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Technical note

The effect of compression loading on fatigue crack propagation after a single tensile overload at negative stress ratios

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ABSTRACT

Experiments on fatigue crack propagation under a loading history with a single tensile overload at an overload ratio of $R_{OL} = 1.8$ were performed at different baseline stress ratios of $R = 0$, -0.25, and -1 for aluminium alloy 2A12-O. The widely accepted fatigue crack propagation retardation due to a single tensile overload (OL) in the case of a positive stress ratio (R) was observed at $R = 0$. However, the retardation effect gradually decreased from $R = 0$ to $R = -0.25$ and disappeared at $R = -1$. These results indicate that the applied compressive load has a significant effect on the fatigue crack propagation after a single tensile overload for aluminium alloy 2A12-O. To reveal the mechanism of this effect of compression loading, a detailed elastic-plastic finite element (FE) analysis was performed. Based on the results of finite element analysis, a mechanism of additional reverse plastic damage caused by compression loading was proposed to explain the interaction of tensile overload and compressive load. The parameter of reverse plastic zone size was applied to characterize the additional reverse plastic damage. A parameter describing the effect of compression loading on fatigue crack propagation retardation due to a single tensile overload was developed. Using this parameter it was verified that the mechanism of additional reverse plastic damage is effective to explain the compression loading effect on the fatigue crack propagation retardation due to a single tensile overload.

1. Introduction

It is widely accepted that the tensile overloads during variable amplitude loading produce fatigue crack propagation retardation at a positive stress ratio. However, overloads occur very frequently under negative stress ratios [1]; a few papers [2–9] reported that the compressive loads during cyclic loading have significant influences on fatigue crack growth under constant amplitude loading and variable amplitude loading.

1.1. Constant amplitude loading

It is well known that the fatigue crack growth rate (FCGR) can be predicted using the stress intensity factor range ΔK and the applied stress ratio (R). Paris and Erdogan [10] first proposed the following equation (Eq. (1)):

$$da/dN = C(\Delta K)^m \tag{1}$$

where C and m are the constants dependent on the material and the stress ratio R [10]. The crack closure concept formulated by Elber [11] is the most accepted method to correlate crack growth to different R. There are also partial crack closure models [12], a two parameter method using the stress intensity factor range, ΔK, and the maximum stress intensity factor in a stress cycle, K_{max}, to describe the fatigue crack propagation [13] and other models based on residual stresses [14] or environmental factors [15,16]. Almost all of these models ignore the contributions of the compressive load part of the fatigue load cycle, as recommended by ASTM E647–2013a [17]. Therefore, in a tension–compression loading, $\Delta K = K_{max}$, the approach is based on the assumption that the fatigue crack tip has been closed during compression loading. Thus, there is no stress concentration around the closed fatigue crack tip. Moreover, no stress intensity factor is associated with the closed crack. The reverse plastic damage produced by the compressive load during a tension–compression loading is also very small.

However, during the last decades, some papers [2–9] reported that compression loading plays an important role on fatigue crack growth during tension–compression loading.

Kemper et al. [2], Tack and Beevers [3], Carlson and Kardomateas [4], Pommier et al. [5], Zhang et al. [6,7] and Silva [8] all found a strong detrimental effect of the compressive part of the cycle. Carlson

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and Kardomateas [4] also observed a saturation phenomenon that the FCGR was slightly increased with a more highly applied compressive load.

Kemper et al. [2] observed that the effect of compression loading on FCGR differed significantly for three different alloys. Some papers [8,9,18], and [19] also reported that the effect of compressive load on FCGR is strongly material-dependent. For Ti6Al4V and Al7175 [8], the compression part of the fatigue load cycle had little effect on FCGR. Nevertheless, for Al 2024-T351 [8,9,18], Al 2A12-O [19], ck45 and 0.4% mild steel [9,18] and N18 base super alloy [5] the compression part of the fatigue load cycle had a significant effect on FCGR.

Using the closure phenomena, either roughness induced closure or plastic induced closure, Kemper et al. [2], Tack and Beevers [3], and Carlson and Kardomateas [4] explained the partial fatigue crack propagation behaviour observed under negative R.

Pommier [5], Zhang et al. [6,7] and Silva [8], however, all concluded that this particular fatigue crack propagation behaviour under negative R was attributed to plastic properties of the material and the amount of Kinematic hardening of the alloys. The crack propagation behaviour under tension-compression loading is not in accordance with the crack closure concept and Newman's equations [20].

Moreover, roughness properties do not appear to be relevant [8]. Chen and Lawrence [21] concluded that roughness-induced crack closure may be as relevant as plastic-induced crack closure for positive R ratios, but roughness-induced crack closure is not a relevant mechanism for $R = -1$. Plastic-induced crack closure is dominant at $R = -1$.

Therefore, the compression loading effect on FCGR cannot be ignored for a constant amplitude loading under negative R. The plastic properties, mainly the cyclic plastic properties, have increased importance on the crack growth rate.

1.2. Variable amplitude loading

Dabayeh [22] reported that the fatigue crack propagation behaviour after tensile overloads at a negative stress ratio was the same as that under a positive R. However, Halliday [23] reported that tensile overloads had no influence on FCGR at $R = -1$, and it had a retardation effect at $R = 0.5$. Makabe and McEvily [24] found that a tensile overload has an acceleration effect on the FCGR when $R < 0$, rather than a retardation effect on fatigue crack propagation. These results indicate that the compression part of cycle also has effects on the FCGR after a single tensile overload under negative R.

Silva [1,8] found that the property of cyclic hardening and the Bauschinger effect showed a close relation with the applied compressive load. By comparing different FCGR models, Silva [25] concluded that the mechanism based on the fatigue crack closure concept was not suitable to explain the crack propagation behaviour under negative R. Silva [25] developed a competing mechanism between damage accumulation and residual stress shielding to explain the effect of the tensile overload both at negative and positive R. By considering the material's cyclic plasticity, the competing mechanics can also explain the material-dependent feature of a compression loading effect on the fatigue crack propagation after tensile overloads.

However, no mathematical model based on this competing mechanism has been developed to characterize this damage accumulation. Moreover, no detailed mechanics analysis results on this competing mechanism have been reported.

Under constant amplitude, Zhang et al. [6,7] found that the maximum stress intensity factor $K_{\max}$ and the maximum applied compressive load σ_{maxcom} of cyclic loading were the two external loading parameters that determine the crack tip stress, displacement and plastic deformation under a tension-compression loading cycle of constant amplitude. The reverse plastic zone size was a suitable internal parameter for correlating FCGR under negative R. Unfortunately, they only discussed the fatigue crack propagation under constant amplitude loading.

This work will focus on the following aims:

A. to verify that the applied compressive load of cyclic loading is the key parameter controlling FCGR after a single tensile overload at negative R.
B. to further clarify the mechanism of the effect of compression loading by comparing the stress field before and after overloading.
C. to develop a mathematic model describing the effect of compression loading on the fatigue crack propagation retardation after a single tensile overload at negative stress ratios and to verify the effectiveness of the mechanism of the compression loading effects.

2. Material and methods

2.1. Materials and specimens

An annealed 2A12 aluminium alloy (2A12-O) sheet with a thickness of 3 mm used in this work was produced at the Northeast Light Alloy Co. Ltd. in Harbin, China. The aluminium alloy 2A12 (Chinese chemical composition standard GB/T3190-2008, Chinese technique standard GB/T 3880-2012) is an important material used in the structural parts of aircraft; its nominal chemical composition according to GB/T3190-2008 is provided in Table 1. The microstructure feature of this alloy was reported in detail in papers [26,27].

The tensile test was performed; the following and mechanical properties were obtained: elastic modulus of 70 GPa, 0.2% yield stress of 120 MPa, and ultimate tensile stress of 230 MPa. The middle tension, M(T), specimen for the test of fatigue crack growth, with a 2 mm diameter centre bore, was machined along the rolling direction of the alloy sheet using linear cutting. All specimens were not subject to further heat treatment before tensile tests and fatigue tests. The geometry of each specimen is shown in Fig. 1; the dimensions of each specimen are 70 mm wide, 280 mm long and 3 mm thick. In addition, the M(T) specimens were all prepared along the L-T directions. Here, the L direction is the rolling direction of the alloy sheet; and the T direction is perpendicular to the rolling direction. The direction of applied load is along the L direction, and the T direction is the fatigue crack growth direction.

All the M(T) specimens have an initial artificial pre-fabricated crack of 8 mm length, as shown in Fig. 1, through linear cutting and polishing. The surfaces of the specimens were subject to grinding to remove the surface scratches. The surface finish of each specimen is less than 0.8 μm.

2.2. Test procedures

The fatigue crack growth rate tests were conducted in laboratory air at 20 °C, using a MEP-200-200kN Microcomputer Control servo-hydraulic fatigue-testing machine that manufactured by Jinan East Testing Machine Co., Ltd, in China. This fatigue-test machine has a force sensor with a measuring range of 2%-100% of the maximum applied force and a measuring accuracy of ± 1%. Tests were performed using axial cyclic loadings under loading control at a frequency of 20 Hz.

In the fatigue crack growth tests, the half crack length a is determined by measuring the horizontal distance from the centre of the bore to the crack tip, as shown in Fig. 1. A pre-crack of approximately

Table 1
Chemical composition of 2A12-O aluminum alloy (Wt., %).

Si	Fe	Cu	Mn	Mg
0.5	0.5	3.8–4.9	0.3–0.9	1.2–1.8
Ni	Zn	Fe + Ni	Ti	Al
0.1	0.3	0.5	0.15	Bal.