International Journal of Fatigue 42 (2012) 95–103

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Crack retardation mechanism due to overload in base material and laser welds of Al alloys

S. Daneshpour [a,*], J. Dyck [b], V. Ventzke [a], N. Huber [a]

[a] Helmholtz-Zentrum Geesthacht, Institute of Materials Research, Geesthacht, Germany
[b] University of Waterloo, Dep. of Mechanical Engineering, Waterloo, Canada

ARTICLE INFO

Article history:
Available online 30 July 2011

Keywords:
Overloads
Fatigue crack growth
Weld metal
Aluminium alloys
Damage

ABSTRACT

To determine the retardation mechanisms due to overload and to predict the subsequent evolution of crack growth rate, investigations are conducted on crack retardation caused by single tensile overloads in base material and laser-welded sheets of AA6056-T6 Al alloy. The effect of the overload ratio on the fatigue crack propagation behaviour of the C(T) 100 specimens was analysed by using experimental and Finite Element (FE) methods. The crack growth rate and fracture surface features were investigated for both base material and laser-welded sheets. The retardation due to overload is described in terms of the affected regions in front of the crack tip. The size and shape of the crack-tip plastic zone and the damage profile induced during the application of the overload in the base material are predicted by FE analysis in conjunction with a porous-metal plasticity model. The results show that the mechanisms of retardation in under-matched welds are substantially different from that of the homogenous base material. More significant crack retardation due to overload has been observed in the laser weld of AA6056-T6. Based on SEM observations of the fracture surfaces and the damage profiles predicted by the proposed FE model, the shape of the crack front formed during the overload application can be predicted. During the overload, the crack front extends into a new shape, which can be predicted by the ductile damage model; a higher load results in a more curved crack front. These outcomes are used to determine the dominant retardation mechanisms and the significance of retardation observed in each region ahead of the crack tip and finally to define the minimum crack growth rate after overload.

1. Introduction

Aircraft structures operate under spectrum loading (variable amplitude cyclic loading) where load history effects occur. The occurrence of an overload (high-low load sequence) has a strong effect on the crack propagation behaviour; tensile overloads lead to favourable crack retardation or even crack arrest, particularly in laser-welded Al sheets [1]. The reliability of fatigue life prediction methods depends mainly on their ability to account for the mechanisms of damage taking place during cyclic loading. An accurate understanding of the mechanism for the load-interaction effects and its consequence on the material ahead of the crack tip and its consequence on growth rate of the ongoing fatigue crack is essential for the damage tolerance design and the development of the lifetime prediction models. Conventional fatigue life calculations, e.g. the Miner rule [2], lead to an imprecise fatigue life prediction in the real components subjected to spectrum loading. Improvements in the accuracy of life prediction methods can be made by adding the effect of load interactions that are always occurring in a load spectrum.

Laser beam welding (LBW) is currently replacing the conventional riveting technology in several aircraft structures to reduce weight and fabrication cost [3,4]. LBW technology is currently employed to fabricate integral stiffened panels containing T-joints between a stringer and a skin sheet. This advanced LBW technology is capable of producing highly complex and competitive airframe parts for current and future metallic aircrafts [5]. To extend the current application area of the welded panels, it is essential to improve the current level of knowledge on the damage tolerance performance of the welded Al-alloy components. Here, fatigue crack propagation (FCP) is one of the main areas of interest to improve the structural performance of the aircrafts. Clearly, damage tolerance design concepts based on FCP performance are important to describe design life and inspection intervals.

Crack retardation due to tensile overload is one phenomenon that makes damage accumulation dependent on the sequence of the stress time series. A typical effect of overload on the extension of fatigue life (N_D) is schematically shown in Fig. 1a. According to Fig. 1b, a delay in the crack growth rate due to an overload can be divided into two separate phases [6]: Phase 1 occurs directly

---

* Corresponding author. Tel.: +49 (0) 17662396151.
E-mail address: s.daneshpour@gmail.com (S. Daneshpour).

0142-1123/$ - see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.ijfatigue.2011.07.010

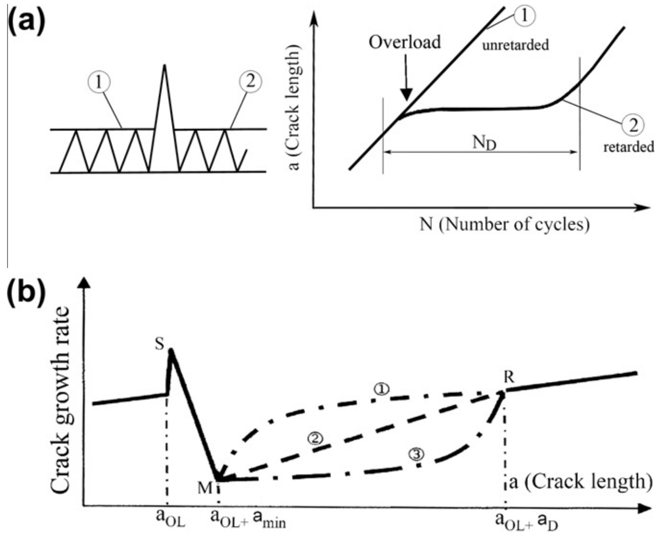

Fig. 1. (a) Typical fatigue life extension (N_D) due to an overload and (b) delay in crack growth rate after overload [6].

after applying overload (point *S* in Fig. 1b) and is due to the loading cycle effect; the growth rate decreases to reach the minimum growth rate (point *M* in Fig. 1b). Phase 2 is due to crack growth. A total restoration of the crack growth rate (until point *R* in Fig. 1b) may occur under one of the paths described in Fig. 1b.

Two aspects that support the study of overload (OL) effects (or in more general terms, load interaction effects) on fatigue crack growth are summarised below:

(I) The development of damage tolerance design and accurate life prediction of aircraft components under variable amplitude loads requires a deep understanding of the micro-mechanism of crack retardation due to OL. The delay phenomenon of the crack growth in fatigue following an OL, remains only partially understood, although it has been investigated by numerous researchers [7–12]. Due to the lack of experimental capabilities to measure stress/strain fields within the bulk material under applied load, the relationship between overload and retardation has not yet been quantitatively established.

(II) Overloads can be used as a way to improve the fatigue performance of welded structures where the weld metal is softer than the base material. It has been shown that the application of a single overload (SOL) during cyclic loading may cause a significant decrease in the crack growth rate or even full arrest of the crack [1].

The cause for crack retardation due to overload can be explained by several phenomena such as crack deflection and bifurcation, crack tip blunting [13], strain hardening of the material at the crack tip [14], crack closure (induced by plasticity [15], roughness or oxidation), and compressive residual stresses ahead of crack tip [16]. Among these mechanisms, plasticity-induced crack closure and compressive residual stresses are the two most widely accepted overload-related retardation mechanisms. Both mechanisms are widely used to model post-overload crack growth. However, it is difficult to consistently explain the retardation phenomenon based on any single mechanism. The problem is even more complicated in the case of welded components, as the material heterogeneity and residual stresses caused by the welding process influence the crack propagation rate, but their effects cannot be treated independently from that of an overload.

There is currently little explanation found in the literature for the delayed effect of overload crack retardation, particularly for the deceleration part of the curve (*S*–*M* path in Fig. 1b) and the exact value and location of point *M* at minimum crack growth rate (a_{min}). In this study, investigations were carried out to understand the mechanisms of fatigue crack growth retardation due to an overload and to provide evidence to determine the value and location of the minimum crack growth rate. The aim is to develop a reliable fatigue life prediction, a central theme in the design of aerospace components and assemblies. Finite Element (FE) simulations in conjunction with experimental tools, such as scanning electron microscopy and an optical plastic strain measurement have been used to analyse the fracture surface and to provide a better understanding of the dominant retardation mechanisms due to overload. In the following sections, the effects of an overload on the crack growth rate and shape of the crack front are discussed for laser welded/non-welded AA6056-T6 sheets in standard Compact-Tension specimens, C(T) 100.

2. Methods

2.1. Experimental details

The materials used in this study were AA6056-T6 aluminium alloys sheets with a thickness of 6.1 mm; the 6xxx series of aluminium alloys, where the primary alloying components are magnesium and silicon, grant a good weldability. The aluminium sheets were welded with a CO_2 laser beam in the butt joint configuration with full penetration. The details of the welding parameters and the weld configuration are explained in Ref. [17].

To determine the effect of a single overload on the fatigue crack retardation, a standard Compact Tension specimen, C(T) 100, prepared in accordance with the standard test method for the mea-

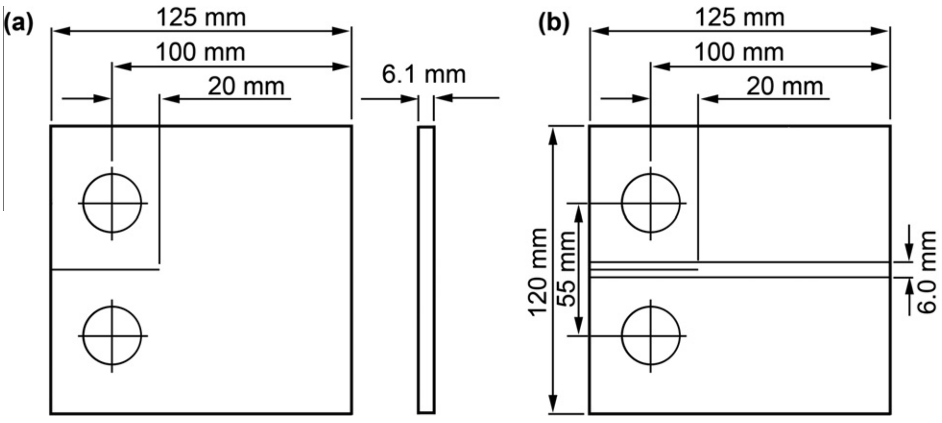

Fig. 2. Geometry of C(T) 100 specimens used in this study: (a) base material and (b) laser welded specimen.