Mechanical Characteristics of Aluminium Powder Filled Glass Epoxy Composites

Pujan Sarkar¹, Nipu Modak¹, Prasanta Sahoo^{1*}

¹Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India

*Corresponding author (E-mail: psjume@gmail.com)

Keywords: Aluminium Powder, Glass Fiber, Epoxy, Tensile strength, Tensile modulus, Flexural strength, Inter laminar shear strength

Abstract. Mechanical characteristics of glass epoxy and aluminium powder filled glass epoxy composites are experimentally investigated using INSTRON 8801 testing device as per ASTM standards. With a fixed wt% of fiber reinforcement, glass epoxy and 5-15 wt% aluminium powder filled glass epoxy composites are fabricated in conventional hand lay-up technique followed by light compression moulding process. Experimental results show that aluminium powder as a filler material influences the mechanical properties. Density and void fraction in composites increase whereas steady decrease of tensile strength is recorded with aluminium powder addition. Micro hardness, flexural strength, inter laminar shear strength (ILSS) of 5 and 10 wt% aluminium content composites are improved compared to unfilled glass epoxy composite and with further addition of aluminium up to 15 wt% decreasing trends are observed. Glass epoxy with 5 wt% aluminium concentration shows the highest improvement. Tensile modulus for aluminium addition of 5 wt% decreases whereas 10 wt% aluminium filled composite shows improvement in tensile modulus. These are explained on the basis of material properties, void fractions and bonding strength among the constituents.

Introduction

Glass fiber reinforced epoxy composites are very popular in composite industry for its increasing use in numerous engineering applications such as seals, gears, rollers, cams, wheel, clutches and bearings because of many advantages including improved mechanical properties, wide varieties of availability and design flexibility as compared to metal based counterparts. As a reinforcing material, glass fiber has a wide range of availability [1] out of which bi-directional woven glass fiber reinforced polymer composites are getting acceptance in many industrial applications due to low weight, ease of processing and price. It provides better resistance to impact than unidirectional composites and display behavior that is closer to a fully isotropic material [2-3]. The mechanical performance of glass epoxy composite can be further improved by incorporation of filler particles. The reason to incorporate filler in glass epoxy is to enhance specific properties and to reduce the cost of the final product. Glass fiber reinforced epoxy composites containing different filler are used in many applications where mechanical properties are the critical issues [4-10]. Most of the studies made on particulate filled glass fiber reinforced epoxy composites reveal that the mechanical properties are strongly influenced by many factors such as type of filler and glass fibers, their volume/weight fraction, aspect ratio, strength and modulus; fiber orientation, type of matrix, matrix strength and the interface bonding among the filler/fiber and matrix to enable stress transfer at the interface etc [11]. Among the factors, filler material and proportion in composite are very significant in respect to the mechanical properties. Many investigations are reported with the use of ceramic, natural and other types of particles as filler material but when weight reduction is one of the major issues for composites, the use of soft particles is required to be explored much. Suresha et al. [12] studied the mechanical properties of glass-fiber-reinforced epoxy composites with and without graphite particulate filler. Experimental investigation reveals that tensile strength and dimensional stability of the glass epoxy composite increased with increasing graphite content. The effect of CaCO₃ as a filler in E-glass/ epoxy composites on mechanical properties has been studied

by Paliwal and Chaturvedi [13]. Yusriah et al. [14] studied the effect of particulate fillers on specific mechanical properties of vinyl ester epoxy reinforced with woven glass fiber composites with different filler of calcium carbonate and phenolic hollow microspheres and particulate filler contents (1%, 3%, and 5% by wt). Woven glass fabric composites filled with particulate phenolic hollow microspheres were observed to have better specific flexural strength and specific impact strength, as well as lower density as compared to those filled with particulate calcium carbonate. The use of other particles like mica in glass epoxy composite is helpful to improve the hardness and compressive strength of unidirectional E-glass fiber reinforced epoxy composite [15]. Similarly, the soft particles i.e particles of mica and tricalcium phosphate in glass epoxy composite improved the mechanical properties based on the filler contributing to the bonding strength between fiber and epoxy resin [16]. Hybrid composites consisting of bi-directional E-glass-fiber reinforced epoxy filled with different Linz-donawitz (LD) slag content (0, 7.5, 15, 22.5 wt%) were studied by Pati and Satapathy [17] who opined that LD slag, in spite of being a waste, possesses fairly good filler characteristics as it modifies the strength properties and improves the composite micro-hardness.

Aluminium possesses low weight, high strength, superior malleability, easy machining, and excellent corrosion resistance, good thermal and electrical conductivity. Aluminium is also very easy to recycle [18]. Mechanical properties including hardness, dimension accuracy and thermal conductivity is improved by incorporation of aluminium powder with epoxy resin [19-22]. It is also established that on decreasing the particle size, mechanical properties improve more whereas with the increase of particle size, improvement of thermal conductivity is more. Hence selection of particle size of aluminium powder requires more attention. Extensive literature survey reveals that very few researchers have attempted to explore the mechanical behavior of aluminium filled glass epoxy composites considering different process parameters. In tri-phase materials, composed of an epoxy resin, aluminium particles and milled fibers, Vasconcelos et al. [23] observed that the mechanical and thermal performances are better than the single materials. This was established through a Charpy impact tests with electronic instrumentation. Hamed [24] investigated the tensile strength of aluminium powder mixed glass/ kevlar/ PVC fiber reinforced epoxy composites. He showed that the tensile strength increased with increased volume fraction of aluminium powder from 20% to 40% and the sample kevlar epoxy had higher tensile strength than all other samples for both volume fractions.

In general, researchers have attempted to evaluate the thermal properties of such composites and the role of aluminium incorporation in polymer composites. Though there may be many benefits of using aluminium filler in polymer composites, but the use of this material for the improvement of mechanical properties is yet to be reported. The present work is an attempt to fill this void. In the present research work, the effects of addition of aluminium powder on mechanical properties of woven glass epoxy composites have been studied. This work would be a great help in understanding the function of aluminium powder in glass epoxy composite.

Experimental Work

Materials. Medium viscosity epoxy resin (ARALDITE CY 205 IN) with glass transition temperature (T_g) of 108°C and curing agent hardener (HY 951) at room temperature constitute the matrix system. Fine aluminium powder, average particle size not exceeding 40 micron with a purity of about 98.70% is used as filler material. As reinforcement, woven roving glass fiber containing E-glass fibers of diameter 5-10 μm , orientation $0/90^{\circ}$, density 2.59 gm/cm^3 and 360 gsm, has been used. Fig. 1 (a) and 1(b) represent the aluminium powder and SEM photograph of aluminium particles respectively. Fig. 1(c) shows the woven E glass fabric and Fig. 1(d) represents the geometry of fiber orientation.

Figure 1. a) Aluminium powder; b) SEM photograph of aluminium particles, c) Woven E glass fabric; d) geometry of fiber orientation.

Some details of the constituent matrix materials and mechanical properties of epoxy resin, glass fiber and aluminium powder are shown in Table 1 and Table 2 respectively. At a glance, the mechanical properties of aluminium do not suggest its use as a filler material for improvement in mechanical properties. However, researchers have incorporated aluminium into such composites particularly to improve the thermal properties of such composites. From that perspective, here an attempt is made to see even if one needs to incorporate aluminium for improvement of thermal properties then up to what extent so that there is not much degradation in mechanical properties.

Table 1. Properties of epoxy resin and hardener.

Material	Trade and chemical name	Epoxide equivalent	Density (gm/cm ³)	Parts by weight
Resin	Araldite CY 205 IN	182-196	1.27	100
Hardener	Hardener, HY 951	-----	0.94	10

Table 2. Mechanical properties of epoxy, glass fiber, and aluminium powder.

Property	Epoxy	Glass	Aluminium powder
Tensile strength GPa	0.11	3.4	47×10^{-3}
Elastic modulus GPa	4.1	72.3	70
Poisson's ratio	0.35	0.2	0.33

Fabrication of Composites. The designation and composition of the composites prepared for this study are listed in Table 3. The composite C with fixed amount of fiber reinforcement (60 wt%) and 0 wt% of aluminium content is termed as unfilled glass epoxy or simply glass epoxy composite. In composites D₁ – D₃, the quantity of glass fiber has been maintained fixed at 60 wt%. Aluminium wt% varies as 0, 5, 10, and 15 for each composite. The fabrication of the composite slabs C and D are done by conventional hand-lay-up technique followed by light compression moulding. All the composites (C and D) are fabricated in three steps. On the basis of the mould dimension, certain pre calculation is exercised to determine each constituent quantity. It is essential to maintain the desired wt% of constituents in composites.

Table 3. Designations and compositions of the fabricated composites.

Sample code	Designation	Composition
C	GE	Epoxy (40 wt%) + Glass Fiber (60wt%)
D ₁	5AlGE	Epoxy (35 wt%) + Glass Fiber (60wt%) + Aluminium (5 wt%)
D ₂	10AlGE	Epoxy (30 wt%) + Glass Fiber (60wt%) + Aluminium (10 wt%)
D ₃	15AlGE	Epoxy (25 wt%) + Glass Fiber (60wt%) + Aluminium (15 wt%)

Required numbers of woven fabric of 150 mm×100 mm size is cut with the help of a steel rule and sharp cutter on a wooden platform without disturbing the actual fiber orientation. For unfilled glass epoxy composite, a dry and clean glass container with a starrer is put on a weighting machine and reading is set to zero. Epoxy resin, Araldite CY-205 IN is slowly poured in the glass container till the machine display the required reading. Hardener (HY 951) at a ratio 10:1 by weight of resin is added to the epoxy and stirred mechanically for about ten minutes for proper mixing and exothermic reaction is just about to start. In case of aluminium particulate composites, aluminium powder is added to the epoxy resin first and mixed well in continuous stirring process then the hardener is added with the aluminium epoxy mixture. Stirring of the mixture continues for a certain duration based on the exothermic reaction. A specially designed and fabricated HSS mould (Fig. 2) is used for this purpose to avoid bending during compression. The inner sides of the mould is covered with very thin tear resistant plastic film of few microns thickness to perform the similar function of releasing agent to avoid the possibility of infusion of releasing agent into the glass fiber. Epoxy (resin and hardener) or aluminium mixed epoxy is lapped on the woven fibers uniformly and then the wetted fibers are placed one above the other into the mould. The whole assembly is pressed in a hydraulic press (20 kg) and is left for 24 (twenty four) hours at room temperature. The compression ensures that the entrapped air bubbles are completely removed with the excess resin. After demoulding, post curing is done at room temperature for 48 hour to complete the fabrication process.

(a)

(b)

Figure 2. (a) Mould and (b) hydraulic press used for composite fabrication.**Table 4.** Dimensions of different test samples.

Serial no	Name of the test	Sample dimension
1	Density	30 mm× 12 mm× 6 mm
2	Micro hardness	16 mm× 12 mm× 6 mm
3	Tensile strength (ASTM D3039-07)	150 mm× 12 mm× 6 mm
4	Flexural test (ASTM D790-10)	60 mm× 12 mm× 6 mm
5	Inter laminar shear strength (ILSS)	60 mm× 12 mm× 6 mm

Specimens of required dimensions for mechanical characterization are cut by a diamond cutter. Fine cutting of the samples are carried out with the help of perma grit hacksaw, flat file, sanding block. Final finishing of the surfaces is done with 600 grade and 1000 grade SiC paper. Dimensions of the different samples used for mechanical characterization are shown in Table 4.

Test Procedure

Density. The theoretical density (ρ_{ct}) of composite materials in terms of weight fractions of different constituents can easily be obtained using the following equation [25].

$$\rho_{ct} = \frac{1}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right)}, \quad (1)$$

where W and ρ represent the weight fraction and density respectively. The suffixes f and m stand for the fiber and matrix respectively. Since the composites under this investigation consist of three components namely matrix, fiber and particulate filler, the expression for the density is modified as

$$\rho_{ct} = \frac{1}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right) + \left(\frac{W_p}{\rho_p}\right)}, \quad (2)$$

where the suffix p stands for the particulate filler. The actual density (ρ_{ca}) of the composite is however, determined experimentally by simple water immersion technique with the use of the sample of 30 mm× 12 mm× 6 mm dimensions. Four samples of same composite are tested and average value is presented. The volume fraction of voids (V_v) in the composites is calculated using the following equation:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ca}} \quad (3)$$

Micro-hardness. Hardness is the resistance of a material to deformation, indentation or scratching. The basic goal of hardness testing is to quantify the resistance of a material to plastic deformation. The indentation value has high importance for technical applications which reflects the resistance to deformation which is a complex property and related to modulus, strength, elasticity, plasticity and dimensional stability of a material. Hardness is generally classified into three different categories with respect to the depth of indentation (d). When the depth of indentation ranges between 1-50 μm , it is termed as micro hardness. The test methods commonly used for expressing the relationship between hardness and the size of impression are Brinell, Vicker's and Rockwell hardness tests.

Measurement of hardness. Hardness values offer a comparative measurement of a material's resistance to plastic deformation from a standard source, as different hardness techniques have different scales. The Vickers hardness test is very popular among researchers since it is easier to perform compared to other hardness tests and also the hardness calculations are independent of the size of the indenter and load applied. In this study, Vicker's hardness test setup is used to find out the microhardness values of different composites. Microhardness testing is carried out in a UHL micro hardness tester (Model - VMHT MOT, Sl. No. 1002001, Technische Mikroskopie) with a Vickers diamond indenter. The specimen used for the test is of the dimension of 16 mm $\times$ 12 mm $\times$ 6 mm. Fig. 3 shows the Vicker's microhardness test setup. The dwell time is kept at 10s while the speed of indentation is set at 50 $\mu\text{m/s}$ and indentation load of 1000 kgf. The two diagonals (d_1 and d_2) of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average (d) calculated. Vickers hardness (HV) is calculated with the following equation:

$$HV = \frac{1.8544F}{d^2} \quad (4)$$

where load (F) is in Kilogram force and the mean of two diagonals created by the pyramidal indent (d) is in millimeter. It should be mentioned here that as the hardness is measured on the finished test sample surfaces where glass fiber orientation is perpendicular and no separate surface preparation is done, an average of at least three hardness values for each sample is reported.

Figure 3. Vicker's microhardness tester.

Tensile strength. The tensile tests are conducted on INSTRON 8801 as per ASTM D3039-07 standards test method for tensile properties of composite specimens. This test method determines the in plane tensile properties of glass epoxy composites with or without aluminium particulate filler. The dimension of the sample is 150 mm x 12 mm x 6 mm with a fixed gauge length of 100 mm. Tests are conducted for the samples at normal room temperature (27Deg C) and quasi-static strain-rate of 10E-4/s. At least three specimens for each composite are tested to get the mean value of the tensile strength. INSTRON 8801 with tensile test setup and the test specimens are shown in Fig. 4.

Figure 4. a) INSTRON 8801, b) tensile test setup, c) test samples.

Flexural and inter laminar shear strength (ILSS). The flexural strength of a composite is the maximum tensile stress that it can withstand during bending before reaching the breaking point. The three point bend test is conducted on glass epoxy and aluminium powder filled glass epoxy composite samples using a testing machine INSTRON 8801 as per ASTM D790-10 standard test method. The dimension of each specimen is 60 mm × 12 mm × 6 mm with a span of 50 mm length and a constant cross head-speed of 1.5 mm/min is maintained. The arrangement for the test and the test specimen are shown in Fig. 5. For both flexural strength and ILSS, the test is repeated three times for each composite type and the mean value is reported. The flexural strength of the composite specimen is determined using the following equation:

$$\text{Flexural strength} = \frac{3PL}{2bt^2} \quad (5)$$

where L is the span length of the sample (mm); P is maximum load (N); b the width of specimen (mm); t the thickness of specimen (mm); The data recorded during the three point bend test is used to evaluate the Inter laminar shear strength (ILSS). The ILSS values are calculated as follows:

$$\text{ILSS} = \frac{3P}{4bt} \quad (6)$$

Figure 5. a) INSTRON 8801 with 3-point bending fixture; b) larger image of the fixture showing the point of loading; c) test samples.

Result and Discussions

The mechanical properties of glass epoxy and aluminium powder filled glass epoxy composites with different filler concentration are studied. The relative effects of aluminium filler concentration on various mechanical properties of the composites are presented with respect to filler concentration.

Density and void fraction. Density is a material characteristic which is of prime importance in several weight sensitive applications. Density of a composite depends on the relative proportion of matrix and the reinforcing materials. There is always a difference between the measured and the theoretical density values of a composite due to the presence of voids and pores. These voids significantly affect some of the mechanical properties and even the performance of composites. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering [25]. The knowledge of void content is desirable for estimation of the quality of the composites. The theoretical and measured density of glass epoxy and aluminium particulate glass epoxy composites, along with the corresponding volume fraction of voids is presented in Table 5. It is found that the composite density values calculated theoretically from weight fractions using equation (1 and 2) are not equal to the experimentally measured values, as expected. It is evident from Table 5 that density and void fraction of glass epoxy composite increase with the incorporation of aluminium powder.

Table 5. Measured and theoretical densities along with the void fractions of glass epoxy and glass epoxy filled with aluminium powder composites.

Composition			Measured density (gm/cc)	Theoretical Density (gm/cc)	Volume fraction of voids (%)
C ₂	60GE	Epoxy (40 wt%) + Glass Fiber (60wt%)	1.77	1.79	1.11
D ₁	5AlGE	Epoxy (35 wt%) + Glass Fiber (60wt%) + 5 wt% Aluminium	1.84	1.87	1.60
D ₂	10AlGE	Epoxy (30 wt%) + Glass Fiber (60wt%) + 10 wt% Aluminium	1.91	1.95	2.05
D ₃	15AlGE	Epoxy (25 wt%) + Glass Fiber (60wt%) + 15 wt% Aluminium	1.97	2.03	2.95

Micro-hardness. Hardness is considered as one of the most important factors that govern the wear resistance of any material. In the present work, micro-hardness values of glass epoxy and glass epoxy composites with different aluminium concentrations are obtained. The test results (Fig. 6) show that with the presence of aluminium filler upto 10 wt%, microhardness of the composites is improved as compared to unfilled glass epoxy and with further addition of aluminium up to 15 wt%, micro hardness decreases.

Figure 6. Micro-hardness of composites with aluminium concentration.

Tensile Properties. The tensile strengths of glass epoxy and glass epoxy composites filled with aluminium powder are shown in Fig. 7. It is found that, there is a gradual drop in tensile strength with increase in aluminium content. The unfilled glass epoxy composite has strength of 347.60 MPa in tension, and this value drops to 306.64 MPa, 278.75MPa and 210.29 MPa with aluminium powder addition of 5 wt%, 10 wt% and 15 wt% respectively. The reduction in tensile strength with filler addition may be due to the chemical bond strength between filler particles and the matrix is too weak to transfer the tensile load or the sharp corners of irregular shaped filler particles result in stress concentration zones in the matrix body during tensile loading or due to the increase in void percentage in the composites with increase in filler content [26].

Figure 7. Tensile strength of composites with different aluminium concentration.

Figure 8. Tensile modulus of composites with different aluminium concentration.

The variation of tensile modulus with different aluminium concentration in glass-epoxy composites is shown in Fig. 8. It is observed that the tensile moduli of glass epoxy composites improve significantly with 10 wt% of aluminium powder content (10AlGE). But in case of 5 and 15 wt% aluminium powder filled glass epoxy composites (5AlGE and 15AlGE), it decreases with respect to unfilled glass epoxy composite (GE). Previous reports demonstrate that normally the fibers in the composite restrain the deformation of the matrix polymer, reducing the tensile strain [27, 28]. So even if the strength decreases with filler addition, the tensile modulus of the composite is expected to increase for a certain wt% of aluminium powder addition as observed in the present investigation. But further increase in filler content up to 15 wt% or to decrease it to 5 wt%, the tensile moduli of the composites are found to be decreasing.

Flexural Strength. Composite materials used in structures are prone to fail in bending and therefore the development of new composites with improved flexural characteristics is essential. The variation of flexural strength of glass-epoxy composites with different wt% of aluminium filler concentration is shown in Fig. 9. The highest improvement in flexural strength with 5 wt% of aluminium content is recorded whereas 15 wt% aluminium filled glass epoxy composite shows the lowest strength even lower than the unfilled composite. But for the composite with 10 wt% of aluminium powder shows the better performance than glass epoxy composite but less than the 5 wt% aluminium filled composite. The improvement in the flexural strength of the composites with filler content (upto 10 wt%) is probably caused by good compatibility of the particulates and the epoxy matrix, leading to increase in interfacial bonding. The lower values of flexural properties (as 15AlGE) may also be attributed to fiber to fiber interaction, voids and dispersion problems.

Inter laminar shear strength (ILSS). The variation of inter-laminar shear strength (ILSS) of glass epoxy and glass epoxy with aluminium filler composites is presented in Fig. 10. It is observed that with the addition aluminium powder up to 10 wt%, the ILSS of glass epoxy composites increases in comparison to unfilled glass epoxy composite but starts decreasing on further aluminium addition. This reduction may be due to the formation of voids in the matrix which is generally located at the inter-laminar region of composites or may be because of poor interfacial bond among the constituents of the composites. The maximum value of ILSS is observed for glass epoxy with 5 wt% aluminium concentration. The present study reveals that incorporation of aluminium in glass fiber epoxy composites should be done judiciously particularly with respect to its amount; otherwise there may be deterioration of mechanical properties. Also there are other aspects of composite preparation [29-32] that needs to be care of for enhancement of properties.

Figure 9. Flexural strength of composites with different aluminium concentration.

Figure 10. Inter-laminar shear strength of composites with different aluminium concentration.

Conclusions

In this study, processing and experimental investigations are conducted to evaluate the mechanical properties of woven glass-fiber reinforced epoxy composites filled with different proportion of aluminium powder. The following main conclusions are drawn from the study:

1. Fabrication of woven glass fiber reinforced epoxy composites filled with different proportion (wt%) of aluminium powder is possible in simple hand lay-up technique followed by light compression molding process.

2. The density and void fractions of glass epoxy composites increase with increase in aluminium concentration.

3. Micro hardness, flexural strength, inter laminar shear strength (ILSS) of 5 and 10 wt% aluminium content composites are improved than unfilled glass epoxy composite and these properties decrease with further addition of aluminium powder. With respect to these mechanical properties, 5 wt% aluminium content yields the maximum property values whereas 15 wt% aluminium yields the minimum value.

4. The tensile strength of the glass fiber reinforced epoxy composites decreases effectively with increasing aluminium proportion.

5. In order to reach the best tensile modulus properties, the optimal content of aluminium powder in the filled epoxy matrix is recommended as 10 wt%.

Acknowledgements

Authors gratefully acknowledge the support of University Grants Commission (UGC), Govt. of India through Major Research Project [F. No. 42-882/2013(SR)] in Engineering.

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