Fracture behaviour of 2024 aluminium alloy with discreet 1D residual stress fields

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Abstract: Residual stresses are well known to affect the fatigue, fracture and creep failure of metals; tensile stresses can contribute to driving crack growth whilst compressive stresses are inhibitive. Compressive surface stresses have been shown to influence toughness and crack path followed during fracture. Controlled plasticity burnishing allows concentrated regions of surface residual stress to be generated with a high degree of spatial resolution. This technique was applied to modified double cantilever beam specimens (mDCB) to provide discontinuous 1D residual stress fields. Investigations were conducted into the fracture behaviour of mDCB specimens with discrete burnished regions; CTOA measured using direct techniques has been used to characterise fracture toughness and observe its variation with stress field. Additionally, variations in the stress-strain relationship are monitored in conjunction with crack path stability. Results from this study demonstrate that direction of the residual stress field alters constraint levels and therefore fracture toughness and crack path stability.

1 Introduction

Compressive residual stresses are widely used to control the behaviour of metals under loading. Shot-peening is an industry standard method applied to many commercial components to improve fatigue behaviour and reduce susceptibility to stress corrosion cracking. Burnishing techniques have been recently developed to introduce compressive residual stresses whilst reducing the damage introduced into the surface.

The effect of residual stresses on ductile fracture behaviour can be categorised in two ways; firstly an additional component of stress can contribute to the crack tip stress field, either reducing or increasing the load required to sustain propagation; secondly, a change in constraint through modifying T-Stress and thereby changing crack stability [1].

For this study a ductile tear test was conducted using burnished modified double cantilever (mDCB) specimens. This specimen geometry was developed by Shterenlikht [2] to give large amounts of steady state crack propagation. For fracture toughness characterisation, the crack tip opening angle (CTOA) was used. Previous work [3] has shown that it works well for characterising changes in fracture toughness when there is extensive crack growth. Measurements were done with the aid of digital image correlation.

2 Controlled Plasticity Burnishing

A technique referred to here as Controlled Plasticity Burnishing (CPB) has been developed at the University of Sheffield to introduce compressive residual stresses into the surface of metallic specimens [4]. This involves compressively loading a cylindrical tool on the specimen surface and traversing the specimen to allow the tool to roll over the surface causing localised yielding. Loading is minimised to an amount just sufficient to take the material past its yield point. Increasing the load will result in higher compressive stresses until tool damage starts to occur. The CPB equipment has been designed to minimise slip at the tool/specimen interface and thereby limit any possible damage through scuffing and wear.

The compressive residual stress state resulting from CPB has been measured using synchrotron x-ray diffraction and has been shown to be approximately one-dimensional in the direction of burnishing [4]. Figure 1 shows the residual stress state in a 20x20x150mm specimen made from the same 2024 alloy as used in the current work. The stresses presented are principal directions, they are related to the specimen geometry such that σ_1 is parallel to the burnishing direction and $\sigma_{1 \text{ and } 2}$ define the plane of the specimen surface. A shallow region of tension can be seen in the surface followed by a significant region of compression in the burnishing direction, it is this compressive region which is considered here to modify crack behaviour.

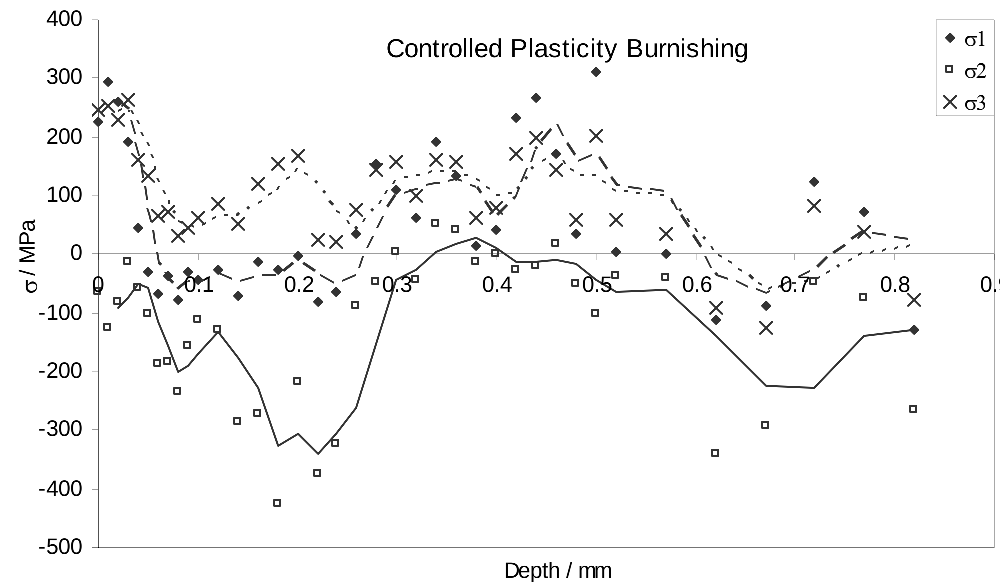

Figure 1 3D residual stress state in CPB 2024-T351

3 Experimental work

3.1 Tear test with mDCB specimens

The material used in this study was aerospace grade Al 2024-T3 aluminium alloy in 5 mm plate form. It was used due to its ductile fracture characteristics as well as its tendency to exhibit substantial amount of stable tearing during fracture which will be useful this study. The specimens were cut from the plate in both LT and TL directions and machined down to specifications. A schematic of the specimen is shown in Figure 2. The notch which was 82 mm in length resulted in the specimen having a crack length to specimen length ratio of 0.45 and approximately 50 mm of steady state crack extension.

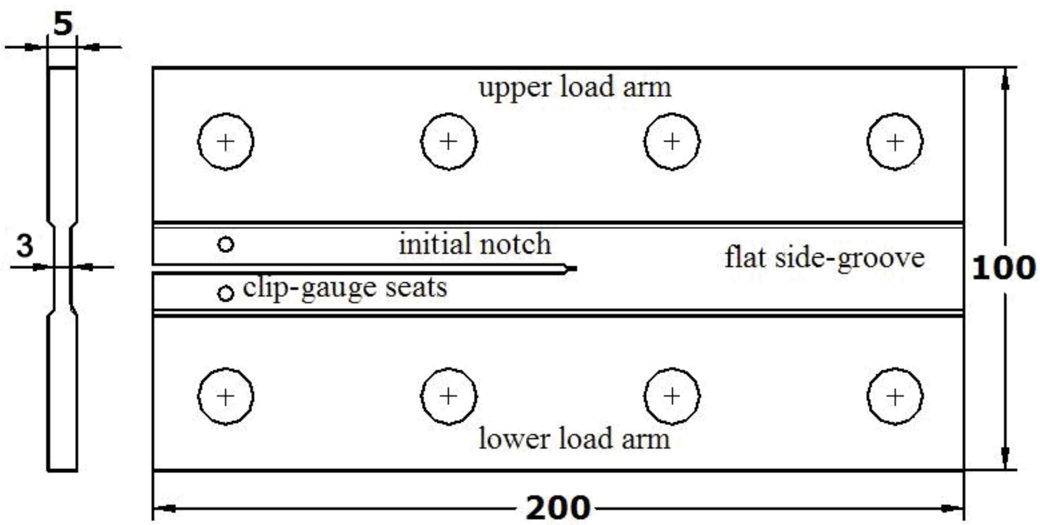

Figure 2 Dimensions of mDCB specimens used.

The tear test was conducted with a Schenck hydraulic test machine under quasi-static mode I loading conditions. Actuator displacement was fixed at 0.05 mm/s under position control. Bespoke loading plates were needed to load the specimens as shown in Figure 3 which also shows the experimental set-up. Image and data acquisition was done using a LA Vision DIC system which had an integrated data acquisition system to synchronise parameters of interest such as load and displacement with images.

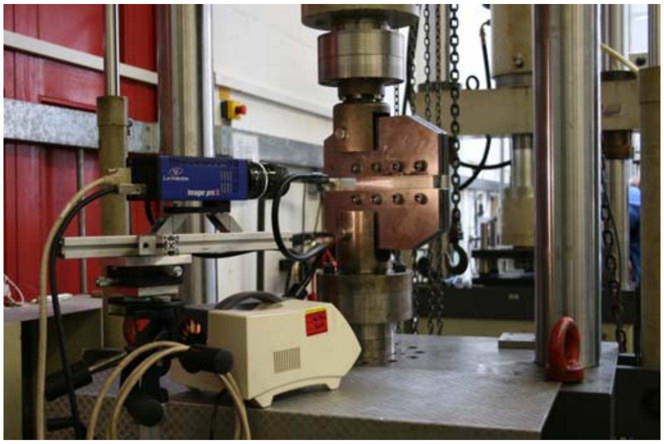

Figure 3 Experimental setup for tear tests.

Measurement of CTOA was done with the aid of DIC in measuring the CMOD at a specific location on the surface and a subroutine (Sobel edge finding) for finding the location of the crack tip from which CTOA can be calculated using the equation below. The most appropriate location of the virtual strain gauge for measuring CMOD was the crack initiation point [3]. Figure 4 illustrates the CMOD measurement scheme. For comparison with data from earlier work, the grid technique of measuring CTOA from the rotated gridlines adjacent to the crack path was also used.

$$CTOA_{\theta} = 2\tan^{-1}\frac{CMOD}{2A}$$

Where, A = distance from crack tip to measurement position

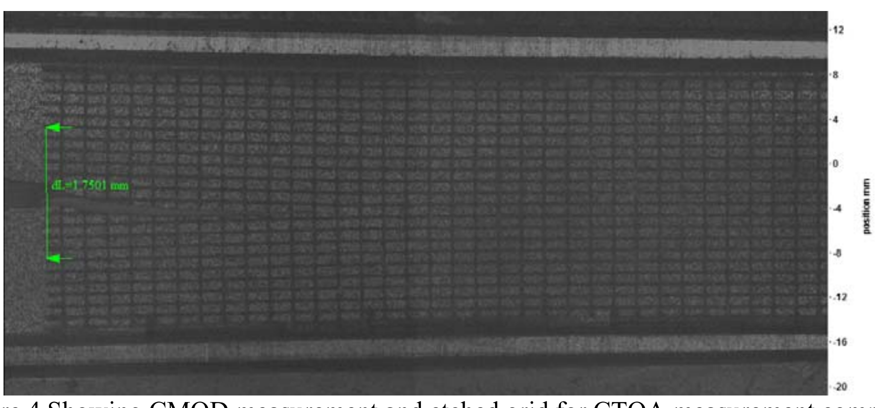

Figure 4 Showing CMOD measurement and etched grid for CTOA measurement comparison

3.2 Controlled Plasticity Burnishing

Two different burnishing regimes were employed to investigate the influence of stress direction. The specimen in the LT direction was burnished with discrete stripes 12mm wide and 8mm apart perpendicular to the crack propagation direction on both faces as shown in Figure 5A. This results in an intermittent compressive residual stress field across the crack path. The specimen in the TL direction was burnished with a single pass along the crack path resulting in a compressive residual stress field in the direction of crack propagation as illustrated in Figure 5B. Figure 6 shows the LT specimen being burnished.

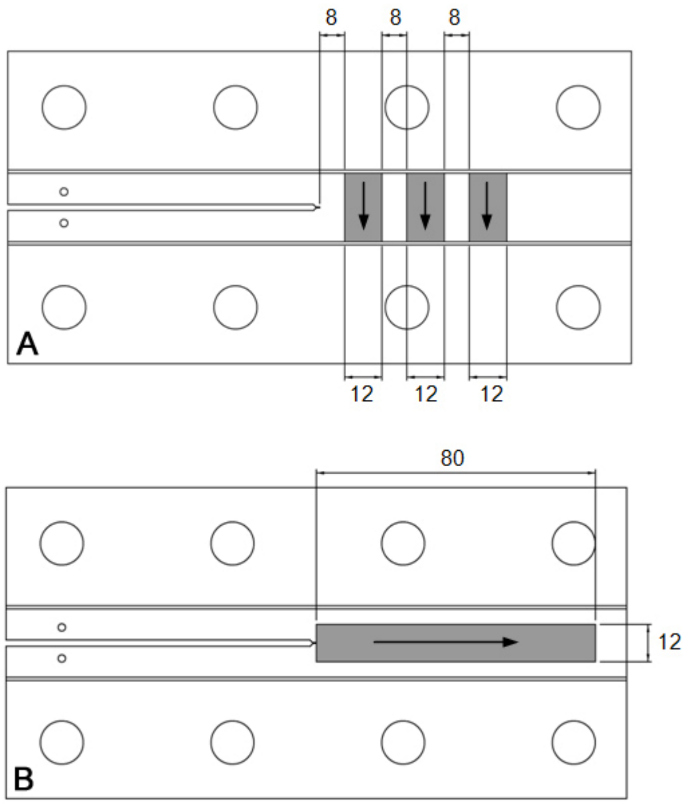

Figure 5 Burnishing regimes, grey areas indicate burnished stripes and arrows indicate the direction of burnishing. Identical regimes were applied to both sides of the specimen.

Figure 6 Burnishing the LT specimen

4 Results

Figure 7 below shows the load displacement curve obtained for both DCB specimens in the LT and TL direction. The curves do not exhibit any significant deviation from standard load displacement curves for this material and specimen geometry. It is clear that the material is marginally tougher in the LT direction. There is also more elongation in the loading direction for the LT specimen as demonstrated by the higher values of measured CMOD to achieve similar crack lengths.

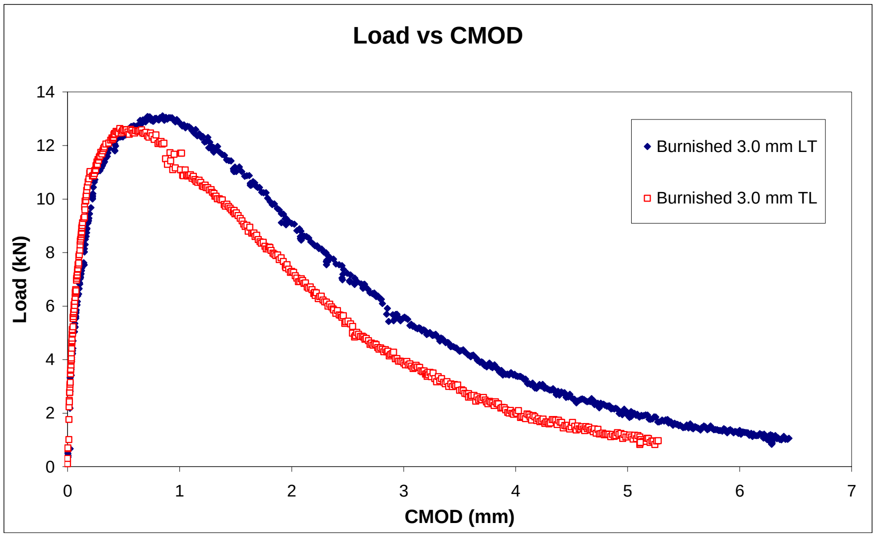

Figure 7 Load – CMOD data for both specimens.

Figure 8 shows a 3D reconstruction of the fracture surface for the LT specimen. The white dashes along the bottom edge correspond to the burnished stripes across the crack. Fracture mode for both specimens was predominantly slant fracture. In the LT direction, there was evidence of crack tunnelling from the onset of fracture as well as in the transition region which was approximate 6 mm in length. In the TL direction, there was no evidence of crack tunnelling but at the beginning of the fracture process, flat fracture was the predominant fracture mode. The onset of slant fracture took precedence after approximately 10 mm of crack extension. The fracture characteristics above were observed before in previous work and there is no evidence to suggest burnishing had a significant effect on the fracture mode and crack path stability. It is however worth noting that this material and specimen geometry possesses very stable crack growth characteristics. Further work is underway to test material and specimen geometries which tend to have more unstable characteristics.

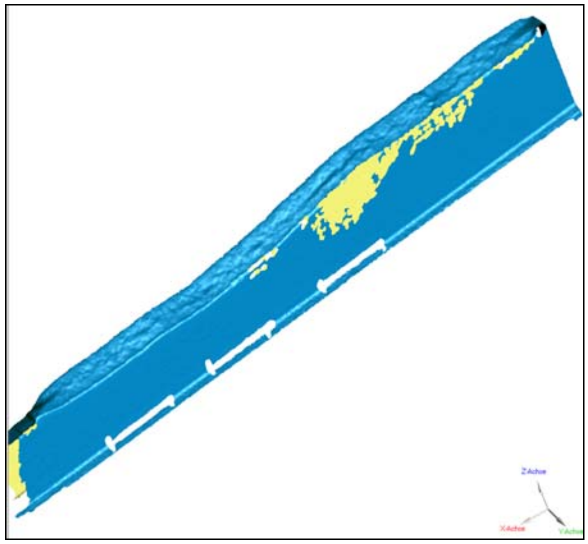

Figure 8 3D reconstruction of the fracture surface (courtesy of IVB GmbH)

CTOA measurements were done using the technique described previously, the results are shown in Figure 9. The average steady state CTOA value in the LT direction was 3.93° (std dev ±0.29°). A more significant observation from the CTOA resistance curve is the apparent rise in CTOA values when the crack extends into the burnished regions as highlighted by the arrows in Figure 9. This is good evidence of 1D compressive residual stresses marginally increasing the fracture toughness. Small variations in the shear angle can be observed in the LT specimen as shown in Figure 8, particularly between the burnished stripes. The average increase in CTOA terms was approximately 0.25°. In the TL direction, the average steady state CTOA value obtained was 3.47° (std dev ±0.15°). Due the burnishing regime for this specimen, local variations were not observed and it was also not possible to carry out relevant comparisons of the data at the moment. Work is in progress to address this issue.

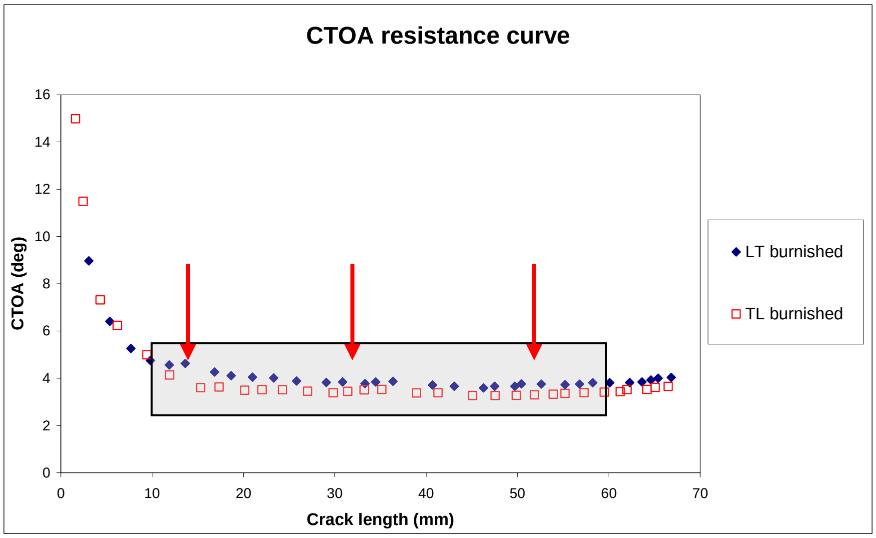

Figure 9 CTOA Resistance for both specimens, grey box indicates the steady state region and arrows denote the centre of the burnished stripes on the LT specimen.

Figure 10 is the cumulative probability plot of steady state CTOA data in Figure 9. It highlights the difference in fracture toughness between the two directions. More importantly is the larger distribution of data for the specimen in the LT direction with intermittent burnishing which further highlights the small increase in fracture toughness of the burnished regions.

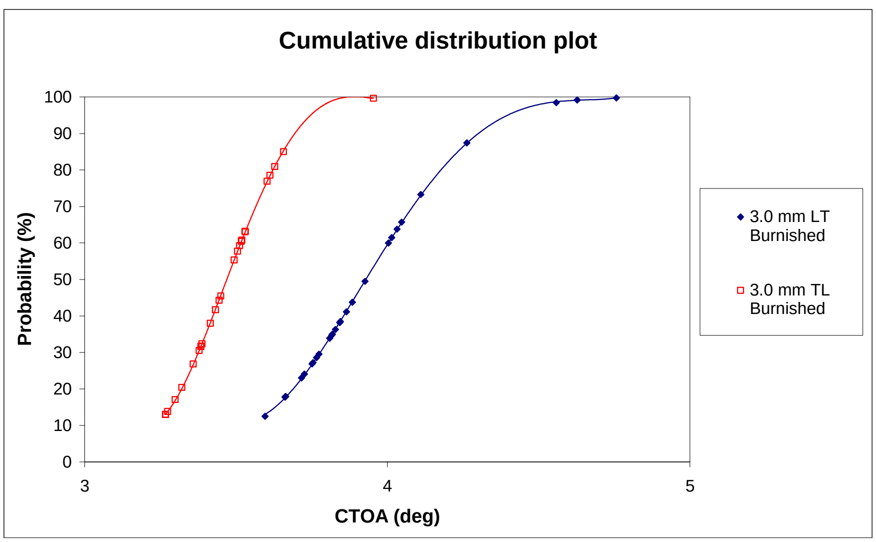

Figure 10 Cumulative probability plot for CTOA data in the steady state region.

Further work was carried out with a variety of different burnishing regimes on thin sheet aluminium 4%Cu CT specimens 5 mm thick. One of the regimes involved the same burnishing regime used for the specimen in the TL direction but at different burnishing loads, one specimen was burnished at the standard loads and the other with double the loads. Preliminary analysis on the results showed that by doubling the loads which leads to an increase in compressive residual stresses, there is a noticeable increase in the fracture toughness as illustrated in Figure 11.

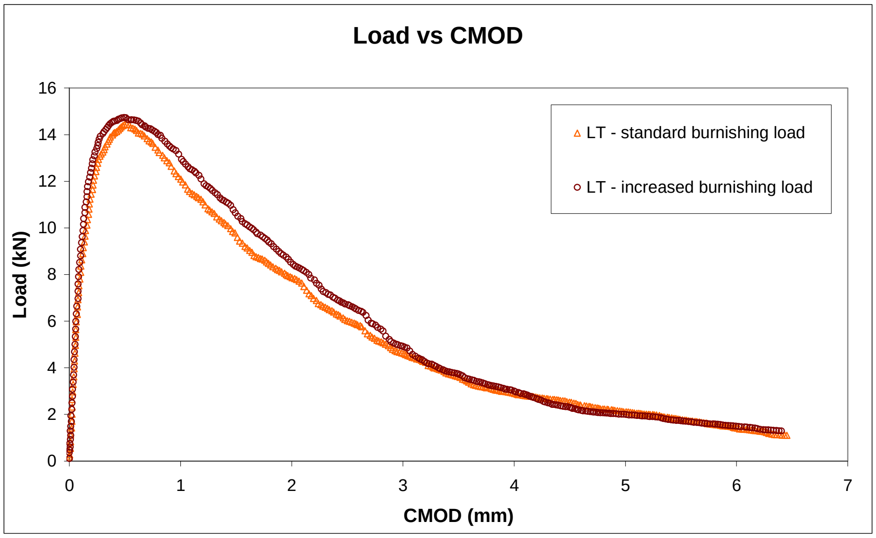

Figure 11 Preliminary data for CT specimens burnished under similar conditions.

5 Conclusions

The results presented here show that controlled plasticity burnishing has an influence on fracture toughness as characterised by the measured CTOA data. The variation of CTOA shown for burnishing conditions used here is relatively small but demonstrates the applicability of discrete stress fields for influencing crack behaviour. Additional work has shown that increasing the burnishing loads further increases the fracture toughness.

References

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