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Influence of mechanical properties on load sequence effect and fatigue life of aluminium alloy

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ABSTRACT

Most of the structural components in real applications are subjected to variable amplitude loading. The load sequence may have a significant effect on the number of cycles to failure. However, the relationship between the mechanical behaviour of material and the load sequence effects has scarcely been reported. Therefore, this paper discusses the influence of mechanical properties on the load sequence effect and fatigue life behaviour of aluminium alloys AA6061 and AA7075. Tensile and fatigue tests were performed according to ASTM E8 and ASTM E466, respectively. The variable amplitude loading signal was obtained from the engine mount bracket of an automobile in normal driving conditions. Constant amplitude loading, and high-to-low and low-to-high spectrum loadings were derived from the variable amplitude loading to assess the effects of load sequence on fatigue life. The results showed that AA7075 has better fatigue life properties compared to AA6061. Both alloys were significantly influenced by load sequences. The number of cycles to failure for low-to-high spectrum loading is about 56 % higher than the CAL for AA6061 compared to about 82 % higher than the CAL for AA7075. Thus, it can be concluded that the load sequence effect was more pronounced on AA7075 compared to AA6061.

Keywords: Aluminium alloy; fatigue life; load sequence effect; mechanical properties.

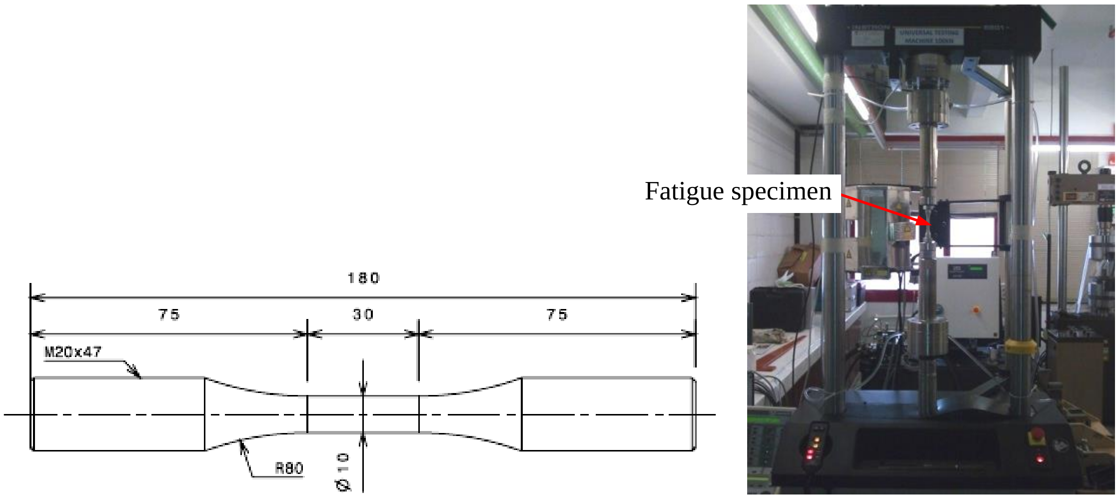
INTRODUCTION

Structural and engineering components are designed to sustain a certain amount of load. Failure of these structures may result in significant losses in manufacturing, maintenance, and time costs and user safety. These losses may occur because of the interaction between loading and environment over time. Fatigue failure is one of the main failure mechanisms of structural and engineering components [1, 2], contributing to more than 90% of mechanical failure [3-7]. This type of failure mechanism is caused by cyclic loading, which occurs below the ultimate strength of the material. This loading causes progressive degradation of the material, which leads eventually to failure. Fatigue life assessment and the prediction of the number of cycle loads to failure are among the key aspects of almost all engineering applications [8-14]. Traditionally, most fatigue characterizations of a material are performed under constant amplitude loading (CAL) to accommodate machine capability of fatigue and to simplify the analysis. However, most structural and engineering components are subjected to variable amplitude loading (VAL), where the stress amplitude varies over time. Variable amplitude can be generated by external sources, such as the roughness of road surface, wind, ocean waves, and vibration effects [15]. Fatigue assessment through VAL is more complex because it involves load history and loading sequences. Understanding failure mechanisms and quantifying fatigue life are important because most engineering components are associated with VAL [16]. The load sequence has been shown to be affected mainly by the loading conditions, such as the magnitude and position of overloads/underloads in the sequence, arrangement of block loadings, stress ratio, and mean stress. These parameters affect the fatigue crack initiation and propagation, as well as the total number of cycles to failure [9, 17-20]. However, there is still a lack of discussion on how loading sequence effect is influenced by material behaviour.

This paper studies the mechanical properties of AA6061 and AA7075 and the relation of these properties to the load sequence effects on fatigue life. Tensile tests were performed according to ASTM E8, while the fatigue tests were performed according to ASTM E466 standards. Three types of loading sequences were used in the fatigue tests to study the effect on these materials: CAL, high-to-low, and low-to-high loading. The fatigue life of both aluminium alloys was expected to be affected by the load sequences. Furthermore, their mechanical properties were expected to affect the load sequences effect on fatigue life.

MATERIALS AND METHODS

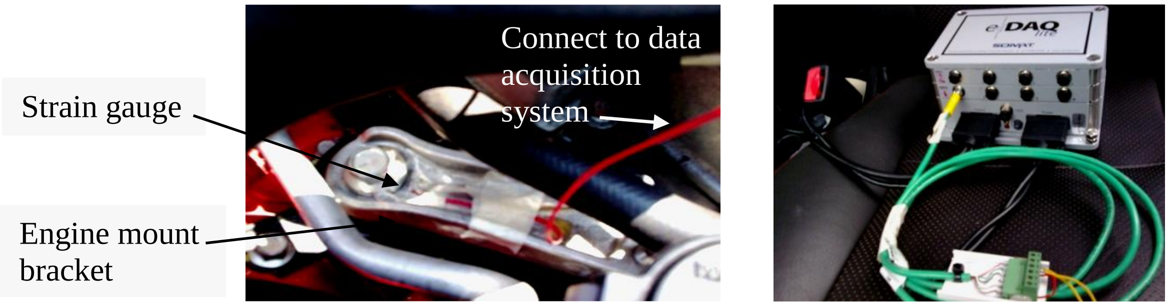
Aluminium alloy grade AA6061-T6 and AA7075-T6 were used in this study. Both AA6061 and AA7075 are widely used in applications because of their good mechanical properties, high strength-to-weight ratio, market acceptability, and extensive use in alloy development [21-24]. Hence, understanding their mechanical properties and fatigue life behaviour can reduce maintenance costs. The materials were received in T6 condition, indicating that the material had been solution-heat treated and aged artificially to increase the alloy strength. Tensile and fatigue test specimens were machined from solid wrought bars according ASTM E8 and ASTM E466 specifications.



(a) (b)

Figure 1. (a) Geometry dimension of the fatigue specimen (in mm); (b) Servo-hydraulic fatigue testing machine.

Tensile tests were performed to determine the mechanical properties of the as-received material. Then, cyclic tests on the cylindrical section of specimens were performed using the 100 kN servo-hydraulic fatigue testing machine shown in Figure 1(a) and 1(b). The tests were conducted under load controlled mode at room temperature using fully reversed axial loading (*R*= -*1*). The cyclic load used was a sinusoidal signal operated at a frequency of 5 Hz. CAL, high-to-low, and low-to-high spectrum loadings were used in the fatigue tests. These loads were derived from the VAL of the fatigue strain history collected from the engine mounting bracket of a 1300 cc car while travelling on a residential area road surface (Figure 2 and 3). A strain gauge with 2 mm gauge length and 120 Ω resistance was mounted on top of the engine mounting bracket and connected to the strain data acquisition system. Prior to that, the surface of the engine mounting bracket was polished with sand paper and a clean cloth to remove stains and facilitate the fixing process.



(a) (b)

Figure 2. Capturing a time series signal using (a) strain gauge; (b) fatigue data acquisition system SoMat eDAQ.

Figure 3. Surface condition of the residential area road used in this study.

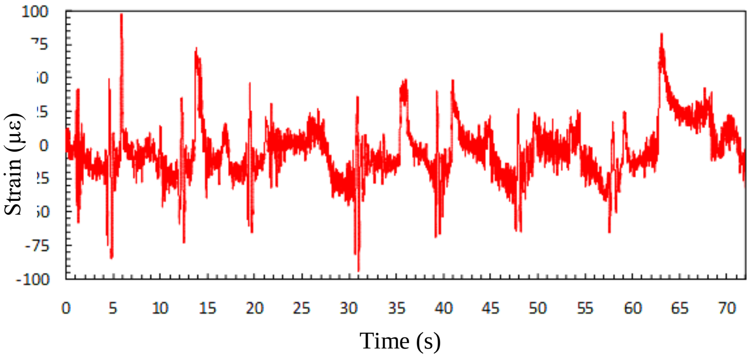
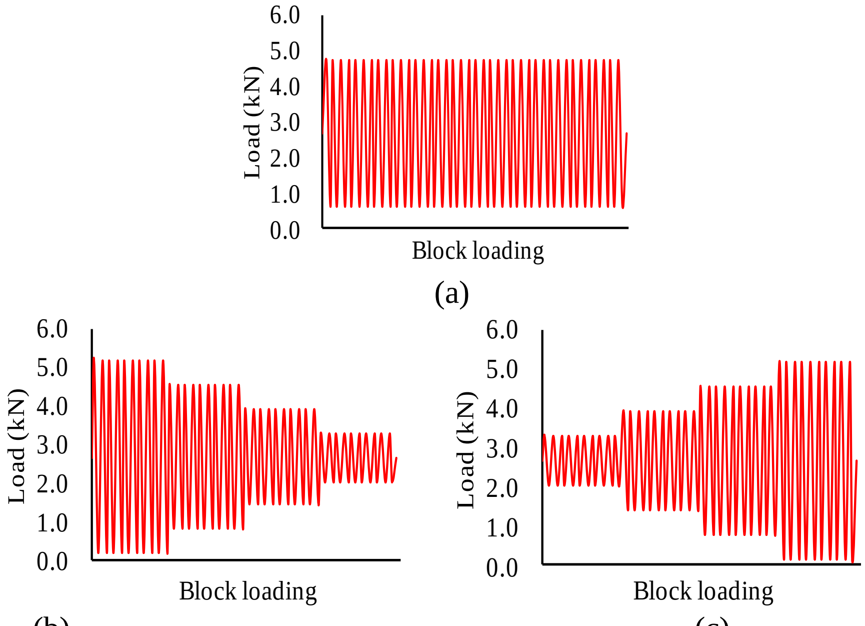


Figure 4. Strain signal history collected on the residential area road surface.

The time history strain signal is presented in Figure 4. The loading sequences as shown in Figure 5 were generated from the original strain signals and used to study the cyclic sequence effect on fatigue life. These spectrum loadings were developed based on the calculated equivalent damage values in the cycles. Details of the load designing process have been discussed in the previous work of the authors [25].



(a)

(b)

(c)

Figure 5. Spectrum loadings of different sequences used for the tests (a) CAL; (b) High-to-low; (c) Low-to-high.

RESULTS AND DISCUSSION

Figure 6 shows the stress-strain curves from tensile tests for both as-received AA6061 and AA7075 alloys. The experimental data extracted from the stress-strain curve are summarized in Table 1. The ultimate strength of AA6061 is 332 MPa, the yield strength is 305 MPa, and the modulus of elasticity is 70.1 GPa. The ultimate strength of AA7075 is 687 MPa, the yield strength is 607 MPa, and the elastic modulus is 70.4 GPa. The results are almost the same as the standard properties of these alloys [26, 27]. The ultimate strength for both alloys is slightly higher than the standard, with differences ranging from 7.1% to 20.5%. The variations can be attributed to the different batches for production and variations in manufacturing [28].

Table 1. Mechanical properties of AA6061 and AA7075

Aluminium alloy Series	Ultimate stress σ_{UTS}, (MPa)	Yield stress σ_y, (MPa)	Elastic modulus *E*, (GPa)
AA6061 (experiment)	332	305	70.1
AA6061 (standard)	310	275	69.0
Difference (%)	7.1	10.9	1.6
AA7075	687	607	72.4
AA7075 (standard)	570	505	72.0
Difference (%)	20.5	20.2	1.9

Table 1 shows that AA7075 had higher ultimate strength and elastic modulus compared to AA6061. Therefore, AA7075 was categorized as a high strength aluminium alloy and AA6061 as a medium strength aluminium alloy [29]. Zinc, Copper, and Magnesium in AA7075 assisted in precipitation hardening. At peak aging conditions (T6), the microstructure of AA7075 is very heterogeneous with formation precipitation of Mg_2Al_3, Al_2Cu and $Al_{32}Zn_{49}$ that contributed to its higher strength [30].

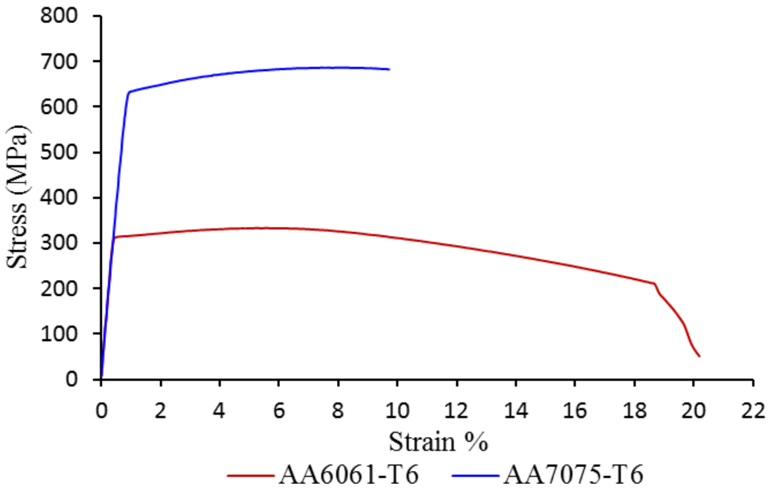
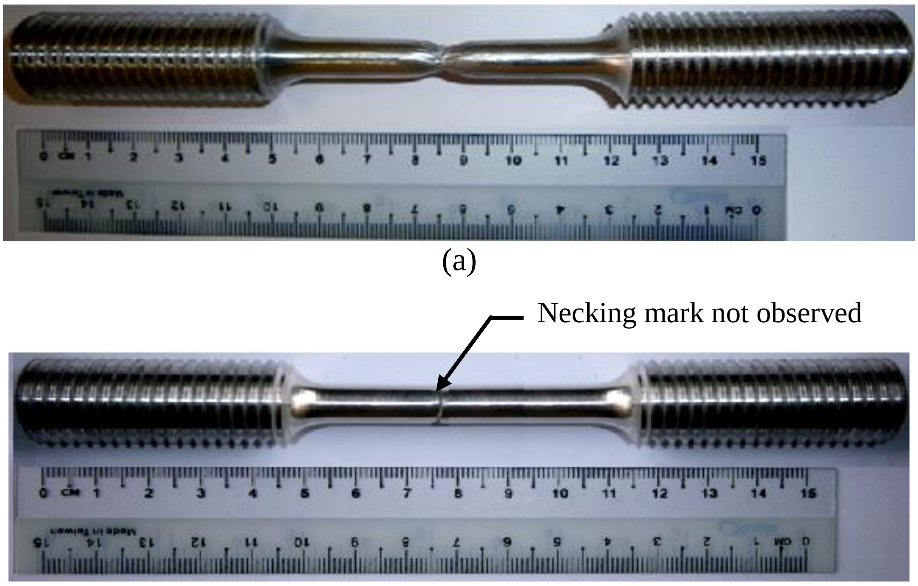


Figure 6. Stress-strain curve for aluminium alloy AA6061 and AA7075.



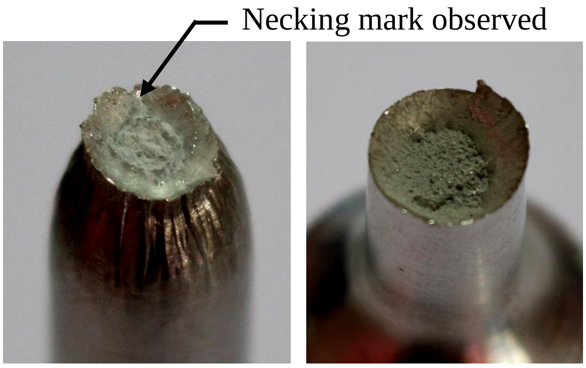
(a)

(b)

Figure 7. Fracture of specimen after tensile test for aluminium alloy (a) AA6061; (b) AA7075.

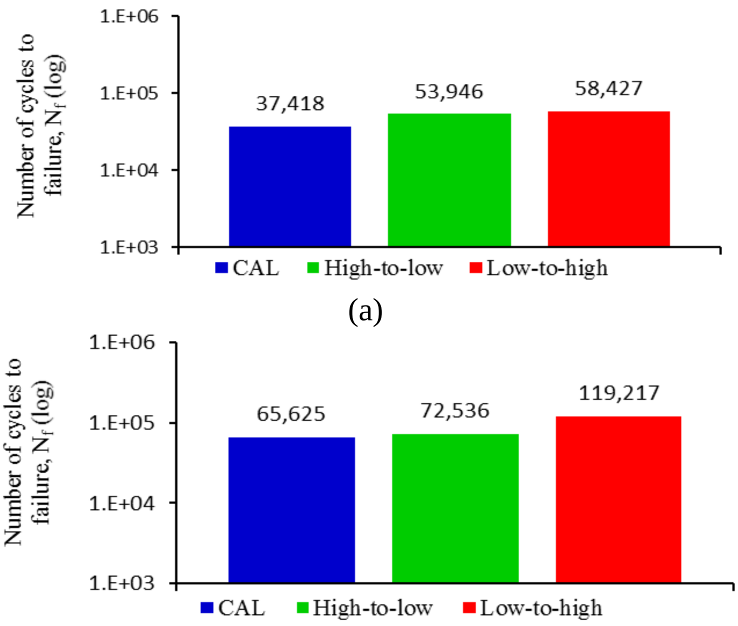
The stress-strain curve in Figure 6 indicates that the strain percentage before failure of AA6061 is higher than that of AA7075; thus, AA6061 is more ductile compared to AA7075. The tensile test specimens also indicated that during the test AA6061 is more elongated and has necking marks. A smaller elongation and no necking mark were observed for AA7075, as shown in Figures 7(a) and 7(b), respectively.

Figure 8 shows a comparison of the fracture surface after tensile tests on AA6061 and AA7075. AA6061 had ‘cup and cone’ marks indicating that ductile fracture occurred at room temperature. However, AA7075 had unclear ‘cup and cone’ marks and the fracture surface of the specimen was rougher with a sharper edge, indicating a less ductile fracture.



(a) (b)

Figure 8. Fracture surface condition after tensile test for aluminium alloy (a) AA6061; (b) AA7075.



(a)

(b)

Figure 9. Comparison of the number of cycles to failure under CAL, high-to-low and low-to-high sequence loading for (a) AA6061 and (b) AA7075.

The number of cycles to failure of the aluminium alloys when subjected to different loading sequences is shown in Figure 9. AA7075 has higher fatigue life compared to AA6061 because of its higher strength. Fatigue life is shortest under the CAL, followed by high-to-low and then low-to-high spectrum loadings for both AA6061 and AA7075. The differences can be attributed to the interaction of overload and underload in the VAL, which resulted in higher fatigue life. Tensile overload in the cycle caused crack retardation whereas compressive underload caused crack acceleration [18, 31, 32]. This study also found that ductility of aluminium alloy affected the load sequence effect. AA6061 had higher ductility but a lower loading sequence effect compared to AA7075. The number of cycles to failure for low-to-high spectrum loading is about 56 % higher than the CAL for AA6061, whereas it is about 82 % higher than the CAL for AA7075. According to Sonsono [33], ductility or brittleness may affect the fatigue life of materials. A material with lower ductility normally has longer fatigue life because of the differences in the localized deformation process. The load sequence effect on fatigue life can also be affected by the load interaction that occurred in cycles, which induced plasticity at the crack tip during the crack propagation [34-36]. Plasticity is related to ductility, and thus, the load sequence effect on fatigue life was also affected by the ductility of the aluminium alloy.

CONCLUSIONS

This paper studied the mechanical properties of aluminium alloy A6061 and AA7075 and their relationship with the load sequence effect on fatigue life. The findings indicate that AA7075 has higher strength and fatigue life compared to AA6061. Observations from the fracture surface also indicated that AA7075 has lower ductility than AA6061. In terms of fatigue life, the number of cycles to failure is affected significantly by the load sequence. Fatigue life was observed to be lowest under CAL, followed by high-to-low and low-to-high sequence loads for both types of aluminium alloy. The number of cycles to failure for low-to-high spectrum loading is about 56 % higher than the CAL for AA6061, whereas it is about 82 % higher than the CAL for AA7075. Therefore, it can be concluded that the lower ductility behaviour of AA7075 is attributed to the more pronounced load sequence effect on fatigue life of AA7075 compared to AA6061. Further studies are recommended on other grades of aluminium alloy to obtain more correlation data of mechanical properties and the load sequence effect.

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