Tribological Comparative Study of the Effect of Boride and Silicon Particles on Aluminum Matrix Composites

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ABSTRACT

An Al-Si-Sn alloy and an Al-B-Sn composite intended for bearing applications were manufactured by centrifugal casting and their resulting tribological properties were compared. Microstructure gradients of silicon particles and boride dispersoids were observed on both materials, increasing from the internal to the external casting zones. Superficial hardness and pin-on-disk wear tests performed showed a higher hardness and lower wear coefficient in the external regions. The boride-reinforced composite exhibited lower wear and higher hardness than the aluminum-silicon-based alloy.

1. INTRODUCTION

The production of aluminum bearings with high performance tribological properties is a constant adversity faced by the aerospace industry. The widespread use of lead in such composites poses a series of technical issues due to a wide miscibility gap in the molten states of lead and aluminum, a large freezing range, mutual insolubility among both elements at room temperature and large differences in component densities /1/. Furthermore, concerns for the environmental repercussions of lead have sparked interest in the development of new bearing alloys with more environmentally friendly components /2/.

Although an oxide layer usually protects aluminum bearings, this layer is subject to fracture and wear under high stress conditions compromising the lifetime of such. To prolong the onset of this phenomenon, aluminum is reinforced with hard ceramic particles, typically silicon. The protruding hard silicon particles (hardness ≅ 12 GPa) then serve to bear higher loads, prevent adhesion and resist wear /3/. These effects are enhanced by the presence of an antifriction, soft phase. For this purpose, tin is one of the preferred choices for bearing applications because of its excellent mechanical properties /4/ and small environmental risks.

The presence of tin in aluminum composites introduces a beneficial effect for wear resistance due to several factors. Tin is the major alloying element for bearing applications because of its solid lubricant properties, compressive strength, fatigue strength and corrosion resistance/4/. Of all the mentioned properties the most important one is the self-lubrication effect, which arises from the alloying of soft impact resistant components with a hard matrix, leading to the formation of crystallites along grain boundaries of the matrix to prevent plastic deformation of the material/5/. Ultimately, this brings about an increase in the wear resistance of the composites without sacrificing other mechanical properties.

The recent development of aluminum-boron-based composites, which were designed to possess higher hardness, toughness and wear resistance /6-7/ could provide a reasonable alternative material. More so, bearings are typically produced by gravity or die casting. In that respect, the recent successful fabrication of Al-B composites through centrifugal casting results in the production of a superior wear resistant material due to segregation of hard diborides onto outer casting surfaces/8-9/.

The purpose of the present study is to investigate the effect of the segregation of such diboride particles, produced by centrifugal casting, on the wear behavior of an Al-B-Sn composite. The volumetric fraction, superficial hardness and wear behavior have been analyzed and discussed, as compared to those of Al-Si-Sn alloys.

2. EXPERIMENTAL MATERIALS AND METHODS

Composite Fabrication

Aluminum (purity > 99.5 wt%), tin (99.95 wt% purity), Al-12 wt.% Si master alloy and Al-5 wt,% B master alloy were used to prepare Al - 10 wt.% Sn – 3 wt.% Si and Al - 10wt.% Sn - 3wt.% B composites, respectively. The charge mix was then melted in a graphite furnace at 850°C and the resulting melt was cast using a centrifugal casting machine. The prepared cylindrical samples were cut into four 15 mm-thick sections according to Figure 1 and prepared for all subsequent tests.

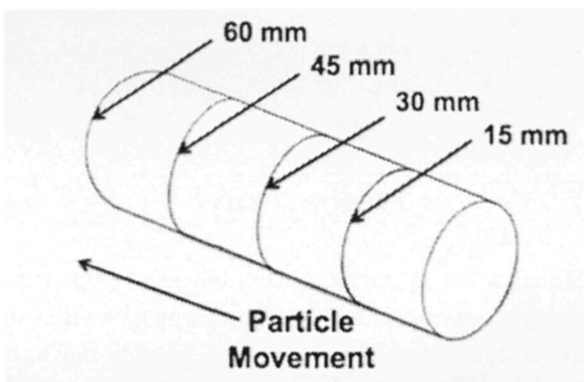


Fig. 1: Sketch of the centrifugally cast specimen showing the position of the studied surfaces.

As indicated on the image, the 15 – 30 mm and 45 – 60 mm zones correspond to the internal and external casting zones, respectively. The 60 mm position corresponds to the bottom of the casting crucible, which is used as a reference point for all measurements.

Centrifugal Casting

All samples were melted at 850°C and thoroughly mixed to ensure homogeneity. The molten composites were then centrifuged at 300 rpm for 1 minute, i.e. 37.76 G force, after which the samples were allowed to cool to room temperature inside the cylindrical graphite mold.

Metallographic Preparation

All samples were ground using SiC paper up to 1200 grit size and subsequently polished on a short fiber cloth using a 3μm diamond suspension. A final polishing with a 0.05μm silica emulsion allowed clean and smooth surfaces for optical microscopy.

Characterization Techniques.

Optical Microscopy

The composites microstructure was analyzed utilizing an inverted optical microscope. The public domain image analysis software Image J was used to measure particle volume percent in all composites.

Hardness Tests

The composites matrix hardness was evaluated using Vickers microindentation tests. The overall composite hardness was tested using a Rockwell unit with 15W superficial hardness scale.

Wear Analysis.

Wear tracks were made on all samples using pin-on-disk tests set to the conditions specified in Table 1.

Table 1

Pin-on-disk test parameters

Rotation Speed (m/s)	Track Diameter (m)	Rotation Time (s)	Load (N)
0.00411	0.00335	600	0.981

The resulting wear tracks were studied via scanning electron microscopy (SEM) operated at 10 kV acceleration voltage. The removed volume upon pin-on-disk wear tests was quantified using ImageJ image analysis software.

3. RESULTS

Microstructure and Compositional Analysis

The typical microstructures of Al-Si-Sn and Al-B-Sn composites are shown in Figures 2 and 3, respectively. As observed in the micrographs, the distribution of silicon and diboride particles varies in both composites along the longitudinal axis of the cylindrical castings. Quantitative assessment of the particles volume fractions are presented in Figure 4 and evinces the increasing number of particles towards the external casting zone.

Superficial Hardness and Wear Behavior Analysis

The Rockwell superficial hardness values of these silicon and boride-reinforced composites are shown in Figure 5 at various casting lengths. Figure 6 presents the removed volume on both composites that was produced by the pin-on-disk tests and Figure 7 shows SEM images of the resulting wearing track.

4. DISCUSSION

The compositional gradient in the microstructures shown in Figures 2 and 3 is the direct consequence of the centrifugal forces acting on the reinforcement particles. In effect, the particle volume fraction analysis performed, (Figure 4) showed an increasing trend from the internal to the external zone of the casting for both composites while the particle volume percent, obtained from quantitative image analysis performed with ImageJ, in Al-B-Sn composites was equal or larger than in Al-Si-Sn composites. The aforementioned internal and external casting zones (Figure 1) are intended to represent the regions of an alloy which are subject to higher and lower wear, i.e. the teeth of a grinder and the adjacent zones of the device, respectively. The observed outcome is due to the strong dependence of the process of centrifugal casting on rotational speed and pouring temperature /10/. This means that, even though it has been established that high boron levels (that is larger concentration of boride particles) increase melt viscosity /5/, the high rotational speed and pouring temperature at which the composites were prepared can counteract the increased viscosity caused by the presence of diboride particles.

Figure 5 shows the hardness gradient in the composites and similarly to the particle distribution, the hardness increases as a function of distance from the internal to the external casting zones. Having analyzed the particle fraction in the different zones, the observed behavior in hardness was as expected and can be attributed to the particle distribution obtained through centrifugal casting. The processing method renders external zones with a very high particle density and, naturally, a zone with higher reinforcement is expected to have higher hardness.

Figure 6 presents the calculated removed volume by the pin-on-disk tests on all zones of both composites. The presented values were calculated from track width, length and depth and in turn allowed for the calculation of a wear coefficient for each of the studied zones and the obtained results are presented in Table 2.

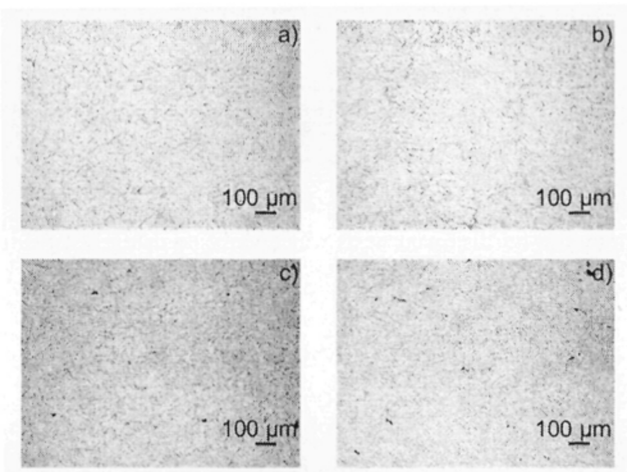


Fig. 2: Optical microscopy images of the resulting microstructure in centrifugally cast Al-10wt.% Sn–3wt.% Si composites at a) 15 mm b) 30 mm c) 45 mm d) 60 mm along the main axis of the cylindrical specimens.

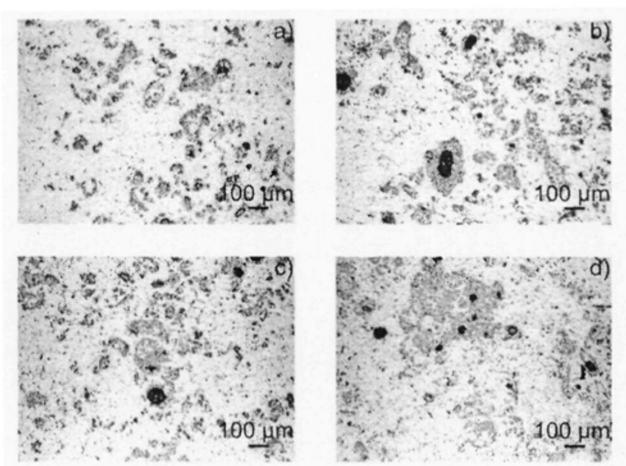
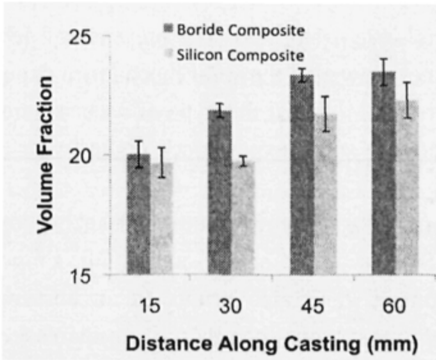


Fig. 3: Optical microscopy images of the resulting microstructure in centrifugally cast Al-10wt.% Sn–3wt.% B composites at a) 15 mm b) 30 mm c) 45 mm d) 60 mm along the main axis of the cylindrical specimens.



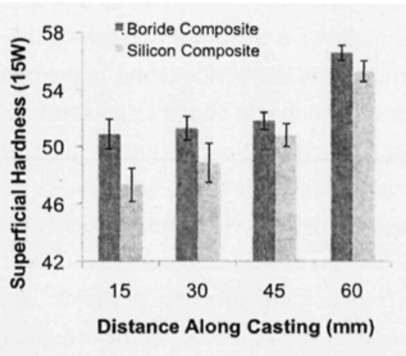


Fig. 4: Silicon and boride particles volume percent as a function of distance along the centrifugally cast Al-10wt.% Sn–3wt.% B and Al-10wt.% Sn–3wt.% Si composites.

Fig. 5: Composite superficial hardness as a function of distance along the casting of centrifugally cast Al-10wt.% Sn–3wt.% B and Al-10wt.% Sn–3wt.% Si composites.

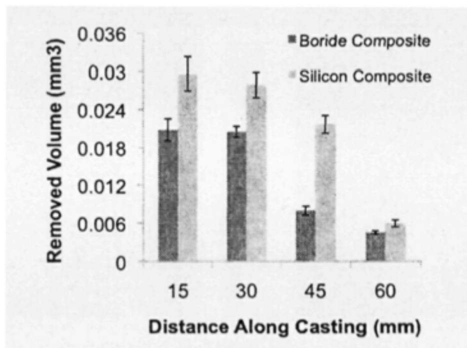


Fig. 6: Removed volume due to wear caused by pin-on-disk tests as a function of distance along the casting of centrifugally cast Al-10wt.% Sn–3wt.% B and Al-10wt.% Sn–3wt.% Si composites.

Table 2
Wear coefficient as a function of casting distance

	Wear Coefficient (mm^3/N•m)[a]	
Distance (mm)	**Al-B-Sn**	**Al-Si-Sn**
15	0.00861	0.0122
30	0.00847	0.0115
45	0.00330	0.00896
60	0.00187	0.00245

[a] The experiments performed determined wear resistance as a bulk property of the materials and, as such, they take into account the wear resistance contributions from all phases present in the composites.

As seen from the graph, the magnitude of wear decreases from the internal to the external zones of the casting. This result is in agreement with the particles volume fraction and hardness analysis discussed previously in which higher particle density and hardness were found in the external zones, which explains the higher resistance to wear in these latter regions.

Figure 7-a shows a SEM micrograph of the composite after wear tests were performed. The presence of debris and *leftover* particles and the trends found in the composite's superficial hardness revealed the wear mechanism experienced by the material, which was found to be abrasive. Since the primary requirement to resist this type of wear is hardness, it is only natural to expect the previously discussed results in which the internal zones experienced higher wear than the harder external casting zones.

Figure 7-b shows an SEM micrograph for the silicon-containing composite. Previous studies of such alloys have determined that their most common wear mechanism is abrasive /11/. Similar to the boride-containing composite, in which the presence of abrasive particles, i.e. boride ones, in the contact zone also points to an abrasive wear mechanism. As in the Al-B-Sn composite, the hardness results support this assertion since there is an increase in wear resistance that corresponds to the increase in hardness, from the internal to the external casting zones.

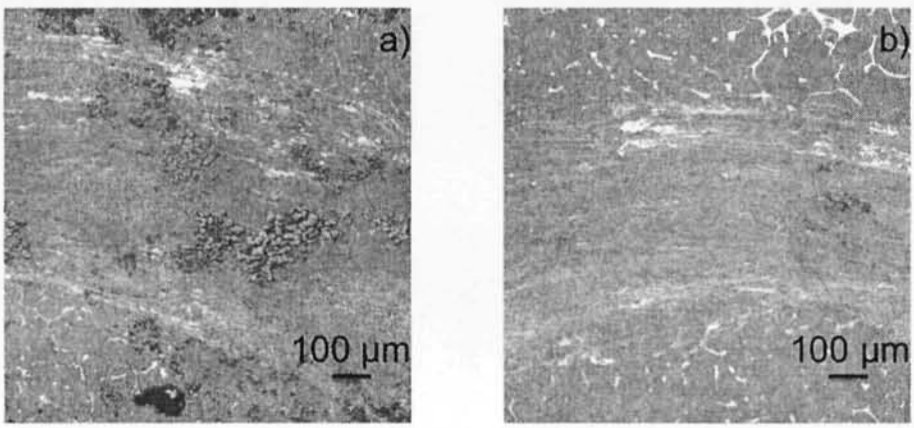


Fig.7: SEM images of wear tracks due to pin-on-disk tests performed under identical conditions on a) Al-10wt.% Sn–3wt.% B and b) Al-10wt.% Sn–3wt.% Si composites both at the 60 mm position (as indicated in Figure 1).

5. CONCLUSIONS

In the present research the authors have comparatively investigated an Al-Sn-Si bearing alloy and an alternative AlB_2-reinforced Al-Sn composite. The hardness, wear resistance and volumetric fraction of reinforcement particles in the Al matrix are directly related to the superficial distribution of reinforcement particles by centrifugal casting. The increase in volume fraction of reinforcement particles from the inner to the external casting zone is reflected on an increase in wear resistance and surface hardness of both Al-B-Sn composite and Al-Si-Sn alloy. The volume percent analysis revealed a similar distribution of hardening particles in both composites. However, the study of the wear resistance and superficial hardness helped discover an advantage in the use of boride dispersoids to reinforce the aluminum matrix. Also, superficial hardness was found to be directly affected by the concentration of reinforcement particles on the aluminum matrix surface. Consequently, Rockwell superficial hardness results indicate a superior surface hardness of AlB_2-reinforced aluminum matrix over silicon-based Al matrix. The wear resistance analysis, done by using a pin-on-disk apparatus, indicates that Al-B-Sn composites have a superior wear resistance over Al-Si-Sn composites, which reflects in a lower wear coefficient of AlB_2-based composites. In addition the presence of debris and leftover particles combined with the experimental trends found indicated an abrasive wear behavior in both materials. In summary, AlB_2-based composite demonstrated a superior wear resistance and superficial hardness over the aluminum-silicon-based bearing alloy.

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