Journal of Engineering Science and Technology
Vol. 10, No. 6 (2015) 730 - 742
© School of Engineering, Taylor's University

INFLUENCE OF HEAT TREATMENT ON FATIGUE AND FRACTURE BEHAVIOR OF ALUMINIUM ALLOY

M. F. I. A. IMAM[1,]*, M. S. RAHMAN[1], M. Z. H. KHAN[2]

[1]Department of Mechanical Engineering, Rajshahi University of
Engineering & Technology, Rajshahi, Bangladesh
[2]Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku
University, Sendai 980-8577, Japan
*Corresponding Author: forhadibne@gmail.com

Abstract

Fatigue failures of various types are key concern in increasing the reliability of products. In this study heat treatment of the aluminium alloy substrate was carried out at three different temperatures 420°C, 460°C, and 500°C. The effects of heat treatment on the fatigue life and fatigue strength were studied. The fatigue life of Aluminium alloys specimens was improved significantly compared to those of non-treated specimens. It was revealed that after proposed heat treatment, the initiation of fatigue cracks is likely to be retarded by specimen surface since fatigue cracks have been observed to form first at the surface and subsequently to propagate towards.

Keywords: Aluminium alloy, Heat treatment, Fatigue and fracture, Microstructure.

1. Introduction

All materials have different properties that result in advantages and disadvantages. Study and understanding of these properties is critical to the design of a mechanical system and the selection of the correct materials for a given part. One crucial failure mode is fatigue. Fatigue is the weakening or failure of a material resulting from prolonged stress. However, it is understood that when a mass is repeatedly cyclically loaded at a location on the material, cracks begin to form. These cracks spread enough to eventually cause failure and break the piece at the location. Consequently, when designing a mechanical system, it is important to know these limits.

Nomenclatures

HR	Average hardness number
K	Kappa single phase region
N	Number of cycle

Greek Symbols

θ	Theta phase
σ	Fatigue strength, MPa

Abbreviations

ASTM	American Society for Testing and Materials
BSI	British Standards Institution
LCF	Low Cycle Fatigue
OES	Optical Emission Spectroscopy

Aluminum alloys have been long used for aircraft construction since the 1930s. The aerospace industry relies heavily on 2xxx and 7xxx aluminum alloys, while a wide variety of aluminum alloys are now used by the automotive industry. Currently, the automotive industry shows an increasing interest in aluminum alloys as structural materials. 6xxx aluminum alloys are of particular interest for both the aerospace industry (for fuselage skins and other applications) and the automotive industry (for body panels and bumpers) because of their attractive combinations of properties such as low weight, good strength, formability, weld ability, corrosion resistance and low cost.

Fatigue tests are widely used to characterize the behavior of materials, though they tend to be more used for sample testing of uniform material. To determine the fatigue tendency of welded joints, the study and control of the tests is more complex, as welded joints present microstructures variations over small distances, not to mention complex distributions of residual stresses. A more detailed study of the fatigue behavior of welded joints is necessary as it provides data for determining the resistance of structures [1].

At the moment, fatigue and fracture tests are undertaken in accordance with standards and codes devised by different institutions such as the American Society for Testing and Materials (ASTM) and the British Standards Institution (BSI). To carry out these tests on non-uniform materials, various techniques and recommendations were suggested for preparing and evaluating the results. In all cases, welding is the primary joining method and fatigue is a major design criterion. However, as is well known, welded joints can exhibit poor fatigue properties. Thus, clear design guidelines are needed to ensure that fatigue failures can be avoided in welded aluminum alloy structures. Apart from basic design of new structures, there is also increasing interest in methods for assessing the remaining lives of existing structures [2].

Not only could catastrophic fatigue failure cause a large loss in money due to a poor design but it could result in a loss of lives as well. Critical examples of fatigue failure range from train axles to wing cracking on airplanes [3]. The damage evolution mechanism is one of the important focuses of fatigue behavior investigation of composite materials and also is the foundation to predict fatigue life of composite structures for engineering applications [4]. The cyclic stress -

strain path are dependent on the material microstructure [5]. Fatigue cracks frequently initiated from intensively stress concentration regions, increasing volume fraction and particulate sizes result in early crack initiation [6]. Aging resulted in the formation of second phase with associated reduction in the toughness and Low Cycle Fatigue (LCF) lives of the alloy [7]. Fatigue life was found to decrease with increase in the duration of hold time in both tension and compression and it is increased and decreased according the type of heat treatments [8, 9].

Alloying can increase the strength; hardness; electrical and thermal conductivities; corrosion resistance or change the colour of a metal. The addition of a substance to improve one property may have unintended effects on other properties e.g. the best way to increase the electrical and thermal conductivity of copper is to decrease the impurity levels [10-12]. Cyclic fatigue involves the microstructural damage and failure of materials under cyclically varying loads. Structural materials, however, are rarely designed with compositions and microstructures optimized for fatigue resistance. Metallic alloys are generally designed for strength, intermetallic for ductility, and ceramics for toughness; yet, if any of these materials see engineering service, their structural integrity is often limited by their mechanical performance under cyclic, loads [13-16].

Santana et al. [17], were investigated the dynamic response of fatigue damaged 6061-T6 aluminum alloy and AISI 4140T steel specimens under high cycle fatigue and low cycle fatigue. The analysis results show an increase in the ductility of the aluminum alloy when increasing the fatigue damage level. While Ding et al. [18] studied the fatigue behavior of AA6061 as a composite material.

The aim of this study was to observe the influence of heat treatment on tensile strength, hardness and fatigue strength of aluminium alloy. We compared the mechanical properties at different solution heat treatment temperatures. It was also aimed to observe the fatigue failure behavior of the specimens at different temperatures. Moreover we did compare all results with non-heat-treated specimens.

2. Materials and Method

The raw material used in this study was Aluminium alloy. The chemical composition of Aluminium alloy was tested by using an Optical Emission Spectroscopy (OES) of ARL 3460 model at BCSIR, Dhaka, Bangladesh.

The sample preparation was homogeneous. The sample was a flat solid metal with a minimum dimension of 1.5 cm × 1.5 cm × 0.5 cm and mirror polished. For smaller size sample was mounted. From Fig. 1 it can be seen that the maximum solubility of copper in Aluminium is 5.65 percent at 548°C and the solubility decreases to 0.45 percent at 300°C. Therefore alloys containing between 2.5 and 5 percent copper will respond to heat treatment by age hardening.

The theta phase (θ) is an intermediate alloy phase whose composition corresponds closely to the compound $CuAl_2$. Solution treatment was carried out by heating the alloy into the kappa (K) single phase region followed by rapid cooling. Subsequent aging, either artificially, will allow precipitation of theta phase, thus increasing the strength of the alloy. Ageing was carried out at 165°C. Ageing may be carried out at room temperature or at elevated temperature of the order of (149-204°C).

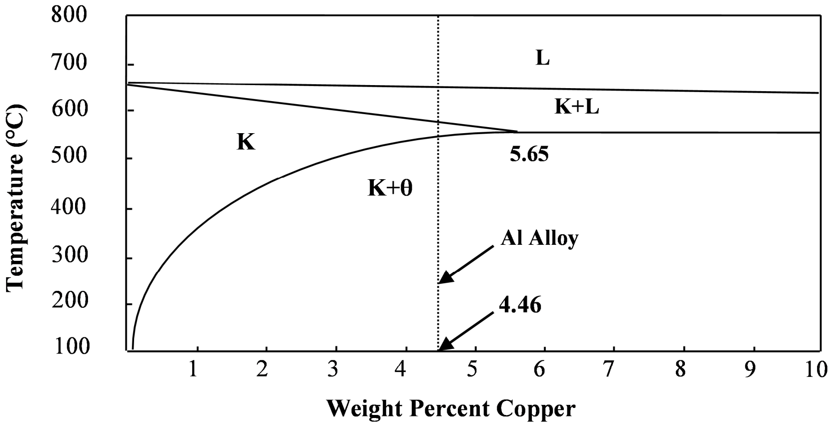

Fig. 1. Aluminium Rich Portion of the Copper Aluminium Alloy System.

A muffle furnace was used for solution heat treatment and age hardening. Temperature control devices were on it. An automatic temperature control light indicates perfect temperature range. The temperature was raised to 420°C or 460°C or 500°C. The solution heat treatment was done by keeping sample in furnace for an hour and quenched (rapidly cooled) to room temperature in water. Aging treatment was carried out at 165°C for 6 hours.

Fatigue strength, tensile strength and hardness of the specimens were tested using different machines by following the standard test procedure. The analysis of the fatigue fracture surface with fatigue initiation point before and after heat treatment was carried out by a metallurgical microscope MM-017CC (input 230 V-50 Hz, bulb type 6 V-20 W, fuse 250 V- 0.5 A) the operating camera views picture with a monitor linkage with the microscope. The observation focusing powerx20 was used for the observation.

3. Results and Discussion

In this section results of experimental investigation on aluminium alloy have shown in details for different conditions. The impact of solution heat treatment and age hardening of Aluminium alloy on fatigue strength, tensile strength, hardness and fatigue initiation point on fracture surface were presented by different graphical representations. The fracture behavior of the specimens has also discussed.

3.1. Fatigue strength of aluminium alloy

In cycle fatigue situations, materials performance was commonly characterized by an σ-N curve. This was a graph of the magnitude of a cyclic stress (σ) against the logarithmic scale of cycles to failure (N). σ-N curves were derived from tests on samples of the material to be characterized where a regular sinusoidal stress was applied by a testing machine which also counts the number of cycles to failure. The significance of the fatigue limit was that if the material was loaded below this stress, then it will not fail, regardless of the number of times it was loaded. Fatigue life is the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs and fatigue strength, as the maximum stress that a material can endure for a given number of stress cycles without breaking [17]. The fatigue strength with number of cycles for aluminium alloy was shown in Fig. 2. It was found that the fatigue strength decrease with increase the number of cycle for aluminium alloy and heat treated aluminium alloy.

Figure 2 shows the comparison of fatigue strength of aluminium alloys at different number of cycles with and without solution heat treatment. In this test solution heat treatments were done at 420°C, 460°C and 500°C for 1 hr followed by age hardening at 165°C for 6 hrs. Those three curves were compared with a curve which represents the fatigue strength of aluminium alloy without any heat treatment. Fatigue strength increased by increasing the solution treatment temperature because the solubility of copper in aluminium was maximum at high temperature. Solution heat treatment at 420°C, 460°C, 500°C for 1hr, followed by aging at 165°C for 6 hrs, the number of cycles were increase to 44% ,55%, 64% respectively compare with without heat treatment aluminium alloy. This improvement may be related to be stopped the crack propagation by microstructure barriers produced by applied heat treatment [18].

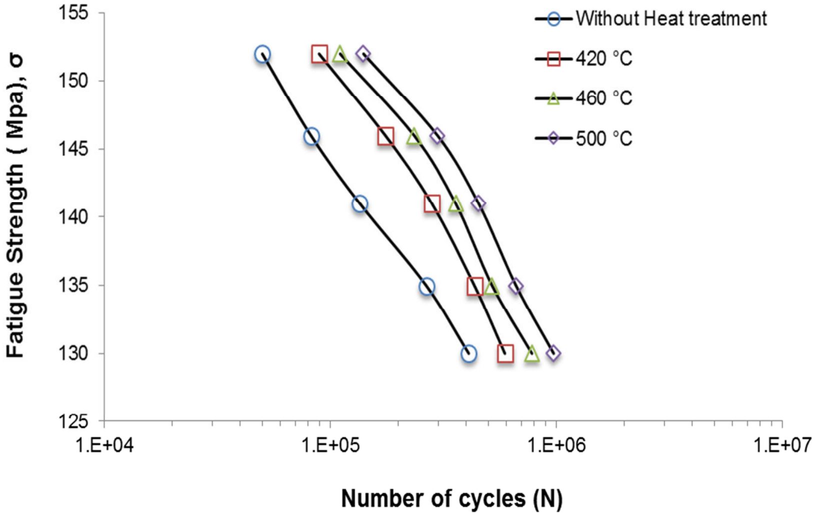

Fig. 2. Comparison of Fatigue Strength with Number of Cycles for Al Alloys Solution Heat Treated at 420°C, 460°C and 500°C for 1 hr and Age Hardened at 165°C for 6 hrs.

The result of solution heat treatment at 600°C for 1hr and age hardened at 165°C for 6 hrs on the Aluminium alloy specimen were shown in Fig. 3. The specimen was reached a temperature beyond its melting temperature (560°C) during the heat treatment at 600°C. As a result it has shown very low fatigue failure resistance compared to all other specimens.

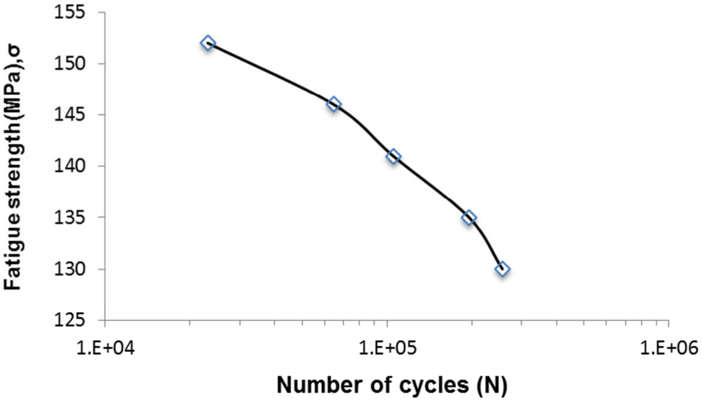

Fig. 3. Variation of Fatigue Strength with Number of Cycles for Al Alloys at Solution Heat Treated at 600°C for 1 hr and age Hardened at 165°C for 6 hrs.

3.2. Tensile strength of aluminium alloy

The relationship between the stress and strain that a particular material displays was known as that material's Stress-Strain curve. It was unique for each material and was found by recording the amount of deformation (strain) at distinct intervals of tensile loading (stress). These curves reveal many of the properties of a material. Stress-strain curves of various materials vary widely and different tensile tests conducted on the same material yield different results, depending upon the temperature of the specimen [17]. Stress-strain curves were an extremely important graphical measure of a material’s mechanical properties, Perhaps the most important test of a material’s mechanical response was the tensile test, in which one end of a rod specimen is clamped in a loading frame and the other subjected to a controlled displacement. The maximum tensile load divided by the original cross-sectional area was called the ultimate tensile strength, or just the tensile strength, of the material [17]. At the maximum load the deformation of most metal specimens becomes localized in the form of an abrupt reduction in cross section along a small length in the gage section.

With the increasing of the solution heat treatment temperature tensile strength increases, where strain decreases with temperature rise. Figure 4 shows the relative curves for tensile strength testing of aluminium alloys with and without heat treatment. This strength increases like fatigue strength due to precipitation of copper in aluminium alloy structure with the increasing of solution heat treatment temperature. When after solution treatment and quenching, the alloy was in supersaturated condition, with copper atoms distributed at random in the lattice structure. During aging the excess copper atoms tend to migrate to transitional plane. It was this distortion that interferes with movement of dislocation and account for the rapid increase in strength [19].

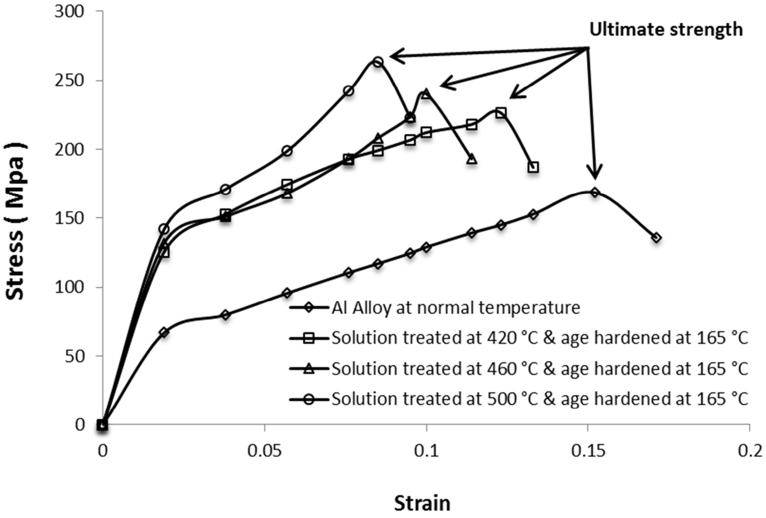

Fig. 4. Comparison of Tensile Strength of Al Alloy Heat Treated at Different Temperatures.

Figure 5 shows that the dependence of ultimate strength, when cycles of microstructure was held constant, can relate to the temperature dependence of tensile strength. Fatigue strength increase with increase tensile strength when the heat treatment temperature was rises. It was observed that the increase of ultimate strength was sharply up to at a point of 136 MPa but it becomes slower after that next point, even the cycles increases up to last point.

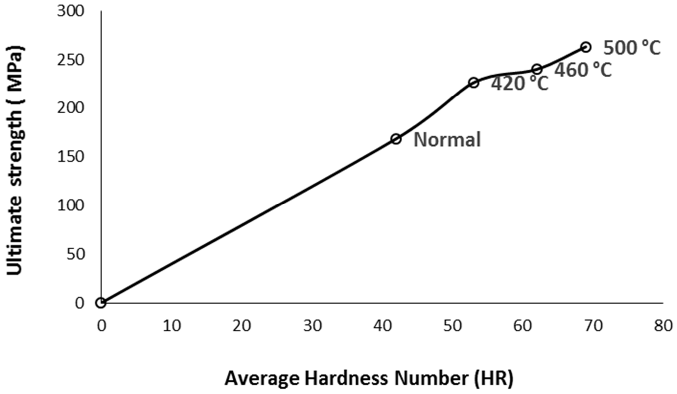

Fig. 5. Relation between Average Hardness at Fixed Cycles and Ultimate Strength of Aluminium Alloy Heated at Different Temperature.

3.3. Hardness of aluminium alloy

Rockwell hardness testing was that the indenters and the loads were smaller and therefore the resulting indentation on the specimen is smaller and shallower. This test was faster because diameter of indentation need not be measured; the Rockwell machine gives arbitrary direct reading. It needs no surface preparation of the specimen whose hardness is to be measure.

Comparison of hardness of aluminium alloys before and after heat treatment shown in the Fig. 6. After solution heat treatment a supersaturated solid solution of copper induced in aluminium. In the aging, $CuAl_2$ dominant precipitation than the other types of precipitates. As a result hardness increases with the increasing of solution heat treatment temperature. This precipitation was same in all case considered, but the densities of the phase in the structure change depending on aging treatment.

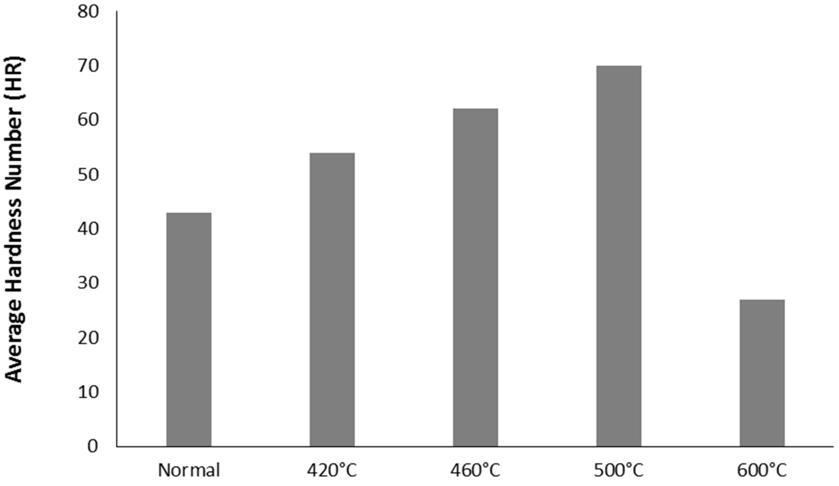

Fig. 6. Comparison of Hardness of Al Alloy Heat Treated at Different Temperature.

In case of aluminium alloy solution heat treated at 600°C, for 1 hr and age hardened at 165°C for 6 hrs. The Average hardness number was 27.Because equilibrium phase was formed with its own lattice structure. This causes a loss of coherency and less distortion. The hardness was decrease and the alloy was over aged.

Figure 7 shows a relationship between the ultimate strength and average hardness number of aluminium alloy for the heat treatment at different temperatures (420°C, 460°C and 500°C). This curve is commonly showing an increasing trend of both co-ordinates with the increasing of heat treatment temperature, where only difference at 420°C. At this point with the increasing of average hardness the ultimate strength was increased very slowly up to 460°C. After 460°C both sides was increased again at the same quick pattern.

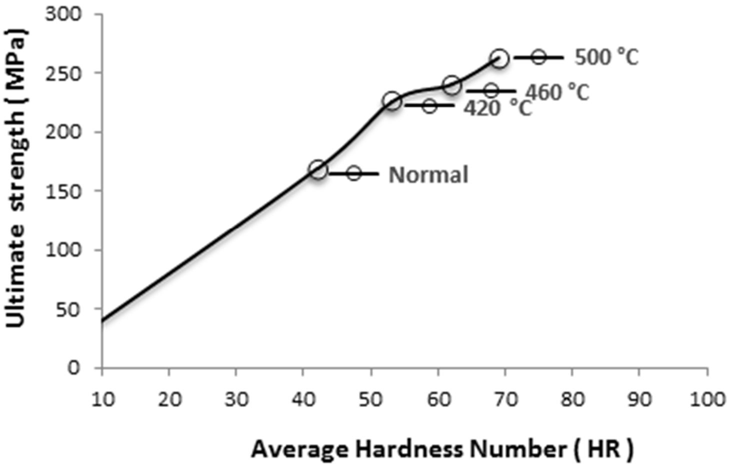

Fig. 7. Relation between Ultimate Strength and Average Hardness Number of Al Alloy Heat Treated at Different Temperature.

3.4. Fatigue fracture and crack initiation of aluminium alloy

The metallurgical microscope observation was mainly focused on the determination of the fatigue crack initiation sites, the occurrence of heat treatment during cyclic loading and the role of the heat treatment during the propagation of the cracks. Therefore, the observations required were not only of the fracture surfaces but also initiation site of the fractured surfaces. The figure presented was included to provide information on details of fatigue failure fracture location. It was highly emphasized to find out the location of crack initiation as well as crack propagation behavior of without heat treatment and solution heat treatment and age hardening at different temperature specimens. Fatigue failure was the phenomenon leading to fracture under repeated or fluctuating stresses that were less than the tensile strength of the material.

Fatigue fractures were progressive, beginning as minute cracks that grow under the action of fluctuating stress. The initiation site was minute, never extending for more than two to five grains around the origin. The location of the initiation was at a stress concentration and may be extremely small and difficult to distinguish from the succeeding stage of propagation, or crack growth. The crack initiation site was always parallel to the stress direction. As repetitive loading continues the direction of the crack changes perpendicular to the tensile stress direction.

After the original crack was formed, it becomes an extremely sharp stress concentration that tends to drive the crack ever deeper into the metal with each repeating of the stress. The local stress at the tip of the crack was extremely high because of the sharp notch, and with each crack opening. Although striations were the most characteristic microscopic evidence of fatigue fracture, they were not always present on fatigue fracture surfaces. After fatigue fracture at different load conditions fracture surfaces were observed to show crack initiation site as shown in Figs. 8 (a-d).

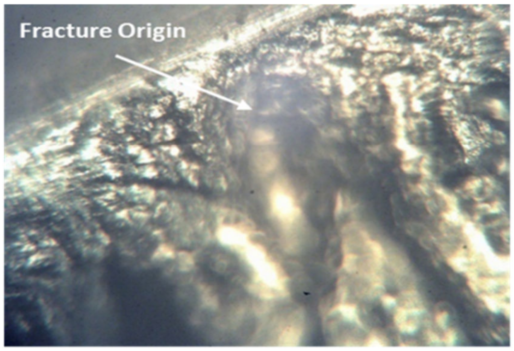

Fig. 8 (a). Fatigue Fracture Surface of Aluminium Alloy with no Heat treatment (σ=130Mpa & N=40.95×10^4).

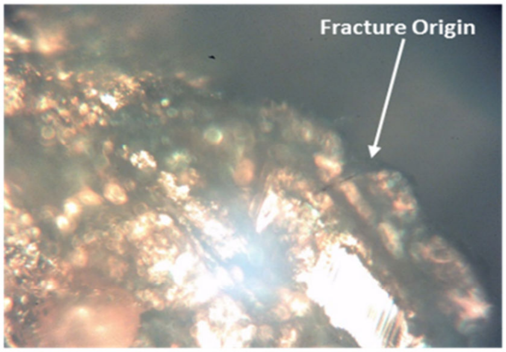

Fig. 8 (b). Fatigue Fracture Surface of Solution Treated Specimen at 420^{0}C for 1 hr, followed by Aging at165^{0}C for 6hr (σ=152 Mpa & N=8.91×10^4).

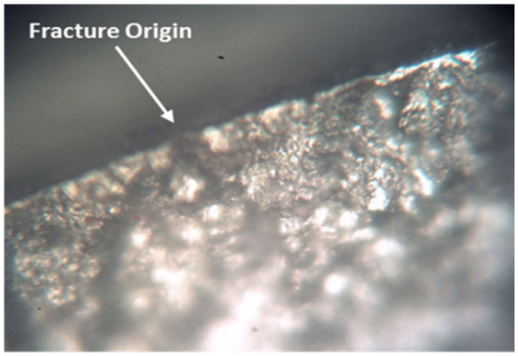

Fig. 8 (c). Fatigue Fracture Surface of Solution Treated Specimen at 460^{0}C for 1 hr, followed by Aging at165^{0}C for 6hr (σ=146 Mpa & N=23.46×10^4).

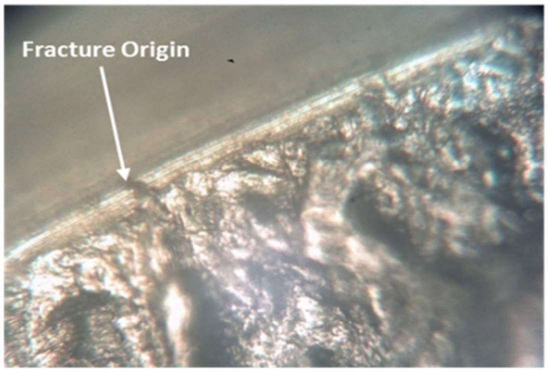

Fig. 8 (d). Fatigue Fracture Surface of Solution Treated Specimen at 500^{0}C for 1 hr, followed by Aging at165^{0}C for 6hr (σ=130 Mpa & N=97.2×10^4).

4. Conclusion

The effect of solution heat treatment and age hardening on the properties of aluminium alloy was examined in this study and it was observed that fatigue strength of aluminium alloy increase due to increasing the solution heat treatment temperature and it was maximum at 500°C in this study. Solution heat treatment followed by age hardening increase tensile strength and hardness of the specimen. These properties also increase with the increasing of solution heat treatment temperature to certain level. In case of Aluminium alloy 4.46% Cu contribute to improve the physical properties by forming $CuAl_2$ combined with Al atoms. Some other compound of Fe, Si, Mn, Mg and Zn also participate to improve those properties.

The solution heat treatment followed by the aging confirmed its efficiency in giving a remarkable improvement of fatigue performances. With these treatments, Fatigue strength, Tensile strength was considerably improved in comparison with that of as cast materials. For higher improvement of strength was often in specimen heat treated at high temperature since the hardening phase are completely dissolved prior to quenching. The dependence of fatigue strength can be linearly related to the temperature dependence of ultimate tensile strength. Fracture of the specimen propagates from the surface of the specimen. Appearance of crack-like defects with inclusions, which is important root for the stress concentration, is the remarkable cause for the crack initiation.

References

1. Maddox, S.J. (2003). Review of fatigue assessment procedures for welded aluminium structures. *International Journal of Fatigue*, 25(12), 1359-1378.

2. Wang, C.; and Chang, Y. (1996). Effect of post-weld treatment on the fatigue crack growth rate of electron beam-welded AISI 4130 steel. *Metallurgical and Material Transactions,* 27(10)*,* 3162-3169.
3. Khan, S.; Wilde, F.; Beckmann, F.; and Mosler, J. (2012). Low cycle fatigue damage mechanism of the lightweight alloy Al2024. *International Journal of Fatigue*, 38, 92-99.
4. Wu, F.; and Yao, W. (2010). A fatigue damage model of composite materials. *International Journal of Fatigue*, 32(1), 134-138.
5. Christ, H.J.; and Mughrabi, I.I. (2007). Cyclic stress-strain response and micro- structure under variable amplitude loading. *Fatigue & Fracture of Engineering Materials & Structures*, 19(2-3), 335-348.
6. Kulekci, M.K.; and Uygur, I. (2002). Low cycle fatigue properties of 2124/SiCp al-alloy composites. *Turkish Journal of Engineering and Environmental Sciences*, 26, 265-274.
7. Shankar, V.; Valsan, M.; Kannan, R.; and Bhanu, K. (2006). Low cycle fatigue behaviour and microstructure evolution of modified 9Cr-1Mo ferritic steel. *Journal of Material Science and Engineering: A*, 437(2), 413-422.
8. Shankar, V.; Valsan, M.; Kannan, R.; and Bhanu, K. (2010). Low cycle fatigue and creep-fatigue interaction behaviour of a modified 9Cr-1Mo ferritic steel and its weld joint. *Journal of Transactions of the Indian Institute of Metals,* 63(2-3), 622-628.
9. Yahya, M.M. (2009). *Low cycle fatigue failure of medium strength aluminum alloy 7020 at different heat treatment.* Ph.D. Thesis. University of Baghdad, 2-47.
10. Volkov, I.A.; Korotkikh, Y.G.; Tarasoy, I.S.; and Shishulin, D.N. (2011). Numerical modelling of elastoplastic deformation and damage accumulation in metals under low-cycle fatigue conditions. *Journal of Strength of Materials,* 43(4), 471-485.
11. Stephens, R.I.; and Fatmi, A. (2001). *Metal Fatigue in Engineering.* 2nd edition, Wily Inter-science, New York.
12. Ahmed, N.; and Al-Khazraji. (2010). Effect of heat treatment on fatigue life of aluminum alloys 2024 and 7075. *Engineering & Technology Journal*, 28, 22-29.
13. Ritchie, R.O. (1999). Mechanisms of fatigue-crack propagation in ductile and brittle solids. *International Journal of Fracture,* 100(1), 55-83.
14. Zhao, Y.Y; Pitman, A.; and Greene, A. (2006). Correlation of strength with hardness and electrical conductivity for aluminium alloy 7010. *Materials Science Forum,* 519-521, 853-858.
15. Evren, T.; and Bilgehan, O. (2007). Influence of heat treatment on the mechanical properties of AA6066 alloy. *Turkish Journal of Engineering and Environmental Sciences*, 31*,* 53-60.
16. Shan, D.; and Nayeb-Hashenil, H. (1999). Fatigue-life prediction of SiC particulate reinforced aluminum alloy 6061 matrix composite using AE stress delay concept. *Journal of Material Science,* 34(13)*,* 3263-3273.
17. Snchez-Santana, U.; Rubio-Gonzlez, C.; Mesmacque, G.; and Amrouche, A. (2009). Effect of fatigue damage on the dynamic tensile behavior of 6061-T6

aluminum alloy and AISI 4140T steel. *International Journal of Fatigue*, 31(11-12), 1928-1937.

18. Ding, H.Z.; Biermann, H.; and Hartmann, O. (2002). A low cycle fatigue model of a short-fibre reinforced 6061 aluminum alloy metal matrix composite. *Composites Science and Technology*, 62(16), 2189-2199.
19. Liu, X.S.; He, G.Q.; Ding, X.Q.; Mo, D.F.; and Zhang, W.H. (2009). Fatigue behaviour and dislocation substructures for 6063 aluminum alloy under nonproportional loadings. *International Journal of Fatigue,* 31(7), 1190-1195.