Cold compression residual stress reduction in aluminium alloy 7010

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**Abstract**

7010 is one of the high strength aluminium alloys used mainly as plate and forgings in the aerospace industry. Its high strength is achieved through a quenching operation where the material is rapidly cooled from the solution heat treatment temperature (475°C) to room temperature. As with all rapid quenching operations, residual stresses develop, leaving the material unsuitable for further machining operations and for service. Regular shaped forgings are generally cold compressed after quenching to relieve residual stresses. The effect of friction, increasing/decreasing the amount of cold compression and applying cold compression in ‘bites’ on residual stress magnitudes is unknown. This paper aims to study the effect that these variables have on final residual stress patterns through use of a finite element model.

**1. Introduction**

In 1906 Dr. Alfred Wilm, a German scientist, discovered that after an aluminium-copper-magnesium alloy had been heated to a high temperature and subsequently quenched, its strength increased rapidly when held at room temperature. A team of metallurgists in the United States headed by Paul D. Merica uncovered the mechanism leading to this rapid increase in mechanical strength in 1919 allowing other alloys to be developed using the same principles. With this improved understanding and demand for strong lightweight material by the military towards the end of the Second World War, the Al-Zn-Mg-Cu alloys were developed. Age hardening of these materials led to strengths that exceeded those obtained using the original Al-Cu system. This group of alloys was later designated the 7xxx series of aluminium alloys while the Al-Cu system was designated the 2xxx series. Both of these alloy series are still used extensively in aircraft manufacture today [1].

7075 was one of the first of the 7xxx series of aluminium alloys to be mass produced. For about 15 years after its introduction it was invariably heat treated to its highest strength temper where resistance to stress corrosion cracking (SCC) in thicker sections was inadequate due to a combination of its quench sensitivity and the ageing treatment applied. Low SCC resistance in addition to high residual stresses led to numerous failures of 7xxx series alloys in the late 1960’s after the material had become popular in the construction of civil aircraft [2]. Although the mechanism of SCC in aluminium alloys is now better understood, complete eradication has been found difficult to achieve [3].

Aluminium alloy 7010 (DTD5636 [4]) was developed during the mid 1970’s under the sponsorship of the British Ministry of Defence by Alcan and HDA Forgings Ltd. to exploit the strength of the existing 7xxx series alloys over a greater range of plate thickness by reducing their quench sensitivity [5]. The alloy chemistry of 7010 (Table 1) places control limits on the levels of iron and silicon impurities thereby improving the material’s toughness [5]. These improvements combined to make 7010 more favourable over traditional alloys such as 7075 when used in large die forgings. 7010 aluminium alloy attains its high strength through a high temperature (475°C) solution heat treatment followed by a rapid quench into water/organic quenchant and a subsequent artificial
Residual stresses can be reduced by applying a less severe quench using quenchants such as boiling water or organic quenchants. However, reducing the cooling rate generally reduces the final mechanical properties, as alloying elements will precipitate out of the aluminium matrix at the slower cooling rates leading to the development of coarse equilibrium precipitates. Residual stress reduction after solution heat treatment is generally achieved by plastically deforming parts after quenching in a controlled manner. This plastic deformation can take the form of tensile deformation (designated Tx51), compressive deformation (Tx52) or a combination of the two (Tx54). While application of tensile deformation has been found to result in an almost complete removal of residual stresses [6, 7] the technique is limited to parts that have a substantially uniform cross-section in the stretching direction [8] (e.g. sheet products). Similarly, application of a combined compression-tension loading is limited by configuration, shape and size [9]. Application of cold compression to closed die forgings is difficult in the finished dies given the large difference in thermal expansion coefficient between the tool steels and aluminium while manufacture of special cold reduction dies for more complex forgings results in a large increase in cost. Open die forged products can be cold compressed relatively easily using standard platens with plastic deformation in the range of 1-3% generally applied. However, the effect of variable process parameters during cold compression on the final residual stress magnitude is not generally known. This paper aims to model the development of residual stresses during quenching using the finite element method and to observe how the variable process parameters during cold compression listed below affect the final stress magnitude and distribution.

- While application of 1-3% plastic deformation is generally applied to open die forgings the effect of the different amount of plastic deformation (i.e. 1% as opposed to 3%) on final residual stress distribution is not generally available. It has been shown for aluminium alloy 7075 however, that plastic deformation (compression or tension) of 0.5% results in relief of the majority of residual stresses while cold compression greater than 5% can lead to wrinkling and cracking [6]. The effect of varying the percentage plastic deformation between 1 and 5% to see how this affects the final residual stress magnitude is modelled using the finite element method.

- Frictional effects between the steel compression platens and the forging can result in a complicated stress distribution on the surfaces that are in contact with the platens [6]. While these frictional effects cannot be completely eradicated, their effect can be minimised using suitable lubricants. The effect of varying the friction coefficient on the final residual stress distribution can be studied using the finite element technique.

- Certain large forgings cannot be completely cold compressed in one pass, as they are too large to fit under the cold compression platens. These forgings are therefore compressed in ‘bites’ until the whole forging has received between 1 and 3% plastic deformation. These bites can overlap and may lead to a complicated stress distribution that may cause parts to fail final residual stress inspection tests. An attempt is made at modelling this effect.

2. Finite element calculation of residual stresses

The ABAQUS [10] finite element model used to predict residual stress distributions after quenching 7010 has been described in a previous paper [11]. This model predicted compressive surface residual stress magnitudes greater than 200MPa. This residual stress prediction has been experimentally determined to be accurate [11] and is similar to values published in literature [7, 12, 13]. The original model assumed isotropic material behaviour that was strain rate dependent and
followed a perfectly plastic stress-strain behaviour at all temperatures observed during quenching. While this assumption is valid at high temperatures, it is not true at room temperature (<40°C). Therefore, in the cold compression models the input data has been modified to assume that the material work hardens and is strain-rate independent at room temperature. This is achieved through use of tensile test data measured for 7010 directly after solution heat treatment (Figure 1). All other mechanical and thermal properties remain the same.

The block modelled was an open die forged block measuring 124(ST)*156(LT)*550(L)mm. One-eighth of the block was modelled due to symmetry (see Figure 2) for all of the models included in this paper. The change in material properties at room temperature evoked a reduction in the final residual stress magnitudes predicted after quenching (7-25%). The predicted residual stress distribution indicated surface compressive stresses (maximum of 212MPa) and tensile stresses in the core (maximum of 256MPa). To give an indication of the stress distribution after solution heat treatment, directional stresses (ST/LT/L) are plotted as a function of distance from the core of the block in both the LT and ST directions in Figure 3. The location of these stress distributions is indicated by the AB and AC lines shown in Figure 2.

Cold compression was carried out by deforming the forged blocks at a rate of 6mm/sec in the ST direction. This was modelled by moving a rigid surface towards one surface of the block while constraining the model in the opposing direction.

**Figure 1** Stress-strain curve for aluminium alloy 7010 measured directly after solution heat treatment

**Figure 2** Diagram indicating section of block modelled for cold compression analysis

**Figure 3** Graphs indicating residual stress distribution as a function of distance from the core of the block at a cross-section at its centre along AB (LT) and AC (ST) (see Figure 2) after solution heat treatment
3. Results and Discussion

3.1 Effect of application of cold compression between 1 and 5%

A coefficient of friction of 0.06 [14] was assumed to exist between the forged block and the steel platens in the computer model. This value compared well with a value of 0.03 determined by HDA Forgings Ltd., Redditch, UK using the ring test [15] with a Mobil DTE circulation oil used for lubrication. Cold compression of 1, 2, 3, 4 and 5% was applied to the forging using this model. As for the solution heat treated material, directional stresses (ST/LT/L) are plotted as a function of distance from the core of the block in both the LT and ST directions (Figure 4). After 1% cold compression most of the residual stresses are relieved. The largest residual stresses (compressive up to 170MPa) remain at the unconstrained edges of the model where the material undergoes little plastic deformation (not shown in Figure 4). Tensile stresses remain in the core of

Figure 4 Graphs indicating residual stress distribution as a function of distance from the core of the block at a cross-section in its centre along AB (LT) and AC (ST) (see Figure 2) for cold compression of 1-5% with a coefficient of friction (cf)=0.06 and 2% with cf=0.
the forging with magnitudes of up to 30MPa. Surface stresses generally remain compressive on the LT surfaces, while those close to the ST surface rise to high tensile magnitudes due to the presence of friction between the forging dies and the forging. 

2% cold compression results in all of the core stresses becoming compressive – as does cold compression of 3-5%. Stresses acting in the ST direction become tensile approaching the LT surface, reaching a peak (13.4MPa for 2%) approximately 15mm below the surface and then falling off to compressive magnitudes. This peak increases in magnitude with increasing cold compression (20.8MPa at 5% cold compression). Tensile stresses acting in the longitudinal direction also increase in magnitude on the LT surface from 8MPa at 2% to 31.9MPa at 5% cold compression. Stresses on the ST surface acting in the L direction increase from 83.3MPa at 1% to 125MPa at 2% cold compression. These stresses then begin to fall as cold compression is increased up to 5% where their magnitude reaches 90MPa. Stresses on the ST surface acting in the LT direction rise from 80MPa at 2% to 96MPa at 5% cold compression. 

From the resulting final stress distribution there appears to be no advantage to applying more than 2-3% cold compression to the forging. Applying up to 5% cold compression results in no further decrease in the residual stress distribution while tensile surface stresses in certain directions are increased. Application of 1% cold compression results in tensile stresses remaining in the core of the forging.

3.2 Influence of friction during cold compression

On the strength of results achieved, it was decided to model 2% cold compression with variation in the coefficient of friction to observe the effect of friction on the final residual stress magnitude. Reducing the coefficient of friction to zero (from cf=0.06) results in tensile stresses remaining in the core of the forging (see Figure 4). Surface tensile stresses are greatly reduced (133MPa with cf=0.06 to 32MPa with cf=0) with the highest area of tensile stresses remaining in the centre of the ST face in the forging. While the overall Von Mises stresses appear lower for the case of zero friction, tensile stresses of up to 32MPa remain in the core of the forging. Increasing the friction coefficient from 0.06 to 0.5 results in a stress distribution that is mainly compressive in the core (to values lower than –220MPa) of the forging with areas of high tensile stress on the surface (up to +262MPa). The presence of compressive stresses in the core is desirable in machined parts, but given their overall magnitude, any machining operation could result in distortion. The Von Mises stress pattern indicates that the stresses on the surface approach a yield state in the material. Increasing the coefficient of friction to 1 exaggerates the previous increase with surface tensile stresses increasing in magnitude along with core compressive stresses. To conclude, a low coefficient of friction is therefore advisable to ensure low residual stresses.

3.3 Effect of applying cold compression in bites.

Using a coefficient of friction of 0.06 and applying plastic deformation of approximately 2%, the models described above were modified to allow the block to be cold compressed in the ST direction in a series of bites. The width of the bites was 90mm allowing the block to be fully cold compressed using an overlap of 20mm and 50mm requiring four and seven bites respectively. An attempt was made at modelling the effect of cold compression in bites without the bites overlapping and without any gaps between the bites. This model did not reach a solution as the stresses on the surface of the block at the interface between the first and second bites produced stresses (compressive and tensile) that were far in excess of the yield strength of the material. This indicates that cold compression in bites without an overlap results in stresses that may cause cracks to develop during this stress reduction process. An overlap of 20mm results in large compressive stresses (>240MPa acting in the LT direction) developing on the forging surface at the location of the overlap. High tensile stresses acting in the both the LT and L direction (>250MPa) develop close to the overlap at a location at the end of the initial bites. Core stresses remain high about the location of the overlap with compressive stresses reaching magnitudes of up to 180MPa (ST) and tensile magnitudes of up to 130MPa (LT). Increasing the overlap to 50mm results in similar compressive stress magnitudes at the location of the overlap to those obtained for the 20mm overlap. Given that the bites are smaller, there are more
overlaps and hence more areas of compressive stress. Again, on the surface, there are still high levels of tensile stress acting in the LT and L directions close to the location of the overlap. The advantage of the increased overlap appears to be a reduction in residual stress magnitudes in the centre of the forging where stress levels reach compressive magnitudes of up to 80MPa (L) and tensile magnitudes of up to 50MPa (L). These magnitudes are less than half those obtained for the 20mm overlap.

4. Conclusions
1. Application of 1% cold compression results in relief of the majority of the residual stresses set up during quenching with development of smaller surface tensile stresses than achieved with higher levels of cold compression. The disadvantage of applying 1% cold compression as opposed to higher levels is that tensile stresses that remain in the core of the forging may enhance SCC in machined parts.
2. Application of 2-3% cold compression relieves the majority of residual stress, resulting in core compressive stresses. From the results achieved, there appears to be no advantage in increasing the percentage deformation beyond 3%, as increased levels of cold compression tend to lead to increased residual stress magnitudes.
3. High levels of friction between the forging and the steel dies can result in both high tensile surface stresses and compressive core stresses remaining. These levels of residual stress would be likely to result in distortion during any subsequent machining operation. Zero friction results in tensile stresses remaining in the core of the forging that may enhance SCC in machined parts.
4. When cold compression is carried out in bites, larger overlaps result in more areas of both high compressive stresses and tensile stresses developing on the surface of the forging. However, the larger overlap also results in reduced stresses in the core of the forging. This stress distribution may be desirable for machined parts where surface stresses will be removed and the remaining stresses are low in magnitude.

5. References: