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Laser cladding of Al-Si on Al-Cu sintered alloy to improve wear resistance

J.B. Fogagnolo [a,*], J.J. Candel [b], V. Amigó [b]

[a] Universidade Estadual de Campinas, Rua Mendeleiev, 200, 13083-970, Campinas, Brazil

[b] Universitat Politècnica de Valencia, Camino de Vera s/n, 46022, Valencia, Spain

* Corresponding e-mail address: fogagnolo@fem.unicamp.br

ABSTRACT

Purpose: To improve the wear resistance of Al-Cu sintered parts by the use of a coating layer of hypereutectic Al-Si alloy deposited by laser cladding.

Design/methodology/approach: Coaxial laser cladding was used to deposit a coating layer of hypereutectic Al-Si alloy on sintered Al-Cu alloy to improve its wear resistance. The laser cladding parameters were varied; firstly obtaining single laser cladding tracks and finally obtaining a larger area of coating by overlapping tracks.

Findings: The Al-Si coating layer presented good metallurgical bonding with the sintered Al alloy and was composed mostly of eutectic Al-Si in the upper zone and alpha Al dendrites plus eutectic Al-Si in the lower zone. Laser also generates a melted layer in the base-sintered material, mainly composed of a columnar dendritic structure with copper segregated in the interdendritic region, which assured a gradual transition to the clad structure. Pin-on-disc tests showed that the wear resistance of the part was improved with the Al-Si coating.

Practical implications: The wear resistance of sintered Al-Cu alloy was improved more than 70% using a coating layer of hypereutectic Al-Si alloy deposited by laser cladding.
Originality/value: Single tracks and a continuous layer of Al-Si were successfully deposited by laser cladding on Al-Cu sintered parts. Pin-on-disk comparative tests showed an increase of more than 70% in wear resistance due to the Al-Si coating.

Keywords: Powder metallurgy; Surface treatment; Laser processing

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MANUFACTURING AND PROCESSING

1. Introduction

New materials with lower densities and superior mechanical properties are one of the main requirements for application in the transport industry, and are essential for the reduction of fuel consumption. In this context, aluminum alloys are very attractive materials because of their high specific mechanical strength, good formability, good corrosion resistance, and recycling potential [1-3], but their low wear resistance imposes some serious limitations for several applications. The low wear resistance of aluminum alloys is quite significant in parts obtained by powder metallurgy due to their porous surface [4,5]. Thus, to expand the industrial application of powder metallurgy aluminum alloys, their wear resistance must be improved.

The incorporation of hard ceramic particles to obtain aluminum matrix composite material has been the traditional route to enhance the wear resistance of this class of materials [6-8]. However, problems such as particle agglomeration and poor compatibility of matrix and reinforcement, which are detrimental to mechanical properties, make it imperative to find alternative routes.

Wear is basically a surface phenomenon, so surface modifications can be made to improve the wear resistance of sintered parts. Closing the pores at the surface of the part by laser melting [9] or using coatings of materials with higher wear resistance [10] are interesting alternatives. The latter alternative also allows for the selection of coating material from a wide range of wear-resistant materials, which constitutes an important additional degree of freedom in materials design. The laser cladding (LC) technique enables the application of several classes of coating materials in order to coat small parts with narrow heat-affected zones [11-13]. LC, which is defined as a material surface enhancing process performed by applying a powdered material onto the base surface using a laser, has been used to coat Al and Al alloys with different materials such as titanium carbide [14,15] and silicon carbide [16].

The superior wear resistance of Al-Si alloys among Al alloy systems, including the Al-Cu heat treatable alloys, is well known [17,18]. Thus, we investigate the deposition of a coating layer of Al-Si alloy on sintered parts of Al-Cu-Si-Mg alloy by LC aimed basically at improving their wear resistance. The process parameters were varied and the resulting coatings were characterized by optical and scanning electron microscopy. Pin-on-disc tests were performed to check the effectiveness of the coating.

2. Materials and methods

Sintered Al-4.5Cu-0.7Si-0.5Mg alloy was used as base material. The powder was supplied by Ecka Granules-Metal Powder Technologies. The powders were cold-pressed under 200 MPa in a hydraulic press equipped with a floating die. Rectangular pressed parts (31.7 mm x 12.7 mm x 7.0 mm) were obtained. The specimens were sintered at 580°C for 40 min in a nitrogen atmosphere. Sintered density was around 2.38 g/cm^3. Al-20%$_{\text{in mass}}$ Si atomized powder with typical hypereutectic microstructure, with particle size was in the range between 70 and 140 µm (see Fig. 1.), was used as raw material to deposit the coating.

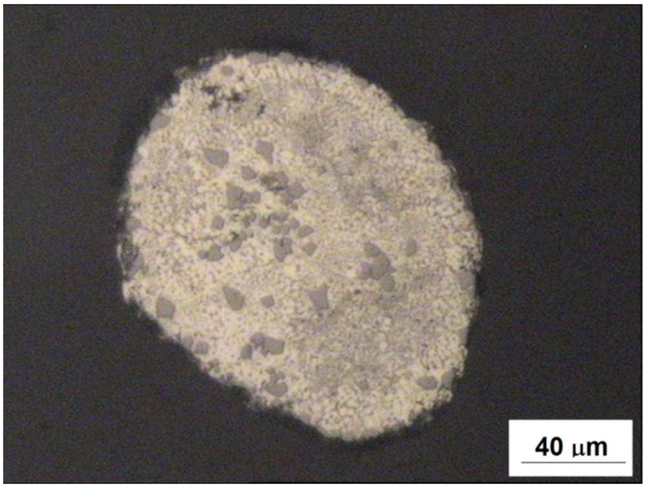

Fig. 1. Microstructure of the Al-Si powder used as coating raw-material

The LC experiments were performed using 1 kW in continuous wave mode Nd:YAG laser source equipped with a coaxial cladding nozzle and helium 5.0 as protective gas. Helium was used as protective gas due its high ionization potential, which is advantageous to prevent plasma from forming around the laser beam. The beam was guided through an optical fiber 0.6 mm in diameter and focused by a lens of local length f = 200 mm to produce a spot size of D = 1.5 mm. The powder was injected from the nozzle through three holes arranged at 120° around a central hole through which the laser beam was applied to the target.

Firstly, single LC tracks were deposited, using laser power of 700 and 900 W and scanning speed of the laser beam of 7.5 and 12.5 mm/s. The powder feeding rate was fixed at 83 mg/s. Continuous coating was then obtained by overlapping the LC tracks, maintaining a distance of 0.6 mm between the centers of the tracks.

For the metallographic analysis, the coated samples were cut perpendicularly to the LC tracks, mounted in resin, ground and polished. The etching solution was prepared as follows: 10 g of sodium hydroxide plus 5 g of potassium ferrocyanide in 60 ml of distilled water. The coatings were characterized by optical (OM) and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS).

To prepare the surface of the continuous-coated samples for the wear tests, the samples were machined to obtain a flat surface. In addition, both the coated and non-coated materials were ground using SiC paper up to a 1000 grit size paper to achieve Ra = (2 ± 0.2) μm. Finally, samples were cleaned in ethanol ultrasonic bath and dried at 90°C in an oven. The wear behavior was evaluated by pin-on-disc tests under dry sliding. 5 mm diameter AISI 52100 chromium steel balls (1.0% C, 0.35% Mn, 0.3% Si, 1.4% Cr in % wt.) were employed as counter body material. The tests were performed under a load of 10 N, at a sliding speed of 200 mm/s. The sliding distance used in the wear tests was 250 m. The friction force and the change of relative position between pin and disk were measured continuously during wear testing. The wear was quantified by mass loss wear rates and friction coefficient evolution. The surfaces of the sample and the steel ball counterpart were examined by SEM.

3. Results and discussion

3.1. Coating characterization

Figure 2. shows a deposited track (a) on the porous surface of the sintered sample and the melted zone of the substrate (b and c), using a constant laser power of 900 W and a scanning speed of 7.5 mm/s. Open porosity of the upper zone of the sintered substrate is partially closed or rounded (Fig. 2b) and the microstructure observed by scanning electron microscopy (Fig. 2c) allows to state that the interface between the melted and unmelted zones can be achieved without cracking. The high specific energy applied during the LC process not only melted the powder but also produced a melted layer in the substrate, which promoted a columnar dendritic structure with copper segregated in the interdendritic region. Chemical analysis performed by EDS in the upper part of the Fig. 2c showed that the copper content in this region (close to the border of the melted zone) was around 4.5% in mass, which is similar with the copper content of the sintered alloy was used as base material, and the silicon content was around 2.5% in mass, indicating the diffusion of Si in the bottom part of the melted region. The melted layer of the base material had a depth of approximately 260 μm, which was similar to the height of the track.

The microstructure of the coating is crucial for wear improvement. According with Torabian, the Al-Si wear rate is strongly dependent on the silicon content of the alloy as the wear rate decreases continuously with increasing silicon content up to 15 wt. % under a high variety of loads [17]. Beyond this level, shape, size and distribution of primary or eutectic particles plays an important role. Finer and spherical silicon particles as well as absence of acicular silicon particles will be optimal for mechanical properties.

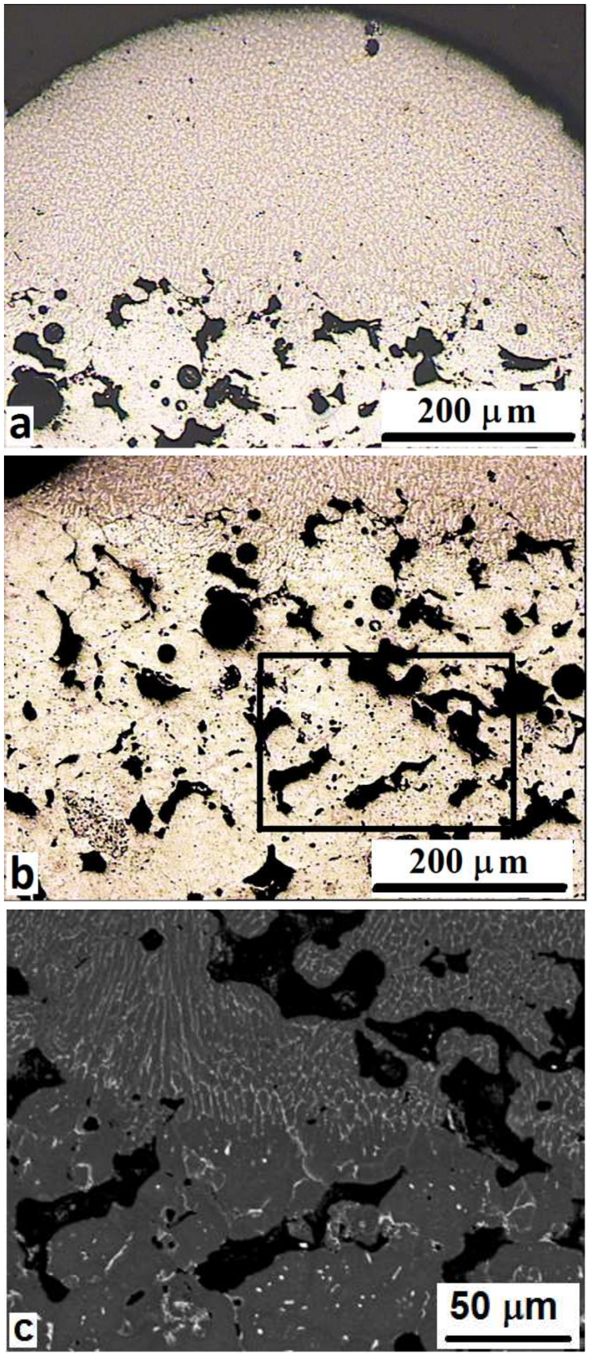

Fig. 2. The LC track (a) obtained using a laser power of 900 W and a laser scanning speed of 7.5 mm/s and the heat affect zone of the substrate (b and c). The rectangle inserted in (b) corresponds to the area observed in (c)

Figure 3. shows the microstructures in the center of the tracks. In all the conditions were observed aluminum dendrites plus eutectic Al-Si without acicular silicon particles formation. The existence of Al dendrites can occur if there is high dilution that reduces composition coating material to hypoeutectic values or in hypereutectic compositions if solidification occurs in conditions with high growth rates, where growth of that phase is kinetically favored over the equilibrium phases.

Since the chemical analysis performed by EDS in all of the tracks indicated silicon contents between 18 and 20% in mass, which is consistent with the composition of the powder used as raw material, the former hypothesis should be discarded. As described by Granger and Elliott [19], aluminum dendrites can be present in hypereutectic Al-Si alloys, when using high solidification rates. Such microstructure was an evidence of the high cooling rate imposed on the deposited material during the laser treatment [20]. This non-equilibrium microstructure has been observed previously in laser-processed Al-Si eutectic and hypereutectic alloys [21]. The microstructures shown in Fig. 3. reveal the tendency for greater refinement of the dendrite structure and lower volume fraction of the eutectic phase at a higher laser scanning speed, due to the lower heat input and the resulting higher cooling rate. This correlation between the dendrite size and laser scanning speed was also reported by P. Volovitch et al. [22] in Al-Si coated ZE41 magnesium alloy.

The results obtained with the isolated LC tracks indicate that the material was well bonded and without significant defects in all the tested conditions. However, the combination of the lower laser power (700 W) and the higher laser scanning speed (12.5 mm/s) produced a smaller melted layer in the base material and produced a more refined microstructure in the deposited material. Thus, the lowest energy input condition tested has been selected to produce a continuous coating by overlapping single LC tracks.

Figure 4 shows the microstructure in the upper (a) and middle (b) zone of the continuous coating obtained by overlapping LC tracks coating. Mostly eutectic Al-Si was formed in the upper zone, and no aluminum dendrites developed. Dendrites were observed in the middle zone, which was due the dilution of Si in the melted zone of the substrate. EDS results showed silicon content below the eutectic compositions in this zone. The higher heatinput of the continuous coating process, when compared with the deposition of a single track, decreased the cooling rate and allowed these microstructures development.

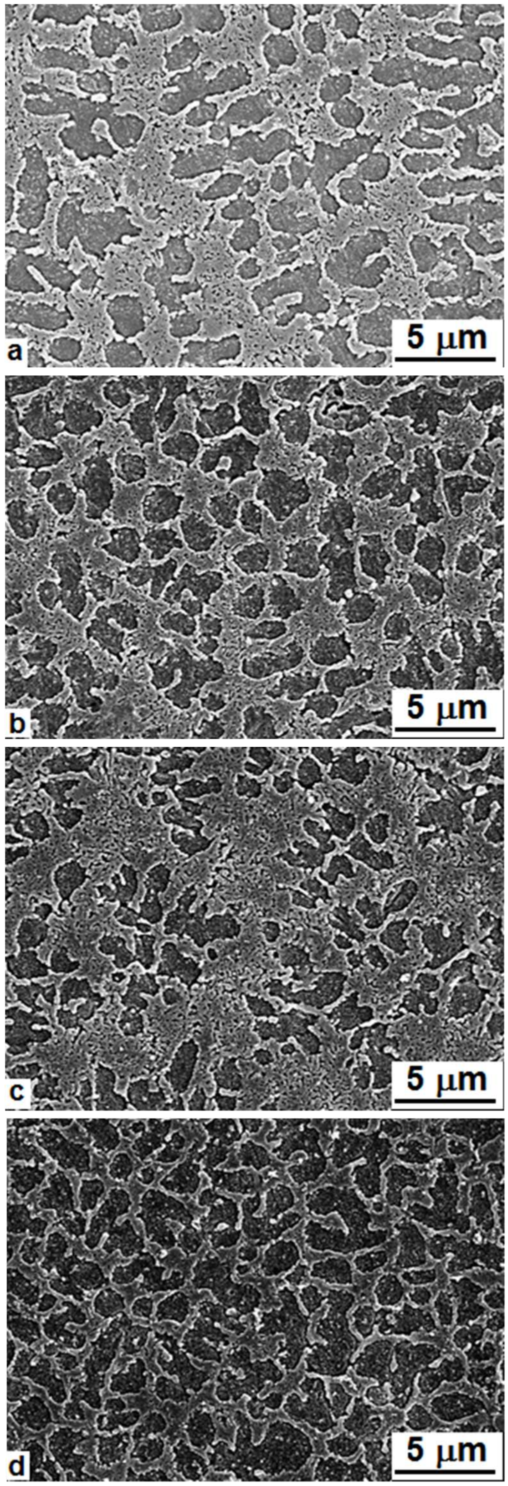

Fig. 3. Microstructures observed in the center of the LC tracks using a laser power of 700 W (a, b) and 900 W (c, d) and a laser scanning speed of 7.5 mm/s (a, c) and 12.5 mm/s (b, d)

These results indicate the possibility of applying Al-Si coating on Al sintered alloy, achieving perfect bonding with a small melted zone of base material. The phase distribution inside the coating seems to be suitable for the proposed objectives: aluminum dendrites enhance the metallurgical bonding between coating and substrate; Al-Si eutectic at the surface should be better for wear resistance.

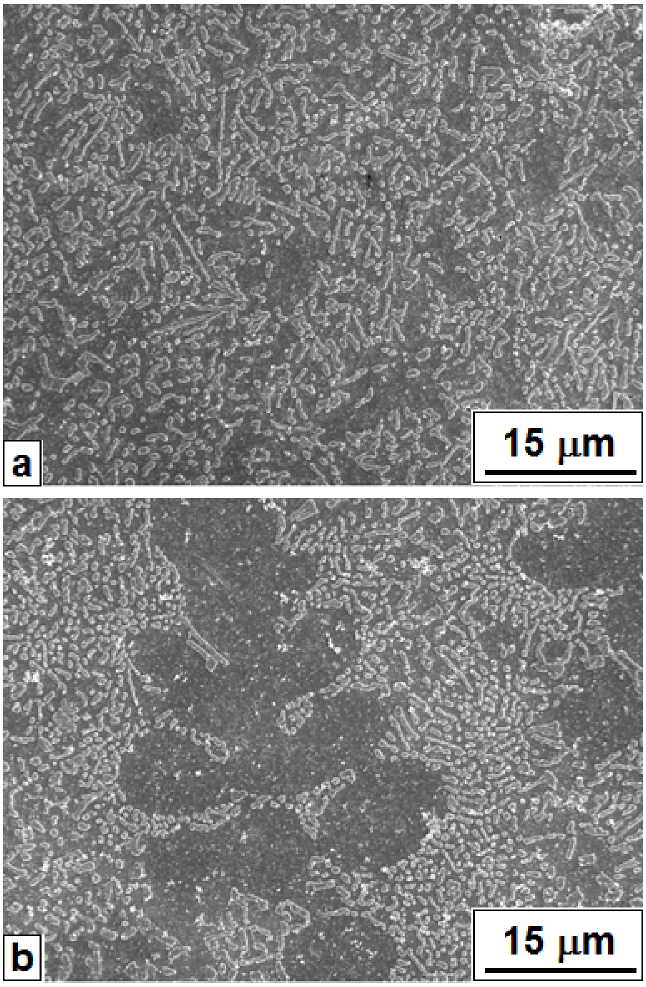

Fig. 4. Microstructures observed in the upper (a) and middle (b) zone of the coating

3.2. Wear tests

Al-Si layers produced with best laser processing conditions were compared with uncoated substrate using dry sliding wear tests. A constant wear rate (slope of the pin position x sliding distance curve) was established after a transition period, which was longer and with higher wear loss in the case of the sintered non-coated samples, as can be seen in Fig. 5. Moreover, a progressive change in wear slope was observed with these samples.

Aluminum alloys can suffer different wear mechanisms against steel depending on the contact pressure [23]. Severe wear occurs at initial stage of the test due to the high contact pressure and adhesion between ball and flat surface. As the contact area increases, there is a transition towards mild wear due to cyclic oxidized debris accumulation and removal process. This transition can be also observed on friction coefficient curve of sintered samples shown in Fig. 6. During severe wear period, the friction coefficient in the sintered sample was about 0.7 and dropped to 0.6 after the wear mechanism transition. However, Al-Si coated samples not only suffered less wear loss but also presented minor friction coefficient. The finer and rounded Si particles in the coating microstructure (see Fig. 4) were crucial to achieve this beneficial effect. The wear rate (see Table 1) calculated through the mass loss, which is the difference of the mass of the sample before and after the wear test, also indicated the same behavior. There was an increase of more than 70% in the wear resistance.

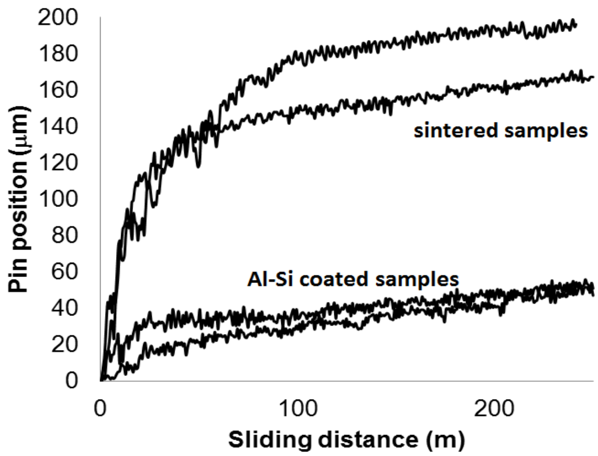

Fig. 5. Pin position (ball penetration in sample) vs sliding distance of Al-Si coated compared with sintered (no-coated surface) samples

The morphologies of worn surfaces for the coated and non-coated samples are shown in Fig. 7. The sintered sample presented multiple cracks not aligned to wear directions, which could be related to intergranular cracking and detachment of the particles during adhesion with steel ball. On the other hand, coated sample presented a uniform oxidized surface with concentrically ploughed furrows. In order to check the occurrence of adhesion mechanism, counterpart has been observed by SEM (see Fig. 8) after wear tests.

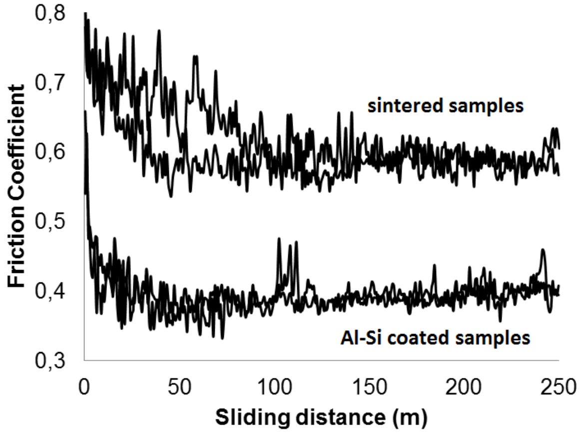

Fig. 6. Friction coefficient evolution of Al-Si coated compared with sintered (no-coated surface) samples

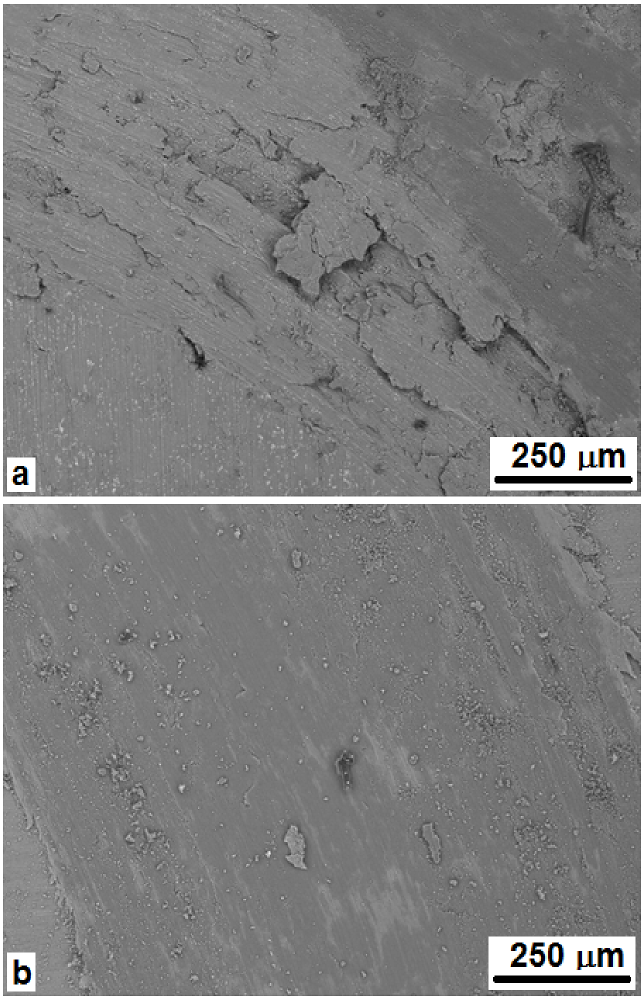

Fig. 7. Worn surfaces observed in the wear tracks of sintered (a) and Al-Si coated (b) samples

The counterpart of the Al-Si coated sample presented much less debris accumulation than the one of the Al-Cu sintered sample, which may be a result of adhesive inhibition effect of silicon particles.

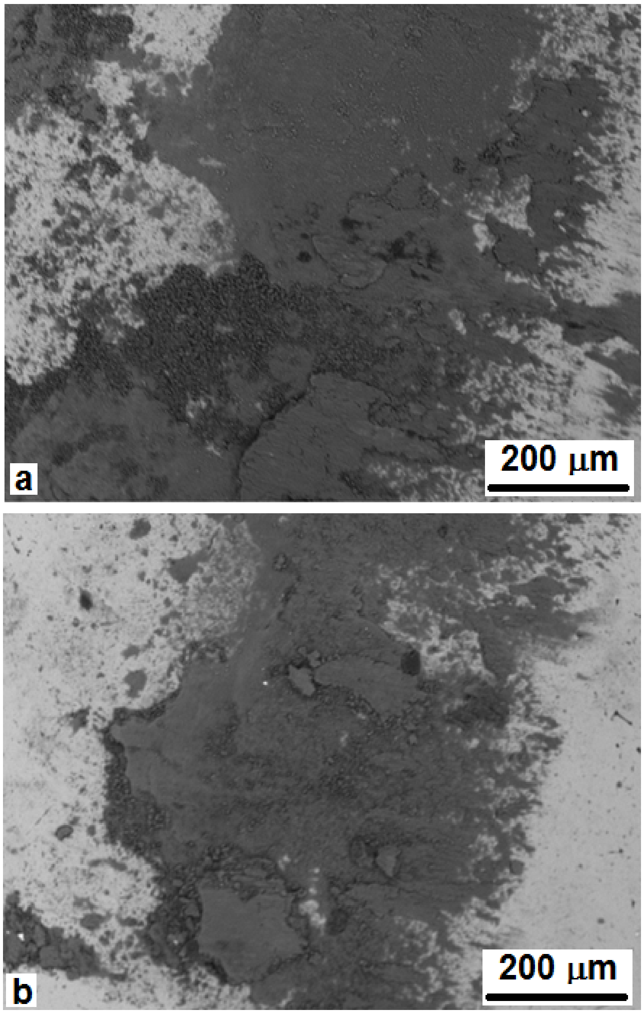

Fig. 8. Steel ball counterpart surfaces after wear tests observed in the sintered (a) and Al-Si coated (b) samples

These results demonstrated the effectiveness of Al-Si coating on sintered Al-Cu alloy in improving the wear resistance and reducing friction coefficient against steel. The principal mechanism appears to be the influence of the hard silicon particles. The fact that the hard silicon particles are surrounded by a softer and relatively tough matrix enhanced the overall toughness of the material and improved the wear resistance by reducing subsurface crack propagation.

4. Conclusions

Single tracks and a continuous layer of Al-Si were successfully deposited by LC on Al-Cu sintered parts. The microstructure obtained with single track deposition was composed of aluminum dendrites plus eutectic Al-Si and the continuous coating layer obtained by overlapping single LC tracks was composed of eutectic Al-Si in the upper zone and aluminum dendrites plus Al-Si eutectic phase in the middle zone.

The heat input during LC deposition produced a melted layer in the substrate with almost the same height as that of the track, composed of a columnar dendritic structure with copper segregated in the interdendritic region.

Pin-on-disk comparative tests showed an increase of more than 70% in wear resistance due to the Al-Si coating, as showed by the mass loss. The influence of the hard silicon particles of the Al-Si coating layer is probably the main reason for this increase in wear resistance.

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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