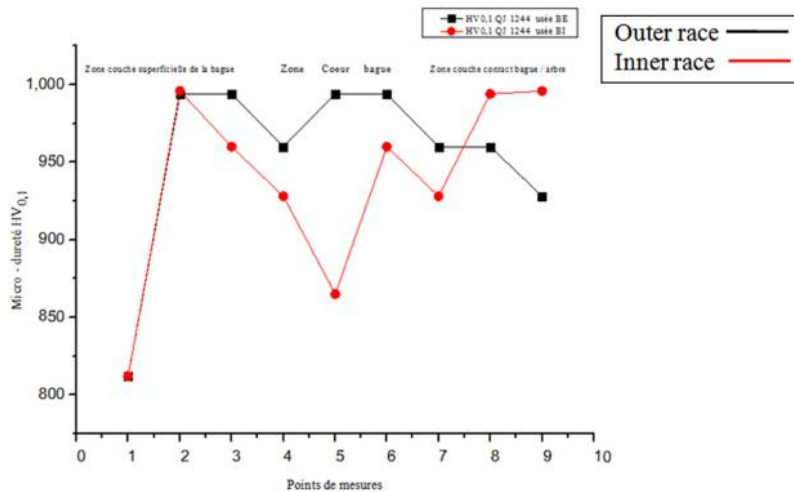
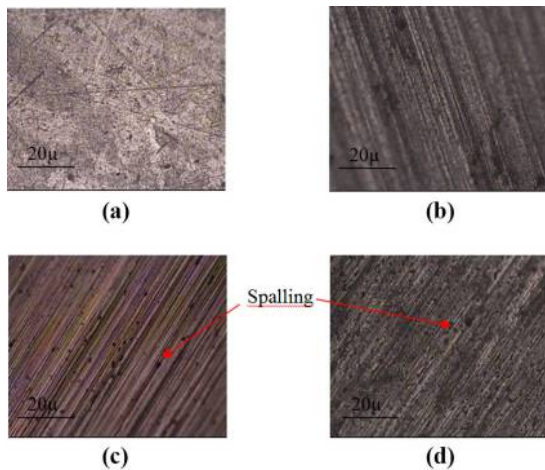
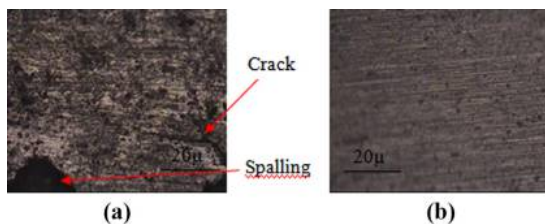


Figure 6 Evolution of the microhardness of the bearing QJ1244 at beginning of wear



There are two types of wear. The first is a continuous mode of damage when the interactions between the roughness of the surfaces of materials in contact may occur. This mode of damage causes a removal of material at each charging cycle.

The second mode is the wear by a third body of wear debris in suspension in oil for example. These are the harsh wear particles which machined materials in contact. The macrographic observation is a part of the inner raceway of the

Figure 7 Evolution of the microhardness of the worn bearing QJ1244 (spalling)**Figure 8** Macrostructure of the bearing QJ1244 at beginning of wear (a) of the ball, (b) of the outer raceway, (c) of inner raceway and (d) of the inner race/shaft**Figure 9** Macrostructure of the worn bearing QJ1244 (spalling) (a) of inner raceway and (b) of the outer raceway

worn bearing QJ1244 (spalling) and shows a damaged area containing very deep scratches and spalling holders of different sizes. Spalling results from the propagation of cracks through the thickness of the material generally give rise to cracks in sub-layer depth hertz. It depends on the shear stress at the surface and the thickness of the oil film.

3.4.2 Micrographic observations

Figures 10-12 present the micro-structures of HSS and bearings, respectively.

In the figures, we can see that the bearings' microstructure contains finely acicular martensite with an even distribution of high-density fine carbides. The presence of the carbides in the microstructure (heterogeneous) of 100Cr6 tends to decelerate the movement of dislocations during plastic deformation. To overcome these dislocations, the stress must be high.

4. Conclusion

One can conclude that there are two types of bearing wear: the first is a continuous mode of damage caused when the interactions between the surface roughness of materials in contact may occur. This damage leads to a cut at each charging cycle. The second mode is the wear by a third body of wear debris in suspension in oil. These are the harsh wear particles which machine materials in contact.

Spalling results from the propagation of cracks through the thickness of the material that generally give rise to cracks in sub-

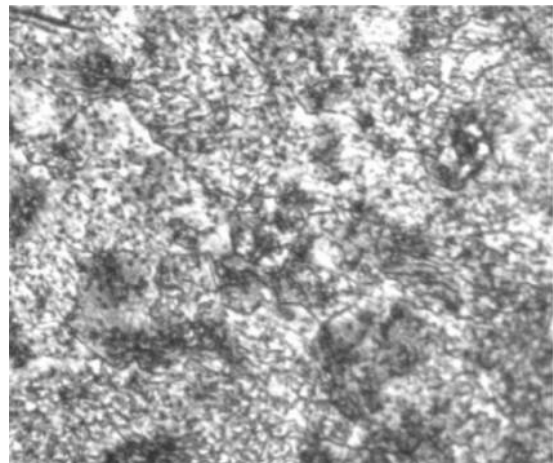
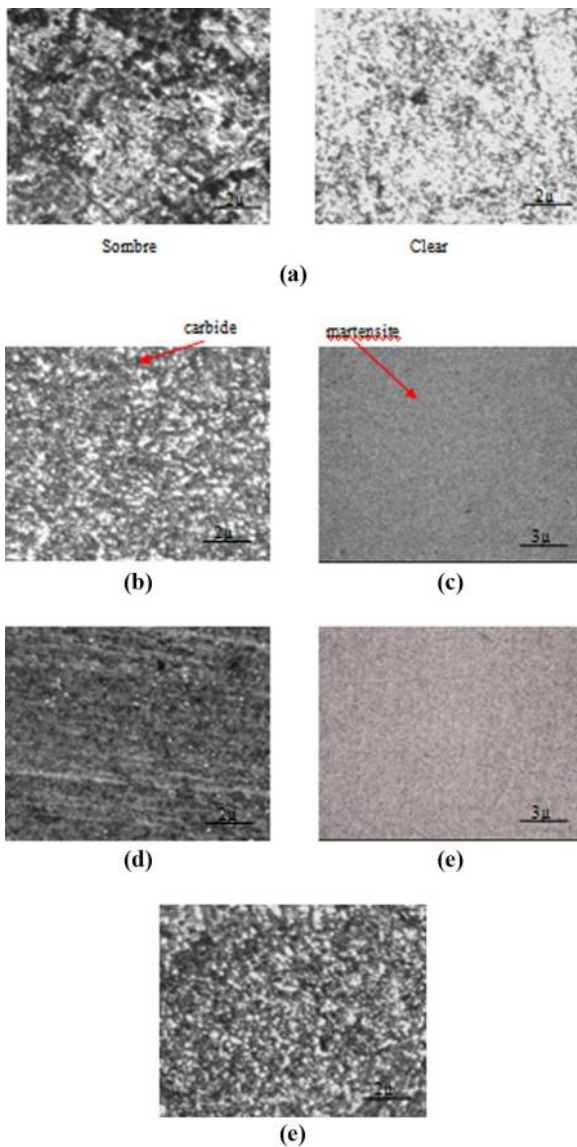
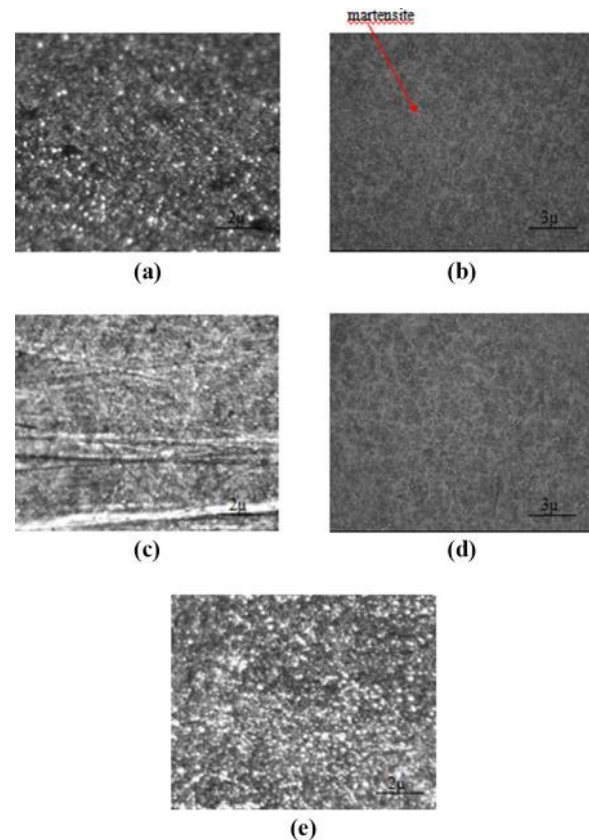
Figure 10 Microstructure of HSS

Figure 11 Superficial microstructure and at the heart of the bearing QJ1244 beginning of wear

Notes: (a) Superficial microstructure of the ball; (b) superficial microstructure of outer raceway; (c) microstructure in heart of the outer race; (d) superficial microstructure of inner raceway; (e) microstructure in heart of the inner race; (f) superficial microstructure Inner race/shaft

layer depth hertz. It depends on the shear stress at the surface and the thickness of the oil film.

The Vickers hardness of the steel 100Cr6 located just under the surface of bearings QJ1244 way beginning wear and worn bearing QJ1244 lubricated, defective, was measured at a much higher than normal value varies from 720 to 800 HV. The unusual hardening suggests that the damage was caused by the dissipation of a large surge of frictional energy lasting several milliseconds. Instead of a surface with pitting or cracks raceway, typical consequences of an overload, the material in

Figure 12 Superficial microstructure and at the heart of the worn bearing QJ1244 (spalling)

Notes: (a) Superficial microstructure of outer raceway; (b) microstructure in heart of the outer race; (c) superficial microstructure of inner raceway; (d) microstructure in heart of the inner race; (e) superficial microstructure Inner race/shaft

the raceway seemed to have been plated or rolled onto the surface. It has been noticed that the microhardness of the worn bearing is very high relative to the beginning wear bearing, which is due to the quantity of carbides formed.

The heating due to insufficient lubrication of the bearing has led to the formation of high-density fine carbides in the microstructure (heterogeneous) of 100Cr6, which tends to decelerate the movement of dislocations during plastic deformation.

The thermo-mechanical stresses do not affect the main phases such as martensite, but they accelerate the fracture propagation at the surface.

The proposed methodology is simple, efficient and easy to use for the characterization of bearings wear in industrial mechanical systems.

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Corresponding author

Menasri Noureddine can be contacted at: nmenasri@univ-msila.dz