Experimental Analysis of Deformation Effects on the Mechanical Characteristics of 6061 Aluminium Alloys

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Abstract- This paper reports on an experiment to assess the influence of deformation on the mechanical properties of aluminium 6061 alloys. Mechanical properties such as tensile strength, toughness and hardness is affected by deformation under load. Cast samples underwent mechanical (static and dynamic) testing after being cold rolled to reduce their thickness by 0 to 20 percent. The results indicate a notable improvement in hardness. The observed behaviour can be attributed to the type, quantity, and distribution of Mg2Si secondary phase particles that precipitated inside the matrix and were impacted by the degree of cold-work. Although deformation can enhance the hardness of aluminium 6061 alloy, it also decreases ductility of the creation of voids and microcracks. This may cause the material's elongation and reduction in area indicating a lower ability of the material to deform before failure. Moreover, fatigue behaviour of 6061 aluminium alloys can be affected by deformation. Fatigue fractures can begin and spread as a result of the introduction of flaws and dislocations during deformation, which can serve as stress concentrators. This may cause the material's fatigue life to decrease.

Index Terms- Cold Work, Tensile Strength, Toughness, Hardness, Microcracks.

I. INTRODUCTION

Pure aluminum when subjected to deformation shows an increase in ultimate tensile strength (UTS), electrical resistance and decrease in toughness and conductivity as the amount of deformation increased [1]. Aluminum 6061 alloy processed by upset forging and cold rolling at ambient temperature has shown that the UTS and hardness increase as the range of thickness reduction suffered increases from 0 to 50 percent while the ductility decreases, an indication of a low strain-hardening exponent [2]. Grain distortion and crystal structure imperfections brought about by cold working metal alter the alloy's electrical characteristics.

Combining cold working and heat treatment greatly improves structural homogenisation, which helps manage the final physical and mechanical qualities. [3]. The random alignment of crystals in a forged matrix greatly improves physical qualities including ductility, strength, and toughness compared to the base metal. [4]. This explains why alloys are preferred to have some degree of distortion in order to attain better mechanical characteristics.

There are strong interactions between the solute atoms and defects in aluminum alloys that result in structural instabilities, variation in solute profiles and changes in solute diffusion rates. The Portevin-Le Chatelier (P-L) effect causes increased solute diffusion during tensile straining, which pins mobile dislocations. [5]. Aluminium alloys exhibit this behaviour at a variety of temperatures, both above and below room temperature. Plastic deformation not only increases the mobility of solute atoms in aluminum alloys but also cause clustering at dislocations and these clusters act as nucleation sites for subsequent strengthening precipitates at temperatures well below the conventional aging temperatures [6]. This paper investigates the effect of varying levels of cold work on the mechanical and electrical properties of Al 6061 alloy.

II. EXPERIMENTAL PROCEDURE

For this investigation, rectangular test pieces measuring 350 x 30 x 12 mm were made from AA6061 aluminium alloy ingots that had been melted in an oil-fired crucible furnace.

The chemical composition of the samples is presented in Table 1.

Table 1: Chemical composition of Cast 6061 aluminum alloy sample.

Element	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Ca	Sr	Al
% weight	0.444	0.202	0.011	0.013	0.571	0.006	0.002	0.008	0.003	0.003	98.737

For cumulative and non-cumulative thickness reduction, the cast samples were machined to 200x30x9 mm and 100x25x9 mm, respectively. The samples were subsequently rolled using a four-high mill set to reduce thickness by 0 to 24 percent at room temperature, 250C.

Figure 1 displays the results of the Rockwell Hardness Tester model 6402 used to determine the hardness of the deformed samples. Using standard notched impact specimens, samples were also put under impact loading in a charpy-v test; the outcome is shown in Figure 2.

The tensile test was conducted using an Otto Wolpert Werke tensometer at a rate of 50 mm/min, and the results are shown in Figure 3. The electrical resistance of the samples was measured using a resistomat type 2319, and Figure 4 shows the outcome.

Cold-rolled samples were successively ground using emery paper grades 80, 220, 320, and 600 microns to prepare them for photomicrographic analysis. Etching of the samples for 20 seconds was done using a mixture of dilute nitric acid (68%), hydrofluoric acid (30%), and sodium hydroxide (2%). Samples (Plates 1-4) were photographed under a magnification of X200.

III. RESULTS AND DISCUSSION

3.1 Microstructure

The as-cast sample contains clusters of Mg_2Si precipitates that are well-distributed in the α-aluminum matrix as shown on Plate 1.

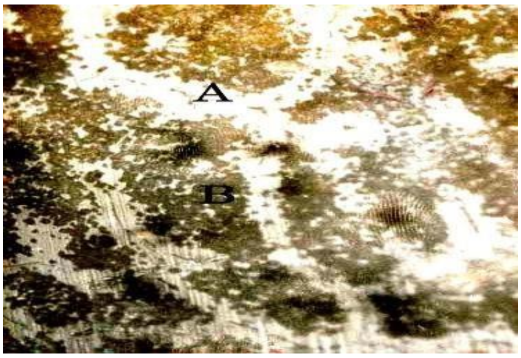


Plate 1 Microstructure of as-cast sample (A- α-aluminum, B-Mg_2Si)

Rolling the sample at ambient temperature to 4 percent thickness reduction causes most of the precipitated Mg_2Si to be absorbed into the matrix (Plate 2a) exhibiting thin and visible grain boundaries. There is re-precipitation of fine Mg_2Si crystals that are not as coherent as those of the as-cast with reduced volume fraction at 8 percent reduction (Plate 2b).

a

b

Plate 2 Microstructure of as-cast sample (A- α-aluminum, B-Mg_2Si)
(a) 4% reduction (b) 8% reduction

However, greater coherency of Mg_2Si crystals was observed in sample subjected to 12 percent reduction with high intensity and high volume fraction when compared to the as-cast (Plate 3a).

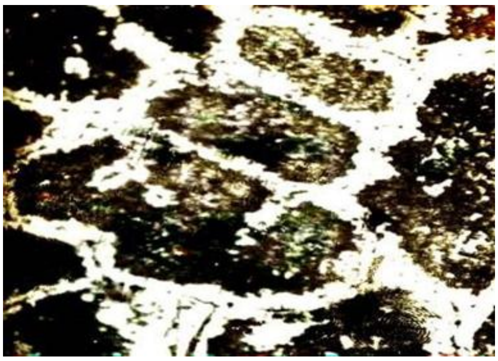
The intensity and coherency of crystals of Mg2Si is reduced relative to as-cast sample at 16 percent reduction (Plate 3b).

a

b

Plate 3 Microstructure of as-cast sample (A- α-aluminum, B- Mg2Si).
(a) reduction (b) 16% reduction

At 20 percent reduction in thickness, clustering and volume fraction of Mg2Si increases (Plate 4a). Processing to 24 percent reduction resulted in increase in fineness of Mg2Si crystal in the α-aluminum matrix as shown on Plate 4b.



a

b

Plate 4 Microstructure of as-cast sample (A- α-aluminum, B-Mg2Si)
(a) 20% reduction (b) 24% reduction

It should be noted that clustering and fineness of crystals increases both the hardness and strength of cold worked test samples. Similarly, incoherency and coarse crystals in the matrix and other solute phases promote fracture toughness of the material.

3.2 Hardness

The hardness of test samples increases nearly linearly initially within 0-8 percent thickness reductions whereas there is no significant increase in hardness between 8 and 14 percent thickness reduction. At 15 percent and beyond, hardness values increase gradually to the maximum, 52 HRE, at 24 percent reduction (Figure 1). The reason for this is that at 8-14 percent reduction, there seems to be temporary saturation in the generation of immobile dislocations as a result of reduction in the amount of Mg2Si precipitates produced.

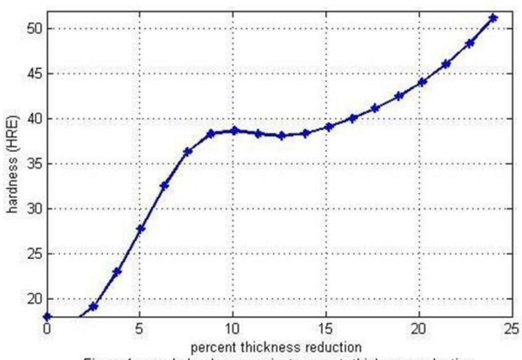


Figure 1 sample hardness against percent thickness reduction

3.3 Impact Energy

The test samples behavior under impact loading increases from 0-5 percent thickness reduction, the maximum energy absorbed, ~880J, occurred at 5 percent reduction (Figure 2).

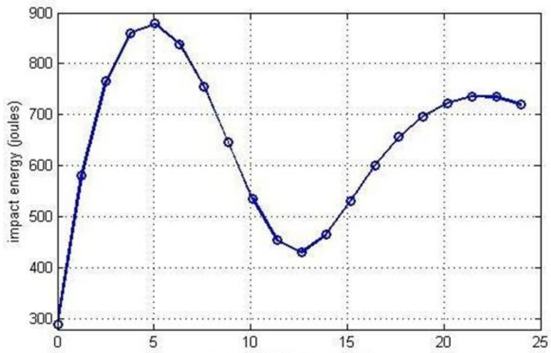


Figure 2 sample impact energy against percent thickness reduction

Impact energy also decreases slowly to a minimum of 425J at about 13 percent reduction. However, beyond this level of reduction, impact energy increases gradually to 730J with a tendency to decrease at higher reduction. The minimum of 425J occur at 13 percent reduction in the domain of immobile dislocation generation saturation. The toughness of a material reduces as the level of cold work increases [7].

This may be explained using the 16 percent cold work microstructure (Plate 3b) in which the presence of the second phase precipitates, Mg2Si, reduces progressively at grain boundaries corresponding to test sample's percent thickness reduction.

3.4 Tensile Strength

The effect of thickness of samples reduction during deformation at ambient temperature on the UTS is sinusoidal (Figure 3). The peak tensile strength, 142MPa, occurred at 17 percent reduction while the minimum of 100MPa was obtained at 23 percent reduction. The non linearity of the curve at 16 percent cold work is as a result of precipitates of second phase intermetallic, Mg2Si, which were more pronounced than for other levels of cold work (Plate 2a, 2b, 3a, 4a and 4b). According to Li and Ghosh [8], uniaxial tensile test usually serve as a major screening for ranking relative strength of alloy deformation behaviour. Hence, there are more clustering of the second phase crystals within the matrix in tandem with percent thickness reduction sequence.

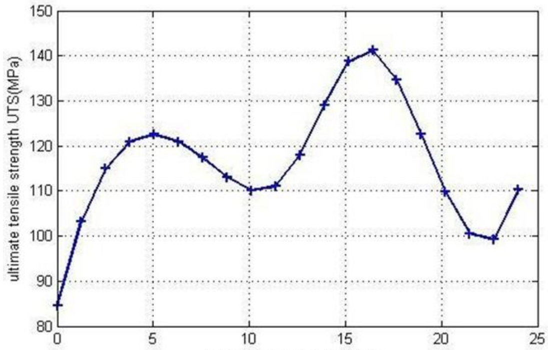


Figure 3 sample ultimate tensile strength against percent thickness reduction

3.5 Resistance

The electrical resistance of test samples after deformation shows a near linear relationship with thickness reduction for reduction in the ranges from 5-24 percent (non-cumulative). However, the increase in resistance is rather slow as reduction increases (Figure 4).

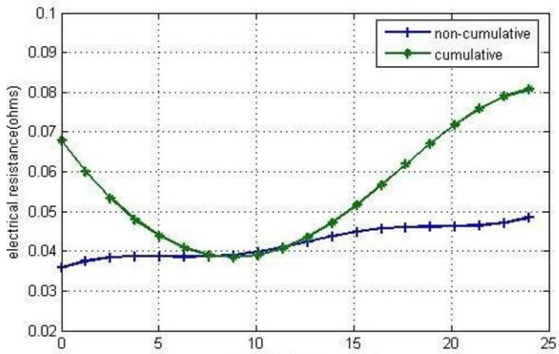


Figure 4 sample electrical resistance against percent thickness reduction

In the as-cast state the resistance is ~0.07Ω but rises steadily to a maximum value of 0.08 Ω at 24 percent reduction. Graphical representation of the non-cumulative and cumulative test result shows that the electrical resistance of aluminum alloy 6061 increase with increased cold work. This is because the resistance of a material does not only depend on the length but also on imperfections such as the distribution of second phase crystals and the volume fraction of matrix constituents in the material [9].

CONCLUSION

The study conducted revealed that cold working of 6061 aluminum alloy impacts significant effects on its mechanical and electrical properties. It has been shown that hardness and resistance increased from 0 to 24 percent thickness reduction. Substantial improvement in toughness, strength, hardness and low resistance to current flow is feasible at a thickness reduction in the neighborhood of 5 percent. At this level of reduction, most of the precipitated Mg2Si crystals are absorbed into the matrix and there is increase in homogeneity of solution as it becomes more isotropic. Though the degree of deformation has significant effect on the conductivity of the alloy however, this will be impaired if the material is made to suffer severe deformation.

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