AL22 - Effect of Graphene on the Mechanical and Conducting Properties of Aluminium

Priyambada Nayak[1], Balaram Polai[2], Arijit Mitra[3] and Saroj. K. Nayak[4]
1. Post-Doctoral Fellow
2. Junior Research Fellow
3. Post-Doctoral Fellow
4. Professor
School of Basic Science, Indian Institute of Technology, Bhubaneswar, Odisha, 752050, India
Corresponding author: priyambada.pce@gmail.com,

Abstract:

Aluminum, its composites and alloys have already been widely applied in the fields of aircraft, space, automobile, transportation and building industries due to their dynamic properties such as high strength, excellent stiffness, low density with good thermal and electrical properties. In view of the above, certain alloys and composites of aluminium are being produced in the smelters by adding unit operations. In the current paper, the authors have tried to incorporate graphene (a relatively new material) in to aluminium to find its effect on the mechanical and conducting properties. The high fracture strength of graphene (125 GPa) offers better platform as a reinforcing material in aluminium matrix composites when introduced in a given set of conditions. In the present work graphene reinforced aluminum (Al-Gr) with different compositions were fabricated under a set of experimental conditions. The crystal structure, surface morphology and grain size of the fabricated Al-Gr materials were analyzed with the help of X-Ray diffractometer (XRD), scanning electron microscopy (SEM) and Raman spectroscopy. Microstructure analysis shows uniform distribution of graphene throughout the matrix. Micro-hardness test reveals a significant increase in hardness up to 0.5wt.% of graphene reinforcement and later on decreases with more percentage of graphene. The improvement of mechanical properties observed are attributed to the uniform dispersion of graphene in the aluminium matrix and an excellent interfacial bonding between graphene and aluminium. Further, both electrical and thermal conductivity of all the prepared samples have been performed to find the effects. Incorporation of graphene in aluminium metal shows excellent mechanical and conducting properties compared to virgin metal.

Key words: Graphene (G), graphene reinforced aluminium (Al-Gr), mechanical properties, electrical and thermal conductivity.

1. Introduction

Aluminium is one of the potential engineering materials because it has excellent properties such as high specific strength, high thermal and electrical conductivities, superior corrosion resistance and low density with cost-effectiveness [1-5]. Due to these properties, aluminium and its alloys are used in the field of electronics, thermal management, automotive, aerospace and aeronautical industries. However, in last two decades, there has been high demand for the improvement of strength of aluminum and its alloys due to its low strength to weight. Therefore aluminum-based metal matrix composites have great attention by the research community.

In general, the matrix will be the low-density metal (herein aluminium) and the reinforcing material will be a different material such as fibre, ceramic, polymer etc. Matrix in as monolithic material is continuous in nature and the diverse materials are embedded in it. Reinforcements are added to the matrix in order to improve its properties like hardness, strength, elongation, conductivity, corrosion resistance, etc. But due to the lightweight requirements traditional reinforcements corresponding to ceramics and fibers cannot fulfill the need.

Carbon-based materials such as carbon nanotubes (CNTs), graphite and graphene are getting special attention in modern society due to their superior mechanical [6], electrical [7], thermal properties [8] and tribological behavior [9, 10]. Among them the two-dimensional (2-D) Graphene with sp^2-hybridization has much attracted because of its excellent properties, such as high Young's modulus (1 TPa) [11], high fracture strength (125 GPa) [12], extremely high thermal conductivity (5000 W/mK) [13] and super charge-carrier mobility (200 000 cm^2/Vs) [14]. At present, reports are available on graphene-reinforced polymer [15] and ceramics [16] matrix composites. However, aluminium reinforced with is still in its infancy because of the preparation technology. On the other hand, powder metallurgy method is widely used for the preparation of AMCs (Aluminium metal matrix composites) due to its low processing temperature, which is beneficial for interface reactions and uniform dispersion. Wang et al. fabricated Al-metal matrix composites with the reinforcement of grapheme by powder metallurgy technique and obtained a tensile strength of 249 MPa in the 0.3 wt% graphene nanosheet addition which was 62 % greater than pristine Al [17]. Also the mechanical properties are investigated by Bartolucci et al in 0.1 wt % GNSs/Al composite samples by hot isostatic pressing and hot extrusion and found a remarkable decrease in tensile strength and elongation [18]. Similarly, Li et al. reported an increase of the elastic modulus and hardness (17-18 %) with the addition of 0.3 wt% graphene oxide in Al [19].

All the above studies showed that the mechanical properties of aluminum metal matrix composite can be improved by addition of grapheme platelets and graphene nanosheets. Therefore, still it is a great challenge to produce well-dispersed graphene in aluminium via a conventional metallurgical process due to the environment issue and density mismatch between graphene and aluminum matrix. In the present work we are trying to prepare Al metal matrix composites with the reinforcement of graphene by ball milling and vacuum sintering process. The effect of graphene contents on the mechanical and conducting properties of the prepared Gr/Al composites were investigated in detail.

2. Experimental

Pure aluminum powder (99.7 % purity; Loba Chemie Pvt. Ltd.) with particle size 20–45 µm and density 2.71 g/cm^3) and Graphene (purity 99 %) density 0.24 g/cm^3 and mean diameter in the range of 0.5–20 mm was used as the starting material. Figure 1(a, b) shows the SEM images of the received aluminium powder and graphene, respectively. Graphene reinforced (0.25 wt %, 0.5 wt %, 1 wt % and 2 wt %) aluminium composites were fabricated by powder metallurgy method. Therefore, respective weight of powder ratios was taken into a stainless steel (SS) jar along with stainless steel (SS) balls in the presence of toluene as a process control agent. The balls to powder ratio was maintained 10:1. The milling was carried out for 10 hours at 300 rpm in high energy ball mill. After the milling, the Al based composite powder was dried and green pellets of different size were prepared using hydraulic press machine. The applied pressure was of 163 MPa with holding time of 3 minutes. The green pellets were then subjected to vacuum sintering at 550 °C for 2 hours, with heating rate of 5 °C /min, and then cooled down and finally taken for various characterizations.

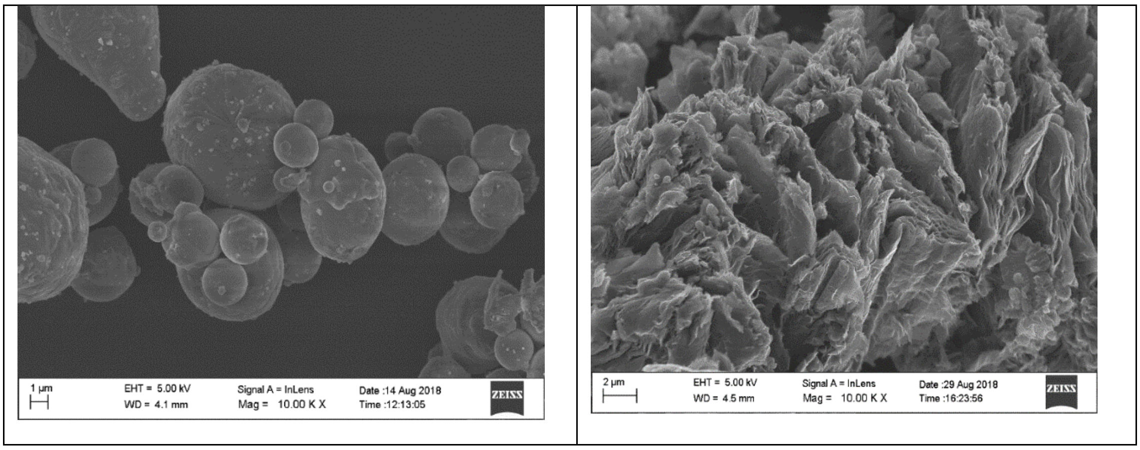
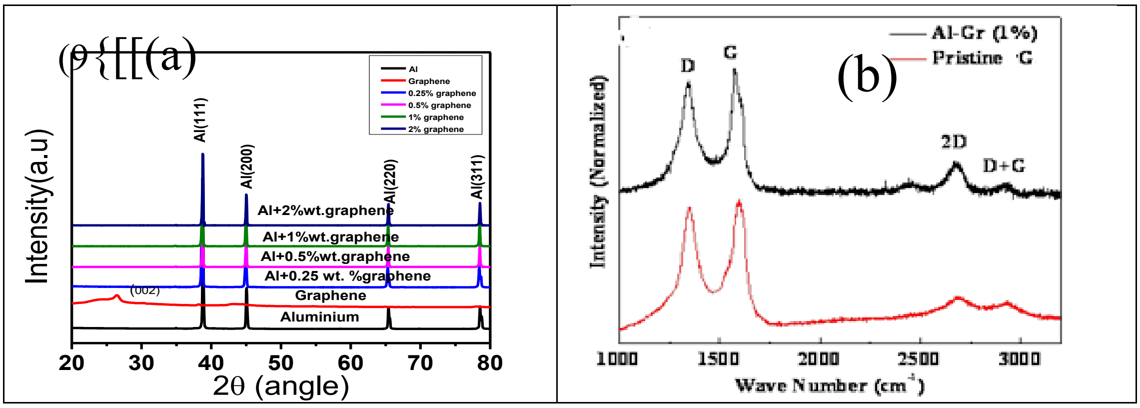


Figure 1. SEM of pure aluminium and graphene.

X-ray diffraction analysis (XRD, Rigaku Ultima IV) with Cu-target (Kα, λ = 0.15406Å) radiation was used to analyze the phase formation after sintering compositions. The microstructural evaluation was characterized by scanning electron microscopy (SEM, Jeol JSM-7001F). Density measurement was carried out by the Archimedes method with the help of a density kit. Hardness measurements of the samples were carried out by Vickers hardness testing machine (Shanghai Shuangxu, Inc., HVS-50, China), using a load of 9.8 N, and the mean values of at least five measurements conducted on different areas of each sample were calculated. The thermal conductivity measurement was carried out with C-THERM thermal conductivity analyzer at room temperature, whereas electrical conductivity was measurement was made by four-probe method. Tensile properties of the Gr/Al composites were carried out on an AGS-J tension machine with a speed of 0.5 mm/min at room temperature.

3. Results and Discussion:

The crystal structure of pristine Al and Al-G metal matrix composites were examined by X-ray diffraction technique (XRD). Diffraction pattern of all the composites depicts the cubic phase (FCC) with four peaks at 38.8° (111), 45.0° (2 0 0), 65.4° (2 2 0), 78.5° (3 1 1) as shown in Figure 2(a) [20]. The absence of any extra peak in the Al-G composites reveals a pure phase of the as-prepared composite. To confirm the graphene content, Raman spectra analysis was carried out and shown in Figure 2(b). The characteristic D, G and 2D bands of graphite are observed in graphene and Al-G composites. Therefore, the presence of graphene in the composite samples is confirmed. Although Raman spectroscopy does not provide any information about the distribution of graphene in Al matrix composites. To understand the distribution of graphene content in Al matrix, Raman mapping was performed. Raman mapping at D and G peak (Figure 2 (c, d) of graphene indicates a homogeneous distribution of graphene throughout the composite sample.



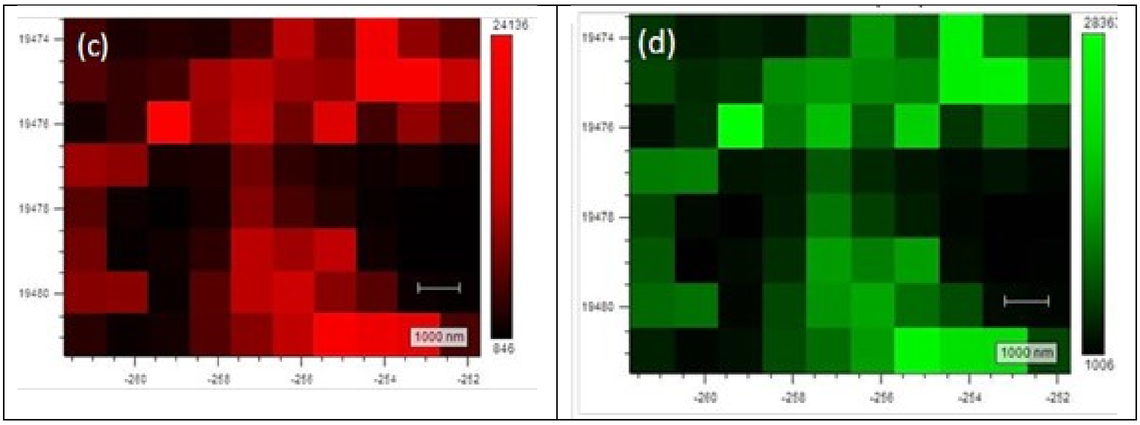


Figure 2. (a) XRD pattern of pristine Al and Al-G composite of different weight ratios (b) Raman spectra of pristine graphene and Al-G composite with 1 % graphene weight fraction. Raman mapping at (c) D band and (d) G band of graphene.

Fig. 3(a-d) represented the morphological view of 0.25 %, 0.5 %, 1 % and 2 % graphene-reinforced aluminium matrix composites by scanning electron microscope. The distribution shows the uniformity of Al and graphene constituents. However, with the increase of the graphene content, the graphene content on the aluminium particles gradually increased, which was mainly distributed on the surface of the aluminium powders and shows no obvious agglomeration, when the content of graphene in the Al-Gr composites is up to 0.5 wt%. The grain boundaries are clearly visible in the sample and bonding between the particles is good. Due to its very high conductivity the graphene particle is highly illuminated in comparison to the surrounding microstructure of the sample. On the other hand, slight agglomeration with some minute amount of channel pores was determined when the grapheme content was >0.5 %.

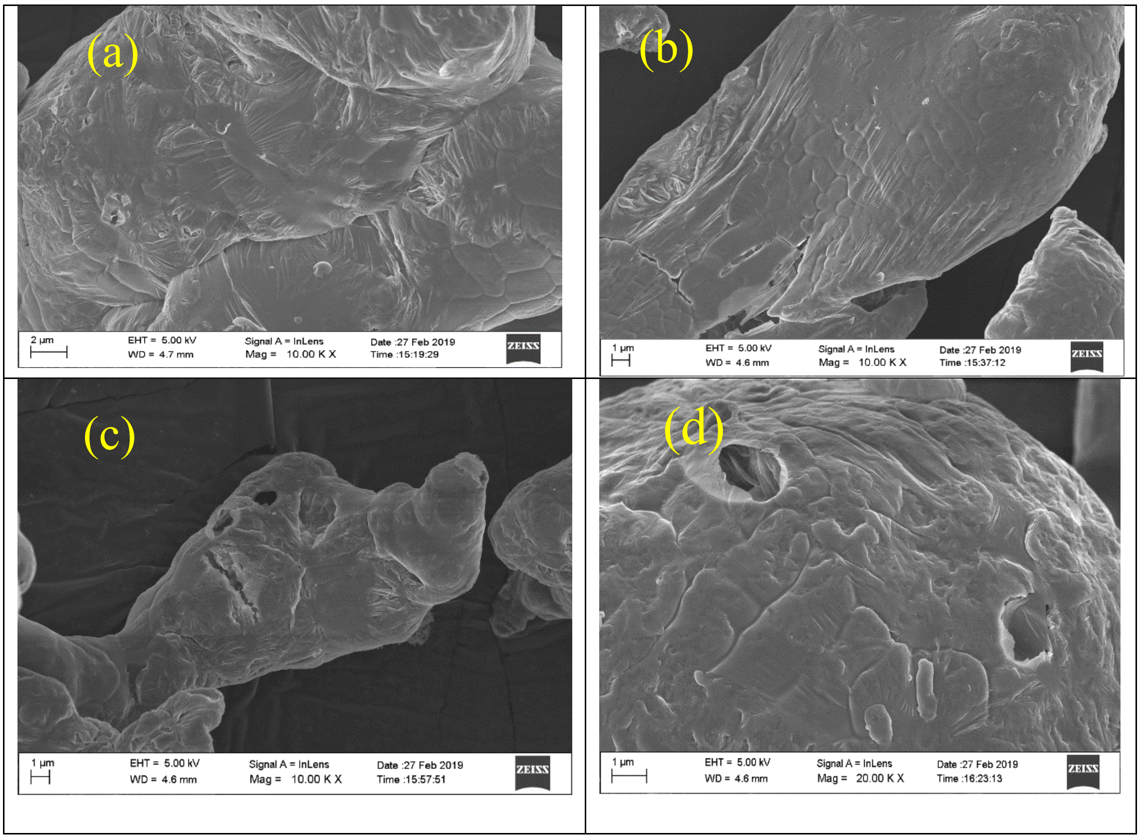


Figure 3. SEM image of aluminium- graphene composite.

In order to determine the physical property of 13 mm diameter and 3 mm thickness sintered sample, density measurement was carried out by using Archimedes method. According to this, bulk density was measured by weighting the sample in air and then in water [21]. The results are summarised in Figure 4 and finally, we compared with the theoretical density. It is found that all the samples had ≈ 97 % of the theoretical solid density of aluminium, which is 2.699 g/cm^3 [22]. This indicates the samples are highly densified, which may have given better conductivities. The density of the modified composites gradually decreases with the increase of graphene content. The reason behind this is may be poor combination of graphene among aluminium particles and resulting increase of porosity in composites, which finally declines the density.

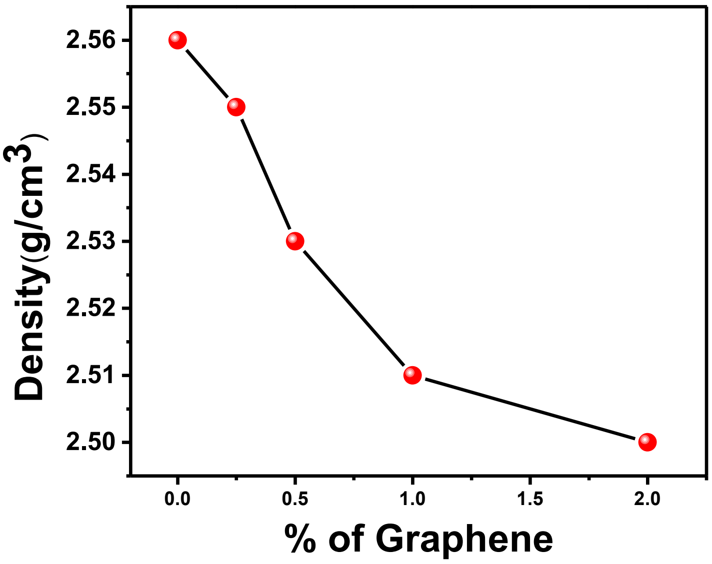


Figure 4. Measured density measurement of different Al-Graphene composites.

The micro-hardness of the Al-G metal matrix composites was carried out with Zwick/Roell machine with the help of ZH micro HD software. The measurements were repeated five times for each sample at random surface locations and averaged. Figure 5 shows the micro-hardness of Al-G composites represented as Vickers pyramid number (HV). Vickers hardness is calculated as $HV = 0.18 \times F/d^2$, where, F is applied force and d is the diagonal distance of the diamond indenter [23]. As shown in the figure, maximum hardness is obtained when the graphene content is 0.5 wt.%. Meanwhile pure aluminium shows Vickers hardness of 34 HV and hardness of the composites increased for graphene $\leq$ 0.5% and then decreased. Due to the low density of graphene, a low mass fraction results in a high volume fraction. But, for higher percentage of graphene, agglomeration and coalescence takes place, which affects the micro-hardness. Also, there may be the possibility that graphene inhibits the grain growth by grain boundary pinning.

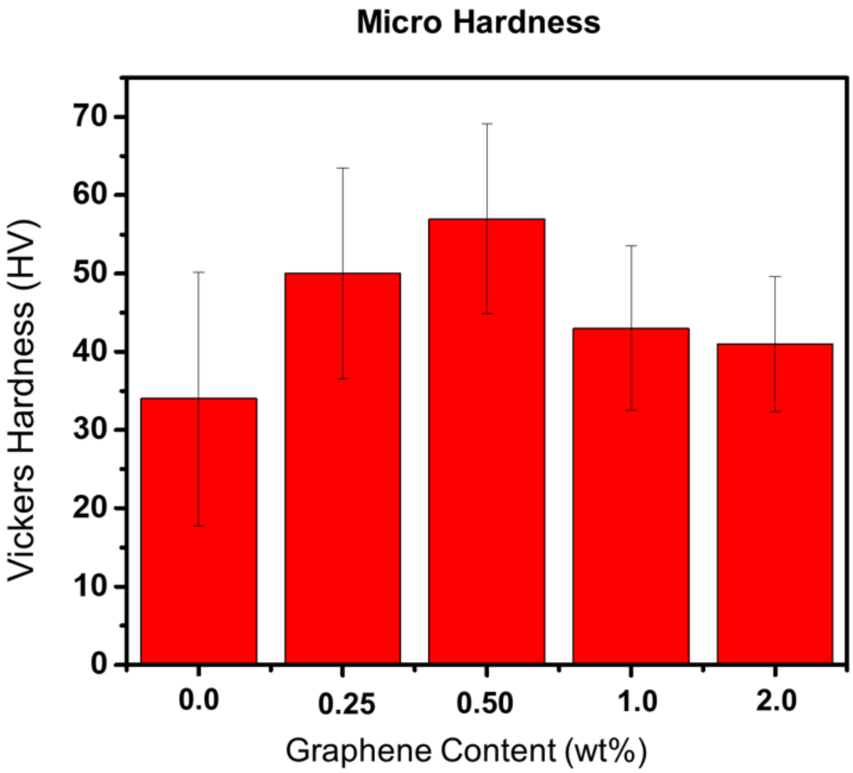


Figure 5. Micro hardness of aluminium graphene composite.

Figure 6(a) shows the change in thermal conductivity (K) as a function of graphene weight percentage at room temperature (RT). It can be observed that K increases monotonically with the increasing graphene percentage in the Al-G composites. Pristine Al has thermal conductivity of 130 W/mK which is increased up to 310 W/mK for Al-G composite with 2 % G. The increment in K is much larger than for pristine graphene. The increment of K is observed due to the incorporation of G in Al matrix. As graphene has extremely high thermal conductivity of 3000 W/mK, an increase of K with graphene weight percentage can be easily realized as the effect of graphene amount in Al [24]. Figure 6(b) shows variation of electrical conductivity with graphene content. The observed electrical conductivity is maximum for 0.5 wt.% graphene addition in the sample and at higher graphene content it decreases. This may be due to the formation pores which was already discussed in the micrograph shown in Figure xx.

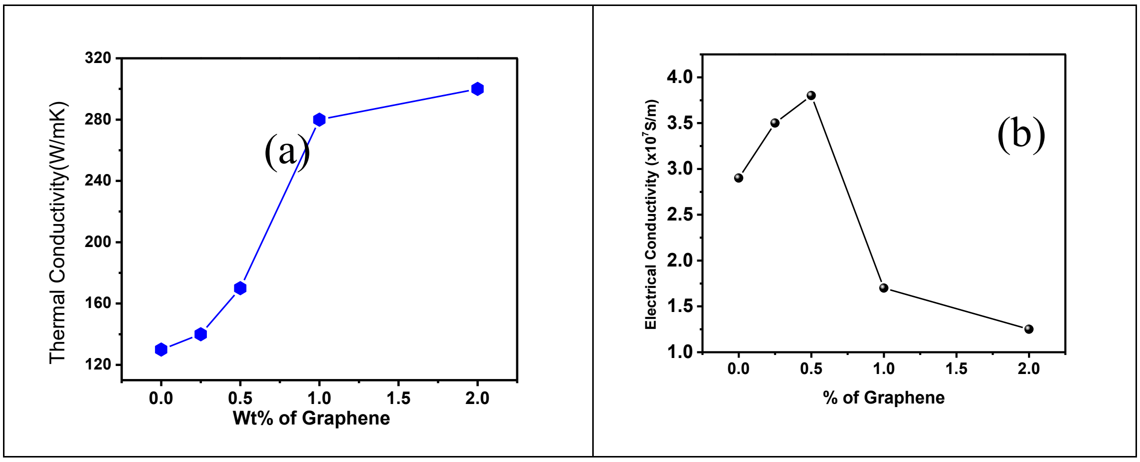


Figure 6. Thermal and electrical conductivity aluminium graphene composite at room temperature.

All the above results indicate that graphene is uniformly distributed in the modified composition. Therefore graphene content plays an important role in determining tensile properties of the composites. Figure 7(a) depicts the tensile properties of Gr/Al composites. The size of the tensile samples is shown in Figure. 7(b).

From the figure it is found that with the increase of graphene content, the UTS (ultimate tensile strength) of Gr/Al composites increases and then decreases. But when the graphene content is 0.5 wt.%, it reaches the maximum value which is much higher than for pure Al [25]. The increasing value may be due to two reasons. Firstly, the homogeneous dispersion of graphene content in Al matrix. Secondly, during electrostatic self-assembly, large sizes of graphene are protected. Therefore, contact areas between graphene and Al matrix are enhanced which increases load-transfer sites. In other words, structural integrity of graphene is also favorable to increase the load transfer. However, when graphene content is greater than 0.5 wt.%, graphene located at the grain boundaries of Al, as discussed in the previous section, causes the loss of associativity among Al powders, resulting in decreasing the tensile properties. Again, the increasing value of tensile strength is small compare to other reports because graphene is randomly distributed, therefore, not all graphene is parallel with the tensile direction. Also, since the interface bonding of graphene and Al matrix is not optimized, the load-transfer efficiency is not high enough.

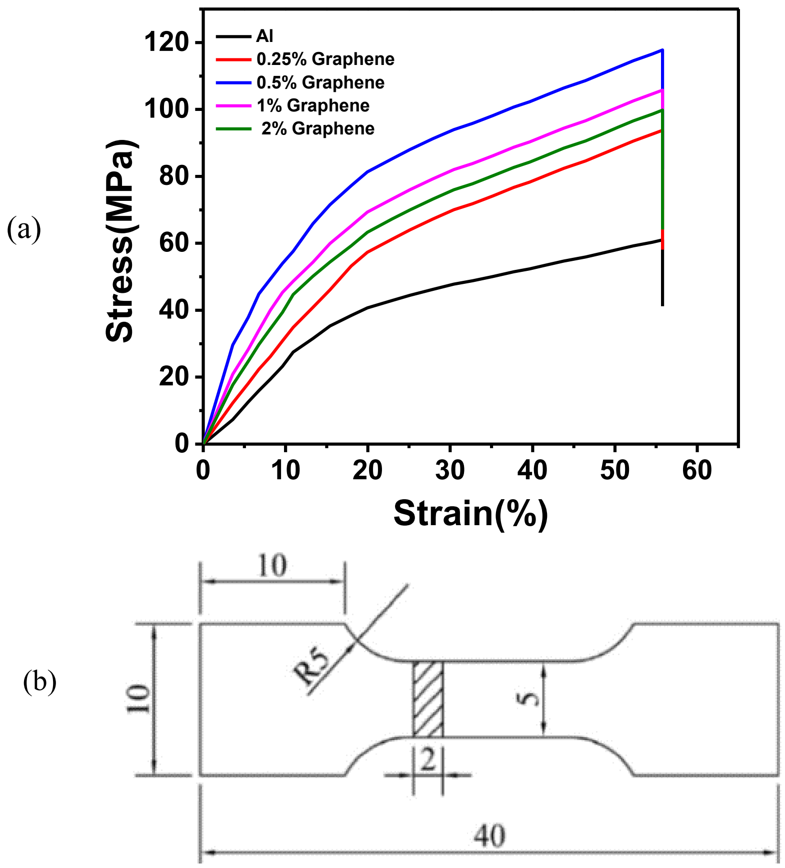


Figure. 7(a) Stress-strain graph of aluminium-graphene composite (b) Size of the sample in mm.

4. Conclusions

From the current research work the following conclusions are drawn

1. Aluminium-graphene metal matrix samples of different composition have been prepared successfully by powder metallurgy techniques.
2. SEM result reveals the composite materials as spherical grains along with some minute amount of channel pores for higher graphene reinforced composition, which are uniformly distributed throughout the material.
3. Measured density of the composite samples was found to decrease with an increase in graphene content.
4. Vicker’s hardness increases with graphene content and it was maximum when the graphene content was 0.5 wt%, which is related to the microstructural properties.
5. Similarly, ultimate tensile strength and electrical conductivity are maximum for 0.5 wt.% graphene content sample and this is related to effective load transfer. On the other hand, thermal conductivity increases linearly with the graphene content.
6. In summary, the increase in hardness, tensile strength and conductivities indicates that graphene is an appropriate reinforcing material in aluminium for different applications.

5. Acgnowledgement

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