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EFFECT OF NANO-ALUMINA AND COPPER MICRON SIZE PARTICULATES ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF MAGNESIUM ALLOY AZ31

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Abstract

In this paper, magnesium composites are synthesised through the addition of nano-alumina and copper micron size particulates in AZ31 magnesium alloy using the technique of disintegrated melt deposition. The simultaneous addition of Cu and nano-alumina particulates led to an overall improvement in both microstructural characteristics and mechanical response of AZ31. The 0.2% yield strength increased from 180 to 300 MPa (67%), while the ductility increased by almost 24%. The overall tensile properties assessed in terms of work of fracture improved by 66%. An attempt is made to correlate the tensile response of composites with their microstructural characteristics. The results suggest that these alloy composites have significant potential in diverse and wider engineering applications when compared to AZ31 alloy.

Introduction

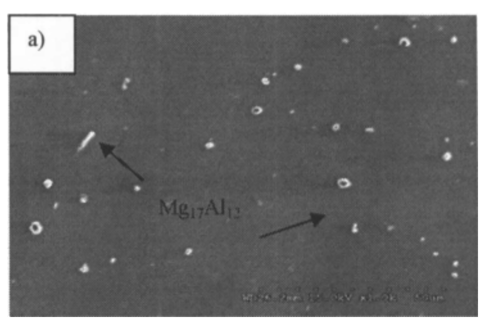
Weight reduction is now a big challenge in civil defence, aerospace, sports and automobile industries. This has been enchanting research scientists around the globe to look for structurally light weight materials. Among the elements in the periodic table of elements, Mg is one such potential candidate which can even bring down the weight of a structure by about 30% and 70% when compared to aluminum and steel structures, respectively]. Magnesium materials exhibit some advantages such as lowest density amongst structural materials, good castability and machinability. However, main disadvantages of current magnesium materials include low ductility, low strength, loss of strength with increase in service temperature and low corrosion resistance [1].
Magnesium alloy AZ31 (Mg–3wt%Al–1wt%Zn) is commonly employed in light weight engineering applications. The literature search in recent years shows that serveral attempts have been made to further improve the properties of this alloy through the addition of different reinforcements and subjecting to different deformational processes. Commonly used reinforcements consist of nano-Al_2O_3 particulates [2] and micro-SiC particulates [3]. Among these reinforcements, addition of nano-Al_2O_3 particulate reinforcement enhanced the failure strain of AZ31B alloy remarkably [2]. The literature research also reveals that some attempts have been made to alloy magnesium and magnesium alloys with different alloying elements [4]. The results showed that Cu is a potential alloying element to improve strength of magnesium based materials. However, no attempt so far is made to improve overall mechanical properties of AZ31 by the simultaneous incorporation of nano-Al_2O_3 and micron Cu using cost effective and industrially viable solidification route.
Accordingly, an attempt is made in the present study to add nano - alumina particulates to improve ductility and copper to enhance microstructural characteristics, hardness and strength of AZ31 alloy. The main objective was to make an attempt to improve the combination of 0.2%YS, UTS and failure strain when compared to AZ31. The choices of these additions, further, are also expected to enhance high temperature properties and oxidation behavior as established before. Disintegrated melt deposition technique is used in the present study to synthesize these materials and all the characterization studies were performed on the extruded samples.

Materials and Synthesis

In the present study, AZ31 magnesium alloy ingots with chemical composition of (2.94% Al, 0.87% Zn, 0.57% Mn, 0.0027% Fe, 0.0112% Si, 0.0008% Cu, 0.0005% Ni and balance Mg) were cut into rectangular pieces. To obtain reasonable distribution of particulates into the AZ31 matrix, holes (10mm diameter and 55 mm deep) were drilled into these pieces and required amount of 50 nm alumina particulates and 50 μm average sized copper particulates were subsequently filled in these holes (see Fig. 1). Two volume percentages of Cu (2% and 4%) were chosen for addition into AZ31 magnesium alloy. The amount of 50nm Al_2O_3 particulates was kept at 1.5 volume percentage as this composition showed best combination of strength and ductility when compared to other AZ31B-Al_2O_3 formulations [2]. Synthesis of AZ31-Cu-Al_2O_3 composites was carried out using disintegrated melt deposition (DMD) technique. The deposited preforms were machined to 36 mm diameter and hot extruded to 8 mm diameter rods.

Results and Discussion

Fig. 1 shows principally three regions in different colors, matrix in gray, $Mg_{17}Al_{12}$ phase in bright white color and Mg_2Cu phase in light gray color. Microstructural studies conducted on the extruded samples revealed reasonably uniform distribution of the particulates/intermetallics in the AZ31 matrix. This can be attributed to: (i) minimal agglomeration of reinforcements during melting of matrix, (ii) minimal gravity-associated segregation due to judicious selection of stirring parameters, and (iii) the effect of nano-Al_2O_3 hard particulates in dispersing second phases of AZ31 [2].



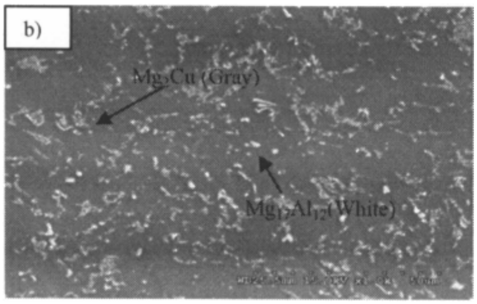
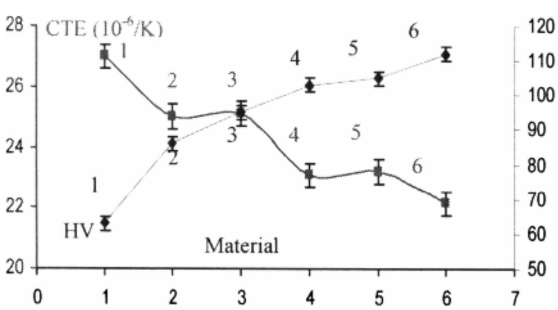


Fig. 1. Representative FESEM micrographs showing the distribution characteristics of secondary phases in the cases of: a) AZ31 and b)AZ31-2Cu-1.5Al$_2$O$_3$.

The microstructural characterization reveals the presence of minimal porosity in all samples. Presence of minimal porosity can be attributed to: (i) good compatibility between the AZ31 matrix and particulates/intermetallics, leading to the absence of voids and debonded regions usually associated with ceramic reinforcements, and (ii) judicious selection of experimental parameters during primary and secondary processing. The results of microstructural characterization of monolithic and composite samples also indicated a near defect-free interface formed between secondary phases and the matrix. The interfacial integrity was assessed in terms of interfacial debonding and the presence of microvoids at the interface.

Fig. 2 shows the results of coefficient of thermal expansion measurements obtained from monolithic and composite samples. The results revealed a reduction in CTE of the AZ31 matrix with an increase in amount of Cu and due to presence of nano-Al_2O_3 particulates. The reduction in CTE can be attributed to much lower CTE values of copper and alumina when compared to AZ31 (17.4 x 10-6K-1 and 7.4 x 10-6K-1 for Cu and Al_2O_3 respectively) and the ability of the reinforcements to effectively constrain the expansion of the matrix [5]. The lower CTE value of AZ31-Cu and AZ31-Cu-Al_2O_3 samples may also be attributed to the additional presence of Mg_2Cu. The lower CTE values of composite samples suggest that composites are more dimensionally stable as a function of temperature when compared to monolithic AZ31.



1– AZ31; 2 – (AZ31-1.5Al$_2$O$_3$); 3 – (AZ31-2Cu); 4 – (AZ31-2Cu-1.5Al$_2$O$_3$); 5 – (AZ31-4Cu); 6 – (AZ31-4Cu-1.5Al$_2$O$_3$).

Fig. 2 Diagram of CTE and microhardness of samples.

The results of microhardness measurements revealed a significant increase in average microhardness with an increase in amount of nano-alumina and micron copper particulates (see Fig. 2). The increase in hardness of composites with increasing amount of copper and nano-alumina can be attributed primarily to: (i) an increase in the presence of harder intermetallic phases and nano-Al_2O_3 ceramic particulates and (ii) greater constraints on localized matrix deformation during indentation due to the increased presence of intermetallic phases [2].

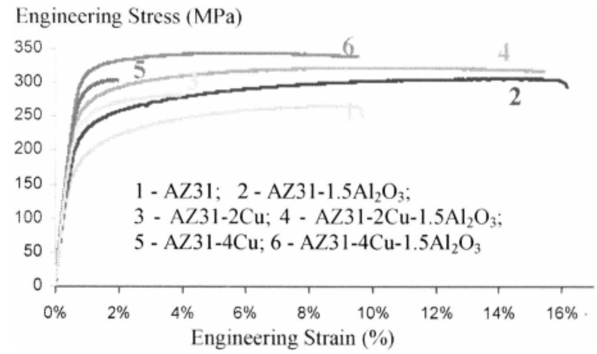


Fig. 3 Engineering stress- strain curves of AZ31 and its composite samples.

Fig. 3 shows results of room temperature tensile properties of studied samples. Simultaneous addition of nano-alumina and micron copper particulates led to a significant improvement in 0.2% yield strength and ultimate strength of AZ31 up to 4vol.% Cu. The yield strength increased from 180 MPa to 300 MPa (67% increment), the ultimate strength increased from 265MPa to 350MPa (32% increment). Ductility increased in case of AZ31-2Cu-1.5Al$_2$O$_3$ from 10.9% to 13.5% (~24% increment). However, when only copper was added, strengths went up but the ductility was significantly compromised. The net outcome was an enhanced work of fracture of AZ31-Cu-Al$_2$O$_3$ system from 27.3MJ/m^3 and 4.5 MJ/m^3 to 45.2 MJ/m^3 in the case of AZ31-2Cu-1.5Al$_2$O$_3$ (66% and 904% increments) when compared to AZ31 and AZ31-Cu system, respectively.

The significant increase in 0.2% yield strength and ultimate tensile strength of monolithic AZ31 due to addition of copper and nano-alumina particulates can be primarily attributed to: (i) grain refinement [6]; (ii) The presence of reasonably distributed harder particulates/intermetallics phases [7]; (iii) Orowan strengthening due to a significantly reduced interparticulate spacing of intermetallics phases [8]; (iv) the effective load transfer between matrix and secondary phases; and (v) the formation of internal stresses due to different thermal expansion behavior between particulates/intermetallics and the matrix [9].

Fig. 3 also shows the increase in ductility of AZ31 when nano-alumina or nano-alumina and copper particulates were added. 38% and 24% ductility was increased in the case of AZ31-1.5Al$_2$O$_3$ and AZ31-2Cu-1.5Al$_2$O$_3$ when compared to AZ31 sample, respectively. The increase in ductility can primarily be attributed to: (a) grain refinement; (b) presence and reasonably good distribution of intermetallics; (c) reduction in size and roundness of second phases [2]; and (d) the re-orientation of basal plane (0 0 0 1). Grain refinement particularly benefits hexagonal metals in ductility increment. The increase in ductility of brittle materials such as magnesium can also be attributed to the presence of nano-size particulates such as Al_2O_3 and CNT. The nano-particulates have been shown in the previous study to provide sites to open cleavage cracks ahead of advancing crack front and altering the local effective stress from plane strain to plane stress in the neighborhood of crack tip. The reduction in size and roundness of the secondary phase in the microstructure can also be attributed as one of the reason in improvement in failure strain. It has been established before that breakdown of the secondary phase located at grain boundaries and the change in their distribution from a predominantly aggregated type to dispersed type as also observed in the present study can assist in improving ductility [2]. Lastly, the nature of redistribution of basal plane in the extruded directions can also be attributed as a reason for an increase in failure strain.

Further increase in amount of copper (AZ31-4Cu-1.5Al_2O_3) led to reduced failure strain but still stayed close to that exhibited by AZ31 and much higher when compared to AZ31-Cu samples (see Fig. 3). The results clearly reveal the inherent characteristic of Cu addition in reducing failure strain [16] and that of alumina particulates at nanolength scale to increase the failure strain of magnesium based materials.

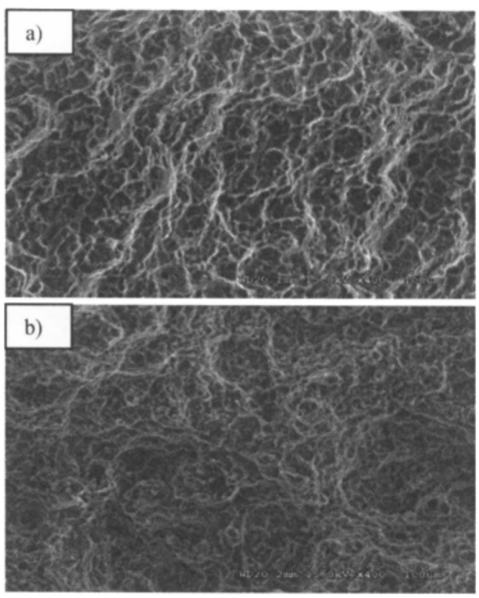


Fig. 4 Fractographs showing fracture characteristics of samples: a) AZ31 and b) AZ31-2Cu-1.5Al_2O_3.

The tensile fracture surfaces of monolithic and composite samples are shown in Fig. 4. The study of uniaxially deformed fracture surfaces indicated the microstructural effects on fracture characteristics of nanocomposites. The monolithic and AZ31-Cu-Al_2O_3 samples showed mixed-mode fracture, presence of microcracks and evidence of plastic deformation [10-11].

In essence, the results of present study clearly indicate the ability of simultaneous addition of copper and nano-Al_2O_3 particulates in enhancing the overall ambient temperature mechanical response of AZ31. Considering the ability of copper to improve high temperature strength of magnesiumand that of nano-alumina to enhance the oxidation resistance of AZ31 till 450°C [12], it is expected that AZ31-Cu-Al_2O_3 formulations can be strong candidates for a wider range of engineering applications.

Conclusions

The main conclusions that may be derived from this work are as follows:

1. Addition of Cu particulates leads to formation of Mg_2Cu secondary phase in matrix. Reasonably uniform distribution of secondary phases in the AZ31 matrix is obtained.
2. The increasing presence of copper in AZ31-Cu-Al_2O_3 samples leads to a significant improvement in hardness, 0.2%YS and UTS and ductility. The ductility is relatively uncompromised up to 4vol.% Cu.
3. Fracture behavior of AZ31-Cu-Al_2O_3 samples shows evidence of mixed-mode fracture with limited presence of microcracks and limited evidence of plastic deformation while AZ31-Cu samples exhibited significant presence of microcracks and the breakage of Cu particulates.

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