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The influence of quench sensitivity on residual stresses in the aluminium alloys 7010 and 7075

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ABSTRACT

The most critical stage in the heat treatment of high strength aluminium alloys is the rapid cooling necessary to form a supersaturated solid solution. A disadvantage of quenching is that the thermal gradients can be sufficient to cause inhomogeneous plastic deformation which in turn leads to the development of large residual stresses. Two 215 mm thick rectilinear forgings have been made from 7000 series alloys with widely different quench sensitivity to determine if solute loss in the form of precipitation during quenching can significantly affect residual stress magnitudes. The forgings were heat treated and immersion quenched using cold water to produce large magnitude residual stresses. The through thickness residual stresses were measured by neutron diffraction and incremental deep hole drilling. The distribution of residual stresses was found to be similar for both alloys varying from highly triaxial and tensile in the interior, to a state of biaxial compression in the surface. The 7010 forging exhibited larger tensile stresses in the interior. The microstructural variation from surface to centre for both forgings was determined using optical and transmission electron microscopy. These observations were used to confirm the origin of the hardness variation measured through the forging thickness. When the microstructural changes were accounted for in the through thickness lattice parameter, the residual stresses in the two forgings were found to be very similar. Solute loss in the 7075 forging appeared to have no significant effect on the residual stress magnitudes when compared to 7010.

1. Introduction

One of the unavoidable end results arising from the heat treatment of precipitation hardened aluminium alloys is the introduction of high magnitude residual stresses. Severe thermal gradients arise when thick section products are rapidly quenched from the solution heat treatment temperature. These gradients cause inhomogeneous plastic flow to occur, which in turn produces distortion and residual stresses [1,2]. For a rectilinear block like those investigated here, immediately after quenching tensile plastic strains occur initially at the rapidly cooling edges of the material. The plastic zone then expands to cover all the rapidly cooling surfaces. The block at this point consists of a soft hot interior surrounded by a harder and cooler exterior stretched shell. As the central region starts to cool, it tries to contract but is constrained by the hard outer shell and also undergoes tensile plastic deformation. As the block cools further, the magnitude of surface plastic strains diminishes as a compressive stress is developed, finally resulting in a surface stressed into compression and a centre into tension [3]. The final stress pattern is a reflection of the geometry of the component and of the temperature gradients generated throughout in the quench.

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When applied to heat treatable aluminium alloys, the term quench sensitivity is a relative measure of the loss of solute from solid solution as precipitation, occurring during quenching from the solution heat treatment temperature [4]. The alloy 7075 (registered in 1954) is classed as being quench sensitive while 7010 (registered in 1975) is far less so. This is illustrated in the time–temperature property curves presented in Fig. 1 [5]. These "C curves" show the times required to precipitate sufficient solute to change the strength by a specified amount, in this case to give strengths of 70% and 99.5% of that achievable in material quenched infinitely quickly. Precipitation that occurs during quenching changes the subsequent response of the material to ageing, but can also potentially influence the magnitude of the residual stress distribution introduced by rapid cooling by lowering the flow stress [6]. This investigation examines the residual stress distribution and magnitudes in two large rectilinear 7010 and 7075 forgings. The forgings were cold water quenched (CWQ) to induce a large residual stress which was then characterised using neutron diffraction at the ENGIN-X instrument located at ISIS, UK. The residual stresses were then also determined using the incremental deep hole drilling method (iDHD) at the University of Bristol, UK. The cores extracted during iDHD were then analysed for lattice parameter variations using neutron diffraction on the E3 instrument at the Helmholtz Centre in Berlin.

2. Experimental Procedures

2.1. Material Details

Two rectilinear forged blocks were studied. Each forging was approximately 215×215 mm and 300 mm long as shown in Fig. 2. The specification alloy chemistry of 7010 and 7075 is shown in Table 1.

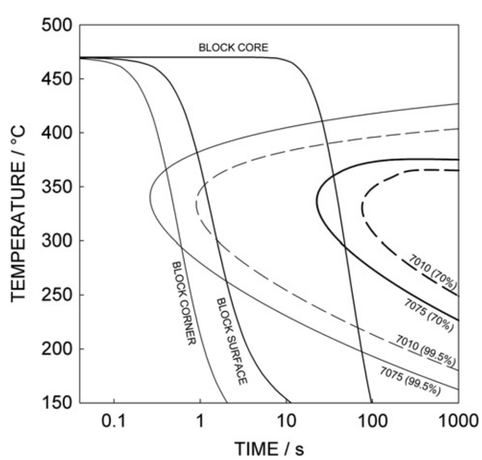

Fig. 1 – Time–temperature property curves for over aged 7010 and 7075. Each alloy has two TTP curves in this figure, the 99.5% curves are the locus of times required to produce 99.5% of the tensile properties associated with an infinitely fast quench. The other curves are for the times to produce 70% of the tensile properties produced by an infinitely fast quench. The cooling curves correspond to the core and corner of the rectilinear forgings investigated here, and the centre of a 300×215 mm surface.

Both samples had been manufactured from cast slab and triaxially forged. The 7010 block was sectioned from a much larger rectilinear forging whereas the 7075 block was forged from slab as a separate entity. Relative to the cast slab material origin and forging procedures, for the 7010 forging x=LT (long transverse), y=L (longitudinal) and z=ST (short transverse). For the 7075 forging x=L, y=LT and z=ST. Due to the forging method, neither forging was expected to show pronounced grain elongation. Both forged blocks were solution heat treated at 470 °C and immersion cold water quenched to room temperature. Quenching was accompanied with mild agitation of the water and the water temperature was <20 °C. The forgings were not artificially aged and hence naturally aged during the experiment. This condition is referred to the W temper (unstable aging). Forging and heat treatment were carried out by Mettis Aerospace Ltd, Redditch, UK. Each forging had a mass of approximately 39 kg with a surface area of 0.35 m^2. The Biot number estimated for the cold water quench was approximately 2.6. The Biot number is a dimensionless number that gives an index of the ratio of the heat transfer resistances inside and at the surface of a body. If the Biot number is >0.1 then the thermal gradients are significant within the body. The Biot number was calculated using a characteristic linear dimension for the forgings of 40 mm (ratio of block volume to surface area), an average thermal conductivity of 180 W m^{-1} K^{-1} and an average heat transfer coefficient of 12,000 W m^{-2} K^{-1} calculated from quenching experiments.

The microstructure of the 7010 forging consisted of approximately "pancake" shaped grains flattened in the short transverse direction with the mean grain length in this direction being 85 μm as shown in Fig. 3. In the longitudinal and long transverse the grain characteristic dimension was 160 μm. Within these grains a substructure was observed consisting of well defined polygonised equiaxed sub-grains. The mean diameter of the sub-grains was <30 μm. Other coarse phases noted were fragmented Al–Cu–Fe constituent particles and a very small volume fraction of undissolved $MgZn_2$.

The microstructure of the 7075 forging consisted of approximately equiaxed shaped grains with the mean grain size being 86 μm as shown in Fig. 4. The difference in grain size and shape between the two forgings reflects the different triaxial forging practices used. A substructure was also observed, again consisting of well defined polygonised equiaxed sub-grains. The mean diameter of the sub-grains was <20 μm, noticeably smaller than the 7010 sub-grains. Coarse phases were also observed, being present in a significantly greater volume fraction compared to 7010, a consequence of the higher combined iron and silicon content in 7075. Both microstructural samples were from the same location as the strain free reference used for neutron diffraction measurements.

2.2. Transmission Electron Microscopy

Slices cut from positions in the incremental deep hole drilled cores (see Section 2.5 later) corresponding to the centre and surface of the forgings were mechanically ground to a thickness of approximately 150 μm from which discs of 3 mm diameter were punched. The material was in the naturally