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***Research paper***

# Dry Sliding Wear Behaviour of Rheocat Al-5.7si-2cu-0.3mg Alloy

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**Abstract**

In this study, the effect of improved microstructure of Al-5.7Si-2Cu-0.3Mg alloys by using semisolid process on hardness and dry sliding wear behaviour were investigated. The microstructures of conventional cast alloy were totally dendritic, while in rheocasting the dendritic transfer to fine globular microstructures after using cooling slope casting. Tribological tests were carried out by using a pin-on-disc apparatus in dry sliding conditions. Wear tests were at low sliding speed 1ms$^{-1}$ ,applied load at 50N and three different sliding distance (i.e., 1.8Km, 5.4Km and 9Km) respectively. An optical microscope and a scanning electron microscope were used to examine the microstructure and to understand the wear mechanism on the worn surface of both samples. The results showed that, the wear resistance of rheocast alloy was improved and higher than that those produce by conventional casting. The volume loss of rheocast alloy show reduction more than 18% at 1.8Km and 10% at 9Km compared to as-cast alloy. Moderate wear regimes were appeared in both alloys, according to the range of wear rate. The friction coefficient had increased due to increase in the contact point between pin and disc materials. The dominant wear mechanism for conventional and rheocasting alloys was adhesion wear and abrasive wear respectively.

***Keywords***: *Aluminum-Silicon alloy; cooling slope; wear resistance; wear mechanism*

## 1. Introduction

Al-Si alloys are widely used in tribological applications in automotive industries, due to their superior mechanical and tribological properties [1,2]. These alloys are manufactured using different techniques such as, liquid phase process (casting), forming at process between solidus and liquidus temperature (semi-solid processing), solid phase (forging) or powder metallurgy process. Compared with these processes semi-solid process produce product with some advantage over casting process and lower cost than forging and powder metallurgy [3]. These advantages such as produce complex shapes with some reduction in forming steps, less energy consumption, less solidification shrinkage, prolonged die life, good filling of the die and improved mechanical properties [4].

Recently some research has worked to produce material with semi solid processing. The results showed that, better uniform distribution, lower porosity and enhanced mechanical properties when the semisolid slurry temperature start. To produce feedstock material with non-dendritic microstructure for semisolid processing (thixotropic feedstock), requires specialized techniques (rheocast process), which discovered in early 1971 by Spencer [5]. Rheocast processes divided into two groups: melt agitation methods such as; magnetohydrodynamic (MHD) stirring [6], stir cast [7] and ultrasonic vibration [8]. Second rheocast methods are without melt agitation such as; recrystallization partial remelting (RAP) [9], stress-induced and melt activated (SIMA) [10] and the cooling slope method [11]. Among these techniques the cooling slope casting method is an attractive process due to its simplicity, low amount of equipment as well as low cost effective [3,12].

There appears to be no literature that discusses the effect of sliding distance of rheocasting process on dry sliding wear properties of rheocast Al-5.7Si-2Cu-0.3Mg alloys. The main objective of this study is to address the dry sliding wear behaviour of rheocast Al-5.7Si-2Cu-0.3Mg by using pin-on-disc tribometer.

## 2. Experimental Procedure

Hypoeutectic Al-Si-Cu alloy has been used in this study. The chemical composition of the starting material were determined by using X-Ray florescence technique (XRF), as shown in Table1. Differential scanning calorimetry (DSC) used to determined solidus and liquidus fraction vs. temperature relationship. A 10mg cut from alloy for testing using a Netzsch-STA (TG-DSC) 449 F3 simultaneous thermogravimeter, sample were in heating rate 10$^{o}$C/min in Ni atmosphere to prevent oxidation. The liquid fraction vs. temperature for alloys were obtained from heat flow vs. temperature curves by a combination of partial areas under the heating curves as shown in Figure 1.

**Table 1:** Chemical compositions of studies alloy (wt. %).

| Si | Fe | Cu | Mg | Mn | Zn | Ni |
|---|---|---|---|---|---|---|
| 5.67 | 0.32 | 1.92 | 0.32 | 0.12 | 0.03 | 0.02 |
| S | Cl | Cr | Ca | Al | | |
| 0.16 | 0.12 | 0.05 | 0.04 | Bal. | | |

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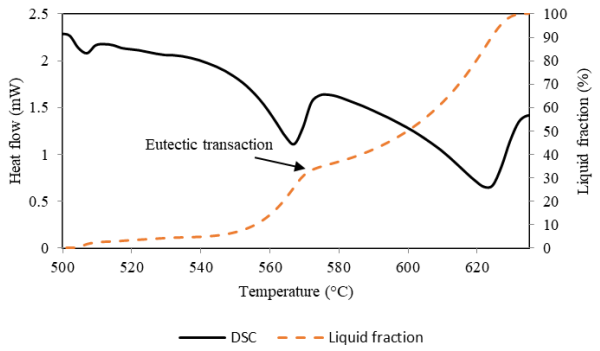



**Fig. 1:** .DSC and liquid weight fraction versus temperature curves for Al-5.7Si-2Cu-0.3Mg alloy

Cooling slope process have been used to obtain feedstock alloy with thixotropic behaviour for thixoforming technique. The alloy has melted in a silicon carbide crucible with a protective atmosphere (argon gas) to prevent oxidation. The melt metal superheated at 700°C then cooled to the selected an appropriate pouring temperature before the material being poured on the surface of a 90mm wide inclined plate made of stainless steel (6mm thick) Figure 2. The inclined plate has been covered with boron nitride to prevent sticking between material and plate surface. Cooling slope plate was arranged with coolant water motion underneath for increasing the nucleation rate of the α-Al particles and to produce a fine and less dendritic microstructure. The parameters of cooling slope experiment were (650°C pouring temperature, 60° angle of cooling slope plate, 400mm of cooling slope length) the melt metal was poured and collected directly into cylinder stainless steel mold then allowed to cool in room temperature.

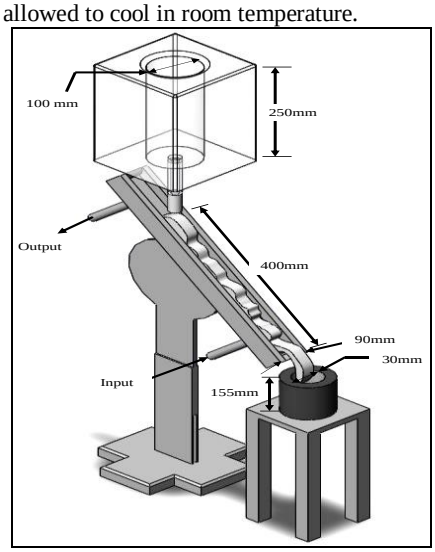



**Fig. 2:** Schematic diagram Cooling slope casting

Dry sliding wear tests were carried out using a pin-on-disc tribometer apparatus according to standard of ASTM G 99 [13] scheme diagram of pin-on-disc aperture shown in Figure 3.The counterface material was M2 tool steel disc hardened to 62 HRC, before each test the disc was grinded and polished to get surface roughness ~0.2µm and then cleaned with acetone. The roughness is determined by using (Perthometer surface roughness testers contour measuring system). The wear tests were performed at a constant sliding speed 1m/s and 50N applied load and at different sliding distance in the range of 1.8-9Km. Track radius fixed at 80mm and environment conditions at 25°C and humidity ~58% were applied to all the tests in the laboratory. Pin samples with dimension of Ø8mm diameter and 20mm length were cut from the central regions of the rheocast billet by an electro discharge wire cut machine. Further, pin samples were machined by grinding by using 600, 800 and 1200 grit and then polishing by using 6µm, 3µm and 1µm diamond pastes to obtain roughness of surface at ~0.1µm, then cleaned with aceton in ultrasonic cleaner and dried in hot air and weighed using an electron weight balance with accuracy of reading ±0.0001g prior to testing and at the end of experiment. The weight loss was converted to volumetric wear loss with the support of a density measurement using Archimedes' principle.

The weight loss, Δw for each specimens have recorded and wear rate was converted to volume loss VL ($mm^3$) by dividing the weight loss to density, ρ (kg/mm3) and the time, t (s) as mention in (1) [14].

$$VL = \frac{\Delta W}{\rho} \quad (1)$$

Furthermore, to calculate the specific wear rate (SWR) for determining the wear result [15,16] have used (2);

$$SWR = \frac{VL}{N * S} \quad (2)$$

Where, SWR is specific wear rate (mm3/N.m), V is volume loss of material (mm3), N is the applied load (N) and S is the sliding distance (m).

The value of the friction force was listed via the weight sensor of the pin on disc tribometer to estimate the COF (µ) using (3).

$$\mu = \frac{F}{N} \quad (3)$$

Where F: the friction force (N). Wear test time for each sample depends on the sliding distance and in is in the range of 0.5-2.5 hours, were test for each sample. Worn surface and collected debris of experiment were examined after finished the test under the Olympus optical microscope type reaches a maximum of 500 magnifications and Field Emission Scanning Electron Microscope (FESEM) type MERLIN from Carl Zeiss (SEM) energy-dispersive X-ray spectroscopy (EDX) analyses micrograph of the worn surfaces of the samples has showed some defining to understand wear mechanism.

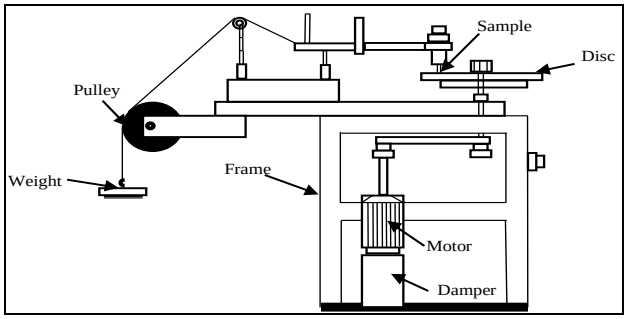



**Fig. 3:** Schematic diagram of pin on disc wear and friction

## 3. Results and Discussion

Figure 4 shows the optical microscope images of cast Al-5.7Si-2Cu-0.3Mg alloy. It can be seen that the microstructure of sample are mainly located in the eutectic of the liquid phase surrounding the dendritic α-Al grains as indicated by a circle.

Figure 5 shows optical microscope images of the Al-5.7Si-2Cu-0.3Mg alloy fabricated using the cooling slope casting process. It can be seen that the microstructure of rheocast sample illustrious by rosettes and a globular primary phase as indicated by a circle in Figure 5. It can be seen that homogeneous distribution of Si particles within the sample along the α-Al grain boundaries compared to conventional cast sample as indicated by an arrow. Furthermore, less porosity is appeared in rheocast sample than conventional cast sample.

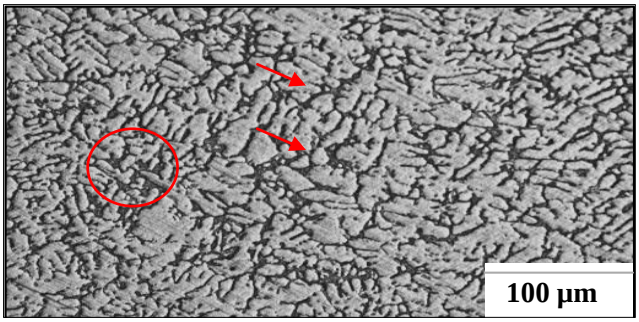



**Fig. 4:** Optical microscope images of conventional Al-5.7Si-2Cu-0.3Mg alloy at100µm

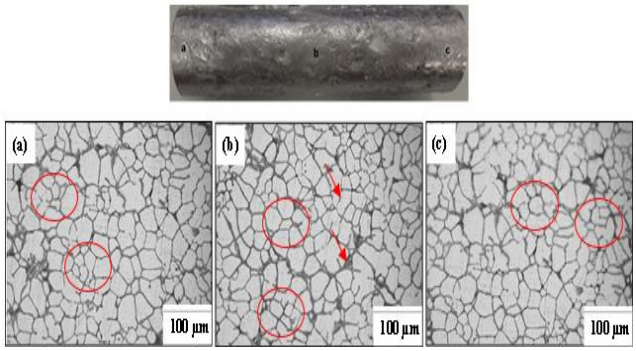



**Fig. 5:** Optical microscope images of Al-5.7Si-2Cu-0.3Mg alloy produced using cooling slope casting at100µm

**Table 2:** Hardness values of conventional and rheocast Al-5.7Si-2Cu-0.3Mg alloys.

| Process | Macrohardness ($N/m^2$) | Density ($Kg/cm^3$) |
|---|---|---|
| As-cast | 261.2 | 2.65 |
| Rheocast | 288.7 | 2.67 |

The influence of sliding distances on volume loss of conventional cast and rheocast of Al-5.7Si-2Cu-0.3Mg alloy, are shown in Figure 6. It clearly reveals that, the volume loss drastically increased from the beginning of wear test and then the volume loss observed little increase above the sliding distance of 6000m. In rheocast sample the volume loss was lower than as-cast sample, due to improve in the microstructure as well as it is higher hardness. However, sliding distance contributed to change wear mechanisms of samples [17]. Additionally, according to [18] the sliding distance was affected significantly on the volume wear loss of samples. Furthermore, it affected the wear and its mechanisms [14]. Where during sliding movement, heat is increased due to friction and cause some of the adhered materials softer and free. As sliding continues, the loss of particles/debris is thrown away giving a higher loss of weight.

Figure 7 presents the connection between volume loss of wear and the sliding distance of conventional and rheocast samples at different state loads. As can be seen, the loss of volume rises with sliding distance for both alloys. This is in agreement with [19] who found further that during his study about the effect of Cu addition on dry sliding wear behaviour of A356 alloy, because of increase in strength/hardness of the alloy after Cu addition and caused improve the wear resistance. On the other hand, the reduction in wear resistance as sliding continues can be attributed to long time of contact between the two pin sample and disc.

It is clear that in the conventional cast and rheocast alloys the volume loss increases with load, which is logical with Archard's law that the volume loss is equal to the applied load. As the sliding distance increases, the real contact surface area increases, which increase the control action between hardness and higher deformation in the surface [12].

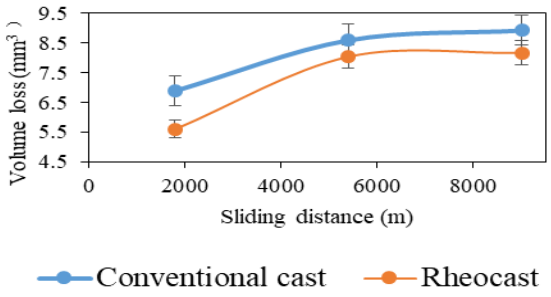



**Fig. 6:** Volumetric wear loss of Al-5.7Si-2Cu-0.3Mg alloy produced by (a) conventional cast and (b) rheocast processing

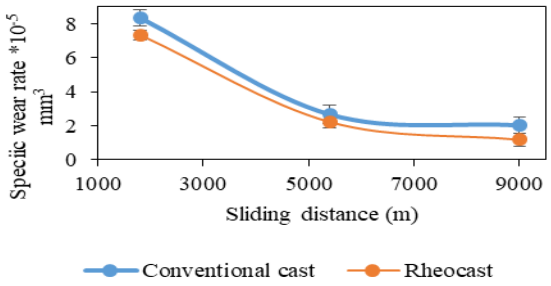



**Fig. 7:** Specific wear rate of Al-5.7Si-2Cu-0.3Mg alloy produced by (a) conventional cast and (b) rheocast processing

The effect of varying sliding distances on the worn surfaces of both alloys are shown in SEM microphotographs Figure 8 (a-d). Conventional cast at 1800m of distance has observed delamination filled with material detachment as shown in Figure 8a indicates adhesive wear as dominant wear mechanism. However, with increasing the distance to 9000m the detachment of material on worn surface increase with delamination filled as shown in Figure 8b resulted severe wear. Moreover, SEM micrographs of rheocast Al-5.7Si-2Cu-0.3Mg alloy exhibited reduction in wear rate at with varying sliding distance Figure 8c, d when compared with conventional cast alloy. Figure 8c observed increasing in oxide layer whereas the delamination has reduced due to increase the hardness of rheocast samples and the dominant wear mechanisms for this alloy was abrasive wear [20] as it is seen from Figure 8d.

Wear debris of both conventional cast and rheocast alloys were collected and examined by SEM microphotographs, are shown in Figure 9(a-d). It was clear that various shape and size of dsebris particles were observed as results of dry sliding wear behaviour at varying sliding distances. The sliding distance and hardness of alloys show an effect on the size of wear debris particles for both alloys. Therefore, at short sliding distance, it was found that large flakes-like morphology as clearly seen in Figure 9 (a) and Figure 9 (b).

It can be concluded that, the size and amount of wear debris in rheocast alloy was smaller particles and lower amount with thicker oxides (mild wear) than that in conventional cast alloy. The greater amount of oxide as observed in rheocast alloy, resulted in spherical shape of wear debris with increase the sliding distances. The spherical shape of debris in rheocast alloy was as a consequence of tribochemical reactions and frictional temperature.

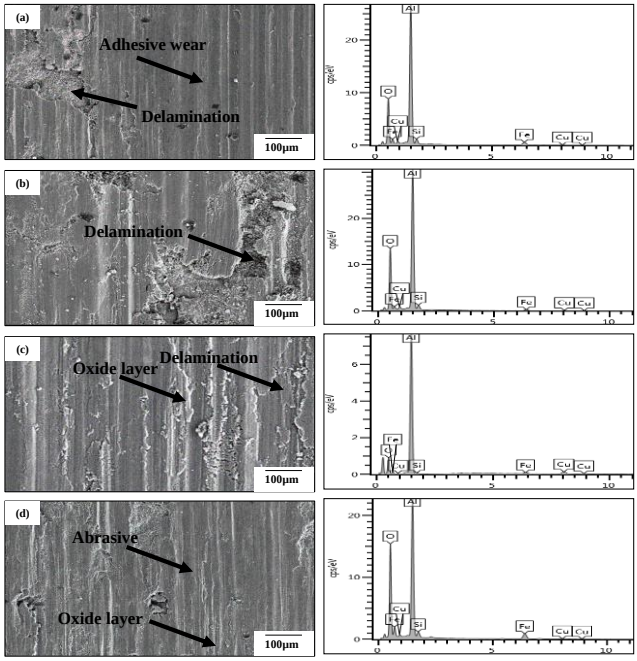



**Fig. 8:** SEM-EDX of worn surface at varying sliding distances of (a) Conventional cast at 1800m (b) Conventional cast at 9000m, (c) Rheocast at 1800m and (d) Rheocast at 9000m of Al-5.7Si-2Cu-0.3Mg alloy at 100µm

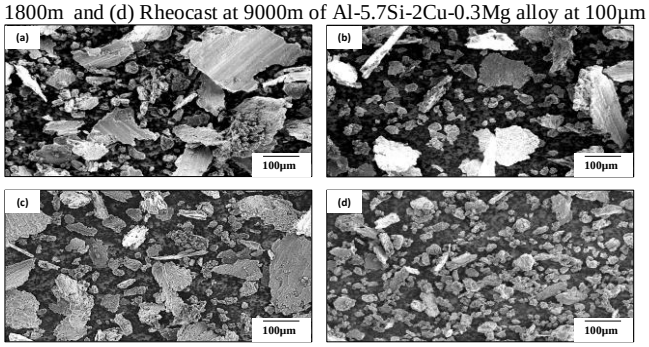



**Fig. 9:** SEM of the wear debris at varying sliding distances of (a) Conventional cast at 1800m (b) Conventional cast at 9000m, (c) Rheocast at 1800m & (d) Rheocast at 9000m of Al-5.7Si-2Cu-0.3Mg alloy at 100µm

Figure 10 observes the different of friction coefficient between conventional cast and rheocast alloys. It was clear that the average of friction coefficient increase with increase the sliding distance due to increase the contact area between pin sample and counter-surface. The average friction coefficient of rheocast alloy was lower than conventionally cast alloy at all sliding distance. It was owing to the hardness of worn surface of rheocast alloy is higher than that in conventional cast alloy.

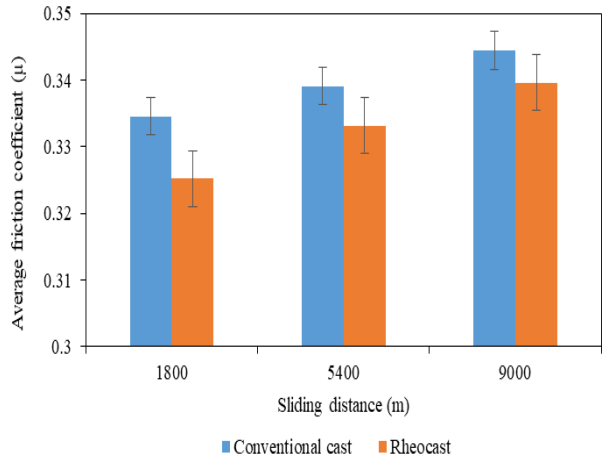



**Fig. 10:** Average friction coefficient of conventional cast and rheocast alloys as a function of sliding distances

## 4. Conclusion

Dry sliding wear tests were conducted on both conventional cast and rheocast Al-5.7Si-2Cu-0.3Mg alloys at different amount of sliding distances. The following conclusions can be drawn based on the test results. The volume loss of rheocast alloy show reduction more than 18% at 1.8Km and 10% at 9Km compared to the as-cast alloy. Although the specific wear rate decrease at higher sliding distances, mostly due to the work hardening effect on the sliding surface. The wear resistance in rheocast alloy was increase about 12% at 1.8Km and 41% at 9Km higher than that in conventional cast alloy. The friction coefficient increases about 2% as sliding distance increase for both alloys. Adhesion and abrasive wear were the dominant wear mechanism for both conventional and rheocasting alloys.

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