Influence of Residual Stress on the Fracture Behaviour of an Aluminum Alloy

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Abstract

Influence of residual stresses on fracture response of an Aluminum alloy is investigated. Cylindrical flat ended punching tools are employed to introduce residual stresses on 15mm thick C(T) specimens. The residual stress field resulting from Local Compression is simulated and analysed using a finite element analysis. The dependence of residual stress field on the size as well as the relative position of the punching tools to the crack tip is also investigated by performing a parametric study. The effect of residual stress on the subsequent fracture response of Aluminum specimens under mode I loading is explored by performing an experimental programme. The scatter of fracture toughness results compared for specimens with and without residual stress. The results show a remarkable reduction in fracture toughness following local compression of the specimens.

Keywords: Residual stress, local compression, punching, and fracture toughness

Introduction

The role of residual stress in assessing the structures integrity containing defects has been given special consideration as these stresses can have a detrimental influence on the performance of such structures [1]. Service fractures have occurred under the influence of residual stress alone with negligible external load [2]. The combination of high tensile residual and operating stresses can promote failure by fracture or may change the susceptibility to a failure mode, e.g., promotion of brittle cleavage failure rather than ductile tearing [1]. The influence of residual stresses on fracture behaviour depends on the level of plasticity in the component prior to failure. The fracture mechanism, which is a function of material characteristic and loading conditions, controls the effects of the residual stresses. Ainsworth et al [3] showed that under predominantly elastic conditions, residual stresses can significantly reduce the load carrying capacity. It has been shown, on the other hand, that the effect of residual stress is reduced significantly when plasticity is widespread [4]. The influence of residual stresses on fracture response can be related to the variation in J-integral. However, O'Dowd et al [4] showed that the J-integral is not path independent in the present of residual stresses and changes with the domain radius. Consequently, they proposed a modified J-integral...
estimation method that is path independent in the present of residual stress [5]. Nevertheless, it is generally accepted that residual stresses alter fracture conditions by contributing to crack-driving force as well as crack-tip constraint [6]. Such an approach would depend on the determination of both J-integral and stress intensity factor due to the residual stress-state acting alone [7,8].

Depending on the direction of the residual stresses relative to the stresses arising from operational loading of structural components, residual stresses may be beneficial or detrimental. Proof-loading or warm pre-stressing are examples of processes that produce beneficial residual stresses. For example Smith and Garwood [9] showed that proof testing appears to produce local crack-tip compressive residual stresses after unloading, which will initially reduce any subsequent fatigue crack growth.

Compressive residual stresses create significant improvements in fatigue life and apparent fracture toughness of the treated components. Tensile residual stress can have detrimental influence in reducing the subsequent load carrying capacity of the component. It is important to develop a consistent method to create residual stress fields. Almer et al [10] employed a radial cold expansion method to produce residual stresses in front of the crack-tip in compact tension C(T) specimens. Ogeman [11] also used a coining process around a hole to introduce residual stresses. Local compression (LC) is a standard method to relax residual stresses that are produced following welding [12,13]. According to the several standards [12,13], the application of local compression to the ligament below the machined notch is often sufficient to reduce the weld residual stresses to low and uniform levels resulting in the growth of an acceptably straight fatigue pre-crack. Hill [8] has used this technique to introduce residual stresses in single edge notch bend specimens.

In this work the influence of residual stresses, generated by local compression, on the fracture behaviour of Aluminum C(T) specimens is investigated. The results obtained by finite element studies and experimental programme are presented.

**Material and specimens**

The material used in this research is a special aluminum alloy, known as Al 2650, developed for supersonic applications in the aerospace industry. The 15mm thick plate of Al2650 was 1000mm long in the rolling direction and 450mm wide. The plate was obtained, by hot rolling, from a 170mm thick die cast ingot. Garcia-Granada [14] carried out an extensive experimental programme to examine the material response. The mechanical behaviour of Al 2650 at room temperature is given in Table 1.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>E-GPa</th>
<th>σ_y-MPa</th>
<th>σ_4%-MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature</td>
<td>72</td>
<td>427</td>
<td>448</td>
</tr>
</tbody>
</table>

The hardening behaviour of this alloy in tensile and compressive loading, shown in figure 1, was also determined by Garcia-Granada [14]. The yield stress, σ_y, was calculated for an initial plastic strain of 0.1%. The plastic response of this material was very close to perfect plasticity beyond yielding. The material response for compression was different from isotropic or kinematic hardening models. It is noticeable that both isotropic and kinematic models illustrate higher compressive stresses in comparison with the experimental data.

To assess the effect of residual stresses on fracture behaviour, standard C(T) specimens were manufactured with a thickness of 15mm. The thickness of the Aluminum plate. Details of the specimen dimensions are shown in figure 2.

**Generation of residual stresses using LC**

Rather than using local compression (LC) to relax existing residual stresses, in this study the LC method was used to generate residual stresses. The phrase 'local compression' is a short definition for the surface compression of a C(T) specimen using flat-ended cylindrical punching tools as shown schematically in figure 3. Local compression was performed on both sides of the C(T) specimen by applying two punching tools simultaneously. Loading was continued until plastic deformation of the specimen surface reached a specified level, referred to as the total indentation. Unloading of the specimen was then achieved by moving the punching tool back to its
original position. This procedure produced a residual stress field in the specimen. The displacement controlled process was adjusted to obtain a final reduction in thickness after removal of the punching tool equal to 1.6% of the specimen thickness. The amount of indentation was chosen based on previous work by Meith et al [8] who showed that the apparent fracture toughness after punching depended on the amount of indentation.

The present work was aimed at conducting tests to establish how fracture toughness is modified in presence of tensile residual stresses. This is achieved by developing LC technique so that it introduces tensile residual stresses ahead of the crack-tip of the C(T) specimens. Finite element (FE) simulations were conducted to establish the most effective LC method for introducing residual stresses. Details of the FE analysis are described next.

**Finite element studies**

Finite element simulations of the local compression and then unloading processes were carried out using elastic-plastic computations. The finite element solutions employed a non-linear, large strain formulation. The commercial code ABAQUS was used to perform the analyses [15]. A three dimensional FE model of the C(T) specimen was created using the CAE pre-processor. Due to symmetry, only a quarter of C(T) specimen was modelled. A fine mesh was introduced at the crack tip, as shown in figure 4. The material model was aluminum alloy 2650. A highly refined mesh at the crack tip region was chosen to provide accurate stress and strain data from FE analyses. The model used eight-node hexahedral elements with reduced integration. A punching tool with elastic-perfectly plastic material behaviour and 0.3mm radius of the rounded edge was modelled in this simulation. Details of punching tools are given later.

**Effect of size and position of punching tool**

From FE analyses it was found that the state of residual stresses was highly dependent on the size as well as the position of the punching tool. In discussing the residual stresses, attention is focused on the stress component normal to the crack-plane, $\sigma_{33}$. To investigate the effect of size and the position of the punching tool a finite element parametric study was carried out using three different tool diameters 25mm, 15mm and 7.5mm.

To specify the position of the punching tools, a dimensionless parameter ($x/R$) was defined using the relative position of the punching tool and the crack in the specimen, where ‘x’ is the distance between the centre of the punching tool and the crack-tip and R, is the radius of the punching tool as indicated in figure 5. The crack length, $a$, was 25-mm with $a/W=0.5$. The position of the centre of the punching tool was changed only along the crack line to maintain symmetry.

Each of the three punching tools was applied at four different positions on the specimen. Figure 6 shows the relative positions of the punching tools with respect to the crack tip used in the FE simulations. The first position corresponded to $x/R$ equal 1.0, which means the edge of the punching tool was tangential to the crack front. The punching tool was then moved towards the crack-tip and positioned at $x/R$ equal 0.75 and 0.5. The last position was where the centre of the punching tool was located on the crack-tip ($x/R=0$).

A sample of the results from the FE analysis is shown in figure 7, where contours of the normal stress, $\sigma_{33}$, are illustrated. The largest region of tensile residual stress was produced by the 25mm punch for $x/R=1.0$. The residual stress field for other $x/R$ locations leads to similar patterns and suggests that the 25mm punching tool produces the greatest region of tensile residual stress ahead of the crack. The tensile residual stress field was widespread throughout the thickness of the specimen in the case of using 25mm diameter punching tool. The 7.5mm diameter punching tool produced tensile residual stresses that extended to almost half of the thickness (figure 7).

To further indicate the magnitude of residual stress, the distribution of residual stresses along two paths, one in the middle and one on the surface of the specimen, starting from the crack tip, are shown in figures 8 and 9. The distributions of residual stress following LC using a 25mm punch in four different $x/R$ positions are shown. The results indicate that positioning the edge of the 25mm diameter punch tangential to the crack front ($x/R=1.0$) results in the greatest region of normal tensile residual stresses, $\sigma_{33}$. 


A tensile residual stress field extends to around 6mm from the crack tip in the middle and to around 4mm on the surface of the specimen. It is expected that the tensile residual stress field should dramatically reduce the apparent fracture toughness. Experiments reported in the next section were designed to investigate how LC influences fracture toughness. The effect of size and the position of the punching tool were also investigated experimentally.

**Experimental programme**

Twenty five C(T) specimens were machined from the Aluminum plate. Cracks for all specimens were created by electro-discharge machining (EDM) technique using a 0.1mm thick copper blade. The resulting notch width was approximately 0.2mm wide.

**a) Local Compression of C(T) specimens**

Punchs were made of En-24 steel and then heat-treated at 600°C and then cooled down in water. The hardness of the tools increased to about 200 Rockwell-C as a result of heat treatment. Local compression was applied on both sides of the specimen simultaneously using the hardened punchs. A linear voltage differential transducer (LVDT) was used to accurately control the displacement during the LC process. The LVDT was attached to the punching tools in a way that the elastic deformation of the tools, the rods and the grips of the servo-hydraulic test machine were excluded.

The specimens were positioned and the punching tool applied at different positions on the specimens and the applied indentation was about 1.6% (of the thickness) after unloading.

The loading speed was set to 0.003 mm/sec. The maximum applied compressive loads appeared to be slightly different with the variation of the compressive load between 270-280kN. This is in a good agreement with the result of finite element simulation.

**b) Fracture tests**

In all tests the load was applied under displacement control at the speed of 0.003 mm/second at room temperature.

Initially five specimens were loaded to fracture. Two were locally compressed using a pair of 25mm diameter punches at x/R=1.0 and x/R=0.6 and another two were punched using a pair of 15mm diameter punches at similar positions. One specimen was fractured in the as-received condition (with no local compression). Figure 10 shows the results of fracture tests for these specimens indicating that the largest reduction in the fracture load occurs when the specimen was punched by 25mm diameter tools at x/R=1.0.

The remaining 20 specimens were used to explore the influence of local compression on the fracture response of the aluminum alloy at room temperature. Ten C(T) specimens were fractured in the as-received condition and another 10 were punched and then fractured as described below.

The fracture toughness was calculated using ASTM standard [16].

\[
K = \left( \frac{P}{BW^{1/2}} \right) f\left( \frac{a}{W} \right)
\]

(1)

K is the fracture toughness when P is set equal to the fracture load. Here B and W are 15mm and 50mm \((a/W=0.5)\) respectively. The non-dimensional geometrical function, \(f(a/W)\), is given by

\[
f\left( \frac{a}{W} \right) = \frac{(2 + \frac{a}{W})(0.886 + 4.64a/W) - 13.32a^2/W^2 + 14.72a/W^3 - 5.6a^2/W^4}{(1-a/W)^{1/2}}
\]

(2)

where \(a\) is the crack length. The distributions of fracture toughness for the 20 tests with or without LC are shown in figure 11. The probability of failure from experimental data was determined using

\[
P_f = \frac{i - 0.5}{n}
\]

(3)

where \(i\) and \(n\) are the order number (rank) and the population (total tests) respectively. The scatter of the fracture toughness in figure 11 indicates a remarkable reduction in the apparent fracture toughness. The average reduction in fracture toughness after local compression was around 50%.

**Discussion**

Local compression has been applied in most studies as a method to relax pre-existing residual
stress [6]. Local compression was used here to introduce residual stress in cracked specimens is investigated here.

Using LC to introduce residual stresses in cracked specimens indicated that the resulting residual stress field was highly dependent on the diameter of the punch as well as its relative position to the crack-tip. Numerical simulations using FE analysis demonstrated that full through thickness tensile residual stresses were achieved for a punch diameter 2R greater than the specimen thickness. It was found that significant tensile residual stresses ahead of the crack tip are obtained by positioning the punch tangent to the crack-tip using a punching tool diameter equal to the ligament.

The presence of tensile residual stress normal to the crack plane has a dramatic effect on the fracture toughness. This is illustrated by the results shown in Figures 10 and 11. The relative size and position of the punch to the crack tip changes the fracture toughness. For example, in Figure 10 a 15mm punch positioned partly over the crack tip at x/R=0.6 reduced the toughness but not to same extent as when at x/R=1.0. The most dramatic reduction in toughness occurred for a 25mm diameter punch located directly over the crack tip.

The statistical distribution in the fracture toughness before and after local compression was very similar. Results shown in Figure 11 reveal that the fracture toughness after LC was reduced from a mean of 31.174 MPa\(\sqrt{m}\) to 15.1 MPa\(\sqrt{m}\).

Conclusions
It was observed that local compression can produce tensile residual stress field in the cracked body even in the region under the punch. Finite element simulations also revealed that the size of the punching tool had a significant effect on the residual stress field produced within the cracked body. In addition the position of the punching tool can alter the extent of tensile and compressive residual stresses ahead of the crack-tip. It has been shown that the tensile residual stress produced by punching process drastically reduces the apparent fracture toughness.

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Department of Marine Structural, Sweden, 1993.

Fig. 1 Hardening behaviour of Al2650 alloy in tension and compression (from 13)

Fig. 2 Dimension of compact tension C(T) specimens (all dimensions in mm)

Fig. 3 Schematic of local compression on a compact tension C(T) specimen

Fig. 4 Mesh refinement for the C(T) specimen and around the crack tip

Fig. 5 Position of the punching tool relative to the crack tip
Fig. 6 Positions of the punch relative to the crack tip

25mm

Compressive residual s.

Tensile residual s.

7.5mm

15mm

Crack tip

Fig. 7 Extent of tensile and compressive residual stress following LC for three different sized punching tools for $x/R=1.0$

Fig. 8 Residual stress distribution along a path in the middle of the specimen using a 25mm diameter punch

Fig. 9 Residual stress along a path on the surface of the specimen using a 25mm diameter punch

Fig. 10 Experimental results of fracture tests for different punch sizes and different punch positions for local compression

Fig. 11 Variation in fracture toughness in as-received condition and after local compression