

The Dry Sliding Wear Behaviour of Aluminum Composites: A Review

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Abstract: Aluminum composites has been of wide applications in the automobile, aerospace, defense and other engineering sectors especially where dry sliding wear plays major role. Many processing techniques have been used over time depending on various predetermined criteria. This review presents effects of dry sliding parameters (sliding speed, sliding distance and load) coupled with process parameters (stir cast and reinforcement parameters) on the dry sliding (adhesive) wear behaviour of aluminum composites produced by stir casting technique. Many investigative works have been done on the impact of sliding speed, load and distance but only few of such studies linked stir casting and reinforcement parameters with the wear properties of aluminum composites.

Keywords: Aluminum composites, dry sliding wear, stir casting, specific wear

1. Introduction

Metal matrix composites (MMC) are engineered non monolithic materials which consist of a metal or an alloy as the continuous matrix and a reinforcement that can be particle, short fibre or continuous fibres. The evolvement of MMCs has initiated feasible combination of different material properties (mechanical, physical and tribological) resulting into availability of large pool of materials used in applications such as aerospace, automotive, building construction, industrial, and sports (Sallahuddin et al., 2015). Metals such as aluminum, titanium and magnesium have been used as matrix over time because of their high strength to weight ratio, high resistant to corrosion, excellent thermal properties among others. However, aluminum alloy has continued to enjoy a more prominent usage because of its properties, performance, economic and environmental benefits (Saravanan et al., 2015). Most of the aluminum alloys chosen as matrix are A356, 2000 and 6000 alloys (Dasgupta et al., 2010).

The need to reinforce aluminum alloy with other materials to produce aluminum matrix composites (AMC), which is useful in applications where aluminum alloy cannot be used is due to poor response of aluminum alloy to such conditions as wear resistant conditions. However, AMCs have proved to be a reliable and efficient wear resistant material especially for sliding wear applications (Dasgupta, 2012). The suitability of materials for wear applications requires good understanding of the concept of wear. Wear has been described as the result of full interaction between surfaces in relative motion or the continuous loss of matter from surfaces as an effect of relative motion (Sergio, 2004; Yust, 1985). Wear is experienced in

different modes in diverse engineering applications. It is understood that complete knowledge of wear mechanism ultimately results in better specification of materials including composition and properties (Rabinowicz, 1965). Wear is affected by several factors, from operational, topography of the surface contact, geometry, speed, load, coefficient of sliding friction, material (hardness, temperature, elasticity, breakage, thermal properties), environmental, the type and degree of lubrication and surface cleanliness parameters (Riyadh, 2012). When wear as experienced in dry sliding surface contacts is examined, it is referred to as dry sliding wear.

Dry sliding wear behaviour of a material could be evaluated from sliding wear parameters and stir cast parameters, such as stirring speed and time, particle size, type and volume fractions (Ashok et al., 2012). The sliding wear behaviour of composites has been found to depend on the volume fraction and particle size of reinforcements, hardness and strength of matrix alloy, applied load and environmental temperature (Umanath et al., 2011; Senthil et al., 2016).

In the production of AMCs, different processing routes have been used over time. These processing routes influence the tribological properties as a result of agglomeration, distribution and segregation of the reinforcing particles in the composites that occurred during production (Raghavendra and Ramamurthy, 2014). The processing routes are based on the state of matter of the matrix metal and can either be solid state process (i.e., powder metallurgy, high energy ball milling, friction stir processing, diffusion bonding, vapour deposition techniques) or liquid state process (i.e., stir casting process, compo-casting, in situ reaction,

squeeze casting, ultrasonic assisted casting, plasma spraying or spray co-deposition) (Wahab et al., 2009; Yuan and An, 2012). The choice of a particular processing route may depend on the size of production, surface finish, material properties and the specific materials application. In this paper, the effect of dry sliding wear and process parameters on the dry sliding wear behaviour of aluminum composites produced by stir cast technique is reviewed.

2. Stir Casting

Stir casting is a simple and cost effective liquid metallurgical technique that is deployed in the production of MMCs especially when the reinforcements are discontinuous fibres or particulates (Rahdika et al., 2011). While there are varieties of processing techniques available for particulate or discontinuous reinforced MMCs, stir casting technique has enjoyed patronage for the production of large quantity of components in commercial practice (Mathur and Barnawal, 2013). Its attractiveness is due to simplicity, flexibility and it is mostly economical for large sized components production (Hashim et al., 1999). Stir casting technique involves application of mechanical energy to stir the mixture of the liquid matrix and the reinforcements to aid uniformity in the distribution of the reinforcement in the liquid matrix.

Uniform distribution of reinforcement is very important for good tribological properties. Uniform distribution or homogenisation of reinforcements in the matrix depends on materials properties and process parameters like wetting condition of the particles with the melt, strength of mixing, relative density of melt, geometry and position of the mechanical stirrer in the melt, stirring speed and time, melting and holding temperature, rate of solidification, holding time, mould material and the characteristics of the reinforcing particles. Hence, uniform distribution can be achieved through good selection of process parameters. These are important factors to be considered in the production of cast metal matrix composites, as these have an impact on quality and properties of casting (Adat et al., 2015; Nahar et al., 2003; Shankar et al., 2013; Kumar et al., 2013; Pradeep et al., 2014; Subramani et al., 2014; Sharma et al., 2008).

3. Effect of Dry Sliding Wear Parameters

This describes the dry sliding wear behaviours of materials thus by extension it determines the suitability of materials for wear resistant operations especially in engineering applications that were dry sliding contacts being expected. Dry sliding wear parameters commonly investigated are sliding speed, sliding distance and load.

3.1 Sliding Speed

Sliding speed is an important parameter in the measurement of wear. The wear behaviour of

composites can also be determined by the sliding speed (Jha et al., 2011). Dasgupta et al. (2010), reinforced a 7075 Al alloy with 10 vol.% Silicon carbide (SiC) and conducted a sliding wear test using a vertical pin-on-disc wear testing machine with loads of 9.8, 29.4 and 49 N and speeds of 400 and 640 rev/min. The test specimens include as produced composite and extruded composites.

Out of the three loads it was observed that for the extruded composite at a load of 9.8 N, the volume loss after a sliding distance of approximately 2,000 m becomes relatively constant irrespective of the speed. Higher sliding speed results in less material loss under a constant load, while more load results in higher material loss under the same rotation speed.

Babić et al. (2013) investigated the basic tribological properties of A356/10SiC/1Gr of compo casted hybrid composites in conditions with lubrication. Tribological tests were carried out using advanced and computer supported tribometer with block-on-disc contact pair under three different values of sliding speed and it was observed that with increasing sliding speed, wear rate of the hybrid composite A356/10SiC/1Gr and the base material decreases.

Manikandan and Karthikeyan (2014) investigated the dry sliding wear characteristics of 7075 aluminium alloy and the composites (Al7075/B4C, Al7075/Alumina, Al7075/SiC) under different load conditions. The applied load is varied from 20N to 60N with sliding velocity of 1-3 m/s for 2000 m sliding distance. The wear rate decreases with increasing sliding velocity in all conditions, the AMCs remains more resistant compared to Al7075 matrix in the order Al7075/B4C < Al7075/Alumina < Al7075/SiC. The result is attributed to the fact that metal to metal contact is high at low sliding velocity and it tends to plough the surface and cause high wear.

3.2 Sliding Distance

Another common measure of wear is the volume of material removed per unit sliding distance. The ratio of the wear in units of volume removed per unit sliding distance to the real interfacial area of contact is a meaningful dimensionless quantity useful in wear studies and is called the dimensionless wear coefficient, or simply the wear coefficient, Kok and Ozdin (2007) investigated the wear resistance of aluminum alloy and its composites reinforced by Al₂O₃ particles. Sliding wear tests on 10, 20 and 30 wt.% Al₂O₃ particles reinforced 2024 aluminum alloy composites fabricated by a vortex method (stir casting). These tests were carried out by using a pin-on-disc abrasion test apparatus where the sample slid against SiC abrasive papers of 20 µm (600 grit), 46 µm (320 grit) and 60 µm (240 grit) under the loads of 2 and 5 N at room conditions. The effects of sliding distance with other parameters (Al₂O₃ particle content and size, SiC abrasive grit size and wear load) on the wear properties of the composites were

systematically investigated. It was observed that wear resistance increased as the sliding distance increases.

Reddappa et al. (2011) studied the dry sliding wear behaviour of Al6061–beryl composites containing four different weight percentages (2, 6, 10 and 15wt. %) of beryl fabricated using stir casting method. A pin-on-disc wear testing machine was used to carry out the dry sliding wear tests on both composites and matrix alloy over a load range of 5-15 N and sliding velocity of 1.66m/s for various sliding distances of 1-6 km. The specific wear rate was determined as a function of sliding distance. It was observed that the specific wear rate decreased with sliding distance for all the compositions indicating improved wear resistance for longer distances.

However, a reverse behaviour was observed in the study by Suresh et al. (2010) on the effect of sliding distance on the wear properties of eutectic Al–Si alloys produced by Stir casting route with fly ash reinforcement (from 1-10 vol. %). It was observed that the wear increased with the increases in distance.

Basavarajappa et al. (2006) investigated the wear behaviour of as-cast aluminium alloy, aluminium alloy (2219) reinforced with SiC particles and aluminium alloy reinforced with SiCp-graphite. The sliding wear test was conducted using unlubricated pin-on disc wear test apparatus to examine the wear behaviour of the aluminium alloy and its composites. It was observed that as the sliding distance increases, the wear of the composites and alloy also increases. Moreover, the wear of the unreinforced alloy is more than that of the composites for all sliding distances. The wear volume loss decreased with the addition of SiC particles and further decreased with the incorporation of graphite reinforcement. At the initial phase, little change in volume loss was recorded for the composites, as the sliding distance increased more change in the wear was observed.

Kumar et al. (2015) investigated the effect of sliding distance on tribological behaviour of Al6061-T6 alloy and its composite reinforced with hard ceramic constituent alumina (3 wt. %) and solid lubricant graphite (3 wt. %) fabricated through stir casting technique. It is observed that wear results exhibited an increasing trend of specific wear rate of Aluminum Hybrid Metal Matrix Composite (AlHMMC) for sliding distance which is absolutely lesser than Al6061 alloy.

3.3 Load

As the applied load and the resulting temperature increases during a sliding wear test, the accumulation of discrete particles on the counter face results in aggregation of larger clusters on the surface of the disk. These clusters subsequently break away from the disk forming loose wear debris and the resulting wear rate becomes severe. It is believed in some quarters that the dominating parameters contributing to the sliding wear

of a given system are the loading and the relative sliding of the contact (Priti and Soren, 1999). Also, applied load has been observed to be the only parameter which largely influenced the coefficient of friction (Ashok et al., 2012); hence applied load is a very important parameter in determining the tribological behaviour of composites.

Sallahauddin et al. (2015) studied the effect of B₄C particulates addition on wear properties of Al7025 alloy composites. The 3 and 6 wt. % of B₄C particulates were added to the base matrix. A pin-on-disc wear testing machine was used to evaluate the wear rate, in which a hardened EN32 steel disc was used as the counter face. It was observed that the volumetric wear loss and wear rate increases with increase in applied load in all conditions. The authors' review of the micrographs shows that the wear rate is dominated by load factor and sliding speeds. The increase in loads led to a significant increase in the volumetric wear loss and wear rate.

Umanath et al. (2011) studied the wear resistance as a function of applied load and volume fraction of the particles of aluminum hybrid composites reinforced with mixtures of SiC and Al₂O₃ particles produced from a stir casting technique. Results showed that load has an intense effect on the wear rate of the aluminum hybrid composites.

Sulardjaka and Wildan (2010) developed a wear rate prediction model for aluminum based composites reinforced with 10 and 30 wt. % in situ aluminum diboride flakes using Taguchi's method. The experimental results showed that the normal load and reinforcement ratio were the major parameters influencing the specific wear rate for all samples.

4. Effect of Process Parameters

Optimising the input process parameters is crucial in enhancing the wear behaviour of aluminum composites (Rhadika et al., 2015). The process parameters will be studied under stirring parameters and reinforcement parameters.

4.1 Stirring Parameters

Stirring parameters such as stirring speed and time, blade angle, pouring temperature and so on have been observed to affect the wear behaviour of composites. These are parameters that are associated with the stirring mechanisms in the stir cast technique.

Haque et al. (2014) studied the effect of process parameters (stirring speed and pouring temperature) on wear rate and microstructure of Al6061-Cu reinforced with SiC by stir casting. The dependent variable was chosen to be the wear rate by pin on disc wear method while the independent parameters include five levels of pouring temperature and stirring speed: 675, 700, 725, 750 and 775 °C, and 50, 200, 400, 600 and 800 rpm at a constant pouring speed of 2.5 cm/s that were considered. The optimal values of wear rate are observed between

ranges of 200 to 600 rpm stirring speed while at high speed (800 rpm) the wear rate increases drastically. The wear rates are stable in range of 700 to 750 °C of pouring temperature, except at stirring speed of 800 rpm.

Rajeshkumar and Parshuram (2013) studied the effect of number of blade angle and pouring temperature on microstructure of aluminum hybrid composites with SiC, alumina and graphite as the reinforcement. The study asserts that for uniform dispersion of material, blade angle should be 45° or 60°C and number of blade should be 4. Also, for good wet ability, operating temperature need to be kept in the semisolid stage i.e., 630 °C for Al (6061) and that at full liquid condition it is difficult to attain uniform distribution of the reinforcement in the molten metal. Mould preheating is noted to help in reducing porosity that will expectedly increase the wear resistance.

Sadi et al. (2015) studied the optimisation of stir casting process parameters to minimise specific wear of Al-SiC composites by Taguchi method. Using Al-Si as the matrix alloy and SiC as the reinforcement, among the variables considered are melt temperature, stirring speed and duration, each with 4 levels or variations. The study observed that optimum stir casting process parameters are melt temperature of 740 °C, stirring speed of 300 rpm and stirring duration of 10 minutes.

4.2 Reinforcement Parameters

Reinforcement parameters such as the volume fraction, nature and size of particles in reinforced composites affect the wear behaviour of composites (Mehtap and Mehtap, 2011). Wear volume of metals decreases with incorporation of particles into matrix on the condition that those particles have higher hardness than the matrix material. Material removal in a ductile metal such as aluminum alloy matrix is due to the indentation and ploughing action of the sliding indenters. Incorporation of hard particles as reinforcements in metal matrix restricts such ploughing action of sliding indenters and improves the wear resistance expectedly. However, the effect of particle (reinforcement) size on the wear resistance of composite was more significant than that of its volume fraction (Kok and Ozdin, 2007).

Altinkok et al. (2013) produced Al₂O₃/SiC particulate reinforced composites by stir casting method and investigated its dry sliding wear behaviour. The 10 wt. % Al₂O₃/SiC with different SiC particles sizes was added to a liquid aluminum matrix (A332) alloy with mechanical stirring between solidus and liquidus temperature under inert conditions. The reinforcements reduced weight loss due to wear in the composites especially where SiC with large grain size was used. The improvement in wear resistance of the hybrid ceramic reinforced metal matrix composites was attributed to the ability of the larger SiC particles to carry a greater portion of the applied load, as well as in protecting the smaller alumina particles from being gouged during the

wear. The composites with fine reinforcement particles had the reinforcements more easily pulled out whole from the matrix when compared to the composite with coarse reinforcement particle size.

Also, Ashok et al. (2012) studied the wear and frictional properties of Al6061 reinforced with SiC particles (10 and 15 wt. %) using dry sliding wear test on a pin-on-disc wear tester. Experiments were conducted based on the plan of experiments generated through Taguchi's technique. A L9 orthogonal array was selected for analysis of the data. Effect of applied load, sliding speed and sliding distance on wear was studied. It was observed that for Al – 6061/ 10 wt. % SiC composites sliding distance has the highest (62.5%) influence on wear rate followed by sliding speed (37.5%) and applied load (1.25%) respectively. However, for the Al – 6061/ 15 wt. % SiC composites, applied load has the highest (57.2%) influence on wear rate followed by sliding distance (7.1%) and sliding speed (7.1%).

Das et al. (2007) observed that composites reinforced with zircon particles of size 44–74 um (with 4.5 wt. % Cu–Al as the matrix) blunts SiC abrading particles before the larger size reinforcement composite (74–105 um), after sliding duration of one minute. This shows higher wear resistance than the later. This was attributed to the action of the sharp edges of the small particles in assisting to cut and blunt the abrading silicon carbide particles more effectively. Hence, the shape of the small particles also plays an important role in decreasing composite' wear volume.

Kumar et al. (2012) studied the aluminum alloy composites reinforced with fly ash particles and observed that coarse fly ash particles reinforced composite exhibit superior wear resistance to those reinforced with fine fly ash particles. Table 1 shows the dry sliding behaviour of various aluminum composites produced from stir casting.

Different types of reinforcements such as SiC, Al₂O₃, B₄C, Zircon TiC, TiB₂ and graphite have been used in many studies to investigate the sliding wear properties of the aluminum MMCs produced by stir casting technique (Kumaran et al., 2015; Ramesh and Prasad 2007; Chen et al., 2015; Panwar and Pandey, 2013; Saravanakumr et al., 2013; Yilmaz et al., 2001).

Kumar et al., (2016) investigated the influence of silicate on the wear behaviour of LM 24/4 wt. % fly ash hybrid composite with 4, 8, 12, 16, 20, and 24 wt.% of silicate using stir casting technique. Tribological properties were evaluated under different load (15, 30, 45, 60, and 75 N); sliding velocity (0.75, 1.5, 2.25, and 3 m/s) condition using pin on disc apparatus. It was observed that the properties of the hybrid composites containing 24 wt. % silicates exhibit superior wear resistance. Moreover, Sivakumar et al. (2014) had shown the influence of fly ash on wear resistance of aluminum alloy. The aluminum MMCs was successfully produced using stir casting route up to 20 wt. % fly ash and the

Table 1. Dry Sliding Behaviour of Aluminum Composites Produced from Stir Casting

S/N	Alloy	Reinforcement	Dry Sliding Wear Behaviour	Authors
1.	7075 Al alloy	10% vol SiC	Wear reduces at higher sliding speed.	Dasguta et al. (2012)
2.	A356	10SiC/1Gr	Wear rate decreases with increasing sliding speed.	Babić et al. (2013)
3.	Al 7075	B ₄ C, Alumina and SiC	Wear rate decreases with increasing the sliding velocity.	Manikandan and Karthikeyan (2014)
4.	Al2024	Al ₂ O ₃	Increasing wear resistance as the sliding distance increases.	Kok and Ozdin (2006)
5.	Al6061	beryl	Specific wear rate decreased with sliding distance.	Reddappa et al. (2011)
6.	Al-Si alloy	fly ash	Wear increases with increase in distance.	Suresh et al. (2010)
7.	Al2219	SiC	Wear of the composites and alloy increases as sliding distance increase.	Basavarajappa et al. (2006)
8.	Al6061-T6 alloy	3 wt.% alumina and 3 wt.% graphite	Increasing trend of specific wear rate with sliding distance.	Kumar et al. (2015)
9.	Al7025	B ₄ C	Volumetric wear loss and wear rate increases with increase in applied load.	Sallahuddin et al. (2015)
10.	Al6061	SiC and Al ₂ O ₃	Load had an intense effect on the wear rate.	Umanath et al. (2011)
11.	Al(99.9%)	10 and 30wt.% in situ aluminum diboride	Normal load and reinforcement ratio were the major parameters influencing the specific wear rate.	Sulardjaka et al. (2010)
12.	Al6061-Cu	SiC	Optimal values of wear rate are observed between ranges of 200 to 600 rpm stirring speed.	Haque et al. (2014)
13.	Al-Si	SiC	Optimum values of specific wear are SiC content of 15 wt.% SiC, melt temperature of 740 °C, rotation speed of 300 rpm and stirring duration of 10 minutes.	Sadi et al. (2015)
14.	Al6061	SiC	Wear behavior is a function of the wt.% of reinforcement.	Ashok et al. (2012)
15.	A332	Al ₂ O ₃ /SiC	Wear reduces with presence of reinforcement.	Altinkok et al. (2013)
16.	4.5wt. %Cu-Al	Zircon	Smaller size reinforcements shows higher wear resistance when compared to the larger sizes.	Das et al. (2007)
17.	Al/3.25Cu/8.5Si	fly ash particles	Coarse reinforcements show higher wear resistance when compared to fine reinforcements.	Kumar et al. (2012)
18.	LM 24	fly ash and SiC	SiC showed higher wear resistance than fly ash.	Kumar et al., (2016)
19.	LM 24	Fly ash	Fly ash increases the composites wear resistance.	Sivakumar et al. (2014)

wear rates was observed to decrease significantly with the incorporation of fly ash.

5. Conclusion

This review shows that a lot of efforts have been made to improve the dry sliding wear behaviour of aluminum composites produced by stir casting technique. Process parameters largely influence the dry sliding wear behaviour of aluminum composites. Understanding of the degree of influence of the process parameters on the dry sliding wear behaviour of aluminum composites is highly important as it helps in the optimal combination of process parameters in the course of its production. The following were observed:

- 1) Considerable works have been done using stir casting techniques to produce aluminum matrix composites due to its simplicity, flexibility and cost effectiveness especially for large volume production.
- 2) Prominent wear apparatuses used in wear test are the pin-on-disc tools and the parameters commonly evaluated are load, sliding velocity and sliding distance.
- 3) Load and sliding velocity plays a major role in assessing the dry sliding wear behaviour of composites.
- 4) Wear resistance of aluminum matrix composites produced by stir casting technique depends also on the type of reinforcement and volume fraction, and

- 5) The trends observed for the effect of sliding distance and reinforcement size vary and could depend on the type and nature of reinforcement used in composites' production.

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