Influence of discrete residual stress fields on fracture toughness

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ABSTRACT. *The rate and direction in which cracks grow during ductile fracture is influenced by both stress state and material properties, particularly plasticity and anisotropy. Previous work has shown that compressive surface residual stress fields such as those caused by shot-peening or burnishing can be used to modify the behaviour of a propagating crack. To exploit the controlling behaviour of residual stresses it is necessary to understand the interaction between secondary applied residual stresses and the crack tip stress field. Controlled plasticity burnishing has been used to create near 1-dimensional compressive residual stress fields in the surface of AA2024 in attempts to modify cracking behaviour. A direct optical method (Digital Image Correlation) has been used to characterise the crack tip displacement fields and subsequently calculate values of CTOA. A series of tests on specimens with continuous and intermittent compressive stress zones was used to explore the relationship between the crack tip and the applied residual stress.*

INTRODUCTION

The ductile tearing behaviour of aluminium alloys is of particular interest in the aerospace industry for life prediction and mitigation of catastrophic failures. Improved understanding and the development of techniques for improving and controlling the tearing behaviour would allow for more economical approaches to aircraft design and operation. It is well established that the presence of residual stresses alters structural integrity and this provided the inspiration to undertake this work.

For this investigation, a series of compact tension (CT) tearing tests were carried out using thin sheet 2024-T3 aluminium. This material was chosen because of its widespread use in the aerospace industry and it is known to have stable tearing properties. Near one dimensional compressive residual stresses were imparted onto the surface using the controlled plasticity burnishing technigue developed at the University of Sheffield [1]. Burnishing was done in different orientations to determine its effects on crack stability and fracture toughness. The CTOA fracture parameter was used because it has been shown to be well suited for characterising ductile tearing fracture [2].

Controlled Plasticity Burnishing

Recently, several burnishing techniques have been developed for imparting compressive residual stresses into the surface of components. Typically these involve applying a loaded rolling element to the component and moving it across the surface leaving a deformed region in its wake. Such a technique has been developed at the University of Sheffield [1] specifically for the study of residual stresses. Controlled plasticity burnishing (CPB) uses a needle roller bearing mounted in a die-press; the specimen is translated using a ball screw type linear slide. Loading is applied via a servo-electric load frame in which the die-press arrangement sits. The apparatus is shown in Figure 1.

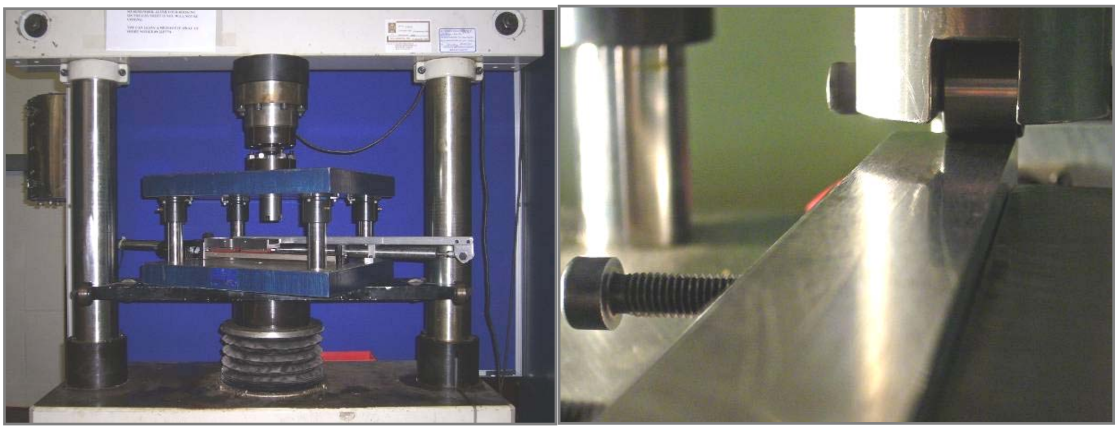

Figure 1 Burnishing apparatus left and closeup of the burnishing tool

Residual stresses are generated by loading the roller bearing which, in this case, is 12mm wide and 15mm in diameter, to such a degree that the maximum pressure in the contact region exceeds the yield point of the material. This can be estimated by considering the contact as a Hertzian line contact and evaluating the pressure profile for the specific geometry. In this work, two load levels were used, one coinciding with previous work (1.06kN) and a second at double that (2.12kN)

The residual stresses arising from CPB have been extensively studied by the authors using synchrotron x-ray diffractron and characterised in 3D [1]. This has been supported with a fatigue programme to compare with other cold-working techniques [1]. Figure 2 shows the principal residual stresses as a result of burnishing AA2024 (in this case T351 but the properties are comparable to T3) at the lower load of 1.06kN. The stress field is predominantly compressive in one direction, that being the direction of rolling, with a maximum value of approximately 320MPa at 200µm depth. This near 1D compressive stress field can be used to study the effects of both stress magnitude and direction in specific regions of a specimen. For the burnishing condition at 2.12kN it is anticipated that the residual stresses will not be of a substantially higher magnitude but should extend deeper into the specimen, due to the fact that the depth of material which has been loaded sufficiently to yield will be greater.

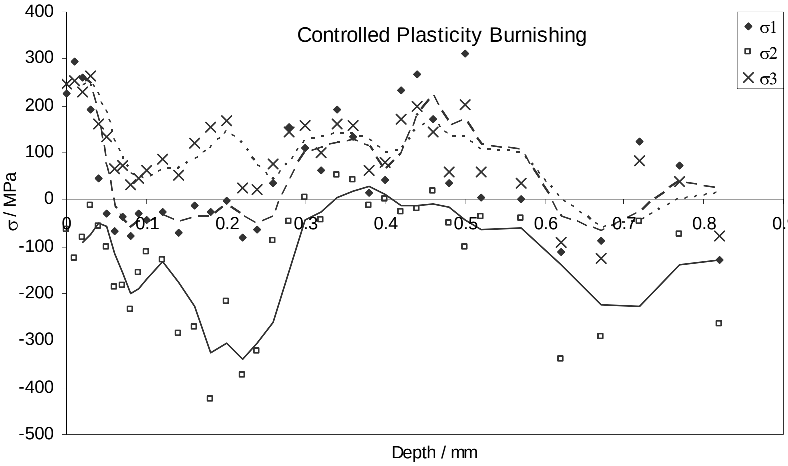

Figure 2 Principal residual stresses in CPB 2024-T351 measured with high energy XRD [1]

Digital Image Correlation

Stereo (3D) digital image correlation was used to measure displacement during the tearing tests. 3D-DIC uses a pair of digital cameras synchronised to each other and a series of analogue measurements which in this case included the load values from the test frame's load cell.

2D DIC is relatively simple [3] in principle; firstly, we define a digital image as a two-dimensional array of intensity values, $I(x,y)$. Given two images, I_A and I_B of the same object from the same point of view, and define an $N \times N$ pixel region of interest, known as a subset, in each image. If the image brightness is approximately constant i.e. $\Sigma I_A^2 \approx \Sigma I_B^2$, then the similarity between the two subsets can be expressed as a cross-correlation product [4]:

$$c(u,v) = \sum_{x=-m}^{n} \sum_{y=-n}^{n} I_1(x,y) I_2(x+u, y+v) \tag{1}$$

Where u and v are the distances between the centres of the two regions of interest along x and y respectively, and $n=N/2$.

If I_A is a reference image of the object and I_B is taken after the object has undergone some deformation or rigid body movement, then the maximum of the cross-correlation function (1) gives the most probable displacement values for the centre of the region of interest in I_A. 3D DIC uses the same principles but requires the prior calibration of two or more cameras which then allows reference and deformed images to be evaluated for out of plane deformations. For DIC to work on metallic specimens a pattern must be applied to the surface, care must be taken to ensure that the pattern is generated using a suitable medium for strain transfer and that the size and distribution are appropriate for correlation. In this work a commercial package, Limess VIC3D was used to collect and evaluate the images.

EXPERIMENTAL WORK

CT specimens were prepared from 5mm thick 2024-T3 aluminium sheet as shown in Figure 3, the proportions follow the guidelines set out in the ASTM E2472 standard [5]. All specimens were made in the LT (crack propagating across the rolling direction) direction which has been shown previously to be reasonably stable in this material [6]. These were pre-cracked in a servo-hydraulic test machine at a maximum load of P_{max} = 2.17kN and stress ratio R = 0.1 for approximately 20,000 cycles until a fatigue crack of at least 0.5mm was grown. A significant number of tearing tests have already been performed in similar geometries on the same batch of material [6] and so only one specimen was retained as a base-line to compare with previous data.

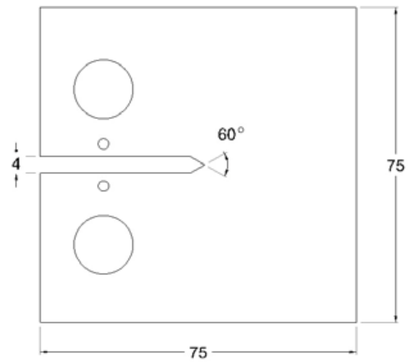

Figure 3 CT specimen dimensions, material was 5mm thick

The remaining four specimens were burnished at two different loads with two different patterns; these are shown in Figure 4. Burnishing was performed on both sides of the specimens which were marked carefully to ensure good alignment of the burnished regions between both faces. Once burnished the specimens, a speckle pattern was then applied using acrylic based spray paint, white for the background and black to generate the speckles.

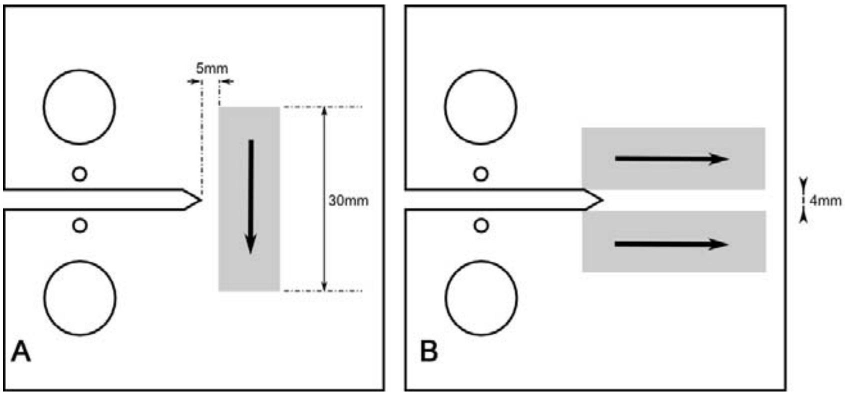

Figure 4 Burnishing patterns used, in both cases burnishing was repeated on the reverse side with feed in the same direction (A) Stripe and (B) Corridor

Specimens were mounted in a servo-electric test machine and pulled at a rate of 1mm/min. Specimens were pulled until the supported load dropped below 0.75kN. Load – image data was collected using a Limess Vic-3D system at a rate of 0.5Hz.

RESULTS AND DISCUSSION

Figure 5 shows a load vs. CMOD curve for the control specimen, this is a typical curve for an aluminium alloy and exhibits very stable, ductile propagation.

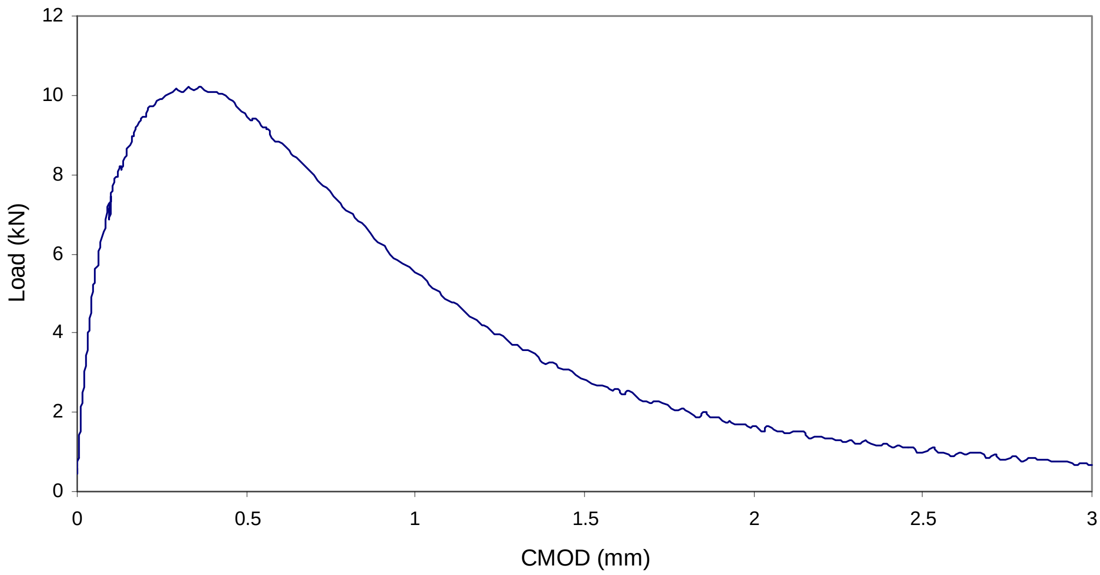

Figure 5 Load vs. CMOD for the untreated control specimen

Figure 6 shows the CTOA resistance curves for the control specimen and two specimens burnished at a load of 2.12kN in the stripe and corridor configurations. A slight increase in CTOA can be seen in the steady state region suggesting that both treatments have altered the toughness. This can be seen more clearly when the data is plotted as a cumulative probablity of CTOA, shown in Figure 7. The data is plotted only for the steady state region (between 5mm and 25mm in this case). Plateauing of the curve is a result of the stablising and destablising of data at the beginning and end of the steady state region. This format emphasises the increase in CTOA with both burnishing configurations and confirms that this treatment increases the resistance to tearing.

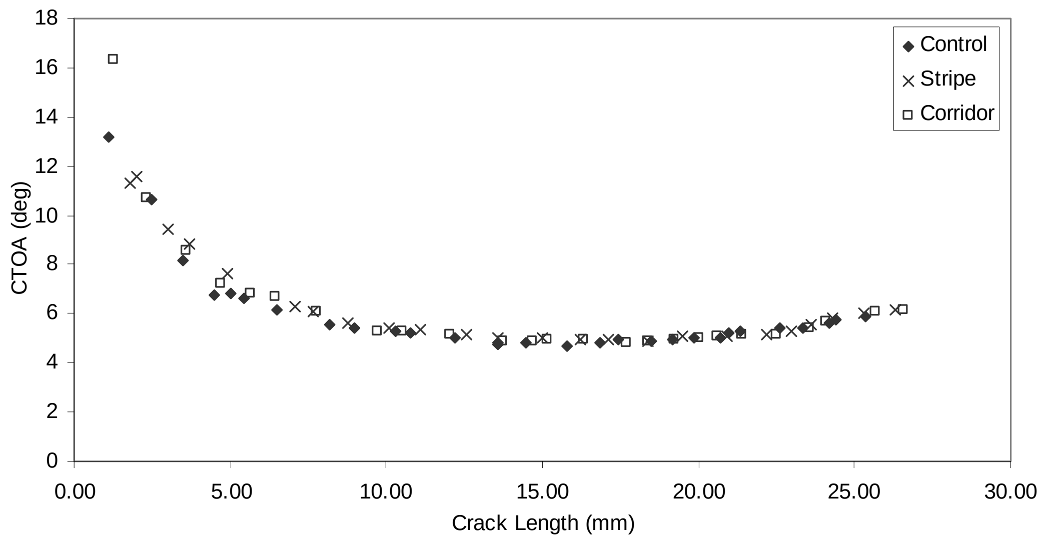

Figure 6 CTOA resistance for two burnished patterns and the control specimen, burnishing was at 2.12kN in both cases

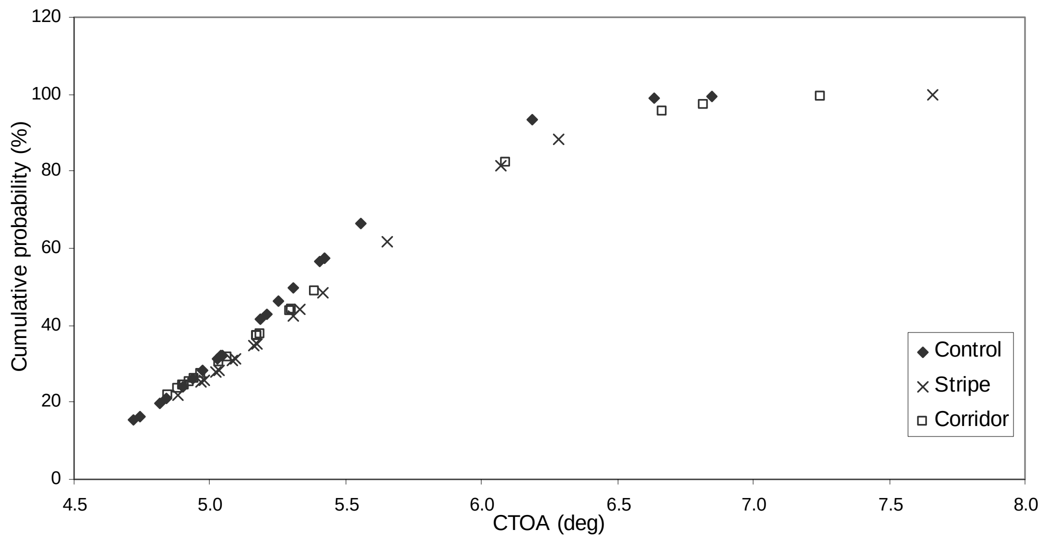

Figure 7 Cumulative probability curves for two burnished patterns and the control specimen, burnishing was at 2.12kN in both cases

The change in CTOA for these specimens is subtle but does demonstrate that the technique is viable for modifying crack behaviour. Preliminary work conducted on a similar alloy (AA2014) in CT and DCB configurations showed that doubling the burnishing load increased the load-displacement characteristics [7]. It is probable that the corridor in this case was too far apart to significantly influence the plastic zone at the crack tip. In hindsight it would be useful to determine this for the specific specimen geometry and material prior to specifying the burnishing pattern. It is also notable that the evaluation of T-stress was hindered by plastic zone size. In the future we intend to use the full field of elastic and plastic displacements collected using DIC around the crack tip to quantify the non-linear HRR field [8, 9]. This offers the possibility of evaluating the non-linear elastic J-integral, and the associated constraint term, Q [10], for a cracked structure.

CONCLUSIONS

Controlled plasticity burnishing can be used locally to increase material toughness, in particular CTOA. This will prove to be a useful technology in the study of crack propagation and possibly of merit for controlling cracks in structures. The highly directional stress field produced by burnishing will enable continued study into the interaction of cracks and stresses.

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