A NUMERICAL AND EXPERIMENTAL INVESTIGATION INTO THE GENERATION OF RESIDUAL STRESS IN FRACTURE SPECIMENS USING LOCAL COMPRESSION

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Abstract

The influence of residual stresses on the fracture behaviour of materials is of fundamental importance for accurate and reliable structural integrity assessments of components and structures In this paper residual stress fields are introduced into standard fracture specimens, particularly C(T) specimens, through ‘local compression’, or side punching. Finite element analysis showed that tensile residual stresses could be generated ahead of the crack, but their magnitude was very sensitive to the position of the punch relative to the crack tip when a single punch was used on each side of the component. Experimental results indicated differing amounts of reduction of the apparent fracture toughness in the presence of residual stresses following local compression for different materials. The method of application of local compression was then extended to the application of a double punching tool. A parametric study revealed that the size and the position of the punching tools had a strong influence on the magnitude and direction of the residual stress field.

Introduction

Most engineering components must be manufactured so they are safe to use and are “fit for purpose” [1]. Pre-service and in-service mechanical loads can increase the possibility of failure. Residual stresses play an important role in increasing and decreasing the possibility of failure. For instance, enhancement in toughness following pre-loading arises principally because of the creation of local crack tip compressive residual stresses [2]. In contrast, a combination of high tensile residual stresses and operating stresses can promote failure by fracture [3]. While compressive residual stresses create significant improvement in fatigue life and apparent fracture toughness of treated components, tensile residual stress fields can have a detrimental influence in reducing the subsequent load carrying capacity of the components. The magnitude and direction of the residual stresses is an important factor in the integrity of engineering structures, including those containing defects [4].

In order to assess the effect of residual stress fields on the fracture behaviour of materials, a well-defined residual stress field, with known characteristics must be generated in a controllable and reproducible manner. Local compression (LC) has previously been used for several purposes.

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For instance, it has been used to relax residual stresses following welding [5,6]. LC has also been used to examine material properties. The complete stress state arising from indentation of an elastic half-space by a circular, flat ended, rigid punch has been determined in closed form [7]. LC, or punching, was also used to introduce a residual stress field into fracture specimens, and the resulting residual stress field determined using Finite Element Analysis (FEA) [8,9]. This method has also been employed to create residual stresses in the SEN(B) specimens [10]. This paper briefly explains the finite element predictions and experimental evidence for the local compression technique using a single punch. In addition, results from experimental measurements of residual stresses following LC are shown. Use of a double punch on fracture specimens is then is then developed in order to limit crack tip plastic strains and thus separate the role of residual stresses on fracture behaviour.

The local compression technique

The phrase local compression is used to describe the surface compression of a C(T) specimen using a flat-ended cylindrical punching tool. Local compression was performed on both sides of a specimen simultaneously. Loading is applied until plastic deformation of the specimen surface reaches a specific level, referred to as the total indentation. Unloading the specimen is then achieved by moving the punching tool back to its original position. This procedure produces a residual stress field in the specimen. Application of local compression using a single punch and double punches is discussed in this paper.

Single punch

Application of the local compression technique on an elastic half-space and the effect of remote boundaries have been discussed in detail in [7]. The details of finite element model have also been defined in [8]. The commercial code ABAQUS was used to performed finite element analyses [11]. A schematic presentation of of single punch method is shown in Fig. 1.

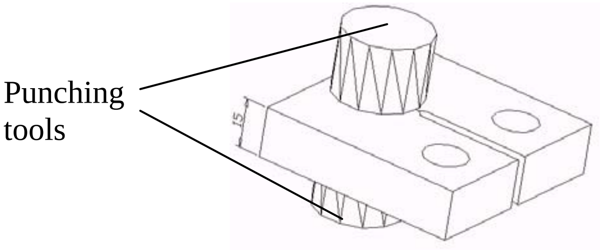

FIGURE 1. Schematic of local compression on a C(T)

Finite element results

A parametric study revealed that the size and the position of the punching tool had a significant influence on the residual stress field generated. In discussing the residual stresses, attention is focussed on the stress component normal to the crack plane, σ_{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 25 mm, 15 mm and 7.5 mm. To specify the position of punching tools, a dimensionless parameter, *x/R*, was defined using the relative position of the 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. 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 specimens. The first position corresponded to x/R = 1.0 which meant that 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 = 0.75, 0.5 and 0.0.

The finite element results of three different punching tools in four different positions suggested that the 25mm punching tool produced the greatest region of tensile residual stress ahead of the crack. Figure 2 shows the distribution of residual stress, σ_{33}, along a path in the centre of the specimen. It was expected that the tensile residual stresses acting ahead of the crack tip decrease the apparent fracture toughness of different materials. The distributions of residual stress in Fig. 2 were obtained using an aluminium alloy, Al 2650, developed for supersonic applications in the aerospace industry. This material has a modulus of elasticity of 72 GPa and yield stress of 427 MPa. A combined hardening model of this material was used as it showed more consistency with the experimental results. To examine the influence of the punching process on fracture behaviour, the technique was used on C(T) specimens made of the aluminium alloy and steel.

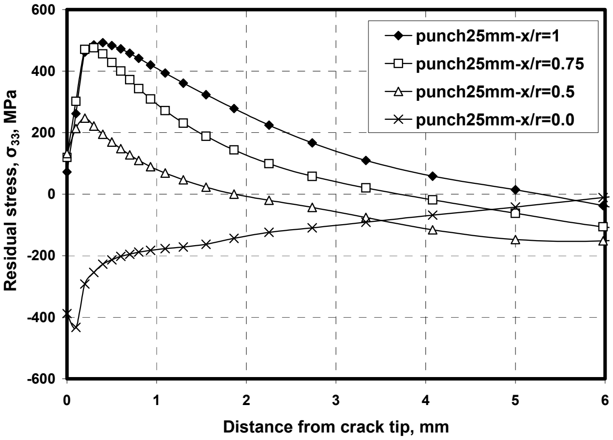

FIGURE 2. Residual stress distribution along a path in the centre of the specimen using a 25mm punch

Experiments

Punching tools were fabricated from EN-24 steel. The punching tools were hardened before being used for punching. They were heated to 600ºC and then cooled in water to increase the hardness by around 200 Rockwell-C. This significantly decreased surface deformation of the punching tools during the punching process. Local compression was applied to both sides of the specimen, at the position x/R = 1.0, simultaneously using the hardened punches. The position of application was chosen to impart maximum tensile residual stresses in the specimen. A linear voltage differential transducer (LVDT) was used to accurately control the displacement during the LC process. The applied indentation was about 1.6% (of the thickness) after unloading. This procedure was applied on ten 15mm aluminium C(T) specimens. The maximum applied compressive load appeared to be slightly different with the variation of the compressive load between 270-280kN. This was in a good agreement with the results of the finite element simulations. In order to study the variation of fracture toughness, ten as-received specimens were also prepared. Electro-discharge machining (EDM) was used to introduce cracks into all of the specimens. Using a 0.1mm diameter wire, the resulting notch width was approximately 0.16mm. All of the fracture tests on the aluminium specimens were performed under displacement control at a speed of 0.003 mm/second at room temperature. The distributions of fracture toughness for the 20 tests with and without LC are shown in Fig. 3(a). The probability of failure from the experimental data was determined using

$$P_f = \frac{i - 0.5}{N}, \tag{1}$$

where *i* and *N* are the order number (rank) and the population (total tests) respectively. The scatter of the fracture toughness in Fig. 3(a) indicates a large reduction in the apparent fracture toughness in the aluminium specimens. The average reduction in fracture toughness after local compression was around 50%.

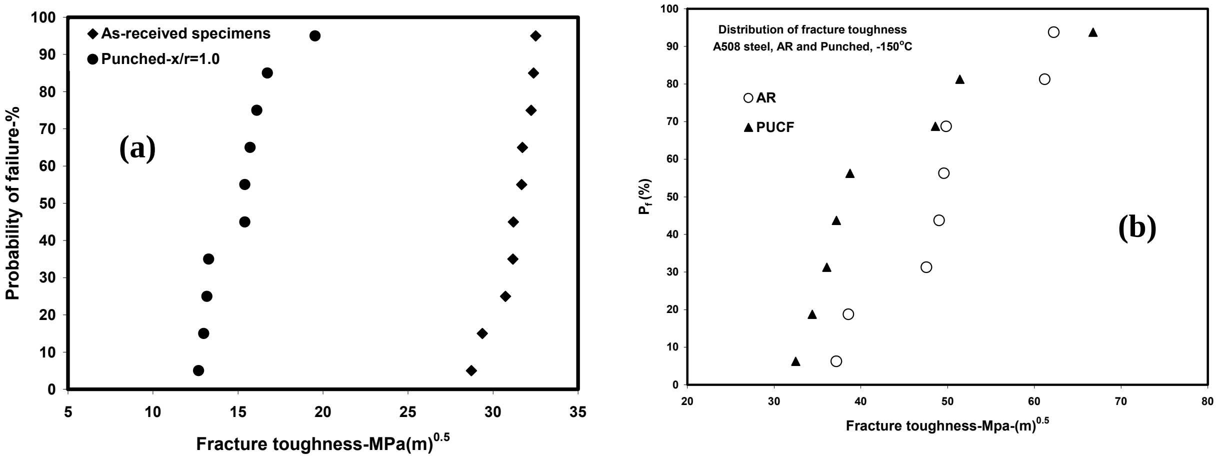

FIGURE 3. Variation in fracture toughness in the as-received condition and after local compression in (a) aluminium specimens and (b) steel specimens

To investigate the above procedure on different materials, a global residual stress field was introduced by applying local compression on both sides of A508 steel 25mm thick C(T) specimens using the same size punching tools and acting at the same position based on the results of earlier parametric study. The compressive load was adjusted such that the remaining indentation was measured between 1.8-2% of the specimen thickness. Fracture tests were carried out for the as-received (AR) specimens and the punched specimens. These specimens are termed punch, unload, cool and fracture, PUCF, conditions. For all of the fracture tests, initial mechanical loading of the specimens was performed at room temperature and the specimens were then fractured at –150°C. All of the specimens failed by cleavage.

Sixteen C(T) specimens obtained from a block of A508 steel were also tested - as two sets of eight specimens - under two load cycles, the as-received and PUCF. Again the electro-discharge machining (EDM) technique was used to introduce cracks into the specimens with a resulting notch width of approximately 0.16mm. The LC process was performed on eight specimens at room temperature. A compressive load between 335-360kN left approximately 2% indentation after unloading. Figure 3(b) illustrates the experimental results for A508 for the two conditions, PUCF and AR. For the PUCF cycle the toughness was reduced, however, the amount of reduction was not as large as in the aluminium specimens, being around 14%. This difference in the change of fracture toughness could be attributed to different micro-mechanical fracture mechanisms in the aluminium and steel. The next section will explain the measurement of residual stresses which confirmed the finite element simulations in the punched specimens.

Residual stress measurement

The measurement of the residual stress fields was performed using the Synchrotron diffraction technique at ESRF, Grenoble. Figure 4 shows the result of one measurement line along a path in the centre of the punched specimen. The measurement results correlated very well with the finite element predictions. Details of the measurement results are available in the experimental report [12].

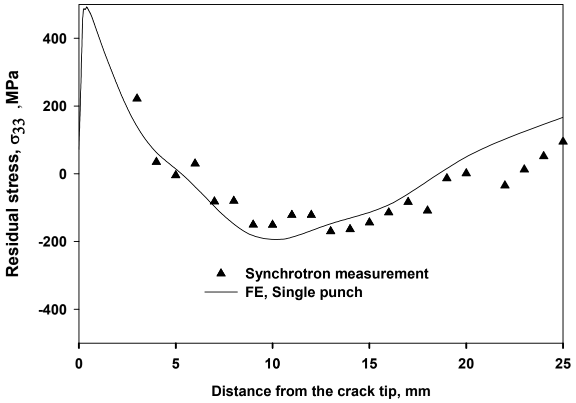

FIGURE 4. Comparison of the FE and synchrotron measurement results

Double punching tool

At this moment the reason for the difference in the amount of reduction between the aluminium and steel specimens, shown in Fig. 3, is not clear. In the LC process using a single punch, the material in the vicinity of crack tip is compressed. One argument is that the observed reduction in fracture toughness might not be due solely to the residual stresses around the crack tip, but may contain a contribution from the effect of pre-straining at the crack front region as well. Therefore

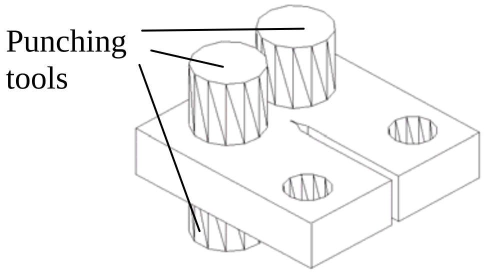

FIGURE 5. Schematic of local compression on a C(T) specimen using double punch

it was decided to move the punching area away from the crack-tip region. In addition, another aim was to use LC technique to impart compressive residual stresses in the crack tip region as well as tensile residual stresses.

Accordingly, the method of application of local compression was then extended in order that (i) both compressive and tensile residual crack tip stress fields may be introduced into specimens and (ii) the area of punching be removed from the vicinity of the crack tip so the chance of accumulating plastic strains adjacent to the crack tip is less. To achieve these objectives, a double punching tool, as shown in Fig. 5, was applied simultaneously to both faces of the fracture specimen. The study of the application of a double punch was focussed on the 15mm aluminium specimens. In the next section the details of the finite element model will be discussed.

Finite element model

The simulation concentrated on the aluminium specimens. A Finite element model of 15mm thick C(T) specimens was created using ABAQUS/CAE [11]. Due to symmetry only one quarter of the specimens were modelled so that the smallest element size in planes normal to the crack plane was no more than 0.05mm in each direction. The model had 12 layers of elements in the thickness direction. The number of elements in total was around 13000 linear hexahedral elements. Also included in the FE model were the punching tools.

Finite element analyses demonstrated that this arrangement was capable of achieving the two objectives listed above. A parametric study was again carried out to assess the influence of punch position and size on the residual stress field. Again results revealed that the size and the position of the punching tools had a strong influence on the magnitude and direction of the residual stress field. In discussing residual stresses, attention is again focussed on the stress component normal to the crack-plane. Three different sizes of double punching tool diameter were examined, 25mm, 20mm and 15mm.

The same dimensionless parameter, *x/R*, was defined using the relative position of the punching tool and the crack tip in the specimen. This time the punches were moved on both sides of the crack tip, front and back, and the travelling line was a line parallel to the crack line. The distance between this line and crack line was y/R=1.2, where y is the distance between the centre of the punch and crack line. When they were moved in front of the crack tip, the position was

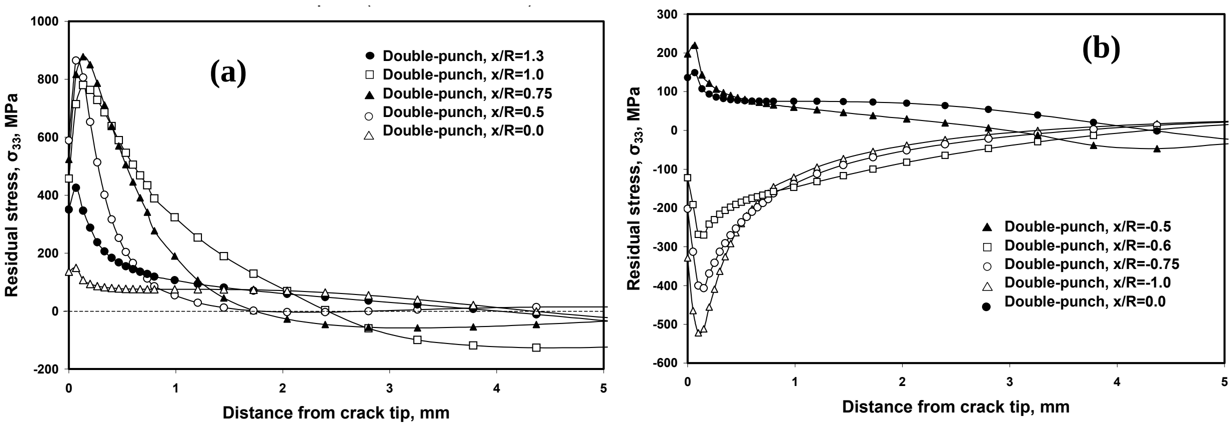

FIGURE 6. Residual stress distributions in the centre of the specimen using a 20mm double punch positioned at, (a)fron of crack tip, (b) back of crack tip

characterised by a positive *x/R*. When it was moved towards the back of the crack tip, a negative value of x/R was recorded. The finite element results showed that the application of double 25mm punches needed a compressive load of around 600 kN. As this numerical study will be followed by experiments, the capability of the available machines was considered. Therefore the parametric study was continued to consider two other sizes of punches, 20 and 15mm. The finite element results showed that using double punches allowed introduction of both tensile and compressive residual stress fields into the region in front of the crack as shown in Fig. 6.

The results also indicated that the application of a 20 mm diameter double punch produced greater residual stress fields than the 15mm double punch. Figure 6 shows the residual stress distributions following LC by a 20mm double punch. In Fig. 6(a) and 6(b), the results of the parametric study to produce tensile and compressive residual stress are shown respectively. It can be seen from these results that the greatest tensile residual stress field is produced when the punches are positioned at *x/R*=1.0, while the greatest compressive residual stresses are introduced when the punches are positioned at *x/R*=-1.0. This is summarised in Fig. 7.

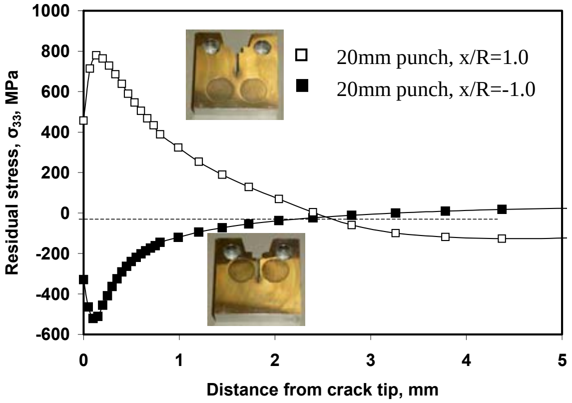

FIGURE 7.Residual stress distributions, 20mm double punch at x/R=1.0 and x/R=-1.0

Discussion

Local compression has been applied in previous studies as a method to relax pre-existing residual stress fields. Application of LC to introduce residual stress into cracked specimens is investigated in this paper. Using LC to introduce residual stress fields into 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. FE analysis demonstrated that full through thickness tensile residual stresses were achieved for a 25 mm diameter punch. The presence of tensile residual stresses normal to the crack plane has a dramatic reduction on the apparent fracture toughness of around 15 MPa√m in aluminium specimens, however, results showed smaller reductions in steel specimens. The residual stress field was measured by synchrotron diffraction and measurements showed good consistency with the FE results.

Double punches were chosen to achieve two aims. Firstly, to be able to produce both compressive and tensile residual stress fields into specimens, and secondly, to remove the punching area from the vicinity of the crack tip in order to reduce the amount of accumulated plastic strain adjacent to the crack tip. Again a parametric study revealed that the residual stresses following LC by a double punch were very sensitive to the size and position of the punches.

Finally, a 20mm diameter double punch showed the best capability of imparting tensile and compressive residual stress fields ahead of the crack.

Concluding remarks

It was observed that the tensile residual stresses following local compression using a single punch could reduce the apparent fracture toughness in both aluminium and steel specimens. However, the amount of reduction was different for the two materials. The difference in fracture mechanism in aluminium and steel may explain this difference. It was also found that a double punch is capable of producing both tensile and compressive residual stresses ahead of the crack tip. Finite element simulations revealed that the size and the position of double punches had a significant effect on the magnitude and the extent of the residual stress field produced within the cracked body and was achieved with less plastic strain in the crack tip region, as compared to the single punch.

Acknowledgement

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