Reducing residual stress in 2014 aluminium alloy die forgings

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Abstract

Closed die forgings manufactured from 2014 aluminium alloys have been subject to both standard and non-standard heat treatments in order to reduce the as quenched residual stress magnitudes. Warm water (60°C) and boiling water quenches are investigated. The influence of changing the surface finish of the forgings during boiling water quenching on the mechanical properties and residual stress has also been determined. In addition, high temperature (200°C) and dual aging treatments have been evaluated in an attempt to combine low residual stresses with the required levels of mechanical properties. Residual stress magnitudes determined by the centre hole-drilling strain-gauge method are reported in addition to stress corrosion cracking, fracture toughness, fatigue and tensile mechanical property variations. The results indicate that boiling water quenching leads to very low residual stress but unsatisfactory mechanical properties. However, the same quenching regime applied to forgings with a black oxide coating results in low residual

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stress in combination with mechanical properties very close to those achieved by warm water quenching.

Keywords

Mechanical and corrosion properties, forging, wrought aluminium alloy

1. Introduction

2000 series aluminium alloys undergo a rapid quenching operation during heat treatment to obtain high mechanical strength and adequate corrosion resistance. Slow cooling leads to the development of coarse equilibrium second phases thereby reducing the aging response. Rapid quenching of aluminium alloys during heat treatment leads to the development of residual stresses of yield point magnitude, with compressive surface stresses balanced by interior tensile stresses. In complex closed die forgings, tensile stresses at the surface may be exposed during machining operations, leaving parts more vulnerable to intergranular stress corrosion cracking and fatigue. With alloys such as 2014, stress corrosion susceptibility is a major concern as failures in service have occurred and the material has been found to be vulnerable to intergranular exfoliation corrosion.[1, 2]

Relief of these residual stress magnitudes can be difficult in closed die forgings using established cold compression type mechanical techniques given that the forgings will not always fit back into the steel dies from which they were manufactured. Reducing the thermal gradients by using heated water and polyalkylene glycol (PAG) type solutions reduces residual stresses at the expense of aging response. Previous research indicates that cooling rates greater than 100°C sec^{-1} are required between 400°C and 290°C to ensure that 2014 has the potential to achieve the maximum tensile strength. Jominy type experiments have also indicated the quench sensitive nature of 2014.[3] In thick components, these cooling rates will not be achieved in the interior, giving rise to mechanical property inhomogeneity.

2014 has found application where high strength, good fatigue and resistance to limited heating are required and have been used to manufacture airscrew hub forgings for a number of years. For the 2014 airscrew hub forgings investigated here boiling water quenches are applied to reduce residual stress magnitudes where they are of concern in service. However, given the quench sensitive nature of 2014, mechanical properties are significantly reduced due to much slower surface heat transfer and component size. To improve the cooling rate during a boiling water quench, the surface of the forging can be modified.

Hot caustic etching is carried out to remove residual forging lubricants after forming and leaves a black copper oxide powder residue on the surface of the part, an example of which is shown in Figure 1. It is normally removed immediately by immersing the forging in nitric acid prior to heat treatment, in a process known as ‘de-smutting’. It is well known that not removing the black oxide coating increases the cooling rates during the quench, but the influence on residual stress magnitudes has not been determined.[4] It is expected that the residual stress magnitudes should be higher than for the standard boiling water quench given the faster cooling rates and increased thermal gradients.

Figure 1 Example of hub forging with and without the black copper oxide residue

This investigation aims to determine if quenching airscrew hub forgings into boiling water, without removing the black copper oxide residue, results in low residual stress magnitudes whilst maintaining mechanical properties that exceed the appropriate specification. These results are compared with a standard quench into water at 60°C and into boiling water, with the black oxide coating removed.[5] Double aging treatments were applied to boiling water quenched forgings in an attempt to improve mechanical properties.

Residual stress magnitudes are determined using the hole drilling strain gauge technique and a deflection mechanical dissection method (longitudinal split saw cut method). Tensile, fatigue, fracture toughness and stress corrosion cracking tests have also been undertaken to indicate the effect that the modified heat treatments have on final mechanical properties.

2. Experimental

2.1. Heat Treatment and Temperature Measurement

The part selected for this investigation was a four port variable pitch propeller hub closed die forging manufactured from aluminium alloy 2014 (Table 1) on a 30MN hydraulic press at Mettis Aerospace Ltd., UK. The width of the forging was approximately 260mm with a mass of approximately 25kg. Prior to heat treatment the forging was bored out to improve cooling rates reducing the mass to approximately 15kg. Cooling during quenching was monitored using 1.5mm diameter type K thermocouples at the centre of the thickest section of the forging.

Table 1 Specification alloy chemistry and chemical analysis results, wt%.

US military specification MIL-H-6088G for heat treating 2014-T6 die forgings recommends quenching from 496-507°C into water at 60–82°C followed by aging for 10hours at 166–177°C.[5] 2014-T4 requires a similar quench followed by a minimum natural aging period of 96 hours at room temperature. Table 2 indicates the heat treatments that were applied to the different forgings, which were labelled 2014-1 through 2014-6. From Table 2 it can be seen that forging 2014-1 was heat treated to a T6 condition as a control (as described above). The remaining forgings were quenched into boiling water and artificially aged for different periods of time and at different temperatures. Forgings 2014-5 and 6 were not desmutted prior to heat-treating. Forging 2014-3 was cut into two equal halves after solution heat treatment and quenching. These halves were labelled ‘A’ and ‘B’ with section ‘B’ receiving a double aging treatment. Forging 2014-4 was reserved as a spare.

To strengthen the forgings and prevent plasticity effects during hole drilling residual stress measurements, the forgings were aged for 12h at 170°C before the measurement. The effect of the heat treatments on the tensile, high cycle fatigue, fracture toughness and stress corrosion cracking properties were measured (Figure 2).

Table 2 Heat treatments applied to forgings

Figure 2 Photograph of hub forging indicating approximate location of test pieces

2.2. Residual Stress Determination

Residual stress magnitudes were determined using the centre hole drilling strain gauge method as detailed in ASTM E837-99. The RS200 milling guide and assembly was used for introducing the hole through a CEA-13-062UM-120 (Type B) strain gauge rosette as detailed in the procedure provided by Vishay Measurements Group Ltd. An orbiting technique for introducing the hole resulted in a diameter of 1.88mm, and therefore a hole diameter to mean gauge diameter ratio of approximately 0.37 – which is within the parameters recommended by ASTM E837-99. The hole was drilled to a depth of 2mm. All measurements were recorded at the same location on each forging.

Introducing a slit into forgings and measuring the amount of closure after cutting to a set depth can obtain an approximate qualitative estimate of residual stress. This destructive method was applied to the forgings by sectioning in a radius between two ports and monitoring the displacement.

2.3. Tensile Testing

Three tensile tests were cut from each forging with a transverse orientation relative to the local grain flow. Tensile testing was in accordance with BS 4A4 using a standard test piece of 5.64mm nominal diameter ($25mm^2$ cross-sectional area) with a gauge length of 28mm, utilising a 25mm gauge length extensometer. Specimens were tested at a strain rate of $3x10^{-4}$ s^{-1}.

2.4. Fatigue Testing

Rotating bending fatigue tests (R=–1) were undertaken in accordance with BS 3518-2 on toroidal smooth specimens with a minimum diameter along the gauge length of 3.81mm. The specimens had a transverse orientation relative to the local grain flow similar to the tensile specimens. Testing was undertaken at room temperature with no further atmospheric controls at a frequency of 50Hz. Specimens that had not failed after 10^8 cycles were considered to have reached infinite life and the test was terminated. A minimum of nine specimens were tested at three different stress levels (146, 187 and 229MPa) for each condition as described in Table 2.

2.5. Stress Corrosion Cracking (SCC) testing

SCC testing was undertaken in accordance with ASTM-G44 using a constant strain test piece with nominal diameter of 3.175mm with a variable but consistent grain flow along the gauge length. Monitoring the strain applied was achieved using a 10mm extensometer with a loading frame that was capable of maintaining the required strain during the test. The level of stress was calculated based on an elastic modulus for 2014 of 73GPa. Three specimens were tested for each condition at approximately 70% of the relevant yield strength in all cases.

The testing environment was controlled at a temperature of 27±1°C and relative humidity of 45±10% with the specimens being periodically immersed (10mins/hour) in salt solution containing 96.5% distilled water with the remainder consisting of reagent grade NaCl. This resulted in a solution with a pH that was maintained between 6.4 and 7.2. Specimens that had not failed after 40 days were considered to be sufficiently immune to the corrosive environment. After this time period specimens were sectioned and mounted for optical microscopic observation to determine if stress corrosion cracks had begun to form. Three specimens were tested for each heat treatment defined in Table 2.

2.6. Fracture Toughness Testing

Fracture toughness testing was undertaken in accordance with ASTM E399-90 and B645-91. Two compact tension test pieces (thickness, B=13mm) were cut from the porthole. These had either an L–T or T–L orientation relative to the longitudinal axis of the forging. Fatigue precracking was performed at 2Hz and crack opening displacements were measured using a clip gauge fitted into integral knife-edges. Fatigue precracks in all specimens were grown under load shedding regimes under the action of a comparable number of fatigue crack growth cycles. The failure mode during the fracture test was always Type III as described in ASTM E399.

3. Results

3.1. Temperature measurement during quenching

Figure 3 indicates the cooling curves obtained for quenching the forgings using the different quenchant temperatures described in Table 2 with the temperature recorded at frequencies of up to 10Hz. Three cooling curves were recorded for each quenching condition with one representative cooling curve shown in each case. The results for the standard boiling water quench and the 60°C water quench were repeatable with small changes in the boiling water quenched forgings. The rate of cooling increased for successive quenches of the forging with the black copper oxide coating. This appeared to be caused by the accelerated build up of an alumina layer in conjunction with the remaining smut layer. For quenching the forging with the black oxide coating, the first cooling curve recorded is indicated in Figure 3.

Figure 3 Sample cooling curves for forgings quenched into boiling water (BWQ), water at 60°C (Q60) and into boiling water without removing the black oxide coating.

For the forgings without the oxide coating, the quench into water at 60°C achieved a maximum cooling rate of approximately 30°C sec^{-1} at 320°C while quenching into boiling water achieved a much slower cooling rate between 400°C and 290°C only reaching a maximum cooling rate of 10°C sec^{-1} at 220°C. The forging with the oxide coating that was quenched into boiling water achieved faster cooling between 400°C and 290°C with a rate of 17°C sec^{-1} compared with 5°C sec^{-1} for the forging without the oxide coating. 17°C sec^{-1} was the maximum cooling rate observed during the quench for this forging.

From this data, it appears that the black oxide coating has a substantial effect on the vapour jacket that develops in normal boiling water quenching, leading to an increase in the heat transfer at all temperatures during the quench.

3.2. Residual Stress

To determine if the centre hole drilling technique used on these die forgings was repeatable and reproducible, residual stress measurements were taken on one solid forging that did not have the portholes bored out as for the samples described above. This allowed measurements to be taken on the porthole surfaces with three surfaces used in total. The forging was solution heat treated for 4h at 500℃ quenched into water at room temperature and aged for 12 hours at 170℃. Given the uniformity of the forging, the residual stress magnitudes would be expected to be of the same order of magnitude on each of the porthole surfaces. Prior to heat treatment the forging draft was milled off the port faces of the hub to ensure a flat surface for attachment of the strain gauges.

The minimum residual stress magnitudes obtained for ports were –162MPa, –169MPa and –170MPa, respectively, while the maximum stress magnitudes were –116MPa, –119MPa and –120MPa respectively. The stress magnitudes are approximately the same for each of the measurements taken with a standard deviation of ±4MPa for the minimum stress and ±2MPa for the maximum stress magnitudes determined. The direction of the maximum relieved strain was parallel to the flashline in all cases. Residual stress magnitudes were found to be uniform with hole depth as defined by ASTM-E837.

Figure 4 details the residual stress magnitudes determined using the centre hole drilling technique and the deflections resulting from the slitting experiment on forgings with reference numbers 1, 2, 5 and 6 (see Table 2). Residual stress magnitudes induced during quenching are a function of the magnitude of the thermal gradients produced. Therefore, quenching into water at 60℃ produced the largest residual stress magnitudes with minimum and maximum principal stresses of –148MPa and –112MPa, respectively and the largest deflection of 2.5 mm.

Leaving the oxide coating on the forgings and quenching into boiling water (forgings 5 and 6) resulted in stress magnitudes reaching a peak of approximately –70MPa, which is less than half that achieved from a 60°C water quench. Removing the oxide coating in conjunction with a boiling water quench (forging 2) gave similar deflection results but a much lower stress magnitude measured by the hole drilling technique (–16MPa and –8MPa). The deflection values measured for the remaining forgings support the results achieved using the centre hole drilling technique.

Figure 4 Residual stress and deflection magnitudes plotted as a function of quenchant type and aging treatment for forging numbers 1, 2, 5 and 6 heat-treated according to Table 2.

3.3. Tensile Properties – As quenched

The tensile strength of the as-quenched material was required to estimate if the residual stress magnitudes determined were close to the yield strength of the material in this condition. To achieve this, tensile specimens were manufactured from a spare forging prior to solution heat treatment and quenching into water at 60°C. Producing specimens after solution heat treatment would have allowed time for natural aging to occur which would have influenced the test results.

The tensile test results indicate a 0.2% proof stress ($R_{p0.2}$) of approximately 160MPa. These properties are close to those previously reported. The maximum residual stress magnitudes determined in forgings quenched at 60°C were of this order of magnitude.

3.4. Tensile Properties – From hub forgings after heat treatment

Tensile test observations (average of three tests) are reported in Figure 5, with the specified properties for 2014 taken from AMS-4133 for material in the T6 condition.[6] The cooling rates associated with boiling water-quenching result in very low tensile properties compared to material quenched at 60°C (45% reduction in $R_{p0.2}$). All of the forgings that were boiling water quenched without the oxide coating had tensile properties below the specification minimum requirements.

Figure 5 Tensile properties for forgings heat treated according to Table 2. A - % elongation; Z - % reduction in area.

Quenching these forgings with an oxide coating acts as an excellent compromise in maintaining properties and reducing residual stress magnitudes due to the increased cooling rate observed. Figure 4 shows residual stresses are significantly reduced but Figure 5 indicates mechanical properties are maintained to within 95% of the warm water (60°C) quenched values and exceed the minimum requirements specified in AMS-4133.

The extra treatment of 8 hours at 205°C applied to forging 6 when compared with forging 5 overaged the material and resulted in a decrease of proof stress and tensile strength such that the material failed to meet the AMS-4133 specified values. However, the additional aging treatment applied to forging number 3B with respect to forging number 3A did not appear to have any effect on the tensile properties. Both elongation (A) and reduction in area (Z) demonstrated the typical inverse relationship with strength.

3.5. Fracture Toughness Results

Fracture toughness results are presented in Figure 6. Fracture toughness values are reported as K_Q values as the majority of tests were invalid. Macroetching the port locations from where the L-T and the T-L fracture toughness specimens were extracted, revealed that the grain flow of the forging was not perfectly longitudinal or transverse, relative to the loading direction applied during testing. This gave rise to some invalid tests due to the final fracture deviating by more than 10° from the plane perpendicular to the loading direction. However, the majority of the invalid tests were due to the specimen thickness B not meeting the $2.5(K_Q/R_{p0.2})^2$ condition for plane strain. Some general observations that can be made are that the L-T orientation was consistently tougher than the T-L arising from more favourable grain flow, and the K_Q values did increase as the $R_{p0.2}$ decreased. There was no evidence from excessive precrack curvature that any residual stresses remained in the specimens prior to testing.

Figure 6 Fracture toughness properties for forgings heat treated according to Table 2. Solid symbols valid K_{IC}, open symbols invalid.

3.6. Stress Corrosion Cracking Properties

The oxide coated forging quenched into boiling water performed best with no failures observed after 40 days even at an applied stress of 297MPa (see Table 3). The remaining specimens that did not fail after 40 days were tested at relatively low stresses (<200MPa) due to the low proof strength of these specimens. Of the forgings that demonstrated low resistance to SCC, at least one specimen in each case failed in less than one day after the beginning of the test. The extra aging treatment applied to sample 2014-3B as opposed to 3A resulted in an improved SCC resistance. The additional aging treatment may have induced further precipitation within the grains, lowering the corrosion potential differences between the grains and the boundary areas, thereby improving the corrosion resistance. However, the additional overaging treatment applied to forging 2014-6 as opposed to forging 2014-5 did not appear to have the same effect. In any case, all specimens indicated the formation of intergranular corrosion cracks when observed using optical microscopy, indicating none of the specimens were immune to SCC.

Table 3 Stress corrosion cracking test results

3.7. Fatigue Properties

Rotating bending fatigue testing results in a loading configuration where a stress gradient exists across the specimen compared with standard axial fatigue testing methods.[1] Testing in this way can result in specimen size, for example, influencing the measured fatigue life.[7] However, using the rotating bending technique, it is possible to relatively quickly determine differences in fatigue properties when specimens are tested under the same conditions.

Rotating bending fatigue results are indicated in Figure 7. The maximum and minimum plots in these figures indicate the fatigue curve predicted from the tensile properties of the strongest and weakest forgings (1 and 2, respectively) indicated on the graphs. These curves are predicted using the equations developed by Seeger.[8] Fatigue data for 2014-T6 material (R_m=483 MPa) from a Goodman diagram is also included. [9]

The scatter in the fatigue results shown in Figure 7 indicate that the number of specimens tested (9) is not sufficient to draw definitive conclusions regarding the effect of the heat treatments applied. However, the forgings exhibiting the higher mechanical strengths did tend to exhibit longer fatigue lives, as predicted in the literature[8] and these were similar to the literature data for 2014-T6.

Figure 7 Rotating bending fatigue results for aluminium alloy forgings heat treated to the conditions outlined in Table 3. Maximum and minimum values indicated

were predicted from tensile property results.[8] Goodman data for 2014-T6 taken from [9]

4. Discussion

This investigation has shown that the residual stress magnitudes measured in forgings quenched into water at 60℃ (forging 2014-1) are similar to the yield strength of the material in the as quenched condition. These residual stresses will be largely unaffected by aging. Subsequent machining will give rise to redistribution of the residual stresses but unless distortion takes place, the magnitudes will remain high. For components operating in fatigue or SCC prone environments this is far from ideal. However, the advantage of warm water quenching the die forgings is that it has the potential to produce the largest tensile properties observed here. When forging 2014-1 was aged for 12 hours at 170℃ the tensile properties at the location measured exceeded the minimum requirements of the AMS specification. The fracture toughness and fatigue properties were in line with expectations for the 2014 alloy. The SCC resistance of the warm water forging was low but this alloy is not known for having good resistance to this mode of failure anyway.

Where subsequent processing or the intended application of a component does not permit the presence of large residual stresses, boiling water quenching is an option. It has been demonstrated here that when a clean metal surface forging is boiling water quenched (2014-2), the residual stresses are reduced almost to zero. This is of course due to the much reduced thermal gradients present in the material during quenching. The problem with this approach is that the mechanical properties are seriously affected by loss of solute caused by precipitation of coarse second phase particles during the quench. For the component application investigated here, a forging quenched in boiling water would be rejected for not meeting the tensile property specification requirements. The aging treatment applied to warm water quenched forgings is not necessarily the most appropriate for boiling water quenched material but the alternative lower temperature and double aging treatments tried here had little effect on tensile properties (forging 2014-3A and 3B).

Closed die forgings are routinely hot caustic etched to remove forging lubricant residues. For alloys with significant copper content the forging becomes covered with a loose black powder coating of copper oxide (CuO). This is normally removed in a desmutting operation, but can be left on if care is taken not to dislodge the powder. This coating influences heat transfer during boiling water quenching and changes the rate of cooling by increased radiation through the vapour jacket, promoting unstable film boiling and then accelerating the transition from film boiling to nucleate boiling. Figure 8 displays how the heat transfer coefficient of 2014 varies with excess temperature for the three surface conditions. This data was generated using a 160 mm diameter, 21 mm thick disc of 2014. A thermocouple was inserted into a blind hole in the centre of the disc face. The hole had been drilled to within 0.5 mm of the surface of the opposite side of the disc. The edge of the disc was insulated using a stainless steel band. Heat was therefore considered to be lost in only one direction, normal to circular disc surfaces. The direction of heat flow was assumed to be from the centre of the disc to these surfaces. Time temperature histories during quenching were used as a boundary condition in a one dimensional finite element model. The model was constructed using the software INTEMP, and this numerically solved the inverse heat conduction problem to give the unknown heat fluxes and heat transfer coefficients.[10] The finite element model had 21 nodes from the centre to the surface of the disc. Values for the material's specific heat capacity, thermal conductivity and density varied as a function of temperature and were taken from the literature.[11]

Figure 8 Heat transfer coefficient for 2014 quenched into boiling water (BWQ), water at 60°C (Q60) and boiling water without removing the black oxide coating.

The increased rate of cooling observed for the blackened forgings (2014-5 and 6) did result in higher residual stress magnitudes when compared to the boiling water quenched clean forgings, but they were less than half those present in the forging quenched into warm water. The forgings with the oxide coating also resulted in tensile properties and fatigue resistance, comparable with the 60℃ water quench for a standard T6 type aging treatment. Both forgings 2014-5 and 6 met the appropriate specification tensile property requirements. Forging 2014-5 also exhibited improved SCC resistance when compared to the warm water quenched sample. [12]

Forging 2014-6 received an additional aging treatment of 8 hours at 205℃ over forging 2014-5, which reduced the tensile strength of the material and resulted in worse SCC resistance. This is likely to be due to the overaging treatment resulting in the further development of coarse grain boundary precipitates. The extra aging treatment did not result in any residual stress reduction. Aging for 12 hours at 170℃ appears to be sufficient to achieve the required mechanical properties in this component after boiling water quenched with a blackened surface.

The influence of surface finish on the rate of heat transfer during quenching is a well known phenomenon but the effect of this on mechanical properties and residual stress is rarely quantified. The simple technique of not desmutting aluminium copper alloy forgings does give some opportunity to increase the quenchant temperature, and thereby significantly reduce residual stresses while maintaining mechanical properties associated with warm water quenching. For structural forgings prone to distortion (for example propellers and spars) this approach could result in reduced costs arising from less remedial setting operations.

5. Conclusions

1. Quenching the closed die airscrew hub forgings into water at 60°C results in good mechanical properties that exceed the specification requirements.
2. Quenching into water at 60°C produces large residual stresses similar in magnitude to the as quenched uniaxial tensile yield strength measured immediately after quenching.
3. Quenching the forgings into boiling water results in low residual stress magnitudes but the mechanical properties are unacceptably low.
4. If the black copper oxide coating produced by hot caustic etching is not removed prior to solution heat treatment and boiling water quenching, low residual stresses in conjunction with good mechanical properties result.
5. The black oxide coated forgings cool significantly faster than uncoated because the heat transfer coefficient is increased at high excess temperatures.

6. Increased radiation, unstable film boiling and acceleration of the transition from film to nucleate boiling are caused by the black oxide coating
7. An artificial aging treatment of 12 hours at 170℃ is sufficient to obtain the best mechanical and corrosion properties reported in this paper for the varying quenching methods tested. Further aging treatments at higher temperatures do not result in any further improvement in either mechanical or corrosion properties or any further residual stress reduction.
8. Modifying the surface of forgings to manipulate the heat transfer coefficient and hence the cooling rate has the opportunity to permit less aggressive quenching whist maintaining good mechanical properties. This approach may be advantageous for fatigue or distortion prone components where minimising the residual stress is very important.

6. Acknowledgements

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7. References

1. MIL-HDBK-5J. Metallic Materials and Elements for Aerospace Vehicle Structures. 2003, Department of Defense, United States of America.
2. Robinson MJ, Jackson N.C. The influence of grain structure and intergranular corrosion rate on exfoliation and stress corrosion cracking of high strength Al-Cu-Mg alloys. Corrosion Science, 1999. 41(5): p. 1013-1028.
3. Stewart-Jones ET. Forgings in Aluminium and Magnesium, Heat Treatment of Engineering Components, ISBN 0900497122, The Iron and Steel Institute, London, 1970.
4. Croucher T. Critical parameters for evaluating polymer quenching of aluminum. Heat Treating, 1987. 19(12): p. 21-25.
5. MIL-H-6088G Heat treatment of aluminum alloys. 1991, United states Department of Defense.
6. AMS4133 Aluminum alloy forgings and rolled rings 4.4CU - 0.85SI - 0.80MN - 0.50MG (2014-T6) Solution and precipitation heat treated. 1988, Society of Automotive Engineers (SAE).
7. Dieter GE, Mechanical Metallurgy. 1988, London: McGraw-Hill Book Company.
8. Bäumel A, Seeger T. Materials data for cyclic loading. Materials science monographs ; 61. Vol. Supplement 1. 1990, Amsterdam; New York: Elsevier.
9. Henry SD, Dragolich KS, DiMatteo ND. Fatigue data book: light structural alloys. 1995: Materials Park, OH : ASM International.
10. Busby HR, Trujillo DM. Numerical Solution to a Two-Dimensional Inverse Heat Conduction Problem. International Journal for Numerical Methods in Engineering. 1985. 21: p. 328-59.

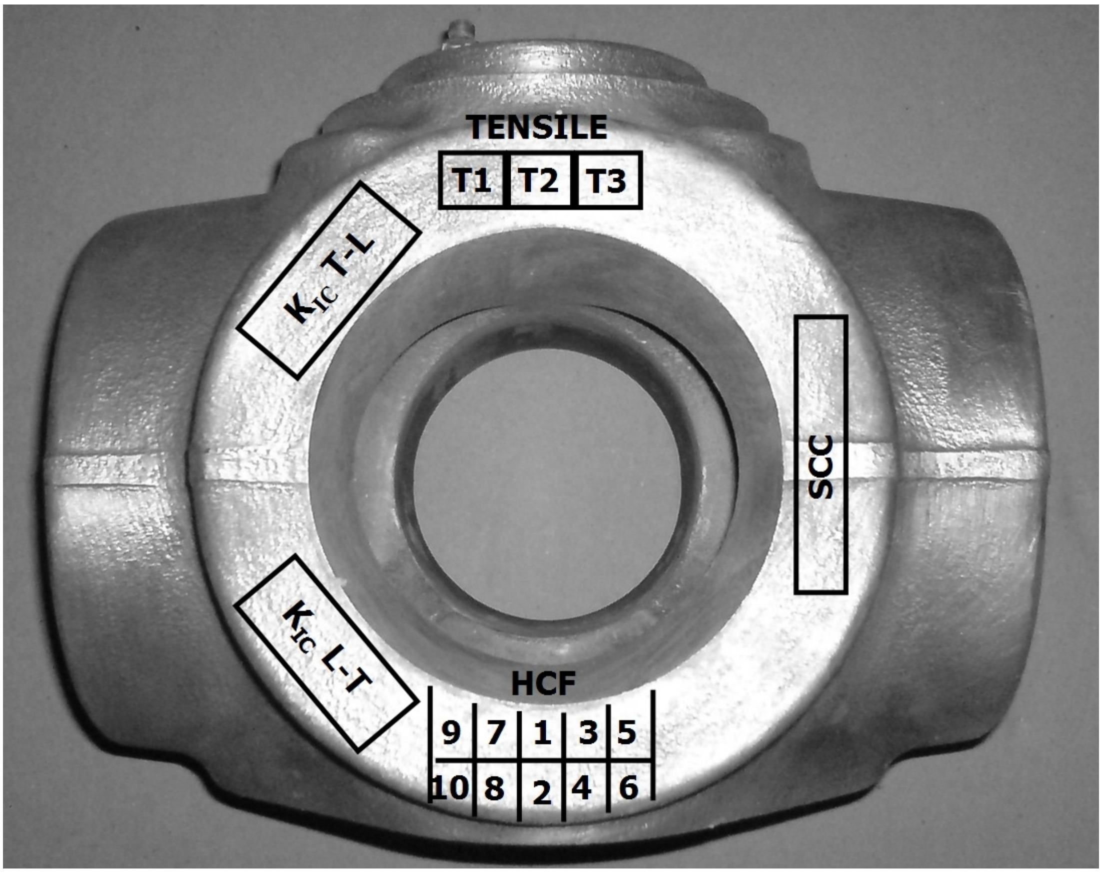
11. Touloukian YS, Powell RW, Ho CY, Klemens PG. Thermal Conductivity: Metallic elements and alloys. Thermophysical properties of matter. 1970, IFI/Plenum Press: New York.

12. Archambault P, Chevier JC, Beck G. A Contribution to the Optimisation of the 7075 Heat Treatment. Materials Science and Engineering. 1980. 43: p. 1-6.

8. List of Figure Captions

Figure 1 Example of hub forging with and without the black copper oxide residue

Figure 2 Photograph of hub forging indicating approximate location of test pieces



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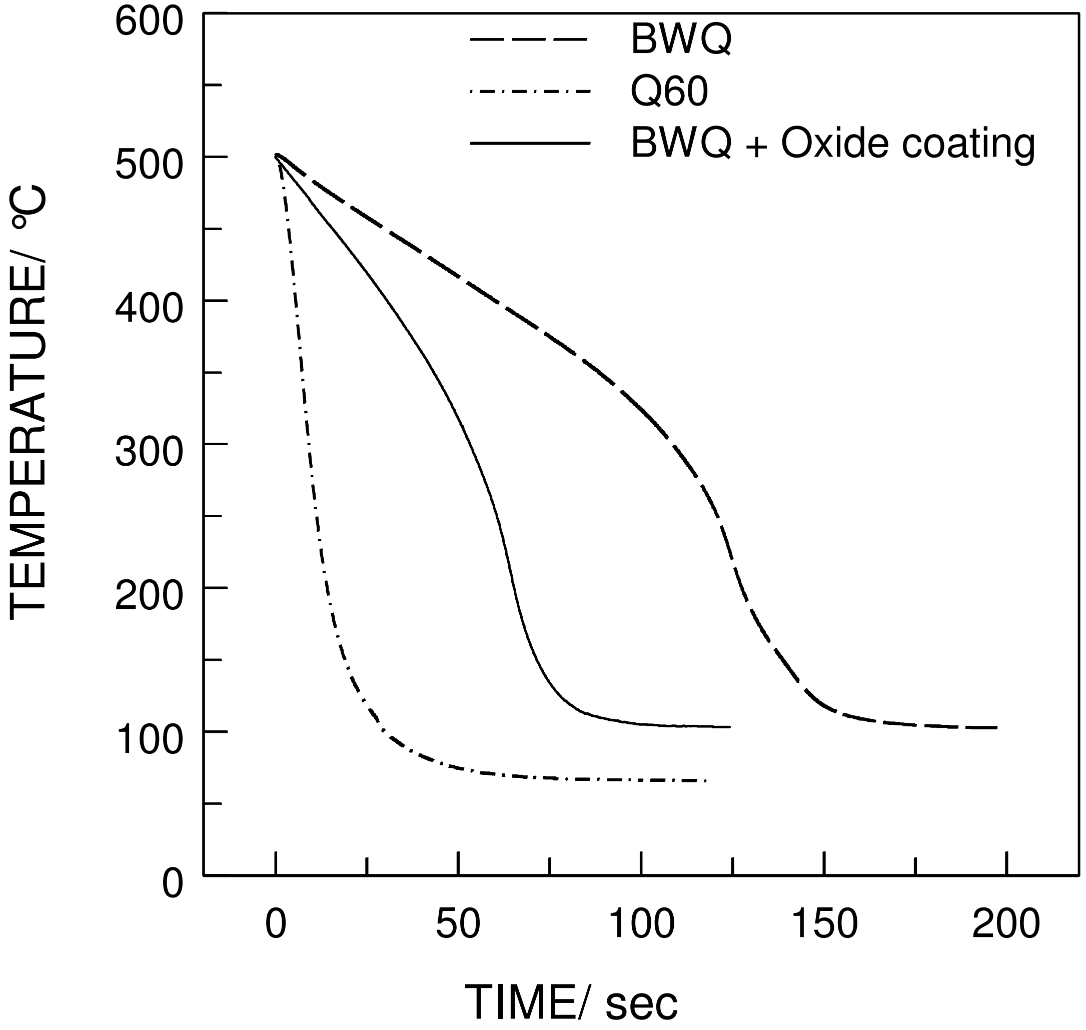

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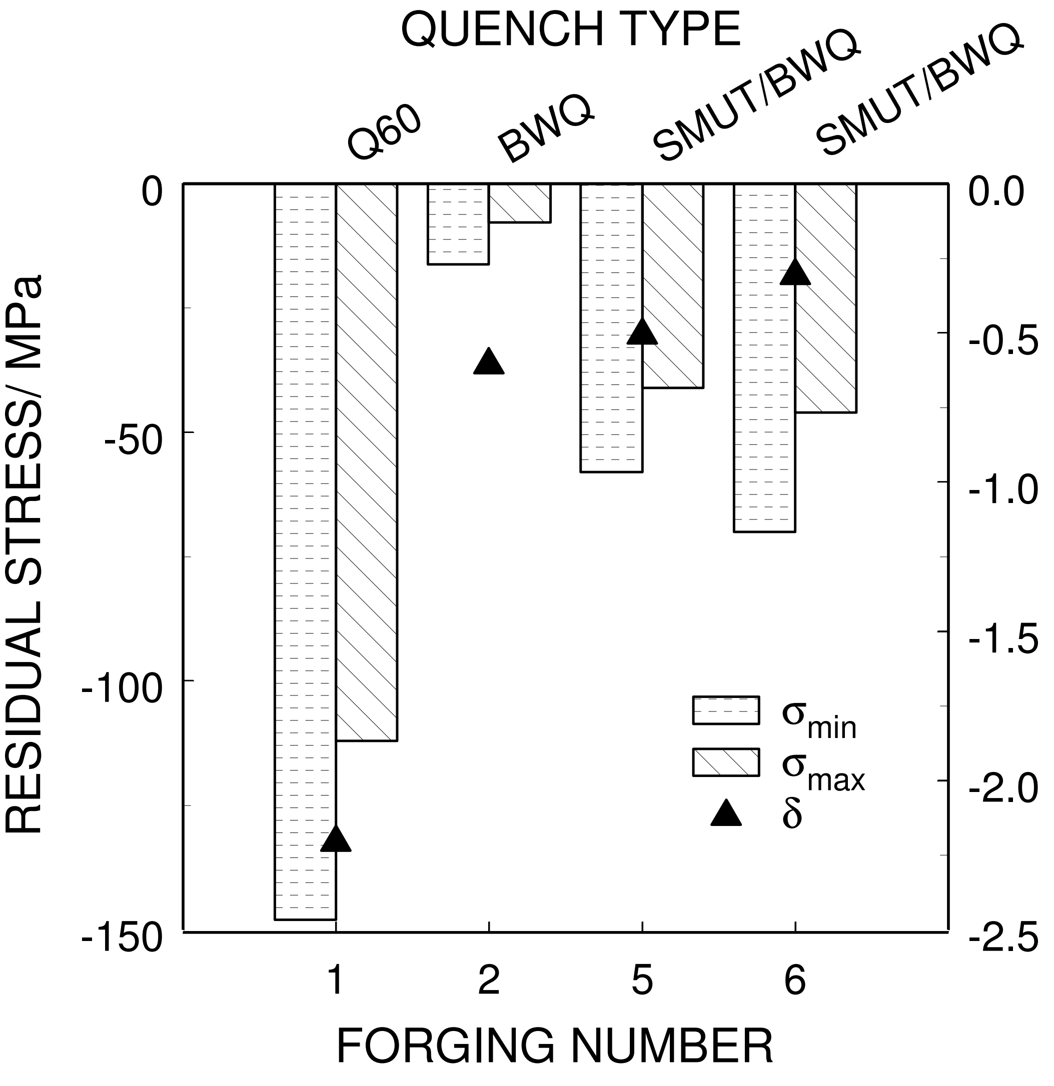
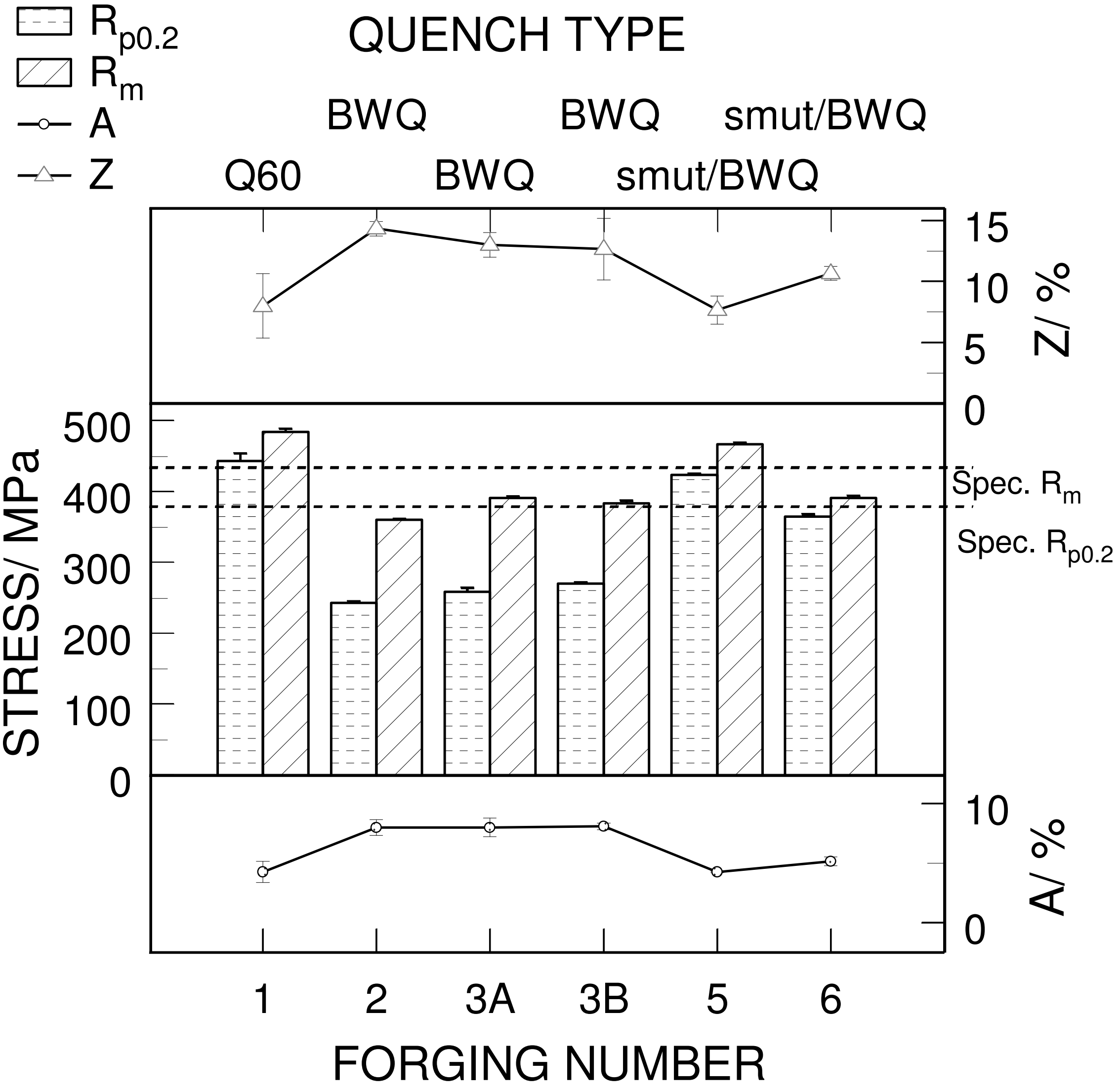


Figure 5 Tensile properties for forgings heat treated according to Table 2. A - % elongation; Z - % reduction in area.



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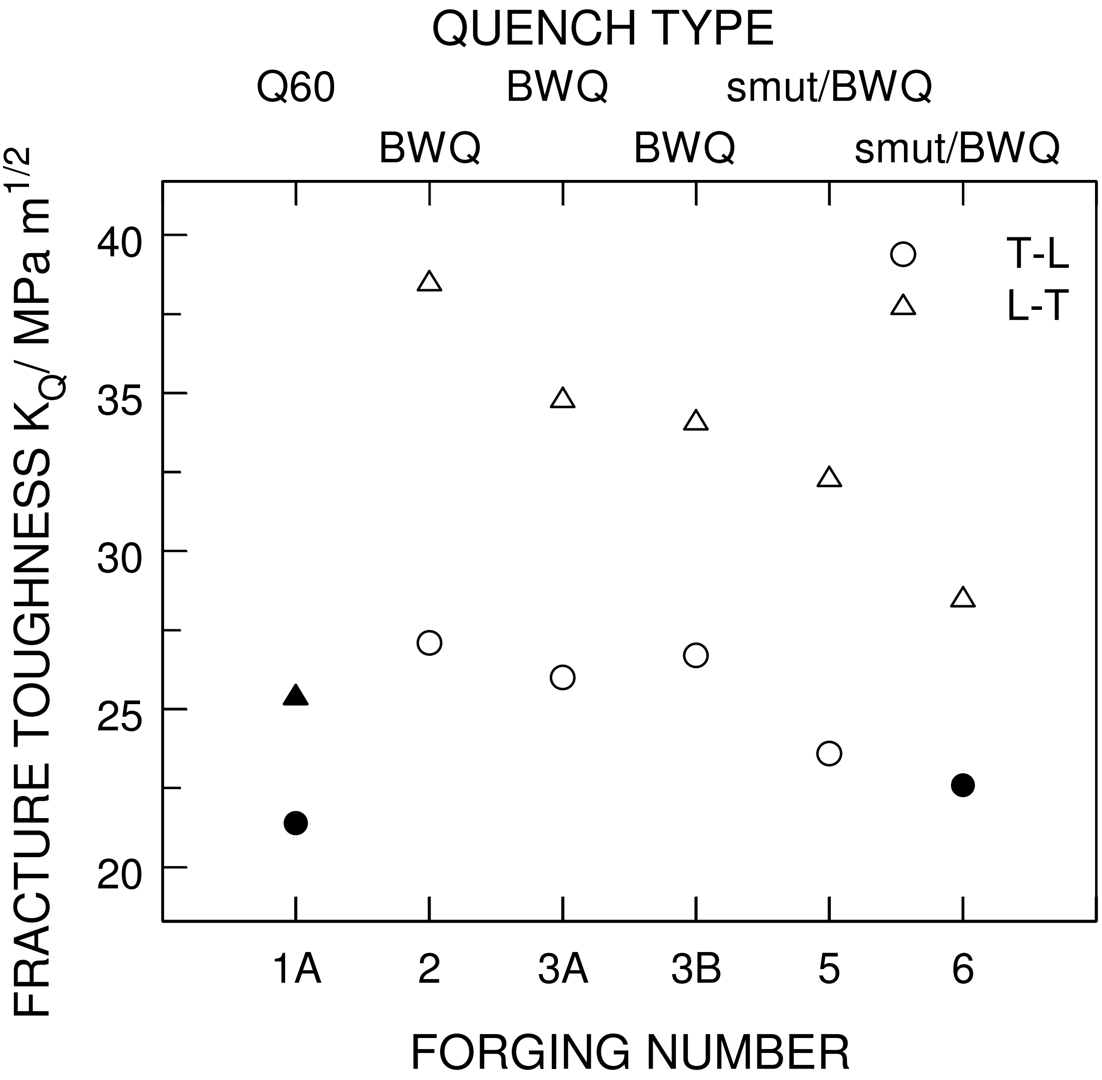

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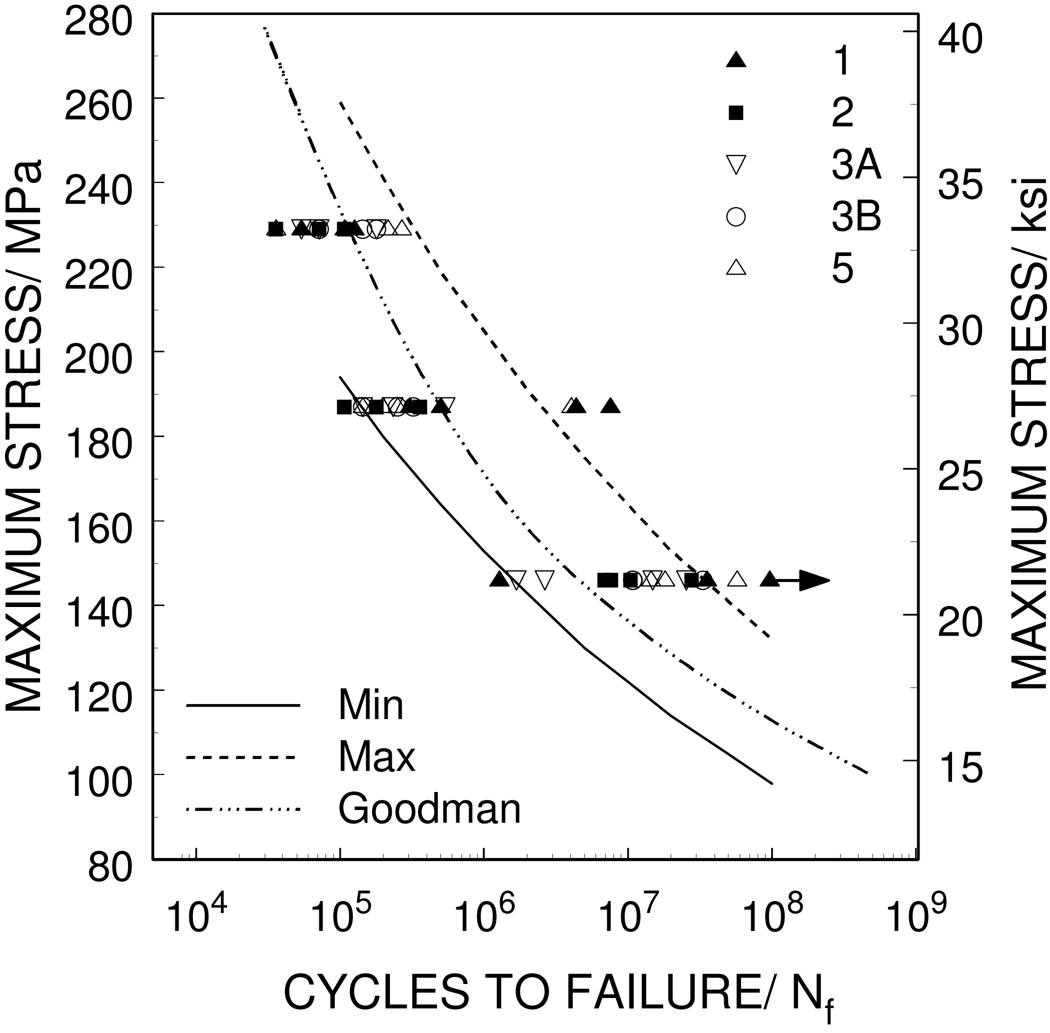

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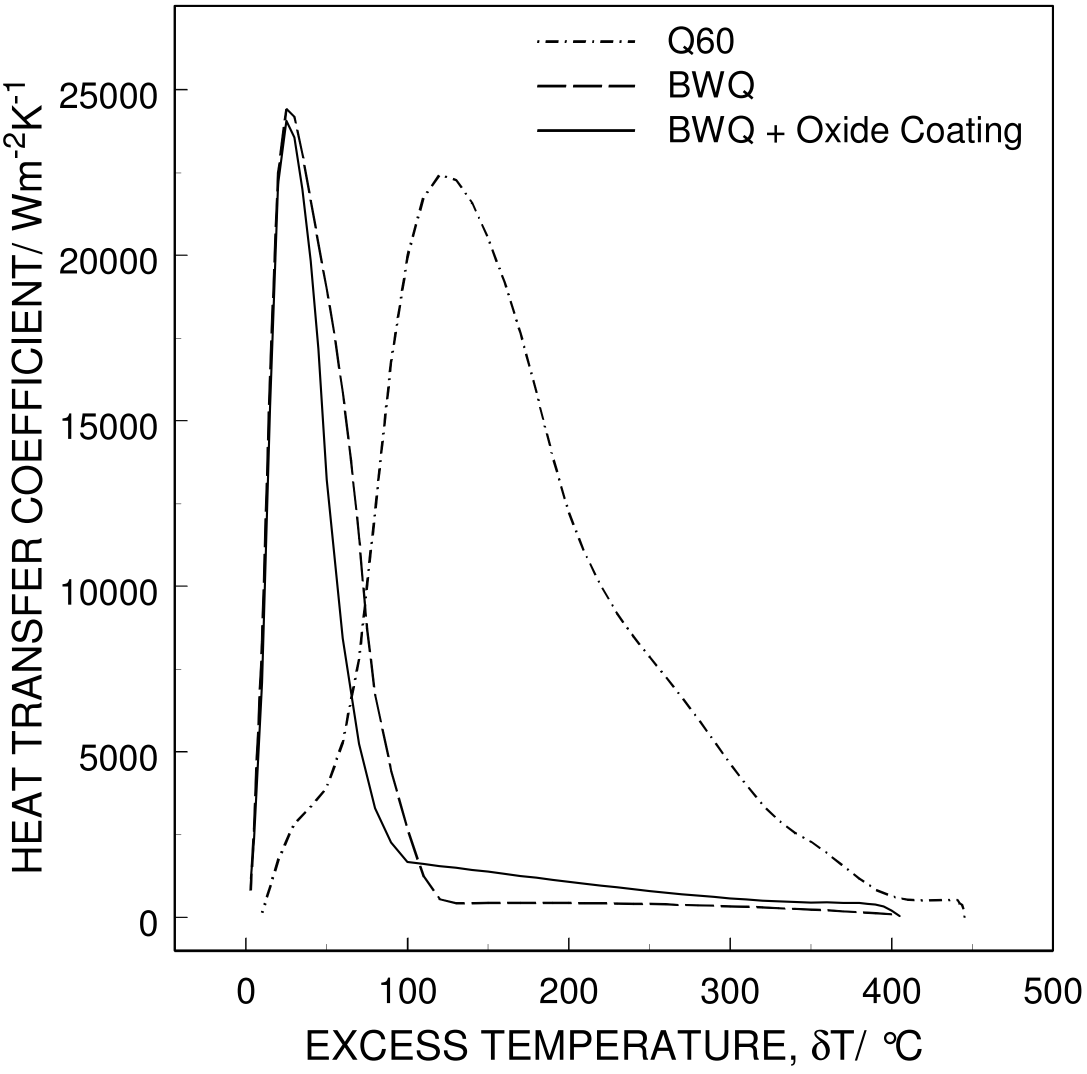

9. List of Table Captions

Table 1 Specification alloy chemistry and chemical analysis results, wt%.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Al
2014	1.2–0.05	0.7 max	5.0–3.9	1.2–0.40	0.8–0.20	0.10 max	0.25 max	0.15 max		Bal.
2014(ca)	0.81	0.27	4.27	0.74	0.52	0.02	0.09	0.02	<0.01	Bal.

Table 2 Heat treatments applied to forgings

2014	SHT	Quench	Aging
1	4h/500°C	Q60	12h/170°C
2	4h/500°C	BWQ	12h/170°C
3A	4h/500°C	BWQ	96h/140°C
3B	4h/500°C	BWQ	96h/140°C + 12h/160°C
5	4h/500°C	BWQ[†]	12h/170°C
6	4h/500°C	BWQ[†]	12h/170°C + 8h/205°C

[†] Smutted before boiling water quench

Table 3 Stress corrosion cracking test results

2014	**Applied Stress (MPa)**	**Failure type**	**Min. days to failure**
1	311	C	1
2	171	A	Passed
3A	181	C	1
3B	190	A	Passed
5	297	A	Passed
6	256	C	1

A – No failures after 40 days

B – Failures observed between 20 and 40 days testing

C – Failures observed within 20 days testing