European Journal of Mechanics A/Solids 29 (2010) 1008–1014

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

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

Microstructure scaling properties and fatigue resistance of pre-strained aluminium alloys (part 1: Al—Cu alloy)

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ARTICLE INFO

Article history:
Received 6 March 2009
Accepted 15 July 2010
Available online 5 August 2010

Keywords:
Fatigue
Impact
Consecutive loadings
Damage tolerance
Scaling exponent
Aluminium alloy

ABSTRACT

The objective of this work is to provide the link between the fatigue behaviour of pre-strained aluminium alloys and the scaling properties of damage induced on the fracture surface. Fatigue tests performed on pre-strained aluminium alloys revealed a large difference in their residual fatigue resistance linked to the material: the Al—Cu alloy demonstrated a sharp decrease of HCF life-time due to the pre-straining whereas the insensitivity of the Al—Mg alloy was clear. For the Al—Cu alloy, the investigations made at a 'mechanical' scale allow us to associate the strain energy absorbed during the prior loading with the aspect of the surface and the residual HCF life-time. The statistical characterization of the fatigue damaged zone was done from the measurement of the surface roughness. Scaling properties were established that allowed the conclusion of the universality of HCF damage kinetics as the mechanism controlling the sensitivity of Al—Cu alloy whatever the pre-straining history.

1. Introduction

The interaction between the pre-loaded states and high cyclic fatigue (HCF) is of great interest. Low cycle fatigue (LCF) and quasi-static and dynamic pre-loadings can represent foreign object damage (FOD) for the application in the aircraft engine industry, for instance (Peters and Ritchie, 2000; Martinez et al., 2002). The natural tendency in the prediction of HCF failure for the pre-loaded materials is the development of the so-called 'damage tolerant' approach (DTA) based on the prediction of crack propagation to detectable flaw size (Nicholas, 1999; Ritchie and Lankford, 1986). In the comparison with LCF, HCF kinetics includes a relatively large fraction of life for the creation of damage to a detectable size. This results in a very small fraction of life-time remaining. Consequently, the estimation of the HCF life-time in the presence of damage from other sources is related to the capability of materials to resist in the conditions of initial or in-service damage. The concept of DTA needs a fundamental understanding of nonlinear aspects of damage-failure transition. It means that one of the main goals of DTA can be formulated as the way to improve the method of estimation of the HCF life-time, when the material capability is reduced by in-service loadings.

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doi:10.1016/j.euromechsol.2010.07.005

Much research has been conducted to identify and detect HCF damage in the early stages of total fatigue life and several types of fatigue damage related to different scales can be identified (Suresh, 1991): persistent slip bands (PSB), striations, micro-cracks formed at the interfaces between PSB and the matrix, damage at grain boundaries. Most of the damage is related to the defect range from 0.1 μm to 1 mm which is below the non-destructive evaluation limit ($\sim$1 mm). Moreover, it is generally observed that a component in-service spends about 80% of its life-time in the formation of dislocation substructures and short crack growth. As a consequence, study of multi-scale damage kinetics becomes an important part in the estimation of HCF life-time (Peters and Ritchie, 2000; Nicholas, 1999).

This research is devoted to the study of two aluminium alloys (Al—Cu and Al—Mg) that revealed qualitatively different fatigue responses on pre-strained states, depending on their compositions and hardening modes (Froustey and Lataillade, 2008). This paper concerns the Al—Cu alloy.

The first part presents the mechanical aspect: the experiments and the residual properties of the material after different configurations of pre-straining. The second part concerns the investigations made on the fracture surfaces to study scaling properties: the measurements on the roughness zones induced from the different types of damage. In the last part, a link between the mechanical behaviour, the damage induced from the pre-loadings and the microstructure properties (scaling invariance) is proposed.

Table 1
Chemical composition (in weight %).

Alloy	Cu	Mg	Mn	Si	Fe	Zn	Cr	Ti + Zr
Al–Cu (2017A-T3)	3.5–4.5	0.4–1.0	0.4–1.0	0.2–0.8	≤0.7	≤0.25	≤0.1	≤0.25

2. High cycle fatigue failure of pre-strained Al–Cu alloy

Impact tensile – fatigue and quasi-static tensile – fatigue loadings have been carried out on Al–Cu alloy. These loadings were chosen to represent the current sequences found during the life of a structural component in the transportation sector.

2.1. Material and experimental set-up

2.1.1. Material and specimen

The 2017A-T3 is an aluminium–copper alloy, largely present in aircraft structures. It is a structural hardening material. The T3 denotes a quenched, cold work hardening and naturally aged state. The microstructure consists of two phases: α (or Al–Cu phase), which is the copper solution in the aluminium matrix and β (Al_2Cu phase), the second phase of precipitates. The β phase is finely dispersed and has a size in the range of about 10×10^{-9} m. In addition, dispersoids and inter-metallic inclusions are contained in the material. The mean size of these precipitates varies from about 100 to 500×10^{-9} m for the first type to about 4 to 5×10^{-6} m for the second type.

The chemical composition (in weight %) of the alloy is provided in Table 1 and its tensile properties are summarized in Table 2.

The geometry of the specimens, which must be adaptable for both fatigue and impact testing machine is given in Fig. 1. They were drawn with a toroidal cross-section to localize the fatigue damage and to minimize the fatigue scatter.

2.1.2. Testing machines

2.1.2.1. Impact device. The impact loadings were carried out using an inertial flywheel. The principle and associated measurement techniques of this device are described in Froustey et al. (2007). It is possible to stretch specimens at medium or high strain rates (up to 10^3 s^{-1}). Its essential elements are a wheel and a pendular system (Fig. 2).

The wheel has a large size (1 m diameter), a large mass (620 kg) and is equipped with a hammer on its circumference. The pendular system consists of a 3 m long bar: one end is used as the pivot and the specimen and an anvil are attached to the other end. To store energy, the wheel turns freely until reaching the selected speed, and then the pendular system is lowered. The hammer impacts the anvil and the specimen is strained.

2.1.2.2. Prior tensile loadings (impact and quasi-static). To carry out prior impact loadings, a specific device coupling a displacement limit stop and a mechanical fuse have been designed (Fig. 3). After the hammer impingement on the anvil, the specimen is stretched until the washers hit against the frame. The fuse, which makes the junction between the two parts of the extension component which is therefore the weakest element, and it therefore breaks. Before the test, the space between the washers and the frame was regulated with calibrated spacers: a controlled extension (DL) was imposed on the gauge zone of the specimen. Various values of prior elongation were applied (DL = 0.5, 1 and 1.5 mm), characterized by the k factor, which was determined as the imposed elongation over the total impact failure elongation (in percent). k values were respectively 25, 50 and 75%. The tests were performed at about 5 ms^{-1} that gave a strain rate of about 300 s^{-1} in the central zone of the specimens.

Prior quasi-static loadings were carried out on a classic tensile machine (Instron 8500 series), using the same specific device. To characterize the strain rate effect of pre-damage, the same elongation values were used.

Characteristic dynamic and quasi-static diagrams for Al–Cu alloy are presented in Fig. 4 and the markers (DL) show the pre-loading configurations.

Table 2
Quasi-static tensile characteristics.

Alloy	Elastic modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
Al–Cu (2017A-T3)	75	427	573	13

2.1.2.3. Fatigue device. The fatigue tests were done on a resonant electromagnetic machine (Amsler Vibrophore) with a controlled force, for fully reversed tensile-compression loading. The principle is to set and maintain a spring-mass system, in which the specimen represents the spring, in a resonant state. The frequency of oscillations is recorded, which makes it possible to detect damage occurrence in the specimen: the appearance of fatigue cracks will cause a decrease of its stiffness and consequently of the oscillation frequency. The frequency shift was used as a test-stop and fixed at 0.4 Hz, equivalent to a crack section of about 2–4 mm^2.

The stress level chosen for the study of the residual fatigue behaviour corresponds to a life-time of about 2×10^5 cycles (220 MPa) for the damage free material. In this field, the number of cycles to failure (N_F) follows a log-normal law, then the stress level was imposed and N_F was recorded. Because of the fatigue scatter, 5–10 samples were tested under each configuration that allows us to determine the mean value and the associated standard deviation of N_F.

2.2. Residual high cycle fatigue properties

2.2.1. Residual fatigue life

The results are summarized in Fig. 5. It represents the mean value (markers) and the associated standard deviation (vertical lines) of the number of cycles to failure, versus the defined k factor. (To compare the difference in behaviour, the results obtained on the Al–Mg aluminium alloy have been plotted on the same figure: its insensitivity to the pre-tensile loading is obvious). Looking at the Al–Cu results, it can be noticed: 1) N_F is highly influenced by the pre-tensile loadings. 2) No influence of the pre-loading strain rate on N_F can be observed: pre-straining from quasi-static loading or pre-straining from dynamic loading result in roughly the same

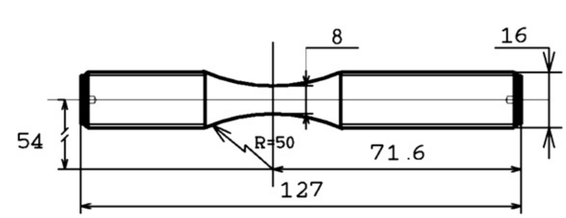

Fig. 1. Specimen geometry (dimensions in mm).