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Effect of Nano Alumina Reinforcements on the Flexural Strength of Magnesium-Based Copper

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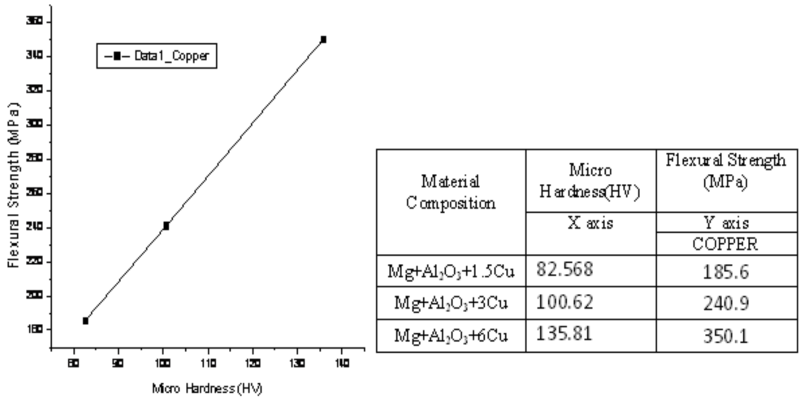
Abstract: Advanced materials, such as Magnesium Metal Matrix Nano Composites offer significant enhancements in a variety of properties, as compared to their bulk, monolithic counterparts. These properties include primarily the flexural and fracture toughness/energy. However, till date, there are hardly any scientific studies that are reported in case of the Magnesium based Alumina reinforced advanced MMMNCs. Which bring out the effects of various experimental conditions on those properties some of these experimental conditions become very important as they simulate nearly the service conditions of components that are made from these materials? In the present study, the effects of various test conditions on the flexural strength of Magnesium Metal Matrix Nano Composites (MMMNCs) materials have been comprehensively evaluate and reported. These conditions include the flexural strength. The results obtained are discussed and rationalized in terms of the material characteristics and the mode of failure. The study reveals that the material exhibits a well defined Flexural Strength, beyond which the mode of failure is tensile (Fully bend or flexural loading).

Keywords: R Curve, Sintering, Nano Composites, Fracture Toughness

I. INTRODUCTION

Magnesium materials have assumed significant technologies importance as structural materials in recent years due to the development of newer structural Magnesium with enhanced fracture resistance. Among several effective means of enhancing the fracture resistance, material design based on Alumina reinforcements has been the most effective [1]. Several structural materials and components have since been devised, developed and fabricated successfully using this approach of Alumina reinforcement. Among much structural Magnesium, amorphous Alumina uniquely combines the different properties to suit several technological applications, including weight saving in metallic aircraft vehicles and transport equipment. These properties include, low density and good damping resistance and excellent weldability and castability properties [2.3]. However, the mechanical properties of Magnesium materials in the monolithic from are far from acceptable levels for any critical structural application [4,5]. Magnesium has, in its bulk form, low strength (flexural) and extremely low values of flexural strength as compared to several structural Magnesium material thus needing significant improvements, so that it can be accepted for certain critical structural applications Fig.1.



Material Composition	Micro Hardness(HV)	Flexural Strength (MPa)
	X axis	Y axis
		COPPER
$Mg+Al_2O_3+1.5Cu$	82.568	185.6
$Mg+Al_2O_3+3Cu$	100.62	240.9
$Mg+Al_2O_3+6Cu$	135.81	350.1

Fig.1. Variation of Micro Hardness (HV) with Flexural Strength (MPa)

One of the means of achieving improved mechanical properties of Magnesium is by using either two or three dimensional for schematic presentation of the Alumina reinforced composites) networks of continuous Alumina as reinforcements within the Magnesium matrix, leading to newer structural materials, known as Magnesium Metal Matrix Nano composites (MMMNCs) [6,7]. Such a design methodology was seen to increase the overall fracture energy of the MMMNCs by mire then an order of to the bulk Magnesium. Other Alumina reinforced materials show similar enhancements in the fracture resistance parameters, especially the fracture energy.

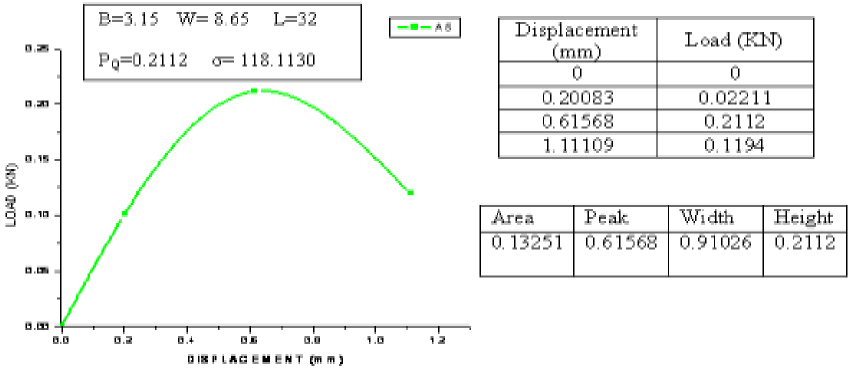
Flexural strength is one of the most widely used properties in characterizing the mechanical behavior of Magnesium based materials. Unlike many test methods adopted for the property evaluation of Magnesium materials, standards exist for the flexural testing of Magnesium in both monolithic and composite forms at ambient temperature. Most of the testing conducted and the results reported in this chapter are according to these standard procedures deviations, if any (for example in the specimen dimensions etc) are duly specified. In the present study, flexural behavior of the MMMNCs materials is evaluated in detail to determine the effects of (i) Nano Alumina with 3.5,7,14 Vol.% Al_2O_3 (ii) 3.5 Vol.% Al_2O_3 + Ni/Cu . The results obtained are rationalized based on the materials characteristics and mode of failure.

2.1 Effect of Reinforcement on Flexural Strength

Flexural tests in 3 point bend loading were conducted on specimens of 45 x 6 x 3mm rectangular cross sectional area with span length of 32mm, for each composition, a minimum of 3 test specimens were tested. The flexural strength (σ_f) is calculated for 3 point bent loading as:

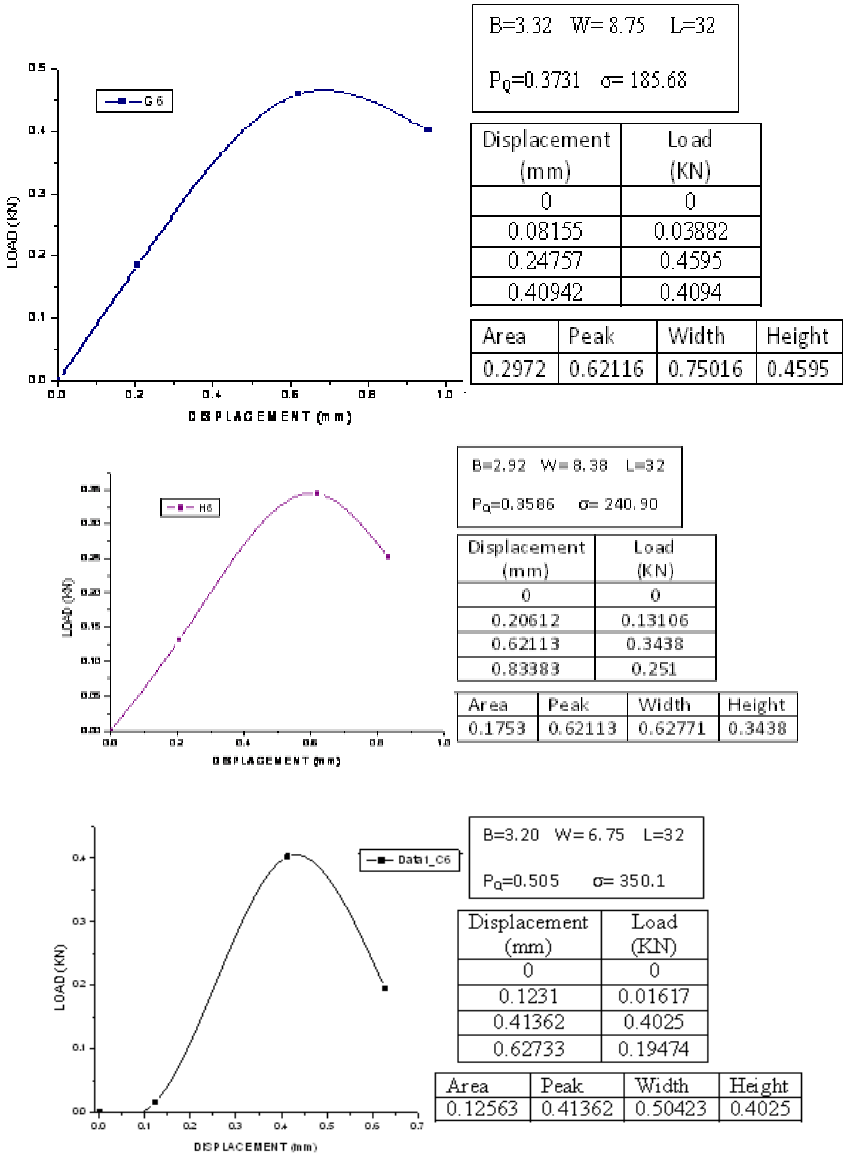
$$\sigma_f = \frac{3\,P_{max}L}{2.b.d^2} \qquad (1)$$

presents the obtained on the variation in the flexural strength with different composition under 3 point bend loading, Specimens with span length of 32mm underwent significant damage (visible crushing and crumbling) under the lower loading pins and as a result a large variation in flexural strength is observed. Hence, the data pertaining to the 32mm span is considered for the analysis. Typical load vs displacement curves obtained at various compositions are shown in Fig.2. These curves show that the specimens with 32mm, namely the 45 and 6mm span specimen, typically exhibit a linear increase in the load with displacement till the attainment of peak load, which corresponds to the maximum flexural strength Fig.2.



Displacement (mm)	Load (KN)
0	0
0.20083	0.02211
0.61568	0.2112
1.11109	0.1194

Area	Peak	Width	Height
0.13251	0.61568	0.91026	0.2112



B=3.32 W= 8.75 L=32

P_Q=0.3731 σ= 185.68

Displacement (mm)	Load (KN)
0	0
0.08155	0.03882
0.24757	0.4595
0.40942	0.4094

Area	Peak	Width	Height
0.2972	0.62116	0.75016	0.4595

B=2.92 W=8.38 L=32

P_Q=0.3586 σ= 240.90

Displacement (mm)	Load (KN)
0	0
0.20612	0.13106
0.62113	0.3438
0.83383	0.251

Area	Peak	Width	Height
0.1753	0.62113	0.62771	0.3438

B=3.20 W=6.75 L=32

P_Q=0.505 σ= 350.1

Displacement (mm)	Load (KN)
0	0
0.1231	0.01617
0.41362	0.4025
0.62733	0.19474

Area	Peak	Width	Height
0.12563	0.41362	0.50423	0.4025

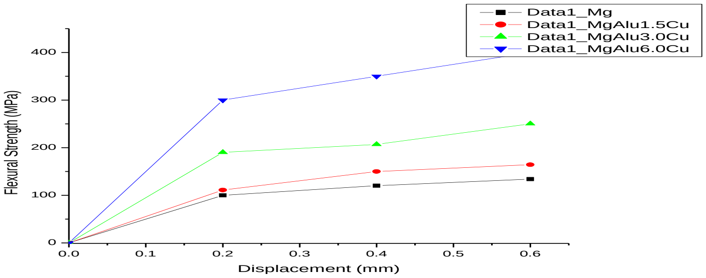
Fig.2. Variation of Load (KN) with Displacement (mm) of Copper (1.5, 3.0, 6.0 Vol.%)

This is followed by complete separation of the specimen under tensile mode and hence a rapid fall in the flexural strength value of the present material is found to be 118.1- 289.0 MPa averages of the values obtain for the specimen of all composites. Hence, the flexural strength values given in Table 1 are the appropriate values to be considered for specimen equal 45±0.5 mm lengths. Instead, it is relevant to consider the shear strength, in this case the interlamellar shear strength (ILSS), for these tests (The details of the ILSS and its dependence on the reinforcement and the mode of failures are given in the discussion part of this chapter). The values of ILSS (σ_s) are computed as

$$\sigma_f = \frac{0.75 P_{max}}{b.d^2} \qquad (2)$$

The computed values of ILSS for the MMMNCs material are given. The data in Table 1 show that the ILSS values very significantly with the three sets of values that are derived using three different specimen values As known schematically in Figs.3., the material is expected to exhibit a load that is independent of the reinforcement when the failure mode is shear while, the same decreases inversely with the increase the reinforcement when the failure mode is tensile or stresses are predominantly bending / flexure in nature (the variation of load in Fig.3. is as shown for specimens of a particular cross sectional area but having varied reinforcement. The transitional value in the reinforcement which separates the shear and tensile loading. It is to be noted that the material a mixture of both tensile and shear modes of failures when the reinforcement are near the maximum value, which value itself does not correspond to a sharp, single value but to a range of reinforcement values [8]. It is to be viewed at the combined effect both reinforcement effects and the effect of mixed failure mode of tensile and shear fracture

Normally, when a specimen is subjected to 3 point bent loading, it would experience both bent at shear loading. The shear stresses in the vertical sections inducting equivalent shear stresses in the horizontal section avoid rotation. These horizontal shear stresses can conveniently be assumed to be constant over the cross section of the specimen, but very with the thickness of the specimen, subjected to pure bending the maximum shear stress (ILSS) can be obtained by eq. 2. Hence the shear stress values are independent of the reinforcement. The failure due to these stresses can be expected to manifest which is the kind of failure observed in the present study when reinforcement are significantly lower facilitating “shear fracture”.



X- axis Displacement (mm)	Y- Axis Flexural Strength (MPa)			
	A	G	H	C
0	0	0	0	0
0.2	100.1	111	190.1	300
0.4	120.1	150	207.01	350
0.6	134.1	164.2	250.2	400

Fig.3. Variations of flexural strength (MPa) with Displacement (mm) of Nano Alumina composition of copper

A sample calculation taking in to the account of both shear and tensile (pure bend) strengths would provide the critical reinforcement beyond which only pure bending stresses exist. This is done in the following manner. For a constant cross sectional area of the specimen, the load at which a tensile failure occurs can be derived from eq.3 as

$P_{tensile} = \sigma_{f\,.}\ b\ d^2 /1.5\ L$ (3)

And load at which shear failure occurs is given as

$P_{shear} = \sigma_s\, b\ d /0.75$ (4)

To avoid shear fracture, $P_{tensile} < P_{shear}$. Combinin Equations for this condition to occur, the ratio of specimen thickness (d) to reinforcement (L) should be

$d/L < 2\ \sigma_s/\ \sigma_f$ (5)

the ILSS (σ_f) and the flexural strength (σ_f) are material properties. The present study shows that the MMMNCs material has an ILSS value of about

MPa and flexural strength of about 118.1- 289 MPa and also a specian thickness (d) of 3mm. Then, according to (eq.2 – eq.4 the minimum reinforcement than is rewuired to avoid shear fracture is approximately 45mm. any change in the properties as a result of prior treatment or test conditions such as temperature and strain rate, would accordingly change this reinforcement value.

The above discussion clearly brings out the importance of reinforcement on the mode of failure. Further, at lower reinforcement where the shear fracture is prominen, the material was found to exhibit predominent delamination and such process involves significant crack path meandering, especially the crack front deflection [9].

Hence, the associated is high. Since the interfaces in the MMMNCs structures are weak, the delamination occurs at lower strengths. On the other hand, at higher reinforcement the failure mode is pure bending or tensile. This involves breakage of reinforcement. This process does not involve any crack front deflection. Hence, the strengths are high. However, the failure and the load drop after the attainment of peak load are abrupt. The associated toughness is relatively lower.

Table 1: Variation of Flexural Strength, Interlamellar Shear Strength, Tensile Failure and shear Failure with 3.5 Vol.% Al_2O_3 and different composition of Copper.

Specimen Composition	Maximum P_{max} (N)	Specimen Length L (mm)	Breadth b(w) (mm)	Depth d (mm)	Flexural Strength σ_f (MPa)	ILSS σ_{fs}	$P_{tensile}$	P_{shear}
Mg	211.2	32	8.65	3.15	118.1130	5.813	211.199	211.186
Mg+(3.5Al_2O_3+ 1.5 Cu)	373.1	32	8.75	3.32	185.68	9.632	373.085	373.079
Mg+(3.5Al_2O_3+ 3.0 Cu)	358.6	32	8.38	2.92	240.90	10.991	358.595	358.593
Mg+(3.5Al_2O_3+ 6.0 Cu)	505	32	6.75	3.20	350.1	17.534	504.144	504.979

Many studies on the flexural strength properties are as one of the basic material properties of Brittle. A few studies are also reported in material processing parameters to the flexural deformation and fracture behavior. Recently, Gonczy and Jenkins have reported elaborately on the results obtained on the flexural strength properties, composites, compiling the results obtained from a multi laboratory round robin testing. Most of these studies emphasize the fact that the flexural strength is one of the most improperly, sensitive to various micro structural characteristics as well as modes of testing and other testing variable. The result in the present study too indicates the versatility of the flexural testing and the dependence of flexural properties on the material characteristic and modes of testing and test parameters. The dependence of the flexural properties on the test conditions indicate that the closely simulate the service conditions indicate that the present MMMNCs material is susceptible to the phase transformations that occur during the thermal exposure conditions.

II. FLEXURAL PROPERTIES

Mechanical behavior of magnesium and magnesium nanocomposites was assessed in terms of flexural strength and flexural strain to fracture, measured at room temperature. The results from bend testing revealed that the use of alumina nano particle reinforcements in pure magnesium led to a significant improvement in flexural strength of pure

Magnesium. The addition of copper and nickel as hybrid reinforcement in a fixed Mg/3.5%Al_2O_3 composition has also led to further improvements in flexural strength when compared to that of Mg and Mg / Al_2O_3 nano composite materials. Such an increase in hybrid nanocomposites can primarily be attributed to the following:

(a) An effective load transfer from matrix to harder and stronger second phases (Al_2O_3, Ni/Cu and Mg_2Cu/Mg_2Ni) [10,11].
(b) Orowan strengthening due to the presence of alumina and copper / nickel reinforcements at nano length scale [12].
(c) Strain misfit between matrix and reinforcements [33].
(d) Difference in coefficient of thermal expansion (CTE) between Mg matrix and reinforcements [14-17].
(e) Strengthening effect through refinement in matrix grain size [18,19].
(f) Additional strengthening from uniform distribution of varied densities of Mg_2Cu/Mg_2Ni intermetallics [11].

The results of this study reveal the clear significance of copper and nickel nano particle additions in improving strength levels up to 6 vol.% reinforcement. Formation of Mg_2Cu and Mg_2Ni intermetallics and their excellent interfacial integrity with Mg matrix seems to be the principal factor that is responsible for the improvements in the flexural properties. The present results on flexural testing also reveal that the failure strain to fracture of Mg increased due to the presence of Al_2O_3 with or without further increase with the additions of Ni or Cu. The results of present study reveal minor effect of grain size reduction on the failure strain as observed in the case of hybrid composites (see data in Table 1). The reduction in ductility of Mg / (3.5Al_2O_3 + 6.0 vol.% Cu or Ni) can be attributed to the increased clustering of intermetallic phase at the micron length scale. A comparison of flexural strength improvements reported in the literature show that the present improvements in the hybrid composites are way above that those reported in cases of Mg/6.0 vol.%Al_2O_3 [10] and Mg/3.0 vol.%Y_2O_3 [12], the materials processed using conventional PM methodologies. The present levels of improvements in flexural strength also seem to be far more as compared to the hybrid composite - 3 vol.% SiC and 3.5 vol.% Al_2O_3 (total of 6.5 vol.% hybrid reinforcement) [20]. These studies, including the present one, clearly point to the fact that the nano reinforcement of alumina with and without hybrid reinforcements of Cu and Ni (as also, the other reinforcements such as SiC and Y2O3) would significantly improve the mechanical properties, especially the flexural properties.

III. FLEXURAL FRACTURE BEHAVIORS

Results of fractographic studies revealed that the monolithic magnesium fails predominantly by brittle transgranualr cleavage fracture. Presence of large, cleave steps confirms the limited plasticity of monolithic magnesium, attributable largely to its HCP crystal structure. With the additions of alumina particles, the mode of fracture has changed to relatively high energy mixed mode fracture of transgranular shear and quasi-cleavage with high density of uniformly distributed microdimples. This indicates significant increase in the extent of plasticity and also, possibly contributes to effective toughening (the studies on this aspect are in progress). The presence of cracked Mg_2Ni intermetallic particles suggests a very good Mg/Mg_2Ni interfacial bonding.

V. CONCLUSIONS

The MMMNCs panels exhibit tensile fracture in specimens of higher reinforcement and intergranular fracture at lower reinforcement dimple like. This value is obtained based not only from the experiments conducted in the present study, but also confirms to the theoretical calculation based on the flexural strength and ILSS values of the present MMMNCs material with a fixed panel thickness of 3mm.

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