INFLUENCE OF COLD COMPRESSION ON THE RESIDUAL STRESSES IN 7449 FORGINGS

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ABSTRACT

The through-thickness residual stress distributions within three large rectilinear aluminium alloy 7449 forgings have been determined using neutron diffraction. The results from two neutron diffraction instruments, ENGIN-X at ISIS, UK and SALSA at ILL, France are reported. Both instruments indicate large magnitude (>250 MPa) tensile residual stresses in the core of the as quenched forging balanced by surface regions stressed in compression (> -200MPa). The other two forgings had been stress relieved by cold compression and had significantly lower residual stress than the as-quenched forging. Increasing the amount of cold compression from 2½% to 4% was found to cause an insignificant difference in the final residual stress distribution. The neutron diffraction results are also compared to measurements made by the new incremental deep hole drilling technique and show good correlation.

INTRODUCTION

Heat treatable aluminium alloys are subject to severe thermal gradients when quenched from the solution heat treatment temperature. These gradients cause inhomogeneous plastic flow to occur which in turn bring about deformation and residual stresses. A complex three dimensional residual stress state is introduced into heat treated aluminium parts by heat treatment. In thick aerospace components (t > 75 mm), several researchers have indicated that surface compressive stresses in cold water quenched 7000 series plate and forging alloys can have magnitudes >200MPa using the mechanical dissection layer removal technique.¹ ² ³ ⁴ Other investigations using the compliance technique indicates subsurface stress magnitudes >200MPa while surface stresses were approximately -160MPa.⁵

The magnitudes of these as quenched residual stresses are such that critical aerospace parts are stress relieved where possible. For simple parts this can be done by applying plastic deformation using stretching or cold compression.⁶ ⁷ ⁸ The residual stresses after plastic deformation are significantly reduced but they are not removed completely, as illustrated in Figure 1. OS-OC-OS describes the as quenched residual stress distribution from surface to core while 1S-1C-1S is the reduced stress distribution after compression but before removal of the load. The remaining residual stress distribution after completion of the process is described by 2S-2C-2S. For complex shapes, applying plastic deformation is rarely possible.

In either case, the residual stresses can cause part distortion and dimensional instability during subsequent machining. Characterisation of the as quenched residual stresses in heat treated aluminium alloys by neutron diffraction has received limited attention. The aim of this investigation was to quantify the through thickness residual stresses in rectilinear forgings made from the very high strength aluminium alloy 7449. It was not possible to measure these stresses non-destructively using any other method except neutron diffraction. Three forgings with similar geometry were investigated. One forging was left in the solution treated condition, while the other two were stress relieved by applying either 2½% or 4% cold compression. The residual
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stresses were measured using neutron diffraction on ENGIN-X at ISIS, in Didcot, UK and SALSA at the Institut Laue Langevin in Grenoble, France. After completion of the neutron diffraction measurements, the residual stresses in the forgings were also measured using the deep hole drilling technique at the University of Bristol.

Figure 1 The mechanism of cold compression, illustrating how plastic deformation reduces residual stress

EXPERIMENTAL METHODS

Material details. The three rectilinear blocks were forged as a single unit from a 400 mm x 145 mm x 700 mm (115 kg) rectilinear cast slab provided by Alcan, Issoire, France. Forging was carried out on a 2000 Ton hydraulic press by Mettis Aerospace Ltd., Redditch, UK. The slab was forged triaxially and then drawn out to form a rectilinear forging of size 1000mm (L) x 550 mm (LT) x 124 mm (ST). This forging was then sectioned and machined to give the sample size required for this experiment, which was 430 mm (Longitudinal) x 156 mm (Long Transverse) x 123 mm (Short Transverse), where the orientations refer to those of the original primary working direction of the forging. The sectioned blocks were solution heat treated at 470±5°C for 5 hours followed by immersion quenching into agitated water at less than 20°C. Each block had a mass of approximately 23 kg with a surface area of 0.28 m². The Biot number for the cold water quench was approximately 2.0. This number was calculated using a characteristic linear dimension for the forgings of 29 mm and an average heat transfer coefficient calculated from quenching experiments. Forging B was left in the as quenched condition (W temper). Forging C was cold compressed in the short transverse direction by 4%, and forging D was cold compressed 2½% in the short transverse direction (W52 condition). The post quench delay prior to cold compression was less than two hours. The cold compression was applied over the whole surface in just one application of force (bite). The blocks were not artificially aged (however, 7449 does naturally age quite rapidly). Table 1 summarises the experimental details.

Neutron diffraction procedures. Measurements were made following the guidelines present in ⁹, ¹⁰. All three forgings were examined on SALSA, while only forgings B and D were measured on ENGIN-X. For both instruments, a gauge volume of 4 x 4 x 4 mm³ was used. The number of grains contained in this volume was estimated at 6 x 10⁴. The samples were positioned to permit determination of stresses in the three principal orthogonal directions of the forgings.
The locations of the ENGIN-X measurements are shown in Figure 2. As ENGIN-X is a time-of-flight facility, multiple diffraction peaks were acquired simultaneously. This enabled the lattice spacings to be obtained directly using a Pawley refinement of the whole profile. On SALSA, each forging was measured the same way with three orthogonal line scans originating from the vertex at the centre of the forging, moving out to the edges with the directions following the primary mechanical working directions (L, LT and ST). The octant measured was consistent with that sampled on ENGIN-X. The wavelength of the monochromatic radiation was 1.6Å. The position of the aluminium {311} peak was measured by the SALSA diffractometer. A 10 mm thick slice was cut from one end of each block prior to the neutron diffraction measurements. d0 measurements were performed on a small cube sample cut from the corner of each slice. The elastic modulus for 7449 was assumed to be 70 GPa with Poisson’s ratio \( \nu = 0.3 \). Residual strains were converted to stresses using the standard transformations.

![Neutron diffraction measurement locations for ENGIN-X](image_url)

**Figure 2** Neutron diffraction measurement locations for ENGIN-X are shown as points. SALSA measurements were made on the three straight lines originating from the central vertex.

**Deep hole drilling (DHD) and incremental deep hole drilling (iDHD)**. Normal DHD measurements were performed on forgings C and D while a non standard iDHD measurement was carried out on forging B. Full details of the DHD measurement techniques are given in [11]. A 3.18 mm diameter reference hole was drilled through the centre of the forgings in the ST direction using a gun drill (see Figure 6 (i)). The diameter of this hole was then accurately measured using an air probe. A hollow electro discharge tool with 10 mm diameter was then used to introduce a circular cut around this hole. For the incremental DHD measurement, the
circular cut was introduced incrementally to a distance of 12 mm following an extension of the DHD procedure detailed in \(^{12}\). After each incremental cut the air probe was reintroduced into the 3.18 mm diameter hole and the hole diameter measured as a function of depth of cut. The hole diameters were then used to calculate strains and these were then transformed into \(\sigma_{LT}\), \(\sigma_{L}\), and \(\tau_{LT-L}\). It was assumed after extraction from the forgings that the deep hole drilled cores were stress free.

**RESULTS**

When measured on ENGIN-X, the strain free reference sample of forging B indicated that the unstrained lattice parameter, \(d_0\) was 4.0546 Å. The variation with orientation was found to be very small so an average \(d_0\) was used to calculate all the residual stresses. The residual stress distribution of \(\sigma_{LT}\), \(\sigma_{L}\), \(\sigma_{ST}\) in forging B is shown in Figure 3. The contours plots were generated using the linear contour plotting algorithm of Systat SIGMAPLOT V10.0 software. The pattern of residual stress distribution within this forging varied from highly biaxial compression in the exterior surfaces to triaxial tensile in the centre. The maximum compressive stress measured by neutron diffraction was -251 MPa while the maximum tensile stress was 294 MPa. The average error in the residual stresses arising from the fitting of curves to the diffraction peaks was ± 9 MPa. The distribution of the residual stresses did conform to that expected in that as free edges were approached, the magnitudes of the stress normal to the face containing the edge approached zero.

The residual stress distribution in forging D as measured by ENGIN-X is shown in Figure 4. The average \(d_0\) measurement in this block was 4.0540 Å, however there was some variation with orientation so the appropriate \(d_0\) measurement was used when calculating \(\sigma_{LT}\), \(\sigma_{L}\), \(\sigma_{ST}\). The residual stress magnitudes in this cold compressed forging were significantly smaller than forging B. The range of stresses measured varied between 30 and -90 MPa with a fit error of ± 12 MPa. Relaxation of the residual stress did not result in a discernible pattern of redistribution with a similar degree of reduction in stress occurring everywhere within the forgings.

When measured using SALSA, the distributions of residual stress for the sampled line scans were similar to the ENGIN-X results as shown in Figure 5 (i, ii, iii). They were not identical in magnitude and the SALSA values were always less tensile than the ENGIN-X measurements. Fit errors were similar to ENGIN-X. However the distributions of residual stress along the lines measured were the same using both instruments and demonstrated the rapid change from a tensile core to a compressive surface. In the 2½ % cold compressed forging D, again both instruments displayed similar results as shown in Figure 5 (iv).

The forging cold compressed by 4% displayed very low levels of residual stress also like forging D. The range (and standard deviation) of residual stress appeared to be same, suggesting that there was no additional stress relieving benefit from the increased level of cold compression.

The incremental deep hole drilling measurements performed on forging B are reported in Figure 6 (ii). The change in the \(\sigma_{LT}\) and \(\sigma_{L}\) from surface compression to tensile core was detected by the technique and the shape of the distribution in residual stress through the thickness was the same as that determined by the neutron diffraction measurements. However, the magnitude of the residual stresses was quite different and the iDHD measurements were significantly greater than both sets of \(\sigma_{LT}\) and \(\sigma_{L}\) neutron diffraction data. The DHD and neutron diffraction measurements for forging D are shown in Figure 6 (iii) and for forging C in Figure 6 (iv).
correlation between the sets of data was reasonable with the DHD measurements being centred around zero residual stress whereas the neutron diffraction data tended to indicate the presence of compressive $\sigma_{LT}$ and $\sigma_L$ residual stresses.

Figure 3 Residual stresses present in forging B, (cold water quenched, no cold compression) as determined by ENGIN-X. Anticlockwise from top right, $\sigma_{LT}$, $\sigma_L$, $\sigma_{ST}$

Figure 4 Residual stresses present in forging D, (cold water quenched, 2½% cold compression) as determined by ENGIN-X. Anticlockwise from top right, $\sigma_{LT}$, $\sigma_L$, $\sigma_{ST}$
Figure 5 Residual stress in the as quenched Forging B measured using SALSA and ENGIN-X (i, ii and iii), and the 2½% cold compressed forging D (iv). Errors bars omitted for clarity.

DISCUSSION

All the residual stress measurements on the as quenched forging indicated large magnitude residual stresses. On the external surfaces, the maximum biaxial compressive residual stresses were approximately -300 MPa. The magnitude of these stresses are greater than the observations of other researchers that have used neutron diffraction, the contour method, crack compliance, layer removal and centre hole drilling. 7449 is a high strength alloy but its as quenched strength is similar to other 7000 series alloys (0.1% proof stress is 130 MPa) so its capacity to accommodate residual stresses should be similar to other alloys. The SALSA observations indicated lower tensile magnitudes but higher compressive stresses compared to the ENGIN-X data. The observations can be made to coincide by manipulating the d0. In the core of forging B the maximum triaxial tensile residual stresses were significantly larger when measured by iDHD compared to the neutron diffraction data. The iDHD and DHD data did indicate a close to zero shear stress on the LT-L plane which does confirm the L, LT and ST directions are principal.
CONCLUSIONS

1. Neutron diffraction data from two different strain scanning instruments indicates that cold water quenching the aluminium alloy 7449 forgings results in biaxial surface compressive stresses of magnitude in the range 250-300 MPa. These surface stresses are balanced by interior tensile stresses up to 350 MPa.

2. When the same forging is measured on both neutron diffraction instruments, the same residual stress distribution shape is observed for the line scans investigated but the magnitudes are not identical. The differences are significant when large stresses are present as for the as-quenched forging, but for the cold compressed forgings the differences are within the uncertainties of the measurement technique.

3. The differences between residual stresses by the two neutron diffraction instruments are most likely due to the d0 measurements.
4. There is no discernible benefit or disadvantage from cold compressing to 4% when compared to 2½%.

5. When large residual stresses are present, the residual stress magnitudes as measured by the incremental deep hole drilling technique are significantly larger than the equivalent measurements made by neutron diffraction.

6. The absence of a shear stress as determined by the deep hole drilling technique confirms the orthogonal primary working directions of the forgings are principal directions.

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REFERENCES

7. T. Bains: 'Residual stress reduction in aluminum die forgings', 1st International Non-Ferrous Processing and Technology Conference, St. Louis, Missouri, USA, 221-231.