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Mechanical behavior of magnesium-steel particles composites with interpenetrating phases

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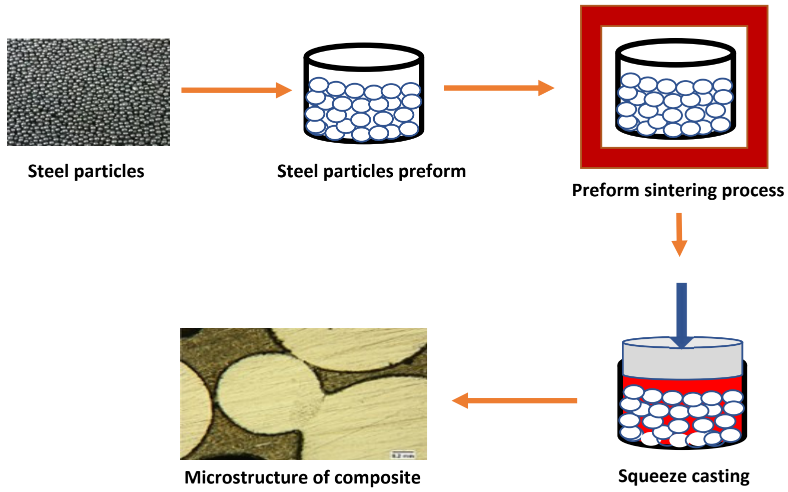
HIGHLIGHTS

- High volume fraction of particulate interpenetrated phase magnesium-steel shot composites fabricated with sintered steel shots using the preform and squeeze casting method.
- The mechanical properties (compressive strength and hardness) of the composites were affected by steel shots reinforcement connectivity.
- Interface deboning and interparticle breaking are dominant damages in the composite's fractures.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, steel particles were used to reinforce the magnesium matrix. To fabricate the magnesium-steel particle composite, steel particle preforms were made in different sizes; some were sintered at 1000 - 1200 °C and some without sintering. These preforms were preheated at 750 °C and then infiltrated with melted magnesium with the squeeze casting method. The microstructure of the preforms and the composites were investigated by SEM and optical microscope. Microhardness and compression tests were performed to investigate the mechanical behavior of the composites. The microstructure study showed the rigid connectivity between the steel particles in the interpenetrating phase composites. Also, hardness and compression test results showed higher hardness (61 VHN) and strength (218 MPa) for the composites with 1mm steel particle size sintered at 1200 °C. Hence, the composites with 3D-dimensionally interconnected steel particles show significant changes in their mechanical properties.

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1. Introduction

Interpenetrating phase composites (IPCs) are fundamentally different from other composite materials due to the arrangement and geometry of their reinforcements. The composites consist of a reinforcing phase that is isolated or connected within a continuous matrix phase. The reinforcements and matrix phase's dual connectivity and continuity microstructure generally change the composites' properties. Each phase offers its own benefits due to its complete continuity, and the continuous stiffer reinforcement phase has the most significant influence on the composite behavior [1-5].

Interpenetrating phase metal matrix composites are a type of metal matrix composite material whose reinforcements have 3-D dimensions and permanent connectivity in the composite, and this reinforced skeleton can improve the composite's mechanical and thermophysical properties. These composites are fabricated by pure metallic and alloy matrix materials, such as aluminum, magnesium, titanium, and copper, with ceramics and metallic reinforcement particles [6-10]. Among these composites, magnesium metal matrix composites have a variety of applications in the transportation and biomedical industries due to their specific strength and biocompatibility. The particle characteristics and connectivity influence the microstructure of composites, particularly in IPCs composites. [11-19]. Hence, controlling these factors is essential for the properties of the composite.

In IPCs composites with particle reinforcements, the particles contact each other with a permanent and solid bridge bonding. The reinforcements in IPCs composites with three-dimensional skeleton reinforcements through interpenetrated matrix have better mechanical properties than the traditional composites. The IPCs composites can be produced by different methods, such as solid, liquid, and vapor states. In the liquid state, squeeze casting is a suitable method to fabricate particulate metal matrix composites. In this method, the molten metal is infiltrated within porous preforms [20-23].

Due to their relatively unknown mechanical behavior, this research aims to study the effect of the steel particles' connectivity on the mechanical behavior of the metal matrix composites. This study focuses on the compression and hardness behavior of magnesium-steel particle IPCs composites. The squeeze-casting infiltration route was used to produce these composites.

2. Experimental

The materials used for the IPCs composite making were pure magnesium (99.99%) as the matrix and steel particles (1 wt% C, 0.9 wt% Si, 0.86 wt% Mn, and 0.02 wt% S) of different sizes (1, 1.5, 2, and 2.5 mm) as the reinforcement. The composites-making process was done in two steps. First, the steel particles' green preforms were fabricated by the vibrations compaction method, with a 35 mm diameter and 40 mm height. Then, the green compacted preforms were partially sintered at different temperatures (1000 °C, 1100 °C, and 1200 °C) for 2 h at maximum temperature to make interconnected steel particles. Next, the composites with and without sintered preforms were fabricated using the squeeze casting infiltration process (Fig. 1). Finally, samples were cut from the composites to study microstructure, hardness, and compression behavior.

The selected sections of the as-cast composite were studied with an optical and SEM (KYKY, Model-EM3900) microscope. A Vickers hardness testing machine measured the microhardness of the composites. The compression standard test (H/D < 2.5) was conducted using a Universal testing machine (Instron, Model 4206) at a 1 mm/min speed and room temperature.

3. Results and discussion

3.1. Microstructures

The typical optical and SEM microstructure of the sintered preforms with different steel particle sizes are shown in Figs. 2 and 3. As can be seen, after sintering, the particles tend to connect by forming necks at contact points. These micrographs of the porous steel particles preform also show that particle and pore channels remain interconnected within the preform. Optical microstructure results (Fig. 4) showed no defects in the composites; hence, the squeeze-casting infiltration is a good method for producing magnesium-steel particle composites.

Also, the sintering process changed the particle shape and connectivity. Furthermore, sintering should eliminate the regions of the highest capillarity at the contact points of two touching particles and it is expected to reduce residual porosity in the IPCs composites.

3.2. Hardness

The VHN microhardness of the composites is shown

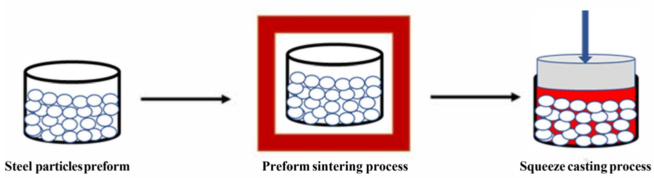


Fig. 1. Schematic of the composites production process.

Fig. 2. Optical images of the sintered steel particles with different size preforms.

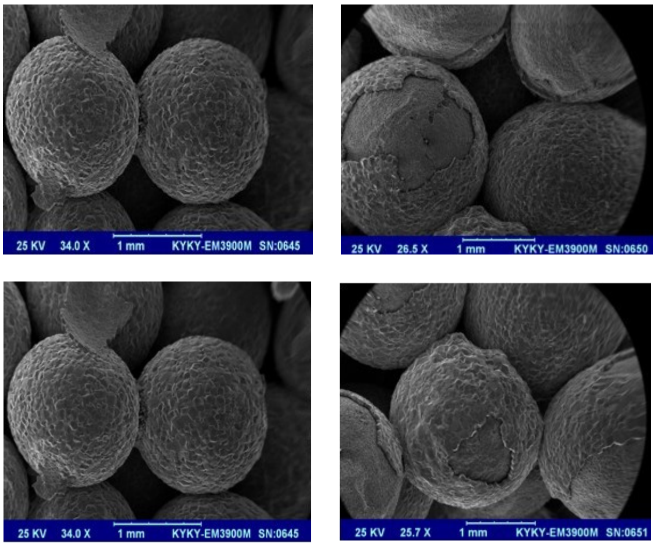
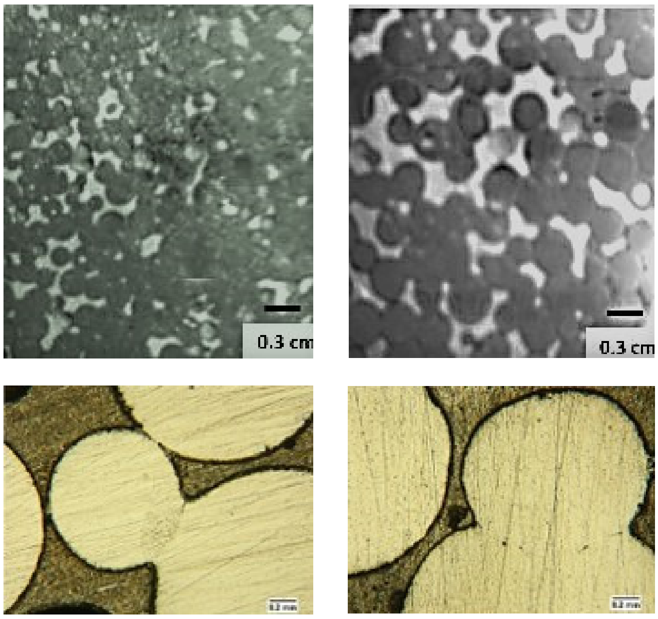


Fig. 3. SEM images of the microstructure of sintered steel particles with different size preforms.

in Fig. 5. As can be seen, as the sintering temperature increases and steel particle size decreases, the hardness of the magnesium matrix increases. It seems that the sintering temperature of the harder phase increases their connectivity and affects the hardening of the matrix in the IPCs composites [19,22]. During the fabrication of the composite, thermal strain plastic deformation is hindered by the reinforcement connectivity, increasing the dislocation density of the magnesium matrix. Hence, the microhardness increases with connectivity for the same-sized steel particles and higher sintering temperatures.

3.3. Compression

The compression stress-strain curves of the composites



(a) (b)

Fig. 4. Optical microstructure of the composites with sintered steel particles, (a) 1 mm and (b) 2.5 mm.

are plotted in Figs. 6 to 9. As can be observed from the general trend of stress-strain curves, the composite strength increases as the steel particle sizes decrease and the sintering temperature increases. The IPC composites fabricated with high sintering temperature (1200 °C) preform showed high strength because of good three-dimensional connectivity between steel particles reinforcement. These particle connectivity arrangements in the composites affect compression behavior. Other researchers have also proved the effect of particle connectivity on the strength of IPCs composites [19-25].

The SEM microstructure of the composite fracture surfaces is given in Fig. 10. The fracture surfaces of the IPCs

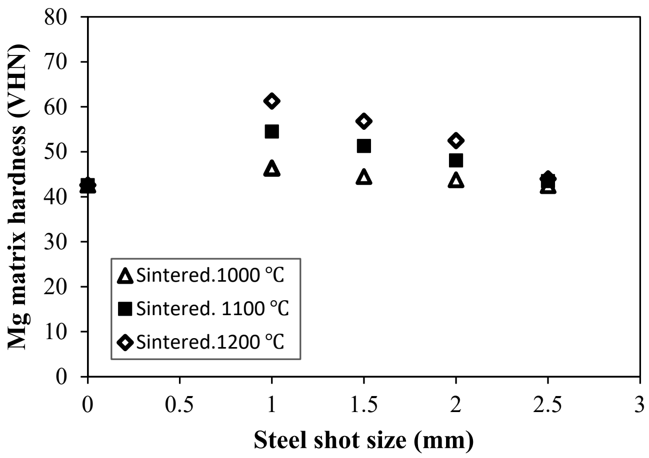


Fig. 5. Microhardness Mg matrix-sintered steel particles size in the IPCs composites.

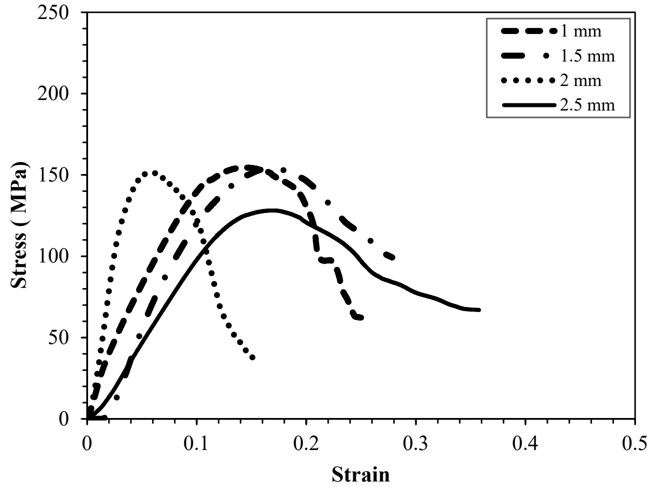


Fig. 6. Stress-Strain curves of the composites with nonsintered steel particles.

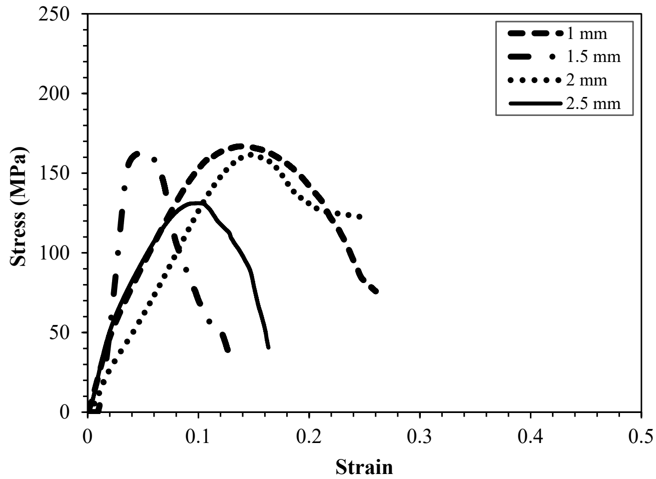


Fig. 7. Stress-Strain curves of the IPCs composites with sintered steel particles at 1000 °C.

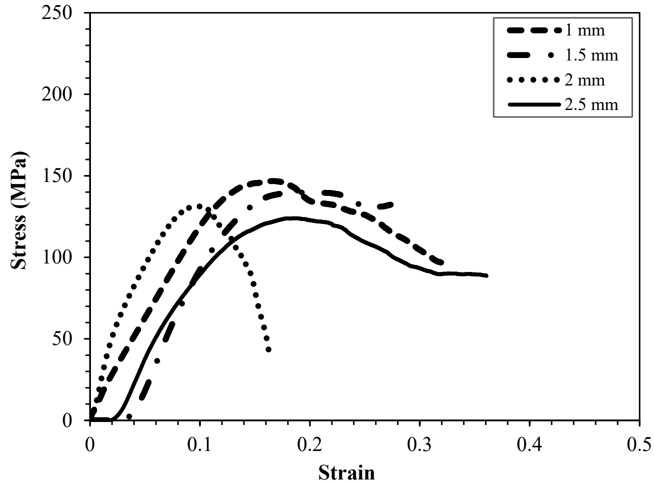


Fig. 8. Stress-Strain curves of the IPCs composites with sintered steel particles at 1100 °C.

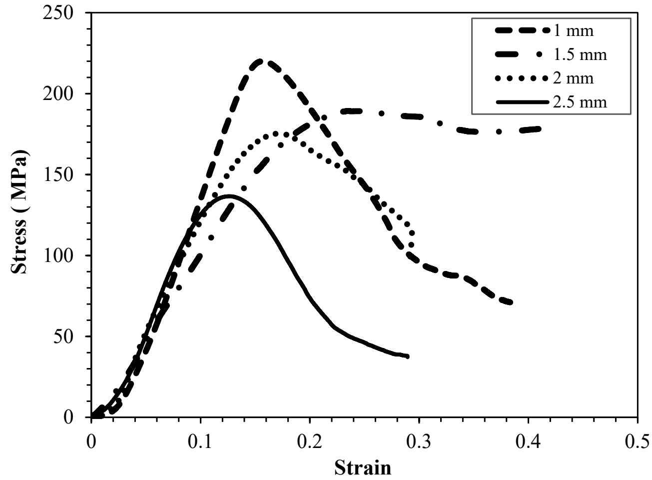
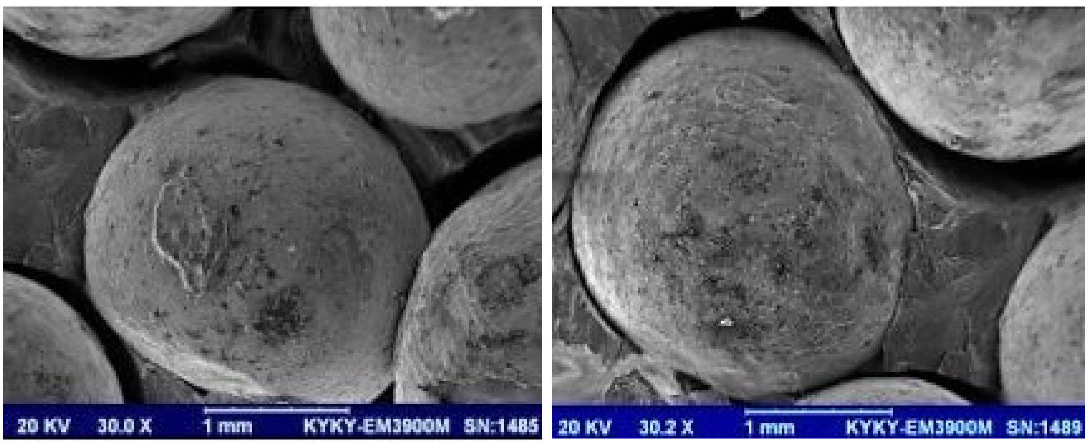


Fig. 9. Stress-Strain curves of the IPCs composites with sintered steel particles at 1200 °C.

composites showed interface deboning, and this mechanism causes the primary damage in the composites. Hence, resistance to breaking the steel particle interconnections was proposed to explain the higher compressive strength.



(a) **(b)**

Fig. 10. SEM images of the fracture surface of the IPCS composite with different steel particle sizes, (a) 1.5 mm and (b) 2 mm.

4. Conclusion

The IPCs magnesium-steel particle composites showed higher compressive strength and hardness than those with no interpenetrating phases. The rigid skeleton of the steel particles in the composites resists deformation during applied loading and hence increases the mechanical properties of the composites. The IPCs composite with steel particles sintered at 1200 °C showed the highest compressive strength and hardness. Also, the fracture surfaces showed interface deboning damage.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Additional information

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