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Residual stress relaxation measurements across interfaces at macro- and micro-scales using slitting and DIC

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Abstract. In this paper digital image correlation is used to measure relaxation of residual stresses across an interface. On the macro scale the method is applied to a tri-layer bonded aluminium sample, where the middle layer is in tension and the top and the bottom layers are in compression. High contrast speckle pattern was sprayed onto the surface. The relaxation was done with the slitting saw. Three dimensional image correlation was used. On the micro scale the technique was applied to a heat treated large grain brass loaded in tension. Mechanical and electro polishing was used for surface preparation. A focused ion beam was used for slitting across a grain boundary and for imaging. Grain orientation was measured using electron back-scattering diffraction. Two dimensional image correlation was employed. In all macro- and micro-scale experiments the range of measured relaxation was sub-pixel, almost at the limit of the resolution of the image correlation algorithms. In the macro-scale experiments, the limiting factor was low residual stress, due to low shear strength of the Araldite glue used for bonding. Finite element simulation of the relaxation agreed only qualitatively with the experimental results at both size scales. The methodology is intended for use with inverse methods, i.e. the measured relaxation is applied as the boundary conditions to an appropriate FE model which produces stresses equal to the relaxed residual stresses, but with opposite sign. The main conclusion is that the digital image correlation method could be used to measure relaxation caused by slitting in heterogeneous materials and structures at both macro- and micro-scales. However, the repeatability of the techniques needs to be improved before residual stresses can be determined confidently.

1 Introduction

Measurement of residual stress in areas of high stress gradient is an active research area. The most successful technique to date is the crack compliance, or slitting, method, which involves introduction of a slot to a material under stress and measuring the relaxation caused \cite{1, 2}. In this work an attempt is made to use the digital image correlation (DIC) technique for relaxation measurement at macro- and micro-scales. The Istra 4D DIC system by Dantec Dynamics \cite{3} has been used in this work.

2 Macro-scale experiments

The specimens were machined from aluminium alloy 7050-T7351 provided by Abaqus UK. A Young’s modulus and a yield stress of 73.3 GPa and 440 MPa respectively were measured for this alloy, and a Poisson’s ratio of 0.33 was assumed. The specimen was prepared as follows: (1) three strips of
aluminium, one long and two short, cross section 6 mm × 12 mm, were prepared, (2) the long strip was loaded to 10 kN in tension, producing a nominal stress of 139 MPa, (3) with the long strip still under load, the two short strips, side plates, were glued to the central strip on both front and back sides using Huntsman’s Araldite 2010-1 adhesive, with a nominal shear strength of 23 MPa, (4) after the glue had cured the load was removed, thus creating a specimen with highly non-uniform residual stress – tensile in the central strip, and compressive in the side plates. Fig. 1 schematically shows the completed specimen. Note the outer edges of the side plates were chamfered along the width to reduce the mode II stress intensity factor at the interface corners.

The speckle pattern was applied to the front of the try-layer beam, Fig. 2(c)-(d), and two 6mm long strain gauges were applied to the two side faces. It is generally accepted that the front face gauge is only sensitive to the first 5-10% of the slot depth and the back face gauge gives useful data from 5-10% to 95% of the specimen thickness [2]. The specimen temperature was monitored with a thermocouple. The temperature drift never exceeded 0.5°C. In addition, the gauges were temperature compensated for aluminium.

Typically electro discharge machining (EDM) is used to introduce a slot at the macro-scale. However, the EDM process requires the area near the cut to be submerged in oil, which would destroy or at least invalidate the DIC pattern. Therefore a 0.4 mm thick slitting saw was used in this work. The cutting was done in 0.25 mm increments. Strain gauge readings and DIC images were taken at each increment and before and after the entire slot was created, see Fig. 2(a)-(b). The position of the specimen relative to the cutting blade was controlled by a milling machine stage. Digital readouts from a pair of LVDTs allowed for positional accuracy of 10 µm. This allowed the specimen to be returned to a reference position for DIC image acquisition after slotting, which significantly reduced rigid body motion.

The imaging was done with the resolution of approximately 20 µm/px. 3D DIC measurement was used with a facet size of 60 px and a facet overlap of 1/3. The DIC relaxation displacement field normal to the slot is shown in Fig. 3, and in Fig. 4(a) it is plotted on the lines parallel to the slot. Even though the DIC displacement field has the expected shape and magnitude, and the profiles on either side of the slot match within the error bars, it was not possible to extract a meaningful strain field from it. This is probably due to the fact that displacement measured were very small, the whole range of relaxation being sub-pixel.

The relaxation strain gauge data is shown in Fig. 2(e) and the FE simulated relaxation strain is shown in Fig. 2(f). The FE predicted residual stress is shown in Fig. 4(b). The FE strain was averaged over the size of the strain gauge, 6 mm. Apart from showing three distinct regions in the back face data, the experimental and the simulated curves do not agree. The shapes of the curves differ, and the FE strain is roughly 500% higher. One possible explanation is that the glue was not fully cured when the loading was removed from the specimen. This would have have reduced the locked-in stresses substantially.
(a) DIC setup. Note that specimen was returned to the initial position for each image.

(b) Slitting of specimen. The front face strain gauges are visible above the blade. The saw is traversing from the rear of the specimen towards the camera, to protect the speckle pattern.

(c) Left hand CCD image. Note the large areas out of focus away from the slot due to the limited focal range of the cameras.

(d) Right hand CCD image. Note the connective ligament at the bottom of the slot—thought to be the reason why the displacement profiles are not precisely symmetrical at each end.

(e) Strain gauge relaxation results. Note the front strain gauge is sensitive to only first 4 mm. Passing the interfaces, at approx. 6 mm and 12 mm, causes sharp peaks in the back face strain.

(f) FE simulated strain gauge relaxation results. Values were averaged over the area where the strain gauges were placed in the experiment. The vertical lines indicate the layers of Araldite at slot depths of 6 mm and 13 mm.

Figure 2: Macro-scale slitting experiment and FE results.
Figure 3: DIC relaxation displacements normal to the slot. Note the concentric circles on the plot, which indicate the pre-experiment milling of the surface has some effect on the displacements. Also clearly visible are the interface lines, one third and two thirds of the way down the image. The maximum side plate relaxation is at the outer edges of the specimen. The maximum relaxation of the central strip is at the centre of the specimen.

Figure 4: (a) DIC relaxation; and (b) FE residual stress. The maximum tensile stress in the central strip is 74 MPa. The maximum compressive stress in the side bars is 23 MPa. The maximum shear stress is 22 MPa, just below the shear strength of the Araldite, 23 MPa.

3 Micro-scale experiments

At the micro- and the nano-scales the focused ion beam (FIB) was used for slotting and imaging. For the basics of FIB refer to [4]. In this work FEI Strata FIB201 system was used [5].

A combination of FIB and DIC has been used successfully to measure residual stresses at micro-scale. However, most results to date have been obtained on special materials, e.g. non-metallic thin films [6, 7, 8]. Conducting measurements in metals could be significantly more complex due to an effect called ‘re-deposition’, a condition where material removed from the slot is being re-deposited on the surface near the slot, thus preventing successful application of DIC. This effect was observed in mild steels in previous work [9].

In this work 40% zinc brass was used. It was heat treated to 875°C and quenched, resulting in purely β phase large grain brass. A 5 mm × 4 mm specimen was machined from heat treated brass.
Given the complexity of creating a controlled residual stress sample at the micro-scale, tensile stress was locked in the specimen using a specially machined loading device, shown in Fig. 5(a).

3.1 Mechanically polished sample
The sample was mechanically polished to 1 μm, and stressed to 200 MPa. In contrast to mild steel, there was no re-deposition on brass. In fact, the gas assisted etching (GAE), used in FIB milling of steel to alleviate the re-deposition problem, made FIB imaging of brass worse, see Fig. 5(b)-(c); note these are two different experiments on the same sample.

Because FIB imaging uses a single camera, FIB imaging is inherently two-dimensional. Therefore a 2D version of the Istra DIC software was used. The DIC results, Fig. 5(d)-(f), show the maximum relaxation at the centre of the slot, dropping to zero towards the ends of the slot and decreasing to the noise, ‘reference’, level away from the slot. Once again, these results are at the very limit of the DIC resolution.

3.2 Electro-polished sample
It is frequently claimed that mechanical polishing can itself introduce residual stress in the surface layers. To investigate this effect, the specimen was electro-polished (details are given in [10]).

Results of slitting the electro-polished sample are shown in Fig. 6(a)-(e). The surface now had much less detail, which led to poorer DIC results. The best DIC relaxation displacement field is shown in Fig. 6(g). However, only a very general relaxation pattern can be seen.

FE modelling of the grain boundary interface required grain orientations, which were measured with electron back scattering diffraction (EBSD) method, Fig. 6(f). The outline of the FE model is shown in Fig. 7(a), and the FE predicted relaxation displacements are shown in 7(b). Orthotropic copper material properties were assumed with \( E_{1111} = 169 \) GPa, \( E_{1122} = 122 \) GPa and \( E_{1212} = 75.3 \) GPa.

In the absence of reliable DIC results, FE relaxation displacements could not be verified. One of the assumptions in the FE model was that the grain boundary is normal to the surface. This is based on Fig. 6(d). However, in other experiments oblique grain boundaries have been observed, Fig. 6(e). In such cases new FE models, with correct grain boundary angles, must be created.

Conclusions
The proposed tri-layer residual stress specimen is useful as a macro-scale highly non-uniform residual stress test case. The DIC was successful in producing qualitative measurement of relaxation displacement caused by the removal of residual stress. However, the DIC resolution remains one of the major limiting factors. As the DIC resolution is linked to the quality of imaging, significant efforts were directed towards obtaining images rich in detail and of high contrast. At the macro-scale the best pattern was produced using spray paint. At the micro-scale mechanical polishing left substantially more surface detail than electro polishing. The macro-scale results were slightly better than the micro-scale, probably due to a superior surface pattern. However, at both scales the relaxation displacement ranges were sub-pixel, at the limit of the DIC resolution.

An obvious route for improvement is to use a bigger CCD, which would give a better image and DIC resolution. Another interesting direction is an investigation of alternative cut geometries, e.g. ring core, see Fig. 8, has an advantage that the whole of the material inside the ring is in the fully relaxed state, provided the slot is sufficiently deep.

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Figure 5: Mechanically polished micro-scale slitting experiment and FE results.
(a) ×5k image, a faint outline of the ×10k image location can be seen, due to exposure to the damaging ion beam.

(b) ×10k image of the same slot.

(c) Side slot profile. Note a typical ‘V’ shape.

(d) Slot depth profile. Note irregular depth in the left grain.

(e) Detail of unrelated FIB slot, note grain boundary at oblique angle to the surface.

(f) EBSD inverse pole plot. Colours represent crystal orientations. Locations of the FIB images for slotting are marked.

(g) DIC relaxation displacement in pixels. Note the range is only 0.2 pixels.

Figure 6: Electro polishing micro-scale slitting experiment.

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(a) Schematic of micro-scale FE model

(b) Predicted relaxation.

Figure 7: Micro-scale FE model and predicted relaxation.

Figure 8: FIB images of ring core. Note the grain boundary crosses the sample surface at an oblique angle.

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