Effect of Al₂O₃-MoS₂ on hardness and wear loss of Al-6061 hybrid metal matrix composite

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Abstract. Aluminium Composites are presently conquering their massive practice in aerospace, marine, automobile and other industrial applications due to their vital properties such as better strength, light weight etc. The main purpose the present research is to investigate the role of Al₂O₃-MoS₂ on Al6061 Metal Matrix Composites (MMCs). Composites with varying weight percentages of reinforcements like Al₂O₃ (3, 6 and 9%) and MoS₂ (3, 6 and 9%) manufactured by using stircasting method. The result shows that uniform dispersal of reinforcements within the matrix. Increasing the wt. % of Al₂O₃-MoS₂ in Al6061 leads to improve in hardness and exhibits the better wear resistance of the composites. SEM analysis reveals the Al6061 alloy shows the deepest and widest wear tracks and whereas in hybrid composite (Al6061/Al₂O₃/MoS₂), width and depth of wear tracks are considerably smaller which leads to improve the wear resistance

1. Introduction
Aluminum (Al) alloys are chosen as engineering materials for automobile, aerospace, marine and several processing activities for innumerable high performance components that are been used for several engineering applications because of light weight, high strength and tremendous thermal conductivity. Among the numerous series of Al alloys, the heat treatable Al6061 are much reconnoitered, these alloys are particularly corrosion resistant in nature and shows adequate strength and applicable in the various fields like civil construction, marine applications and automotive areas. Al6061 possesses greater toughness and high strength which desired in automobile and as well in aerospace sector. Composites produced from Al are of extensive attention due to their improved strength, stiffness, toughness and high wear-resistance. Generally, the composites prepared with the adding of reinforcement/s in the form of particles, whisker and fibers. Adding of particles is simple with inexpensive and efficient technique to recognize the composite. MMCs (Metal Matrix Composite) consist of some remarkable characteristics when they are related with existing base matrix. They include strength absorbent at a good electrical conductivity, high temperature, better strength, tremendous corrosion resistance and so on. One of the foremost limitations of the composites is their progressive density and poor mechanical properties when compared to the polymer composite [1]. Al composites made with such method, has comprehensive applications in the area of automobile industry for the manufacturing of liners, cylinder heads, brake drums and driving shaft, aerospace and defence [2, 3]. The Aluminum composite reinforced by hard ceramic particles is under existing possibility of study in progressive materials. In general, hard particulates in the composites like Al₂O₃, B₄C, SiC, and TiC, TiB₂, etc., which increases the mechanical properties and resistance to towards the fatigue [4]. Al ceramic composites were pointed out for the virtuous strength, frictional and self-lubrication properties and stating frequently used lubricants like MoS₂, Gr, BN and CaF₂ [5, 6].
Among the several self-lubrication particles, MoS$_2$ is a smart layered structure which as increased a substantial attention in the technical areas, especially in current years. The MoS$_2$ is a comparatively cheaper material which is available in nature [7]. The manufacturing method of MMCs plays an energetic role in mechanical characteristics and it was observed that composites produced by stir-casting process improved mechanical properties when it is compared with another techniques. Application of stir-casting method develops good wettability and tremendous bonding among the ceramic particles and the base metal [8 - 10]. Stir casting is a flexible technique for high productions. Al 6XXX has greater structural and architectural applications, and only less number of research attempts was observed to enhance its material properties. A hard ceramic particle like Al$_2$O$_3$ (alumina) is stated to be the most functioning parameters which influence the mechanical characteristics of Al composites. Adding of alumina to Al will develop the improvement in its mechanical characteristics of composites [11]. Though a plentiful diversity of reinforcements are obtainable, only a few particles have the material properties like lubrication, molybdenum-disulfide (MoS$_2$) is one of the better solid lubrication material. The research efforts made on the study of Al composites on improvement of mechanical behavior are: The increase of Wt. % of Al$_2$O$_3$ decreases the plastic deformation of composites and improves the wear behavior [8, 12]. Adding of Al$_2$O$_3$ to Al alloy shows improvement of mechanical in composites. Reinforcing Al alloys with the hard ceramic particles (Al$_2$O$_3$) causes a significant enhancement in mechanical properties when compared to Al alloys. However, this reinforcement/s has significantly abridged ductile when it is compared to base alloy [13]. The addition of alumina reinforcement leads to improve the mechanical characteristics. The outcomes found stimulated that Al composite exhibited 30-40% improvement of hardness. Improved hardness than in composites, evidently shows it residues a clear supernumerary for components of aircraft with better strength [14]. The alumina particulates cause decrease in the corrosion of the composites. This is because of arising the corrosion on the grain boundary of hard particles and the base matrix [15]. The density of MoS$_2$ is higher compared the Al alloy and hence an increase in the MoS$_2$ content will increase the density of the composites. The hardness increases significantly due to the additions MoS$_2$ from 3% - 9%. This is because of increase in the proportion of the hard particles with in the composites, which improves the composite resistance to indentation when compared to the base alloy [16]. The wear loss increases when the wt. % of reinforcements reduced. To solve these drawbacks of hard reinforcements, the soft reinforcements like graphite (Gr) and MoS$_2$ are been added as a secondary reinforcing particulates which provides the lubrication against wear behavior [8]. Rajesh P N and Edwin Raja D J [17] studied the effect of TiC and MoS$_2$ reinforced Al MMCs. They concluded that, Al composites reinforced with MoS$_2$ particles displayed a predominant mechanical and tribological behavior contrasted with Al composites.

From the study of literature survey, the substantial applications of Al and its prominence on the enactment of mechanical behavior was recognized. Based on the found remarks, the present research work attempts to produce Al composite by reinforcing Alumina Oxide and Molybdenum Disulfide. Further, the micrographic study and hardness of the developed Al composite was studied.

2. Material and formation of the composites

For the manufacture of composite, Al6061 is used as base material and reinforced by Al$_2$O$_3$ and MoS$_2$ of 100 mesh size each. Wt. % of reinforcements is varied like 3, 6 and 9 of Al$_2$O$_3$ and 3, 6 and 9 of MoS$_2$. The present work, liquid Stir-casting technique has been adopted for the drive of manufacture process. Stir casting method is currently the simple method in production of MMCs [18-20]. The melting of materials was made by using electric furnace. When the molten melt is prepared, the preheated reinforcing particulates were added to the ceramic crucible based on the wt. %. Then the stirring was done to obtain uniform mixture of reinforcements and base material. Finally the molten melt was poured to the metal die unceasingly. The Al composite cast parts were obtained. The standard specimen samples were produced by CNC machining and same was subjecting to study the metallographic, hardness and wear behavior. The test samples are as illustrated in the Fig. 1.
3. Results and discussion

3.1. Microstructural Analysis
Type distribution of reinforcing particulates will have a better impact on the material properties of MMCs. It is vital to retain the uniform dispersal of particulates with in the casting at the time of manufacturing the composites. The micrographic shown in Fig. 2(a) designates the pure Al alloy which indicates the casting without any particulates. The ensuing microstructure depicted in Fig. 2(b) for micro-structure indicates the existence of the particulates. It is witnessed from the micro-graphical vision, the constant dispersal of particulates was observed in the composites. The particulates within the composite are evidently determined at the grain boundaries and as well as larger particulates within the grains of primary Al as depicted in Fig 2(b) [21-23]. The uniform dispersal of particulates is increased by increasing in reinforcement content. Al grain solidifies nearby the reinforced particles which are performing the nucleation center which offers the resistance to grain growth [24].

![Figure 2](image)

**Figure 2.** (a) Pure aluminum alloy; (b) Al+Al₂O₃/MoS₂ composite with uniform distribution.

3.2. Hardness
The best collective type of investigation for the study of mechanical behavior of material is the hardness test. The micro-hardness experiments are been conducted based on the standards (ASTM) by using Vicker’s hardness testing apparatus by using 10 mm ball indenter with a load of 1/2 kg for a duration of 30 seconds. The hardness of the material is recorded at 3 different places on the test sample for an average value of the material hardness. The increase in hardness of MMCs is depicted in the graphical representation shown in Fig. 3. It is found that, the hardness of MMCs enhances with increasing in the content of Al₂O₃ particulates. This is because of Al₂O₃ acts like a barrier to the flow...
of dislocation with in the Al matrix [25]. The hardness specifies that addition of reinforcing particles increases in hardness of the composites. More amount of Al$_2$O$_3$ particulate in the area of indentation resist the deformation and leads to improve the hardness due to better interface bonding between the base material and reinforcements [26].

![Figure 3. Vickers hardness of varying contents of Al$_2$O$_3$ and MoS$_2$.](image)

Further, it is marked that the composite hardness is gradually reduced with increasing in MoS$_2$ content. Decrease in hardness is due to the lubrication properties of the MoS$_2$ particulates which facilitate the ease movement of the grains in planes owing to which the composites deforms certainly under the hardness testing indenter [27].

### 3.3. Wear loss

The addition of hard ceramic particles into Al is thought to considerably improve the wear resistance of the base matrix. The wear tests were executed as per the standards (ASTM) under the fixed sliding speed of 2 m/s at the constant load of 30 N against steel disc (EN-32). The test specimens of length, 25-30 mm and diameter of 8 mm were prepared. The wear behavior of as-cast and hybrid composites were evaluated by calculating the difference between initial and final weight. Fig. 4 shows the wear loss of Al$_2$O$_3$ and MoS$_2$ particles reinforced Al composite. Because of existence of hard Al$_2$O$_3$ particles with in the Al matrix and Al$_2$O$_3$ leads to enhance in transition load because of strengthening mechanism. Al$_2$O$_3$ particulates reduces the spacing between inter particles and act like a strong barrier dislocation of motion. The hard ceramic particulates has an capability to carries the higher load predominantly because of its high hardness and fractured Al$_2$O$_3$ particulates will be rubbing against the steel disc which results in decrease in wear loss of hybrid composites as compared to Al6061 (base alloy). Wear resistance of Al6061/Al$_2$O$_3$/MoS$_2$ increased compared to Al6061 and Al6061+Al$_2$O$_3$ composites. In Al matrix existence of Al$_2$O$_3$ particles grips the load and MoS$_2$ (solid lubricant) forms the lubricating film, which results in reducing of plastic deformation. The existence of MoS$_2$ is fundamentally responsible for sustainment of high wear resistance. When the surface under contact load, the MoS$_2$ particulates flows very easily and also squeezes out. The uniform dispersal of MoS$_2$ particulates forms continues and thick film which is known as a tribo film on the surface. Generally, this shields the subsurface from the counter surface and leads to reduce the wear loss of Al6061/Al$_2$O$_3$/MoS$_2$ composite compared to Al6061 and Al6061+Al$_2$O$_3$ composites [28]. Fig. 5 and 6
shows wornout surface of base material (Al6061 alloy) and hybrid composite (Al6061/Al2O3/MoS2). As compared to Al6061 alloy the Al6061/Al2O3/MoS2 composite are better and exhibits improved wear behavior due to less wear loss. Whereas at the sliding direction, the grooves and scratch are almost parallel and it is named as abrasion, the existence of Al2O3 and MoS2 in matrix will controls the deformation and also resists the diffusion and cutting of the slider into the surface due to the development of tribolayer. It can be observed that the creation of tribofilms, glazing layers and oxide layer are present in worn surface. This results in reducing the wear loss and decreases the material removal rate within the hybrid composites because of higher hardness. Finally the SEM study reveals the Al6061 alloy shows the deepest and widest wear tracks and whereas in hybrid composite (Al6061/Al2O3/MoS2), width and depth of wear tracks are very smaller and this leads to improve the wear resistance [28].

![Figure 4. Wear loss of varying contents of Al2O3 and MoS2.](image)

![Figure 5. Worn surface image of base material (Al6061).](image)
Figure 6. Worn surface image of hybrid composite (Al6061/Al2O3/MoS2).

4. Conclusion

In the present research study, the Al6061-Al2O3/MoS2 hybrid MMCs is effectively manufactured using stir-casting technique. The microstructural study and hardness of produced composites are assessed. The results are summarized as follows:

- It is observed that the uniform dispersal of particulates found in the developed MMCs. The particulates with in the MMCs are evidently resolved within the grain boundaries.
- It is evidently found that the hardness of developed composites enhanced by increasing alumina content. This is due to alumina acts like a barrier for flow of dislocation within the Al matrix.
- It is seen that the decrease in hardness of developed MMCs by increasing in MoS2 content is due to the presence of lubrication properties within the MoS2 particulates.
- The wear resistance of Al6061/Al2O3/MoS2 increased compared to Al6061 and Al6061+Al2O3 composites.
- The SEM analysis reveals that the Al6061 alloy shows the deepest and widest wear tracks and whereas for the hybrid composite (Al6061/Al2O3/MoS2), width and depth of wear tracks are very smaller which leads to improve the wear resistance

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