Materials and Design 49 (2013) 48–57

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Comparative study of fatigue life behaviour of AA6061 and AA7075 alloys under spectrum loadings

K.A. Zakaria, S. Abdullah *, M.J. Ghazali

Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 8 November 2012
Accepted 8 January 2013
Available online 20 January 2013

Keywords:
Aluminium alloys
Elevated temperatures
Fatigue damage
Fatigue life
Load sequence effect

ABSTRACT

The study aimed to present several fatigue tests under loading sequences, and to compare the fatigue life behaviour between AA6061 and AA7075 alloys subjected to spectrum loadings at room and elevated temperatures. Constant amplitude loading (CAL), high-to-low and low-to-high loading sequences were derived from a real-time variable amplitude loading that captured from an engine mount bracket of a 1300 cc automobile under normal driving conditions. The shortest fatigue life was found under CAL, followed by the high-to-low and low-to-high loading sequences at both room and elevated temperatures with difference between the maximum and minimum cycles ranged from 7% to 84%. Increased testing temperature (from 27 °C to 250 °C) exponentially decreased the number of cycles by 75–84%. The effect of loading sequence was more significant at room temperature than at elevated temperature.

1. Introduction

Aluminium alloy is used in many automotive and airplane applications due to light weight, excellent weldability, and corrosion resistance [1]. The use of aluminium alloys in automotive structural application is rapidly growing [2]. In terms of fatigue strength, aluminium alloys still offer lower fatigue strength than high-strength steel [3,4]. On the other hand, as an alternative to steel, aluminium has potentially increasing the efficiency of vehicles by provide a lower weight. The amount of energy needed for transportation decrease with efficiency gains, reducing the emissions, and improving the energy security of the country [5]. In applications, aluminium alloys are used as automotive frames, aircraft structures, wheels, pipelines, etc. The high-temperature parts made of aluminium alloy include the engine block, cylinder head, piston, engine oil pan, intake manifold, and heat exchanger. Generally, the fatigue strength of a material decreases with increased temperature [6–8].

Aluminium alloy grade AA6061 is one of the most widely used alloys in practical applications because of the following properties: good mechanical properties; relative ease with which it can be cast, extruded, rolled, machined, etc.; acceptable in the market; and extensively used for the alloy development [9,10]. Meanwhile, aluminium alloy 7075 is widely used in the aircraft industry since it's provide a high strength and low density alloy [11]. Their combination of high strength with moderate toughness, low density, and high corrosion resistance is required is attractive for a number of aircraft and aerospace structure applications [12–14]. Therefore, according to their applications, both of these aluminium alloys have been studied for many years and enhanced with the aim of increasing the service lifetime. Concurrently, understanding the fatigue behaviour of these alloys can reduce the maintenance costs.

Most engineering components in service are subjected to cyclic loading, and the fatigue fracture is the most common form of failure [15], such as in automobile steering connecting rod, piston connecting rod, marine drive shaft, aircraft body, landing gear. The majority of the fatigue life characterisation of a material is performed under a constant sinusoidal loading [16], which is easier to accommodate with most of the fatigue testing machine's capabilities and also to simplify analysis [17,18]. However, in actual applications, most of the engineering components are subjected to stress amplitude that varies with time [19]. Thus, the failure mechanism associated with variable amplitude loading (VAL) is important to understand to quantify the crack growth rate and fatigue lifetime under the VAL condition [17]. Engineering components operated at elevated temperatures are also vulnerable to fatigue failure at elevated temperatures. Thus, the fatigue life at elevated temperatures must be characterised because some of these components are operated and may fail at elevated temperatures, thereby requiring critical safety levels [20].

The fatigue strength of materials subjected to constant amplitude loading (CAL) at elevated temperature significantly decreases compared with that at room temperature. The fatigue resistance of metals in air decreases with increased temperature. Fatigue at elevated temperatures produces large strain deformation, assists in the crack-initiation process, and accelerates the crack propagation

* Corresponding author. Tel.: +60 3 8911 8411; fax: +60 3 89118389.
E-mail addresses: kamarul1@eng.ukm.my (K.A. Zakaria), shahrum@eng.ukm.my (S. Abdullah), mariyam@eng.ukm.my (M.J. Ghazali).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.01.020

rate. Crack initiation occurs much earlier at elevated temperatures. The crack growth rates at elevated temperatures are considerably higher than those at ambient temperatures [7,8,21]. Finally, the total fatigue life decreases with increased temperature. At elevated temperature, the material or structure subjected to cyclic loading may also fail in different modes from normal fatigue fracture [22]. Hence, determining the temperatures at which the strengths of materials become optimal is a critical issue. Many structural components are subjected to cyclic loading at various temperatures; thus, the effects of elevated temperatures on the fatigue life behaviour need to be understood.

The load sequence has been shown to be affected by the material type and loading conditions, such as the magnitude and position of overloads/underloads in the sequence, arrangement of block loadings, stress ratio, mean stress. These parameters affect the fatigue crack initiation and propagation, as well as the total number of cycles to failure [23–32]. However, all these fatigue studies were performed at room temperature. Accordingly, our group was prompted to study the load sequence effect at elevated temperatures.

This paper aimed to investigate the fatigue life of medium- and high-strength aluminium alloys, AA6061 and AA7075, respectively, when subjected to different loading sequences under ambient and heated environments. The fatigue study of these materials at elevated temperatures, particularly under VAL, is important to understand their behaviour and durability for applications at high temperatures. The effect of loading sequences on these alloys at room and elevated temperatures was analysed and compared relative to the three types of loading sequences, i.e., CAL, high-to-low loading, and low-to-high loading sequences. All these loadings were derived from the VALs that were measured on a car component under real-time driving conditions. Fully reversed axial loading fatigue tests were performed using a 100 kN servo-hydraulic fatigue testing machine according to the ASTM: E466-07. The loading sequences and temperatures were expected to affect both aluminium alloys significantly.

2. Theoretical background

Structural or engineering components made of different materials are commonly subjected to cyclic or fluctuating stress in service. Various parts of moving machine are subjected to severe vibration with load fluctuations. The response of a material to cyclic loading significantly differs from that to static loading [33,3]. Fatigue failures occur on a component when subjected to cyclic loadings even though the maximum cyclic load is much lower than the static strength of a material.

There are three major methods can be used to predict the fatigue life, namely, strain-life, stress-life, and fracture mechanics. Strain-life analysis requires a description of the material response to cyclic elastic–plastic strains as well as the relationship between these strains and fatigue life to crack initiation. Strain-life prediction is normally applied with a strain-life model. The strain-life relationship or Coffin–Manson relationship is based on the total strain amplitude [35], which is defined by the following equation:

$$\varepsilon_a = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \quad (1)$$

where ε_a is the true strain amplitude, σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, E is the modulus of elasticity, and $2N_f$ is the number of reversals to failure for a particular stress range.

A simple correction was proposed by Morrow [35] and Smith et al. [36], known as the Morrow and Smith–Watson–Topper (SWT) strain-life models, respectively. These two models consider the mean stress effect in the calculation. Morrow's strain-life model is mathematically defined by the following expression:

$$\varepsilon_a = \frac{(\sigma'_f - \sigma_m)}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \quad (2)$$

and the SWT strain-life model is defined according to the following formula:

$$\varepsilon_a\sigma_{\max} = \frac{(\sigma'_f)^2}{E}(2N_f)^{2b} + \sigma'_f\varepsilon'_f(2N_f)^{b+c} \quad (3)$$

where σ_m is the mean stress and $\sigma_{\max}$ is the maximum stress for the particular cycle.

Among fatigue damage accumulation rules, the linear damage accumulation rule (also known as Palmgren–Miner's rule) is the most commonly used [37]. The fatigue damage accumulation under VAL can be calculated using this rule, which is stated as:

$$D = \sum_{i=1}^{k}\frac{n_i}{N_i} \quad (4)$$

where D is the fatigue damage of the material, n_i is the number of applied loading cycles corresponding to the ith load level, and N_i is the number of cycles to failure at the ith load level from constant amplitude experiments. The calculation of fatigue damage accumulation using Palgren–Miner's rule does not take into account the loading sequence effect [38]. However, the loading sequence effect on the fatigue life was clearly demonstrated in experimental results.

The stress-life (S–N) curve provides useful fatigue data for estimating the number of cycles to failure of material at a certain level of applied stress. The S–N curve for a CAL is plotted on a semi-log or log–log scale that contains few experimental data. The S–N curve was developed by curve fitting on tabular data following the Basquin equation [39], which can be written as:

$$\frac{\sigma}{2} = \sigma_a = \sigma'_f(2N'_f)^b \quad (5)$$

where σ_a is the stress amplitude, σ'_f is the fatigue strength coefficient, $2N'_f$ is the number of reversals, and b is the Basquin exponent.

In term of statistical analysis in engineering practice, the Weibull distribution is a useful theoretical model of life data that has been successfully applied. In this model, a general distribution can be made to model a range of life distributions. From the Weibull analysis, the component's life distributions can be obtained. Representations of the data from graphical plot are useful in detecting outliers, estimating the minimum life, and observing failure times from a Weibull distribution [40]. The two-parameter Weibull distribution function can be written as [41]:

$$F(x; b; c) = 1 - e^{-\left(\frac{x}{b}\right)^c} \quad (6)$$

In term of this study, $F(x;\ b;\ c)$ represents the probability of the fatigue life being equal to or less than x, b is a scale parameter, and c is a shape parameter. b and c are estimated by observation.

3. Methodology

Throughout this study, fatigue tests were performed on specimens fabricated from two types of aluminium wrought alloy (AA6061-T6 and AA7075-T6). These materials were received in T6 condition, indicating that the material had been solution heat treated and then artificially aged to increase the alloy strength. This aging process is usually maintained until the maximum or near-maximum strength is achieved [42,43]. The typical chemical compositions [44] of AA6061and AA7075 are shown in Table 1.

The dumbbell-shape specimens were machined from solid wrought bar and their dimensions were set according to the ASTM: