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Fatigue and Anisotropic behaviours of cold rolled AA1200 Aluminum Alloy

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ABSTRACT

This study examines the fatigue and anisotropy behaviour of cold rolled AA1200 aluminum alloy for light weight automotive connecting rod application. Aluminum (Al) 1200 ingots were melted at temperature of 680 ^{0}C (after one hour of heating) cast in sand mould and cast samples homogenized for 6 hrs at 480 ^{0}C. The cold rolling process was carried out after homogenisation for 10, 20, 30, 40 and 50% thickness reductions. The samples were characterised in 0^0, 15^0, 30^0, 45^0, 60^0, 75^0 and 90^0 to the rolling direction. The results show that degree of deformation increase linearly with mean stress, stress range, stress ratio, stress amplitude, thickness and area ratio for all the reductions and directions examined. Area and thickness ratio increases linearly with deformation at higher inclination ($> 15^0$). The fatigue life obtained in this work shows life cycles at different degrees of deformation: 7.5 x 10^4 cycles at 10% reduction, 1.3 x10^5 cycles at 20% reduction, 4.3 x 10^4 cycles at 30% reduction; 2.6 x 10^5 cycles at 40% reduction and 1.09 x 10^5 cycles at 50% reduction). The results of this study provide evidence that systemic controlled cold deformation can potentially be used to significantly enhance the fatigue life of AA1200 aluminum alloy components subjected to cyclic loadings.

1. Introduction

Studies on fatigue properties of aluminum alloys have been centred mainly on environmental [1-4] microstructural [5-10], fatigue model [11-13] and surface treatment impacts [14-16]. However, cold rolling has not been known to have been used as a means of improving fatigue behaviours of AA1200.

Work hardening is known to create grains fragmentation with increase tensile strength and hardness but decrease in elongation [17]. The deformation behaviour of cold rolled AA1200 aluminum alloy carried out after annealing showed that both the Ultimate Tensile Strength (UTS) and hardness improved as degree of deformation, but decline with annealing temperatures [18]. Thus, the texture and microstructure evolved earlier during rolling are replaced by a new one during annealing. The 5xxx, 6xxx and 7xxx series alloys, which have found patronage in automotive and construction industry, are required to meet specific tensile properties and fatigue strength, among other properties [19]. However, studies have shown that about 50 – 90 % of automobile components service failures are attributed to the process of fatigue [20, 21].

In this study the suitability of using AA1200 aluminum alloy as replacement for the traditional cast iron and steel alloys as connecting rod in light weight automobile application through cumulative work hardening is examined. The fatigue parameters of the strain hardened alloy are consequently determined.

Major Limitations

The limitations of this study include the non-availability of CNC machine that could have produced excellent surface finish devoid of surface scratches on test samples. The presence of surface scratches would normally reduce fatigue life of deformed metal alloy.

The melting process of the aluminum was done under normal atmosphere. A control atmosphere could have ensured a clean melt that would have enhanced the fatigue life as the matrix would be more homogeneous than the one used in this study.

2. Materials and Method

2.1 Material

AA1200 aluminum ingots with chemical composition as shown in Table 1 were melted at 680 0C in an oil-fired furnace and poured into 300×150×20 mm sand mould. Cast samples were machined to 295×120×18 mm and then homogenized for 6 hrs at 480 0C in a muffle furnace before cold rolling. The cold rolling process was carried out in a two high mill with 10, 20, 30, 40 and 50% thickness reductions with 10, 17, 23, 23 and 23 cumulative passes respectively.

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The samples were characterised at 00, 150, 300, 450, 600, 750 and 900 to the rolling direction and final dimensions were taken.

Table 1: Chemical Composition of AA1200 aluminum

Element	Al	Si	Mg	Ti	Pb	Mn	Fe	Sn	Cu	Zn
% comp	99.244	0.183	0.002	0.011	0.005	0.052	0.391	0.015	0.039	0.058

2.2. Methods

The morphologies of samples before fatigue test were done using scanning electron microscope (SEM). Cylindrical shaped samples were mounted on a double-sided carbon tape and firmly placed onto specimen stubs. The stubs were placed into a multiple stage sample holder, which was inserted into the electron microscope for microstructural characterization.

A Field Emission Scanning Electron Microscope (JEOL JSM-7600 F), equipped with Energy Dispersive X-ray Spectrometer (Oxford Instrument X-Max) was used for the characterization. Image acquisition on the SEM was conducted using both secondary electron imaging (SEI) mode and COMPO mode. The accelerating voltage used for the analyses ranged between 10 and 20 kV and the working distance between the objective lens pulpy and the specimen surface was between 8 and 9 mm.

2.3 Fatigue Test

For this test, five identical specimens were used to get data points for the S-N curve.

The fatigue machine clamps the specimen as a cantilever. The load on its free end creates tension on the top half of the specimen and compression on the lower half. However, because it rotates, there is alternate compressive and tensile stress on any given part along the unsupported length of the specimen.
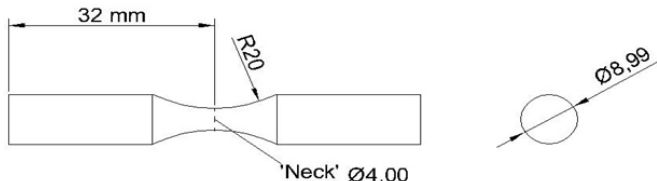

Fig 1. Fatigue test specimen

3. Results and Discussion

3.1 Effect of thickness reduction on thickness ratio

Figure 2 shows ln (to/t) changes with increase in reduction in thickness nearly linearly. The applied force required for thinning is exercised in the thickness direction and this is achieved through the creation of paths for dislocations to move for the reduction needed to be achieved. Since ln (to/t) increases with increase percent thickness reduction, it become convenient to assumed hard precipitates in the path of dislocation are either pushed away in other directions, broken down, made to go into solid solution or form intermetallics with α-aluminum or other solute constituents. The nature, volume and distribution of these dislocation obstacles would determine the ease of reduction and whether the rate of deformation will be uniform or not. On the other hand, it will determine the nature and size of cracks that will be carried over to the service environment.
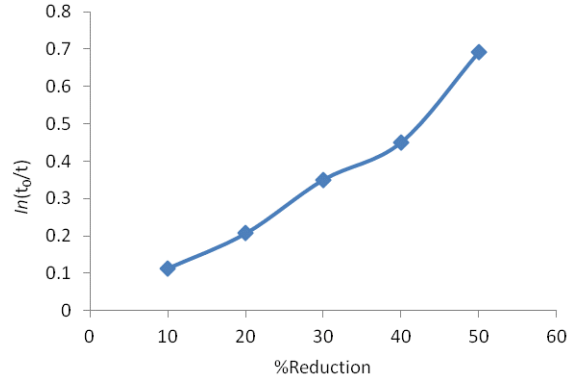

Fig 2. ln (t0/t) of AA1200 Aluminum alloy

3.2 Effect of % thickness reduction on area ratio

The ln(A0/A) varied near linearly with thickness reduction of the Aluminum alloy (Figure 3). This property increases with angular variation from the rolling direction towards the normal direction. The rise in this property is probably related to the increment in dislocations with degree of deformation. In the rolling and 150 directions the area reductions seem similar and minimal compared to higher inclination and oscillate around -1 to 0. The area reduction has peak value (~ 1.5) in normal direction at 50 percent thickness reduction and also revolve around 0.3 and 1.5 for inclination higher than 150. This behaviour may be attributed to increasing microstructural inhomogeneity of matrix as degree of deformation increases. Plastic deformation increases the mobility of solute atoms in aluminum alloys and also promotes clustering at dislocation sites. These clusters act as nucleation sites for subsequent strengthening precipitates [22].
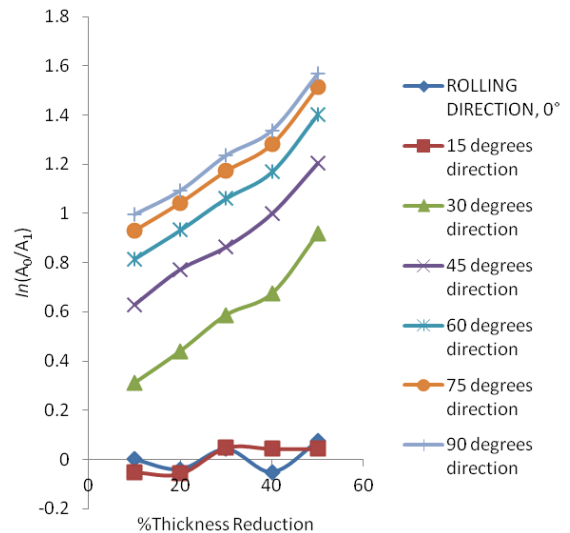

Fig 3. In(A0/A) of AA1200 Aluminum alloy

3.3 Anisotropy of AA1200 Alloy

In Figure 4 the normal anisotropy decreases from maximum at 10% thickness reduction as degree of deformation increases and it is maximum at 10 percent reduction (4) and minimum at 50%(0). The planar anisotropy of the alloy increases with increasing percentage reduction and it lies between -1 and 0. Here, the plane of the alloy experience anisotropy and the width does not increase proportionally. This could be attributed to increase in the number of dislocations as the degree of deformation increases due to increase thickness reduction [23] as dislocations tangling helps to refine grains in work hardening process [10]. Thus, the alloy changes from normal anisotropy to planar anisotropy as defects are produced in alloy matrix.
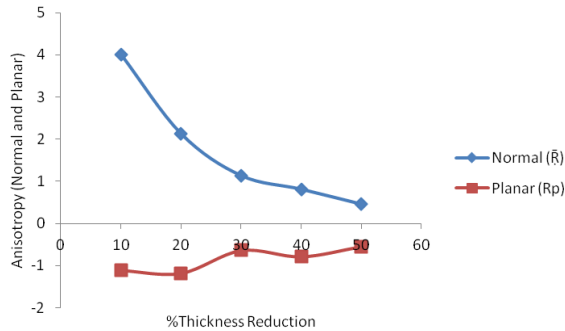

Fig 4. Normal and Planar Anisotropy of AA1200 Aluminum alloy

3.4 Effect of thickness reduction on Plastic strains

The plastic strain decreases as the percentage thickness reduction increases for all inclinations to the rolling direction higher than 150 (Figure 5). The decrease is attributed to the negligible increment in the width direction on one hand and the fact that dislocations, which are produced at defects owing to the reduction taken acts as a hindrance to the expected increment. These hindrances to the motion of dislocations in the length direction increase with degree of deformation [24]. Mobile dislocations enhance plastic deformation and when these are prevented from easy movement, the amount of increment that can be attained in the length direction will decline with percent thickness reduction [24]. Naturally, for constancy of

volume, it is expected that the amount of reduction exerted on the thickness direction should be compensated for by proportional increment in the length at constant width. However, this does not occur as solute solubility in the matrix is affected by deformation and depending on the nature of the precipitated intermetallic. The effect becomes severe with decrease in plastic strain [25-27]. This could lead to early failure as a result of crack development at these hindrances [28, 29] with decreasing plastic strain. The anisotropic state of the material before deformation would also contribute to this decline in plastic strain with deformation.
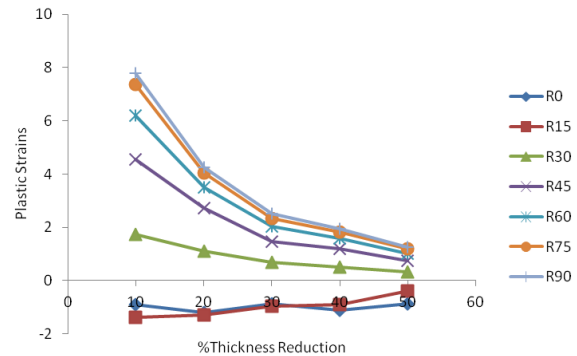

Fig 5. Plastics strain of AA1200 aluminum alloy

3.5 Effects of thickness reduction on Fatigue parameters

In the rolling direction the fatigue life of wrought Aluminum alloy expressed in terms of the number of cycles to failure under fixed load increases with deformation and decline momentarily at 30% reduction before climbing to peak ($269,464 = 2.7 \times 10^5$ cycles) at 40% reduction (Figure 6). Higher reduction at 50% does not produce an increase but a decrease ($109071 = 1.09 \times 10^5$ cycles), which is higher than that at 30% reduction ($43323 = 4.3 \times 10^4$ cycles). The decline in fatigue life at 30% and 50% reductions are attributed to the extensive brittle nature of the matrix (Figure 7). These fatigue results in this work is an improvement over that of Borrego et al. [30] where fatigue life was found to be about 744 and 1030 cycles for alloys 6082-T6 and 6060-T6, respectively.
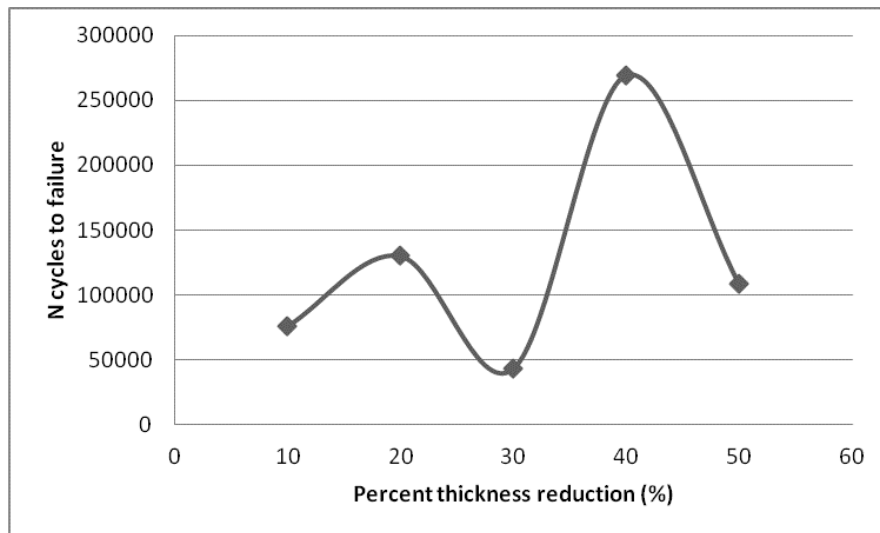

Fig 6. Fatigue life of AA1200 aluminum alloy
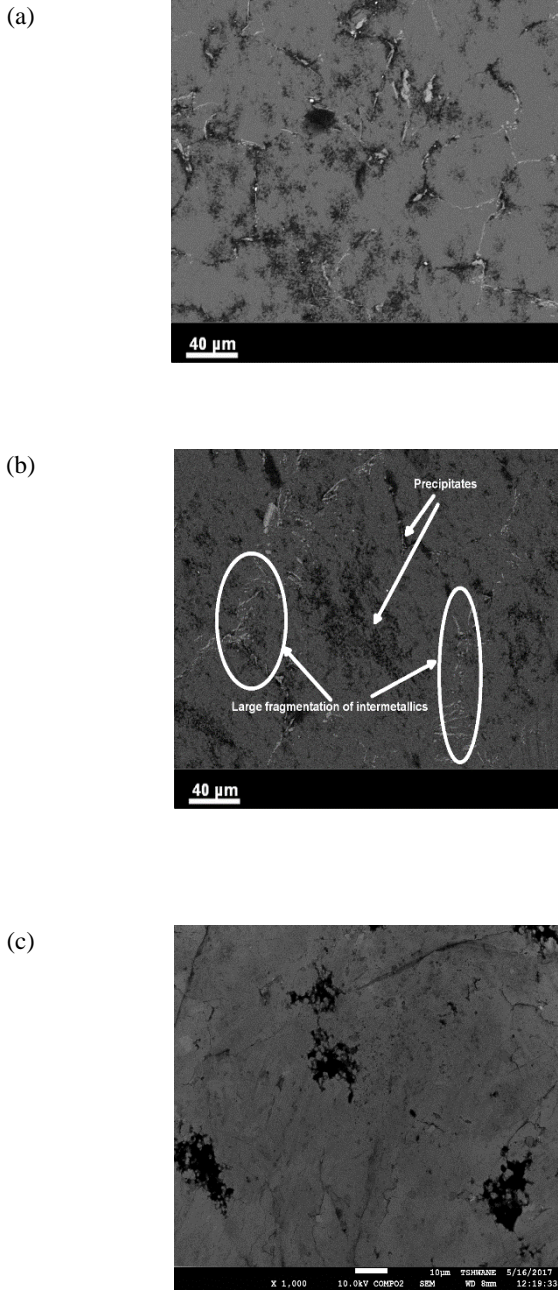
(a)

(b)

(c)

Fig 7. SEM of cold worked AA1200 (a) 30 (b) 40 (c) 50 % thickness reductions

The stress range, which is the difference between maximum and minimum stress in a fatigue test increases with degree of deformation. Although a decline is observed at 20% thickness reduction, however, the relationship is nearly linear (Figure 8). It is known that increase in stress range means decrease in strain range and this implies increase in fatigue life. Fatigue life decreases as the total strain range increases and this occur from the activation of slip system and the increase in plastic deformation that is produced [31]. The cyclic stress response continuously increased as the total stress range increased.
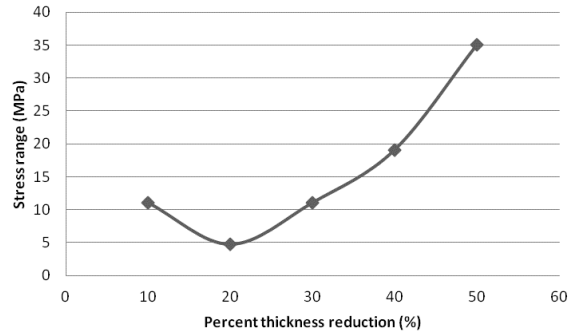

Fig 8. Stress range of AA1200 aluminum alloy

The mean stress increase from ~ 22.5 MPa to 42.5 MPa at 10% and 30% reductions respectively before it declines at higher thickness reductions (Figure 9). Thus, the effects of mean stress are important, as an increase in mean stress will produce decrease in component fatigue life [32].

The stress ratio, which is the ratio of minimum stress to maximum stress increase early from 0.6 to 0.9 at 10% and 30% reductions respectively. Above 20% reduction this fatigue parameter increases (Figure 10). Apart from the behaviour at 10% reduction, the stress ratio decreases with degree of deformation. As deformation reduction progresses, defects and cracks are presumed to increase with increase in dislocation density. The growth of fatigue crack, thus, depends on the stress ratio and the stress amplitude. Increase in stress ratio will accelerates crack growth rate, while its decrease reduces the rate (Saeed, [33]. $R = -1$ and $R = 0$ are two reference test conditions usually used to obtain fatigue properties. When $R = -1$, it is the fully reversed condition as $\sigma min = -\sigma max$; $R = 0$, where $\sigma min = 0$, is called pulsating tension.
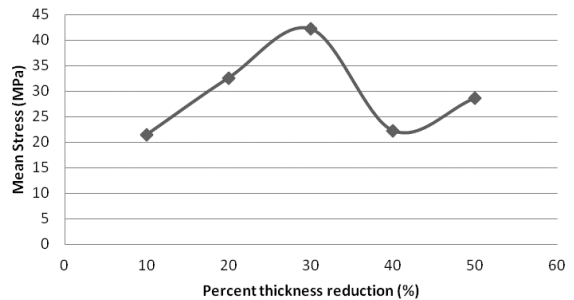

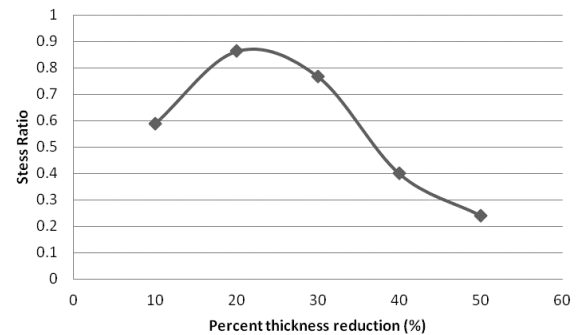**Fig 9.** Mean Stress of AA1200 aluminum alloy

Fig 10. Stress Ratio of AA1200 aluminum alloy

The stress amplitude bears some resemblance in pattern of relation with degree of deformation as the stress range. An initial decline occurs at 20% reduction but it increases nearly linear as the

degree of deformation with maximum (18 MPa) attained at 50% reduction (Figure 11). The fatigue life is established to decrease with decreasing stress amplitude [34]. Thus, the fatigue life as obtained in this study increases with deformation percent reduction taken for this low fatigue cycle process.

The alternating stress –thickness reduction relationship is similar also to stress range with peak value (0.6) at 50% reduction (Figure 12). Thus, the fatigue life of cold rolled AA1200 aluminum alloy increases as the alternating stress. The results of alternating stress obtained in this study increase with degree of deformation. Hence, the extent of prior deformation on the aluminum alloy directly correlates with the expected fatigue life of the components in service under low stress cycle.
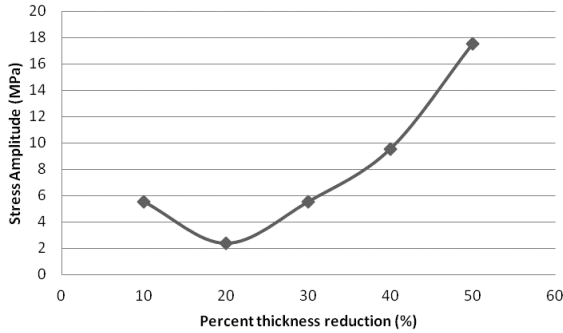
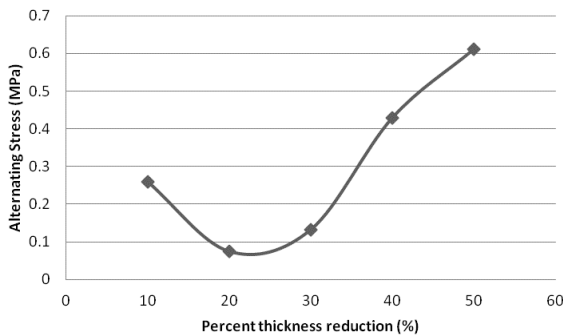**Fig 11.** Stress Amplitude of AA1200 aluminum alloy

Fig 12. Alternating Stress of AA1200 aluminum alloy

With increase in applied fatigue stress, the fatigue life decreases owing to crack growth and propagation. At low fatigue stress, the fatigue life is higher and the growth and propagation of crack rates are slow [35].

4. Conclusion

The study on the fatigue responses of cold rolled AA1200 aluminum alloy has been carried out. The results have shown that degree of deformation can produce fine crystals with ability to promote the fatigue characteristics of the alloy. In this work the mean stress decline at 40% reduction at which the fatigue life was peak. The growth of fatigue crack thus depends on the stress ratio and the stress amplitude. Generally, the stress ratio decreases as degree of deformation and this agrees with literature as increase in stress ratio will accelerates crack growth rate, while its decrease reduces the rate. As deformation reduction progresses defects and cracks are increased with increase in dislocation density. Increase in stress range as obtained in this study corresponds to decrease in strain range and this produced increase in fatigue life.

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