Tribo-Mechanical Behaviour of Al-Cu-Si castings

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Abstract. Al-Cu-Si alloy of 1.5% copper and 0.5% silicon was sand casted into ingot rods with Nitrogen degassing. The sand casted rods were homogenized at different temperatures for a time of 10 hours. The homogenized and as cast rods were then tested for mechanical and tribological properties by taking samples from different regions surface, middle and inner regions respectively. The Microhardness, microstructure, Ultimate tensile strength(UTS), elongation in percentage (%), rate of wear and specific wear rate were determined and investigated. The results show improved mechanical and tribological properties of homogenized compared to as cast. The hardness and tensile strength values showed similar pattern of decrease from outer to middle to inner regions whereas elongation in percentage showed the opposite. The greater hardness and tensile strength at the outer surface can be attributed to the faster solidification (or higher cooling rate at the surface) compared to the slower cooling rate at inner region of ingot. Microstructure examination also revealed finer grains at inner The Adhesive wear properties were determined using Pin on Disc wear tester as per ASTME standards of dry sliding friction condition. The results showed adhesive dry Adhesive wear is carried out by Pin-on-Disc wear tester. Wear rate of the alloy rises with applied load conducted at different speeds. The specific wear rate and the friction coefficient vary with load. The diffusion of disc material into the specimen material which changes the alloy composition. It was observed through energy dispersive X-ray spectroscopy (EDX) analysis. The worn-out surfaces were studied by using SEM analysis.

Keywords: Homogenization, Tribology, Mechanical, Microhardness

1. Introduction

The development of materials with good tribological (or less wear and tear) and mechanical properties, capable of withstanding extreme operating conditions has always been the top priority for many manufacturing industries. In this context, Aluminium and its alloys with copper and silicon has been the widely recommended materials in almost all general, automobile aerospace, machine tool applications [1]. Aluminium alloys present different enhanced properties by alloy additions and heat treatment variations [2,3]. Aluminium and copper alloys by proper selection of alloying elements and heat treatments, hardening and strengthening process give tribo-mechanical properties than the required level [4]. The Al alloy application in microelectronics as interconnect devices use copper-silicon as alloying elements to minimize the 'spiking' [5]. Addition of copper usually between 0.5 and 4 wt. % reduces the electro- migration failure rate [6]. As the content of copper increases in these alloys, longer time is needed for complete dissolution of the Al₂Cu phase and other intermetallic phase. This sluggishness (or longer dissolution time) makes the solution treatment of the alloy expensive and irrelevant to achieve the optimum strength. Also, it is found that prolonged annealing causes porosity which deleteriously affects the mechanical properties [7]. The mechanical properties of Al-Cu-Si alloys is greatly influenced by the shape and distribution of the Si particles.

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The strengthening mechanism behind these alloys during age-hardening has been attributed to the precipitation of Mg and Cu-rich phases [8-11]. Formation of Al$_2$Cu phases and other intermetallic compounds influences the strength and ductility [12] of Al-Si alloys with Cu addition. By implementing adaptable alloying- and process technology, the mechanical properties can therefore be readily enhanced, leading to larger application fields of complex cast aluminium components such as safety details. Generally, the mechanical and microstructural properties of aluminium cast alloys are dependent on the composition, melt treatment conditions, solidification rate, casting process and the applied thermal treatment [13].

Thus, the ever-growing popularity of aluminium alloys with good castability, workability, forgeability, machinability with higher corrosion resistance and strength to weight ratio gives increased performance and fuel economy. Workability means the amount of material that undergoes deformation without failure [14,15]. Moreover, the Al-Cu-Si alloy castings give a variety of improved tribo-mechanical properties based on alloying elements added, use of Sb modifiers [16] and heat treatment variations. This makes it suitable for most of the general engineering applications, where moderate mechanical properties are required. Further, the casting characteristics of Al-1.5Cu-0.5Si alloy permit it to be used for the production of reasonably thin sections and for pressure tight castings. Moreover, in the heat-treated condition, the casted Al-Cu-Si alloy maintains a relatively high static loading performance. Based on the above advantages and the Al-Cu and Al-Si phase diagrams, the Al-1.5Cu-0.5Si alloy is taken into consideration and carefully analyzed for sand casting and homogenization for various temperatures of 425°C, 500°C and 575 °C respectively. The mechanical properties were then studied at outer, middle and inner zones.

The present paper investigates the tribo-mechanical properties of Al-1.5Cu-0.5Si alloy with excellent sand and permanent mould castability and relatively good machinability; when compared to difficult and easy machinable other aluminium alloy groups. The wider possibilities for these castings therefore requires huge mechanical and wear properties data base and their correlation to alloy compositions and heat treatment processes. Further, there is little evidence on the study of the effect of parameters on the tribo-mechanical wear behavior of alloy Al-1.5Cu-0.5Si. Hence, by considering the above gap in the study, casting of Al-1.5Cu-0.5Si alloy was used to analyze the tribological properties.

2. Methodology of Work

2.1 Alloy Ingot preparation using melting and sand casting

Aluminium -copper -silicon alloy of 1.5% copper and 0.5% silicon was fabricated into ingots by melting pure aluminium (LM0) and electrolytic copper wire of 1.2 gauge and silicon powder in small amounts. The melting was performed in an electrical muffle type furnace with mechanical stirring and nitrogen degassing to reduce porosity. The furnace temperature was maintained around 750 °C (based on ternary Al-Cu-Si phase diagram) and the alloying elements added. The molten metal composition was then poured into sand moulds prepared by CO$_2$ process as shown in Fig. 1. The sand casted standard ingot rods of diameter 110mm and length 120 mm was checked for alloy composition (shown in Table 1) and later machined to diameter 100mm and length 100 mm respectively (Figure 2.) Keeping one ingot in as cast condition, the rest were sent for Homogenization heat treatment at three different temperatures.

| Table 1. Chemical composition of the Casted Al-Cu-Si Alloy. |
|-----------------|-------|-----|-----|-----|------|------|-----|-----|-----|
| Al   | Si   | Fe  | Cu  | Mn  | Mg   | Cr   | Ni  | Zn  | Pb  |
| 97.89| 0.5  | 0.18| 1.55| 0.01| 0.03 | 0.002| 0.019| 0.023| 0.02 |
2.2 Homogenization Heat Treatment of Sand casted rods

Homogenization heat treatment was performed to get uniform composition throughout the As - cast rods which otherwise have a non-uniform composition due to normal solidification process of nucleation and dendritic growth structure. The sand cast rods were homogenized in an electric resistance type muffle furnace at 425 °C, 500 °C and 575 °C respectively for a homogenizing time of 10 hours. After homogenization the ingots were furnace cooled to room temperature and the whole process was done under nitrogen atmosphere. The homogenised and As- cast sand ingots were then cut using Electric discharge machining (EDM) process and machined to standard ASTM E 92-82 specimen for Vicker’s Microhardness testing and ASTM E 8M-04 standard specimen for tensile testing. Each time samples were made from surface, middle and inner regions for both As cast and Homogenized specimen conditions. The wear testing sample *12 mm x 40 mm was also prepared from different regions of the ingot under strict ASTM G99 standard condition [17].

2.3 Mechanical Testing

2.3.1 Microhardness

The Microhardness testing on Al-Cu-Si casting was done on a Microhardness tester, (Model: ‘Mitutoyo, Make: MVK - H11) for both as cast and homogenized samples at three different regions of the ingots at surface, middle and inner respectively. Hardness testing was done for 10 observations per sample per zone for inner, middle and surface regions for an applied load of 100gf for time 15s both conditions (as cast and homogenized). Before testing, the samples were prepared as per ASTM E 92-82 standard and polished with emery grade sheets 1/0 and 2/0 [18].

2.3.2 Tensile strength and Elongation in percent (%)

The tensile strength and elongation in percent was determined by performing tensile testing on a universal testing machine (Model: H25KT, Make: Tinius Olson) at a speed of 1mm/minute for samples taken from the three different regions (surface, middle and inner) for both as cast and homogenized conditions. The Ultimate tensile strength (UTS) of the specimen is measured by slowly extending it until it fractures. The results and plots were taken from the computer data output and the specimen tested followed standard ASTM E 8M-04 standard.

2.4 Adhesive Wear Testing

Using a Pin on Disc wear tester DUCOM make, Adhesive wear tests were performed on samples taken from three different regions (surface, middle and inner respectively) for 425 °C homogenized specimen. The reason behind choosing 425 °C homogenized specimen was that it provided the highest microhardness values among all conditions. Table 2,show the wear parameters analysed. The wear samples were prepared as per ASTM G99 standard *10mm x 40 mm and the track radius of 50 mm was chosen. The machine wear track was made of steel disc (EN 31, HRC 60). The density was calculated using Archimedes method. From the difference in initial and final weight of the sample the weight loss and hence the rate of wear and specific wear rate (SWR) was determined. The wear rate was defined by volume by sliding distance and the specific wear rate was determined as wear rate by speed. The COF indicates the friction with contact surfaces which was calculated using Winducom software.
Table 2. Wear parameters.

| Sl no | Load (N) | Sliding Speed (rpm) | Sliding Time (min.) | Homogenization Temperature (°C) |
|-------|----------|---------------------|---------------------|---------------------------------|
| 1     | 10       | 287                 | 10                  | 425                             |
| 2     | 20       | 382                 | 10                  | 425                             |
| 3     | 30       | 478                 | 10                  | 425                             |

3. Results and Discussion

3.1 Microstructure Examination

The Microstructure Examination was performed on samples taken from the surface, middle and inner regions of the Homogenized specimen ingot at 575 °C as shown in figure 3. below. The samples were prepared to standard size and surfaces polished and etched using Kelly’s reagent. The samples were then presented for scanning electron microscopy (SEM) examination for a magnification of 5000X.

![Figure 3. SEM Microstructural images from three regions (surface, middle, and inner) of ingot homogenized at 575 °C.](image)

3.2 Mechanical Testing

The Microhardness and tensile testing was performed for determining the essential mechanical properties such as Microhardness, Ultimate tensile strength (UTS), Elongation percentage (%) for the alloy Al-1.5 Cu-0.5Si and the results summarized in table 3. Figure 4. gives the various plots drawn based on the table 3 data. The data results indicate superiority of homogenization process in giving enhanced and improved properties wherever normal one is desired. Improved hardness values are obtained for homogenized samples at lower temperatures than as cast. The hardness value is maximum (89HV) at surface region for 425 °C homogenized sample whereas for the same region for as cast the value is 80HV. In all cases homogenized and as cast microhardness values are found to decrease from surface to inner region because of varying rates of solidification(higher at surface). The lower hardness value compared to as cast at higher homogenization temperature at 575 °C show improved plastic and ductile properties. These data are well corroborated by the tensile strength and elongation percentage results (Table 3). The tensile strength follows similar pattern as microhardness for the Al-1.5Cu-0.5Si alloy indicating soft core and a hard outer surface properties. This phenomenon observed is an enhancement possibility for this light aluminium alloy and can be exploited for many applications. The elongation in percentage, a measure of ductility or plastic deformation behaviour show increased plastic deformation capability at higher temperature (maximum 7.0%) for homogenized inner region at 575 °C than as cast alloy (5.92%). The elongation in percent increases from surface to inner for all temperatures and specimen conditions. After the homogenization treatment, table 3. data clearly indicate the improvement of the Micro-Hardness, UTS of Al-1.5Cu-0.5Si alloy. The mechanical properties of pure aluminium have been improved upon by alloying it with copper and silicon addition. The lower values are just indicative of the furnace cooling adopted during heat treatment procedure. The properties can be significantly and remarkably enhanced over a wide range by employing different cooling rates and cooling medium during heat treatment.
Table 3. Mechanical properties of Al-1.5Cu-0.5Si alloy for different regions and conditions.

| Condition | Hardness (VHN) | Tensile strength (MPa) | Elongation in percent (%) |
|-----------|----------------|------------------------|---------------------------|
|           | Surface | Middle | Inner | Surface | Middle | Inner | Surface | Middle | Inner |
| As cast   |        |        |       | 80      | 76     | 72     | 61      | 42     | 30    | 2.25  | 3.75  | 5.92  |
| h425      | 89      | 82     | 73     | 87      | 67     | 57     | 1.34    | 1.73   | 3.17  |
| h500      | 87      | 78     | 75     | 75      | 51     | 40     | 1.73    | 2.48   | 3.83  |
| h575      | 78      | 74     | 69     | 52      | 30     | 22     | 2.48    | 4.35   | 7     |

Figure 4. The variation of mechanical properties for various specimen regions and conditions.

3.3 Tribological Behaviour

The tribological behaviour of the alloy Al-1.5Cu-0.5Si is studied by investigating the wear parameters and their influence on rate of wear and specific wear rate (SWR). The adhesive wear test is conducted on the Pin on disc wear tester under dry sliding condition for the wear parameters as per table 2. The wear parameter applied load (10N, 20N, 30N) and the sliding time (10 minutes) is made constant and the sliding velocity made to vary from 1.5 ms⁻¹, 2.0 ms⁻¹, 2.5 ms⁻¹ (or sliding speed of 287 rpm, 382 rpm, and 478 rpm respectively) for a constant track radius of 50 mm. The adhesive wear test is done for both As-cast and 425 °C homogenized condition for specimens taken from all the three regions (surface, middle, and inner regions) of the ingots. Prior to the wear test, standard samples are made from these regions (surface, middle, and inner) of the ingots both for the as cast and 425 °C homogenized, and their initial weights determined in a standard weighing balance under standard test conditions. The volume loss is one of the significant parameters of the wear behavior. So, the weight loss is converted into volume loss by dividing it by density applying Archimedes method. The experiment is performed and the final weight of the sample, determined by a standard weighing balance under standard test conditions. The difference in initial and final weight or the weight loss is determined and divided by the density (2.76g/cm³ found by Archimedes method) to get the ‘volume loss’. The rate of wear is calculated by dividing volume loss by sliding distance (calculated from track radius and sliding time) Finally, the Specific wear rate or the Rate of Wear divided by load is determined. It is obvious that as sliding distance increases, the volume loss increases. From the volume loss, the wear rate is calculated and the coefficient of friction is identified using the Winducom software. The wear rate was gradually increasing with respect to applied load because the interface temperature between the pin and the disc increases with increase in load [19] conducted at different speeds shown in figure 5. At medium speed and medium load conditions, the wear rate attained maximum and then started decreasing showing that the effect of load and speed is not significant at higher loads and speeds (load = 30 N and speed = 478 rpm). Figure 9(d), (e), (f) represents the SEM micrographs of the minimum wear condition. Minimum wear rate was observed at minimum load and only scratches were visible in the surface but further increase in load makes the scratches turn to grooves.
Table 4. The rate of wear and specific wear rate for As cast surface region.

| Exp. No | Load (N) | Speed (rpm) | Time (min.) | Condition | Wear Rate (mm\(^3\)/m) | SWR (mm\(^3\)/Nm) |
|---------|----------|-------------|-------------|-----------|------------------------|--------------------|
| 1       | 10       | 287         | 10          | As cast   | 0.006307342            | 0.000360734       |
| 2       | 10       | 382         | 10          | As cast   | 0.061212505            | 0.00612125        |
| 3       | 10       | 478         | 10          | As cast   | 0.001684298            | 0.00016843        |
| 4       | 20       | 287         | 10          | As cast   | 0.002564273            | 0.000128214       |
| 5       | 20       | 382         | 10          | As cast   | 0.073685901            | 0.003684295       |
| 6       | 20       | 478         | 10          | As cast   | 0.004329611            | 0.000216481       |
| 7       | 30       | 287         | 10          | As cast   | 0.004711763            | 0.000157059       |
| 8       | 30       | 382         | 10          | As cast   | 0.006234189            | 0.000207806       |
| 9       | 30       | 478         | 10          | As cast   | 0.00746069             | 0.00024869        |

Table 5. The rate of wear and specific wear rate for Homogenized surface region.

| Exp. No | Load (N) | Speed (rpm) | Time (min.) | Condition | Wear Rate (mm\(^3\)/m) | SWR (mm\(^3\)/Nm) |
|---------|----------|-------------|-------------|-----------|------------------------|--------------------|
| 1       | 10       | 287         | 10          | Homogenized| 0.003006118            | 0.000300612       |
| 2       | 10       | 382         | 10          | Homogenized| 0.033504999            | 0.0033505         |
| 3       | 10       | 478         | 10          | Homogenized| 0.00240614             | 1.60196E-06       |
| 4       | 20       | 287         | 10          | Homogenized| 0.00532888             | 0.000266444       |
| 5       | 20       | 382         | 10          | Homogenized| 0.005772397            | 0.00028862        |
| 6       | 20       | 478         | 10          | Homogenized| 0.00517148             | 0.000258574       |
| 7       | 30       | 287         | 10          | Homogenized| 0.008721774            | 0.000290726       |
| 8       | 30       | 382         | 10          | Homogenized| 0.006173955            | 0.000205798       |
| 9       | 30       | 478         | 10          | Homogenized| 0.013276819            | 0.000442561       |

Figure 5. Wear rate vs. Load for As-cast condition.
Figure 6. Specific Wear rate vs. Load for As-cast condition.

Figure 7. Coefficient of Friction vs. Load for As-cast condition.

Figure 8. SEM of wear specimen homogenized at 425 °C for loads: (a) 10 N (b) 20 N (c) 30 N.

Figure 9. SEM of wear specimen in As-cast condition for loads: (a) 10 N (b) 20 N (c) 30 N.
At high load the scratches and grooves were deep and peel of material starts forming because of maximum wear rate. The minimum wear rate was observed due to the smearing and embedding of oxidized Al-Cu alloy. The Al-1.5 Cu-0.5Si alloy shows better wear resistance from the observed sliding distance and load conditions. The specific wear rate was calculated under varying load conditions and identified that when speed increases specific wear rate increases initially up to 20 N load and then decreases when the load was further increased for low and medium speeds as shown in figure 5 and 6. The coefficient of friction versus load plot showed (Fig. 7) sharp decrease initially from 10N to 20N for high and medium speeds and then gradually increasing to 30N (high load). This can be attributed to the increasing wear rate and specific wear rate for medium and high speeds. For low speed at 287 rpm the specific wear rate was increasing which can be attributed to the gradually increasing coefficient of friction with respect to load and speed.

3.4 EDX Analysis

The EDX are analyzed for the wear specimen. It was found that iron and carbon content which was present in the wear sample. Because of diffusion of disc material into the specimen material which changes the alloy composition which leads to variation in wear rate and oxygen content was found due the atmospheric contamination as revealed in figure 10.

![Figure 10. EDS plot of wear specimen homogenized at 425 °C for a load of 10 N.](image)

Conclusions

- The microstructure examination shows finer grains at inner regions of the ingot and equi-axed grains at the surface. This is due to insufficient grain growth or faster solidification at the surface resulting in increased hardness values which decreased towards the inner regions.
- Increased hardness values were shown by ingots homogenized at lower temperatures (425 °C and 500 °C) compared to the as-cast specimens while at higher homogenization it showed hardness below the as cast indicating its better plastic deformation behavior or elongation properties measured at three different regions.
- The as cast hardness values decreased from outer (80 HV) to inner (72 HV) regions. It is due to the higher cooling rate of the surface region as compared to the middle and inner regions. Within the specimen, the hardness value decreases from outer to inner regions for all temperatures. As the homogenization temperature increases, the hardness value decreases.
- The tensile strength of the alloy follows the same trend as the hardness values decreasing from surface to inner regions. The maximum tensile strength for homogenized is observed for 425 °C surface sample 87 MPa and for as cast 61 MPa surface sample. The tensile strength also decreases from surface to inner regions for all temperatures and conditions (both as cast and homogenized) indicating less strength at the interior of the ingot or more plastic deformation flow behavior.
- As the homogenization temperature increases, correspondingly the tensile strength also decreases in all the three regions. Therefore, it can be concluded that both hardness and tensile strength are functions of each other.
- The elongation percentage which is also a measure of the plastic behavior increases from surface to inner regions for all temperatures (both for as cast and homogenized conditions).
The elongation percentage found maximum for the inner region sample homogenized at 575 °C indicates the plastic deformation capability of the alloy which can further be enhanced. The variation in percentage elongation within a region is least for outer region, and between regions is least for the ingot homogenized at 425 °C.

The properties can still be enhanced and improved upon by selecting or optimising the cooling rate and cooling medium adopted during heat treatment process.

For As-cast Al-Cu-Si alloy, the wear rate increases with respect to applied load because with increase in load conducted at different speeds, the interface temperature between the pin and the disc increases.

At medium speed and load (20 N and 382 rpm) the wear rate reached maximum and then decreased showing reducing influence of parameters load and speed at higher levels.

The Minimum wear rate was observed at minimum load and only scratches were visible in the surface but further increase in load makes the scratches turns to grooves.

The effect of higher loads and speeds (load = 30 N and speed = 478 rpm) wear rate is found less significant. The minimum wear rate is observed due to the smearing and embedding of oxidized Al-Cu alloy.

The Al-1.5Cu-0.5Si alloy shows better wear resistance from the observed sliding distance and load conditions.

The specific wear rate calculated under varying load and speed conditions showed increase of specific wear rate with speed initially upto 20 N load and then its decrease with the load d for low and medium speeds.

The coefficient of friction versus load plot show decrease at low and medium loads for 382 rpm and 478 rpm and then gradually increasing at high load (30 N). This can be attributed to the increasing wear rate and specific wear rate for medium and high speeds. For low speed at 287 rpm the specific wear rate was increasing which can be attributed to the gradually increasing coefficient of friction with respect to load and speed.

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