Visual Abstract

Study on microstructure, mechanical and fracture behavior of Al_2O_3 - MoS_2 reinforced Al6061 hybrid composite

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ABSTRACT. Al composites usage is growing and is gaining importance in aerospace, automotive and marine industries due to their excellent characteristics. Aluminum composites exhibit high resistance to wear and corrosion, possess high strength, offer durability and more such properties. In this study, Al 6061 alloy, reinforced with Al_2O_3 - MoS_2 was produced by a stir casting technique and its microstructure and mechanical behavior were evaluated. Reinforcements were added in the range of 0 - 9 wt. %. The microstructure analysis, tensile and compressive strength of the hybrid MMCs (Metal Matrix Composites) have been analyzed and examined. From the investigational study, it was found that the reinforcing particulates are evenly dispersed in the base matrix. The porosity and density of the hybrid composites were found to be enhanced. The ultimate tensile and compressive strength of the hybrid MMCs could be improved by addition of ceramic (Al_2O_3) particulates compared to monolithic. Further, the strength of hybrid composites was decreased by adding of MoS_2 (solid lubricant) along with hard ceramic particulates. Finally, fractured surface of the UTS test specimens were analysed using a SEM analysis.

KEYWORDS. Al6061; MMCs; Stircasting; Microstructure; Mechanical behavior; SEM analysis.

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INTRODUCTION

An advanced material entitled MMCs (Metal Matrix Composites) substitute the traditional materials due to their higher wear resistance, better strength in several engineering applications such as cylinder liners, pistons, and other engineering materials. Composites have been the subjects of a competitive and stimulating field for research from past 2-3 decades [1, 2]. Nowadays, instead of other engineering materials, Al is extensively used in various industries like aerospace, automobile and defence, due to its lower density, better resistance to wear and corrosion, high strength with better thermal conductivity and better machinability. As technology progresses, requirement for a stronger, harder, inexpensive and lightweight materials in the industries [3]. Presently, less weight materials such as Al alloys are chosen as better material for marine industries and as well as aerospace due to better thermal and physical characteristics. Among the different types of Al alloys, Al6061 alloy possesses better corrosion resistance and exhibits the excellent strength and also finds a lot of material applications in the areas such as commercial, automotive, and structural applications. MMCs from Al alloys have attracted lot of attention due to higher strength and high wear resistance. Particulates reinforced

MMCs consist of uniform dispersal of strengthening hard ceramic particles embedded within a base matrix [4]. In general, these materials show better strength and good stiffness and low density, when it is compared to the matrix. The addition of hard particulates in Al MMCs can enhance the tensile strength and resistance to wear in soft Al matrix. The enhancement in mechanical characteristics is generally influenced by uniform dispersal of reinforcements and the interfacial bonding between the reinforced particulates and matrix. Generally, hard ceramic particulates such as Al_2O_3, SiC, B_4C, TiC and marble dust are used as reinforcement for several engineering applications. It is found that most of the researcher/s has studied the wear characteristics of hard ceramic reinforced Al composites. But yet the mechanical and wear behavior of Al is not adequate for the practical applications [5-8]. Further, this type of Al composites exhibits enhanced mechanical properties with low-coefficient of thermal expansions. The soft particulates (MoS_2) impart better machinability to the base material. This provides for a wide usage of composites in automotive, aeronautical and also in thermal management applications [9-11]. The manufacture of Al matrix composites is undertaken through squeeze casting, stircasting and powder metallurgy methods. The most often used production method is the stircasting route. When considering the stircasting method, the parameters like speed of the stirrer, geometry of stirrer and stirring time are considered. The stirring must be accurate vigorous so as to ensure a uniform mixing of the reinforcements with in the matrix which in turn to increases their material properties. Suitable selection of parameters is essential to attain the end properties failing which will be resulting in reduction of material properties. From literature survey it was observed that when improper parameters were chosen and there was a decreased in the resulting materials properties [12]. The stircasting method is cost effective and least expensive. In this method, the hard particles are added at the melting point of the matrix. The development of MMCs is very less expensive with particulates reinforcement in comparison with fiber reinforcement [13, 14]. Suresh et al [15] evaluated the mechanical strength of Al 7075/Al_2O_3/Mg hybrid MMC's produced by stircasting technique. From the outcomes it was observed that the mechanical properties of hybrid composites were enhanced when compared with the base alloy. Sharanabasappa [16] conducted the experiments trials on mechanical characteristics of fly-ash and Al_2O_3 reinforced MMCs. It was observed that the mechanical strength of the composites increased with the increase in Al_2O_3 content. Chennakesava Reddy [17] studied the tensile and fracture behavior of Al-6061/Al_2O_3 MMCs. It was found that the strength of material showed an increase with increasing wt. % of Al_2O_3 content, whereas ductility of composites decreased. Alaneme [18] investigated the mechanical characteristics of Al-Al_2O_3 MMCs. The outcomes shown that the material properties improved by incorporation of hard particles. It was also found that the rate of fracture was reduced by increase of wt. % of Al_2O_3 content. V. Bharath et al. [19] in their study, made efforts to develop an Al composite reinforced with Al_2O_3 by using liquid stircasting method. It was observed that, composites mechanical behavior improved by the adding of Al_2O_3 content up to 15%. By adding of Al_2O_3 particles in the base matrix, it was found that, the ductility of MMCs decreased. Bhargavi Rebba [20] evaluated the mechanical characteristics of MMCs reinforced with MoS_2-B_4C. The tensile and yield strength improved by increase in B_4C - MoS_2 particulates. The increase in the strength of hybrid MMCs may be due to the existence of hard ceramic particulates. Mitesh and Ashok [21] evaluated mechanical strength of MMCs reinforced with MoS_2/Al_2O_3. From the outcomes it was observed that the ultimate tensile strength decreased significantly due to the addition of MoS_2 content from 3% - 9% by weight. The reduction of tensile strength may be caused by various mechanisms like the crack propagation and particle pull-out, which are instigated by the existence of MoS_2 content. However, many researcher/s have carried out material characteristics such as mechanical, wear behavior and machinability of Al metal matrix composites with Al_2O_3 or MoS_2 content as reinforcing materials. Whereas, in the case of Al6061 Al_2O_3-MoS_2 hybrid composites, inadequate literature survey is available. So effort was made to examine the microstructure and mechanical characteristics of Al 6061 Al_2O_3-MoS_2 hybrid composites.

MATERIAL AND FABRICATION OF THE COMPOSITES

Reinforcements and instruments

In the present research work, Al6061 was used as matrix material and two different reinforcements such as Al_2O_3 and MoS_2 of wt. % of 3, 6 and 9 with particulates size of 100 mesh were used for the development of hybrid metal matrix composites. Stircasting method is presently the simple and effective technique available for the fabrication of hybrid MMCs [22-24]. So, stircasting method has been successfully used for the production of hybrid composites. Electric furnace was used to melt the matrix material at 700ºC. When the molten melt was ready, preheated reinforcements were added in to the melt on the required content. The stirring process with ceramic coated SS steal blades stirrer with speed of 250 rpm for the duration of 5 min were used during the development of MMCs. Continuous stirring process was maintained to achieve uniform mixture of matrix and reinforcements. Latter the ready molten metal was poured in to pre-heated metallic die. After solidification, castings were removed from the die.

The tensile and compression test samples were pre-machined by using CNC machining. Tensile test samples were prepared as per the ASTM E8 standards. Compression test sample were prepared as per the E9 standards [4, 6 & 11]. These test samples were subjected to study the micro-structure and mechanical strength. The test samples of hybrid composites are shown in the Fig. 1.

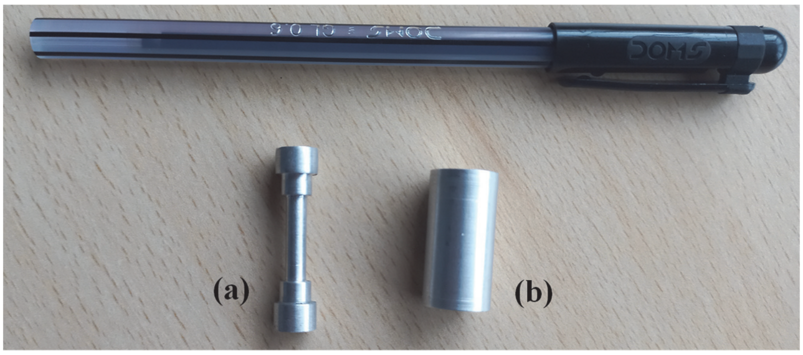

Figure 1: (a) Tensile test specimen (b) Compression test specimen

RESULTS AND DISCUSSION

Microstructure analysis

Uniform dispersal of reinforcing particles show better influence on the mechanical behavior of MMCs [25]. The microstructure depicted in Fig. 2(a) shows pure base alloy that shows the cast part without any reinforcements. The Fig. 2(b) shows the optical micrograph of Al 6061 reinforced with 9% Al_2O_3 - 3% MoS_2 with uniform dispersal. The reinforced particles in the MMCs are evidently resolute near the grain boundaries. It is found that, the particles are free from clustering and agglomeration due to the stircasting method adopted to fabricate the hybrid composites. The dispersal of hard particles in Al matrix is a vital requirement for enhancement of the mechanical strength of the hybrid composites [26, 27]. Reinforcing of hard particles in the Al matrix increase the grain refinement. The microscopic study shows that the grain around hard reinforcements is much finer when compared to the grains around reinforcements free matrix alloy. So, hard particulates can induce the recrystallization of the Al alloy by accelerating particles nucleation among the matrix and reinforcement phase. Similar outcomes have been found by other researchers [28, 29] and they concluded that, aluminium grain solidifies near by the reinforced particulates which are execution the nucleation center generally which compromises the resistance to the grain growth.

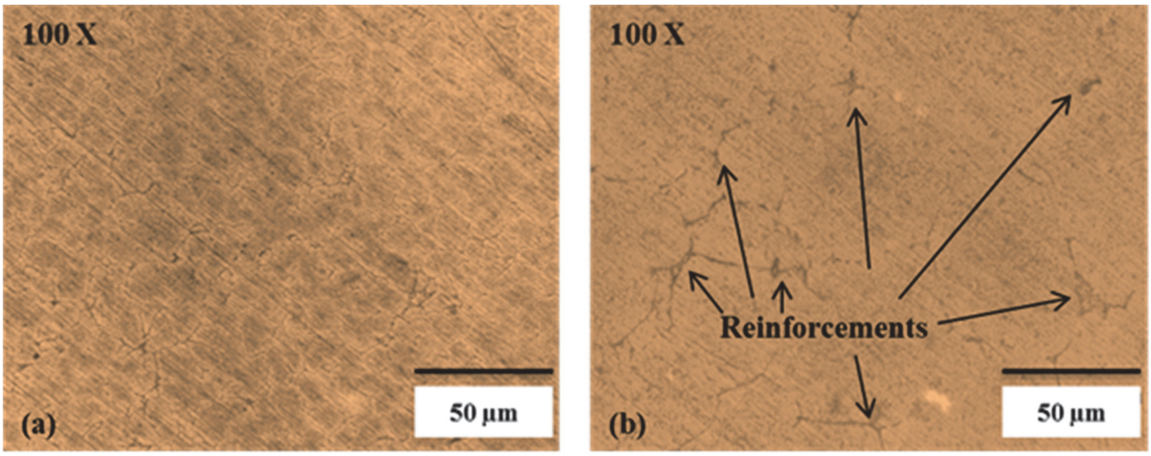

Figure 2: Optical Micrograph of (a) Pure Al alloy in as-cast condition (b) Al 6061 reinforced with 9% Al_2O_3 – 3% MoS_2 with uniform dispersal.

Density and porosity

Density of the samples was measured to know the level of porosity, which affect the reliability of the casting technique. The influence of MoS_2 on the density of developed composite measured by Eqn. (1). Porosity can be calculated by differentiating the density values of theoretical (ρ_{th}) and experimental ($\rho\varepsilon\xi\pi$) by Eqn. (2). The density of composite samples calculated with Archimedes' principle (water displacement method) as given in Eqn. (1):

$$\varrho_{exp} = \frac{m}{V} \tag{1}$$

here, m = mass and V = volume of the test samples.

Porosity level in the developed composites normally appears, due to the entrapment of air while casting. Porosity can effect the mechanical and other properties of the composite material, which cannot be removed entirely, but can be reduced by controlling the casting process.

$$\text{Porosity (\%)} = \left(\frac{\varrho_{th} - \varrho_{exp}}{\varrho_{th}} \right) * 100 \tag{2}$$

The theoretical density for composites can be calculated by using Eqn. (3), which is known as a rule of mixtures,

$$\varrho_{th} = \varrho_m V_m + \varrho_r V_r \tag{3}$$

where ϱ_m denotes the density of matrix, V_m denotes the volume fraction of the matrix, ϱ_r denotes the density of reinforcement and V_r denotes the volume fraction of the reinforcement.

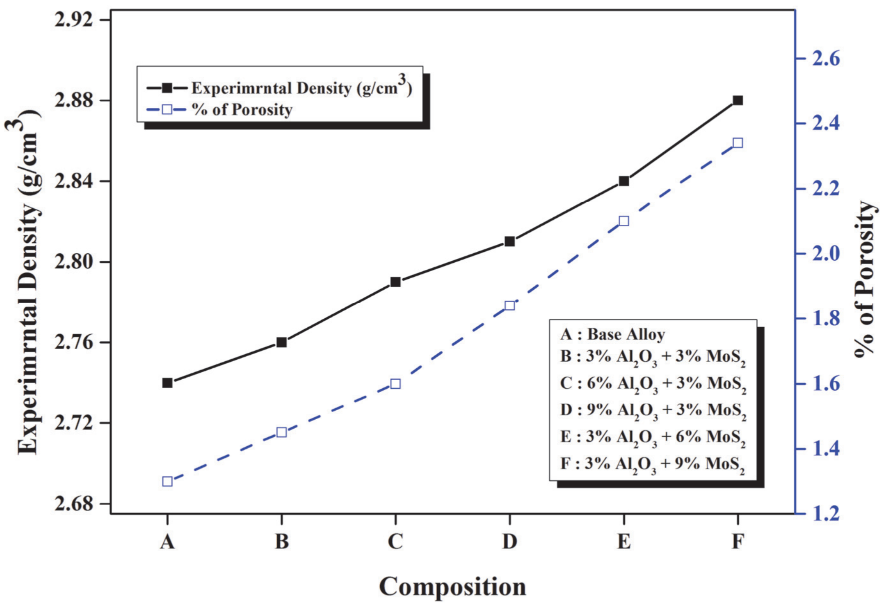

Figure 3: Effect on Density and porosity

Density and porosity of Al_2O_3 and MoS_2 reinforced hybrid Al composites are depicted in Fig. 3. From the results it is seen that the high relative densities are attained for all the developed composites. The outcome indicates good interface between the matrix and the reinforcements. Density of Al_2O_3 is 3.98 g/cm^3, whereas the density of Al is 2.7 g/cm^3. So, the density of Al_2O_3 is high compared to Al matrix. As Al_2O_3 was added to the Al mixture, it increased the sintered density. Though, density is not proportional to quantity of Al_2O_3 since addition of Al_2O_3 caused development of pores. Density is a measure of assessing a composites compactness and porosity [30]. Further, density of the developed MMCs was enhanced due to the existence of MoS_2 particulates. In developed composites, further due to adding of MoS_2 content, it was observed that there was an increase in density when compared to matrix alloy. The enhancement of density is generally due to the existence of the denser particulates in the composites. The porosity of the developed composites was studied. The presence of porosity in the developed hybrid MMCs was because of formation of gasses with in the molten melt. It was observed that, there was absorbing of air bubbles in the molten melt and also some amount of bubbles due to the diffusion of the gas at the time of the stirring. High porosity was found at higher wt. % of reinforcement composites. Generally, the porosity has a major influence on reducing the mechanical strength of the developed composites [3]. This investigation results are in line with Daniel [31] who developed Al MMCs reinforced with hard ceramic particles and MoS_2 content by a stircasting method and it was observed that the porosity and density increased by increasing wt. % of MoS_2 particulates.

Tensile strength

The test specimens were prepared as per ASTM standards and tests were conducted on UTM whose maximum load is 400 KN. Fig. 4 depicts that the tensile strength of the hybrid composites enhanced with increasing in the wt. % of alumina content. The observed results are in conformity with observations in most hard ceramic particulate reinforced MMCs [18, 32]. The strengthening mechanisms were reported by Chawla and Shen [33] who attributed it to increased load sustaining capacity of the developed composite by increasing the wt. % of the ceramic particulates and the enhanced resistance to dislocation of movement by the particles. The strength of the developed MMCs increased because of the resistance of the dislocations and hence the MMCs strength was enhanced by increasing the content of ceramic particles. The nature of hard particulates caused an improvement in material strength. Ceramic particulates compare with the dislocations which led to enhancement in the ultimate tensile strength. Similar results were witnessed by various other investigators [34, 35]. The ultimate tensile strength improved with an increase in the alumina content which is generally ascribed to less degree of porosity and also uniform distribution of reinforced hard ceramic particles. This observation is the witnessed in the results of most ceramic particles reinforced hybrid composites. Abhishek et al. [36] studied the mechanical properties of MMCs reinforced with hard particles. The results have shown that, the solidification of the MMCs was higher due to the amount of reinforcement's present in matrix. Usually, this is due to the complexity involved because of addition hard particles which hinders the dislocation movements over the base matrix. Further, it is seen that the decrease in tensile strength may be caused due to several mechanisms like crack propagation and the particle pull-out which are instigated by the existence of MoS_2 particulates [21]. Because of MoS_2 particles, high porosity & interfacial de-bonding of hybrid composites may result in the reduction of ultimate tensile strength [37]. Similar results were observed by other researcher/s [38] who stated that, decrease in the strength of developed MMCs may be because of porosity and presence of higher wt. % of MoS_2 in the developed composite samples.

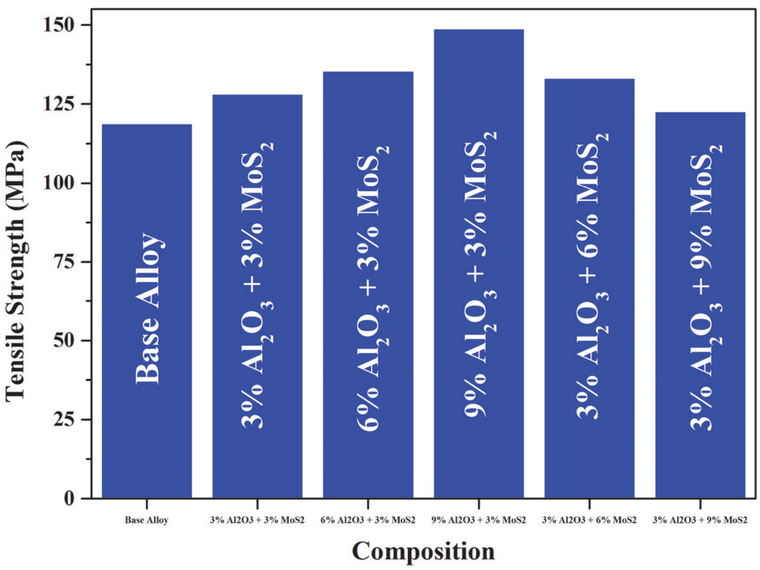

Figure 4: Tensile strength test results of base alloy and hybrid MMCs with different reinforcements

Generally, materials used for engineering applications are selected on the basis of their properties, like hardness, tensile strength and maximum flexural stress. Tensile test is the common test applied for evaluating the mechanical properties. Stress-strain curve for the developed composites were plotted as depicted in the Fig. 5.

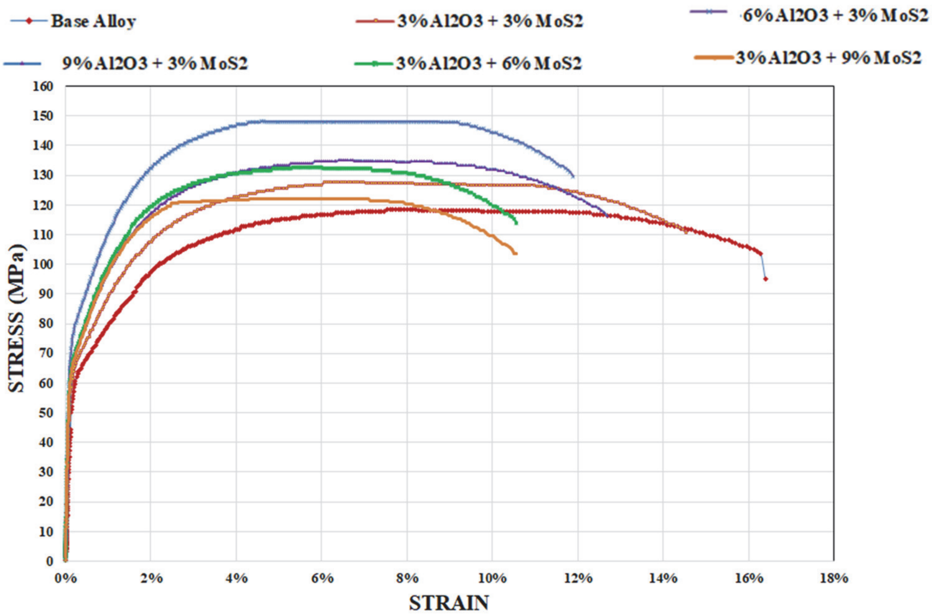

Figure 5: Stress-strain curve.

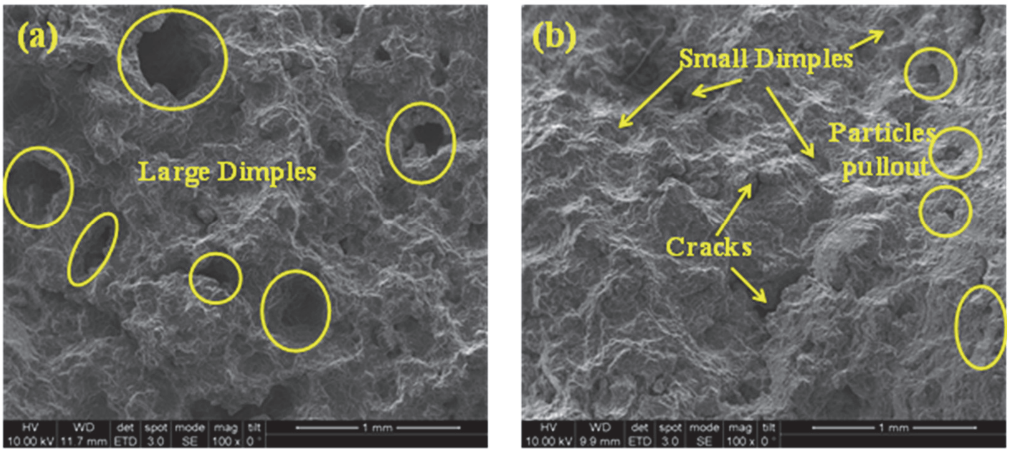

Figure 6: SEM images of fractured surface of tensile test samples (a) as-cast condition (b) Al 6061 with 9% Al_2O_3 - 3% MoS_2.

It indicates that the strength of the hybrid composite reinforced with of Al_2O_3 with MoS_2 content is enhanced as compared to Al alloy. Hard particles which exhibit better bonding with matrix alloy which enables to endure higher load when compared to matrix alloy. The tensile test of MMCs sample results indicated the deformations with different wt. % of ceramic reinforcement's shows the different behavior of failures. The MMCs with 9 % of Al_2O_3 and 3 % of MoS_2 shows the highest % of elongation and tensile strength when compared to the base alloy and all also other developed MMCs. The analysis results reveals that, 9% of Al_2O_3 and 3 % of MoS_2 shows the better results due to increasing in the wt. % of reinforcements content gives better strength and good machinability characteristics. After tensile tests, surface fracture tests were performed to characterize the fracture behavior as well as the relationship of the interface among the reinforcement and the matrix. SEM images of fractured surface were captured at uniform magnifications for both non-reinforced matrix and hybrid MMCs. This study enables analysis of the microstructural effects on tensile properties of developed hybrid composites. In case of hybrid MMC, it is always a brittle when compared to the base alloys. Subsequent growth of voids causes dimple rupture is related with in the fracture progression. Since ceramic particles are introduced as a reinforcing material the fracture process changes markedly. This micro-mechanism is because of change in particulates fracture and cracking along with the interface from the formation of shear crash and voids in base matrix [39]. Fig. 6 depicts the SEM analysis of fractured samples of matrix and hybrid MMCs. Extreme ductility is desired in the fabrication of MMCs caused by micro pores on the surfaces of fractured materials. More number of dimples formations was seen on the fractured surface non-reinforced base material, which results in higher ductile strength when compared to hybrid composites. The fractographic study shows that increase in the wt. % of the Al_2O_3 & MoS_2 content changed the kind of failure from ductile to brittle. Generally, this could be clearly observed from the deformed region and dimples present within the fractured area. Due to increased hard reinforcement content, it is found that more number of micro cracks have occurred signifying decreased ductility. Generally, the topology of the fractured surfaces appears with more number of cracks and voids. The formation of voids is caused by the presence of hard particulates with soft matrix initiating the triaxial state of stress in the vicinity of a particulates. It specifies good bonding the reinforcements and matrix. Usually, the grain size and shape of reinforcements determine the bonding ability. Generally, dimple size indicates the directly proportional relationship with the composite strength. The fractured surface of tensile specimens indicates the combination of hard particulates at the interface. The combination of hard particles fracture and pullout was stated to be a fracture mechanism. The voids at the interfaces between the particulates and matrix increased the crack propagations from their center. The existence of hard ceramic particles on the fracture surface and as well as in micro voids also enhance the mechanical properties by improving the bonding of the matrix and decreased in the ductility [40, 41].

Compressive strength

Compression tests of the developed hybrid composites were done as per ASTM-E8 standards. It was found that, the compressive strength enhanced by increasing the wt. % of reinforcement. However, the presence of alumina content contributes to improved compressive strength as compared to base alloy (Fig. 7). It is concluded that the strength improved owing to the interface among the matrix and the reinforcement [7]. The presence of stiffer reinforcement particulates in the base matrix acts like an obstacle which resists the plastic flow and motion-of-dislocations with in the base alloy. Compressive strength of developed hybrid MMCs is higher compared to monolithic owing to the homogenous distribution of reinforcing particles in Al alloy. As depicted in Fig. 7, the compressive strength of developed hybrid MMCs reduced when MoS_2 content was increased. Similar outcomes were observed by other researcher/s [21]. Researcher [6] has confirmed that the solid lubricant (MoS_2) effectively affects compression stability, though the negative results impact the robustness. The observed reduction in compressive strength may be due to the various mechanisms such as particulates pull-out and crack propagations, which are initiated by the existence of MoS_2 content [21].

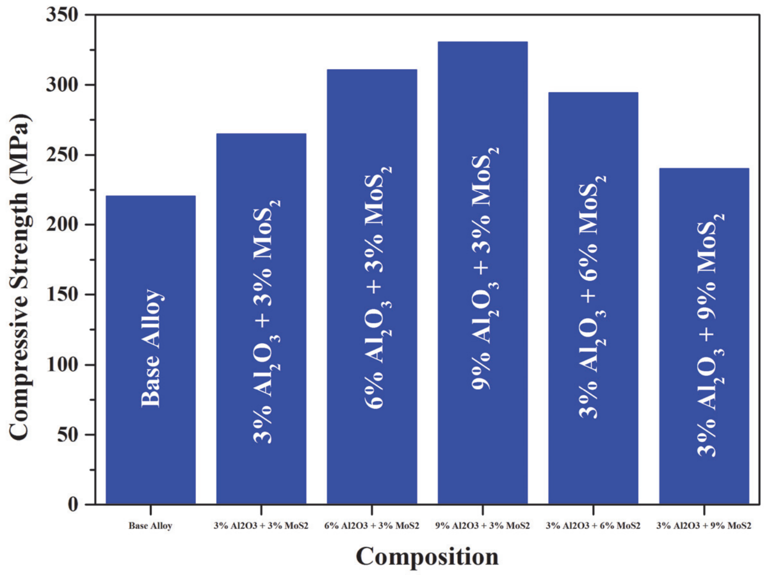

Figure 7: Compressive strength test results of base alloy and hybrid MMCs with different reinforcements

CONCLUSIONS

The micro-structure and mechanical behavior of Al6061 by adding of Al_2O_3-MoS_2 particles as reinforcements were studied. The main outcomes are shown below:

- The particulates dispersal was consistently perceived from micro-structure and clear interface among particulates and base matrix was observed.

- Density and porosity of hybrid MMCs increased by increasing in Al_2O_3 and MoS_2 content due to high density of MoS_2 particulates when compared to base matrix.
- Tensile and compressive strength of hybrid MMCs increased with addition of Al_2O_3 content. But on further increase in wt. % of MoS_2 particulates decrease in mechanical strength was observed. The strength of hybrid composite enhanced because of change in CTE of reinforcement and matrix, which led to an increase in the dislocation of density. Generally, it is confirmed that by increase in the dislocation of density, the strength of the composites can be improved.
- Fracture mechanism shown in SEM pictures indicates higher size and uniform size of dimples in base alloy. Dimples size decreased by adding of reinforcements. Reduced dimple size is because of grain refinement ensued by the addition of reinforcements.

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