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Research article

Tribological Behavior of Cast Aluminum Matrix Composites After Multiple Remelting

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A B S T R A C T

One of the limiting factors for expanding the applications of aluminum alloy castings in many high-tech industries is the insufficient level of tribological properties, especially under conditions of dry and abrasive wear. Reinforcing of aluminum alloys with hard ceramic particles, i.e., transition to aluminum matrix composites, allows significantly increasing their resistance against dry sliding friction, scuffing, and seizure in wide temperature and force intervals of operation. Among the numerous problems related to the industrial implementation of cast aluminum matrix composites, the problem of their recycling takes the important place. This work is aimed at establishing the influence of metallurgical processes during remelting on the change in tribological properties of cast Al-Si-B4C aluminum matrix composites. For this purpose, tribological tests in conditions of dry friction according to the ball-on-disc scheme were used. Reinforcing of an AlSi12 matrix alloy with B4C particles leads to a decrease in the composite friction coefficient and the mass wear in the as-cast state in comparison with an unreinforced matrix alloy. During remelting, the tribological properties of the aluminum matrix composites do not deteriorate. Repeated remelting leads to the improvement in particle distribution uniformity, formation of the Al3BC phase at the matrix/particle interfaces, fragmentation of reinforcing B4C particles due to cyclic thermal loads as well as an increase in the porosity fraction. The changes in the structural-phase composition during remelting have a direct influence on the level of tribological properties. Typical effects associated with dry friction, such as plastic deformation of the matrix material and the formation of areas of adhesion-cohesive fracture, indicative of scuffing, were revealed by SEM analysis of the wear tracks of an unreinforced matrix alloy. For the composite material, these effects manifested to a much lesser extent. A qualitatively similar sliding wear behavior was observed for all composite samples, regardless of the remelting iteration. The study suggests that the formation of a transitional tribolayer may occur during dry sliding friction of aluminum matrix composites, which can reduce the friction coefficient.

1. INTRODUCTION

Cast aluminum matrix composites are prospective for application in various industries due to a complex of valuable properties such as high specific strength and stiffness, damping capacity, and wear resistance in conditions of dry and abrasive wear over a wide temperature and force interval of product operation [1–3]. Expansion of industrial implementation of aluminum matrix composites will promote reduction of expenses for repair and service of machinery arising from its premature failure due to friction and wear, and also increase productivity and efficiency of machines and equipment, reducing negative technogenic effects on the environment [4, 5]. One of the problems restraining the development of cast aluminum matrix composites is the insufficient study of their recycling processes, including the behavior of the material during multiple remelting.

Repeated remelting can have a significant effect on the as-cast structure of composite materials, in particular manifesting itself in changes in the size and morphology of reinforcing particles, their distribution in the volume of the ingot, as well as in the formation of specific types of casting defects [6–8]. In turn, such changes affect the mechanical properties and tribological behavior of composites. At the same time, the data on the change of tribological characteristics of cast aluminum matrix composites after their processing by remelting in the literature are very limited.

In the present paper, the influence of repeated remelting on the tribological properties of cast Al-Si-B_4C aluminum matrix composites is considered. On the basis of the obtained experimental data, the possible mechanisms explaining the observed character of the tribological behavior of composite materials are discussed.

2. MATERIALS AND METHODS

Aluminum matrix composites were produced in alundum crucibles up to 1 kg (by aluminum) in a vertical electric resistance furnace GRAFICARBO (Italy), using the commercial aluminum alloy AlSi12 as the matrix alloy and B_4C powder (75–63 μm) as the reinforcement. The components were dosed according to a nominal B_4C content of 10 vol.% (9.39 wt.%) in the composite. The matrix alloy was superheated to 850 °C, the slag was removed, and B_4C powder was fed to the melt surface under constant stirring by a four-bladed impeller made of stainless steel AISI 316 with protective coating. Stirring was performed at an impeller speed of 300 rpm for 10 min. After adding the particles and stirring, the surface of the melt was cleaned from the slag again and the resulting composite suspension was poured at a temperature of 750 °C into steel molds to obtain ingots with a diameter of 20 mm and a height of 100 mm. Within the recycling concept, three remelting iterations were performed under fixed conditions (holding time, melting and pouring temperature) without using an impeller, simulating the possibility of using secondary charge in real industrial production. In each case, the melt was manually stirred with a graphite rod before pouring to eliminate possible structural inhomogeneity. Samples for tests were cut at a distance of 15 mm from the bottom end of the obtained ingots.

The coefficient of friction was determined in air under conditions of dry sliding contact interaction between the sample and a steel ball using a ball-on-disc scheme on a Tribometer (CSM Instruments, Switzerland) automated friction machine. Tests were performed under a load of 10 N and a constant sliding speed of 0.2 m/s. The friction path in all experiments was 300 m. Mass wear was determined by weighing the specimens before and after tribological tests with an accuracy of 10^{-4} g. The morphology of friction paths and debris particles was investigated using a FEI Quanta 200 3D scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

Figure 1 shows summary data of tribological tests of AlSi12 matrix alloy and AlSi12 + 10 vol.% B_4C aluminum matrix composites, subjected to repeated remelting.

Analysis of the obtained data shows that reinforcing of the AlSi12 alloy with B_4C particles leads to a reduction of the friction coefficient and mass wear of the samples. In particular, the friction coefficient decreases from ~0.51 to ~0.37. The value of mass wear changes more significantly. If, for the matrix alloy, the average value of mass wear in the specified test conditions was 14.8 g, the value for the composite materials did not exceed 2.5 g. It should also be noted that the dispersion of the results decreased with the increasing number of remeltings of the composites. This indicates an improvement in the homogeneity of the composite properties with an increase in the number of remelting, which can be explained by an improvement in the uniformity of the distribution of reinforcing particles in the matrix, as was shown previously [9,10].

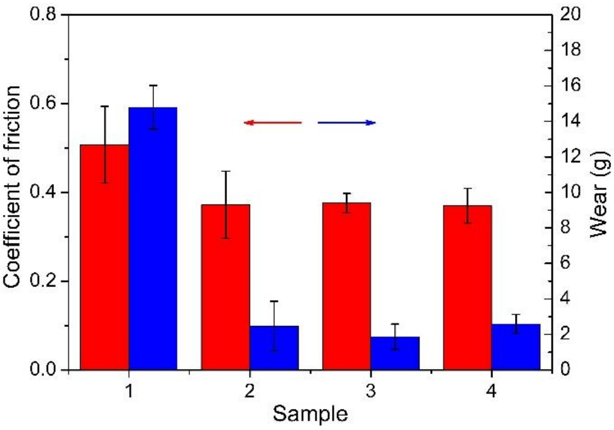
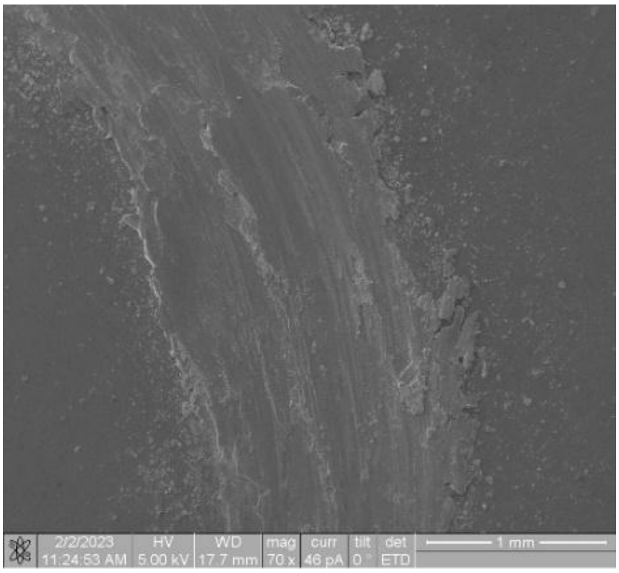


Fig. 1. Friction coefficient and mass wear of samples of AlSi12 matrix alloy (1) and AlSi12 + 10 vol.% B_4C composite at the first (2), second (3) and third (4) remelting iterations.

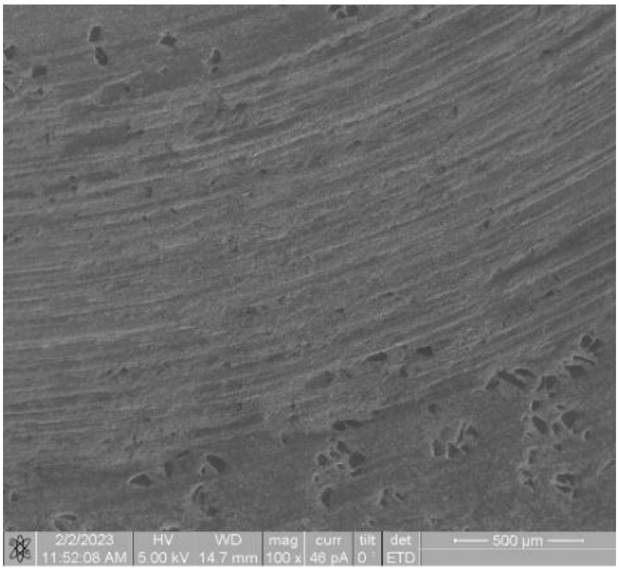
The examination of the wear tracks of the investigated samples allowed to reveal the wear mechanisms. Figure 2a shows SEM images of the wear surface of the AlSi12 matrix alloy.

Based on the SEM images provided, it is evident that the surface damage is caused by the deformation and separation of particles of the softened matrix alloy, which is typical in dry friction between aluminum and steel [9]. The wear pattern observed is characterized by localized adhesive seizing of the contacting surfaces, followed by cohesive destruction of the contact zones and separation of particles ranging from 50 to 500 microns in size. Additionally, micro-scratches can be observed on the friction surface, indicating the occurrence of micro-cutting in the contact zone. The oxidized particles of the matrix aluminum alloy appear to act as the abrasive in this case.

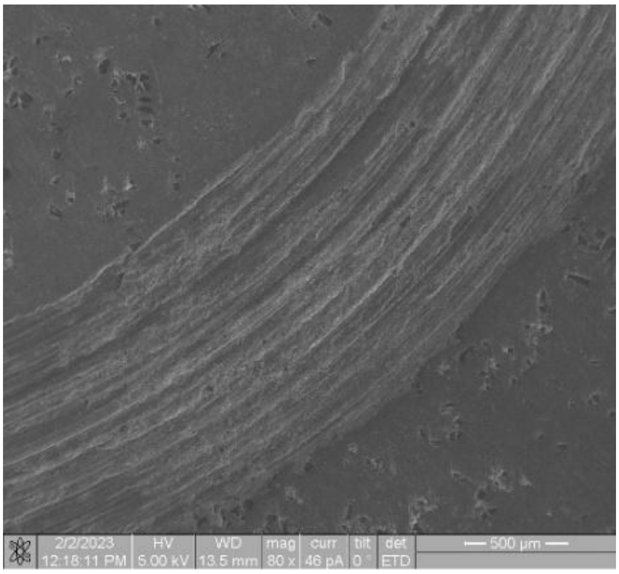
A different picture was observed for aluminum matrix composites (see Fig. 2b-d). SEM images of wear tracks of composite materials after remelting did not show any qualitative differences. However, after comparing the images with data from the microscopy of the matrix alloy (see Fig. 2a), significant differences were noted. For example, micro-scratches corresponding to micro-abrasive wear were more pronounced in the composite samples. In addition, in this case, the areas of adhesive-cohesive destruction had smaller sizes, which were limited by the presence of reinforcing particles.



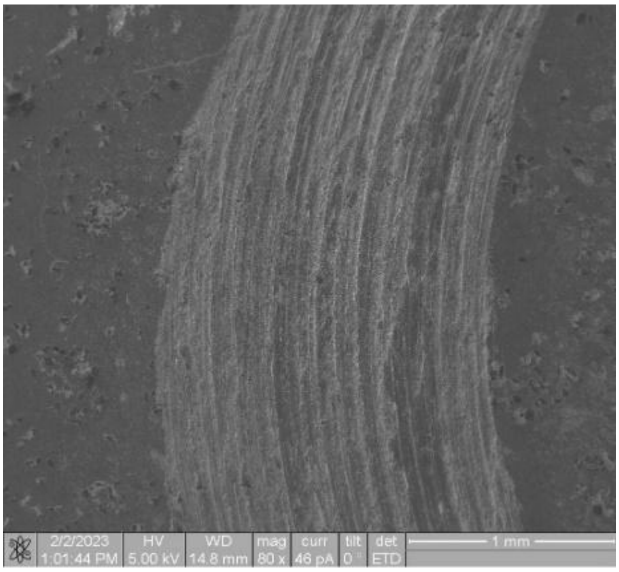
(a)



(b)

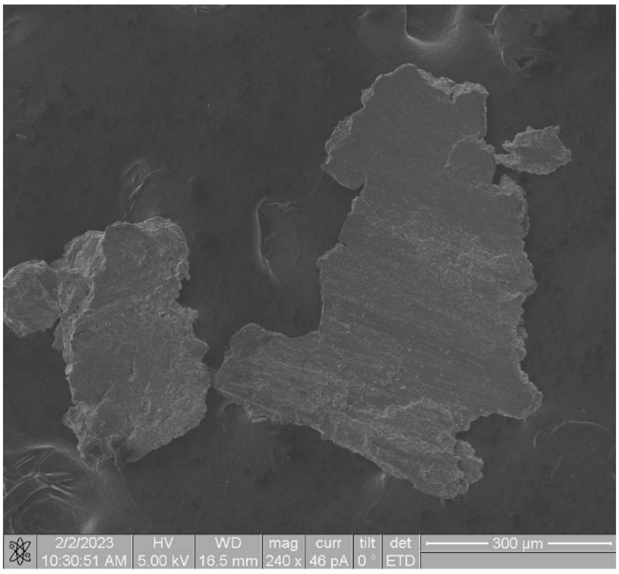


(c)

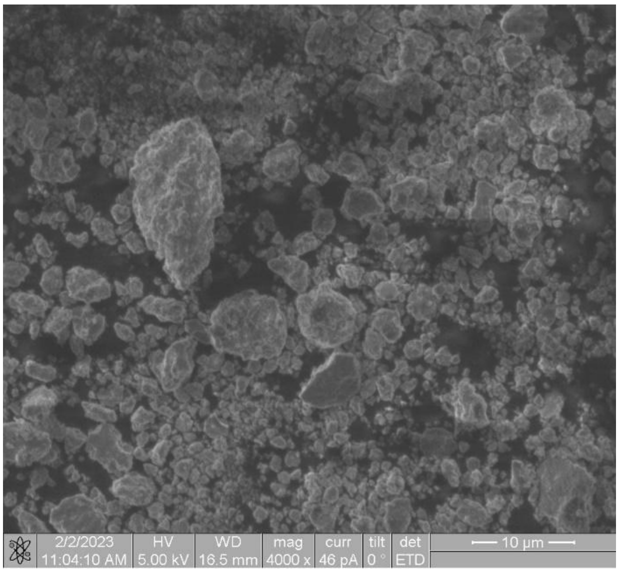


(d)

Fig. 2. SEM images of wear tracks of AlSi12 matrix alloy (a) and AlSi12 + 10 vol.% B_4C composite at the first (b), second (c) and third (d) remelting iterations after dry friction tests in pair with steel.



(a)



(b)

Fig. 3. Typical SEM images of debris after dry friction of AlSi12 matrix alloy (a) and AlSi12 + 10 vol.% B_4C composite (b) in pair with steel.

It has been previously shown [10] that in addition to the improvement in particle distribution uniformity during remelting, partial degradation of boron carbide particles can occur due to interaction with the aluminum melt, leading to the formation of the Al_3BC phase at the "matrix-particle" interface. Multiple remeltings cause fragmentation of B_4C particles due to cyclic thermal loads, as well as an increase in the porosity content in the cast structure of the composite.

The aforementioned changes in the structural-phase composition of the composites during remelting can have a direct impact on the level of tribological properties, which could explain some increase in mass wear after the third remelting iteration.

Figure 3 shows typical SEM images of debris formed during dry friction of matrix alloy and composite material paired with steel.

For the AlSi12 matrix alloy, debris particles have a flake shape with a size of up to 500 µm, which is characteristic for delamination wear. The debris generated during dry wear of composite materials is a mechanical mixture consisting of particles of the matrix material with a size of no more than 20 μm and B_4C reinforcing particles subjected to fragmentation.The summary analysis of the noted regularities of morphological changes of friction surfaces and debris particles testifies to the complex character of wear of friction pairs with the presence of adhesive, oxidizing, and abrasive components. Based on the debris characterization after the friction of the composite material and considering the results of tribological tests (see Fig. 1), it is possible that the formation of a transitional tribolayer may occur during the dry sliding friction of Al-Si-B_4C aluminum matrix composites, which can reduce the friction coefficient between contacting surfaces.

4. CONCLUSION

The results confirm that the tribological properties of Al-Si-B_4C aluminum matrix composites are maintained at a sufficient level after remelting. A decrease in the dispersion of the friction coefficient and mass wear was observed, which may be attributed to the improved uniformity of the distribution of reinforcing particles during remelting. These processes of particle redistribution can partially counteract the negative effects of increased matrix-reinforcement interaction.

Acknowledgement

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