Research Article

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On the applicability of Cu–17Zn–7Al–0.3Ni shape memory alloy particles as reinforcement in aluminium-based composites: Structural and mechanical behaviour considerations

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Abstract: The potentials of CuZnAlNi shape memory alloys to serve as viable reinforcement in Aluminium matrix composites (AMCs) was investigated. The AMCs were double stir cast developed, containing 4, 6, and 8 wt% CuZnAlNi particles; and their structural characteristics and mechanical properties were compared with that of the unreinforced Al alloy and AMC containing 8 wt% SiC. Scanning electron microscopy and X-ray diffraction results show that the CuZnAlNi refined the grain size, and increase in the CuZnAlNi wt% resulted in the formation of varied AlCu-based intermetallics, apart from the primary Al rich phase. The strength indicators – hardness, ultimate tensile strength, and specific strength largely improved with increase in the CuZnAlNi wt% and were comparatively higher than that of the unreinforced Al alloy and AMC reinforced with 8 wt% SiC for the 6 and 8 wt% CuZnAlNi reinforced AMC (specific strength being the only exception). The percentage elongation and fracture toughness values of the AMCs reinforced with CuZnAlNi (12–14.5% and 10.5–12.3 MPa $m^{1/2}$) were equally superior to the SiC reinforced AMC (9% and 6.5 MPa $m^{1/2}$, respectively). However, a partial reduction in the % elongation was observed with the increase in the CuZnAlNi wt%. Improved matrix/particle interface bonding, matrix refinements, thermoelastic-induced compressive residual stresses, inherent ductile, and tough nature of the SMA were advanced as mechanisms responsible for the improvements in properties.

Keywords: aluminium matrix composites, metallic reinforcements, Cu based shape memory alloys, strengthening mechanisms, damage tolerance, thermoelastic effect

1 Introduction

The commercial application of aluminium matrix composites (AMCs) in technological sectors such as automobile, electronics, aerospace, military, and sports has witnessed a huge surge, since the beginning of the new millennium [1–3]. This is due to the amazing material property combinations, which they are tailor-made to possess. For structural and damage-sensitive applications, there are currently efforts aimed at making AMCs more service reliable and competent. The widespread use of inherently brittle ceramics as reinforcement in AMCs has resulted in considerably low toughness and ductility in the AMCs, lowering damage tolerance [4–6]. In order to address these short-comings in structural and damage tolerant properties observed in AMCs, interest has now shifted to the assessment of metallic materials in place of ceramics, as reinforcement [7].

Metallic materials are fundamentally tougher and more ductile than ceramics, thus are hypothetically,

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projected to offer improved toughness and ductility in AMCs [8,9]. Several studies have attested to the validity of this hypothesis [7]. However, in some structural and damage tolerant applications, the capacity of AMCs to dampen the effect of vibration in addition to offering other basic service properties is considered an important performance index. Since most metallic materials such as steel, which have been used as metallic reinforcement, are known to possess relatively low damping properties [10–12], there has been concerns if they could impart lower damping capacity on these metallic reinforced AMCs. On this premise, some authors have explored the use of shape memory alloys (SMAs) as reinforcement in AMCs, because of their native high damping properties and good mechanical properties [10,13,14].

A number of studies have shown that the use of NiTi as reinforcement in AMCs help enhance the adaptive properties of the AMCs, through the reversible thermo-elastic martensitic transformation which engenders native sensing, high damping capacity, and self-strengthening [14–18]. On account of limited $NiTi_p$/Al interfacial diffusion, the shape memory properties of the $NiTi_p$ in the composite is significantly preserved. Thus, its capacity to undergo the reversible phase transformation between martensite and austenite is unhindered. In $NiTi_p$, pre-deformed in the martensite state, the shape memory thermo-elastic transformation is reported to induce microscopic scale compressive residual stresses into the matrix, which contributes to strengthening and enhanced fracture toughness [14,17]. In friction stir processed $NiTi_p$ reinforced Al 5083, strengthening in SMA reinforced AMCs has also been linked to grain refinement, geometrically necessary dislocations, and load transfer effect due to well bonded $NiTi_p$/Al 5083 matrix interfaces [14].

Critical survey of existing literature shows that most of what is understood about SMA reinforced AMCs are based on systems where NiTi was used as reinforcement. NiTi is, however, noted to be quite expensive, delicate, and difficult to process [10]. Thus, a more cost effective SMA, matching reasonably the shape memory properties of NiTi, would be logically open for consideration. In the present study, the use of low-cost SMAs based on CuZnAlNi is proposed for use as reinforcement.

CuZnAl based SMAs are largely noted for their modest thermoelastic characteristics and excellent damping properties [10,13]. On account of their intrinsic high damping properties, a CuZnAl- based reinforcement in AMCs is expected to yield an overall improvement in mechanical damping capacity.

In this preliminary study, the room temperature mechanical properties of AMC reinforced with Cu–18Zn–7Al–0.3Ni, is investigated. Alaneme and Umar [12] reported that Cu–18Zn–7Al–0.3Ni SMA possesses very good combination of mechanical and damping properties. Its use as reinforcement in AMCs was only reported in a recent study by some of the authors, but the scope of the investigation was on the flow stress behaviour during hot deformation processing [19]. To the best of our knowledge, there is no literature which has reported on the room temperature mechanical behaviour of this grade of AMC reinforced with Cu–17Zn–7Al–0.3Ni-based SMA. The study intends to provide answers to the following: How does the mechanical behaviour of the Al–CuZnAlNi-based composites differ from that of the unreinforced Al alloy and the Al alloy reinforced with SiC? Are these mechanical properties dependent on the weight fraction of the CuZnAlNi SMA? Can the outcomes from structural characterization provide useful insights in understanding the reasons for the observed mechanical properties trends?

The answers to these research questions will help provide better understanding of the suitability and applicability of CuZnAlNi-based SMAs as reinforcement in the development of AMCs for structural-damage tolerant and mechanical damping applications.

2 Materials and method

2.1 Materials preparation and composite production

Al–Mg–Si alloy with composition Al–0.43Si–0.42Mg–0.1Fe–0.11Cu–0.02Mn–0.01Zn was selected as composite matrix, while Cu–18Zn–7Al–0.3Ni-based SMA developed from a previous study [12] was selected as reinforcement. The CuZnAlNi SMA was milled to average particle size of 30 μm using a conventional planetary ball mill (with steel ball diameter of 10 mm and milling time of 4 h), while analytical pure grade SiC (30 μm) was procured to develop the AMC composition that served as control sample. AMCs containing 4, 6, and 8 wt% of the CuZnAlNi SMA particles and AMC containing 8 wt% SiC were developed alongside the unreinforced alloy. The composites were produced using double stir casting, guided by charge calculations and the processing routines reported in detail by Alaneme and Aluko [21]. The Al–Mg–Si alloy was melted completely in a crucible furnace, then cooled slowly to 600 ± 20°C. CuZnAlNi/SiC particles, preheated at 250 ± 10°C, were added at this stage to form a semi-solid metallic slurry, with manual stirring for 5 min, to achieve a homogeneous mix.

The mixture was superheated to 750 ± 20°C, and stirred with a mechanical stirrer, operated at 400 rpm for 10 min. The composite was then cast using sand moulds.

2.2 X-ray diffraction (XRD) and scanning electron microscopy (SEM)

Phase identification on the AMC samples was carried out by conducting XRD scans on a Bruker D2 phaser® diffraction machine. The measurements were taken at room temperature within 2θ angles of 10–90°. The machine was operated at a generator setting of 30 kV and 20 mA and fitted with Co Kα radiation. PANalytical (v3.0e) X'pert Highscore software was then used in analysing the patterns obtained from the scans.

The microstructural features and the phase composition of the AMC samples were analysed using a Zeiss Sigma field emission gun SEM (FEG-SEM) operated in backscattered mode. The FEG-SEM is also equipped with an Oxford energy dispersive X-ray (EDX) detector. The backscattered electron (BSE) imaging was carried out at 20 kV to distinguish between the phases present in the samples. EDX spectroscopy area analyses were conducted on the samples to verify their composition.

The samples for the examination were subjected to grinding using silicon carbide abrasive paper with different grit sizes (500–4,000 grit). Thereafter, they were polished to mirror-like surface finish using alumina suspension. For BSE imaging, the samples were etched using Weck's reagent for ~18 s before cleaning with ethanol in an ultrasonic bath and then dried using compressed air.

2.3 Mechanical behaviour

The mechanical behaviour of the Al–CuZnAlNi-based composites was evaluated to assess the composites' strength indices, capacity to sustain plastic deformation and formability (% elongation), and damage tolerance as evaluated by the resistance to crack propagation of the composites (fracture toughness). These properties were compared with that of the unreinforced Al alloy and the Al-8 wt% SiC composite.

2.3.1 Hardness testing

The hardness of the Al alloy Al–CuZnAlNi- and Al–SiC-based composites was evaluated using Vickers hardness measurement in accordance with ASTM E92-17 standard [21]. The samples were prepared plane parallel to metallographic finish, and testing was conducted with the use of a 300 kgf load for a dwell time of 10 s. Six repeat tests were performed on the samples and values obtained (with the exception of potential outliers), which were then used for the computation of the average hardness values.

2.3.2 Tensile testing

The tensile properties of the Al alloy, Al–CuZnAlNi- and Al–SiC-based composites were evaluated using a universal testing machine. The samples were machined to gauge length and diameter of 30 and 5 mm, respectively. The test was conducted in tensile loading mode at a strain rate of 10^{-3}/s till fracture of the samples. Three repeat tests were performed on each category of the test samples, for repeatability and reproducibility of results to be assured. The testing procedure and analysis of obtained data were performed in accordance with ASTM E8/E8m-16a standard [22].

2.3.3 Fracture toughness testing

Tensile testing of circumferential notch cylindrical bar specimens in conformance with the procedures reported in Alaneme [23] was used for the assessment of the fracture toughness of the Al alloy, Al–CuZnAlNi- and Al–SiC-based composites. The samples were machined to 6 mm, 30 mm, 4.2 mm and 60°, gauge diameter, gauge length, notch diameter, and notch angle, respectively. A universal testing machine was used to subject the notched samples to tensile mode loading to fracture at a strain rate of 10^{-3}/s. The fracture toughness was evaluated from the load data, using empirical relation by Dieter [24], as given in Eq. (1):

$$K_{1C} = \frac{P_f}{D^{3/2}}\left[1.72\left(\frac{D}{d}\right) - 1.27\right], \quad (1)$$

where P_f, D, and d, are the loads at fracture, un-notched, and notched diameters, respectively, of the samples. Criterion for valid fracture toughness is normally specified with the attainment of plane strain condition, and for notched cylindrical bar samples given by Eq. (2), which is in accordance with Nath and Das [25]:

$$D \geq \left(\frac{K_{1C}}{\sigma y}\right)^2. \quad (2)$$

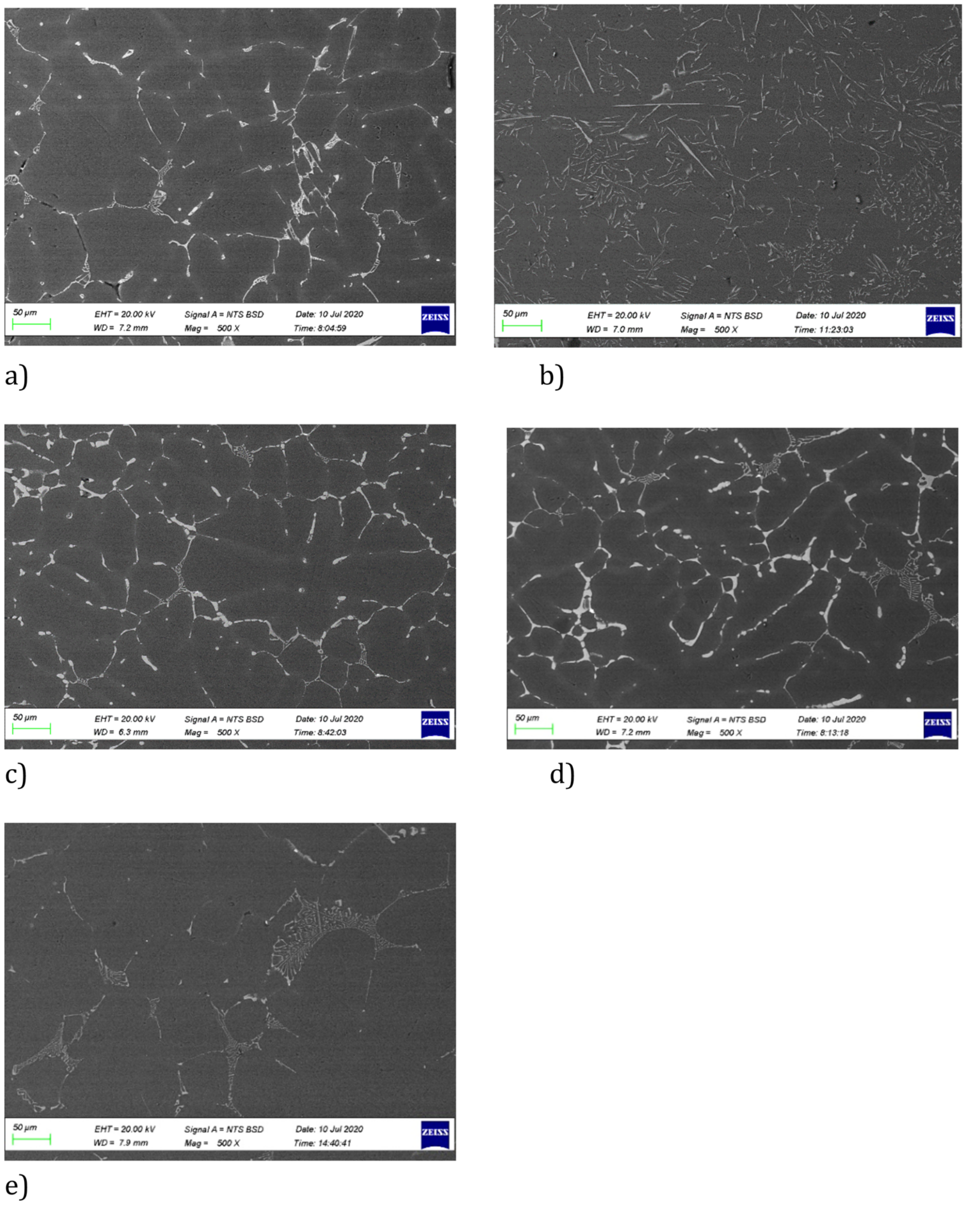

Figure 1: Showing the microstructures of (a) Al alloy, (b) Al–4 wt% CuZnAlNi, (c) Al–6 wt% CuZnAlNi, (d) Al–8 wt% CuZnAlNi, and (e) Al–8 wt% SiC.

Three repeat tests were performed for each category of test samples to assure the credibility of the results generated.

3 Results and discussion

3.1 Microstructure

The microstructures of the unreinforced Al alloy and the AMCs produced are presented in Figure 1. From the microstructures it is observed that the grain boundaries are well delineated with considerably discernible differences in grain sizes. The unreinforced Al alloy and the CuZnAlNi SMA reinforced AMCs are noted to have relatively more finer grain structures in comparison with the SiC reinforced AMC (Figure 1e). This can be attributed to greater undercooling offered by the metallic particles in contact with the molten Al alloy by virtue of their higher thermal conductivity in comparison with SiC, which can retain heat more and hence lower rate of undercooling [26].

A higher degree of undercooling is noted to facilitate, during solidification, the formation of a large number of stable solid nuclei as the liquid to solid activation energy barrier is easily overcome [27]. The implication is that the CuZnAlNi SMA reinforced AMCs achieved greater grain refinement in comparison to that reinforced with SiC.

Representative micrographs and EDS analysis profiles of the AMCs are presented in Figure 2. The presence of Al and Cu in the Al–8 wt% CuZnAlNi composite can be observed in Figure 2a, while the presence of Al, Si, and C can be noted in Figure 2b, suggesting the presence of SiC as reinforcement in the composite. The XRD profile in Figure 3 provides further insight on the phase constitution of the composites produced. The XRD peaks show distinct variation in phase constitution of the composites. It is observed that the unreinforced Al alloy contains essentially Al, indicated with the presence of Al peaks, while the SiC reinforced AMC shows peaks of Al, SiC, and Si, which are essentially the expected phases for AMCs reinforced with SiC [28]. The AMCs reinforced with CuZnAlNi SMA particles are observed to contain essentially Al and Al_2Cu phase, while the presence of additional phases AlCu and $Al_{0.92}Cu_{1.08}Mg$ are observed in the 6 and 8 wt% CuZnAlNi reinforced AMCs, respectively. This clearly suggests that the proportion of Cu added to the AMC during processing affects the phases formed in the composite, which potentially contributes to the variation in mechanical behaviour. Also, the stir casting process adopted could have influenced the phases formed. Further investigation by the authors on these systems will seek to study the structural characteristics of the AMCs reinforced with CuZnAlNi SMA particles, when powder metallurgy is adopted for the composite production. Nonetheless, a

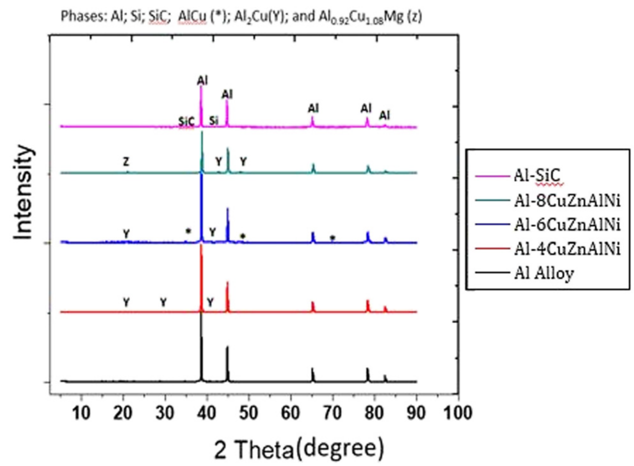

Figure 3: XRD pattern of the AMCs produced.

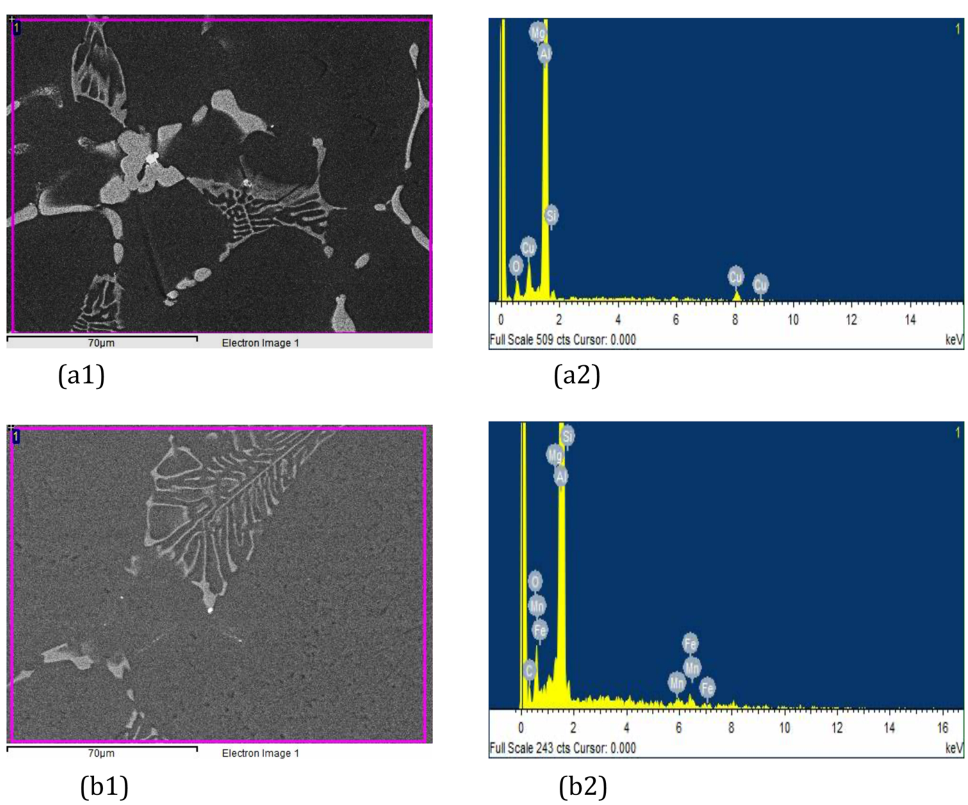

Figure 2: SEM micrographs and EDS analysis profiles of (a) Al–8 wt% CuZnAlNi and (b) Al–8 wt% SiC.

number of studies have confirmed that intermetallic phases such as AlCu and Al_2Cu in composites increase the strength and hardness properties through particle strengthening on account of the precipitation of intermetallic phases [29–31].

3.2 Hardness

The hardness results are presented in Figure 4. The hardness values of the CuZnAlNi SMA reinforced AMCs are observed to be basically higher than that of the unreinforced Al alloy and that of the SiC reinforced AMC. The CuZnAlNi SMA is essentially harder than the Al alloy, thus the presence of the Cu SMA particles in the Al alloy matrix will serve as barriers to the gliding of dislocations – providing relatively greater resistance to indentation [32]. Also, the relatively finer grain structure and the better wettability between metals compared to metal–ceramic systems contribute to matrix strengthening and interface strengthening [8], which can be linked to the improved hardness of the CuZnAlNi SMA reinforced AMCs compared with the AMCs reinforced with SiC. Additionally, the intermetallic phases formed in the CuZnAlNi SMA reinforced AMCs are also noted as contributing to its high hardness. Furthermore, the hardness of the CuZnAlNi SMA reinforced AMCs is observed to be sensitive to the wt% of the SMA added as reinforcement. AMC containing 6–8 wt% CuZnAlNi SMA is observed to yield higher hardness values compared to that when 4 wt% is used as reinforcement. This is largely due to the effects of increased particle strengthening, and phase strengthening due to the formation of additional intermetallic phases in the 6 and 8 wt% CuZnAlNi SMA reinforced AMC compositions [33,34], as noted in the XRD patterns presented in Figure 3.

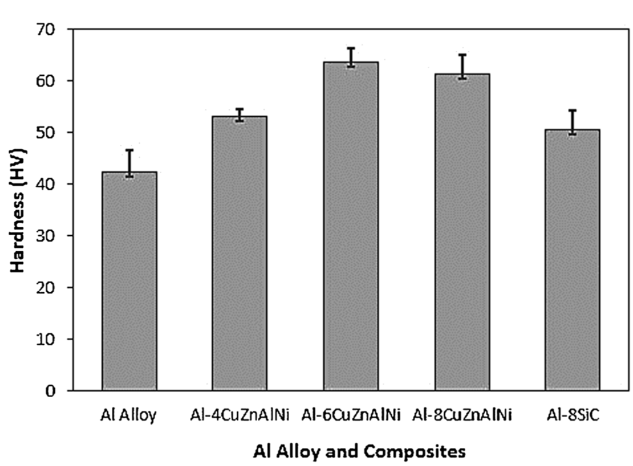

Figure 4: Hardness of the Al alloy and Al-based composites.

3.3 Ultimate tensile strength

The results of the tensile properties are presented in Figure 5. From Figure 5a, the tensile strength of the CuZnAlNi SMA reinforced AMCs are observed to increase with the increase in wt% of the CuZnAlNi SMA particles, basically due to increased particle strengthening. Also, all the composites have higher tensile strength than the unreinforced Al alloy, which is linked to direct and indirect strengthening mechanisms reported in particle reinforced AMCs [14]. The particles which are harder than the Al matrix have better load bearing capacity, thus more effectively support load or stress transferred from the matrix [35], this is coupled with the hindrance offered by the reinforcing particles to the motion of dislocations [8].

The indirect strengthening emanates from the thermal mismatch engendered by the difference in coefficient of thermal expansion between the particles and the matrix during solidification, which results in the generation of more dislocation that also serves as obstacles to the motion of other dislocations [36]. In addition, the 6 and 8 wt% CuZnAlNi SMA reinforced AMCs possess higher tensile strength than the SiC reinforced AMC. The likely improved interface bonding between the particles and matrix, and the compressive type residual stresses are reported to be asserted by SMA particles on the matrix on cooling [37,38]. Metallic reinforcements are reported to offer better interface bonding to metallic matrices compared to ceramic particles [39,40]. This improved bonding results in enhanced interface strength, which allows for effective load transfer between the matrix and the particles [41].

3.4 Specific strength

The specific strength is a measure of the tenacity of a material, it is principally referred to as the strength-to-weight ratio of a material. From Figure 5b it is observed that there is progressive increase in specific strength with increase in the weight percent of the CuZnAlNi SMA. Also, marginal difference in specific strength exists between the 8 wt% CuZnAlNi SMA reinforced AMC and that of SiC reinforced AMC, despite the relatively higher density of the SMA (7.60–7.65 g/cm^3) compared to SiC (3.2 g/cm^3).

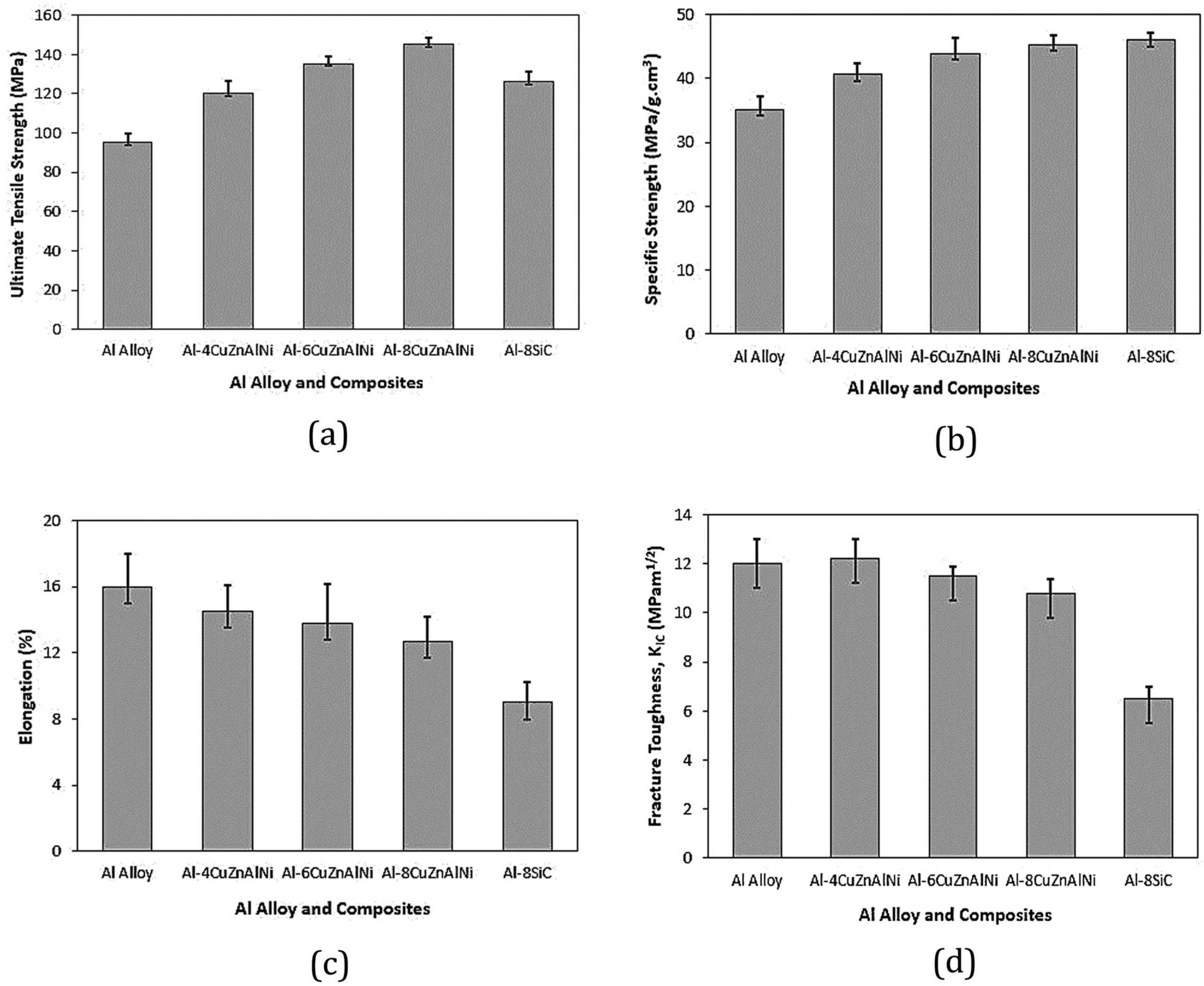

Figure 5: Showing variations in (a) ultimate tensile strength, (b) specific strength, (c) % elongation, and (d) fracture toughness of the Al alloy and Al-based composites investigated.

The implication is that thinner grade structures of comparable strength levels with that of the SiC reinforced AMC can be produced using the CuZnAlNi SMA reinforced AMCs without any adverse effect on strength performance.

3.5 Percentage elongation

The results of the percentage elongation of the composites are presented in Figure 5c. The Al alloy had the highest percentage elongation value of 16% in comparison with the AMCs studied. The percentage elongation of the CuZnAlNi SMA reinforced AMCs are observed to be within the range of 12–14.5%, and decreased with increase in CuZnAlNi SMA wt%. It is also noted that the CuZnAlNi SMA reinforced AMCs possess elongation values higher than that of the SiC reinforced AMC (9%). This can be attributed to the potentially improved interphase bonding between the Al alloy matrix and the CuZnAlNi SMA particles, and the inherent ductile nature of the CuZnAlNi system in comparison with SiC, which is ceramic and intrinsically brittle [42]. The implication is that the CuZnAlNi SMA reinforced AMCs will exhibit a higher capacity to sustain plastic deformation.

3.6 Fracture toughness

The results of the fracture toughness evaluation are presented in Figure 5d. The values are reported as valid fracture toughness, as the condition, $D \geq \left(\frac{K_{1C}}{\sigma y}\right)^2$, stipulated for plane strain condition for the cylindrical round sample geometry were met [24]. It is observed that 4 wt% CuZnAlNi SMA reinforced AMCs have the highest fracture toughness values which is 12.3 MPa $m^{1/2}$, and the value decreased with increase in wt% of the CuZnAlNi SMA particles. However, it is noted that all the CuZnAlNi SMA reinforced AMCs have fracture toughness values higher than that of the SiC reinforced AMC. This could be linked to the predisposition to brittle fracture of the SiC reinforced AMC due to the inherent brittle nature of SiC. The greater likelihood of discontinuous interface bonding between the Al (metallic) matrix and the SiC (ceramic) particles, which is common in metallic matrix/ceramic reinforcement systems, can result in the facilitation of crack initiation centres and stress concentration build-up within the vicinity of the particle/matrix interfaces [43]. This stress state often results in rapid crack propagation and low fracture resistance [44]. The implication is that the CuZnAlNi SMA reinforced AMCs will show greater reliability in an environment where fracture and impact resistance are critical service requirements.

4 Conclusion

The viability of CuZnAlNi based SMAs as reinforcement in AMCs were preliminarily assessed using structural characterization and mechanical behaviour evaluation. The following conclusions are drawn from the results:

- The microstructures indicated a relatively more refined grain structure with the use of CuZnAlNi as reinforcement, while increase in the CuZnAlNi wt% resulted in the formation of varied AlCu based intermetallics, in addition to the primary Al rich phase.
- The hardness, ultimate tensile strength, and specific strength largely improved with increase in the CuZnAlNi wt% and were higher than that of the unreinforced Al alloy and Al–8 wt% SiC for the 6 and 8 wt% CuZnAlNi reinforced AMC (specific strength being the only exception).
- Increase of 50.25 and 52.63% in hardness and ultimate tensile strength, respectively, was achieved with the use of 6–8 wt% CuZnAlNi as reinforcement in the AMC as compared to 19.48 and 32.63% increase in hardness and ultimate tensile strength, respectively, when 8 wt% SiC is selected as reinforcement.
- The percentage elongation and fracture toughness values of the AMCs reinforced with CuZnAlNi (12–14.5 and 10.5–12.3 MPa $m^{1/2}$) were equally superior to the Al–8 wt% SiC composite (9% and 6.5 MPa $m^{1/2}$), respectively.
- The observed improvement in properties were linked to the improved and continuous matrix/particle interface bonding, matrix refinements, thermoelastic-induced compressive residual stresses, inherent ductile, and tough nature of the SMA.
- The CuZnAlNi reinforced AMCs are recommended for further assessment for potential use in automobile, stress bearing, and damage tolerant applications.

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