MICROSTRUCTURE EXAMINATION AND TENSILE PROPERTIES OF Al-20%Mg_2Si-XZRO_2 HYBRID COMPOSITES

Hamidreza Ghandvar[1], Tuty Asma Abu Bakar[2,*] and Mostafa Abbas Jabbar[3]

[1]Department of Chemical and Materials Engineering, New Uzbekistan University, Movarounnahr Street 1, Tashkent, Uzbekistan
[2]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Johor, Malaysia
[3]Department of Mechanical Techniques, Al-Nasiriya Technical Institute, Southern Technical University, Thi-Qar, Al-Nasiriya 64001, Iraq

*tuty@utm.my

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 (ZrO_2) particles were introduced to the Al-Mg_2Si composite via stir casting technique. The influence of various concentrations of ZrO_2 on the structural and tensile properties of the Al-Mg_2Si composite was examined using Scanning Electron Microscope (SEM) and tensile tests, respectively. The findings showed that the introduction of ZrO_2 to Al-Mg_2Si decreased the average mean size of primary Mg_2Si particulates. Adding ZrO_2 particles up to 10 wt.% had a decent distribution in the Al-Mg_2Si matrix; however, increasing the ZrO_2 content to 15 % led to agglomeration of ZrO_2 particles. Furthermore, tensile results demonstrated that Al-Mg_2Si composite with 10% ZrO_2 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% ZrO_2 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, Mg_2Si, ZrO_2, microstructure, tensile properties

Article Info

Received 27th October 2023
Accepted 13th December 2023
Published 20th December 2023

ISSN: 1823-7010, eISSN: 2600-7444

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 47μm, in which with the addition of 5% B_4C, the particle size decreased to 33 μm. 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 μm, which was reduced to 88.36 μm 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%Mg_2Si composite, ADC12 alloy in commercial grade (> 98.0% purity) as well as pure aluminium (> 98.0% purity) were employed. To produce an Al-Mg_2Si-ZrO_2 hybrid composite, initially, the ZrO_2 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 ZrO_2 particles were fixed at 0, 5, 10 and 15%, respectively. Next, inside a graphite crucible, about 300 g of Al-20%Mg_2Si composite was melted. Afterwards, the pre-oxidised ZrO_2 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 Mg_2Si features in the composites, the metallographic specimens underwent the standard grinding and polishing before observing Mg_2Si 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 Mg_2Si 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 ZrO_2 powders to fabricate hybrid composites with the corresponding XRD results of the particles is illustrated in Figure 2.

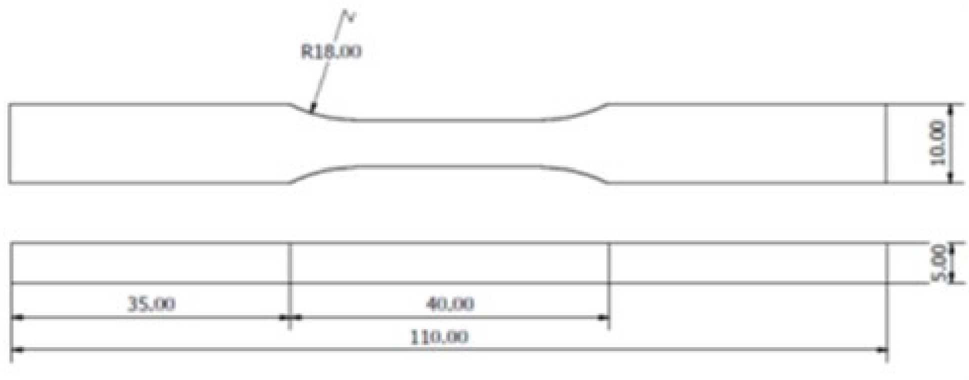

Figure 1: Schematic drawing of the tensile sample according to ASTM E8/E8M (all dimensions are in mm)

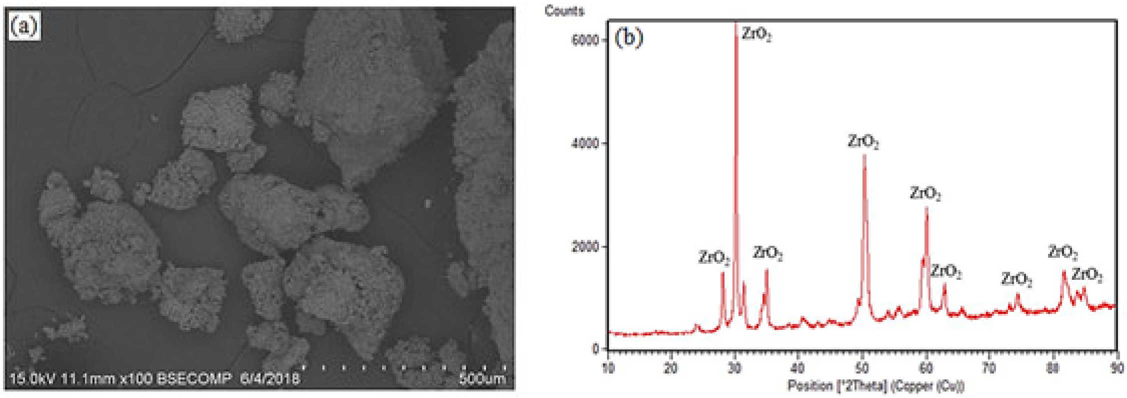

Figure 2: (a) SEM micrograph of ZrO_2 powder and (b) corresponding XRD analysis

Results and Discussion

Thermal Analysis

The cooling curves and derivative curves of Al-20%Mg_2Si in-situ composite with and without various concentrations of ZrO_2 particles are demonstrated in Figure 3(a) to (d).

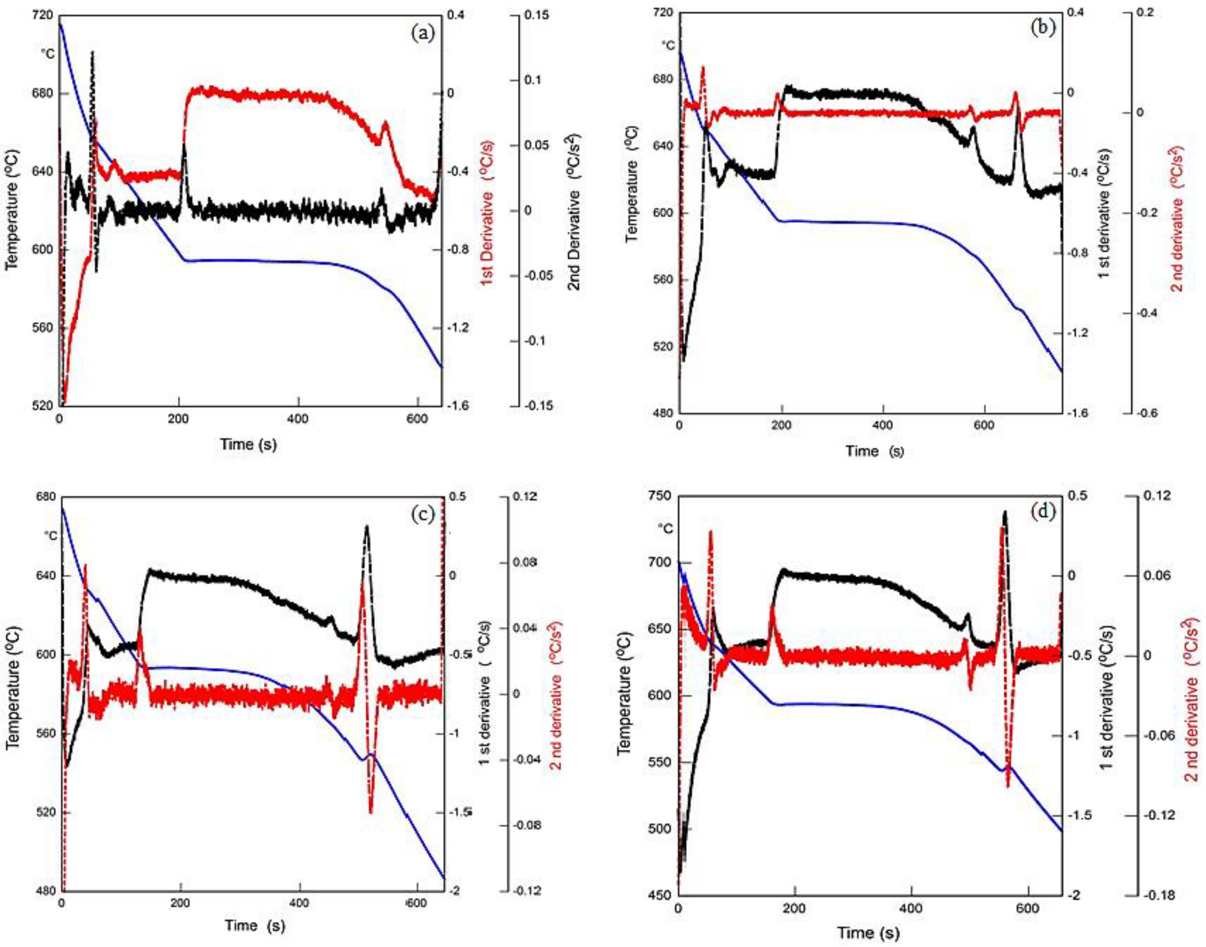

Figure 3: Cooling curve and related derivative curves of (a) Al-20% Mg_2Si, (b) Al/ (Mg_2Si+5%ZrO_2), (c) Al/ (Mg_2Si+10% ZrO_2) and (d) Al/ (Mg_2Si+15% ZrO_2)

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.

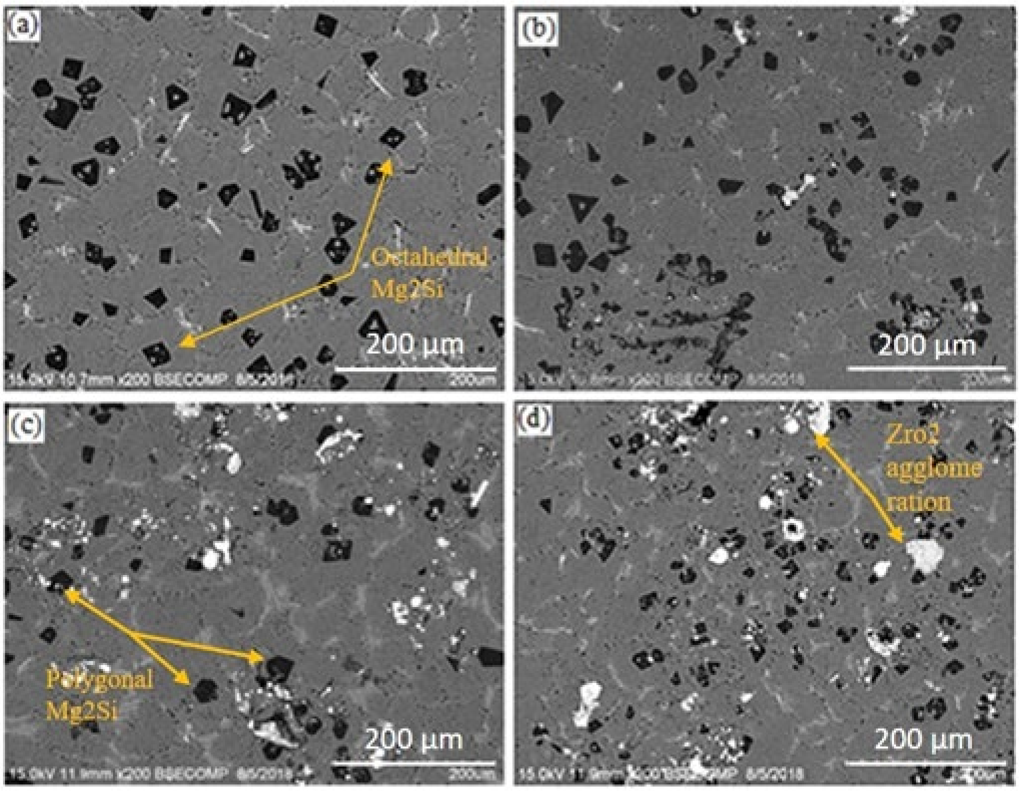

Figure 4: BSE electron micrographs of (a) Al-20%Mg_2Si, (b) Al-20%Mg_2Si-5%ZrO_2, (c) Al-20%Mg_2Si-10%ZrO_2 and (d) Al-20%Mg_2Si-15%ZrO_2 hybrid composites

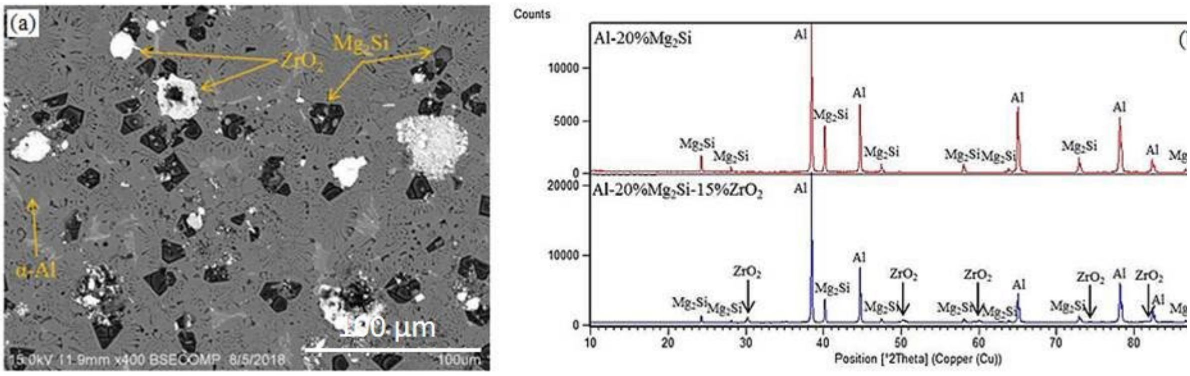

Figure 5: (a) BSE micrograph of Al/ (Mg_2Si + 15% ZrO_2) and (b) Al-20%Mg_2Si composites and X-ray diffraction (XRD) patterns with and without 15% ZrO_2 addition

Tensile Properties

The UTS and El % of Al-20%Mg_2Si composite with and without different contents of ZrO_2 particles are depicted in Figure 6. The UTS and El% increased by 11.7 and 22.8%, respectively with the addition of ZrO_2 particles up to 10%. This was due to the effect of ZrO_2 particles in the reduction of the primary Mg_2Si particles size to 33 µm as well as the morphology alteration of the Mg_2Si crystals to polygonal shape.

Furthermore, another reason for the improvement of tensile properties of Al-Mg_2Si+5/10%ZrO_2 is the existence of proper interfacial bounding in the MMC structure. Indeed, the applied load was supposed to be supported by ZrO_2 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 ZrO_2 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 ZrO_2 exceeded 15%, the tensile properties (UTS and El (%)) decreased due to the agglomeration of ZrO_2 reinforcement in the Al matrix.

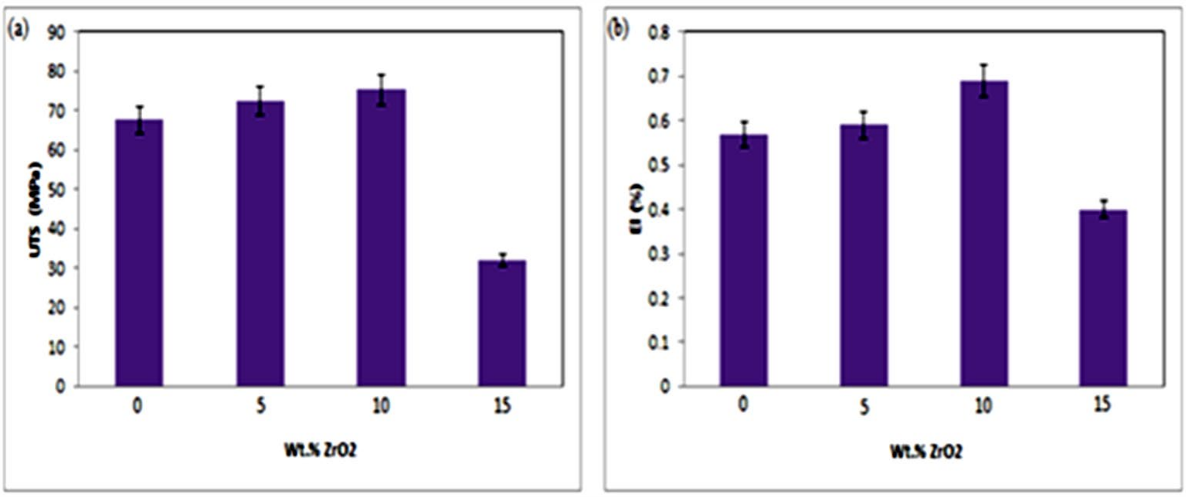

Figure 6: (a) UTS and (b) El% of Al-20%Mg_2Si composite with and without different concentrations of ZrO_2 particles

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%Mg_2Si composite as a result of fracture planes of coarse Mg_2Si 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.

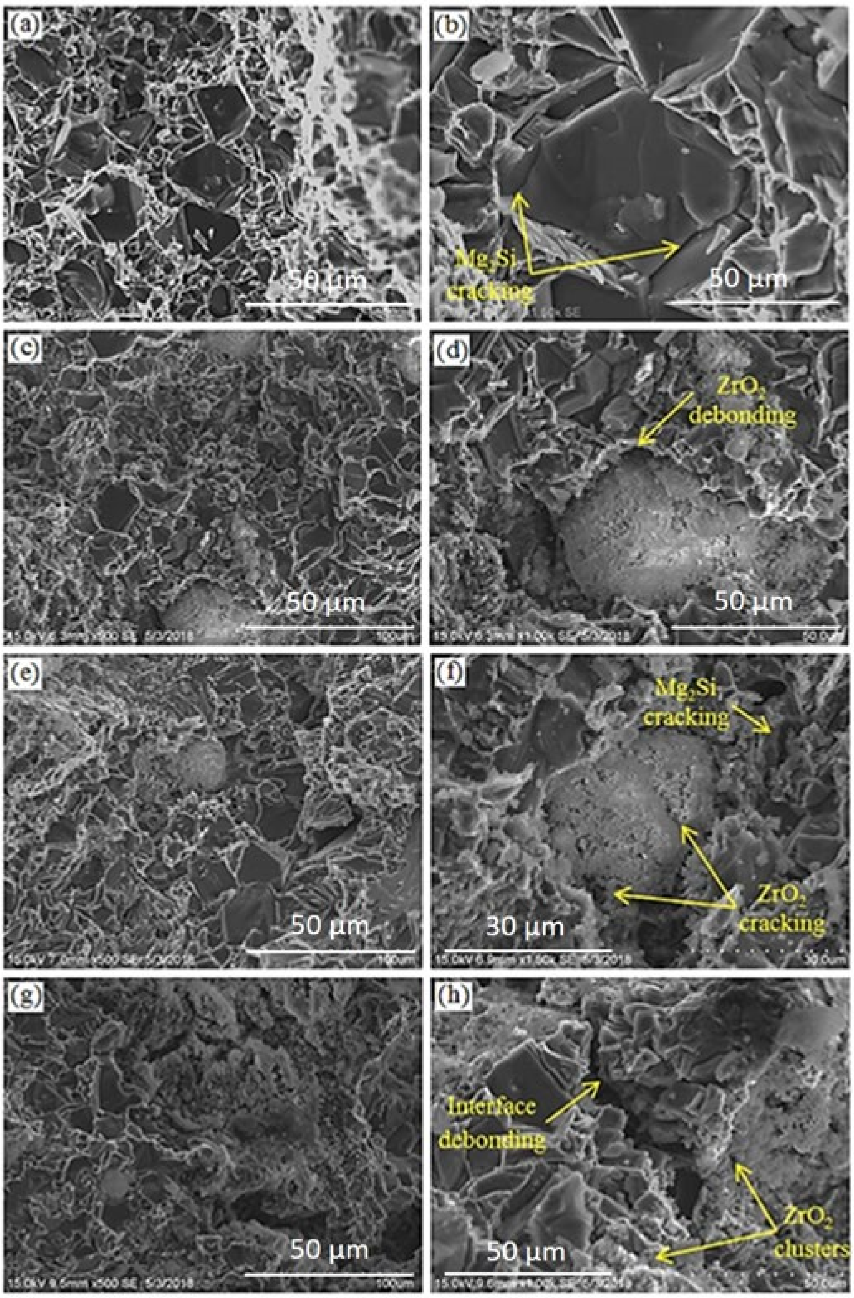

Figure 7: Fracture of hybrid composites with various ZrO_2 concentrations. (a,b) 0, (c,d) 5, (e,f) 10, and (g,h) 15% in low (left) and high (right) magnifications.

The fracture faces of almost all coarse Mg_2Si 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 Mg_2Si. 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.

Acknowledgements

This work is funded by the Ministry of Higher Education under the Fundamental Research Grant Scheme (FRGS), Registration Proposal No: FRGS/1/2022/TK10/UTM/02/45.

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.

References

[1] Kaushik, N. C. & Rao, R. N. (2016). The Effect of Wear Parameters and Heat Treatment on Two Body Abrasive Wear of Al–SiC–Gr Hybrid Composites. *Tribology International*. 96, 184.

[2] Ghandvar, H., Farahany, S., Idris, M. H. & Daroonparvar, M. (2015). Dry Sliding Wear Behavior of A356-ZrO_2 Metal Matrix Composite. *Advanced Materials Research*. 1125, 116-120.

[3] Li, J., Zhao, G., Wu, S., Huang, Z., Lü, S., Chen, Q. & Li, F. (2019). Preparation of Hybrid Particulates SiCp and Mg_2Si Reinforced Al-Cu Matrix Composites. *Materials Science and Engineering A*. 751, 107–114.

[4] Umanath, K., Selvamani, S. T. & Palanikumar, K. (2011). Friction and Wear Behaviour of Al6061 Alloy (SiCp+ Al_2O_3) Hybrid Composites. *International Journal of Engineering Science and Technology*. 3, 5441–5451.

[5] Sharma, S. S., Jagannath, K., Prabhu, P. R., Gowri, S., Harisha, S. R. & Kini, U. A. (2017). Metallography & Bulk Hardness of Artificially Aged Al6061-B_4C-sic Stir Cast Hybrid Composites. *Materials Science Forum*. 880, 140–143.

[6] Ghandvar, H., Jabbar, M. A., Koloor, S. S. R., Petru, M., Bahador, A., Bakar, T. A. A. & Kondoh, K. (2021). Role B_4C Addition on Microstructure, Mechanical, and Wear Characteristics of Al 20%Mg_2Si hybrid Metal Matrix Composite. *Applied Sciences*. 11, 3047.

[7] Ghandvar, H., Jabbar, M. A., Petru, M., Abu Bakar, T. A., Ler, L. J. & Rahimian Koloor, S. S. (2023). Role of YSZ Particles on Microstructural, Wear, and Corrosion Behavior of Al-15%Mg_2Si Hybrid Composite for Marine Applications. *Journal of Marine Science and Engineering*. 11, 1050.

[8] Yuguang, Z., Xiaobo, L., Yuanyuan, Y. & Tianjun, B. (2014). Effect of SiC Particle Addition on Microstructure of Mg_2Si/Al Composite. *China Foundry*. 11(2), 91-96.

[9] Ikeno, S., Matsuda, K., Rengakuji, S. & Uetani, Y. (2001). Precipitation Sequence in a SiC/Al-Mg_2Si Alloy Composite Material. *Journal of Materials Science*. 36, 1921.

[10] Daoud, A. & Abo-Elkhar M. (2002). Influence of Al_2O_3 or ZrO_2 Particulate Addition on the Microstructure Aspects of AlNi and AlSi Alloys. *Journal of Materials Processing Technology*. 120, 296–302.

[11] Chawla, N. & Shen, Y. (2001). Mechanical Behavior of Particle Reinforced Metal Matrix Composites. *Advanced Engineering Materials*. 3, 357-370.

[12] Lewandowski, J. J., Liu, C. & Hunt Jr, W. H. (1989). Effects of Matrix Microstructure and Particle Distribution on Fracture of An Aluminum Metal Matrix Composite. *Materials Science and Engineering A*. 107, 241–255.

[13] Warmuzek, M. (2004). *Aluminium Silicon Casting Alloys: An Atlas of Microfractographs*. (ASM International), pp. 1-124.