Residual stress development and relief in high strength aluminium alloys using standard and retrogression thermal treatments.

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Abstract
Residual stresses develop in the aluminium alloy 7010 when the material is quenched from the solution heat treatment temperature. Residual stress measurements have been made using the x-ray diffraction technique and a longitudinal split saw cut method to determine the magnitude of residual stress that develops in specimens sectioned from large open die forgings as a result of a) quenching these specimens into water at different temperatures, and b) cold water quenching from different furnace temperatures. Residual stress reductions as a result of retrogression and reageing and standard thermal treatments have been determined. The longitudinal split saw cut technique is used to demonstrate the viability of a cheap, rapid technique for determining surface stress magnitudes in specimens of suitable geometry. The variation in room temperature tensile properties of 7010 with natural ageing time has also been determined. The surface residual stress magnitudes can significantly exceed the as quenched materials uniaxial limit of proportionality.
Introduction
The aluminium alloy 7010\(^1\) is a descendant of the Al-Zn-Mg-Cu alloys first used towards the end of Second World War. It is a precipitation hardenable alloy developed in the late 1970s by Alcan International Ltd. and HDA Forgings Ltd. under the sponsorship of the UK Ministry of Defence. The alloy was primarily designed as a plate and forging alloy with reduced quench sensitivity allowing for use in thick sections and a low combined Fe+Si content for good fracture toughness. The combination of strength, fracture toughness and stress corrosion cracking resistance was improved when compared to alloys like 7075T651 and 7079T6.\(^2\) It is mainly used for strength critical aerospace structural applications.

To produce useful strengthening, the great majority of precipitation hardenable aluminium alloys rely on rapid cooling from the solution heat treatment temperature to suppress the formation of coarse equilibrium second phases. Precipitation nucleation and growth kinetics dictate that the critical temperature range is between 400 and 290°C and the cooling rate through this range must exceed 100°C sec\(^{-1}\) for most alloys, although chromium containing quench sensitive alloys like 7075 require up to 300°Csec\(^{-1}\).\(^3\) Quenching into cold water by immersion or spraying produces the greatest possible thermal gradients in aluminium alloys and is an ideal quenchant from a mechanical properties perspective. Unfortunately, the severe thermal gradients can result in inhomogeneous plastic deformation, reported to occur as the material passes through the 450-300°C temperature range.\(^4\) In thick components such as plate and large forgings, this results in the introduction of surface compressive residual macrostresses of yield point magnitude balanced by tensile sub-surface macrostresses.
Reducing the thermal gradients by using heated water and inversely soluble polyalkylene glycol (PAG) type solutions can reduce residual stress magnitudes. However, the subsequent ageing response is diminished, the degree being dependent on the alloy. Other quenchants have been developed which purport to reduce quench induced residual stresses while still maintaining the required mechanical properties. Recent research has also resulted in the development of new alloys and processing routes that maintain mechanical properties and reduce distortion during machining.

Residual stresses can cause warping during machining and subsequent dimensional instability. The strengthening mechanism of age hardenable aluminium alloys precludes the application of normal thermal methods to relieve the residual stresses induced by quenching, and stress relief of heat treatable aluminium alloys is usually performed using mechanical methods.

Established procedures exist to reduce if not eliminate residual stresses from semi-finished products through controlled mechanical stress relief. The early development of mechanical stress relieving methods arose in the 1950s when aircraft manufacturers started to adopt machined components in place of small part assemblies. Roller levelling was applied to sheet, and stretching applied to plate and long rectilinear forgings. These processes were inappropriate for die forgings but it was recognised that roller levelling was applying compressive deformation so this was extended to cold compression. Cold compression is a much more suitable process for forgings and this alternative stress relieving process was introduced in the mid 1950s for open die forgings and the late 1950s for die forgings. All these methods involve the application of between 1 and 5% plastic deformation to the solution treated and quenched component and result in significant reduction in
residual stress magnitudes. Cold compression has the obvious disadvantage of requiring an extra trip back to the forging press. For this reason an alternative thermal method has been investigated involving cooling solution heat-treated material to sub-zero temperatures and then rapidly heating the surfaces with superheated steam. This process is known as uphill quenching and has found limited commercial application.

Retrogression and reageing thermal treatments can be used to improve the combination of strength and stress corrosion cracking resistance in 7XXX series aluminium alloys. 7150 and 7055 are two recently developed alloys that find application as extrusions and plate in the T77x retrogression and reageing temper. The retrogression treatment normally involves re-heating material in the peak-aged condition to a temperature between 180-240°C for short periods of time, cooling back to room temperature and then reageing. There is evidence that limited stress relief occurs during normal ageing treatments.

This paper attempts to quantify residual stress development in aluminium alloy 7010 by observing stress variation in specimens that are quenched from different temperatures, and in specimens that are quenched from the solutionising temperature into water at different temperatures. Residual stress magnitudes are also determined after the application of standard heat treatments and retrogression and reageing thermal treatments to determine if these heat treatments effect any substantial stress reductions. Surface residual stress magnitudes are determined using a deflection mechanical dissection technique (longitudinal split saw cut method) and the x-ray diffraction technique. This mechanical dissection technique is included to demonstrate a rapid, cheap alternative for determining approximate surface residual
stress magnitudes in rectilinear components without the need for sophisticated equipment. This technique can also be used qualitatively on more complicated shaped products where the deflection upon slitting can be monitored to give a comparison between different stress relieving processes.\textsuperscript{15}

Several researchers using the layer removal technique\textsuperscript{12, 16-18} and neutron diffraction\textsuperscript{19} have indicated that surface compressive stresses in cold water quenched plate and forging alloys similar to 7010 can have magnitudes >200MPa. A more recent investigation using the compliance technique indicates subsurface stress magnitudes >200MPa while surface stresses were approximately 150MPa.\textsuperscript{20} These values greatly exceed the proportional limit of as quenched 7010 measured in small specimens.

The mechanism by which residual stresses are introduced during quenching implies that these stresses cannot exceed the yield stress of the material. As the flow stress of aluminium alloys decreases with increasing temperature, the maximum residual stress should bear some relation to the strength properties measured at room temperature.\textsuperscript{21} It would therefore be expected that the maximum as-quenched residual stress should be similar in magnitude to the uniaxial yield stress measured at room temperature. Tensile properties have been measured for 7010 directly after solution heat treatment and after varying periods of natural ageing in an attempt to determine how rapidly the material strengthens in this condition. The room temperature work hardening performance of naturally aged 7010 has also been determined as work hardening during quenching could contribute to the apparent high residual stress magnitudes.
Experimental Details

Material details

7010 is very similar to 7050 and Table 1 details the specification composition of 7010 and quantitative analysis of a specimen from the forging performed using standard analytical techniques. The specification compositions of 7050, 7150 and 7055 are provided for comparison.

Table 1 Chemical composition corresponding to aluminium alloy specifications and chemical analysis results, wt%.

Rectangular section open die forged blocks of 7010 were received from HDA Forgings Ltd, Redditch, England. These blocks were of 3m length and had cross sections of 156 (LT-Long Transverse) x 125 mm (ST-Short Transverse). The blocks had received either the T7652 heat treatment: solution heat treated 6 h at 475°C, quenched into cold water (<40°C), cold compressed 2½±½%, aged 10 h at 120°C + 8 h at 172°C, or were left in the W52 condition: solution treated and cold compressed.

Figure 1 Microstructure of 7010T7452. Keller’s reagent.

The microstructure was typical of a forged product with characteristic large 'pancake' grain morphology. These original grains contained a well-defined equiaxed sub-grain structure with diameters of ~8µm, easily resolvable using light microscopy. Figure 1 indicates the typical microstructural features of the material. Observation of unetched sections revealed the presence of constituent phases with particle sizes up to 20µm. The major constituent phase was present as clusters of fragmented rounded grey coloured particles strung out into the longitudinal directions. Smaller (1–5µm) iridescent blue oval particles were also observed.
Qualitative energy dispersive x-ray analysis of these particles in a scanning electron microscope identified the large fragmented pale grey/brown as aluminium, copper and iron rich and the iridescent blue Mg and Si rich. Upon etching in Keller's reagent, the larger particle clusters turned light brown confirming their identification as \((\text{Al}_7\text{Cu}_2\text{Fe})\) and the smaller iridescent blue particle turned black \((\text{Mg}_2\text{Si})\). All specimens used in this investigation were resolution heat-treated but this had no influence on the \(\text{Al}_3\text{Zr}\) stabilised grain structure when examined by normal optical methods.

**Residual stress determination**

Longitudinal split saw cut (slitting) method

The longitudinal split saw cut method is an approximate deflection method used for estimating surface residual stress magnitudes.\(^7\)\(^{,22}\) This destructive mechanical dissection method involves introducing a bandsaw cut into a section of material and simply measuring the end deflection as a function of cut depth. In this paper it is compared to the x-ray diffraction technique when measuring stress reduction arising from quenching and ageing treatments. Thirty-three specimens of size \(26(\text{L})\times156(\text{LT})\times26\text{mm(ST)}\) were sectioned from the as received forging. All specimens were solution treated in an air circulating furnace for 2 hours at \(475\pm5\)°C. Specimens were quenched into water and further heat-treated according to Table 2. Specimens were stored in a freezer at \(-18\)°C to delay the onset of ageing or stress changes occurring before either residual stress measurements or further heat treatments were undertaken. After completion of the heat treatment, specimens were slit using a vertical band saw at 10mm increments to a maximum cut depth of 120mm (see Figure 2) with a feed rate chosen to prevent specimen heating. The maximum deflections are the significant observation and obtaining measurements for
every 10mm increment is not absolutely necessary. However, the presence of abrupt deviations from a smooth curve when deflection is plotted against cut depth gives an indication of stress variation in the LT direction.

**Figure 2 Longitudinal split saw cut method specimen.**

The slit was introduced into the L-LT plane (parallel to the ST-LT face, with the cut being made in the LT direction). When this technique is applied to material containing a compressive surface stress, the resulting deflection causes the specimen tines to pinch the blade and more material is removed, as the blade has to be periodically reinserted. Tapered tines with reduced section modulus result, the degree being a function of deflection. These tapered tines in conjunction with the continuous removal of material containing a tensile residual stress will lead to greater deflections being recorded and are a potential source of error. Using a thicker specimen can reduce this error.

**Table 2 Heat treatments applied to longitudinal split saw cut specimens. AC-air cooled, CWQ cold water quenched (<40ºC).**

Strength of materials calculation of residual stress

The deflection technique can be used to calculate surface residual stresses from simple beam theory. The expression for the maximum stress in the surface of the block in the direction of the saw cut is as follows:

\[ \sigma = \frac{E' t \delta}{2l^2} \]

Where \( E' = E/1 - \nu^2 \), \( E \) is the elastic modulus (70GPa for 7010) and \( \nu \) is Poisson’s ratio (0.3), \( t \) is the block thickness (26mm), \( l \) is the length of the bent beam (120mm) and \( 2 \delta \) is the end deflection. This technique was originally applied to wide plate
where the residual stress distribution was assumed to be linear and elastic through the thickness, and constant along both length and width. The technique can also be applied to square section bar but unlike the case for plate there will be significant residual stress on the adjacent faces along the length of the bar. However, for the current specimen geometry the residual stresses acting in the LT direction on planes parallel to the cut are assumed to make the major contribution to the deflection. The validity of this assumption can be confirmed by the linearity of deflection plotted against the square of the cut length.

X-ray diffraction

Uniaxial residual stress magnitudes were determined using the local strain x-ray diffraction technique (XRD) as outlined in literature.\textsuperscript{24-28} Residual stress was determined along the LT direction from the centres of both LT-L faces of the square section bars using a Philips X’Pert x-ray diffractometer, unless otherwise stated. The stress measured in this direction will be comparable with the stress calculated using the longitudinal split saw cut method. All x-ray measurements were recorded on as heat-treated surfaces with the heat treatments outlined in Table 3.

Scan parameters were controlled using Philips X’Pert Data Collector (V1.2a) software with 2\(\theta\) values (2\(\theta\) – angle between source and diffracted x-ray beam) chosen to encompass the Cu-K\(\alpha\) doublet for the \{422\} planes: 136° ≤ 2\(\theta\) ≤ 139°. A minimum of eight scans were performed for each measurement using evenly distributed \(\psi\) angles within the range 0° ≤ \(\psi\) ≤ 60° (\(\psi\) – angle between the surface normal and the bisector of source and diffracted x-ray beam). Only positive tilting was used as negative tilting can lead to poor quality peaks when using the \(\omega\)-
diffraction geometry.\textsuperscript{25} Pseudo-negative tilting (rotating the specimen through 180° around the φ–axis) did not affect the stress magnitudes achieved.

The resulting spectra were analysed using Philips X’Pert Stress Software.\textsuperscript{29} The \(\sin^2 \psi\) technique was used with a \(\frac{1}{2}S_2\) value of \(19.07 \times 10^{-12} (\text{m}^2/\text{N})\) taken from literature for the \{422\} plane.\textsuperscript{24} The Pearson VII technique was used to calculate the peak position on the diffracted intensity plots.\textsuperscript{30} The measurements taken indicated that the lattice spacing \(d\) versus \(\sin^2(\psi)\) plots were linear, confirming that texture and stress gradient did not affect the calculated stress magnitudes. Shearing stresses were assumed negligible when compared with normal stress magnitudes. The errors quoted are fit errors of the \(d\) versus \(\sin^2(\psi)\) plots calculated by the software. This software allowed a misalignment calculation to be performed confirming that the specimen height and machine alignment was correct even though specimen height has not been found to have a large effect on determined stress magnitudes.\textsuperscript{25}

When using the x-ray diffraction technique to measure residual stress on aluminium specimens, magnitudes can vary from specimen to specimen due to local variations in the microstructure of the material. To minimise these errors when comparing residual stress magnitudes after ageing treatments, stresses were determined for the same location on the same specimen after solution heat treatment and in the final condition.

**Table 3 Heat treatments applied to x-ray diffraction specimens.**

**Hardness and electrical conductivity measurements**

To ensure that heat treatments were carried out correctly, hardness and electrical conductivity measurements were made upon completion of the ageing treatments. Hardness testing was conducted using an Instron Wolpert Testor 930/250 (HV20)
calibrated with a test block to the requirements of ASTM E92-92. Electrical conductivity was measured using a KJ Law Verimet M4900C eddy current conductivity meter. This meter was calibrated against 7010 and 5154 standards of known conductivity and measured in units of %IACS (International Annealed Copper Standard) where 1%IACS=0.58MS.m⁻¹.

**Tensile testing**

Tensile testing was performed in accordance with ASTM B557-84, using a non-standard round LT tension test piece geometry of gauge length 30mm and diameter 6mm, on a Dartec 500kN servo-hydraulic load frame utilising a 25mm gauge length extensometer. Specimens were tested at a strain rate of 3x10⁻⁴s⁻¹. To eliminate quench sensitivity effects, the fully machined tensile test specimens were heat treated and quenched, with a minimum delay between quenching and testing of 3 minutes. The duration of the tensile test was approximately 20 minutes but the 0.2% proof stress (R_p0.2) was achieved within the second minute of testing.
Results

Residual stresses development
To aid the understanding of the development of residual stress in 7010, a 26(L)x156(LT)x26mm(ST)mm specimen was cold water quenched (<40°C) from successively increasing furnace temperatures. To achieve this, the block was solution heat treated at 475°C and allowed to furnace cool to the required temperature prior to quenching and residual stress determination using the x-ray diffraction technique. Figure 3 confirms that significant residual stresses are only introduced when 7010 is cold water quenched from temperatures >200°C. The measurement of negligible residual stress in a block allowed to furnace cool to room temperature suggests that the x-ray diffraction technique is capable of reliable measurements of this type.

Figure 3 Residual stress magnitudes produced by quenching 7010 into cold water (<40°C) from different furnace temperatures.

Six specimens were quenched into water at <40°C from 475°C and were slit to a depth of 120mm. The average measured maximum deflection for these blocks was -5.5mm with a standard deviation of 0.5mm with the variation in deflection with cut length indicated in Figure 4. When this result for the final deflection is substituted into the strength of materials equation it results in a calculated surface stress of –190MPa with a standard deviation of 17MPa.

The x-ray diffraction calculated residual stress magnitudes after solution treating but prior to any ageing treatment are indicated in Table 4. These results consist of the average value from eight measurements taken on both opposing ST-LT faces of four specimens. The standard deviation in this case is calculated from the stress magnitudes, not the error in the fit of the d versus Sin²ψ plots. The stress magnitudes
determined using x-ray diffraction (~193±10MPa) compare well to those calculated using the slitting technique.

**Table 4 X-ray diffraction residual stress magnitudes before and after a T6 type ageing treatment for specimens quenched into water at <40°C.**

It is well known that increasing the water temperature used for quenching can have a large effect on reducing residual stress magnitudes. To quantify this effect, specimens were quenched from 475°C into water at 55, 80 and 100°C. Three specimens were quenched into water at 55°C, a further three into water at 80°C and two more into water at 100°C to observe the effect on deflection when using the longitudinal split saw cut method. To compare with these results, x-ray diffraction measurements were taken on both LT-L surfaces of two specimens heat-treated to each of these three conditions. After the specimens were quenched they were aged into a T61 type condition by ageing for 24 hours at 120°C. The results from these specimens could then be compared directly with those where the specimens were quenched into cold water (<40°C) and aged to a T6 type condition described later and also detailed in Table 4. Table 5 details the residual stress magnitudes determined on all T61 specimens aged for 24 h at 120°C.

Hardness measurements after ageing indicated a decrease from the cold water quench value with increasing temperature. Boiling water quenched specimens exhibited a hardness of ~180HV20 while the specimens quenched into water at 80°C indicated a value of ~195HV20. Electrical conductivity values for the boiling water quenched specimens were higher than the cold water quenched specimens giving values of approximately 32%IACS. Both techniques used to determine residual stress magnitudes after quenching into water at different temperatures confirmed a substantial reduction in magnitude with increasing quenchant temperature.
Table 5 Residual stress magnitudes for T61 specimens determined using x-ray diffraction and slitting techniques.

Figure 4 Graph of deflection as a function of cut depth for solution heat-treated specimens and those aged into a T61 condition.

Variation of residual stress with ageing treatments

Natural ageing – Residual stress results for naturally aged material
One specimen of 7010 measuring 60(LT)x60(L)x16(ST)mm was solution heat treated at 475°C and quenched into cold water (<40°C). Immediately after the specimen had been quenched the residual stress at the centre of one LT-L surface was determined using x-ray diffraction. The results are shown in Figure 5 where the time after solution heat treatment is plotted against the measured stress. The time plotted is calculated as the time from quenching to the mid-point of time during the residual stress measurement. As determined previously using x-ray diffraction, there is no decrease in residual stress magnitudes with natural ageing time. The average stress measured in this specimen was –198MPa with a calculated standard deviation between the twenty-two measurements of <4MPa. This result again serves as an indicator to the repeatability of this measurement technique.

Figure 5 Residual stress versus natural ageing time for 7010.

Ageing treatment – T6 type treatment
A typical T6 ageing treatment for a 7XXX alloy involves solution heat treatment and quench into cold water, followed by artificial ageing at 120°C for 24 hours. This results in material that has excellent strength properties, but very poor resistance to stress corrosion. Such a heat treatment was applied to three specimens that were subsequently slit and four specimens that were used for x-ray diffraction measurements. Hardness measurements indicated that these specimens had a Vickers hardness of approximately 216HV20 while electrical conductivity
measurements were of the order of 30%IACS. These values are typical of those obtained for this heat treatment.\textsuperscript{34}

Table 4 displays the stress magnitudes determined from the x-ray diffraction technique while the average calculated deflection from three specimens using the slitting technique was \(-5.7\pm0.5\)mm \((-197\pm17\text{MPa})\). The deflection results indicated no significant change in stress after applying a T6 type heat treatment to the specimens and the very small increased deflection at all cut depths for the T6 specimens is attributed to experimental error (Figure 6). The x-ray diffraction technique also implied no significant change in stress magnitude, with the calculated average change in stress magnitude between the eight measurements being a reduction of approximately 3.4%.

**Ageing treatment – T74**

A typical T74 heat treatment normally applied to 7010 die forgings (DTD5636) involves ageing for 8h at 110°C with a further 10-16h at 175°C. To determine if stress relief occurs using this heat treatment, two specimens were heat-treated to this condition (using 10h at 175°C) with the residual stress being determined by the x-ray diffraction technique on both LT-L faces before and after ageing. Two further specimens were slit for comparison with these x-ray measurements. Hardness and electrical conductivity measurements indicated values of \(~178\text{HV20}\) and \(~40\%\text{IACS}\) respectively, both of which are typical for this heat treatment.

Table 6 details the x-ray diffraction measurements and Figure 6 indicates the variation of deflection with cut depth for the T74 condition compared to the mean deflection of specimens in the solution heat-treated and T6 conditions. The ageing period at 175°C resulted in a 25% reduction in deflection compared to the solution
heat-treated condition while the x-ray diffraction results indicate an average reduction in residual stress from the ageing treatment of over 30\% to a magnitude of -126MPa.

Table 6 Residual stress magnitudes for T74 specimens determined using x-ray diffraction.

Figure 6 Deflection in specimens aged into the T74 condition compared to solution heat-treated and T6.

Ageing treatment – Retrogression and reageing
The balance of strength and stress corrosion cracking resistance can be enhanced by the application of retrogression and reageing (RRA) treatments. RRA treatments involve the application of a T6 type ageing treatment (24hrs at 120°C) followed by a retrogression treatment at 180-240°C for short periods of time (typically 1-60 minutes) followed by another T6 type ageing treatment. Two specimens were subject to a RRA treatment utilising a retrogression temperature of 200°C and used for x-ray diffraction residual stress analysis, while a further 6 were heat treated into the same condition for slitting measurements (see Table 2 and Table 3 for details of heat treatments). A further six specimens were RRA treated using a retrogression temperature of 240°C, with two specimens used for x-ray diffraction measurements, the balance being slit. An attempt was also made to observe the effect of uphill quenching on specimens containing a high residual stress. After four specimens had been cold water quenched and aged at 120°C for 24 hours they were immersed in liquid nitrogen until they reached –197°C. Two of them were then immersed into salt at 200°C for a period of 40 minutes while two more were immersed into salt at 240°C for 5 minutes to imitate the application of a retrogression treatment. They were then slit using the longitudinal split saw cut method to determine the stress magnitude.
The results of residual stress measurement and slitting for specimens subject to RRA or uphill quench + RRA heat treatments are given in Table 7. Figure 7 indicates the variation of deflection with cut depth for the RRA and uphill quench + RRA conditions compared to the mean deflection of specimens in the solution heat-treated condition.

The slitting results indicate that retrogression and reageing treatment at 200°C and 240°C results in stress reductions of 29% and 20% respectively while the results from the x-ray diffraction experiment indicate reductions of 24% and 29% respectively. These stress reductions are marginally less than those observed for the T74 condition with both ageing treatments indicating approximately the same reduction when experimental error is accounted for. Uphill quenching did not produce any significant additional stress relief.

Table 7 Residual stress magnitudes for RRA specimens determined with x-ray diffraction and slitting techniques (Quench – water at <40°C).

Figure 7 Deflection of specimens subject to RRA and uphill quenching RRA treatments.

Natural ageing (W-temper) – Tensile test results for naturally aged material

The as quenched and naturally aged tensile properties of 7010 are presented in Figure 8. The as quenched R_p0.2 of 7010 was found to be of the order of 150MPa with a measured proportional limit of 110MPa. The material strengthened significantly after an initial incubation period of approximately 35 minutes. The alloy continued to strengthen over time and did not stabilise for the testing duration (1530 hours). The properties of 7010 (in the cold compressed W52 condition) naturally aged for 5 years are displayed in this figure as horizontal reference lines. The 7010 results are similar to those indicated in the literature for 7050 with a natural ageing response given for the tensile strength almost exactly matching that presented here. This published data
indicates an initial yield strength of approximately 175MPa and an incubation period of over 30 minutes before the material begins to strengthen. Unfortunately, it is not specified whether this yield strength is determined as a 0.2% proof strength.

The room temperature strain hardening characteristics of 7010 are shown in Figure 9. The strain hardening exponent \( n \) and the corresponding strength coefficient \( K \) (MPa) were calculated by assuming the plastic portion of the true stress true strain curve up to the tensile strength could be described by a simple power law type equation, \( \sigma = K \varepsilon^n \). The as-quenched room temperature strain-hardening characteristics of 7010 can be described as having low \( K \) with a corresponding high \( n \) (\( \sigma = 670 \varepsilon^{0.32} \)). This resulted in an overall low strain hardening rate, but with increasing natural ageing, \( K \) increased and \( n \) decreased with a resulting increase in the strain hardening rate (after 1530 hours: \( \sigma = 795 \varepsilon^{0.17} \)). These observations are consistent with established precipitation and strain hardening theory.

**Figure 8** Tensile properties of naturally aged 7010. Horizontal reference lines are for 7010W52 after 5 years natural ageing.

**Figure 9** Room temperature strain hardening characteristics of 7010.

**Discussion**

**Residual stresses in 7010**

For the geometry used in this investigation, quenching specimens of 7010 from 475°C into cold water results in compressive surface residual stresses of magnitude 170-200MPa. From measurements on other geometries including thick (124mm) 7010 open die forgings this level of residual stress appears to be the maximum that can be induced and supported in a surface. Quenching from lower temperatures results in a rapidly diminishing residual stress as the magnitude of the of the thermal gradients decrease and the material offers more resistance to plastic flow as shown in
Figure 3. However, this is not a feasible option for heat treatable aluminium alloys. The successful technological approach to reducing component residual stress has been to reduce the thermal gradients by increasing the water temperature, using alternative quenchants or mechanically working. As shown in Figure 4, the reduction in residual stress arising from quenching into water at 80-100ºC is significant. The forfeit of mechanical properties can be tolerated for some applications and 7010 is routinely hot water quenched as it is not as quench sensitive as other 7XXX series alloys such as 7075 due to the replacement of Cr with Zr.

**Observations about the longitudinal slitting technique**

The residual stress magnitudes determined using the slitting technique have standard deviations of up to 12% of the stress measured when a number of specimens in the same condition are compared. The reasons for this scatter are due to:

- The specimen tines closing in on the blade, which will result in more material being removed in some specimens than others, depending on the amount of deflection.

- The difficulty in ensuring that the cut is central at all stages during cutting. As discussed earlier, the cuts were introduced using a vertical band saw, which required keeping one side of the specimen against a guide. When this technique was initially attempted some measurements resulted in more material being removed from one side than the other. However, with careful monitoring during cutting, the slit can be kept central.

- Inaccuracy in measurement of the deflections. The callipers used to measure the deflection had a precision of measurement of ±0.01mm (equivalent to ~0.4MPa
for the geometry in question at a cut depth of 120mm). The cut tines turn in at the end with each increase in cut depth. It is therefore important that the measurements always be taken from the same location.

Comparison of x-ray diffraction and slitting determined stress magnitudes

Stress magnitudes determined using the x-ray diffraction technique were measured at the centre of the LT-L surfaces acting in the longitudinal direction. In comparison, the slitting method estimates the surface stress magnitudes acting in the longitudinal direction along the LT-ST face. The main difference between these two determined stress magnitudes is that the x-ray diffraction technique measures the stress over an area (measuring approximately 10x4mm) at the centre of the face while the slitting technique averages the stress across the surface. Figure 10 compares the average stress magnitudes as determined using the x-ray diffraction and slitting techniques for all of the results measured using both techniques as described above. From Figure 10 it can be observed that in cases where the stress magnitudes are small, the slitting technique determines stress values lower than the x-ray diffraction technique. This may be due to the fact that the slitting technique estimates a surface stress by calculating the displacement from stress redistribution in the entire specimen, while the x-ray technique only accounts for the surface stress.

Another assumption made by the strength of materials analysis is that the residual stress will be completely relaxed by sectioning. To determine if this was the case the surface residual stress was measured on the LT-ST surface in a specimen quenched at 55°C using the x-ray diffraction technique after it had been cut to a depth of 120mm. The remaining residual stress of magnitude –6 ±6MPa does suggest that most of the surface stress is relieved by slitting the specimen in a central plane.
Figure 10 Comparison of average residual stress magnitudes determined using X-ray diffraction with those determined using the slitting technique.

To summarise, the slitting technique is user dependent but it can be relied upon to give a reasonable estimate of the surface stress magnitude in rectilinear and axisymmetric shapes when these stresses are relatively high. This does appear to limit the usefulness of the technique for estimating residual stresses in mechanically stress-relieved components where typically, residual stresses of ±30MPa remain. This limitation can be mitigated by the selection of a specimen with alternative geometry. Making the specimen and slit longer will amplify the deflections as will reducing the thickness. However, changing the thickness has the potential to increase the errors due to tapered tines and alter the residual stress distribution. It was found that reducing the thickness much below 20mm resulted in a significantly lower surface residual stress in 26mm wide and 156mm long specimens.

Despite these shortcomings, the technique has merit in that it is rapid and cheap and gives a tangible indication of the residual stress magnitude present. Improvements to the technique would require a more uniform method of inducing the cut (e.g. electro-discharge wire cutting technique) and improvements in the measurement of resulting deflections. A more sophisticated approach that accurately measures distortion after electro-wire discharge machining can be found in the contour technique where repeatable residual stress magnitudes have been determined.  

**Reduction of residual stress magnitudes during ageing treatments**

The reduction in stress magnitude will arise from creep involving the plastic flow of dislocations, and will be a function of temperature and time at temperature. Significant stress relaxation is improbable if the predominant residual stress magnitude is much smaller than the appropriate short term strength at the ageing
For the range of ageing and retrogression temperatures used (110-240°C), stress relaxation occurs due to thermally assisted glide (rather than climb) enabling some relaxation of high stress magnitudes. The x-ray diffraction technique calculates residual stress magnitudes based on the inter-atomic spacing of the material. Previous work by the authors had suggested, that x-ray diffraction was unsuitable in detecting stress relief resulting from creep, as the movement of thermally activated dislocations will not initially influence the inter-atomic spacing. However both the x-ray diffraction and slitting measurement techniques investigated here displayed similar stress reductions from the different ageing treatments applied.

For the ageing treatments applied, the T74 and RRA treatments result in the largest reduction in surface residual stress magnitudes. The reductions were of the order of 25-30%, which while significant, would not be substantial enough to prevent distortion during subsequent machining operations. The uphill quenched specimens did not offer any further decrease in residual stress magnitudes above that achieved from the standard retrogression and reaging treatment. This was due to the fact that the rate of heating during the uphill part of the cycle was too low, and the fact that the material was too strong after the T6 type ageing treatment for the uphill part of the cycle to result in yielding of the material which may have reversed the original stress pattern. Original investigations into the use of uphill quenching utilised superheated steam, which results in a substantial increase in heat transfer.

Similarly it has been shown that leaving the material in the naturally aged condition after cold water quenching (W-temper) will not result in any reduction in residual stress magnitude due to the low temperatures involved and the rapidly increasing strength of the material. The T6 type ageing treatment used here does not result in a
significant stress reduction. Other authors have reported stress reductions in the range of 10-35% to as much as 60% (after 40 hours at 120°C) in 7XXX alloys.

**Residual stress magnitudes greater than the as quenched yield strength**

The tensile strength properties described earlier indicate that directly after quenching, the limit of proportionality of 7010 is approximately 110 MPa with a $R_{p0.2}$ of approximately 150 MPa. However, stress measurements using both techniques described in this paper indicate surface stress magnitudes of >170 MPa. Subjecting the surface of a thick section aluminium alloy to a large thermal gradient produces inhomogeneous thermal stresses through the section. If the thermal stress in the surface exceeds the local yield stress the material flows in tension. As the temperature difference between the surface and interior diminishes, the surface further contracts and is placed into a state of residual compression with the yield stress at ambient temperature setting an upper limit. The majority of investigations into the cold-water quench induced residual stress magnitudes of 7XXX series alloys place a range of values between 150-200 MPa for this compressive surface stress.\(^{12,16-19}\) The x-ray diffraction and slitting measurements presented here are in agreement with these observations. The rate of uniaxial strain hardening in these alloys has also been determined and a plastic strain of 0.5\% is required to raise the flow stress to 160 MPa while 2.25\% is required to increase the flow stress to 200 MPa. Ignoring the predicted reversal of strain that occurs during quenching, strains of this magnitude should result in some dimensional changes in the surface of the specimen but none was detected.

The cold-water quenched tensile test specimens themselves will contain a residual stress distribution and this will result in localised plastic deformation occurring at a
lower value of applied load than in their absence. This has been shown to be insignificant.\textsuperscript{39} In addition to strain hardening, homogeneous precipitation\textsuperscript{40} and strain rate effects occurring during the quench could in conjunction with the presence of a crystallographic texture contribute to the raising of the local surface residual stress above the bulk yield stress, but without further investigation it cannot be stated with any certainty what causes this discrepancy.

\textbf{Conclusions}

1. The longitudinal split saw cut technique used in this paper consistently determined surface residual stress magnitudes that compared well with x-ray diffraction measurements, and both techniques were found to be repeatable and reproducible.

2. Compressive surface residual stress magnitudes in solution heat-treated specimens of 7010 were observed to be consistently in the 170–200\text{MPa} range. Residual stresses of this magnitude appear to be the maximum sustainable in a surface.

3. Quenching 7010 specimens into cold water from different furnace temperatures indicates that significant residual stresses are generated when furnace temperatures exceed 200\textdegree{C}.

4. Increasing the temperature of the quenchant results in significant reduction in residual stress with boiling water being the most effective.

5. Natural ageing and T6 ageing treatments were not found to result in a residual stress reduction after quenching, whilst ageing treatments involving higher
temperature exposure such as 175, 200 and 240ºC consistently result in reductions of > 20%.

6. The RRA treatments investigated here do reduce residual stress and could be applied to parts and components that are not mechanically stress relieved. The treatments did not reduce residual stress levels to a point where they could substitute for mechanical stress relieving. Uphill quenching combined with RRA treatments did not result in any additional residual stress relief.

7. The limit of proportionality of 7010 measured using tensile tests immediately after solution heat treatment was found to be approximately 110MPa with a 0.2% proof strength of approximately 150MPa. The reason 7010 surfaces can sustain residual stresses significantly higher than these values has yet to be determined.

**Acknowledgements**

The authors wish to acknowledge the support of Mettis Aerospace Group/HDA Forgings Ltd., UK.
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<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Zr</th>
<th>Al</th>
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</thead>
<tbody>
<tr>
<td>Actual</td>
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<td>0.06</td>
<td>1.69</td>
<td>&lt;0.01</td>
<td>2.44</td>
<td>&lt;0.05</td>
<td>6.26</td>
<td>&lt;0.06</td>
<td>0.14</td>
<td>Bal.</td>
</tr>
<tr>
<td>7010 max</td>
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<td>0.15</td>
<td>1.5-2.0</td>
<td>0.10</td>
<td>2.1-2.6</td>
<td>0.05</td>
<td>5.7-6.7</td>
<td>0.06</td>
<td>0.10-0.16</td>
<td>Bal.</td>
</tr>
<tr>
<td>7050 max</td>
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<td>0.15</td>
<td>2.0-2.6</td>
<td>0.10</td>
<td>1.9-2.6</td>
<td>0.04</td>
<td>5.7-6.7</td>
<td>0.06</td>
<td>0.08-0.15</td>
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<td>7150 max</td>
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<td>2.5-2.0</td>
<td>0.10</td>
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<td>0.04</td>
<td>6.9-5.9</td>
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<td>Bal.</td>
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<td>7055 max</td>
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<td>0.05</td>
<td>2.3-1.8</td>
<td>0.04</td>
<td>8.4-7.6</td>
<td>0.06</td>
<td>0.25-0.08</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
Table 2 Heat treatments applied to longitudinal split saw cut specimens. AC-air cooled, CWQ cold water quenched (<40°C).

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Number of specimens</th>
<th>Quench</th>
<th>Retrogression and/or ageing treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHT</td>
<td>6</td>
<td>Water at &lt;40°C</td>
<td>No further heat treatment</td>
</tr>
<tr>
<td>T6</td>
<td>3</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T61(55)</td>
<td>3</td>
<td>Water at 55±5°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T61(80)</td>
<td>3</td>
<td>Water at 80±5°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T61(100)</td>
<td>2</td>
<td>Water at 100°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T74</td>
<td>2</td>
<td>Water at &lt;40°C</td>
<td>8h at 110°C AC + 10h at 175°C AC</td>
</tr>
<tr>
<td>RRA200</td>
<td>6</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC + 40min. at 200°C CWQ + 24h at 120°C AC</td>
</tr>
<tr>
<td>RRA240</td>
<td>4</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC + 5min. at 240°C CWQ + 24h at 120°C AC</td>
</tr>
<tr>
<td>UHQ200</td>
<td>2</td>
<td>Water at &gt;40°C</td>
<td>24h at 120°C AC + cool to –196°C + 40min. at 200°C CWQ + 24h at 120°C AC</td>
</tr>
<tr>
<td>UHQ240</td>
<td>2</td>
<td>Water at &gt;40°C</td>
<td>24h at 120°C AC + cool to –196°C + 5min. at 240°C CWQ + 24h at 120°C AC</td>
</tr>
</tbody>
</table>
Table 3 Heat treatments applied to x-ray diffraction specimens.

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Number of specimens</th>
<th>Quench</th>
<th>Retrogression and / or ageing treatment</th>
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</thead>
<tbody>
<tr>
<td>SHT</td>
<td>4</td>
<td>Water at &lt;40°C</td>
<td>No further heat treatment</td>
</tr>
<tr>
<td>T6</td>
<td>4</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T74</td>
<td>2</td>
<td>Water at &lt;40°C</td>
<td>8h at 110°C AC + 10h at 175°C AC</td>
</tr>
<tr>
<td>RRA200</td>
<td>2</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC + 40min. at 200°C CWQ + 24h at 120°C AC</td>
</tr>
<tr>
<td>RRA240</td>
<td>2</td>
<td>Water at &lt;40°C</td>
<td>24h at 120°C AC + 5min. at 240°C CWQ + 24h at 120°C AC</td>
</tr>
<tr>
<td>T61(55)</td>
<td>2</td>
<td>Water at 55±5°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T61(80)</td>
<td>2</td>
<td>Water at 80±5°C</td>
<td>24h at 120°C AC</td>
</tr>
<tr>
<td>T61(100)</td>
<td>2</td>
<td>Water at 100°C</td>
<td>24h at 120°C AC</td>
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Table 4 X-ray diffraction residual stress magnitudes before and after a T6 type ageing treatment for specimens quenched into water at <40°C.

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>XRD RS before ageing (MPa)</th>
<th>XRD RS after T6 ageing (MPa)</th>
<th>% change from SHT condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>–194±8</td>
<td>–185±5</td>
<td>–4</td>
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<tr>
<td></td>
<td>–171±6</td>
<td>–175±3</td>
<td>+2</td>
</tr>
<tr>
<td>T6</td>
<td>–189±7</td>
<td>–186±4</td>
<td>–2</td>
</tr>
<tr>
<td></td>
<td>–199±7</td>
<td>–190±14</td>
<td>–4</td>
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<tr>
<td>T6</td>
<td>–192±11</td>
<td>–194±6</td>
<td>+1</td>
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<tr>
<td></td>
<td>–207±12</td>
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<tr>
<td>T6</td>
<td>–197±8</td>
<td>–183±6</td>
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</tr>
<tr>
<td></td>
<td>–198±5</td>
<td>–195±2</td>
<td>–1</td>
</tr>
<tr>
<td>Average</td>
<td>–193±10</td>
<td>–187±7</td>
<td>+3</td>
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</table>
Table 5 Residual stress magnitudes for T61 specimens determined using x-ray diffraction and slitting techniques.

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Quench temperature ºC</th>
<th>XRD RS after ageing MPa</th>
<th>Calculated slitting RS MPa</th>
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<tbody>
<tr>
<td>T6 (&lt;40) (average – deflection)</td>
<td>&lt;40</td>
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<tr>
<td>T6 (&lt;40) (average – x-ray)</td>
<td>&lt;40</td>
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<td>-187±7</td>
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<tr>
<td>T61(55) (average – deflection)</td>
<td>55</td>
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</tr>
<tr>
<td>T61(55)</td>
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<td>-176±7</td>
<td>-163±9</td>
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<tr>
<td>T61(55)</td>
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<td>-177±6</td>
<td>-164±6</td>
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<tr>
<td>T61 (55) (average – x-ray)</td>
<td>55</td>
<td>-172±10</td>
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</tr>
<tr>
<td>T61(80) (average – deflection)</td>
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<td>-35±10</td>
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<tr>
<td>T61(80)</td>
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<td>-46±5</td>
<td>-58±3</td>
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<tr>
<td>T61(80)</td>
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<td>-60±5</td>
<td>-53±6</td>
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<tr>
<td>T61 (80) (average – x-ray)</td>
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<td>-53±8</td>
<td></td>
</tr>
<tr>
<td>T61(100) (average – deflection)</td>
<td>100</td>
<td>-5±1</td>
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<tr>
<td>T61(100)</td>
<td>100</td>
<td>-24±5</td>
<td>-24±5</td>
</tr>
<tr>
<td>T61(100)</td>
<td>100</td>
<td>-33±8</td>
<td>-24±10</td>
</tr>
<tr>
<td>T61 (100) (average – x-ray)</td>
<td>100</td>
<td>-26±4</td>
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Table 6 Residual stress magnitudes for T74 specimens determined using x-ray diffraction.

<table>
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<tr>
<th>Specimen identification</th>
<th>XRD RS before T74 ageing (MPa)</th>
<th>XRD RS after T74 ageing (MPa)</th>
<th>% change from SHT condition</th>
</tr>
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<tr>
<td>T74 (Water at &lt;40°C)</td>
<td>−187±12</td>
<td>−178±8</td>
<td>−28</td>
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<tr>
<td></td>
<td>−170±5</td>
<td>−188±8</td>
<td>−34</td>
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<tr>
<td>T74 (Water at &lt;40°C)</td>
<td>−198±9</td>
<td>−125±7</td>
<td>−26</td>
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<tr>
<td>-average</td>
<td>−183±12</td>
<td>−126±7</td>
<td>−37</td>
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Table 7 Residual stress magnitudes for RRA specimens determined with x-ray diffraction and slitting techniques (Quench – water at <40°C).

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>XRD RS before ageing MPa</th>
<th>XRD RS after ageing MPa</th>
<th>Calculated slitting RS MPa</th>
<th>% change from SHT condition</th>
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</thead>
<tbody>
<tr>
<td>Average (Slitting – RRA 200)</td>
<td>-</td>
<td>-135±16</td>
<td>-29</td>
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<tr>
<td>Average (Slitting – RRA 240)</td>
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<tr>
<td>Average (Slitting – UHQ 200)</td>
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<td>-129±12</td>
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</tr>
<tr>
<td>Average (Slitting – UHQ 240)</td>
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<td>-134±5</td>
<td>-30</td>
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<tr>
<td>RRA 200</td>
<td>-194±8</td>
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<td></td>
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<tr>
<td></td>
<td>-171±6</td>
<td>-158±9</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td>RRA 200</td>
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<td>-142±5</td>
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<tr>
<td></td>
<td>-199±7</td>
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<td>Average (XRD – RRA 200)</td>
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<tr>
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<td></td>
<td>-207±12</td>
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<td>Average (XRD – RRA 240)</td>
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<td>-140±8</td>
<td>-29</td>
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</table>
References


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29. Philips X'Pert Stress. 1.0a, 2001, Philips Analytical B.V.


