Study of mechanical properties of high volume fraction aluminum/steel shots metal matrix composites

Ghodratollah Roudini and Milad Haji Hassan Arez
Department of Materials Engineering, Faculty of Engineering, University of Sistan and Baluchestan, Zahedan, Iran
E-mail: ghodratollah.roudini@eng.usb.ac.ir and milad_ab2011@yahoo.com

Keywords: aluminum, compressive strength, metal matrix composite, sintered, steel shots

Abstract
In this study, aluminum metal matrix composites with different sizes steel shots were produced by squeeze casting method. First, steel shots preforms (0.2–2 mm) were made with and without sintering. Some of the preforms were sintered in an electric furnace at 1000 °C for 2 h. Then, the preforms were placed in steel die with molten aluminum and infiltrated by squeeze casting method. After composite making, microstructure of the composites was studied by optical microscope which showed the features of a homogeneous microstructure, uniformly distributed particles and no visible macrospores. The micrographs also showed that the steel shots were sintered successfully. Furthermore, the hardness, compressive strength and impact strength of the composites were also evaluated. The hardness of the composites clearly increased with smaller steel shots and it was much higher for the composites with sintered shots than nonsintered ones; the composites with 0.2 mm sintered steel shots showed the maximum microhardness (about 180 VHN). The compression tests also showed that the compressive strength of the composites increases by about 50% for the sintered steel shots. The impact results of the composites showed that the impact strength decreases with smaller sintered steel shots. The fracture surface of the impact samples were studied using scanning electron microscope. The fractured interparticle necks were also investigated in the composites containing sintered steel shots. As a result, interconnection of the reinforcement particles is a very efficient way to improve the mechanical properties of the metal matrix composites.

1. Introduction
Particulate metal matrix composites (PMMCs) are a class of metal matrix composites which are generally composed of a ductile metallic alloy reinforced with hard reinforcement particles. The main microstructural factors controlling the properties of these composites include the reinforcement shape, size, volume fraction, distribution, orientation, the matrix composition and state of work hardening or hardening of the matrix by heat treatment [1–13]. The properties of these composites are particularly marked at high volume fraction of reinforcements. Particulate metal–matrix composites are in particular attracting attention because of their mechanical and thermo–physical properties for various industrials applications such as transportation and electronic.

High volume fraction of particulate aluminum matrix composites are a kind of PMMCs to their mechanical properties, light weight, suitable corrosion resistance, and thermal conductivity are the most widely used materials for composites. One of the most important factors in achieving the desired properties in composites is to select the appropriate matrix and reinforcement [2, 3, 5–13]. The main matrix materials employed in MMCs are aluminum, titanium, magnesium, and copper. Ceramic materials and metals are among the most commonly used reinforcements used in aluminum matrix composites. However, due to the undesirable wettability of ceramics and the high cost of producing ceramic reinforcements, metals reinforcements have been more
considered [6, 12, 14–17] in recent years. Iron and its alloys, as cheap materials, with high abundance and suitable mechanical properties, are a very good option for strengthening aluminum and its alloys.

Composite production methods greatly affect their microstructure and mechanical properties. Hence, various methods, including powder metallurgy, casting, and metal forming methods have been used for the production of metal matrix composites. Among of them, squeeze casting method is of great importance due to its considerable advantages [2, 4, 17–22].

The goal of this research is to study the evolution of steel shots reinforcement on the properties of high volume fraction aluminum metal matrix composites. One of the main reasons for this study is their relatively
two metals behavior as a matrix and reinforcement. Hence, studying such materials is interesting from scientific point of view. Squeeze casting metal infiltration was used as the processing route in this research. Then, the effect of size and connectivity of the steel shots on the compression strength, hardness and impact strength of the composites were evaluated.

2. Materials and experimental procedures

Steel shots (table 1) with different sizes (0.2–1.4 mm) and aluminum with purity of 97% (table 2) were used as the reinforcement and the matrix, respectively.

The vibration compaction method was used to make green (nonsintered) steel shots preforms. To produce interconnected steel preforms, "green" steel shots preforms were partially sintered at 1000 °C in a graphite die in an electrical furnace for 2 h at maximum temperature (figure 1(a)). Then, the sintered samples were allowed to cool down slowly in the furnace to minimize the thermal stresses. Cylindrical preforms were produced with 50 mm in height and 30 mm in diameter. Figure 2(b) shows the steel shots sintered preforms.
Suitable steel mold and piston set (figure 3(a)) was prepared for producing the composite. Then, specific volumes of the preform and the pure aluminum ingot were placed in the mold and the mold set (mold and piston) was placed inside the furnace at 750 °C for 2 h. The mold set was then removed from the furnace and finally the infiltration operation was performed by a press machine to fill the open pores of the preform by the molten aluminum. Figure 3(b) shows the fabricated composite.

The microstructure of the samples was studied by optical microscope. The compressive strength of the composite specimens (L/D ratio of 1.5) with different size and connectivity of the steel shots were conducted using universal testing machine (Instron Model 4206). The room temperature compression tests were carried out at a cross head of 0.5 mm min⁻¹. The hardness of the composites was investigated by Vickers test method. For this purpose, the microhardness was measured using 25 g load for 10 s. The fracture behavior of the materials was analyzed by Charpy impact test and the fracture surfaces were studied by SEM (CAM SCAN MV2300 model).

![Figure 5. Microhardness of the composites with different nonsintered steel shot sizes.](image1)

![Figure 6. Microhardness of the composites with different sintered steel shot sizes.](image2)
3. Results and discussions

3.1. Microstructures
Figures 3(a) and (b) show the optical microstructure of the composites with 0.8 mm and 1.4 mm nonsintered steel shots. The microstructure of the composites with sintered preforms and different steel shots (0.2 mm and 1.2 mm) are shown in figures 4(a) and (b). The microstructures show that there are no pores in the composites. This indicates that the squeeze infiltration has yielded sound steel shots-aluminum composites due to the complete penetration of molten aluminum into the spaces between the shots. Also, sintering has clearly affected the connectivity of the steel shots.

3.2. Hardness
The hardness of the composites was measured using a standard Vickers hardness testing machine after polishing, the composite surface. A load of 25 g was applied to the composite surface by the indenter for 10 s. In order to get a reliable result, a minimum of three hardness readings were taken for each specimen at different locations of the test specimen. The results are presented in figures 5 and 6. The hardness of the composites is affected both by the size of the steel shots and the sintering process. For the sintered samples (figure 6), the rate of hardness increasing is slightly higher than nonsintered preforms. So, it seems that increasing the matrix hardness and the connectivity of the reinforcements increases the hardness of the composites. These results are in good accordance with previous works [23–26].
3.3. Compression strength

The compressive stress-strain curves of the composites with different sizes of the steel shots are shown in figures 7 and 8 for each tested sample. As can be seen in figure 7, the composite strength increases with decreasing the size of the steel shots and the ductility generally tends to decrease. From diagrams in figure 8, it can be concluded that the compressive strength increases with sintering process. The size of the steel shots and their connectivity are the two factors that give a relatively high strength to the composites, as has been already reported [26–30].

3.4. Impact

The fracture surface of the impact sample is shown in figure 9. It can be seen from figure 10 that the composites with bigger nonsintered steel shots produced better impact strength relative to the composites containing sintered steel shots (figure 11). The lowest impact strength was obtained by the composite with sintered steel.
Figure 11. Impact energy for the composites with sintered preforms.

Figure 12. SEM fracture surface of the impact composite samples with different size steel shots.
shots and 2 mm size. The connectivity and size of the reinforcements in the composite specimens change the absorption energy and fracture behavior [31, 32]. Scanning electron micrographs of the impact fracture surfaces of the composites are shown in figure 12. These fracture surfaces combine regions of matrix having undergone ductile tearing with bare steel shots regions, along which fractured inter particle necks. The fracture surfaces in the figures suggests that the interface between the particles and the matrix is partly debonded during the fracture process.

4. Conclusions

High volume fraction steel shots interpenetrating phase metal matrix composites have mechanical behavior that is not found in the composites with no sintered preforms. In these composites, both phases are three-dimensionally interconnected which introduces significant changes in their mechanical properties as compared to their non-sintered counterparts. From this work, the following results can be summarized:

1. The hardness of the aluminum matrix is affected by the connectivity of the steel shots as reinforcement. For a given size of steel shots, the hardness of aluminum matrix increased in the presence of sintered preforms.

2. The connectivity of the steel shots (sintered) in the composites increased the compressive strength. These composites showed brittle fracture behavior.

3. The steel shots decreased the impact strength of the aluminum matrix composites. The fracture surfaces of the composites containing nonsintered steel shots showed ductile tearing in aluminum matrix and interface deboning damage mechanisms. For the composites with connectivity reinforcement, the inter particle necks fractured damage mechanism also can be seen.

Acknowledgments

The financial support from the office of research at university of Sistan and Baluchestan under the project 3/9445 for this work is greatly appreciated.

ORCID iDs

Ghodratollah Roudini @ https://orcid.org/0000-0001-6615-9311

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