Influence of severe shot peening on wear behaviour of an aluminium alloy

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Received Date: 5 February 2014; Accepted Date: 24 April 2014

NOMENCLATURE

CSP	=	conventional shot peening (100% coverage)
SP	=	shot peening treatment
SSP	=	severe shot peening (5000% coverage)
SSP-g	=	severe shot peening (5000% coverage)-grinded

INTRODUCTION

Wear is a persistent in-service condition in many engineering applications with important economic and technical consequences. The effect of abrasion is particularly evident in the industrial areas of transportation, agriculture, mining and mineral processing. In economics terms, the cost of abrasion wear has been estimated to range from 1 to 4% of the gross national product of an industrialised nation.[1] The economic importance of wear has been known for a long time. In 1966, a report for a landmark study tabled to the British Government by H. Peter Jost indicated that good tribological practices represented savings in lubricants, maintenance and spare parts of about 40%, and savings in consequential losses due to downtimes substantially higher than the repair itself.[2]

Wear is a critical concern in many types of machines and complex systems, whose functionality depends on the components' behaviour under sliding contact conditions; it is often a major factor in defining or limiting the general lifetime of a component. Precise evaluation of wear resistance is problematic, because there are too many variables involved, including friction, lubrication conditions, surface finish, material microstructure and so on. The study of all these factors is performed under the science of tribology.

Wear is indeed directly related to the surface properties of materials. Normally, because of fabrication methods, surface layers and the ones immediately below the surface have a microstructure that is slightly different from the bulk material. Hence, additional modification of surface properties provides the possibility of improving wear behaviour of components.[3,4] Nowadays, diversity of the available surface engineering treatments, such as thermal spray coatings, electroplated coatings, PVD and CVD coatings, ion implantation, laser surface processing, carburizing, nitriding and nitro-carburazing and severe plastic deformation methods make it possible to modify the surface properties maintaining those of the bulk material. Hutchings[5] presented the wide range of depth

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and hardness modifications, which can be achieved in the surface regions by different surface treatments.

Some of the aforementioned treatments are able to reduce grain dimension at least in the superficial layer of the treated materials, even down to nanocrystalline (NC) size. Ultra fine grains (<1000 μm) and NC (<100 nm) materials have attracted considerable interest because of their novel properties originating form a large volume fraction of grain boundaries.[6–8] In many cases, the physics of these nanostructured/ultra-fine-grained materials can be very different from the same material comprising conventionally sized grains. This may lead to different, unusual and often superior properties, making them attractive candidates for a range of potential applications in automotive, aerospace and biomedical industries.

The problem common to most of the methods able to get NC on the surface layer of materials is the limitations on the geometry and the dimension of the component. Among methods used to enhance surface properties of materials, shot peening (SP) is a widely used process because of its versatility. In this process, the surface of the material is bombarded with a flow of spherical media, which transmit the impact energy onto the material surface. The effects induced by SP mainly include the following: compressive residual stress field due to non-uniform surface plastic deformation; work-hardening due to the increase in the dislocation density; modifying surface topography due to the dents created by the impacts causing the surface roughness increase; and eventually strain-induced phase transformation.[9] We have demonstrated, in our previous works, that this treatment can be applied using unconventional parameters, named severe SP (SSP), in order to reduce grain dimension on a thin superficial layer, down to nano scale (smaller than 100 nm).[10–12]

Despite the roughness increase, this treatment is mainly applied to increase fatigue behaviour of industrial components. Several studies evidence that compressive residual stresses field and work hardening induced by SP improves the fatigue behaviour of components, increasing resistance to crack propagation, which in turn prolongs their lifetime.[12–16]

Nevertheless, very few works have been conducted on the tribological behaviour after SP or SSP treatments, and it is thus not thoroughly understood whether it actually improves the wear resistance. Hashemi et al.[17] demonstrated in their study that SP treatments improve wear behaviour on nitrided 316 L austenitic stainless steel. On the other hand, Zamit et al.[18] do not find wear improvement on a Cu-Ni austempered ductile iron after SP treatments. They conclude that the potential advantages resulting from SP treatment (higher hardness, residual compressive stresses field and austenite to martensite transformation), are counteracted by the increased surface roughness. Wang et al. studied the wear behaviour of a low carbon steel with an NC surface layer of about 10 mm thick obtained by surface mechanical attrition treatment method. They show that the friction coefficient decreases and the wear resistance increases with the presence of the NC surface layer. The improvement in friction and wear properties may be attributed to the increased hardness of the NC surface layer.[19] Guobin et al. performed a set of ring on disc wear test on a medium carbon steel with an NC surface layer about 30 μm thick obtained through surface mechanical attrition treatment. Experimental results show that the friction coefficient and wear weight loss decreases and the wear resistance increases for the surface NC specimens under lower loads.[20]

Indeed, aluminuim and aluminium alloys are very common materials used in various industrial applications because of their lightweight (one-third the density of iron), resistance and malleability. On the opposite, they do not have high hardness, which does not contribute to a good wear behaviour. Some aluminium alloys can be anodized to convert the surface layer to alumina, which provides high hardness and wear resistance. Also, they can be strain-hardened or precipitation-hardened to obtain increased strength. It has been shown that the microhardness in aluminium alloy 6061-T6 increases because of the presence of hard SiC and Al2O3 particles, although the tensile properties decrease as compared with the base material because the reinforcement particles make the matrix more brittle.[21] Grain refining is one of the predominant techniques in improving metallurgical characteristics and mechanical properties of castings. Elements such as Zr and Ti, added to the aluminium alloy Al 7042-Sc display better tensile and wear properties than the unrefined alloy.[22]

With the purpose to clarify wear behaviour of shot peened components, and having in mind the scientific interest for NC structures because of their superior properties compared with their coarse crystalline counterparts, the aim of this paper is to study the wear behaviour of the 6063 aluminium alloy subjected to SP and SSP treatments. Al 6063, a medium strength alloy commonly referred to as Al architectural alloy, is also widely used for structural pipes and tubes. It can be used in many different applications that involve continuous and repeated contact and are consequently prone to wear.

In this study block on ring wear tests were performed on the 6063 aluminium alloy specimens with different surface microstructures, obtained via application of different SP treatments. Four series of specimens with different SP treatments (as-received not peened (NP), conventionally shot peening (CSP), severe shot peening (SSP), and severe shot peening followed by mechanical grinding using sand paper in order to decrease surface roughness (SSP-g), were subjected to wear test.

Prismatic specimens were tested under lubricated sliding wear conditions by means of a block on ring tribometer. Wear results were analysed based on roughness, hardness trend and microstructure of the surface layer of specimens. Results in terms of effect of different SP treatments and the obtained tribological characteristics of the specimens indicate the significant effect of microstructure and surface roughness on the wear characteristics.

MATERIAL AND SPECIMENS

The material used in this study is aluminium alloy Al-6063 produced by Alcoa S.A. company (Asturias, Spain). Chemical composition is shown in Table 1. This alloy is frequently used in civil applications but also in cases where a certain amount of relative motion between adjacent parts can take place (joints, connections,…): this is why a localised application of SP can be considered of practical interest for this material.

In order to perform lubricated block on ring wear tests, prismatic specimens of $16 \times 10 \times 6.5\ mm^3$ were machined according to the ASTM G77 standard.[23] Five specimens for series (NP, CSP, SSP and SSP-g) were prepared and later submitted to the corresponding SP treatment. With the aim of characterising the surface layer of the specimens, microstructure analysis, microhardness profile and full width at half maximum intensity parameter as an index of work hardening (FWHM) measurements were performed on all series.

TESTS AND RESULTS

Shot peening treatments

Different SP treatments were performed on four series of prismatic specimens by means of a Guyson Euroblast 4 PF machine. SP Almen intensity was determined according to SAE J443 standard.[24] All treatments were performed using glass shots of 0.7 mm diameter, with a hardness of around 500–550 HV (AGB 70). The time required to perform the treatments with 100% surface coverage (conventional treatment) was determined using Avrami equation.[25] Application of the Avrami equation requires the determination of the indentation radius and the shot spread area. These two parameters can be determined from simple experimental tests. In this method, a statistically random shot particles arriving at the component's surface at a constant rate creating circular indents of a constant size is assumed.[26,27]

In order to obtain a grain refinement in the surface layer of the material, SSP treatment was performed on two series. After first SP treatment, all the specimens were submitted to a second slight repeening, using small glass shots of 0.2 mm diameter with the aim to improve the surface morphology and decrease the surface roughness.

In one of the SSP series, after the repeening treatment, the specimens were slightly mechanically grinded (SSP-g) with the aim of eliminating highest superficial peaks generated by the high-energy impacts, in order to decrease surface roughness and evaluate the influence of this parameter on wear behaviour. The parameters used in different SP treatments are shown in detail in Table 2.

Surface roughness

Shot peening treatment introduces plastic deformation on the materials surface, altering the topography and the surface roughness. Fig. 1 shows the roughness profile of one specimen from each series: CSP, SSP and SSP-g. Roughness was measured with a confocal microscope, Leica DCM 3D. Main roughness parameters, R_a (average roughness), R_t (maximum height of the profile) and R_z (average distance between the highest peak and lowest valley), and corresponding parameters of waviness W_a, W_t and W_z were measured following ISO 4287 standard,[28] using a Gaussian filter of 0.8 mm. Average values of five measurements performed on each specimen are reported in Table 3.

The results show that surface roughness parameters are higher in the case of SSP specimens because of higher impact energy. Whereas grinding reduces these parameters to values even lower than those of CSP specimens.

Another parameter that it is possible to consider is the waviness that shows the medium frequency components of the original surface profile measured by the profilometer.[26] These data, as presented in Table 3,

Table 2 Shot peening parameters

Treatment	Shot	Coverage (%)	Exposure time	Almen intensity	Grinded
CSP	AGB 70	100	19 s	13A	No
SSP	AGB 70	5000	16 min	13A	No
SSP-g	AGB 70	5000	16 min	13A	Yes

CSP, conventional shot peening; SSP, severe shot peening; SSP-g, SSP-grinded.

Table 1 Chemical composition of Al-6063 (% in weight)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Be	Cd	Pb	Ti
0.41–0.47	0.16–0.22	0.03	0.05	0.45–0.55	0.03	0.03	0	0.01	0.03	0.03

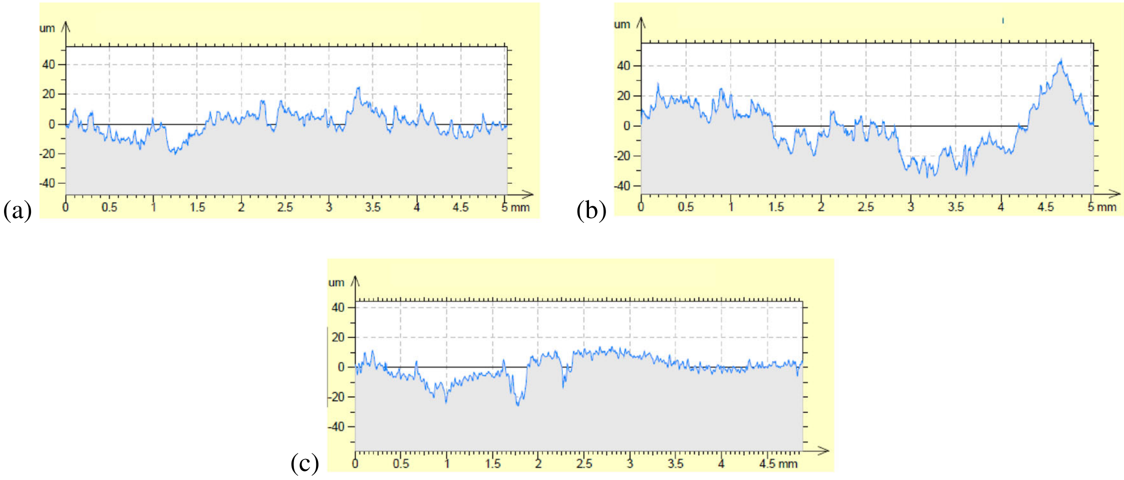

Fig. 1 Surface profiles of Al 6063 specimens after different shot peening (SP) treatments: (a) conventional SP; (b) severe SP (SSP); (c) SSP-grinded.

Table 3 Roughness parameters (μm)

Treatment	R_a	R_z	R_t	W_a	W_z	W_t
CSP	3.40	20.94	25.24	5.68	8.57	22.21
SSP	4.26	21.66	25.60	10.11	16.41	52.63
SSP-g	2.66	19.08	30.06	5.66	7.94	22.68

CSP, conventional shot peening; SSP, severe shot peening; SSP-g, SSP-grinded.

indicate much higher values in the case of SSP specimens. SSP-g series show similar values to the CSP specimens.

Microstructural analysis

Near the surface layer microstructural analysis of shot peened specimens was carried out with the help of an optical microscope to observe the changes occurred on surface microstructure because of SP treatments. After cutting, specimens were impregnated in resin, polished and etched with hydrofluoric acid 40% reagent. A Nikon Epithot 200 microscope connected to a computer with Omnimet-Enterprise program was used for image analyses. Fig. 2 shows the cross section of specimens after CSP and SSP treatments, respectively. As deduced for roughness analysis, surface of SSP specimens is more irregular than CSP ones. Microstructural observations reveal crushing of the grains on the surface layer of the treated specimens. In the case of SSP specimens, the thickness of this layer is bigger and more evident compared with the CSP ones due to the highest plastic deformation generated by larger number of impacts with higher kinetic energy. According to the literature, this densely deformed layer is indicating the grain refinement of the surface microstructure.[12] Fig. 3 represents the grain refinement on a SSP specimen taken by a field emission gun scanning electron microscope (FEG-SEM), using electron backscatter diffraction technique (EBSD).

Microhardness test

In order to evaluate the increment of hardness on the surface layer of the treated specimens, Vickers microhardness tests were performed on the cross section of the specimens after different SP treatments. Microhardness trends, as shown in Fig. 4, were obtained from the surface to the bulk of the material. Measurements were performed following ASTM E384 standard,[29] using 25 g load during 15 s dwell time. Presented results are an average of the measurements taken on all specimens of each treatment.

Having a look at the results, it is possible to appreciate a hardening on the surface layer of the aluminium because of the applied SP treatments. Hardness increase is higher on SSP specimens (maximum value of 103 HV for around 50 μm depth) compared with the ones treated by CSP (maximum value of 83 HV for around depth). This is due to the higher amount of energy induced by SSP treatments. The depth of the work-hardened layer is around 350 μm for both treatments.

Microhardess trend of SSP-g series is similar to the SSP one. Grinding process does not modify the hardness trend.

Full width at half maximum

X-ray diffraction measurements allowed obtaining the FWHM, a parameter index of hardening, grain distortion, grain size and dislocation density.[30]

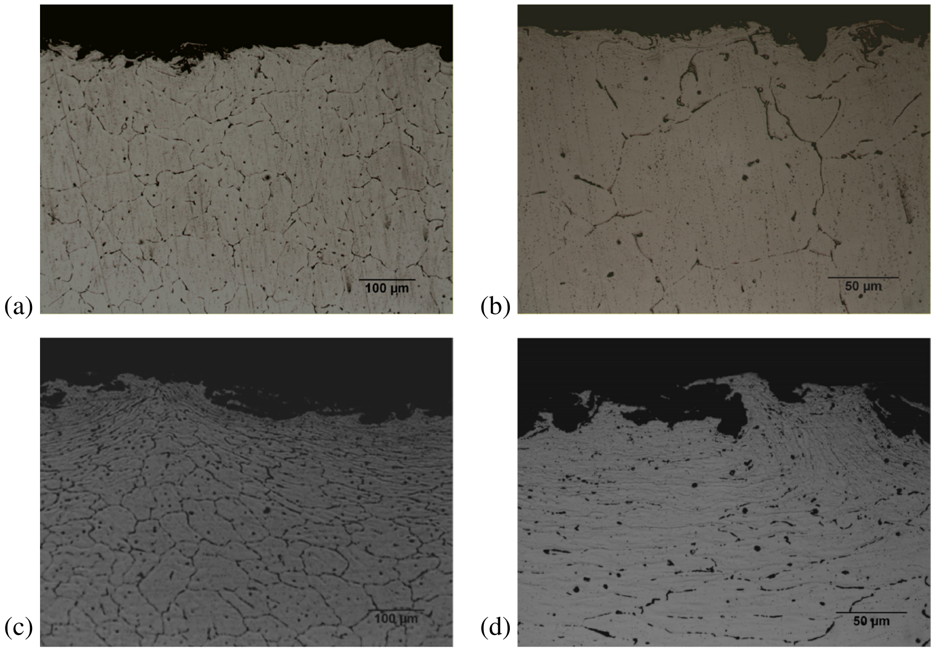

Fig. 2 Microstructure of Al-6063 specimens: (a) conventionally shot peened (CSP) 200×; (b) CSP 500×; (c) severe shot peening (SSP) 200×; (d) SSP 500×.

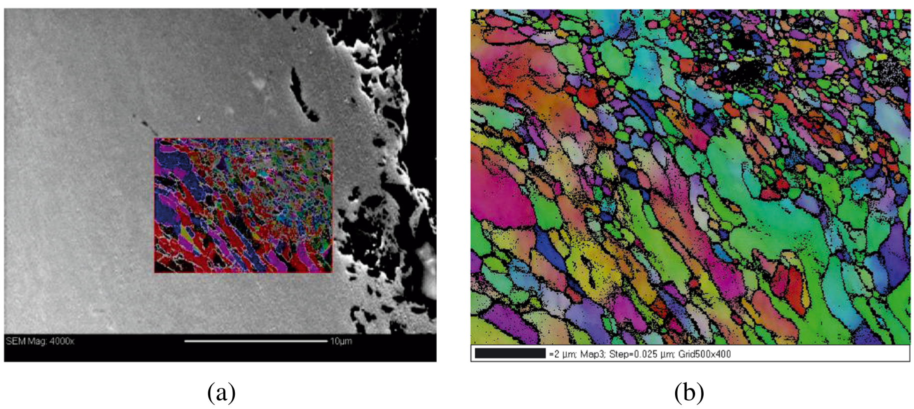

Fig. 3 Field emission gun scanning electron microscope images of (a) position of b image (b) surface microstructure of severe shot peening.

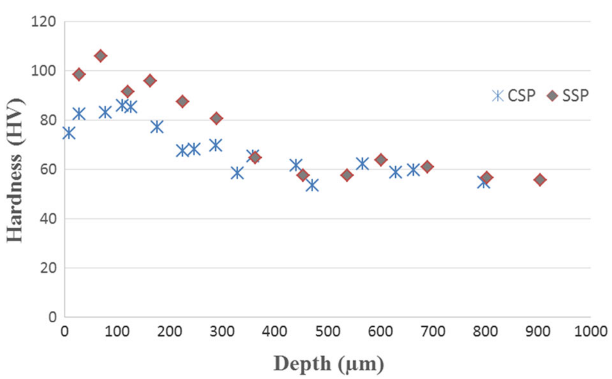

Fig. 4 Microhardness trend on the cross section of the shot peened specimens.

X-ray diffraction analysis on the surface layer of all series (CSP and SSP) was performed using a G3R X-Stress 3000 X-ray diffractometer. Cr K_α radiation was used and 311 (Miller indices) line for normal diffraction ($\psi = 0$) was recorded. The wavelength was $\lambda = 0.2291$ nm and θ that is the angular position of α_1 component, was set to 139°. Electro-polishing was used to remove material in order to perform measurements in depth. The reagent used was 75% CH_3COOH, 5% $HClO_4$ and 20% H_2O, as recommended by ASM Handbook.[31]

Fig. 5 represents the distribution of FWHM parameter for CSP and SSP specimens. A notable increment in FWHM parameter is observed for SSP. Because FWHM is an index of the surface work hardening and of the grain size, the measured trend confirms the hardness measurements and leads to the probable presence of an ultrafine/nanosized surface layer of material caused by SSP, as suggested by previous studies,[10–12] confirming also the microstructures shown in Fig. 2 and 3.

Wear test

Wear tests were performed to evaluate the influence of CSP and SSP on wear behaviour of aluminium. Prismatic specimens ($16 \times 10 \times 6.5$ mm^3) were tested in a block-on-ring tribometer (STAIGER MOHILO, model 0411103IE 100W 10608) under lubricated sliding wear conditions according to the ASTM G77-98 standard.[23] Amalie Imperial 20 W-50 oil was used as lubricant. The tribometer employs a counter specimen disk of Simagaltok 63 aluminium alloy with a hardness of 81–83 HV. Its chemical composition is shown in Table 4.

Ring rotates at a constant speed against a stationary test block (specimen). The test block is loaded against the rotating disk for a specified number of revolutions. Wear test parameters are shown in Table 5. Sliding speed was chosen as the equivalent to 1 m/s linear speed.

Four series of 5 specimens were submitted to wear test: NP, CSP, SSP and SSP-g. All tests were carried out under lubricated conditions at room temperature. After 1000 m of sliding distance, the specimens were taken out and weighed in precisely, subsequently cleaned with acetone and put again in the tribometer to proceed with the test until its conclusion, after 7000 m sliding distance.

Fig. 6 shows the results of the wear tests carried out on the four different series under a normal load of 3 kg. The results indicate the improvement in wear behaviour because of SP treatments. All series present a stable behaviour, as the data obtained are quite linear, corresponding to constant wear rates along the entire sliding distance. SSP-g series showed the best wear behaviour, whereas the NP series present the highest weight loss, thus the worse wear behaviour.

Having in mind the highest values of hardness measured on the surface layer of SSP specimens, they were expected to present the best wear behaviour. However, at the end of 7000 m sliding distance, the SSP series show almost the same weight loss as NP series. It is noted that although the final weight loss is similar, the wear trend of these two series is different: in fact, during the first stages of the test, SSP specimens lose less weight compared with the NP series. Having a look at the wear marks after completing the sliding distance, it is possible to observe how the support surface on SSP series is smaller compared with that of the NP and CSP specimens. It is due to the big deformation caused on the specimen's surface because of the higher amount of energy introduced by SSP treatments that curved the specimen's surface. Thus, even if the applied load is the same in all tests, SSP specimens support higher stress values compared with the NP and CSP series, justifying the biggest weight loss presented in this series. Another consideration that can be carried out to justify the results is that during the last

Table 5 Wear test parameters

Ring material	Sliding speed (rpm)	Sliding distance (m)	Applied load (g)
Simagaltok 63 aluminium alloy	318	7000 (stopped each 1000 m)	3000

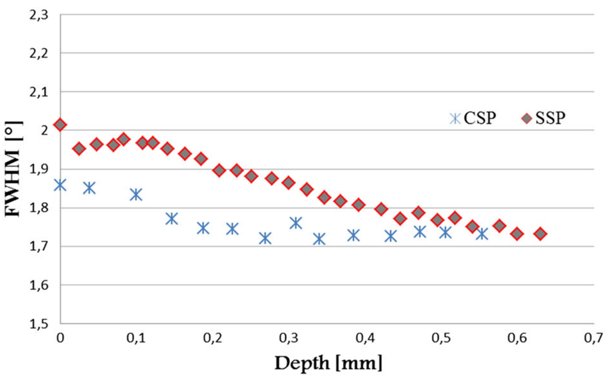

Fig. 5 Full width at half maximum intensity parameter as an index of work hardening trend of shot peened specimens.

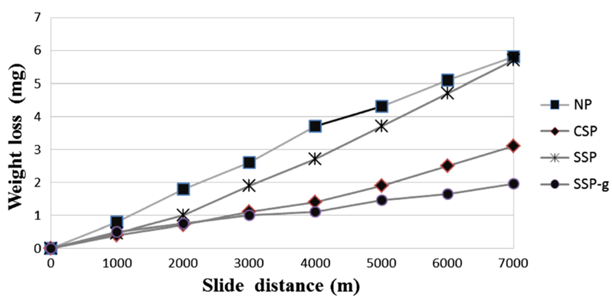

Fig. 6 Wear (accumulative weigh loss) against sliding distance.

Table 4 Simagaltok 63 chemical composition (% in weight)

Si	Cu	Fe	Mn	Mg	Cr	Zn	Ti
0.30–0.60	max 0.10	0.35–0.50	max 0.15	0.60–0.90	max 0.05	max 0.15	max 0.20

stages of the test, the grain refined layer of material caused by SSP is completely worn out and this causes a sudden increase of the wear rate. In Fig. 7, it is possible to observe the wear surfaces of representative specimens after 7000 m sliding for all each series.

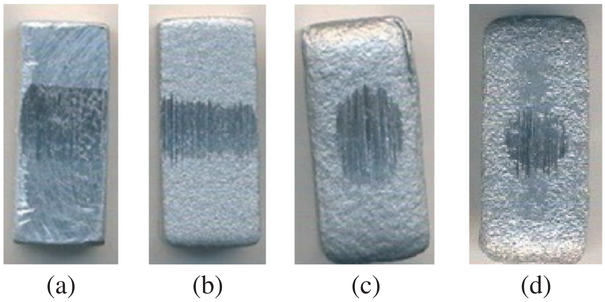

Fig. 7 Representative marks after 7000 m sliding: (a) not peened; (b) conventional shot peening; (c) severely shot peening (SSP); (d) SSP-grinded.

On the other hand, SSP-g specimens have the same surface curvature because of SSP treatment but in exchange show the best wear behaviour of all series. This indicates the big influence of roughness on the wear behaviour.

In Fig. 8, the mark images of one representative specimens of each series obtained by a confocal microscope Leica DCM 3D are shown. As it is observed in Fig. 8, the mark on the NP series is the biggest one, whereas the smaller one corresponds to the SSP-g series. Loss volume measurements were 0.79, 0.34, 0.75 and 0.096 mm^3 for NP, CSP, SSP and SSP-g series, respectively. These values are in good agreement with the wear results shown in Fig. 6.

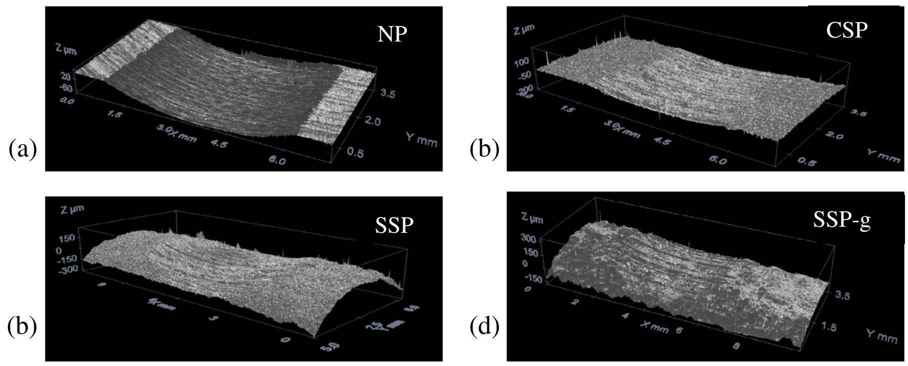

Fig. 8 Confocal microscope marks analysis after 7000 m sliding.

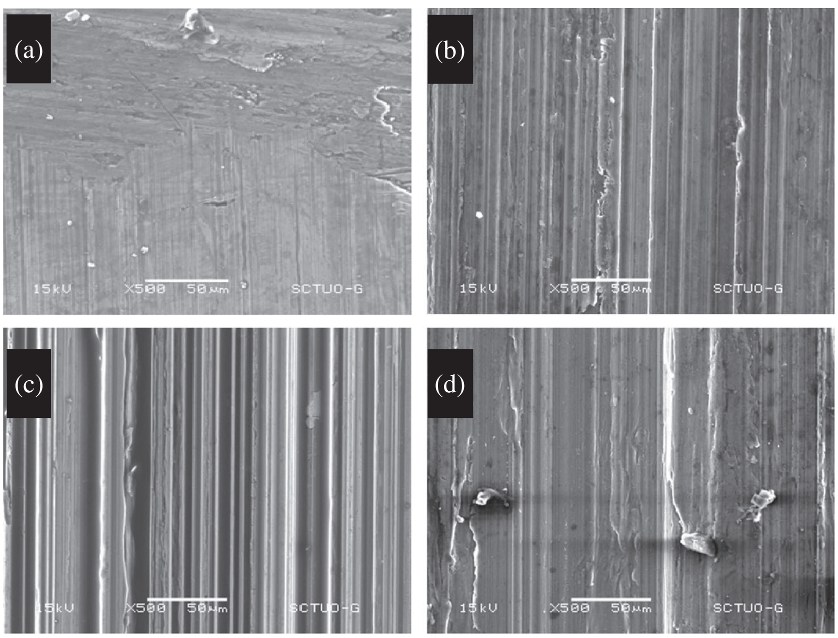

Fig. 9 Scanning electron microscope images of the wear track after 7000 m. Lubricated sliding wear (abrasive wear) testing. Percent coverage: (a) not peened; (b) conventional shot peening; (c) severe shot peening (SSP); (d) SSP-grinded.

The wear surfaces of the specimens were also observed by a scanning electron microscope in order to determine the wear mechanism. Fig. 9 shows the wear tracks at 500× magnification for different specimens. The images reveal an abrasive wear mechanism in all series.

CONCLUSIONS

Tribological study has been performed on aluminium alloy Al-6063 subjected to different surface treatments: as-received NP, CSP and SSP. After first SP treatment, all the specimens were submitted to a second slight repeening to improve the surface morphology and decrease the surface roughness. Slight mechanical grinding was applied to one series of SSP treated specimens (SSP-g) with the aim to eliminate the major peaks and evaluate the influence of roughness on wear behaviour.

The microscopic observations (ESBD) and the XRD measurements (FWHM) clearly show the microstructural modification of the surface layer of material resulting in grain refinement after SSP treatments

On the basis of the performed tests and the analyses, it can be concluded that the SP treatment has the potential to improve the wear behaviour even if further studies are needed to confirm and quantify the possible improvement that could be obtained. The improved behaviour of the SP specimens was mainly attributed to the surface hardening induced by SP. In the case of SSP treatment, surface roughness seems to play an important role because sample series with similar microstructure and smaller surface roughness present better wear behaviour.

Future studies are planned using a different procedure for samples preparation in order to optimise the contact surface between the sample and the block in the test set-up.

Acknowledgements

This work was financially supported by Ministry of Science and Innovation of Spain under grant MAT2009-12308.

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