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Solid Glass Microspheres Filled Aluminum Alloy Metal Matrix Composite Made Through Stir-Casting Technique

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Abstract: Solid Glass Microspheres (SGM) in the range of 10–20 vol. % were used as reinforcement for making aluminium alloy metal matrix composite having density 2.66–2.68 gm/cc using stir-casting technique. Aluminium alloys are not new for synthesizing Metal Matrix Composites (MMC's), as they have already established their exceptional ability to sketch out the material for required properties where high strength is expected from a low density material. This has made them one of the widely used materials for aeronautics and marine applications where strength and weight are among the major governing factors for the suitability of any material. So, an effort is made to enhance the strength of aluminium alloy LM13 without affecting its lightness, by reinforcing it with Solid Glass Microspheres (SGM). This synthesized composite, is characterized in terms of its density and compressive deformation behaviour. It was observed that the developed composite behaves somewhat like a high strength aluminium foam under compressive deformation as exhibited in the stress–strain curves. The results of density evaluation and compression showed a substantial enhancement in the compressive strength of the developed composite with a considerably low change in density.

Keywords : Solid Glass Microspheres, Density, Compressive Strength, Stir Casting, Aluminium Alloy, Metal Matrix Composites.

I. INTRODUCTION

In the previous couple of decades, ton of research work has been observed, committed to the advancement of lightweight and low cost metal matrix composites. In this respect, for multiple purposes in the manufacturing, aviation and building sectors, alloys of aluminium with low-density were utilized as material for matrix components with particulates of several types such as ceramic and carbon [1-5]. The manufacturing method utilized to make most of the parts is casting, and the subsequent microstructure of this as-cast casting determines physical as well as mechanical characteristics of the developed component. Ceramic and carbon based strengthening are mostly used to further enhance aluminium alloy's mechanical, tribological and physical characteristics. The fortifications like fibres of graphite (P-55) [6], carbon fiber packs (K139) [7] and SiC particles [8,9] of various dimensions were utilized to strengthen different aluminium alloys. Metal Matrix Composites (MMC) with aluminium or its alloy as the matrix are gaining broad prevalence in numerous categories owing to their enhanced mechanical characteristics along with lower density, particularly when endurance and weight are of primary significance. In many implementations, aluminium-based MMC's are used as a product, such as engine cylinders, engine pistons, and several others [10]. Particle reinforced MMC's have found outstanding intrigue due to their specific performance and firmness [11]. By far, the assessment work finished on aluminium and its alloy based composite materials, incorporates silicon carbide, Al2O3, beryl, red mud and so forth [12]. Metal matrix composites also have excellent resistance again st wear and are good energy absorbers as metallic foams or sponges.

In this concerned work, endeavour has been put to synthesize an Aluminium LM13-SGM Composite as no research has been observed during the literature review about the development and characterization of composite material having matrix of LM13 aluminium alloy with the structural component as the solid glass microspheres. Hence, it was thought to be an interesting project to study their compressive behaviour in purview of density, so as to understand its worthiness for such applications. This work imbibes compressive behaviour of a novel composite developed by dispersing solid glass microspheres with varying volume concentrations in the LM13 Aluminium alloy matrix, resulting in composite with three different densities. These composites behave like solid foams in general and their behaviour under compression changes along with composite density.

II. MATERIALS AND METHODS

A. Matrix Material

LM13 alloy was found suitable and chosen to be the matrix material because of industrial viability, and the chemical composition of LM13 alloy is given for reference in Table 1. Owing to its good resistance against wear, low coefficient of thermal expansion along with good bearing properties, various uses and applications of LM13 alloy are not limited to pulleys (sheaves),

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pistons for diesel and petrol engines, and other automotive engine parts operating at elevated temperatures. Another impressive characteristic of LM13 alloy is its high resistance to corrosion under atmospheric conditions. It possesses good fluidity due to which it can be cast into comparatively thin sections.

LM13 approximately melts in the range of 525-560 °C whereas its typical pouring temperature is 700 °C but depending on the mould configuration the temperatures may range between 670-780 °C.

Table 1: Elements in LM13 Aluminium alloy

Elements	Si	Mg	Cu	Fe	Ti	Cr	Ni	Mn	Al
Wt.%	12.1	1.2	0.8	0.8	0.02	0.07	0.9	0.2	Bal.

B. Structural Material

Solid Glass Microspheres, also known as glass beads, grants several benefits like low oil absorption and excellent thermal stability as it has good heat and chemical resistance which in turn results in enhanced processing. Owing to these characteristics it has found applications in electrical, automotive, paint, packaging, and construction industry. It is also used in domestic appliances and adhesives. Since these glass beads are made up of glass, hence they are extremely stable, non-toxic, and recyclable as well. Suitability of these solid glass spheres for applications involving high stress or processes where these microspheres will be subjected to high stress is because of its high crush strength.

Soda Lime Glass is one of the several formulations of glass that is known by soda lime silicate glass also, and is used to manufacture these solid glass microspheres. Based on supplier's data, that is, M/s India Glass Beads, some of the important physical properties of this soda lime solid glass microspheres is given in Table 2 and its chemical composition is given in Table 3. These solid glass microspheres are used as reinforcement material for developing the concerned metal matrix composite.

Table 2: Properties of Solid Glass Microspheres

Appearance	Grains
Specific Gravity	2.5
Softening Point	750 Degree Celsius
Hardness	6 Mohs
Size	50 microns

Table 3: Chemical Composition of Solid Glass Microspheres.

Compounds	Quantity
SiO_2	70-71%
Na_2O	11-14%
CaO	7-9%
MgO	4-6%
K_2O	3-5%
Al_2O_3	1%

C. Composite Fabrication

The studied SGM reinforced LM13 alloy MMC was developed using permanent mould die casting assisted with melt-stirring technique. An innovative two-step blending method, preheating of particles, rationally chosen stirrer velocity, and melt degassing using Hexachloroethane tablets (C2Cl6) have assisted to achieve steady dispersion of solid glass microspheres [13-18]. The ingot-shaped LM13 alloy was previously split into smaller parts and then kept inside a resistance furnace of 2 kW Power working at 230 V, in a graphite crucible. It was then heated to 800° C in order to melt this LM13 alloy. Commercially available Hexachloroethane tablets (C_2Cl_6) were used to degas, the molten metal in order to decrease the defects of casting namely porosity, blowholes and voids. Before adding the SGM particles to the melt the temperature of the molten metal was reduced and retained at 730° C. In order to remove loose scales, residues and moisture, the reinforcing SGM particles of size 50 microns were preheated to 200° C for 2 hours. Stirring of molten metal was carried out by a motorized stirrer operated at speed of 550 - 600 rpm in order to generate a whirlpool. The particles of SGM are discharged into the whirlpool of molten metal at 15 - 20 g/minute of speed, through a system of funnel. In view to avoid contamination, the chromium steel blades mechanical stirrer with zirconium coating was used. The stirring speed was maintained at a low rate of 300 rpm for about 15 minutes to obtain adequate dispersion of SGM particles. On the completion of stirring process, the molten mix of metal and reinforcing particles was at last poured into a preheated mold of cast iron, at 700° C of pouring temperature and was cooled at ambient temperature to solidify. Three different types of composites with varying SGM volume percentages namely, SG10 (10 v% SGM), SG15 (15 v% SGM) and SG20 (20 v% SGM) were fabricated to study the reinforcement effect on compressive behaviour of these combinations of matrix and reinforcement in purview of density. Unreinforced LM13 alloy was also cast for comparison purpose. The stir casting experimental set up is given in Fig. 1 and the details of process is given in Table 4 for reference.

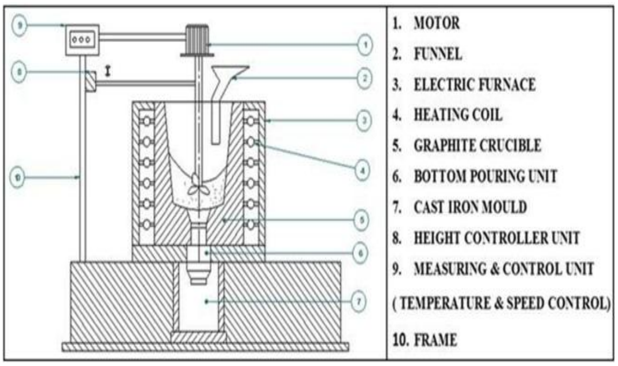

Fig. 1. Schematic of Stir Casting Setup [24]

Table 4: Stir Casting Process Parameters

Impeller Type	Placement of Stirrer	Span of Stirring	Speed of Stirring	Metal Pouring Temperature
3 blades fan type made from chromium steel and coated with Zirconium	Depth of ~2/3 calculated from the bottom of the crucible	~15 min	550 - 600 rpm	700 °C

D. Density of Materials and Volume Fraction of Solid Glass Microspheres

Simply, in both physical and every day terms, density refers to concentration of something within a given defined space, also called "mass density," and it can be better understood as the amount of matter per unit volume. In nature many materials already consist of, or are manufactured from, a mixture of different elements or different structural molecules, each having their own density. For knowing the density of such materials the concept of composite density is important. If the ratio of the materials present in the composite, generally expressed in terms of volume fraction or weight fraction are known along with their individual densities, then the composite density can be precisely calculated. Another thing not to confuse with, for densities is that the density of two solid spheres of similar mass and radius will be same irrespective of the distribution of mass within the solid sphere. For example, two solid spheres of mass M and radius R will have the same density, even if the mass in one of the sphere is evenly distributed throughout the sphere whereas in the other sphere the mass is concentrated almost entirely in the outer shell.

In the concerned study three sets of aluminium alloy metal matrix composites were developed each with a different volume fraction of SGM (f_g). This means that in each set of developed composite, the SGM volume fraction (f_g) and the volume fraction of aluminium alloy LM13 (f_m) is different. And this is the base of this study, as the changes in the f_g will result in MMC' with different quantity of structural material that will further affect the compressive behaviour of these MMC's.

Fig. 2. BiSS Universal testing machine (100kN)

E. Compressive Strength Testing

Compressive strength is the measure of the materials ability to withstand the loads tending to decrease the size of the sample. It is tested by placing the sample under the compression testing fixtures in a Universal testing machine where a moving plunger compresses the sample. Developed metal matrix composite was tested for compressive strength as per ASTM-E9-95 at a strain rate of 1/s on BISS Universal testing machines at Advanced Centre for Material Science at IIT, Kanpur (U.P), India, depicted in Fig. 2. Samples prepared for this test are of cylindrical shape with diameter of 10 mm and length 15 mm. Prior to testing, the friction between the compression test plates and the specimen surface was reduced by mechanically polishing the specimens surfaces and coating them with a thin layer of molybdenum sulphide for lubrication. During the testing, data was recorded for load-displacement and then standard methodology was used to convert it to stress-strain graph.

III. RESULTS AND DISCUSSION

A. Density and Volume Fractions

The density of the developed composite can be effectively calculated on the basis of Rules of Mixtures because the density of reinforcement and matrix along with their volume fraction percent are known. The density of reinforcement particulate that is SGM (ρ_g) is noted to be 2.5 gm/cc whereas the density of the matrix material LM13 aluminium alloy (ρ_m) is known to be 2.7 gm/cc. The percentile volume fractions f_g and f_m must be converted to decimal numbers by dividing it by 100 before they can be used in the equation given below.

$$\rho_c = \rho_g f_g + \rho_m f_m$$

Once the density of the developed MMC (ρ_c) has been calculated on the basis of the rules of mixtures by using the above equation. Then the relative density (ρ_r) can be calculated by using the following relation.

$$\rho_r = \rho_c / \rho_m$$

Three sets of f_g that is 10 v%, 15 v% and 20 v% are used for synthesizing the aluminium alloy MMC. The density of different sets of composite along with its relative density are reported in Table 4. The thermal expansion coefficients of aluminum alloys is considerably larger than that of SGM and this could lead to the thermal residual stress vis-à-vis generation of higher extent of dislocations. There is also a greater possibility of relaxation of residual stress through localized elasto-plastic deformation of the SGM, and sinking of dislocation at the SGM–matrix interface, because of mechanical bonding. With the increase in SGM content, the SGM–matrix interface area increases, and therefore more amount of dislocations get annihilated at the interface. Thus, the dislocation density as well as the residual stress within the matrix in MMC remain invariant to SGM content and matrix strengthening due to SGM addition is negligible [19].

Table 4: Densities for each set of MMC

SGM Volume Fraction	MMC Density	Relative Density
10 v%	2.68	0.992
15 v%	2.67	0.988
20 v%	2.66	0.985

Lowering of density reduces the mass per unit volume and the weight per unit volume also gets reduced. Thus the material gets lighter and lighter as the density goes on decreasing. But as observed in the Table 4, the reduction in the density of the developed MMC as an effect of reinforcement is considerably low in comparison of pure alloy of matrix. Thus, it is clear that the reinforcement of SGM will effect only marginally in making the material lighter that means the same volume of developed composite will only be slightly lighter than the same volume of pure aluminium alloy LM13 of matrix. So, it becomes necessary to see the variation in the compressive strength with the density of the developed MMC with change in the SGM volume fraction. Thus, in order to check the effect of reinforcement of SGM on density and compressive strength of the developed MMC, a graph has been plotted in Fig. 3 between compressive stress at first point of yielding and relative density. It is clear from the graph in Fig. 3 that there is a significant rise in the compressive strength of the developed composite without any increase in the weight per unit volume.

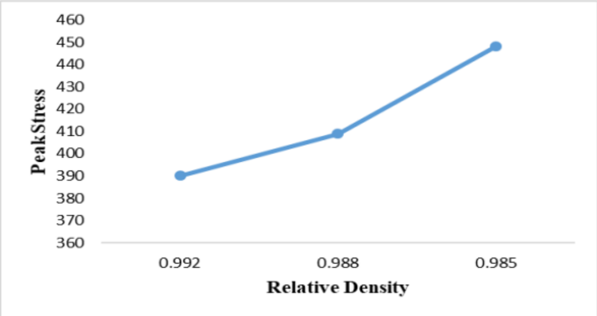

Fig. 3. Variation of Peak Compressive Stress with Relative Density.

B. Compressive Behaviour

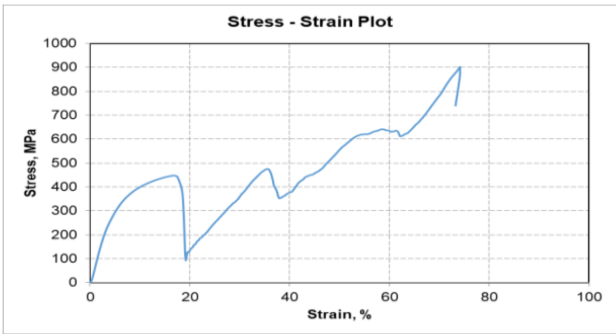

Fig. 4. Stress Strain Curve for 10 v% SGM.

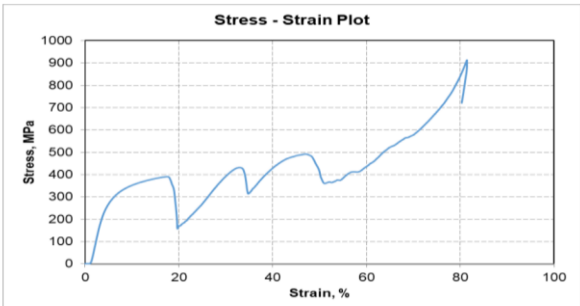

Fig. 5. Stress Strain Curve for 20 v% SGM.

During the compression test, it was observed that the deformation initiates from the corner region of the specimen's surface in contact with the compression platen. This deformation progresses at an angle of approx. 45° along the plane of shear towards the specimen's centre at the middle of the sample. During the course of deformation the sheared zone progresses layer by layer. The maximum deformation is observed to be associated with the planes of shear and at the centre of the samples.

Compressive stress strain curves of the developed MMC with varying density vis-à-vis SGM content is shown in Fig. 4 and Fig. 5. The stress strain curves for all the sets of reinforcement that is for 10 v%, 15 v% and 20 v% are graphically similar to each other. Thus, for simplification and ease of understanding the stress strain curves for the aluminium alloy MMC having 10 v% and 20 v% of SGM are only reported in the Fig. 4 and Fig. 5. The stress strain curves all sets of reinforcement of SGM in the developed MMC shows a linear portion at the initial stage indicating the elastic portion of the graph and then after yielding there is sharp drop in the stress and the strain changes and this is where the first kink band is formed. Further loading leads to the increase in the stress until the next kink band is formed. This sequence of events was found to repeat itself that results in the formation of other kink bands until the compression is completed. In the case of kink banding the maximum strength is determined by the first load drop corresponding to the formation of first kink band. So the maximum compressive strength for the developed MMC's was observed to be in the range of 390 to 448 MPa for the rise in the content of SGM from 10 v% to 20 v%. It can also be clearly observed from the curve shown in the Fig. 4 for 10 v% of SGM that the stress lowering took place at a critical strain of approx. 0.175 after yielding and the stress reaches its lowest point in the curve at a strain of about 0.2. Similarly, for 20% of SGM the stress strain curve is shown in the Fig. 5 where the stress lowering took place at a critical strain of approx. 0.168 after yielding and the stress reaches its lowest point in the curve at a strain of about 0.20. This shows that the strain at the point of stress lowering and the strain at which the stress reached its lowest point are approximately same for both the extremities of reinforcement. But, the peak compressive stress of 20 v% of reinforcement of SGM is comparatively higher than the peak compressive stress for 10 v% of reinforcement. As in the present study, the average size of the SGM is same for all sets of MMC's. So, the extent of stress reduction after yielding may be a measure of either of the two phenomenon. First is the degree of agglomeration or tendency of collapse or breakage of SGM shells during yielding. In this the SGM's in the matrix of MMC begins to deform elasto-plastically ensuing the strain hardening of matrix. But this strain hardening may not be that significant because of the mechanical bonding between the SGM and the matrix material at its interface. And this interface itself acts as the site for dislocation sink that inhibits the matrix strain hardening and is expected to be very marginal. Secondly, in the due course of time, the SGM spheres starts to shear and fracture, resulting in the loss of modulus that subsequently decreases the stress. Now the fraction of SGM that collapsed or broke begins to compact and again the yielding of matrix begins when the level of stress reaches to the extent where the next series of SGM begins to sear and crack. The deformation in the MMC is highly inhomogeneous and localized because of some porosity formed in the MMC during the process of manufacturing. After yielding, at the initial stage, major volume fraction of SGM may get sheared, broken and collapsed leading to higher degree of stress reduction. During the process of deformation, matrix also gets deformed and this deformation of matrix may lead to the strain hardening because of this a steady increase in the stress is expected along with the strain during the deformation.

But the stress does not rise with the strain as expected, instead it oscillates about the average stress value. This behaviour is attributed to the breakage and collapse of SGM spheres and its densification in the due course nullifies the strain hardening effect and is supposed to be responsible for decrease in the values of stress. Whereas a marginal stress hardening takes place when the matrix gets deformed after the densification of localized broken and collapsed SGM spheres and this strain hardening is responsible for the increase of stress [19].

IV. CONCLUSION

- Solid glass microspheres are capable of retaining their shape and size during the process of mechanical stirring and so it can be used effectively to synthesize the solid glass microsphere filled aluminium alloy metal matrix composite.
- Metal matrix composite with up to 20 v% solid glass microspheres was synthesized successfully by using the permanent mould die casting assisted with melt-stirring technique.
- Metal matrix composites density has slightly decreased with rise in the volume fraction of solid glass microspheres resulting in considerably less per unit weight reduction with a significant rise in the compressive strength.
- Compressive strength of the developed metal matrix composites was observed to improve significantly with a peak rise of about 38% with increase in the solid glass microspheres content.
- Solid glass microspheres can be effectively used with the aluminium alloy matrix for the development and production of syntactic foams with superior compressive strength at low cost for applications where good strength and stiffness is needed from a light weight material.

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