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Influence of Elevated Temperature on the Fatigue Fracture Surface Hardness of Aa6061

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Abstract: This study discusses the effect of elevated temperature on the hardness of fatigue test specimens which are made of aluminium alloy, AA6061-T6. The fatigue strength of material normally decreases with temperature increase. The fatigue tests were performed on aluminium alloy specimen using servo-hydraulic fatigue testing machine in concordance to an ASTM E466 standard. Three types of loadings, i.e., Constant-Aplitude Loading (CAL), high-to-low and low-to-high sequences has been used for the tests at various temperature levels of 27, 70, 150 and 250°C. The load sequence has been derived from an original fatigue loading of an engine mount bracket of 1300 cc automobile. Fatigue fracture surfaces were then sectioned and the hardness of specimen below the fracture surface was inspected using Rockwell hardness tester machine. Results indicate that the fatigue lives were significantly influenced by the load sequences and temperature levels. The hardness of material under fracture surface also found influenced by the elevated temperature. Finally, the hardness of the fracture surface will be relates to the fatigue lives at elevated temperature.

Key words: Aluminium alloy, elevated temperature, fatigue life, hardness, load sequences

INTRODUCTION

Aluminium and its alloy are desirable in many industries such as automotive industry, aerospace application and appliances. Al-Mg-Si alloy denoted as 6xxx series have been studied extensively because of their benefit such as medium strength, formability, weldability, corrosion resistance and low cost compared to other types of aluminium alloy (Demir and Gunduz, 2009; Zakaria, 2014) minium alloy, AA6061 is one of the most widely used alloy from this series and theil optimised mechanical properties are achieved by aging process after solution heat treatment and quenching (Oladele and Oyinbo, 2011). The primary reasons for selecting AA6061 used in industry application are its acceptable mechanical properties coupled with its relative ease with which it can be cast, extruded, rolled, machined, etc., market acceptance and relative ease of development.

Most of the engineering component applications are subjected to stress or strain that shows their amplitude changes with the time of service. The Variable Amplitude Loading (VAL) conditions are generated from external excitations such as air plane wind gust, road roughness, sea waves and noise (Varvani-Farahani *et al*., 2005) Thus, it is great important to understand the failure mechanism associated with the VAL since the nature of real service load is in the form of variable amplitude. Basically, the fatigue failure of engineering component is subjected to cyclic loading which is occurred below the ultimate strength of a material. This cyclic loading causes a progressive degradation of the material properties and then eventual failure. The fatigue life of structural components will be influenced by the operating environment tempera-ture. The fatigue strength of material at elevated temperature decrease significantly compare with that at room temperature. Material or structural components that subjected to cyclic loading at elevated temperature may fail in different modes from normal fatigue fracture (Bahaideen *et al*., 2005)

Therefore, the loading condition and operating environment temperature plays an important role which influence the fatigue life of material. Apart from that, the increment of dislocation in material during cyclic loading leads simultaneously an increase of resistance and the hardness of the material. The hardening process will result from the multiplication of dislocations and the increasing in their density that fails to cross the precipitates (Ozturk *et al*., 2010). The influence of elevated temperature on the hardness of fatigue fracture surface need to further investigated since it is scarcely reported.

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The purpose of this study is to discuss the fatigue life behaviour of aluminium alloy, AA6061-T6 subjected to different loading sequences. The effect of elevated temperature test on the hardness of fatigue fracture surface also will be further investigated and compared to the room temperature findings. It was expected that the fatigue lives and hardness of the fatigue fracture surface will be influenced by the elevated temperature used for the tests.

MATERIALS AND METHODS

The fatigue test was performed on specimens made of aluminium alloy, AA6061-T6. The material was received in T6 condition indicated that the material has been solution heat treatment and then artificially aged. The treatment is commonly method to increase the strength of aluminium alloy (Ozturk *et al*., 2010). This consists of heating the alloy to a temperature between 460 and 530°C at which the alloy element are in solution and followed by quenching in water at room temperature. For 6xxx series aluminium alloy, the aging temperature range is generally between 160 and 200°C (Demir and Gunduz, 2009).

The fatigue specimens were machined from a solid wrought bar. They had a cylindrical cross-section with a gauge diameter of 10 mm and gauge length of 30 mm. The specimens were polished using SiC paper grit 300, 500, 1000 and 1200 to achieve good surface finish and prevent stress concentration from an irregular surface finish.

Three types of loadings i.e., in the form of CAL, high-to-low sequence loading and low-to-high sequence loading were used in the fatigue tests to study the effect of the load sequence on fatigue life. These spectrum loadings were derived from the fatigue data loading of the engine mount bracket of a 1,300 cc automobile. Figure 1 show a typical trend of fatigue strain signal that obtained from the engine mount bracket.

The spectrum loadings were developed based on the concept of retaining total damage values in the cycles (Pereira *et al.*, 2008; Zakaria *et al.*, 2013). In this study, the CAL was designed using Glyphwork® software represented the original fatigue strain signal. Strain life analysis of the original strain signals was performed to calculate the fatigue damage and was then compared to the designed loading, as shown in Fig. 2. The designed CAL shall contribute to the same total fatigue damage value as the original strain signal. Similar method was used to design the high-to-low and low-to-high spectrum loadings. All cases of load spectra used in this study are shown in Fig. 3.

The fatigue tests were performed using a 100 kN servo-hydraulic fatigue testing machine, in accordance with the ASTM E466. The tests were conducted at both room and elevated temperature ranges, i.e., 27, 70, 150 and 250°C. An elevated temperature regime

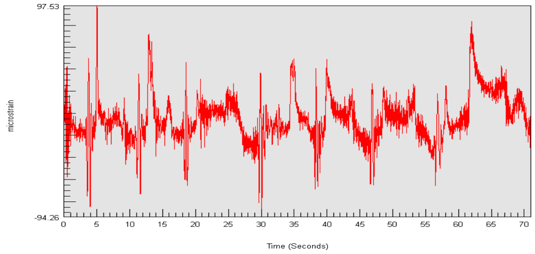

Fig. 1: An original strain signal collected at the residential area road surface

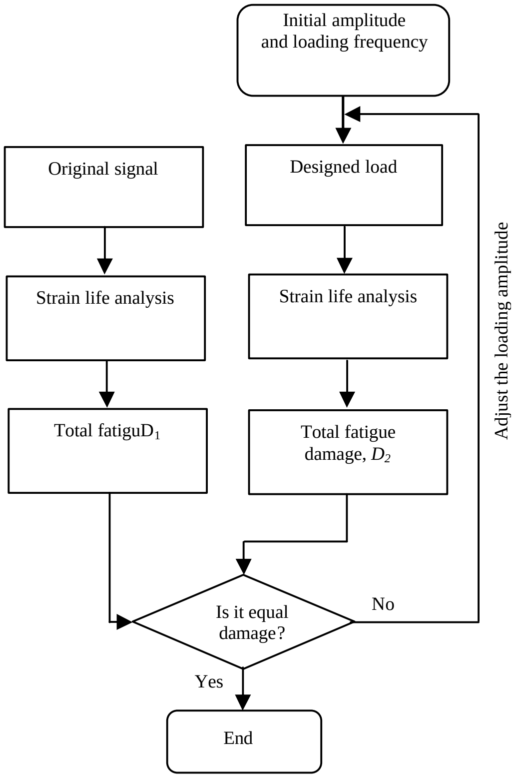

Fig. 2: Flow chart of designing the spectrum loading

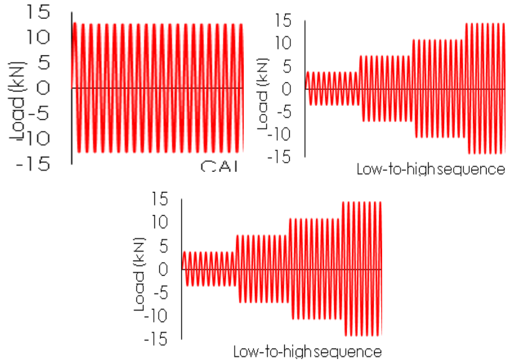

Fig. 3: Spectrum loadings of the different sequences used in the fatigue test

Fig. 4: Test set-up configuration for the cyclic test, (a) specimen attached to the machine and (b) specimen inside the heating chamber

Fig. 5: Fatigue fracture surface indicates by) and the hardness test was performed about mm under the fracture surface as indicated by

Fig. 6: Digital rockwell hardness tester machine

was chosen based on the maximum temperature of the engine mount bracket and cylinder head where a peak temperature as high 250°C can be reached in service (Zhu *et al*., 2006). Figure 4 shows the configuration of test set-up for both room and elevated temperatures. After fatigue tests, each specimen was sectioned into two smaller parts, as shown in Fig. 5. Each portion was subjected to microscopic observation and hardness testing. However, this paper only focused on the hardness test results to relate with the fatigue lives.

The maximum values of the hardness profile after applying cyclic loading is located very near to the fatigue fracture surface (May *et al*., 2011). Therefore, the specimen was cut using a precision saw at almost a constant distance of 2 mm under the fatigue fracture surface to make a comparison, as shown in Fig. 5. The hardness test was performed using a Rockwell hardness tester machine according to ASTM E18. Figure 6 shows a digital Rockwell hardness tester machine used in the study. The recommendation for aluminium alloy was to use the HRB scale using a 1.588 mm-diameter ball indenter with 981 N load. Each specimen was indented at few different points on the sectioned surface to get the mean values.

RESULTS AND DISCUSSION

Figure 7 shows the effect of elevated temperatures on the fatigue lives for each type of load sequence. As the temperature increased, the fatigue lives were shortened because of exterior aggressive conditions and the change in the internal parameters of the material itself. An increase in the testing temperature can accelerate the rate of oxidation and induce the irreversibility of a cyclic slip which can cause damage to the microstructure (Liu *et al*., 2007). The tensile test performed at elevated temperatures also indicates a considerable degradation in strength with increased temperature. All these changes affected the fatigue life of the materials.

For the both tests performed at room and elevated temperatures, fatigue life was the longest under low-to-high sequence, followed by high-to-low sequence and CAL. Figure 8 represents the plot of total fatigue life ranges between the low-to-high sequence and the CAL for each of testing temperature. From the boxplot, the highest different in number of cycles to failure between these two load sequences was found to be at 27°C whereas the shortest different was at 250°C. At 27°C, the number of cycles to failure for low-to-high sequence loading was about 56 % higher than for CAL. Meanwhile, at 250°C, the number of cycles to failure for low-to-high spectrum loading was about 7% higher than for CAL. At room temperature, the plastic deformation tends to be more under the VAL which intensified the crack closure effect and consequently reduced the fatigue crack propagation rate (Yamada *et al*., 2000). In the

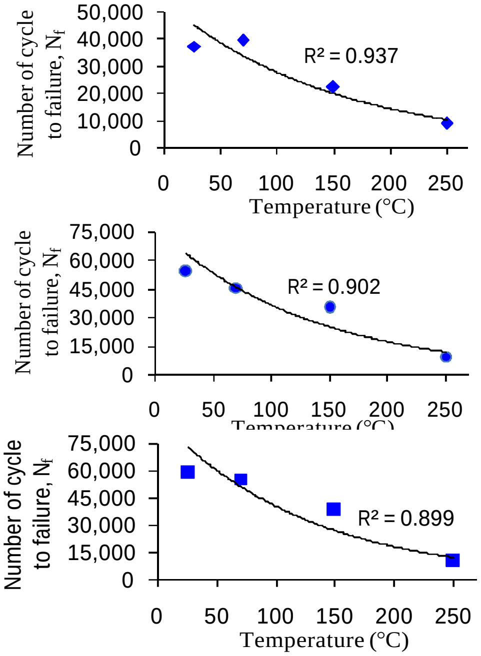

Fig. 7: Effect of testing temperatures on the fatigue lives under the: a) CAL; b) High-to-low sequence; c) Low-to-high sequence loading

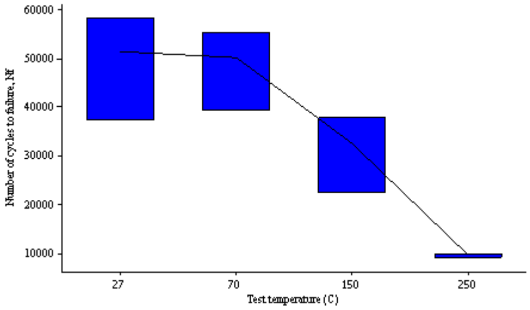

Fig. 8: Total fatigue lives range for all cases of loading sequences tested at different operating environment temperatures

meanwhile, plasticity behaviour of aluminium alloy increased with temperature (Srivatsan, 1999; Juijerm and Altenberger, 2007). Therefore, the increment of plasticity behaviour at this elevated temperatures were reduced the effect of plastic deformation due to load sequences relative to temperature increase.

The hardness of aluminium alloy normally increased with increased the number of applied fatigue cycles (Zhu *et al*., 2006). Comparison of the fatigue fracture surface hardness values which is determined across the specimen's radius, is exhibit in Fig. 9. Hardness values were measured after the fatigue test at room and elevated temperatures. Results showed that the hardness increases up to 150°C for all case of loadings, i.e., under the CAL, high-to-low and low-to-high sequence loadings. At the room and the elevated temperature up to 150°C, there was cyclic hardening in the cycles due to increased dislocation densities and dislocation-dislocation interactions during cyclic deformation (Juijerm and Altenberger 2007). An increase in temperature leads to greater thermal vibration of the atoms in material and increase the average separation distance of the atom (Shackelford, 1998). It was suggested that the dispersion of precipitates, as an effective barrier increases with temperature and lead to a substantial hardening of the alloy. On the other hand, the hardness value was found to decrease at 250 compared to 150°C. The hardness of fatigue fracture surface slightly reduced due to changes in the precipitation state that occurs above the aging temperature. The aging temperature range for 6xxx series aluminium alloy is generally between

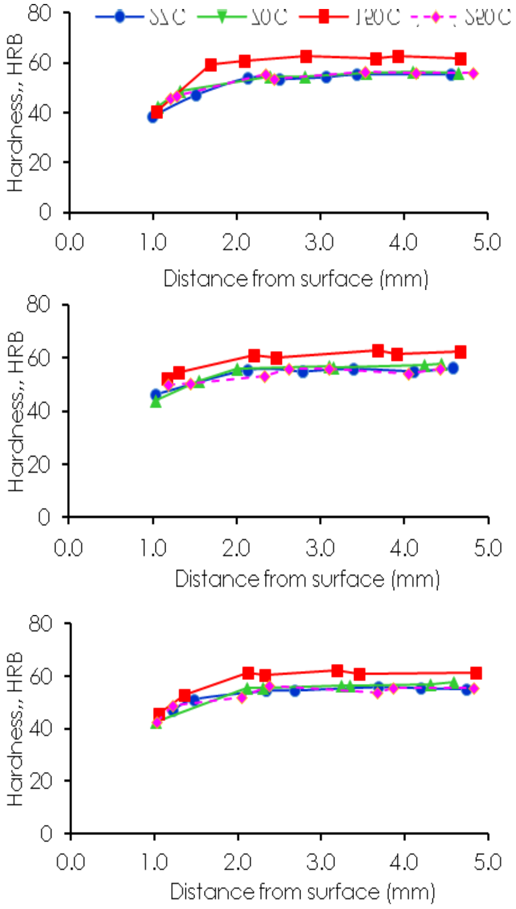

Fig. 9: Hardness profile at different fatigue testing temperature under the: a) CAL; b) High-to-low sequence; c) Low-to-high sequence loading

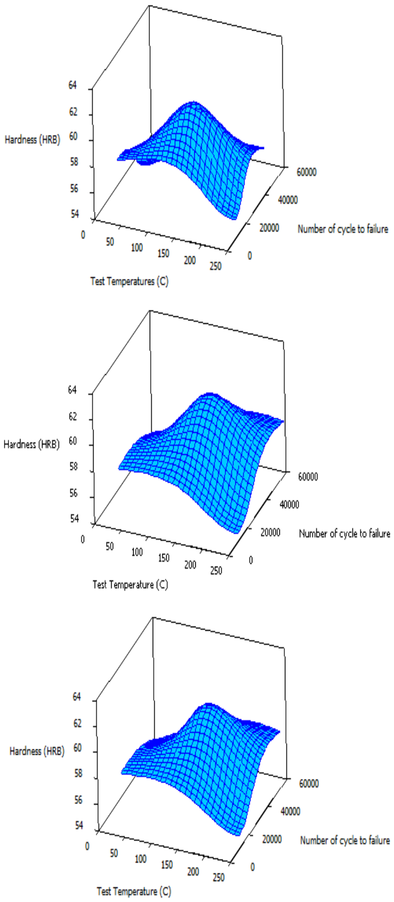

Fig. 10: Surface plot profile showing the relationship between elevated temperature, fracture surface hardness and the fatigue lives under the: a) CAL; b) High-to-low sequence; c) Low-to-high sequence loading

160-200°C. Above this aging temperature, the cyclic hardening process was changed into cyclic softening. During cyclic deformation, the dislocation via the precipitates caused mechanical local scrambling of the atom in the precipitate and consequently, hardening due to the lost ordering contribution (Juijerm and Altenberge, 2007). Figure 10 summarised the relationship between the testing temperature, fracture surface hardness and the number of cycle to failures for each loading sequence used in the tests. The plot profile shows a similar trend of fatigue lives versus the test temperatures for all cases of loading sequences. The number of cycle was reduced with the elevated temperatures. Above the room temperature, the gradient plot profile number of cycles to failure gradually reduced with the temperature increase but its changed to dramatically reduced at the testing temperature of 250°C. For the fatigue fracture surface hardness, there is no obvious change in the hardness trends among the types of loading sequences. For all cases of loading sequences, the hardness was increased with the temperature increase up to 150°C. However, the hardness was slightly reduced for the fatigue test at 250°C. These observations showed that the aging temperature was playing an important factor that influenced the fatigue lives and hardness of the material. The aging process normally introduced to an aluminium alloy to increase the strength of this material. However by expose the aluminium alloy to the operating environment temperature which is above the aging temperature made the beneficial of the aging lost.

CONCLUSION

This study discussed effect of elevated temperatures to the fatigue life and fracture surface hardness of aluminium alloy specimen. Fatigue life was found to be the shortest under CAL, followed by high-to-low and low-to-high sequence loading for both tests at room and elevated temperatures. The load sequence effect was noticed more pronounced at the room temperature compared to elevated temperatures.

The number of cycles to failure was decrease with temperature increase. The fatigue lives at 250°C is found to be 75-80 % shorter than at 27°C for each load cases use in the tests. Apart from that the hardness of fatigue fracture surface was increased when the testing temperature in-creased up to the aging temperature. There is no increment of the hardness values for fatigue test above this tempera-ture.

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