

MICROSTRUCTURE EXAMINATION AND TENSILE PROPERTIES OF Al-20%Mg₂Si-XZrO₂ HYBRID COMPOSITES

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Abstract. Due to the unique properties of aluminium hybrid metal matrix composites (Al hybrid MMC) such as physical, mechanical, and tribological properties, these materials recently achieved considerable attention particularly in automotive and aerospace applications. These unique properties are the result of the presence of two or more reinforcement particles in the composite matrix. In the present study, various concentrations of Zirconium oxide (ZrO₂) particles were introduced to the Al-Mg₂Si composite via stir casting technique. The influence of various concentrations of ZrO₂ on the structural and tensile properties of the Al-Mg₂Si composite was examined using Scanning Electron Microscope (SEM) and tensile tests, respectively. The findings showed that the introduction of ZrO₂ to Al-Mg₂Si decreased the average mean size of primary Mg₂Si particulates. Adding ZrO₂ particles up to 10 wt.% had a decent distribution in the Al-Mg₂Si matrix; however, increasing the ZrO₂ content to 15 % led to agglomeration of ZrO₂ particles. Furthermore, tensile results demonstrated that Al-Mg₂Si composite with 10% ZrO₂ addition demonstrated the highest Ultimate Tensile Strength, UTS (75.35 MPa) and elongation, El % (0.69 %) compared to other fabricated composites. Hybrid composite fracture surface with 10% ZrO₂ revealed a more ductile fracture mode compared to other fabricated composites. This study can be beneficial to tailor new composites with refine structure and high mechanical properties.

Keywords: Al hybrid MMC, Mg₂Si, ZrO₂, microstructure, tensile properties

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Introduction

Magnesium silicide (Mg_2Si) is one the most important reinforcing particles for in-situ Al matrix composites. Al- Mg_2Si composites can be used for brake disks and some engine parts in automotive diligences due to their distinctive features including low density, high hardness, good strength in high-temperature, and ease of production (because the particles are added in-situ into the melt) [1]. However, low-temperature brittleness and insufficient friction properties are among their drawbacks.

Recently, the production of hybrid metal matrix composites (HMMC) is has been investigated widely. With the composition of two reinforcements in the matrix, a hybrid composite with the features of these reinforcements is produced. Hence, for composites including single reinforcement, HMMCs are good options. In applications where wear properties is crucial, these composites are utilised. Examples of frequently used reinforcements in ex-situ aluminium metal matrix composites include Al_2O_3 , SiC, ZrO_2 , B_4C , TiB_2 , TiC, MgO, and TiO_2 [2]. With the addition of these ceramic (reinforcements) particles to the Al- Mg_2Si composite, the size of primary Mg_2Si particles is decreased, which reduces its brittleness and hardness, improving the wear and friction properties of the fabricated composite.

According to [3], nanosized SiC particulates and in-situ Mg_2Si particles reinforcing the Al-Cu matrix were used to fabricate the hybrid composites, and the microstructure and mechanical properties were investigated. The researchers showed that the mixing of in-situ Mg_2Si and ex-situ SiC can effectively alter the morphology of the Mg_2Si particles by changing them from a short strip to a dot shape as well as decreasing the average size of primary Mg_2Si particles. This results in the enhancement of the mechanical properties of the composite. Another study [4] was focused on comparing the characteristics of ADC-12 (AA383) reinforced with nano-SiC and nano- Al_2O_3 composites fabricated by the stir-casting method. It was found that the addition of nano-SiC and nano- Al_2O_3 improved the hardness value while decreasing the wear rate. An examination of the metallography and bulk hardness of artificially aged Al6061- B_4C -SiC hybrid composites was conducted by Sharma et al. [5]. Compared to the aluminium alloy, considerable enhancements in tensile strength and hardness, and a minimal decrease in the ductility of hybrid composites were detected. Ghandvar et al. [6] found that the mean size of primary Mg_2Si in Al- Mg_2Si composite was $47\mu\text{m}$, in which with the addition of 5% B_4C , the particle size decreased to $33\mu\text{m}$. The highest UTS (217 MPa) and El% (7%) was achieved in Al-20% Mg_2Si -5% B_4C hybrid composite. In another study [7] they reported that with the introduction of YSZ particles, the average size of the primary Mg_2Si particles in the base composite was $137.78\mu\text{m}$, which was reduced to $88.36\mu\text{m}$ after adding 9% YSZ. The aspect ratio of Mg_2Si particles also decreased from 3, for the base composite to 1.27 in the composite containing 9% YSZ. Moreover, the hardness value displays an incremental trend from 102.72 HV, as recorded for the base in situ composite, to 126.44 HV in the composite with 9% YSZ.

A non-homogeneous distribution, weak wettability, and particles clustering in the composite matrix are the most disparaging matters faced in AMCs production. These disadvantages negatively impact the tensile properties of the composite. A few investigations of HMMCs containing Mg_2Si and ZrO_2 particles were performed by [8-9]. Therefore, in this study, the impact of different contents of ZrO_2 particles on microstructural and tensile properties of Al-20% Mg_2Si was examined.

Materials and Methods

In order to fabricate the ingot of the Al-20%Mg₂Si composite, ADC12 alloy in commercial grade (> 98.0% purity) as well as pure aluminium (> 98.0% purity) were employed. To produce an Al-Mg₂Si-ZrO₂ hybrid composite, initially, the ZrO₂ particles (> 99% purity) with a size of 10-30 µm were oxidised at 800 °C for 2 h to achieve a proper wettability with the matrix by removing the moisture and oxide layers on the surface of the particles. The contents of the ZrO₂ particles were fixed at 0, 5, 10 and 15%, respectively. Next, inside a graphite crucible, about 300 g of Al-20%Mg₂Si composite was melted. Afterwards, the pre-oxidised ZrO₂ particles were added to the Al-Mg-Si melt using a stirring action at 750 °C. Then, the molten composite was held for 15 min and then heated to 720 °C and poured inside a steel die to fabricate the 30 mm thickness cylindrical samples.

Parallel to the casting of the samples, thermal analysis was conducted using a ceramic mould which was pre-heated at 500 °C for about 15 min. Around 100 g of molten composite was poured in the ceramic mould. A thermal analysis setup (EPAD-TH8-K) was used to record the temperature-time data connected to a computer with DEWESOFT software version 7.5 with a 100 Hz/ch dynamic rate. FlexPro software version 10 was used for flattening of the curves and plotting the cooling curves. The solidified rods were used to prepare the flat tensile bars based on ASTM E8/E8M. A tensile testing machine (Instron Universal 5982) set with a strain gauge extensometer was employed for conducting the tensile tests at 1.0 mm/min constant crosshead speed at room temperature. The tensile samples geometry is depicted in Figure. 1.

In order to observe the Mg₂Si features in the composites, the metallographic specimens underwent the standard grinding and polishing before observing Mg₂Si features in the composites using routines and were inspected using SEM. SEM (model: Philips XL40) was used to examine the specimen's microstructure characteristics, whereas the Mg₂Si particles sizes were examined using the i-Solution image analyser software as a quantitative analysis system. X-ray diffraction (XRD) (PHILIPS binary diffractometer) was used for analysing the phase constituents. The SEM micrograph of the used ZrO₂ powders to fabricate hybrid composites with the corresponding XRD results of the particles is illustrated in Figure 2.

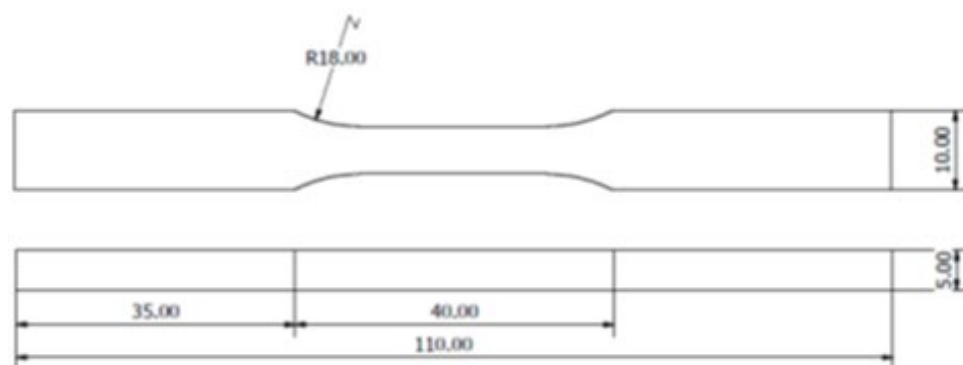


Figure 1: Schematic drawing of the tensile sample according to ASTM E8/E8M (all dimensions are in mm)

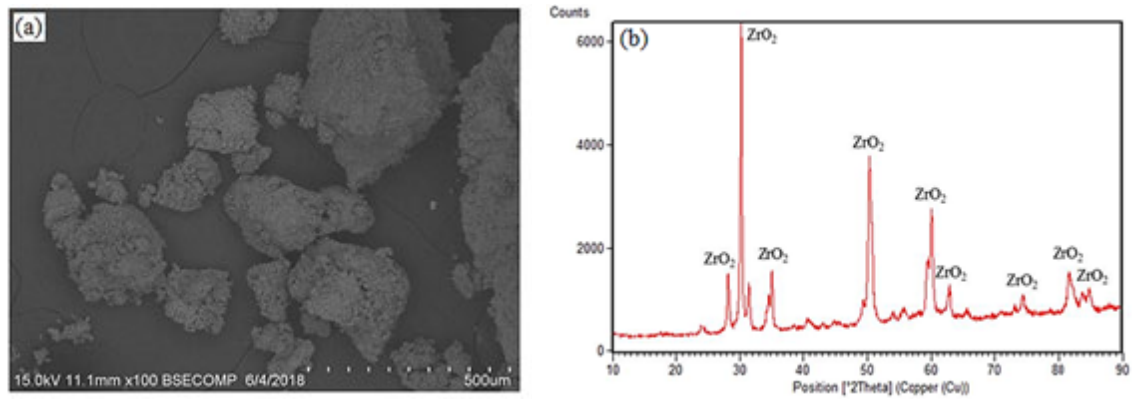


Figure 2: (a) SEM micrograph of ZrO_2 powder and (b) corresponding XRD analysis

Results and Discussion

Thermal Analysis

The cooling curves and derivative curves of Al-20%Mg₂Si in-situ composite with and without various concentrations of ZrO_2 particles are demonstrated in Figure 3(a) to (d).

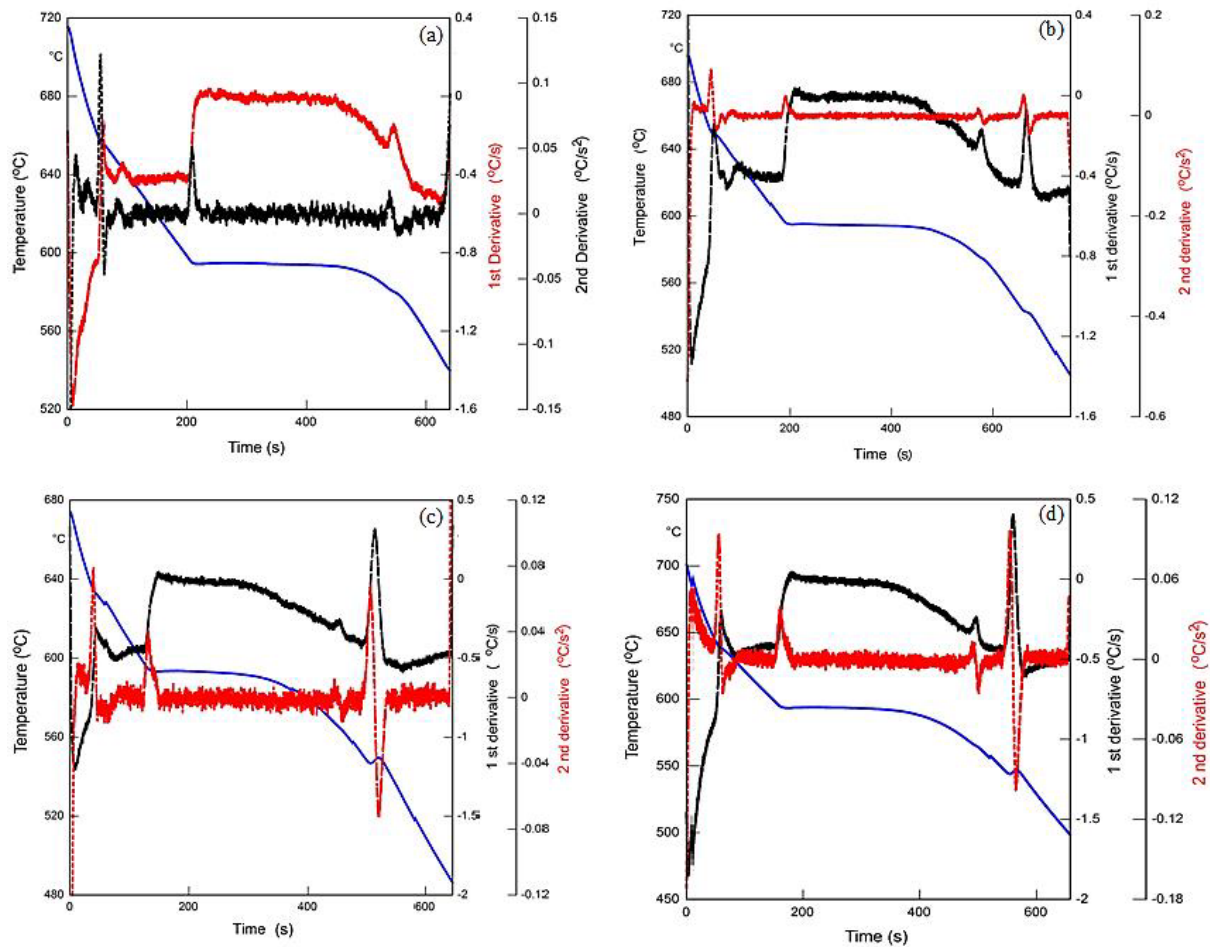


Figure 3: Cooling curve and related derivative curves of (a) Al-20% Mg₂Si, (b) Al/(Mg₂Si+5%ZrO₂), (c) Al/(Mg₂Si+10% ZrO₂) and (d) Al/(Mg₂Si+15% ZrO₂)

As shown, the nucleation temperature (T_N) of primary Mg_2Si particles changed due to the influence of ZrO_2 particles addition on the solidification behavior of the composite. As shown in Figure 3(a), the nucleation temperature (T_N) of the Al-20% Mg_2Si was 656.7 °C. With the introduction of 5 and 10% ZrO_2 , the T_N of Mg_2Si were reduced to 650.7 and 634.4 °C, respectively. However, increasing the content of ZrO_2 to 15% resulted in increasing nucleation temperature (T_N) to 639.6 °C. This behaviour is due to the shifting of the phase diagrams (eutectic points) as a result of the addition of reinforcements [10].

Microstructural Characterization

The micrographs of Al-20% Mg_2Si composite with and without different concentrations of ZrO_2 particles are illustrated in Figure 4(a) to (d). As observed in Figure 4(a), the primary Mg_2Si particle's size in the Al-20% Mg_2Si composite was 50 μm . With the addition of 5, 10, and 15% ZrO_2 , the particles size of primary Mg_2Si decreased to 40, 33, and 25 μm , respectively. In addition, with the addition of ZrO_2 particles up to 10% to Al-20% Mg_2Si composite, the distribution of ZrO_2 particles was uniform, as presented in Figure 4. However, increasing the percentage of ZrO_2 to 15% leads to non-uniformed distribution and agglomeration of ZrO_2 in the Al matrix, as observed in Figure 4(d). The magnified BSE micrographs and XRD result of Al-20% Mg_2Si -15% ZrO_2 hybrid composite are depicted in Figures 5(a) and (b), respectively, an indicative of the existence of Al as matrix and Mg_2Si and ZrO_2 as reinforcement particles in the fabricated composites.

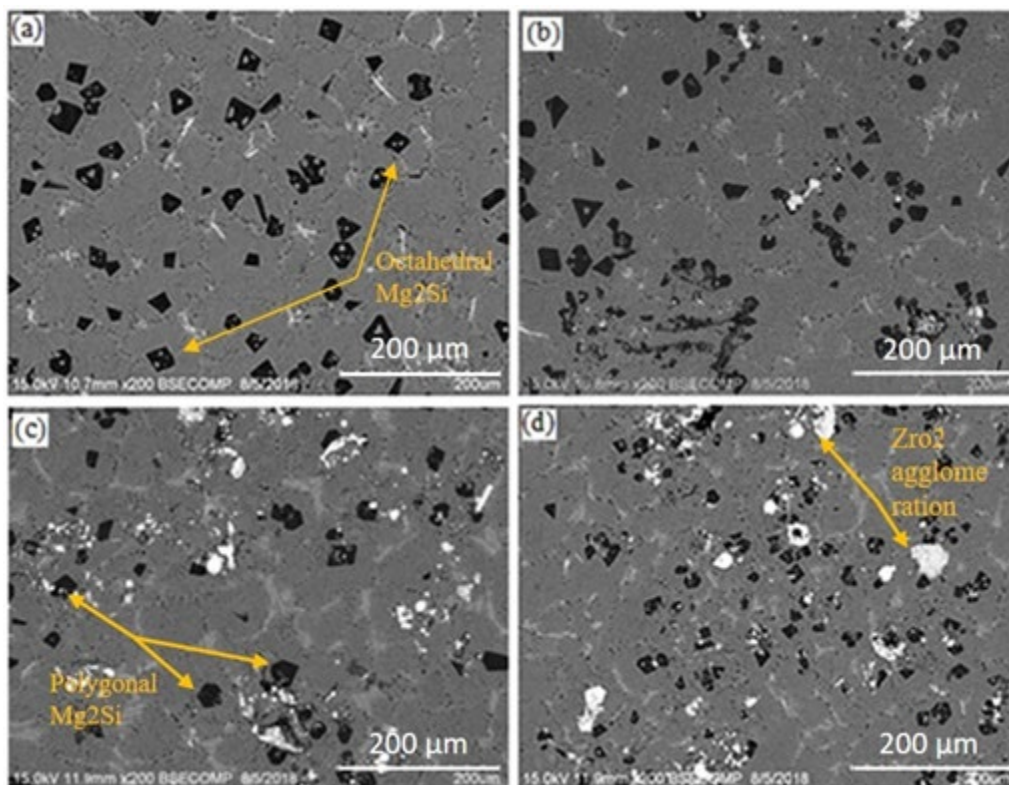


Figure 4: BSE electron micrographs of (a) Al-20% Mg_2Si , (b) Al-20% Mg_2Si -5% ZrO_2 , (c) Al-20% Mg_2Si -10% ZrO_2 and (d) Al-20% Mg_2Si -15% ZrO_2 hybrid composites

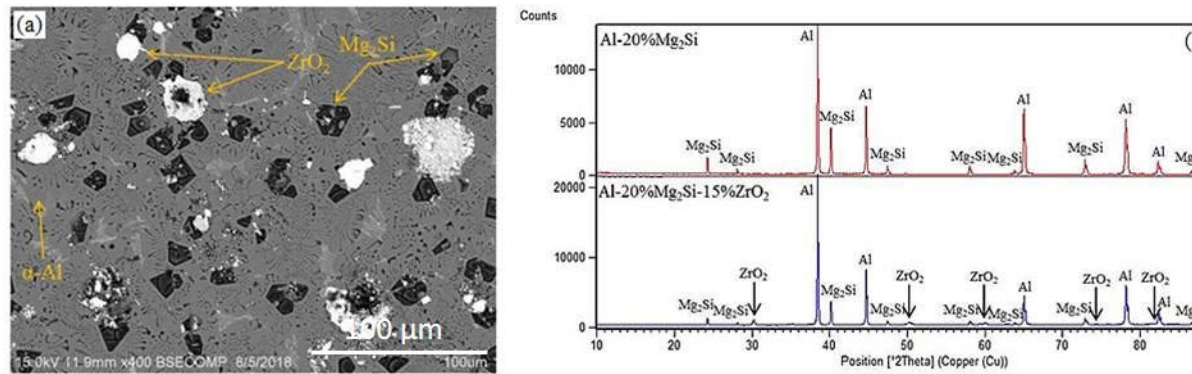


Figure 5: (a) BSE micrograph of Al/(Mg₂Si + 15% ZrO₂) and (b) Al-20%Mg₂Si composites and X-ray diffraction (XRD) patterns with and without 15% ZrO₂ addition

Tensile Properties

The UTS and El % of Al-20%Mg₂Si composite with and without different contents of ZrO₂ particles are depicted in Figure 6. The UTS and El% increased by 11.7 and 22.8%, respectively with the addition of ZrO₂ particles up to 10%. This was due to the effect of ZrO₂ particles in the reduction of the primary Mg₂Si particles size to 33 μm as well as the morphology alteration of the Mg₂Si crystals to polygonal shape.

Furthermore, another reason for the improvement of tensile properties of Al-Mg₂Si+5/10%ZrO₂ is the existence of proper interfacial bounding in the MMC structure. Indeed, the applied load was supposed to be supported by ZrO₂ particles in the matrix through the mechanism of strengthening. The composite was supported by this mechanism by conveying the applied load from the matrix to the ZrO₂ particles over their interface. Therefore, in order to transfer the load effectively, a proper matrix/particles interface is needed [11]. Nevertheless, when the percentage of ZrO₂ exceeded 15%, the tensile properties (UTS and El (%)) decreased due to the agglomeration of ZrO₂ reinforcement in the Al matrix.

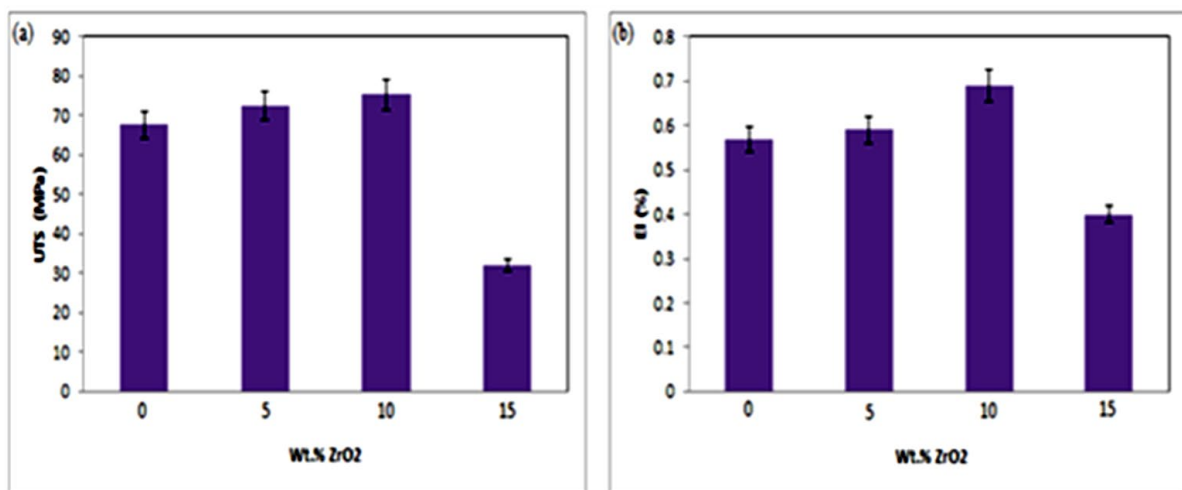


Figure 6: (a) UTS and (b) El% of Al-20%Mg₂Si composite with and without different concentrations of ZrO₂ particles

Figures 7(a) to (h) illustrates the SEM micrographs of MMCs fracture surfaces after conducting tensile tests with 0, 5, 10, and 15% ZrO_2 additions in low (left) and high (right) magnifications. The cellular surface of the Al-20%Mg₂Si composite as a result of fracture planes of coarse Mg₂Si particles [12] is shown in Figures 7(a) and (b). In fact, cellular surface indicates the features of both brittle and ductile fractures on the fracture surface, simultaneously.

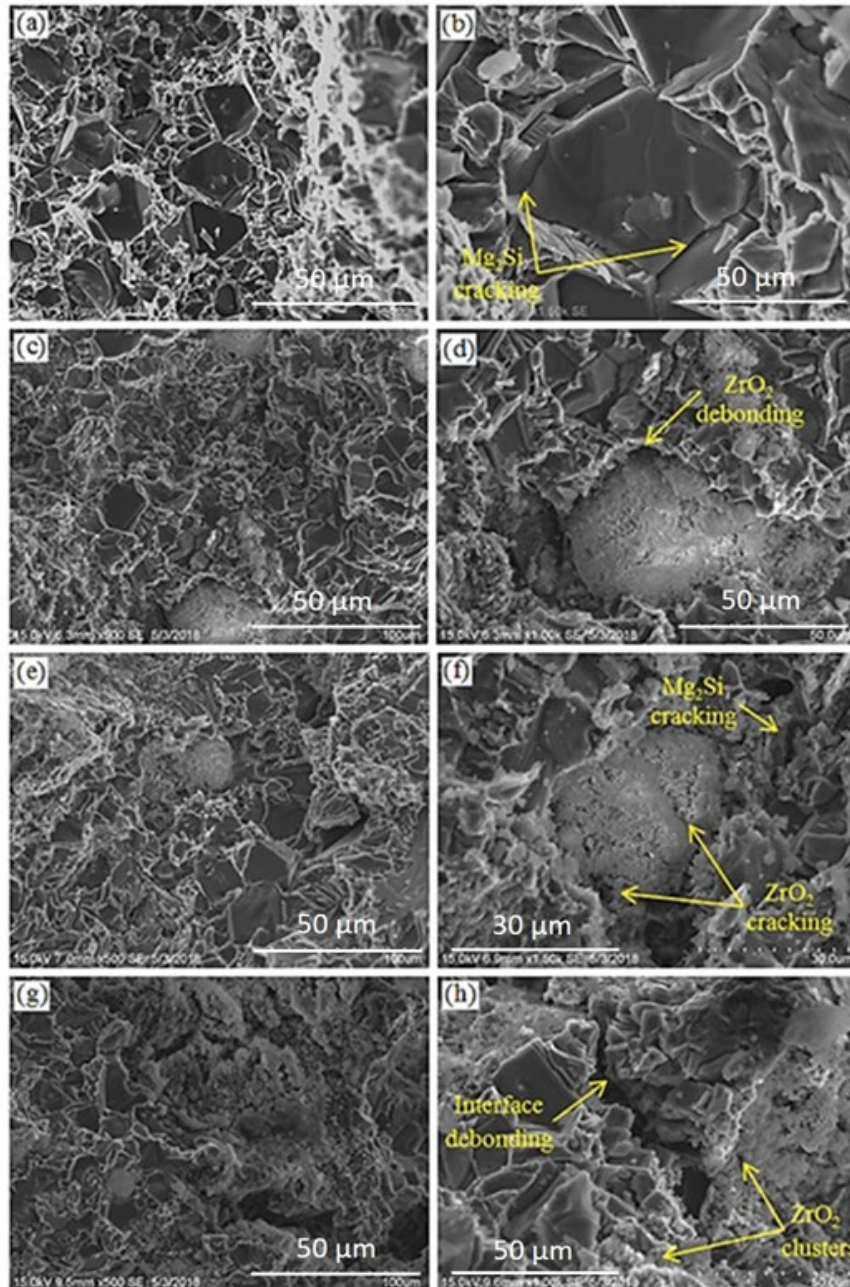


Figure 7: Fracture of hybrid composites with various ZrO_2 concentrations. (a,b) 0, (c,d) 5, (e,f) 10, and (g,h) 15% in low (left) and high (right) magnifications.

The fracture faces of almost all coarse Mg₂Si particles exhibit clear cleavage characteristic creating a rapid fracture deriving from their intrinsic brittleness and pre-cracked structure [13]. As observed in Figure 7(b), the particle fracturing took place in the Mg₂Si. In

fact, in the in-situ composites, the sharp corners of coarse dendritic Mg_2Si particles were the area for localisation of stress concentration; thus, a severe crack with an acute length occurred, causing a brittle mode of fracture. Figures 7(c) and (d) illustrate the Al- Mg_2Si +5% ZrO_2 fracture surface. As shown in Figure 7(d), debonding can be observed in the particle/matrix interface. In fact, the localisation of the stress at the particles' sharp corners may also results in the debonding between the matrix and particles, a likely source of the composite failure.

The Al-20% Mg_2Si -10% ZrO_2 fracture surface is exhibited in Figures 7(e) and (f). As observed, particle cracking was detected on the fracture surface which designated a strong bonding in the matrix/particle interface, indicative of ductile fracture mode. Therefore, stretching load application would result in better support by the ZrO_2 particles. Nevertheless, the fracture surface of Al/ (Mg_2Si +15% ZrO_2) in Figures 7(g) and (h) exhibited a clear cleavage on the hybrid composite fracture surface, a result of inappropriate wettability between matrix and ZrO_2 . Thus, clustering of the ZrO_2 particles took place, representing the debonding in the particles/matrix interface (Figure 7(h)).

Conclusions

With the introduction of the ZrO_2 particles to molten Al-Mg-Si, Al- Mg_2Si - ZrO_2 hybrid composite with relatively homogeneous dispersion of the Mg_2Si and ZrO_2 reinforcements was achieved through in-situ formation of the Mg_2Si particles joined with ZrO_2 ex-situ technique. The addition of ZrO_2 into the Al- Mg_2Si composite decreased the primary Mg_2Si mean size from 50 μm in the base composite to 25 μm after addition of 15% ZrO_2 . Compared to the Al- Mg_2Si composite, Al- Mg_2Si -10% ZrO_2 depicted the highest tensile features in terms of UTS and El (%); nevertheless, Al- Mg_2Si -15% ZrO_2 demonstrated low tensile properties due to the presence of porosity and ZrO_2 agglomeration in the fabricated composites. Cracking of the particles was detected on the fracture surface of the Al/ (Mg_2Si +10% ZrO_2) hybrid composite, indicating more ductile fracture.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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