A Limited Review on the Factors Affecting Wear Behavior of Aluminium Alloys and Aluminium Metal Matrix Composites

Vignesh Nayak U[1*], Shivaramu H T[2], Niranjan Kamath[3], Kaushik M Hegde[4], Prahallad Chowta[5], Irfan[6]

[1, 2, 3, 4, 5, 6] *Department of Mechanical Engineering, Mangalore Institute of Technology & Engineering, Karnataka, India*

---***---

Abstract - *Aluminium matrix composites find wide applications in transportation and weight saving applications. Their density is comparatively lower than those of Al alloys with the advantage that their properties can be tailored as per requirement. A number of processing routes are available for their production ranging from casting, powder metallurgy, infiltration etc. The present work provides a technical review on the Al metal matrix composites processed through stir casting. The findings of various researchers are summarized and analyzed to offer a comprehensive review on Al based composites and hybrid composites. A comparison of wear properties between Al alloys and its composites are also presented.*

***Key Words*: Aluminium, composites, alloys, wear, casting.**

1. INTRODUCTION

To optimize fuel consumption without compromising functionality, reliability and durability modern vehicles must make use of materials having high specific strength. One such material is aluminium and its alloys. The ease with which such alloys can be casted, machined and fabricated has made them the materials of choice in several industrial applications. Further, these alloys possess relatively high resistance to environmental attack due to an adherent surface oxide. However, a limitation of Al and its alloy is their lower abrasive wear resistance compared to steels.

Wear refers to the deterioration of a material at its surface due to relative motion in contact with one or more surfaces. Alloying with Si and Cu into aluminium has shown significant increase in the wear resistance of pure aluminium. Specific wear rate was reduced by about 36% for the Al alloys compared to that of pure Al when tested under identical wet conditions. Further, unlike pure Al, Al alloys do not show an increase in the coefficient of friction beyond a threshold load. Increased tribological characteristics in aerospace, vehicular applications warrant the development of a light weight material whose wear resistance properties are beyond those obtained from aluminium alloys.

The above issue can be partially answered by Aluminium matrix composites. A composite material is one which is made up of a reinforcement phase and a matrix phase. The reinforcement provides strength while the matrix phase acts as an envelope protecting the reinforcement from sudden loading and serves to provide shape to the material. A unique feature of such composites is that the properties can be tailored by varying the volume fraction of the reinforcements relative to the matrix. Furthermore, incorporation of reinforcements into Al does not significantly alter the density of Al. However, the conventional aluminium metal matrix composites make use of macroscopic reinforcements. These reinforcements are not well dispersed throughout the matrix phase and do not prohibit wear effectively. This limitation can be overcome with the help of nanocomposites. Nanocomposites are those materials that have reinforcements in nanoscale. The nano-scaled reinforcements permit superior distribution in the matrix which in turn could lead to improved tribological properties.

The present review provides an overview of Al matrix composites. The state-of-the-art processing methods and the wear test outcomes with variables affecting the experimental evaluation of wear characteristics are presented below.

2. LITERATURE REVIEW

2.1 Wear in Aluminium Alloys

The unique characteristics of Al and its alloys have bolstered their use in a number of engineering applications. Pure aluminium has insufficient strength and wear-resistance property. These shortfalls are remarkably improved with the help of alloy additions. The alloy metals added form intermetallic compounds and offer resistance to slip leading to increased strength in aluminium. However, despite of the advancements in alloy formulations Al alloys do not surpass conventional steel alloys in applications where wear is a significant and detrimental factor. Wear can be of adhesive, abrasive, surface fatigue, fretting and of erosive type. Of these, adhesive wear is the most prominent mechanism that is responsible for decommissioning of components made from Al alloys. Adhesive wear refers to the selective deformation and separation of surface and near surface softer material due to plastic displacement. In adhesive wear, the interacting surfaces involved experience friction leading to localized heat generation and subsequently fragmentation under mechanical action. Based on the surface characteristics observed, abrasive wear may be characterized as ploughing, cutting, wedge formation, micro-crack and fatigue type. The factors that contribute to acceleration of wear are load applied, speed, presence of hard phases between the interacting surfaces and duration of wear study.

The most commonly used Aluminium alloy owing to its castability is the aluminium silicon alloy. In particular the hypereutectic alloy that contains more than 12% Si possesses superior wear resistance. Other alloying elements that are commonly added to Al include copper, magnesium, zinc, nickel, iron etc. The wear behavior of Si is governed by the amount, size, distribution and shape of the silicon [1]. Study on wear behavior of Al-Si alloys showed ambiguous results with some reporting increased wear behavior while others have showed no marked influence of Si content on wear [2, 3, 4]. A threshold load beyond 2 kg and a sliding velocity below 2 m/s was shown to accelerate wear in the case of Al-10% Si- 2.4% Cu alloy. The specific wear rate was found to be higher for pure Al compared to the Al-Si-Cu when tested under higher sliding speed and reduced load. These findings further indicate that high speed and low loads are preferred over low speeds and high loads for minimizing material loss under sliding conditions [5]. It is well known that the rate of wear reduces with increase in the hardness of a material. The hardness of the Aluminium alloys can be increased to a limiting extent by precipitation hardening heat treatment as most of the alloying additions have limited solid solubilities (0.5 to 1 wt. %) in aluminium. The effect of Cr and Ni on the wear resistance of Al-2% Si showed that addition of 4% Cr and 2% Ni increased the hardness of the Al-Si alloy and increased the resistance to wear under both dry and lubrication conditions [6]. An excellent review on the effects of Si in Al alloys and the unclear effect of morphological features of Si influencing wear properties is presented by Shebal et. al [7]. A more prospective method to increase the hardness is by using dispersants which lead to the development of metal matrix composites.

3. METAL MATRIX COMPOSITES

3.1 Conventional Composites

MMC's are formulated by the addition of reinforcements into a softer matrix phase. These composites can be tailored with the required concentration of hard phases to obtain the desired mechanical properties. Efforts have been made in the past to increase the lubricity of Al composites by the addition of graphite, and molybdenum disulfide along with hard reinforcements such as boron carbide. Mechanical members such as crank-shafts, brake drums, cylinder liners are presently utilized and are made from particulate reinforced composite material with Al as their matrix phase.

An investigation on the effect of size and concentration of SiC used as a particulate reinforcement in Al hybrid MMC was performed. The study showed improved wear resistance with higher hardness for the smaller sized reinforcements at increased concentration was observed. A highest hardness of 86.6 BHN for the 10μm sized SiC at 15 wt. % was seen and was reported to be the best alloy that withstood wear at the highest sliding speed and distance [3]. To provide lubricity during wear test MoS_2 was added to Al6061 alloy. The pin-on-disk wear test results showed increased wear volume and accelerated wear occurring beyond the sliding distance of 200 m and at a load of 10 N which intensifies with sliding speed [4]. $Al/Al_2O_3/Gr$ hybrid composites showed reduced wear with increased sliding speed and increased Al_2O_3 content at a constant concentration of Gr. The reduction in the wear rate was attributed to the formation of an oxide film which inhibited direct contact between the sliding surfaces [5]. The wear behavior of Al7075 composites were assessed as a function of TiB_2 concentration, applied load, and speed. Al 7075 alloy exhibited higher wear loss compared with the composites of Al 7075. The wear rate showed reduction in its magnitude with increased amount of TiB_2 reinforcement. The behavior of the wear rate with sliding speed was found to be akin to that of the TiB_2 additions. The wear rate showed up to 18% reduction at 3 Kgs of load at speeds ranging between 200 to 400 rpm for the 15% TiB_2 compared to that of the 5% composite [8]. The COF and wear rate were independent of the sliding speed (600 to 1500 rpm) for the Al-2% Li composite at 1kg load. Deviations with respect of speed were observed when the load was increased between 1.5 to 2 kg. Addition of Si_3N_4 caused increased wear rate while addition of Li to the Al/Si_3N_4 composite provided higher wear resistance compared to Al/Si_3N_4. Further, the specific wear rate was found to be nearly constant for the $Al/Si_3N_4/Li$ composite at applied loads of 1.5 and 2 Kgs for a given speed under consideration [9]. Reduced weight loss (20% less) occurred in the $Al/15\%B_4C$ compared to Al/5% MoS_2 under identical test conditions above 2 m/s of sliding speed [10]. A reduction of about 45% in the wear rate was found for a fivefold increase in the volume fraction of SiC, garnet and $ZrSiO_4$ (particle size of about 105μm) added to LM25 alloy. SiC showed the highest wear resistance which was found to increase with increasing particle size due to the increased agglomeration of the reinforcements at reduced size [11]. Hybrid composites prepared by dispersing fly ash and SiC into Al 7075 alloy showed reduced experimental density compared to those obtained by using the density calculations via rule of mixtures due to porosity. The ultimate tensile strength of the composites was comparable while the modulus of elasticity of the 10% Si-10% fly ash was the highest (80 GPa) and showed the highest wear resistance [12].

The morphology of the reinforcements, their amount, distribution and stability in the matrix affects the wear resistance. Smaller the reinforcement size with increased concentration and uniform distribution in the matrix has reduced the extent of wear. Conventional micro and millimeter sized reinforcements enhance wear resistance up to a certain limit beyond which due to their size limitation they do not markedly increase wear resistance performance. This shortfall due to the size of the reinforcements is dealt with by utilizing nanomaterials instead of the micro and millimeter sized reinforcements and the composites thus formed are termed nanocomposites.

3.2 Nanocomposites

Pin-on-disk wear test of SiC nanoparticles (SiCn) used in A356 alloy showed a four-fold reduction in material loss compared to the base alloy at the highest load of 9 kg used during experiments conducted at 2.5 m/s. The behavior of friction coefficient with increased distance and load showed a near constant and reduced value with increased fraction of SiCn [13]. Comparison of wear behavior between micro and nanocomposite of SiC reinforcements added to an Al matrix comprising of high magnesium content and low concentration of Fe-Zn-Si showed no significant effect of applied load on wear behavior of 2% SiCn nanocomposite (Fig. 1). Significant reduction of over 38% is seen from the data on material loss for the 2% SiCn compared to the base alloy. An improvement of over 36% in wear resistance was obtained at 120 min, 30N for the 2% SiCn compared to the 5% micro SiC under similar test conditions, Chart -1 [14].

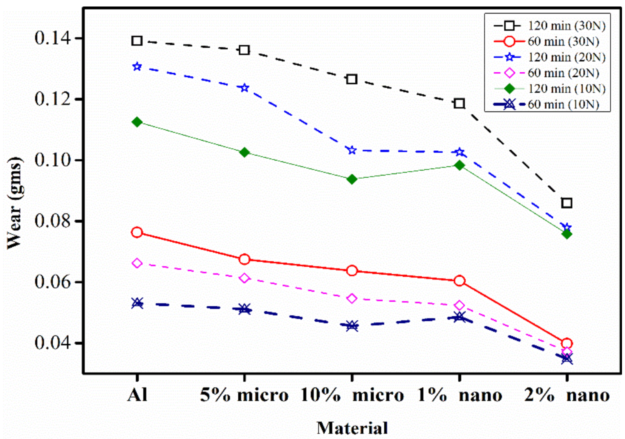

Chart -1: Wear behavior of micro and nano SiC under various loads and test duration [14].

The examined mechanical properties of Al 0.1 wt. % GrO nanocomposite by hot isotactic pressing and extrusion showed reduced tensile and hardness values. This was attributed to the formation of AlC_4 intermetallic due to increased defect density in graphene oxide [15]. Wear results under dry and wet conditions for 1% and 1.5% Graphene in pure aluminium matrix showed remarkably contrasting behavior. The wet sliding (SAE 20 W 50 oil) conditions increased wear rate for the 1% over the dry sliding condition while wear rate was reduced for the 1.5% composite under wet condition compared to that of the dry condition when the applied load was increased from 15 to 60 N. A combination of oxidation, hardness, agglomeration, and adhesion and abrasion phenomenon could be the reason for such an anomaly [16]. Hardness measurements of AA 2024- 2% SiC-1.5 % h-boron nitride hybrid nanocomposites was 38% higher than 2024 base alloy and was the highest amongst the hybrid composites used. Further, the wear resistance of this material was superior compared to the base alloy and other nanocomposites at temperatures ranging from 30°C to 300°C. Moreover, up to 100°C the applied load had insignificant effect on the wear rate. However, there is a three time increase in the wear rate for this composite when tested at 300°C compared to that observed at 30 °C [17]. Optical profilometer measurements for the Al/10 vol. %Al_2O_3/0.25 wt. % GrO hybrid nanoparticles showed narrowest width of deep wear track region compared to the base and 0.5 and 1 wt. % GrO hybrid composite. The superiority of this composite was further validated by the specific wear data that showed the least value for the 0.25 wt. % GrO. Highest oxygen content of 46% was detected on the surface of Al/10 vol. %Al_2O_3/0.25 wt. %GrO subjected to wear [18]. Addition of flat faced irregular shaped ZrO_2 of 26 nm size to Al reduced wear by 44% due to the presence of oxides that provided a hard surface and pinned the grains of Al [19]. The wear resistance and friction coefficient results were in agreement for the compressed and sintered aggregate mixture of Al-Si and SiC (10 wt. %) particles with deposited reduced graphite oxide Nano sheets (0.3, 0.5 and 0.7 wt. %). Highest hardness of 73 HVN was reported for the 0.3% Nano sheets. The hardness measurements for the other 2 concentrations were about 60 HVN. These readings were approximately 5 HVN higher than that for the 0 % Nano sheet hybrid composite. Highest wear resistance was exhibited by the 0.5% Nano sheet hybrid at loads ranging from 1 to 3.5 N [20]. Equal concentrations (2.5 wt. %) of TiO_2 and CuO each added to Al matrix showed comparative hardness to that of the 0.3% Nano sheet composite mentioned above. The research showed that the TiO_2 particles were more effective in mitigating the extent of wear compared to that of CuO [21].

4. CONCLUSIONS

Low-cost, light-weight materials with great strength are required in modern products. This paper discusses the relevance of aluminium alloys, as well as the results of wear tests and the variables that influence the experimental evaluation of wear characteristics. It is claimed that including two different reinforcements in small amounts in hybrid composites is preferable than increasing the single reinforcement and improving the materials' wear resistance. Addition of hard reinforcement particles in the metal matrix has enhanced the tribological performance of the composites. With an increase in the volume percentage of reinforcing elements, the coefficient of friction and weight loss of metal matrix composites reduced. By addition of nano composites to the AMMC's the wear resistance can be significantly improved as compared to that to micro and sub-micro particulate as reinforcement. This is due to the better dispersion caused while fusing it with Aluminium. Further, use of graphene as nanocomposites has shown anomalous behavior under various test conditions. Nanocomposites had lower wear rates than unreinforced aluminium, demonstrating that nanocomposites show major improvement in mechanical properties compared to that of MMC. Therefore, reinforced aluminium matrix nano composites have strong potential to be a substitute to aluminium alloy counterparts in terms of hardness, strength, frictional and wear behavior.

REFERENCES

[1] C. Subramanian, Wear properties of aluminium-based alloys, Surface engineering of light alloys, Elsevier, 2010, (pp. 40-57).

[2] Roop Lal, R. C. Singh, Ranganath M Singari, Ankit Kumar Saxena, Investigation of Wear Behaviour of Aluminium Alloy and Comparison with Pure Aluminium, Materials Science, ICARI-2015.

[3] Ajith Arul Daniel, Sakthivel Murugesan, Manojkumar, S. Sudhagar, Dry Sliding Wear Behaviour of Aluminium 5059/SiC/MoS2 Hybrid Metal Matrix Composites, Materials Research, 2017.

[4] Rinki Yadav, Jai prakash Sharma, Gianender Kajal, Rekha Yadav, Prediction of Mechanical and Wear Properties of Al-6061/MoS2 (Molybdenum Disulphide) Composites, IJIRSET, 2017.

[5] N. Radhika, R. Subramanian, S. Venkat Prasat, B. Anandavel, Dry sliding wear behaviour of aluminium/alumina/graphite metal matrix composites, Industrial Lubrication and Tribology, Vol. 64, 2012.

[6] J Joy Mathavan, Amar Patnaik, Analysis of wear properties of aluminium based journal bearing alloys with and without lubrication, IOP Conference Series Materials Science and Engineering, 2016.

[7] Barrie S. Shabel, Douglas A. Granger, and William G. Truckner, Friction and wear of Aluminium-Silicon alloys, ASM Handbook, Volume 18: Friction, Lubrication, and Wear Technology, 1992.

[8] Madhan Prabhu Deva, A. Parthiban, B. Radha Krishnan, Adisu Haile, Wubishet Degife, Investigation of wear behaviour and mechanical properties of titanium diboride reinforced AMMC composites, Advances in Materials Science and Engineering, 2022.

[9] Raju K, Balakrishnan M, Dry Sliding Wear Behavior of Aluminum Metal Matrix Composite Reinforced with Lithium and Silicon Nitride, Silicon 14, 2022.

[10] Abdul Aabid, Mohammed Ali Murtuza, Sher Afghan Khan, Muneer Baig, Optimization of dry sliding wear behavior of aluminium-based hybrid MMC's using experimental and DOE methods, Journal of Materials Research and Technology, Volume 16, 2022.

[11] Vijayakumar.S, Karunamoorthy.L, Wear characterization of aluminium metal matrix composites, Advanced Composites Letters, Volume: 22, ,2013.

[12] Ravi Kumar Mandava, Vajram Venkata Reddy, Veeravalli Rama Koteswara Rao, Wear and frictional behaviour of Al 7075/FA/SiC hybrid MMC's using response surface methodology, 2021.

[13] MT Alam, S Arif, AH Ansari, Wear behaviour and morphology of stir cast aluminium/SiC nanocomposites, - Materials Research Express, 2018.

[14] Amir Hussain Idrisi, Abdel-Hamid Ismail Mourad, Fabrication and Wear Analysis of Aluminium Matrix Composite Reinforced by SiC Micro and Nano Particles, ASME, Pressure Vessels and Piping Conference, 2017.

[15] SF Bartolucci, J Paras, MA Rafiee, J Rafiee, Graphene, Aluminum nanocomposites, Materials Science and Engineering: A, Volume 528, Elsevier, 2011.

[16] A Jayapragash, G G Solamannan, I Guganeswaran, Comparison study on dry and wet sliding wear behaviour of aluminium/nano composites, IOP Conference Series Materials Science and Engineering, , 2020.

[17] P Paulraj, R Harichandran, The tribological behaviour of hybrid aluminum alloy nanocomposites at High temperature: Role of nanoparticles, Journal of Materials Research and Technology, Elsevier, 2020.

[18] AS Mohammed, OS Aljebreen, AS Hakeem, Tribological Behavior of Aluminum Hybrid Nanocomposites Reinforced with Alumina and Graphene Oxide, Materials, 2022.

[19] M. Ramachandra, A. Abhishek, P. Siddeshwar, V. Bharathi, Hardness and Wear Resistance of ZrO2 Nano Particle Reinforced Al Nanocomposites Produced by Powder Metallurgy, Procedia Materials Science, 2015.

[20] Xiang Zeng, Jin-Gang Yu, Dingfa Fu, Wear characteristics of hybrid aluminum-matrix composites reinforced with well-dispersed reduced graphene oxide nanosheets and silicon carbide particulates, Vacuum 155, 2018.

[21] M. Ahmadi, M. Hossein Siadati, Synthesis, mechanical properties and wear behavior of hybrid Al (TiO 2 + CuO) nanocomposites, Journal of Alloys and Compounds 769, 2018.