FRACTOGRAPHY ANALYSIS OF Al6061 UNDER FATIGUE SPECTRUM LOADINGS

K.A. Zakaria, S. Abdullah, M.J. Ghazali and Z.M. Nopiah
Department of Mechanical & Materials Engineering, University Kebangsaan Malaysia, 43600 UKM, Bangi, Selangor, Malaysia.
Email: kamarul1@eng.ukm.my

ABSTRACT
This paper discusses the fractography observation in crack propagations of Al6061 under a fatigue spectrum loading. Most of the real components and engineering structures are subjected to stress of variable amplitude. The load sequences in variable amplitude loading condition can have a very significant effect on the fatigue crack propagation rate. Fatigue crack propagation tests were performed according to ASTM E647 standard using a 100 kN servo-hydraulic fatigue testing machine. Random loading signals were obtained from the engine mount bracket of an automobile while driven at almost constant velocity onto different surface conditions, i.e. on the residential area and highway road. These random loadings were converted to constant amplitude loading (CAL), high to low and low to high spectrum loadings in order to study the effect of loading sequence on the crack propagation rates. The fatigue fracture surfaces were then analysed using a high magnifying tabletop microscope to identify the fracture behaviour under particular load sequences. Results showed that the fatigue fractography behaviours were influenced significantly by the load interaction and the sequence effect, which can be related to the crack propagation rate of Al6061 under fatigue spectrum loadings.

Keywords: Fatigue; fractography; spectrum loading; variable amplitude loading.

1. INTRODUCTION
In the field of metallic or light structures, the failure of structural components is difficult to assess, particularly under variable loading condition. Furthermore, most of the structural components are practically subjected to a complex loading that is accompanied by a change in the stress amplitude. The prediction of fatigue life of the component under variable amplitude loading (VAL) conditions is becomes a complex subject (Beden at al., 2009 and Carvalho et al., 2010). A significant acceleration or retardation in crack propagation rate can occur as a result of these load interactions. An accurate fatigue life prediction requires an adequate evaluation of these load interaction effects (Borego et al., 2008).

The linear cumulative damage rule, which known as Palmgren-Miner’s rule is probably the most commonly used method to calculate the amount of fatigue damage. On the other hand, Palmgren-Miner’s rule takes no account of the load sequence effect, which often prolongs the fatigue life under VAL conditions (Yamada et al., 2000). By neglecting the effect of cycle load interaction in the fatigue life calculations under VAL can lead to a complete invalid life prediction (Beden et al., 2010).

The most three common fracture mechanisms in metal and alloy are ductile fracture, cleavage and intergranular fracture. Fractography analysis lead to the studies focused on failure modes and fracture mechanisms which relates to the fracture surface examination (Tchuindjang et al., 2006 and Sathiya et al., 2012). The fractography techniques by using a high magnifying microscope, including the uses of scanning electron microscopy (SEM) are extensively used in the fatigue study to identify mode of failures that correlates the material behaviours and properties. On the other hand, Wei et al. (2001) reported that the random loading produced different fracture surface features compared to the CAL. Thus, it is needed to investigate further the fractography observation under both high to low and low to high spectrum loadings in correlating to the fatigue crack propagation rate.

The purpose of this paper is to analyse fractography behaviour of an aluminium alloy that subjected to fatigue spectrum loadings. For that reason, three types of block loading sequences were used, i.e. the CAL, high to low and low to high spectrum loadings have been designed from the original time histories strain signal of the engine mount bracket. The fatigue crack
propagation tests were performed on Al6061 specimens according to an ASTM E647 standard. The fractography observations were made on all specimens in order to investigate the feature of fracture surface. It is expected that the fractographies will be explained the crack growth behaviour of Al6061 which can be used to determine the local crack growth rates under fatigue spectrum loadings.

2. METHODOLOGY

The compact tension (CT) specimen is made of aluminium alloy, Al6061. All dimensions were conformed to an ASTM E647 standard with width of 50 mm and the thickness of 12.5 mm. After machining process, the specimens were polished using SiC paper at the grit scales of 300, 500, 1000 and 1200. It was done in order to achieve a good surface finish, and also to avoid stress concentration occurrence from the irregular surface finish. Experiments were performed using a 100 kN servo-hydraulic fatigue testing machine, and the test were conducted at the room temperature. The specimens were initially pre-cracked to the minimum length of 0.1B or h or 1.0 mm, whichever is greater (Dreyfuss et al., 2003), and growing the pre-crack under a given loading condition. B was the thickness of specimen and h was the height of pre-crack size. The crack length was measured at the front and back surfaces of the specimen by using a travelling microscope with 20 X magnification. During the test, the average crack length and the corresponding number of loading cycles were recorded.

Fractography analysis is important to describe the crack propagation behaviour from the appearance of a fracture surface. The fractographic observation were analysed after each test to describe the crack propagation behaviour under both constant and spectrum loadings. The specimens were sectioned and inspected using a high magnifying tabletop microscope, TM-1000 at a voltage of 15 kV. The task was accomplished by using the image magnifications ranging from 1,000 X to 5,000 X.

On top of that, the variable amplitude time histories strain signal was collected from the engine mount bracket of 1300 cc automobile. The automobile was driven onto the residential area and highway road surfaces with almost at a constant velocity of 15-25 km/hr and 80-90 km/hr, respectively. The VAL was captured using a strain gauge that fixed on the top of engine mount bracket. The size of strain gauge used in this study was 2.0 mm gauge length with 120 Ω resistances. This size was selected as it is suitable to fix on the limited space of the bracket. The strain gauge was then connected to a fatigue data acquisition system to record the time histories strain signals as shown in Figure 1.

Fig. 1 Original time histories strain signals collected at different road surfaces: (a) residential area road, (b) highway road

Six types of loads were derived from the original time histories strain signal in order to study the effect of loading sequences on the fatigue crack propagation rate. CAL was designed using Glyphwork® software represented the residential area and highway road loading, respectively. 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 Figure 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 loading used in this study were summarised in Table 1 and their load spectrums were exhibited in Figure 3.
3. RESULT AND DISCUSSION

Figures 4 and 5 show the trend of normalised crack length as a function number of cycles for both residential and highway road loadings. The crack propagation rate under the CAL (case 1 & 4) was found higher than the VAL. From both figures, a 0.5 normalised crack length was produced by 120 x 10^3 cycles for case 1 compared to 255 x 10^3 cycles for case 2 and 370 x 10^3 cycles for case 3. Meanwhile, a 0.5

normalised crack length was produced by 1700 x 10^3 cycles for case 4 compared to 1700 x 10^3 cycles for case 5 and 2600 x 10^3 cycles for case 6. The load interaction in both high to low and low to high spectrum loadings were reduced the fatigue crack propagation rate. This finding was found agreement with Yamada et al. (2003), which suggested the crack propagation rate under the VAL was slightly lower than the corresponding CAL. It was due to plastic deformation that tends to be greater in this region, which intensified the crack closure effect which consequently reduced the fatigue crack propagation rate.

It was further noticed that the crack propagation rate under high to low spectrum loadings (case 2 & 5) were higher compared to low to high spectrum loadings (case 3 & 6). The total crack growth rate was about 30 % higher in case 2 compared to case 3 and about 35 % higher in case 5 compared to case 6, as shown in both Figures 4 and 5, respectively. These results may be influenced by the magnitude and position of the load steps. In both cases, load interaction effect led to crack retardation and acceleration throughout the process. For low to high spectrum loading, there were some patterns of overload at transition cycle from step 1 to step 2 and at each of the following steps. The fatigue
crack propagation would be decreased or arrested after experiencing overload one or many times (Huang et al., 2005).

By comparing the results in Figure 4 and 5, it shows that the total numbers of cycles for highway road are about 3 to 7 times higher than the residential area road loadings, for all load cases. It was indicated that crack propagation rates were lower for highway compared to residential area road loadings. It was due to smooth condition of the highway road surface. On the other hand, the condition of residential area road surface was found rougher compared to highway road and consequently produced higher strain range amplitudes. Furthermore, the presence of road bumpers in residential area road also causes the engine move up and down more rapidly. As a result, the crack propagation rate become more accelerates.

Macroscopic observation on fracture surface of the specimens can be clearly distinguished by two discrete regions. These two distinct regions are shown by the optical micrograph in Figure 6. The boundaries of these regions were well identified between the fatigue fracture region and rapid fracture region. The crack propagation direction was perpendicular to the loading direction and was indicated from top to bottom of the images. Fatigue crack initiated from the notch of specimen and propagated parallel on both sides. The fatigue fracture region with regular flat surface indicated the gradual crack propagation due to fatigue while the rapid fracture region with irregular surface topography showed the unstable crack propagation and characterised by fast crack features.

Microscopic observation of the fatigue fracture region is shown in Figure 7. The images were taken at the specimen centre that subjected to the residential area road loading. The fractography observations indicated significant striations as shown in Figure 7(a) - (c). The occurrence of striations on the fracture surface confirmed the presence of the fatigue failure. Detailed observations of the striations are shown in Figure 7(d) - (f). The striations can be observed clearly in the CAL with well-defined regular local spacing’s. However, under high to low and low to high spectrum loadings, the striations were found to be irregular with repeated deeper grooves. The striation width will be depended on the increased of the stress range. Local crack propagation rate can be estimated by measuring the average of striation spacing’s (Schijve et al., 2004). The striation spacing’s over one block of loading (40 cycles) were marked by ‘x’, ‘y’ and ‘z’ as shown in Figure 7(d) - (f). In these cases, the local crack propagation rate was equivalence to 1/40 of spacing’s. Thus, local crack propagation rate for CAL was estimated at 0.525 µm/cycle compared to 0.288 µm/cycle and 0.250 µm/cycle for high to low and low...
to high spectrum loadings, respectively. The results confirmed that crack propagation rate was the highest under the CAL and the lowest under low to high spectrum loadings.

The micrographs in Figure 8 illustrate the features of the rapid fracture regions. The fracture surface was covered by uniform and equated dimples. Fracture surface under the CAL presented relatively smaller size of dimples and consisted of higher number of voids compared to the spectrum loadings. The presence of equated distribution of voids, indicated a predominantly Mode I type of failure (De et al., 2008). For the case of spectrum loadings, the size of dimples was relatively bigger and slightly elongated. Elongated dimples indicated that some fractures were in shear state (Jogi et al., 2008), implying higher plasticity which is induced during the crack propagations.

(a)  
(b)  
(c)  
(d)  
(e)  
(f)  

Fig. 7 Striations on fracture surfaces under fatigue spectrum loadings at two magnification levels: (a) CAL at 1000 X, (b) High to low loading at 1000 X, (c) Low to high loading at 1000 X, (d) CAL at 5000 X, (e) High to low loading at 5000 X, (f) Low to high loading at 5000 X.

4. CONCLUSION

This paper discussed the crack propagation rate of Al6061 under fatigue spectrum loadings. The crack propagation rate of Al6061 was influenced significantly with the CAL, high to low and low to high spectrum loadings. Fatigue crack propagation rate was found to be the highest under the CAL and the lowest under low to high spectrum, for both residential area and highway road loading. Besides that, the striation spacing’s were found in good agreement with the recorded visual crack propagation. The features of fracture surfaces exhibited plastic deformation in the VAL. Thus, it is very important to take into account the load sequence effect, which often prolongs the fatigue life under the VAL condition.

REFERENCES


