Influence of Solidification Rates and Stress-Relief Annealing on the Mechanical Properties of Cast 6063 Aluminium Alloy

Joseph T. Stephen, Adeyinka Adebayo, and Gbenga J. Adeyemi

Abstract—This paper reports the influence of solidification rate and stress-relief annealing on the mechanical properties of cast 6063 Aluminium alloy (Al6063). Ingots of Al6063 were melted and then cast using sand and metal moulds. Some of the cast samples were heat treated and then cooled in natural air. Tensile test, hardness test, impact test and microstructural analysis were carried out on the samples. The results show substantial changes in the mechanical properties of the specimens. The ultimate tensile strength, yield strength and hardness percentage elongation of cast Al6063 increases with the use of casting method with high thermal conductivity and reduces when annealing is carried out on the specimens. The ultimate tensile strength of 146.7 MPa and 163.5 MPa were recorded for sand mould and metal mould samples, respectively and the values decreases by 10.3% and 7.5% for the respective moulds. In contrast, the values of impact strength and percentage elongation of cast Al6063 rod improved with the increase in thermal conductivity of casting method and annealing operation. The ductile increased by 51.01% and 45.82% for sand mould and metal mould samples, respectively, after they were annealed. Furthermore, microstructural analysis of cast Al6063 rod revealed a fine-grained structure with increase in thermal conductivity of casting method used; however, the annealing process encouraged grain growth as a result of the stress being relieved from the samples.

Index Terms—Aluminium Alloy; Solidification; Annealing; Mechanical Properties.

I. INTRODUCTION

In recent years, the use of aluminium and its alloys for engineering applications is increasing due to the numerous advantages of its technical properties [1], [2]. The properties of aluminium alloys depend on the amount alloying elements present in them, and are also influenced by the manufacturing techniques [3]-[5]. 6063 aluminium alloy has silicon and magnesium as its main alloying elements, and these elements form the primary hardening phase (magnesium silicide, Mg2Si) which are partly dissolved in the primary α-Al matrix, and partly present in the form of intermetallic phases [6].

6063 aluminium alloy is known for its good workability, high strength to weight ratio, excellent corrosion and heat treatability [1], [7]-[9]. Casting is the main manufacturing method of producing aluminium and its alloys into finished and semi-finished products. Consequently, casting processing of aluminium alloys had been a focus of many previous investigations [6], [7], [10]-[17]. Experimental studies into the effect of solution-ageing treatment on the mechanical properties of semi solid 7A09 aluminium alloy revealed that high temperature or longer soak time encourage grains growth [10]. Surplus phases not melted in the substrate and the solution precipitated supersaturated elements were found to influenced the properties of the alloy. Heat treatment was also found to improve the mechanical properties and also eliminated microsegregations of MgZn present in the as-cast 7075 aluminium alloy [11].

Studies into manufacturing parameters (casting temperature and speed) of the AA 6063 aluminium alloy produced with vertical continuous casting technique and homogenization showed that mechanical properties of the product depend on metal temperature and casting speed, and recommended an optimum metal temperature and casting speed 580°C and 100-100 mm/min, respectively [2]. In addition, the non-equilibrium solidification rates during extruded billet casting of 6063 aluminium could influence formation of coarse eutectic Mg2Si particles, and this has negative effect on mechanical properties and surface appearance in the anodized condition [6], [18]. However, homogenization heat treatment produces fragmentation and spheroidization of the α-Al-Fe-Si and also imparted adequate tensile properties and surface finish to extruded products.

Literature survey states that the mechanical properties of 6xxx aluminium series are not only influenced by proportion of alloying element but also heat treatment (age hardening) parameters employed [12]. Experimental studies carried out on the effect of casting mould (metal moulds, and CO2 process, cement- and naturally-bonded sand moulds) on the mechanical properties of Al6063 alloy showed that naturally naturally-bonded sand moulds displayed superior hardness, tensile strength and ductility, whereas metal mould showed highest impact strength [13]. Addition of additives (tamarind and starch powders, and cast dust) in sand mould during casting was also found to affect the mechanical properties of Al6351 alloy. Studies on effects of mould’s temperature on compressive and fatigue properties casting aluminium alloy showed that the true compressive strength and fatigue life increase, whereas the stress compressive strength and fatigue limit decrease with increase in mould
temperature [14].

In order to improved strength of aluminium alloy Adeosun et al. conducted experimental studies on 6063 aluminium-steel composite [5]. The results showed that tensile strength and hardness of the aluminium-steel composite depend on the volume fraction of intermetallics in the matrix, and 10 wt% steel dust in aluminium 6063 improved the tensile strength and the hardness values. Some important characteristics are impacted on cast aluminium alloys by adding mixtures of some essential agents which increase the rate of heat extraction and thereby enhance grain refining [15], [16]. Influence of inoculant and cooling medium on the mechanical properties of a 6063 aluminium alloy was investigated by [16]. The conglomeration of inoculant addition and water cooling increased the fracture strength of the aluminium alloy.

A deep understanding of how the casting techniques and heat treatment of 6063 aluminium alloy affect mechanical properties of cast products will be of enormous advantage to the designer to ensure that the casting will achieve the intended properties during application [17], [19], [20]. Therefore, present experimental study intends to investigate the effect of solidification rate and stress-relief annealing on the mechanical properties of 6063 aluminium alloy.

II. EXPERIMENTAL METHODOLOGY

A. Material Preparation and Alloy Casting

The principal material that was used for the cast was aluminium alloy (Al6063) which was purchased from a local market in Lagos, Nigeria. Spectrographic analysis was carried out on the specimen to determine chemical compositions with the aid of Plasma Spectroscopy, and the chemical analysis of the mild steel is shown in Table I.

Two set of mould were prepared- the sand mould and permanent metal mould. The “green” sand mould was prepared with silica sand, coal-dust, clay and starch (organic binder) that were mixed with the right proportion of water. Cylindrical wooden rods of length 150 mm and diameter 15 mm were used as patterns. The permanent metal mould was made hardened steel metal.

Melting of the purchased aluminium alloy was done in a 10 kg capacity crucible placed inside the furnace. Flux was added at about 660 °C by covering the surface of the already molten alloy with about 2% by weight of charge covering flux. The dry sand mould cavity was fed with the molten alloy with about 2% by weight of charge covering flux. The dry sand mould cavity was fed with the molten alloy with about 2% by weight of charge covering flux. The dry sand mould cavity was fed with the molten alloy with about 2% by weight of charge covering flux. The dry sand mould cavity was fed with the molten alloy with about 2% by weight of charge covering flux.

B. Specimen Preparation

The cast aluminium rods obtained from sand and metal moulds were machined to obtain tensile, hardness and impact test specimens. The tensile test specimens were machined to the dimensions shown in Fig. 1, while the impact specimens were machined to lengths of 60 mm, diameter of 10 mm and V notched angle of 450 to a depth of 2 mm, and hardness to lengths of 20 mm and diameter of 10 mm.

C. Heat Treatment

Some of the specimens from both sand and metal moulds were stress-relief annealed. Stress-relief annealing was used mainly for the prevention of stress-corrosion cracking and decreasing distortions caused by internal stresses [21]. The specimens were put in a muffle furnace set at an annealing temperature of 200 °C and allowed to soak for 2 hours, after then, it was cooled in air at a very slow rate.

D. Mechanical Testing and Microstructure Examination

The tensile strength properties of both as-cast and heat treated aluminium for sand and metal moulds were determined using an Instron universal testing machine (model 3369). Tensile test was conducted according to according to ASTM E-8 standard. The tensile specimens were subjected to constant extension rate tensile (CERT) tests of 1 mm/min on the machine. The tensile force versus displacement graph was plotted by the machine as straining continued. The yield strength, ultimate tensile strength and stress at fracture of the specimens were respectively evaluated from the forces indicated where the pointer showed momentary rest after elastic limit before taking off again, at the maximum value of the pointer just before the breaking of the specimen occurred, and at the point of fracture. Finally, the fractured specimen was removed from the grips of the machine and percentage elongation at fracture was obtained by putting the two halves back together and measuring the total stretch in the gauge length.

Brinell hardness test was conducted according to ASTM E10-14 standard, the surface of the specimens was stage-grounded and then polished. Measurement of hardness properties were carried out on the specimens. The measurement was carried out on Tensometer (Monsanto Testing Machine). During the test, a load of 250 kg was applied to the hard, spherical indenter forced into the surface of the sample to be tested for a dwell period of 15 seconds. For each specimen, average value of three readings, taken at different positions on the sample, was use to evaluate the hardness. Impact testing of all the specimens was conducted according to ASTM E602-91 standard. Impact energy was recorded using the Izod impact tester. The impact strength of the samples were determined from the energy absorbed when an arm of the tester was released from a specific height (constant potential energy is released) to break the samples.

The microstructural test specimens were progressively grinded to obtain a smooth and flat surface polished with emery cloth in decreasing coarseness attached to a rotating disc machine.

Fig. 1. Samples of the machined tensile.
TABLE I: CHEMICAL COMPOSITION OF MILD STEEL

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
<th>Zn</th>
<th>Cr</th>
<th>Cu</th>
<th>Ti</th>
<th>Mg</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (%)</td>
<td>0.459</td>
<td>0.030</td>
<td>0.221</td>
<td>0.003</td>
<td>0.004</td>
<td>0.003</td>
<td>0.025</td>
<td>0.556</td>
<td>balance</td>
</tr>
</tbody>
</table>

Thereafter, the specimens were washed with water and polished with diamond paste to a mirror-finish appearance. Etching was done with Nital (2% of nitric acid and 9% of ethyl ethanol) to reveal the microstructure of the surface layer. The phases of the specimens were then photographically recorded at 400 magnification using electron microscope.

III. RESULTS AND DISCUSSIONS

The stress-strain curves of the tensile test (Fig. 2) carried out on each specimen were plotted on a single plot using results obtained from the Instron universal testing machine for the as-cast condition and after annealing at 200°C. From the stress-strain curves, the specimens from the metal mould showed higher strain value per point on the graph when compared to samples from the sand mould for both the as-cast and annealed conditions, which might be due to the higher solidification rate of cast using the metal mould.

![Stress-strain curve for as-cast sample from sand mould, annealed sample from sand mould, as-cast sample from metal mould and annealed sample from metal mould.](image)

In order to determine the responses of the specimens to tensile tests, the values of yield strength (σy), ultimate tensile strength (σu), and percentage elongation at fracture were evaluated from the stress-strain curves. The results are showed in Table II and Fig. 4 and Fig. 5. Furthermore, Fig. 3 shows the results of the Brinell hardness and impact tests for as-cast and annealed specimens from the two moulds.

Brinnel Hardness Number (BHN) of the samples is presented in Fig. 3(a). It is observed that as-cast samples had the highest BHN when compared with the annealed samples. The results show that BHN of the samples produced using sand mould decreased by 27% after it was annealed at 200°C for four hours while BHN of samples produced using metal mould decreased by 26.8%. The results also indicate that samples produced using metal mould possesses better BHN in both as cast and annealed conditions.

![Fig. 3. (a) Hardness and (b) Impact of as-cast and annealed samples for sand and metal moulds, respectively.](image)

The decrease in BHN after annealing could be attributed to increase in grain size of the aluminium after annealing. The increase in grain size and stress relieve caused by the annealing process resulted to decrease in hardness and strength of the annealed samples in comparison with as-cast samples. The results of hardness test are consistence with previous works reported by Ajibola et al. [22] and Isadare et al. [11].

It can be observed from the impact test (Fig. 3(b)) that as annealed samples also had better impact strength values when compared to the as-cast samples. The results show that impact value of the samples produced using sand mould increased by 28.1% after it was annealed at 200°C whereas the impact strength value of samples produced using metal mould increased by 72.8%. The results similarly indicate that samples produced using metal mould possesses superior impact resistance both in the as-cast and annealed conditions.

The decrease in impact strength values after annealing could also be attributed to the fact that the annealing carried out on the samples relieved the stress in the aluminium thereby causing reduction in strength in the samples produced from the sand mould.
**TABLE II: TENSILE PROPERTIES OF MILD STEEL COOLED IN LOCAL MEDIA**

<table>
<thead>
<tr>
<th>Mould</th>
<th>Treatment</th>
<th>Yield Strength, $\sigma_y$ (MPa)</th>
<th>Ultimate Tensile Strength, $\sigma_U$ (Mpa)</th>
<th>Percentage Elongation (%)</th>
<th>Hardness (BHN)</th>
<th>Impact (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand mould</td>
<td>As-cast</td>
<td>92.1</td>
<td>146.7</td>
<td>10.39</td>
<td>140.5</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>Annealed</td>
<td>76.7</td>
<td>131.5</td>
<td>15.69</td>
<td>102.6</td>
<td>17.3</td>
</tr>
<tr>
<td>Metal mould</td>
<td>As-cast</td>
<td>127.5</td>
<td>163.5</td>
<td>14.86</td>
<td>170.0</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Annealed</td>
<td>117.9</td>
<td>151.2</td>
<td>21.67</td>
<td>124.2</td>
<td>26.1</td>
</tr>
</tbody>
</table>

Fig. 4. (a) Ultimate tensile strength and (b) Yield strength of as-cast and annealed samples for sand and metal moulds, respectively.

The results of the percentage elongation are presented in Fig. 5. It could be observed from the results that annealed samples had the highest percentage elongation values when compared with the as-cast samples. The results show that percentage elongation value of the samples produced using sand and metal moulds increased by 51.01% and 45.82%, respectively, after they were annealed at 200°C for four hours. The results also indicate that samples produced using metal mould had higher percentage elongation values in both as cast and annealed conditions. The degree of surface smoothness and permeability of the moulds influenced the hardness and impact resistance results of the cast samples made in these moulds. The rate at which heat is being extracted from the alloy as it solidifies in the metal mould is faster than that of the sand mould, and this resulted in improved hardness, impact resistance and strength of the aluminium alloy, as also observed in the study conducted by Ajibola et al. [22].

Contrary to what was observed in the hardness and strengths, the results of the percentage elongation show that annealing improved the ductility of Al 6030 alloy, and this was similar to the observation reported by Abed, 2011 in their study. This implies that the effects of annealing treatment on strength and ductility of Al6030 alloy are in opposite directions. The strength decreases whereas the ductility increases. Hence, attempt to increase the elongation through annealing will cause the decrease of tensile strength, and verse versa.
A. Microstructural Analysis

Microstructural test results for the as-cast and annealed samples using metal mould and sand mould are presented in Fig. 6. The microstructure results show well dispersed crystals of $\alpha$-aluminium and Mg$_2$Si (eutectic phase) in aluminium matrix, but the mean crystal size and shape of these crystals in the matrix for each of the samples are different. In the optical micrograph of the as-cast sample from sand mould (Fig. 6(a)), there is increase in grain size due to lower thermal conductivity when compared with the metal mould (Fig. 6(b)), and dislocations are evident. In the as-cast samples of metal mould, finest grain structure was obtained due to high thermal conductivity of the metal mould. The cluster of the fine Mg$_2$Si in the matrix possesses tendency of obstructing motion of dislocations, hence leading to the observed high hardness and strength values in Table II.

In the optical micrograph of the annealed samples, it is observed that there is significant growth in grain size as a result of stress-relief annealing when compared to that of the as-cast samples, and this adversely affected the hardness and strength values of the annealed samples from both the sand and metal moulds. In addition, reduction in dislocation is also evident in the micrograph of annealed sand mould sample as compared to that of the as-cast sand mould sample and this contribute to the observed improved in the resistance to impact energy. These results show, as also reported in the previous studies [17], [23], [24], that microstructure of the aluminium alloys change depending on the cooling rate and solidification condition as well as the heat treatment employed.

IV. Conclusion

Aluminium and its alloys have high consumption rate in manufacturing and construction industries due to advantages of its technical properties such as high strength and corrosion resistance, and good workability. Like the other alloys of this series, the first step of manufacturing Al6030 alloy begins with casting method. The casting method and heat treatment of the casted products affect the properties of alloys. Hence, experimental investigation was carried out on solidification rates (by varying the casting method) and heat treatment (stress-relief annealing) on the mechanical properties of cast Al6063 rods. The following general conclusions were made from the results of mechanical tests and microstructural examination carried out:

- Ultimate tensile strength, yield strength and hardness percentage elongation of cast Al6063 increases with the use of casting method with high thermal conductivity and reduces when annealing is carried out on the specimen.
- The impact strength and percentage elongation of cast Al6063 alloy increases with increase in thermal conductivity of casting method and annealing operation also improved these properties.
- The micrograph of Al6063 alloy gives a fine-grained structure with increase in thermal conductivity of casting method used; however, the annealing process encouraged grain growth as a result of the stress being relieved from the samples.

Therefore, from the results and analyses, it is evident that the mechanical properties of cast Al6063 alloy can be improved for different applications by varying the casting method thereby achieving different solidification rates and also subjecting the samples to heat treatment.

Fig. 6. Optical micrograph of (a) as-cast sand mould, (b) as-cast metal mould (c) annealed sand mould and, (d) annealed metal mould samples (Mag. 400x).
V. REFERENCES


Stephen, Joseph Temitope is a native of Ado-Ekiti, Nigeria. He obtained Bachelor of Engineering in Mechanical Engineering, University of Ado-Ekiti, Ado-Ekiti, Nigeria, (1997), Masters of Science in Mechanical Engineering, University of Ibadan, Ibadan, Nigeria, (2005), and PhD in Mechanical Engineering, The University of Sheffield, United Kingdom, (2015).

He is a lecturer in the Department of Mechanical Engineering, Faculty of Engineering, Ekiti State University, Ado-Ekiti. His areas of specialisation are design, material and tribocouasotic. Dr. Stephen is a corporate member of Nigeria Society of Engineer, corporate member Nigerian Institution of Mechanical Engineers and registered Engineer with Council for the Regulation of Engineering in Nigeria.

Adebayo, Adeyinka. obtained Bachelor of Engineering in Mechanical Engineering, University of Ado-Ekiti, Ado-Ekiti, Nigeria, (1999), Masters of Science in Mechanical Engineering, University of Ibadan, Ibadan, Nigeria, (2005), and PhD in Mechanical Engineering, University of Cranfield, UK, (2013).

He is a senior lecturer in the Department of Mechanical Engineering, Faculty of Engineering, Ekiti State University, Ado-Ekiti. His areas of specialisation are material and manufacturing process. Dr. Adebayo is a corporate member of Nigeria Society of Engineer and registered Engineer with Council for the Regulation of Engineering in Nigeria.


He is presently a lecturer in the Department of Mechanical Engineering, Faculty of Engineering, Ekiti State University, Ado-Ekiti. His areas of specialisation are material and tribocouasotic. Dr. Adeyemi is a corporate member of Nigeria Society of Engineer, corporate member Nigerian Institution of Mechanical Engineers and registered Engineer with Council for the Regulation of Engineering in Nigeria.