Visual Abstract

Mechanical characterization and analysis of tensile fracture modes of ultrasonically stir cast Al6082 composites reinforced with Cu powder premixed Metakaolin particles

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ABSTRACT. The major drawback observed in the ceramic particles reinforced aluminium matrix composites (AMCs) is the reduction of ductility. Incorporating fine metallic particles along with the ceramic reinforcements in the aluminium matrix tends to improve the ductility of the AMCs. This work highlights the effects of dispersing micro (5-20 µm) copper (Cu) particles along with the nano (100-400 nm) Metakaolin particles in the Al6082 matrix. The Metakaolin particles were premixed with Cu powder by means of manual stirring followed by ball milling before embedding into the Al6082 matrix. The total reinforcement composition was maintained as 7.5 wt.% in which 2.5 wt.% consisted of Cu powder. The composites were synthesized using ultrasonication-aided stir casting process. The composites samples were subjected to T6 heat treatment before performing mechanical characterization. The composites with Cu powder premixed Metakaolin particles showed improvement in tensile strength, ductility, compressive strength and hardness. The microstructure evaluation of the composites was performed using Scanning Electron Microscope (SEM) and Optical Microscope (OM). The tensile fracture modes were studied by analysing the fracture surface morphology using SEM.

KEYWORDS. Aluminium matrix composites; Fracture surface; Stir casting; Cu powder; Tensile strength; Ductility; Compression strength.

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INTRODUCTION

Ceramic particles reinforced aluminium matrix composites (AMC) are renowned for their superior specific strength, hardness, wear resistance, thermal stability etc. However, the incorporation of hard ceramic particles in the matrix results in the loss of ductility compared to the matrix [1]. Reinforcing the aluminium matrix with nano-sized reinforcements is considered as a method for improving ductility [2,3], but the high cost of nano-sized particulate reinforcements is a limiting factor for their utilization [4]. Adding metallic powder as reinforcement is observed to be a better and more economic manner to retain the ductility of the AMCs [5]. Fathy et al. [6] reinforced iron powder in the aluminium matrix and observed improvement in strength and ductility but had to compromise the density. Pal et al. [7] prepared aluminium composites with Nickel as reinforcement and observed improvement in strength, ductility and toughness. But, the high cost of Nickel was reported as a limiting factor. Selvakumar et al. [8] developed Al6082 composites by reinforcing molybdenum powder and observed improvement in toughness, strength and ductility. Abraham et al. [9] developed AMCs by reinforcing vanadium particles in the Al6063 matrix and observed improvement in tensile strength without reduction in ductility. Kumar and Chinta [10] observed improvement in tensile strength, hardness and ductility while reinforcing aluminium matrix with Cu particles. Gopi Krishna et al. [11] observed improved tensile strength, hardness and ductility while reinforcing Cu particles in the A356 matrix by means of friction stir processing. Madhusudan et al. [12] fabricated Cu powder reinforced aluminium matrix composites and observed improvement in hardness when compared to the Al-Cu alloy. From the literature [10,11], it could be noted that the Cu particles while reinforced in the aluminium matrix improve the strength of the matrix. The Cu powder while reinforced in the aluminium matrix might also improve the hardness and ductility of the matrix since Cu is harder and ductile than aluminium. Moreover, the utilization of Cu particles as reinforcement in the aluminium matrix is cost-effective compared to other metallic reinforcements such as Nickel, Molybdenum, Vanadium etc.

The enhancement in the mechanical properties (other than ductility) of the AMCs reinforced with metal powder is not as good as that compared to the AMCs reinforced with ceramic particles. This in turn has led to the concept of developing hybrid AMCs in which the primary reinforcement is a ceramic powder and the secondary reinforcement is a metal powder. Kenneth et al. [13] reported improvement in ductility of silicon carbide reinforced AMCs by adding the steel particles. El-Labban et al. [14] observed improvement in the strength and ductility of AMCs while reinforcing Nickel powder along with Al_2O_3 (Alumina) particles. The stir casting technique is supposed to be the most economic method for preparing AMCs with ceramic reinforcements [15]. The ultrasonication-aided stir casting process is used for preparing AMCs while the reinforcement particles are of submicron or nano-size range [16,17]. While incorporating two or more classes of reinforcements in a metal matrix, adopting a premixing method could improve the wettability of reinforcements in the matrix [18,19]. Guel et al. [19] synthesized AMCs by reinforcing different metallic reinforcements such as Cu, Ni and Silver (Ag) along with graphite (C) powder. The metallic powders were mixed with graphite particles using ball milling before introducing them into the aluminium matrix. The AMCs reinforced with Cu-Graphite blend showed better strength and ductility compared to AMCs reinforced with Ni-C and Ag-C blends.

This work aims to study the effect of reinforcing Cu powder premixed Metakaolin particles in the Al6082 matrix. From the literature study, it was observed that adding metal powder along with a ceramic reinforcement in the aluminium matrix could enhance the mechanical properties of the AMCs without lowering the ductility. Bright et al. [16] developed low-cost AMCs reinforced with Metakaolin particles and observed enhanced strength and wear properties at the expense of ductility when compared to the parent metal Al6082. The best composition of Metakaolin reinforcement in Al6082 was observed as 7.5 wt.% [16]. In this work, 2.5 wt.% Cu powder was premixed with the Metakaolin particles while the total reinforcement composition was maintained as 7.5 wt.%. From the literature [10], it was noted that the addition of Cu powder at a weight fraction of about 8 wt.% degraded the composites due to agglomeration. Also, it is a general fact that the maximum weight fraction of ceramic reinforcements should be within 10 wt.% for better wettability with the aluminium matrix. Therefore, the weight fraction of Cu powder was judiciously fixed as 2.5 wt.% such that the total weight fraction of reinforcements (Metakaolin + Cu) will be 10 wt.%. The tensile strength, compressive strength, hardness and ductility of the AMCs with 2.5 wt.% Cu + 5 wt.% Metakaolin was compared with that of the AMC having 7.5 wt.% Metakaolin and the monolithic Al6082 alloy, under both as-cast as well as heat-treated conditions. The microstructure and the fracture surface morphologies of the composites were studied using OM, SEM and Energy Dispersive Spectroscopy (EDS).

MATERIALS AND METHODOLOGY

The Al6082 alloy with a melting point of 550 ºC and a density of 2.7 g/cm^3 was used as the matrix material. Metakaolin particles of sizes range 100 nm to 400 nm and Cu powder of 99% purity with particle size in the range of 5 μm to 20 μm were used as the reinforcement particles. Tab. 1 represents the chemical composition of Al6082 matrix material and Tab. 2 represents the chemical composition of the Metakaolin particles.

Initially, the predetermined amount of Metakaolin particles and the Cu powder were mixed by means of manual stirring followed by ball milling for 1 hour. The premixing of the reinforcement particles improves their wettability in the aluminium matrix [18]. Fig. 1 (a-c) shows the morphology of the Metakaolin particles, Cu powder and the premixed reinforcements. From Fig. 1a it could be noted that the Metakaolin particles have a flake-like structure and from Fig. 1b it is observed that the Cu particles have a spherical morphology. Fig. 2 represents the EDS result of the Metakaolin powder and that of the premixed reinforcements. In Fig. 2a, the EDS result shows the peaks of elements such as aluminium (Al), silicon (Si) and oxygen (O). Aluminium, silicon and oxygen are the major constituents of Metakaolin. In Fig. 2b peaks of Cu could also be identified along with aluminium (Al), silicon (Si) and oxygen (O). In both EDS reports peaks of carbon (C) could also be identified. The substrate of EDS analysis equipment is graphite and this may be attributed to the presence of carbon peak in the EDS report [16].

Constituent	Si	Cu	Mg	Mn	Fe	Ni	Zn	Ti	Cr	Al
Composition %	1.19	0.03	0.89	0.72	0.041	0.03	0.021	0.1	0.15	96.828

Table 1: Chemical Composition of Al6082 [16]

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2	P_2O_5
Composition %	51.85	43.87	0.89	0.20	0.01	0.03	0.28	1.74	0.15

Table 2: Chemical Composition of Metakaolin [16]

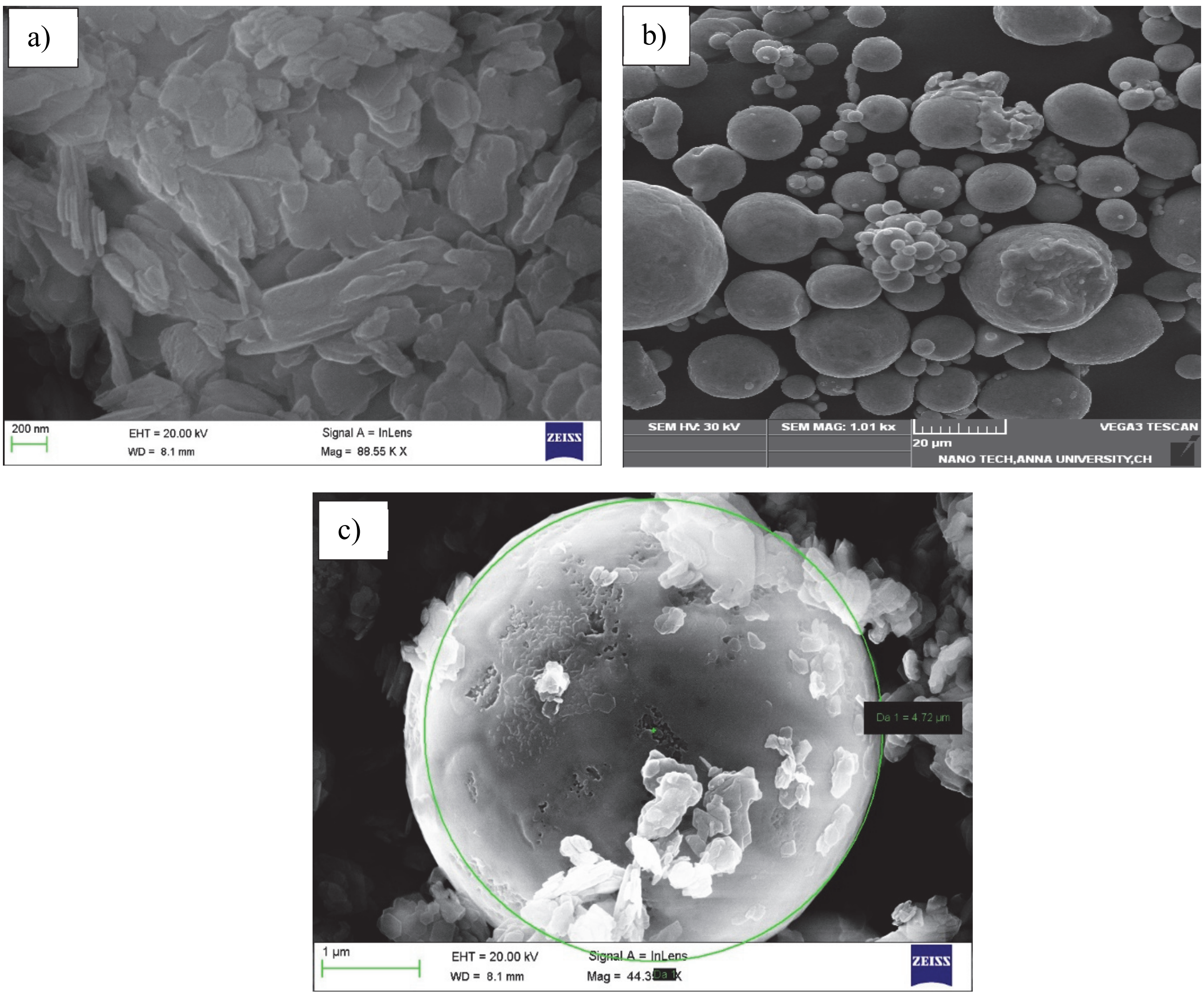

Figure 1: SEM Morphology of (a) Metakaolin Particles; (b) Cu Particles c) Metakaolin and Cu particles blend.

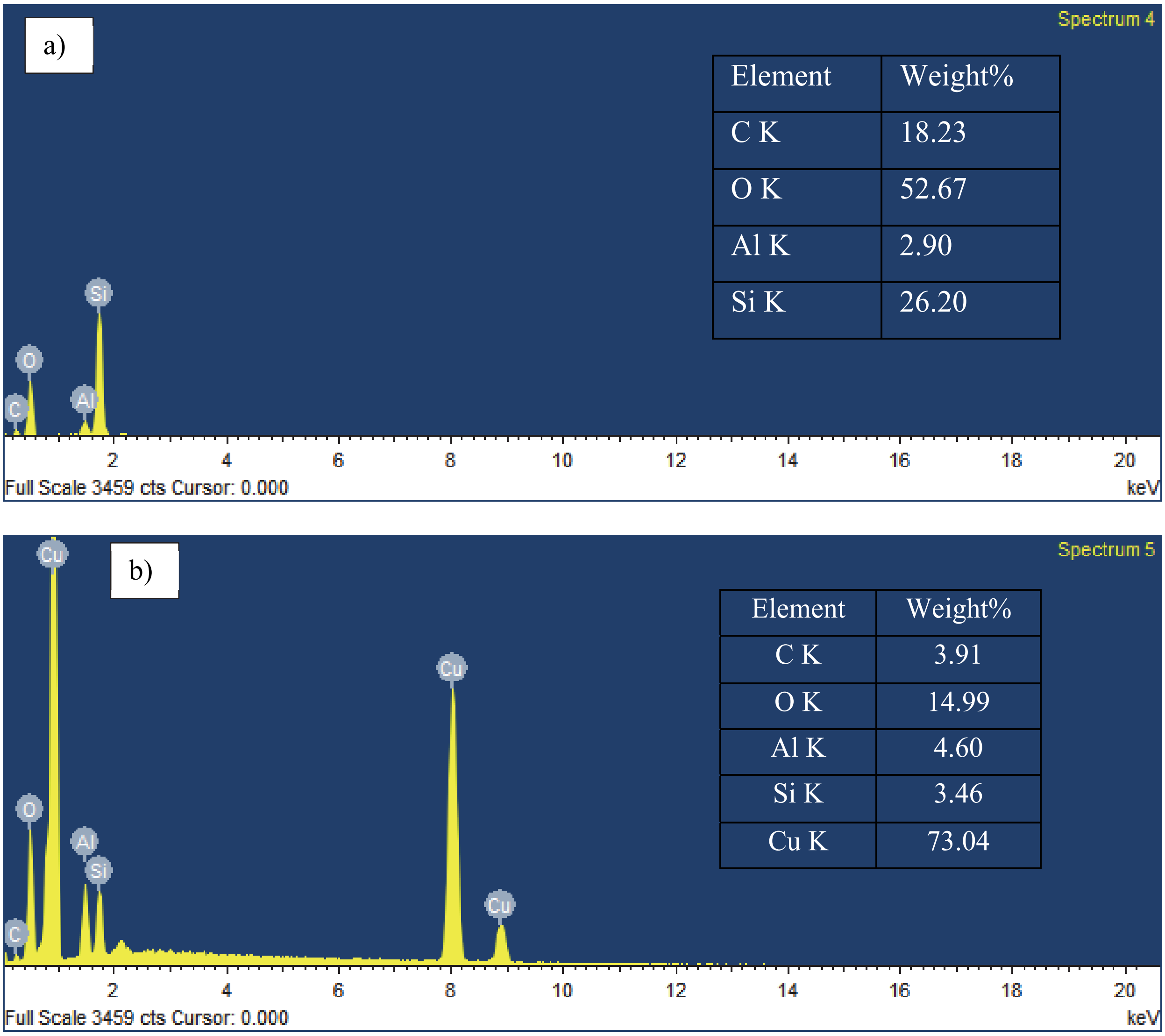

Figure 2: EDS report of (a) Metakaolin Particles; (b) Metakaolin and Cu particles blend.

The schematic diagram for the processing of the aluminium composites is shown in Fig. 3. The ultrasonication-assisted stir casting technique was used for processing the composites. The details of the stir casting setup were explained in Bright et al. [16]. The stir casting setup comprised of an electric resistance furnace with a maximum temperature range of 1000ºC. The ultrasonication setup has a power rating of 2 kW and 20 kHz output frequency. The ultrasonication setup consists of a stepped titanium horn and transducer assembly, ultrasonic generator and inert gas supply. Initially, the Metakaolin and Cu particles were premixed by means of manual stirring followed by ball milling for 1 hour. The premixed reinforcements were then heated to 400°C for 2 hours in a muffle furnace to remove the moisture content and to avoid wettability issues caused due to the thermal mismatch between the reinforcement and matrix [16]. The reinforcement particles were then fed to the aluminium alloy Al6082 melted in the electric resistance furnace. The melt was stirred for 15 minutes initially followed by the ultrasonication process for 45 minutes [16]. The temperature of the melt was maintained at 750 °C throughout the process. The composite samples were subjected to the T6 heat-treatment process. The T6 heat treatment process was performed by solutionizing the composite sample at 530 °C for a duration of 1 hr followed by water quenching and artificial ageing for 8 hours at 175 °C [16]. Tab. 3 shows the composition of the prepared AMC samples. The porosity of the AMCs was computed by finding the difference between theoretical and experimental densities. The theoretical density was evaluated using the rule of mixture principle and the experimental density was measured using the Archimedes principle. The tensile test was performed based on the ASTM E8/E8M standard, the compression test was performed based on ASTM E9/89a standard and the microhardness of the samples have been estimated with respect to the ASTM E92 standard using the Vickers hardness testing machine. Fig. 4a represents the tensile test specimen, Fig. 4b represents the tensile test specimen after fracture, Fig. 4c represents the compression test specimen and Fig. 4d represents the compression test specimen after fracture. All the experiments were done on three different samples and the deviation was demonstrated by means of error bar in the plots representing mechanical properties.

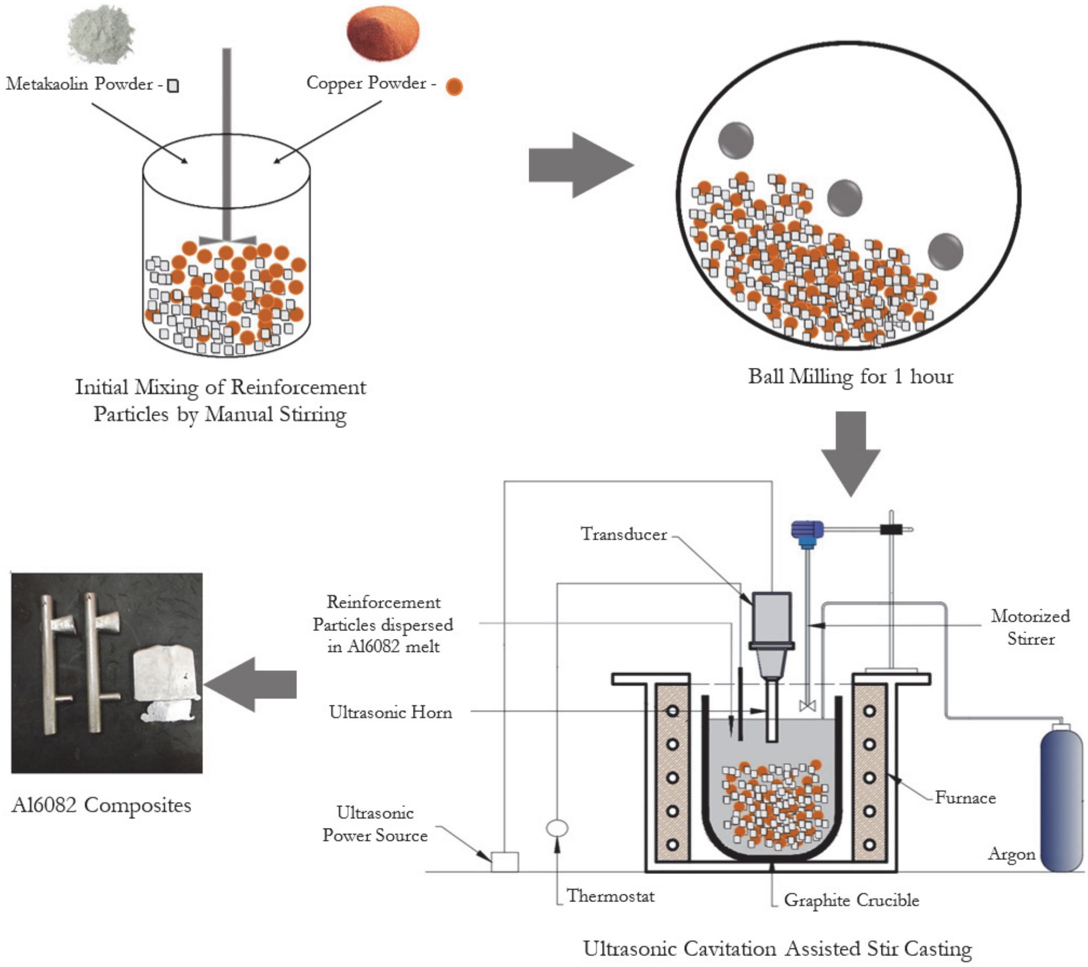

Figure 3: Schematic diagram representing the processing of Al6082 matrix composites.

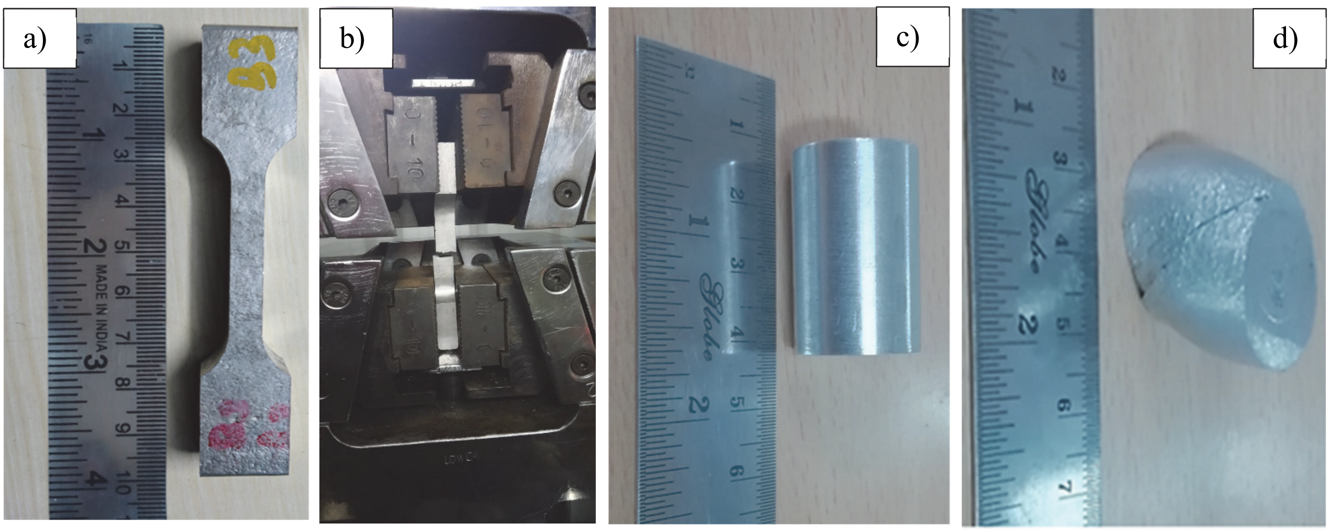

Figure 4: (a) Tensile test specimen; (b) Tensile test specimen after fracture; (c) Compression test specimen; (d) Compression test specimen after fracture

Composite Sample	Metakaolin	Cu (wt.%)	Al6082	Porosity
1	0	0	100	2.31
2	7.5	0	92.5	1.24
3	5	2.5	92.5	1.86

Table 3: Composition of the composite samples and their porosities.

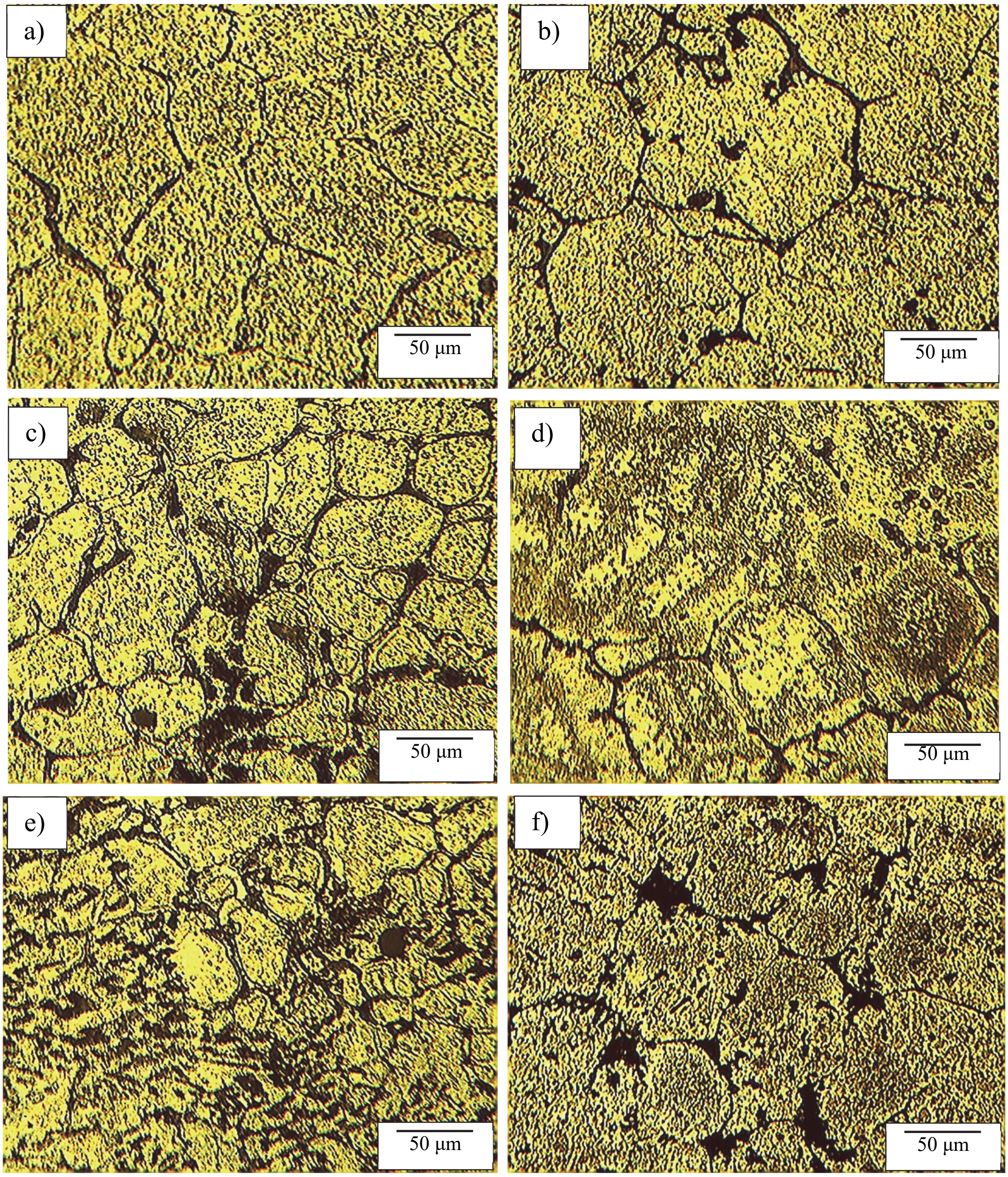

Figure 5: Optical micrographs of (a) As Cast Al6082 (b) Heat Treated Al6082(c) As Cast AMC with 7.5 % Metakaolin; (d) Heat Treated AMC with 7.5 % Metakaolin; (e) As Cast AMC with 5 wt% Metakaolin + 2.5 wt%. Cu; (f) Heat Treated AMC with 5 wt% Metakaolin + 2.5 wt%. Cu

RESULTS AND DISCUSSION

Microstructure

The optical micrographs of the AMCs are shown in Fig. 5 (a-f). Fig. 5a and Fig. 5b represent the optical micrographs of the monolithic alloy under as-cast and heat-treated conditions. The dark lines in the micrograph denote grain boundaries. Fig. 5c represents the as-cast AMC with 7.5 wt. % Metakaolin. The microstructure has a refined grain structure with increased grain concentration. Increased grain concentration could be attributed to the dispersion of the nano-sized Metakaolin particles in the matrix. The reinforcement particles are present in the matrix and along the grain boundaries. Fig. 5d represents T6 heat-treated AMC with 7.5 wt. % Metakaolin composite in which the grain boundaries were occupied by Metakaolin particles. Fig. 5e shows as-cast AMC with 5 wt. % Metakaolin and 2.5 wt.% Cu particles. The micrograph reveals the presence of increased particle clusters as compared to that of the as-cast AMC sample with 7.5 wt.% Metakaolin particles. Fig. 5f represents T6 heat-treated AMC with 5 wt % Metakaolin and 2.5 wt.% Cu particles.

While Al-Cu alloys are subjected to T6 heat treatment, it results in the precipitation of $CuAl_2$ along the grain boundaries which in turn improves the mechanical behaviour of the alloys as mentioned in the literature [12,20]. Similarly, while Al-Mg-Si alloys such as Al6082 are subjected to T6 heat treatment, it results in the precipitation of Mg_2Si along the grain boundaries which in turn improves the mechanical behaviour of the alloys as mentioned in Zhu et al. [22]. Gopikrishna et al. [11] reported on the precipitation of $CuMgAl_2$ intermetallic while subjecting the A356-Cu particulate composite to T6 heat treatment. From the above facts, it could be attributed that there is a possibility for the formation of both Mg_2Si and $CuAl_2$ intermetallic in the solid solution. Since Al6082 is an Al-Mg-Si alloy similar to the A356 alloy, the $CuMgAl_2$ intermetallic might also precipitate along the grain boundaries. However, more detailed characterization is required to arrive at a conclusion.

Fig. 6 represents the SEM with EDS report of AMC with 5 wt.% Metakaolin and 2.5 wt.% Cu particles. The scattered reinforcement particles were observed in the SEM micrograph The EDS report represents the presence of element peaks of aluminium (Al), silicon (Si), oxygen (O) and Cu (Cu).

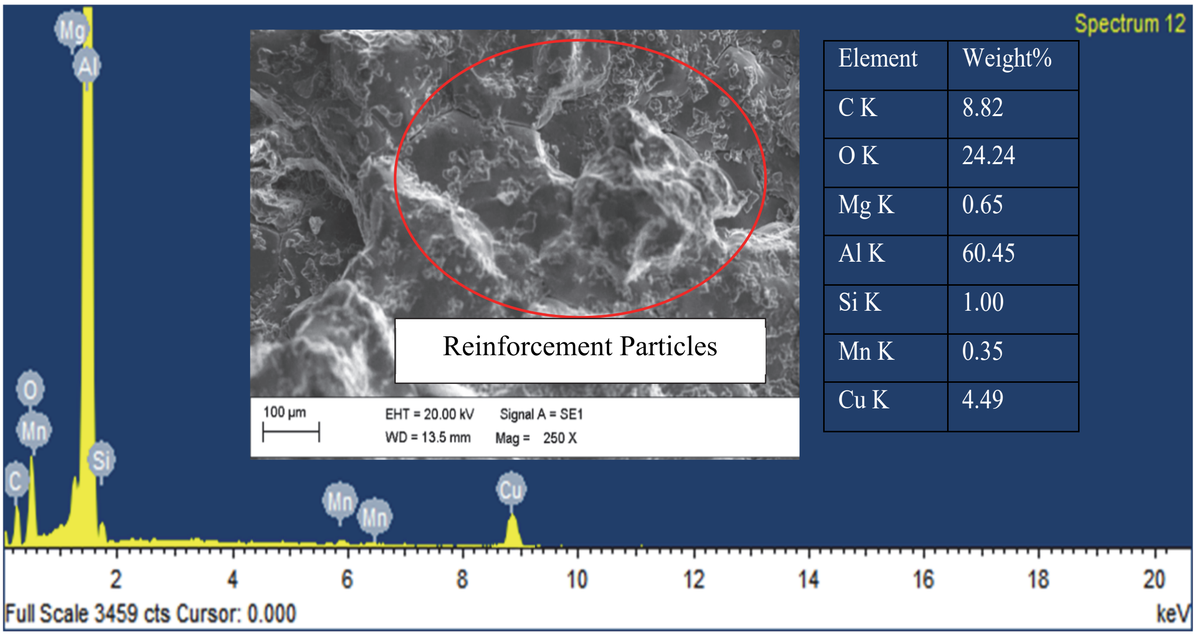

Figure 6: SEM with EDS of the as-cast AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu

Tensile properties

Fig. 7 represents the comparison between tensile strength, yield strength and ductility of the AMCs.

From Fig. 7, it could be noted that the AMCs with 5 wt.% Metakaolin + 2.5 wt.% Cu possesses more tensile strength, yield strength and ductility than the AMCs with 7.5 wt.% Metakaolin reinforcement and the monolithic Al6082 alloy under both as-cast and heat-treated conditions.

The tensile strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was observed to be 22.4% and 20.1% higher when compared to AMCs with 7.5 wt.% Metakaolin under as-cast and heat-treated conditions respectively. Also, the tensile

strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was observed to be 74.1% and 83.9% higher when compared to the monolithic alloy under as-cast and heat-treated conditions respectively. A similar trend was also observed for the yield strength of the composites.
The ductility of the AMCs was characterized by evaluating the % elongation. The ductility of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as 85.5% higher and 28.16% higher when compared to AMCs with 7.5 wt.% Metakaolin under as-cast and heat-treated conditions respectively. Also, the ductility of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as 4.96% higher and 6.99% higher when compared to the monolithic alloy under as-cast and heat-treated conditions respectively.
In all the cases the tensile strength and yield strength of heat-treated AMCs were observed to be higher than that of the as-cast AMCs. However, the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu showed lower ductility under the heat-treated condition compared to the as-cast condition.

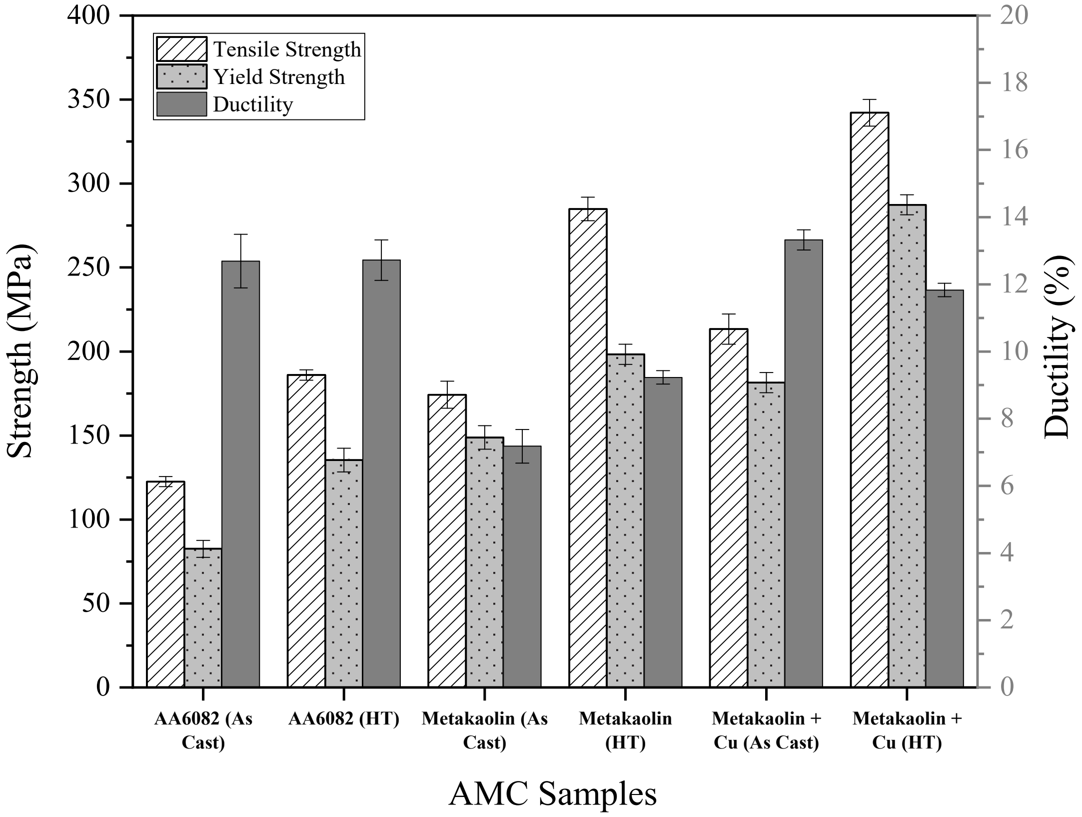

Figure 7: Comparison of tensile strength, yield strength and ductility of AMCs

Fracture surface morphology

The SEM images shown in Fig. 8 (a-d) represent the fracture surface morphology of the AMCs. Fig. 8a denotes the presence of dimples, tear ridges and pores on the fracture surface of as-cast AMC with 7.5 wt.% Metakaolin. The dimples in the fracture surface represent the ductile mode of failure while the pores denote the pull-out of reinforcement particle clusters from the aluminium matrix [21]. The particle pull-out may be accounted for brittle failure mode and justifies the lower ductility of the AMC. The fracture surface of heat-treated AMC with 7.5 wt.% Metakaolin shown in Fig. 8b also implies the presence of dimples, tear ridges and pores. Precipitation hardening results in the formation of the fine precipitates of Mg_2Si which will increase the resistance to the tensile load. The increased strength and ductility of the heat-treated AMC with 7.5 wt.% Metakaolin could be attributed to the combined effect of dispersion of fine Metakaolin particles along the matrix and grain boundaries and the precipitation of the Mg_2Si.

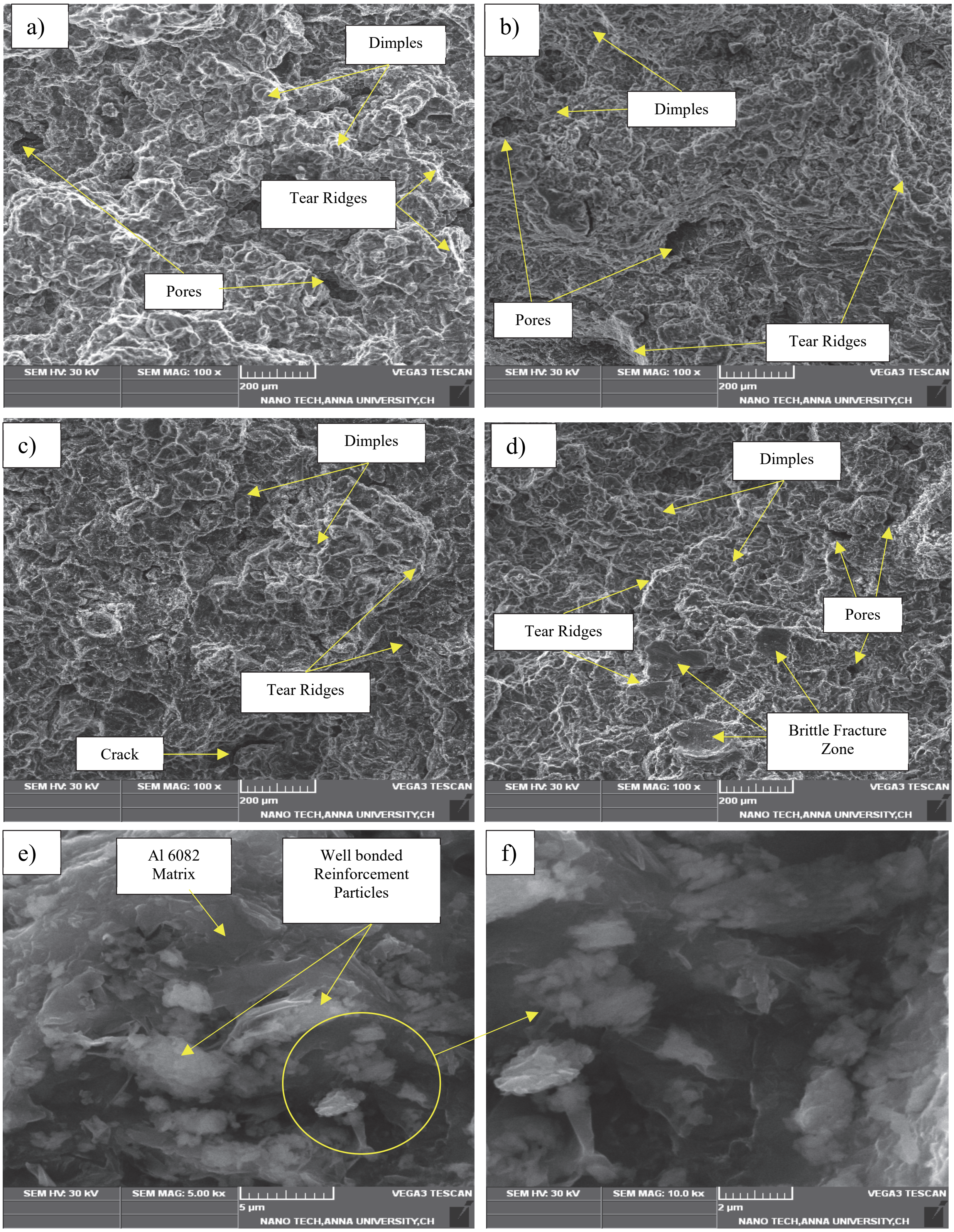

Figure 8: Tensile fracture surface morphologies of (a) As-Cast AMC with 7.5 % Metakaolin; (b) Heat-Treated AMC with 7.5 % Metakaolin; (c) As-Cast AMC with 5 wt% Metakaolin + 2.5 wt%. Cu; (d) Heat-Treated AMC with 5 wt.% Metakaolin + 2.5 wt%. Cu; e) and f) Fractographies of AMC with 5 wt% Metakaolin + 2.5 wt%. Cu - showing good bonding between reinforcements and matrix

Fig. 8c illustrates the fracture surface of AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu. From Fig. 8c, the presence of dimples and tear ridges could be noted in dominance while very few pores were observed. This in turn could be accounted for the enhanced ductility. The Cu particles dispersed along with the Metakaolin particles may take place in solid solution strengthening along with dispersion strengthening. The combined effect of solid solution strengthening and dispersion strengthening induced by Metakaolin and Cu particles might have increased the tensile strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu. Fig. 8d represents dimple and tear ridges on the fracture surface of the heat-treated AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu. The heat treatment results in the precipitation of fine Mg_2Si, $CuAl_2$ and $CuMgAl_2$ phases in the matrix which acts as a barrier to the tensile loading in addition to the resistance offered by the dispersed particles of Cu and Metakaolin. This could be attributed to the higher tensile and yield strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu under heat-treated conditions. However, a reduction in ductility is observed for the heat-treated AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu, which could be attributed to the brittle mode of failure induced due to the precipitation of Mg_2Si, $CuAl_2$ and $CuMgAl_2$ phases. Mg_2Si, $CuAl_2$ and $CuMgAl_2$ intermetallic are hard and brittle. Generally, these precipitates act as a barrier to failure due to tensile load and indentation. Thus, the strength and hardness of the composites are improved. On the other hand, the mode of fracture of the composites induced by these precipitates may be brittle. As a result, the T6 heat-treated AMC with 5 wt% Metakoalin + 2.5 wt% Cu possessed brittle mode of failure which was evident from Fig. 8d. This, in turn, may also be attributed to the reduction in ductility observed for the same when compared to as-cast AMC with 5 wt% Metakoalin + 2.5 wt% Cu.

Brittle zones of failure in which the fracture occurred without the formation of dimples could be noted in the fracture surface of the heat-treated AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu. This trait was absent in the case of the as-cast sample with the same composition. However, the AMCs developed by premixing Metakaolin with Cu exhibited more ductility compared to the AMC without Cu premix. This may be due to the improved amount of wettability of the reinforcements within the aluminium matrix induced by the Cu premixing [12]. This in turn might have improved the interfacial bonding between the reinforcement particles and the Al6082 matrix. The absence of pores and particle pull out in the fracture surface of AMCs with 5 wt.% Metakaolin + 2.5 wt.% Cu could be attributed to the good bonding between the reinforcement particles and the Al6082 matrix as shown in Figs. 8e and 8f.

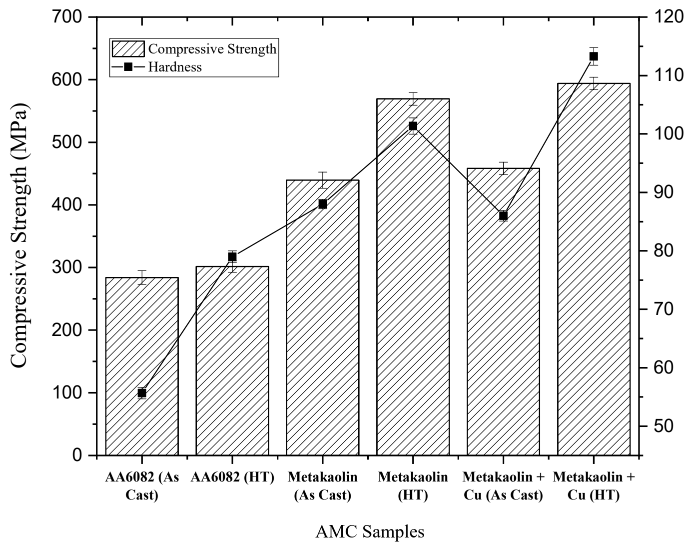

Figure 9: Comparison between compressive strength and hardness of AMCs

Compressive strength and microhardness

Fig. 9 represents the comparison between the compressive strength and microhardness of the AMCs. The compressive strength was observed to be slightly improved for the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu under both as-cast and heat-treated conditions. The compressive strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as 4.26% higher and 4.19% higher when compared to AMCs with 7.5 wt.% Metakaolin under as-cast and heat-treated conditions respectively. Also, the compressive strength of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as almost double as compared to that of the monolithic Al 6082 alloy under both as-cast and heat-treated conditions. The improvement in the compressive strength may be attributed to the dispersion strengthening attained as a result of the scattering of Cu and

Metakaolin particles and solid solution strengthening due to the dissolving of Cu in Al6082. The heat treatment improved the compressive strength as a result of precipitation strengthening. The porosity of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was slightly higher than the AMC with 7.5 wt.% Metakaolin as discussed in Tab. 3. The optical micrographs shown in Fig. 5b also denote the same. The compressive loading might result in the closure of the pore [2,18]. This, in turn, might have resulted in the improvement of the compressive strength of AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu.
The microhardness value of AMCs with 5 wt.% Metakaolin + 2.5 wt.% Cu was observed to be slightly lower than that of AMC with 7.5 wt.% Metakaolin in the as-cast condition. The microhardness of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as 2.27% lower than AMCs with 7.5 wt.% Metakaolin under as-cast conditions. Cu particles are harder than aluminium matrix but the micro-sized Cu particles might not have induced much resistance to the downward motion of the indenter compared to AMC with 7.5 wt.% Metakaolin. The presence of a slightly higher amount of pores in AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu compared to AMC with 7.5 wt.% Metakaolin might also have advanced the deformation due to the micro-indentation [16]. However, under heat-treated conditions AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu is observed to be higher than that of AMC with 7.5 wt.% Metakaolin. The microhardness of the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu was noted as 11.7% higher than AMC with 7.5 wt.% Metakaolin under heat-treated condition. The increased microhardness of the composites under heat-treated condition may be attributed to the formation of $CuMgAl_4$ precipitates along the grain boundaries [11].

Conclusion

The AMCs with Cu powder premixed Metakaolin particles were synthesized successfully and the mechanical behaviour was studied. Following observations were noted,

- The microstructure showed dispersion of the reinforcement particles in the matrix. The presence of the constituent elements was noted by performing the SEM with EDS study of the prepared AMCs.
- The tensile strength, yield strength and ductility of the Al6082 AMC with Cu powder premixed Metakaolin were noted to be higher when compared to Al6082-Metakaolin AMC without Cu powder premix under both as-cast and heat-treated conditions.
- The strengthening mechanism of the Al6082 AMC with Cu powder premixed Metakaolin could be attributed to dispersion strengthening as a result of dispersion of the Cu and Metakaolin particles in the Al6082 matrix, solid solution strengthening due to the dissolving of Cu in aluminium and strengthening due to precipitation hardening as a result of heat treatment.
- The fracture surface of the AMCs showed dimples and tear ridges along with brittle facets. A large number of pores were observed on the Al6082 -Metakaolin composites without Cu powder premix compared to the Cu powder premixed Metakaolin particles reinforced AMCs. The occurrence of pores implies particle pullout during tensile loading due to improper wettability. The addition of Cu powder might have improved the wettability and this could be ensured by the absence of pores on the fracture surface of the Al6082- 2.5 wt.% Cu + 5 wt.% Metakaolin AMC.
- The increase in compressive strength of the Al6082-Metakaolin AMC with Cu powder premix may be attributed to dispersion strengthening and the pore closure phenomenon under compressive loading.
- The reduction in the microhardness of the Al6082 AMC-Metakaolin AMC with Cu powder premix might be due to the presence of pores on the interface of the AMC surface and indentation. The heat treatment might have improved the microhardness as a result of precipitation strengthening.
- The tensile strength, yield strength, compressive strength and hardness of heat-treated AMCs were observed to be higher than that of the as-cast AMCs. The ductility of heat-treated AMC with 7.5 wt.% Metakaolin particles were observed to be higher than that of the same under as-cast conditions while the AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu showed lower ductility under heat-treated conditions compared to AMC with 5 wt.% Metakaolin + 2.5 wt.% Cu as-cast conditions. This trend was attributed to the brittleness induced on the AMCs due to the possibility of the formation of intermetallic phases such as Mg_2Si, $CuAl_2$ and $CuMgAl_2$ as a result of heat treatment.

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