ISSN: 2581-3404 (Online) IF: 5.445 (SJIF)
International Journal of Innovative Research in Technology and Management, Volume-6, Issue-3, 2022.

Fatigue and Fractography Analysis of Artificially Age-hardened Al2016 High strength Aluminium Alloy

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Abstract: *Objectives of this experimental work are to determine the fatigue strength and to examine the fatigue fractured surface of the broken specimens of the Al2016-T6 alloy. Twin rolled Al-Cu alloy was received as cylindrical bar after the artificial aging under T6 condition. Specimens were prepared according to ASTM E606 standard and subjected to fatigue testing. Fatigue tests were conducted under the stress amplitude with an upper range of 250 MPa to a lower bound to fix the fatigue limit. SEM images were taken for the broken specimens where a high-cycle fatigue broken specimen images were chosen and investigated to understand its fracture, origin of fracture, surface morphology of fractured surface and the mechanism of failure.*

Keywords: Al2016**,** T6, Al-Cu alloy**,** fatigue strength, Fractography, Fracture mechanism, SEM.

Introduction

Aluminium alloys have been the primary aircraft elements and began to replace wood after the 1920s. Aluminium is appealing because of its lower cost, and lighter weight and that could be hardened enough to greater strengths it's one of the simply processed the superior performed materials, which generally equates to cheaper prices [1]. Although the usage of composite materials is likely to reduce the importance of aluminium in forthcoming aerospace vehicles where high-strength aluminium alloys will continue to stay as key aerospace materials. Modern aerospace manufacturers are looking for two forms of assistance from their suppliers. On one hand, there are substantial cost-cutting efforts underway on established airplane models that need the development of modern material options. At the same time, technological innovations and upgraded materials are required to meet the demand for massive transport services in the twenty-first century [2]. Al2016 high-strength aluminium alloy is one such innovative, effective material where the composition of elements and various age-hardening treatments provide distinct properties.

In the aerospace sector, one important part of the cost-cutting plan is the replacement of assemblages and architectural features with integral or monolith frameworks. An assemblage is often made up of a series of preformed sheets and extruded or machined elements that are fastened temporally or joined permanently. Each material possesses distinct properties which result in its own merits and limitations. It's usually a critical task to choose the proper material for a mechanical system. Especially, the design and selection of optimized materials for the individual component of a mechanical assembly needs a deep understanding of the characteristics of the materials. The characteristics of materials could be usually adjusted to the expected product usage by modifying their physicochemical and altering the treatment. Moreover, the needs imposed on a part cannot be met by a specific material for plenty of applications, but instead, need a materials process in which various sections of the solution perform distinct jobs.

Al2016 may be the better alternative due to the better composition of elements, especially Ag and Mg. To explore the unique properties of Al2016, it's necessary to treat this alloy at various temperatures and duration including artificial and over-aging conditions [3]. T3 to T8 age-hardening conditions would provide a better result on mechanical properties, and significantly damage tolerances. Fatigue is one of the notable modes of failure where fatigue refers to the deterioration or fracture as a consequence of extended cyclic stress. If an object is continuously loaded cyclically at a particular region of the material, a crack initiates to build and tends to develop. Those fissures gradually grow large to cause failure and finally fracture the component at the site. Therefore, it is essential to understand the fatigue limits of the material once involved in designing a mechanical working model.

Fracture in engineering alloys can occur by a transgranular or an intergranular fracture path. Nevertheless, apart from the fracture path, some other mechanisms of fracture are also involved in the failure [4]. Dimple rupture is one of the fracture modes which is about microvoid development and accumulation along with the metal's granular interface. Another type of metal failure is decohesive rupture which happens along weak material surfaces in a reactionary situation. Cleavage is a sort of crystalline failure, that's linked to brittle fractures with poor energy [4, 5]. All these modes have the characteristics of surface failure aspects with their own procedural way to proceed through the mean the fracture spreads.

Fracture modes are often based on dislocation interactions, involving complex slip and crystallographic relationships. Fracture normally occurs in two stages; nucleation of the crack and propagation of the crack. The micro mechanism of ductile fracture, that is, the initiation, growth, and coalescence of microvoids, has been confirmed, and correlations between void (dimple) size/shape and stress state and material cleanliness have been developed [6]. In the low cycle fatigue dominion, collective microstructural modifications occur in the form of firm slip bands, reordering of dislocation set-up into cell formation, nucleation of microvoids, and its expansion appearing in secondary phase inclusions [7,8]. The latter process is associated with high strain amplitudes, which are typically associated with very short lives. Irrespective of the stress amplitude levels, prior detection of cracks is critical for keeping the structure from failing. Conclusive experimental testing proof on initiation mechanisms of fatigue failures have also been obtained from electron fractography studies.

II. Materials and Methods

A. Materials

Table 1: Nominal Proposition of Al2016

Cu	Mg	Si	Ag	Mn	Ti
4.129	0.616	0.519	0.451	0.185	0.142
Zr	Fe	Zn	Cr	Ni	Others
0.141	0.092	0.027	0.009	0.005	0.05

Table 1 reports the nominal proposition of twin rolled Al2016 aluminium alloy after undergoing artificial age hardening at T6 condition. Solution treatment of 170 °C for 24 hours, followed by the stretching of 3 % was done over this Al alloy. According to ASTM standards, this alloy is designated as Al2016-T6510 Al alloy.

B. Specimen preparation for fatigue test:

Twin-rolled age-hardened Al2016 cylindrical bar of 70 mm diameter was taken and sliced into rectangular pieces. Fig. 1 indicates the dimensions of the specimen, prepared for conducting the fatigue test. According to the ASTM E606 standard, ten specimens were finely machined on an LMW-Smart

Turn CNC lathe [9]; followed that mechanical polishing was done over the circumference of 6 mm diameter for further fine finishing. Specimens were mounted on a desktop lathe and ground manually by using silicon carbide sheets. Range of 20 to 70 microns materials was removed and eventually achieved uniform diameter and a better surface finishing [10].

Then the specimen was immersed in a temperature-controlled bath of sulphuric acid and phosphoric acid mixtures of electrolyte. The specimen served as the anode as it was joined with DC power supply (positive terminal). The negative terminal-point was joined to the copper, cathode. A current passed from the anode, where oxidizing was done on the metal surface. And, it was suspended in the electrolyte solution towards cathode. Followed by, hydrogen was produced after the occurring of reduction reaction at the cathode. This electrolytic polished the specimens were then mounted one the machine for fatigue test. Fatigue tests were conducted in rotating-bending testing machine.

The result of ultimate tensile load was applied to calculate the stress amplitude [3]. Based on the motor spindle ratio and appropriate balancing of the scale of the machine, proper mounting of the specimen was accomplished. A designated mean load, zero and alternating load were employed over the specimens. At the end of the testing, the number of cycles taken for failure was recorded.

Test was continued with identical specimens with distinct cyclic loads. Depending on magnitude of mean and fluctuating stresses, net stress in the specimen probably either on the direction of loading cycle, or in reverse.
S-N diagram was plot based on the counts of the cycles at the time of fracture of the material towards the magnitude of periodic-stress applied, refer to Fig. 1. The test was carried out until the specimen was broken or achieved $1x10^7$ cycles.

C. Specimen preparation for Fractography through Scanning Electron Microscopy

Broken specimens were collected with high care after the fatigue testing in rotating-bending testing machine. Followed by ultrasonic cleaning had been done for five minutes. One side of the individual specimen was screwed in the holder and inserted into the sample chamber of scanning electron microscope. Required images were captured at different magnifications such as 10X, 50X, 100X, 200X, 500X, 1000X and 2000X at different positions for further analysis.

III. Result & Discussion

The following section discusses the results of fatigue strength determined through Wohler's curve and fractographic analysis of the high fatigue cycle of a broken specimen.

A. Determination of Fatigue Strength

Fatigue strength (Sf) of the given alloy was determined by applying the method of endurance limit and Wohler's curve. The ultimate tensile strength of the Al2016-T6 Al alloy was found as 552 MPa [3]. To initiate the experiment on fatigue strength, the endurance limit for the aluminium alloy is approximately considered as 0.4 times the ultimate tensile strength. Hence, the test is initiated from a load of 250 MPa.

Table 2: Nominal Proposition of Al2016

Specimens	1	2	3	4
Stress Amplitude (MPa)	250	240	230	230
Cycles (Nos.)	$2.35x 10^5$	$2.61x 10^5$	$1.37x 10^7$	$8.67x 10^5$

Specimens	5	6	7	8 and 9
Stress Amplitude (MPa)	220	210	210	190
Cycles (Nos.)	$9.93x 10^6$	$1.3x10^7$	$1.01x 10^6$	$1.35x 10^7$

Table 2 indicates the various stress amplitudes involved in the testing, which was conducted until one million cycles (1x107) of running were attained without breaking for two specimens consecutively.

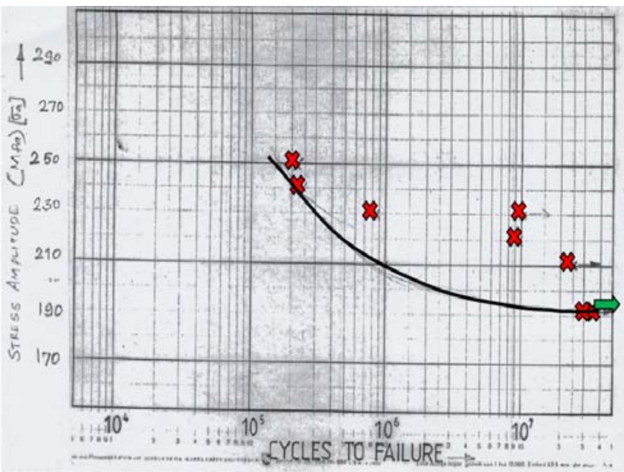

Fig 1: S-N curve of Al2016-T6 Fatigue Tested Specimens.

Specimens 3 and 6 achieved one million cycles with the stress amplitude of 230 and 210 MPa respectively. At the same time, the second specimens with the same respective stress amplitudes of 230 MPa and 210 MPa failed to reach the target of one million cycles: refer to Table 02 on specimens 4 and 7. The specimens numbered 8 and 9 only completed one million cycles consecutively for the stress load of 190 MPa. Hence the fatigue strength of Al2016-T6 was determined as 190MPa.

B. Fatigue Fractography of Al2016-T6

When analyzing the fractography, sample number 7 would be highly suitable for disclosing more on fracture. Fig. 2 shows the SEM fractography of a semi-elliptic fatigue crack on one side of the shaft where the fatigue region looks smoother than the fast fracture zone and may also be in a lighter shade of grey, as seen in the same region of the picture; On top of this specimen, the band-like projections are the fatigue cracks. Fig. 2 and Fig. 3 show macroscopic views and microscopic views of Al2016-T6 conditioned fatigue-tested specimens. Fractured specimens indicated a series of radiating ridges on the failure surface, which can be traced along the direction in which those converge to identify the area of the failure origin.

In such regions, the darker portion represents the initiation of fatigue and slower crack growth before final failure in a single cyclic loading or a few. Moreover, it indicates the beach marks. Such marks are the general aspects of the fatigue failure portions. Concentric rings on the broken portions of the fatigue portions are caused by changes in the crack growth mechanism. Ratchet marks are usually present at the surface of components where a high local stress concentration is presented. These Ratchet marks would be smeared or gently rubbed due to the mutual motion of two sides of the failure surface at the time of cyclic loading. Such rachet marks emphasized the multiple crack initiation areas of distinct glides of the material. In practical, the expansion of cracks, development of tear ridges and shear mechanism are at one point of time connected each other and formed the multiple crack initiation areas.

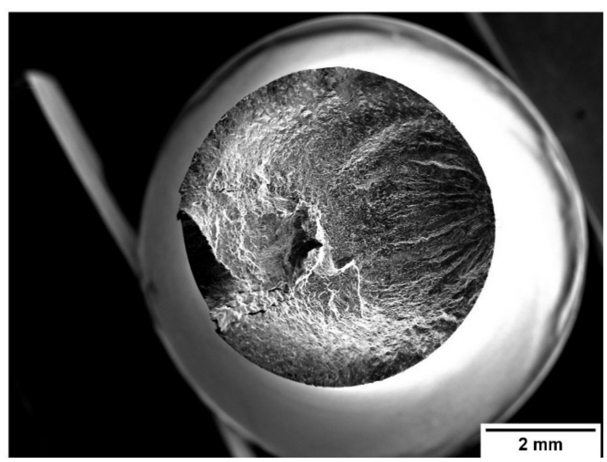

Fig 2: Al2016-T6510 - Fatigue tested broken specimen of high fatigue cycle, at magnification of 10X.

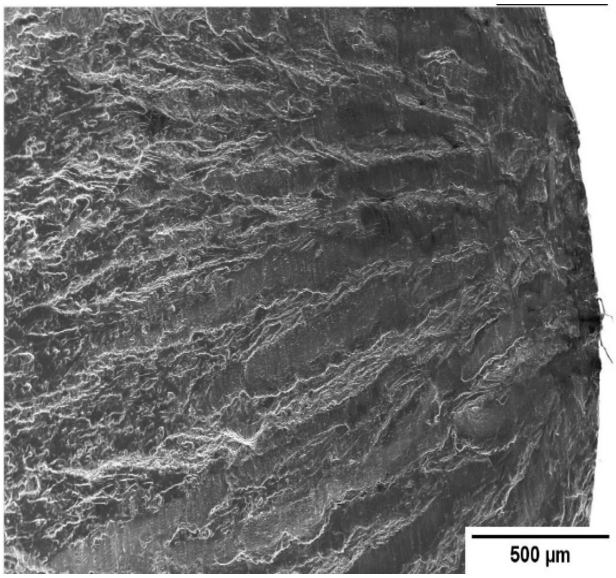

Fig 3: Al2016-T6510 - Fatigue tested broken specimen of high fatigue cycle, at magnification of 50X.

A ratchet mark indicating the boundary between two adjacent failure planes has been added [11]. It has been seen that there are two crack origins, and the ratchet mark is between them. Fig. 4 and 5 indicate the same in a better way.

The existences of rachet marks convey the involvement of numerous root sources and comparatively greater cumulative stresses. Either high-stress concentrations or massive stresses acting on the component would cause for the ratchet marks. Nevertheless, the primary reason of the failure is decided by either applied load or stress concentration. It can be concluded after analyzing the dimensions of the instantaneous region and the ratchet marks. For instance, the mixture of numerous rachet marks and limited-overload region expressed that the acted load was minor in magnitude, at the same time its stress concentration would be high. Moreover, the contribution of torsional loads in failure can be identified by investigating the corners of the ratchet marks.

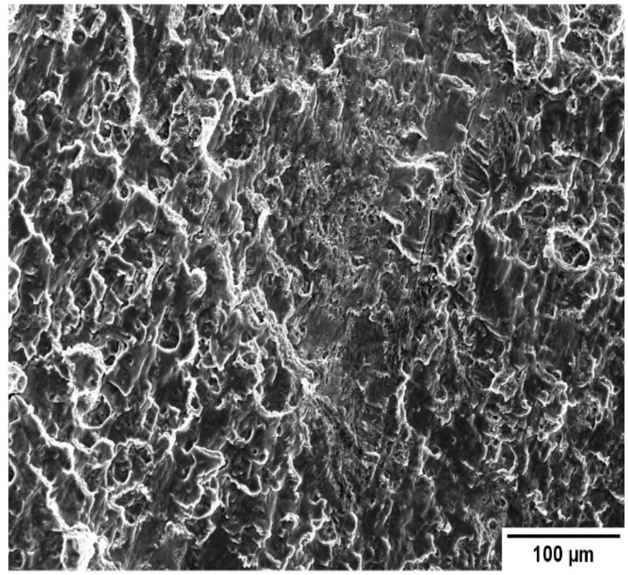

Fig 4: Al2016-T6510 - Fatigue tested broken specimen of high fatigue cycle, at magnification of 100X.

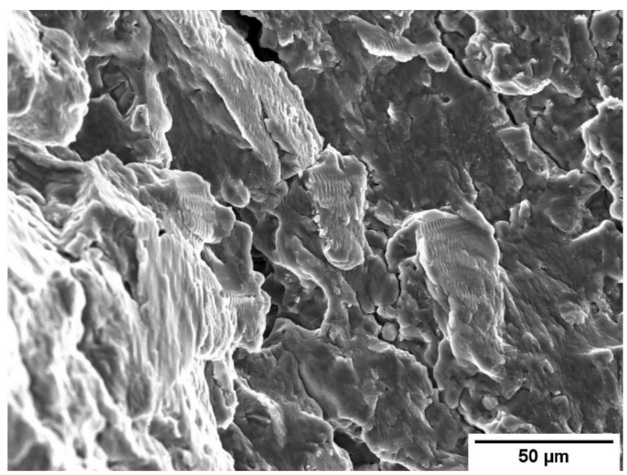

Fig 5: Al2016-T6510 - Fatigue tested broken specimen of high fatigue cycle, at magnification of 500X.

With fractures that have multiple origins, analysis of the angles of the ratchet marks in the fracture plane can usually be used to determine which of the origins, was the primary origin. It can be seen that the two ratchet marks present in the middle are slightly closer to the surface, indicating the failure began between them. Rapid fracture is commonly rougher than the breakages due to fatigue and there are more chances for identifying the witness of ridges. These ridges show the borders in which the distinct planes in the failure faces met up [12, 13].

The ridges on the failure face can be used to locate the crack initiative zones, as indicated. It is also true that striation-like markings are produced by corresponding motion between fracture surfaces when applying repeated loading [14]. Whilst such marks are due to crack extension, probably by fatigue crack growth, the mechanism of formation requires the presence of hard inclusions and a combined mode of tension or shears in orientation of crack growth or shear, normal to the orientation of crack growth loading and tension [15].

Striations may vary in appearance according to alloy type and environmental conditions. In the unstable crack propagation region, Al2016 emphasized the distinctive aspects of ductile failure, produced by nucleation of dimples primarily from the coarser intermetallic particles broke in the brittle way. Within the regions, dimples of far smaller sizes were rarely visible, lying on well-defined planes. These can be correlated with the existing fine particles that in some cases were observed inside the dimples in high magnification images that suggest ductile intergranular fracture.

IV. Conclusion

By applying the Wohler’s curve method, the fatigue strength of the Al2016-T6 graded alloy was determined to be 190 MPa; at which two consecutive specimens had completed a million cycles in an unbroken nature. The SEM images of one high fatigue cycle specimen indicated the nature of the fracture at the stage of breaking.

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