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Quenching of Aerospace Forgings from High Temperatures Using Air-Assisted, Atomized Water Sprays

M. de Oliveira, J. Ward, D.R. Garwood, and R.A. Wallis

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The nickel-based superalloy or titanium materials used in the aerospace industry are cooled from high temperatures during the heat treatment process to obtain appropriate strength properties. However, unacceptably high residual stresses can be developed in some situations if the rate of cooling is too high so that air-assisted, atomized water sprays have been suggested as an alternative to the widely used techniques of quenching in oil or water. Thus, this article examines two aspects of the use of air-water sprays for quenching aeroengine forgings. First, basic experimental heat transfer data are presented for a wide range of water flows and for surface temperatures up to approximately 850 °C, for both plane and recessed surfaces. Second, the heat transfer data are used in numerical simulations to study the influence of nonuniform spray distributions on the residual stress patterns in a typical forging.

Keywords computer modeling, heat transfer coefficients, heat treatment, quenching, residual stress, spray quenching

1. Introduction

The mechanical properties developed in the nickel-based superalloy and titanium forgings used in modern aircraft engines depend on the rate of cooling from the so-called heat treatment solution temperature. Both quenching in water or oil are commonly used for this purpose, but unfortunately in some cases, the rapid cooling rates associated with these techniques can lead to the development of high residual stresses in the component. These in turn can cause distortion during the final machining operations and in recent years the problem has been exacerbated following the introduction of “near net shape” forging. As an alternative, forced convective air cooling can be used to provide an appropriate cooling rate if the components are sufficiently thin. However, there are a range of alloys and components for which air cooling cannot provide a high enough cooling rate while quenching leads to unacceptably high residual stresses.

Air-atomized water sprays have been proposed as alternative cooling systems to fill the “gap” between the currently widely used air cooling or liquid quenching techniques. Consequently, Wallis et al.[1] used preliminary, estimated heat transfer data for air-water sprays together with a finite-element model to predict cooling rates and residual stresses in a typical industrial superalloy aeroengine forging. They showed that appropriate cooling rates could be achieved and that the predicted residual stresses were substantially lower than those generated by oil quenching so that spray systems appear to offer considerable potential in this application.

Most of the previously published work on water spray or air-water mist cooling has generally been confined to temperatures <600 °C, whereas the data in this article will provide results at higher temperatures of up to approximately 850 °C. In addition, the specific water flux (i.e., the water flow rate impinging on a unit area of the test surface) and the spray droplet sizes are generally much larger with conventional water sprays so that previously published data for these systems are not necessarily applicable to air-assisted atomized water sprays; for example, see Hall and Mudawar.[2] Although Buckingham and Haji-Sheikh.[3] studied the fundamental mechanisms involved in air-water spray cooling of high temperature cylindrical surfaces, they presented only overall water flow rates (instead of water fluxes), and this, together with the cylindrical geometry, makes it difficult to apply their data for the design of air-water spray systems.

Consequently, this article presents results from a study of the use of air-assisted atomized water sprays that can result in heat transfer rates between those associated with air cooling and oil quenching. Air-assisted atomization has an advantage over conventional water sprays in that variation of the air and water pressures can provide fine sprays over a wide range of flow rates. In addition, the air “sweeps” the surface and can help to prevent water “flooding” and the build up of deleterious vapour films at high water flows and surface temperatures. This “flooding” can be a particular problem with recessed surfaces so that heat transfer data are presented for both these and plane geometries. The heat transfer measurements are then

Nomenclature

m_o	Water mass flux on the axis of the spray
T	Surface temperature
T_f	Saturation temperature

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M. de Oliveira, J. Ward, and **D.R. Garwood,** University of Glamorgan, Pontypridd, United Kingdom; and **R.A. Wallis,** Wyman-Gordon Forgings, Grafton, MA. Contact e-mail: rwallis@wyman.com.

used in a finite-element model to predict residual stress formation in a typical forging. In particular, this part of the study examines the effects of nonuniform water distribution.

2. Experimental Arrangement

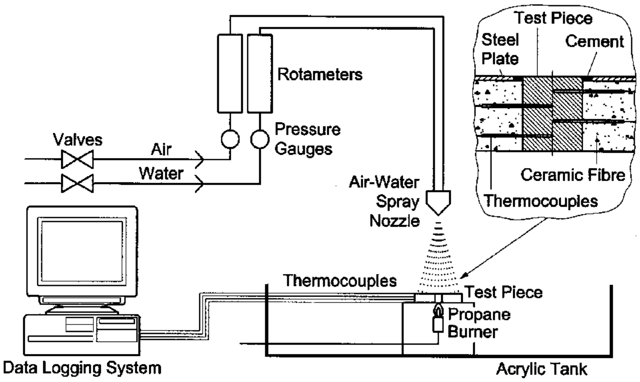
The overall experimental arrangement (Fig. 1) consisted of an air-assisted atomized water spray system that was mounted 800 mm above a 20 mm diameter austenitic stainless steel (AISI 304) test piece. The upper surface of this test piece was either plane or contained an 8 mm deep recess. The test piece was 25 mm long and was heated from below by means of a propane-oxygen burner. It was surrounded by ceramic fibre insulation to ensure that conduction within the stainless steel was one-dimensional in a longitudinal direction. During the heating period, the top surface of the test piece was covered with a ceramic-fiber plug, and in this fashion, relatively uniform temperatures of approximately 850 °C were attained within the stainless steel. This plug was removed prior to spraying the top surface of the test piece. The upper surface of the ceramic fiber insulation was protected from the water spray by means of a steel plate. The circumference of the top surface of the test piece was surrounded by a thin ring of dense ceramic cement to act as a thermal barrier to minimize transverse heat losses into the steel plate and also to protect the underlying ceramic fiber from the water spray (Fig. 1).

The air and water supply pressures were varied to produce water mass fluxes at the test surface ranging from 0.1 to 8.0 kg/m^2 · s. These pressures were maintained constant during a test by manual adjustment, if necessary. The air and water flow rates were measured by means of rotameters, and these instruments provided a further check on the constancy of the test conditions. The water mass fluxes were determined in calibration tests in which water was collected in a series of small diameter collection tubes mounted across the diameter of the spray. Subsequent determination of the mass of water collected in each tube showed that the water mass flux was substantially uniform over the test surface (Fig. 2). Four metal sheathed chromel-alumel thermocouples were positioned at varying depths along the longitudinal center line of the test piece (Fig. 1), and the resultant temperature-time histories were recorded during cooling. The temperature data were then fed into a commercial inverse conduction computer code, INTEMP, which in turn calculated the transient test piece upper surface temperature and heat flux and, hence, the corresponding heat transfer coefficients.

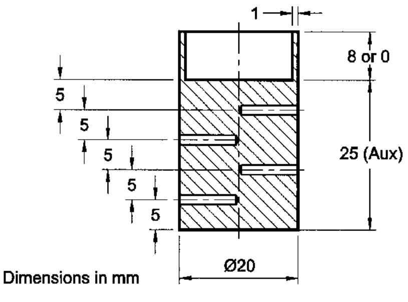
The heat transfer was affected by surface conditions so that the upper surface of the test piece was cleaned by means of emery paper and washed with a solvent prior to each test to remove any thin oxide films formed during prior heating and cooling.

3. Experimental Results

The heat transfer coefficients for the plane surfaces increase substantially as the surface temperature is reduced and the mode of vapour evaporation changes (Fig. 3). The heat transfer



(a) Overall Arrangement



(b) Test Piece Geometry

Fig. 1 Experimental arrangement

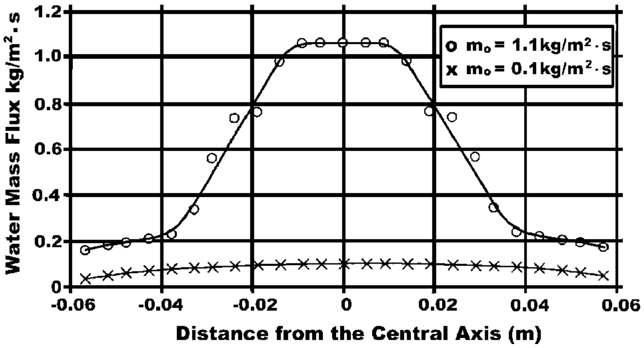


Fig. 2 Spray distributions

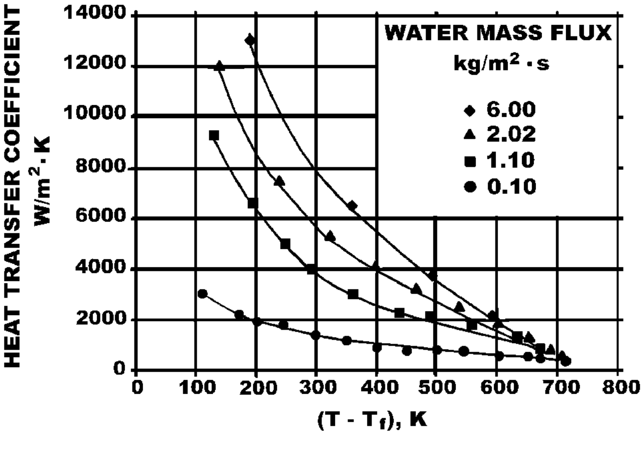


Fig. 3 Heat transfer data for plane surfaces

data include the effect of thermal radiation because in an industrial application it is the total rate of heat transfer that is important. However, it is estimated that at a surface temperature of 800 °C this mechanism contributes between 10 and 20% of the total, depending on the water flow rate, whereas at a lower surface temperature of 400 °C the contribution is <3%.

At high surface temperatures, stable film boiling occurs particularly at the higher water fluxes. As the temperature decreases, transition boiling ensues, and the rate of heat transfer is more markedly influenced by the rate of water inundation. At relatively low superheat temperatures ($T\text{-}T_f$) and high water fluxes, it is possible that nucleate boiling occurs within a thin film of water on the surface, and this results in very high heat transfer coefficients. At the lowest water flow, the heat removed from the surface is more than sufficient to evaporate all the water droplets so that convection to the air makes a significant contribution to the overall rate of heat transfer.

At high surface temperatures, the rate of heat transfer is relatively insensitive to the water flow rate, and this can also be seen more clearly in Fig. 4 in which the heat transfer coefficients are plotted against the water mass flux for various levels of surface temperature. At a surface superheat of 650 °C (i.e., a surface temperature of 750 °C), the rate of heat transfer is virtually independent of water mass flux above a value of approximately 2.0 $kg/m^2 \cdot s$. This corroborates the data of Buckingham and Haji-Sheikh[3] who also found that the heat flux from the surface is relatively constant at high temperatures and high water flow rates. This behavior is consistent with the formation of a stable vapour film beneath a layer of water. The relatively small water droplets have insufficient momentum to penetrate through the layer and the film so that heat transfer across the vapour film is virtually independent of water mass flux. As a result, there is little point in using high water flows in an industrial spray cooling system for quenching superalloys, with consequent savings in water and energy costs.

In this high temperature region at low water flow rates, the air at least partially sweeps the water from the surface (or all the individual droplets evaporate) so that the heat transfer depends on the water flow. Consequently, control of the water mass flux at these low water flow rates provides a reasonable range of heat extraction rates lying between those normally associated with air cooling and oil quenching.

At surface temperatures below 450 °C, the heat transfer rates are heavily dependent on water flow over the whole experimental range (Fig. 4). Undesirably high coefficients are also obtained at flow rates above approximately 1.0 $kg/m^2 \cdot s$. However, this low surface temperature region is relatively unimportant in quenching superalloys because at this stage, the metallurgical effects (which determine the mechanical properties) will be negligible.

The presence of a recess or cavity in the surface can affect the rate of heat transfer so that tests were undertaken with a test piece with an 8 mm deep recess (Fig. 1). At a high water mass flux of 6.0 $kg/m^2 \cdot s$, the recessed surface exhibits significantly lower heat transfer coefficients at all but the highest surface temperatures (Fig. 5). At high temperatures, stable film boiling predominates so that it is reasonable to expect relatively little variation in heat transfer between the two surfaces. With a plane surface water can be "swept away" by the impinging airflow. This effect is inhibited within the surface cavity so that it is likely that a deeper pool of water is formed with a recessed surface. In "shallow" pools of water, nucleate boiling heat transfer rates decrease as the depth of water increases. Consequently, in the transition and nucleate boiling regions, which probably predominate at lower surface temperatures, it is possible that this effect results in the reduction in heat transfer, which is apparent with the recessed component. The reductions in heat transfer may be even greater than those shown in Fig. 5 because the results do not take into account any additional cooling as a result of the flange of the recess acting as a fin or extended surface.

Similar reductions were observed over most of the surface temperature range with a low water mass flux of 0.1 $kg/m^2 \cdot s$ (Fig. 6) At this flow rate, the individual droplets evaporate either before or after impinging on the surface and a water film is not formed. However, the shape of the cavity may significantly affect the characteristics of the flow of air away from the surface and this, in turn, may influence the rate of water droplet impingement. This phenomenon would be less marked at high temperatures where thermal radiation and air convection from the surface play a bigger part. At these high temperatures, a

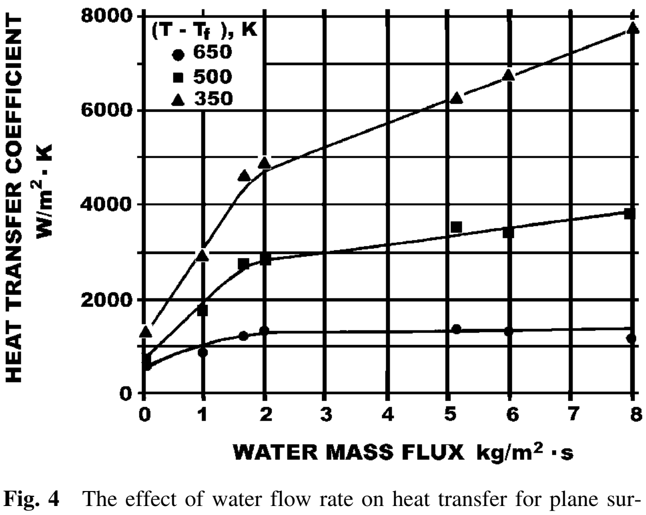


Fig. 4 The effect of water flow rate on heat transfer for plane surfaces

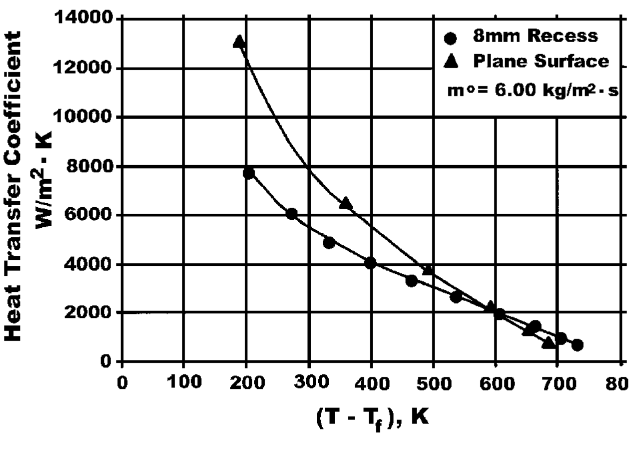


Fig. 5 Comparison of heat transfer from plane and recessed surfaces at high water mass flux

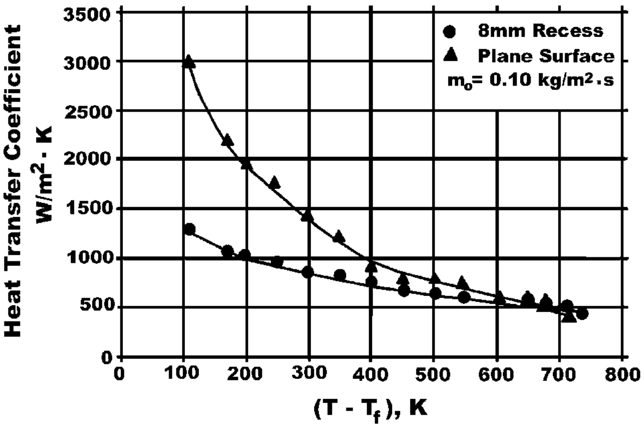


Fig. 6 Comparison of heat transfer from plane and recessed surfaces at low water mass flux

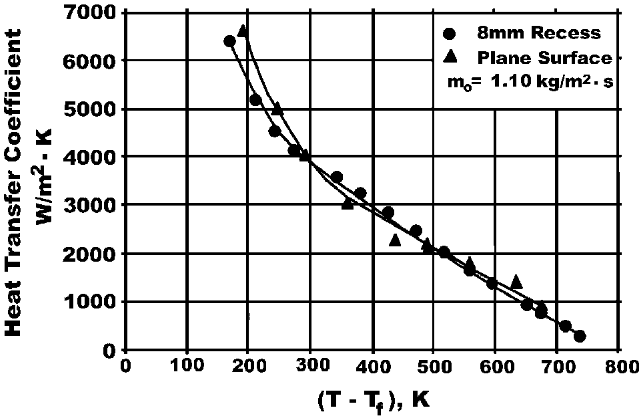


Fig. 7 Comparison of heat transfer from plane and recessed surfaces at medium water mass flux

higher proportion of the droplets evaporate prior to impingement so that variations in droplet inundation would have less overall effect.

Somewhat different behavior was observed at an intermediate water mass flux of 1.10 kg/m^2 · s (Fig. 7) in that the heat transfer coefficients are relatively unaffected over the whole surface temperature range by the presence of the recess. The reasons for the difference in behavior are currently unclear. However, it appears that the effect of the presence of a cavity in the surface of a contoured component may well depend on the water flow rate. Any resultant reductions in heat transfer are most marked at lower temperatures, and generally the coefficients at high surface temperatures are less affected. Thus, any variations in heat extraction rate due to the presence of recessed areas in the surface of contoured parts of complex geometry will be minimized at the high temperatures, which particularly influence the mechanical properties and residual stresses. A more likely cause of substantial variations in heat transfer over the surface is the variation in water mass flux due to nonuniformities within the spray.

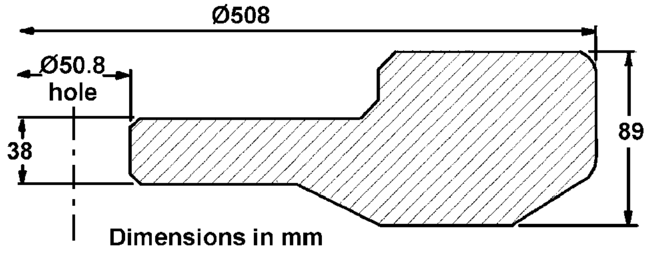


Fig. 8 Forging geometry

4. Prediction of Residual Stresses

The residual stresses developed in a component during cooling can result in distortion of the material during final machining. Consequently, the experimental heat transfer data for air-water sprays were used to predict the residual stresses induced in a nickel-based super alloy forging. The overall method was similar to that described by Wallis et al.[1] in that a finite-element code DEFORM-HT was used to predict the transient temperature distributions and, hence, cooling rates within the forging. The resultant temperature-time histories were then used to predict stress formation during the quenching process and, hence, the residual stresses. This type of approach was validated previously and was shown to provide reasonably accurate estimates of residual stresses (Wallis and Craighead[4]).

The profile of the forging, which was simulated, is shown in Fig. 8 and has an outside diameter of 508 mm and a bore of 50.8 mm. The thickness varied from 38 mm at the inside to 89 mm at the rim, and it was manufactured from a nickel-based superalloy (50-55% Ni) of known mechanical and thermal properties.

The first priority in the quenching process is the need to meet the mechanical strength specification for the forging, which in turn depends on the rate of cooling at high temperatures. The acceptable cooling rate depends on the composition of the superalloy, but in the present study a minimum rate of 80 °C/min was specified.

Wallis et al.[1] previously showed that uniform air-water spray cooling can provide appropriate cooling rates and acceptable levels of residual stresses in superalloy forgings. Thus, the main aim of the present study was to examine the effect of nonuniform spray patterns on the residual stress distributions. Three different cases were studied, and initially, it was assumed that the spray water mass flux and, hence, the heat transfer coefficients were spatially uniform over the surface of the forging. In the remaining two cases (Fig. 9) the water fluxes varied linearly in a radial direction from 1.10 kg/m^2 · s at the spray axis to 0.16 kg/m^2 · s at the edge of the spray. The value of the maximum water flux was selected to provide a minimum cooling rate of 80 °C/min in even the worst case of nonuniformity. The minimum water flux at the edge of the spray approximately corresponded to the measured distribution (Fig. 2). In the uniformly sprayed situation, the water mass flux was maintained constant at the maximum value of 1.10 kg/m^2 · s. The resultant cooling rates in the forging depended on the spray pattern (Table 1), but in all cases they were sufficient to meet the specified minimum rate.

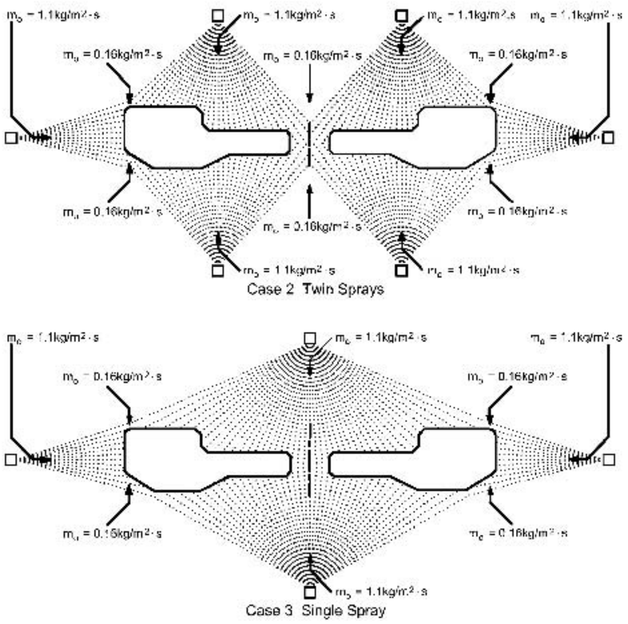


Fig. 9 Spray distribution in the residual stress study

Table 1 Cooling Rates with Different Spray Patterns

Case	Spray System (Fig. 9)	Minimum Cooling Rate (°C/min)	Maximum Cooling Rate (°C/min)
1	Uniform	151	347
2	Twin Sprays	107	266
3	Single Spray	80	281

In practice, the spray distributions would also vary in a circumferential direction. These variations would be complex and were neglected in this preliminary study to maintain axial symmetry in the simulations. Moreover, it was not possible in the models to represent the water flux distributions as continuous functions. Consequently, the surface of the forging was subdivided into 10 zones, each of which was allocated a constant water flux so that the continuous linear distributions were represented by a series of steps. In each zone, the corresponding, experimentally determined temperature dependent, heat transfer coefficients were used as boundary conditions in the simulations. Thus, the spray and, hence, heat transfer patterns are crude approximations but, nevertheless, can provide useful information on the effect of spray nonuniformity on residual stress formation.

As would be expected, the magnitude of the maximum residual stress in the central region of the forging depends on the cooling rate (only results for the circumferential residual stresses are presented in this article because these are adequate to show the general trends). Consequently, the largest stresses were obtained with uniform cooling (Fig. 10) because this distribution provided a minimum cooling rate of 150 °C/min. In this case, however, the residual stresses can be minimized by reducing the water flux while still meeting the specified rate of cooling.

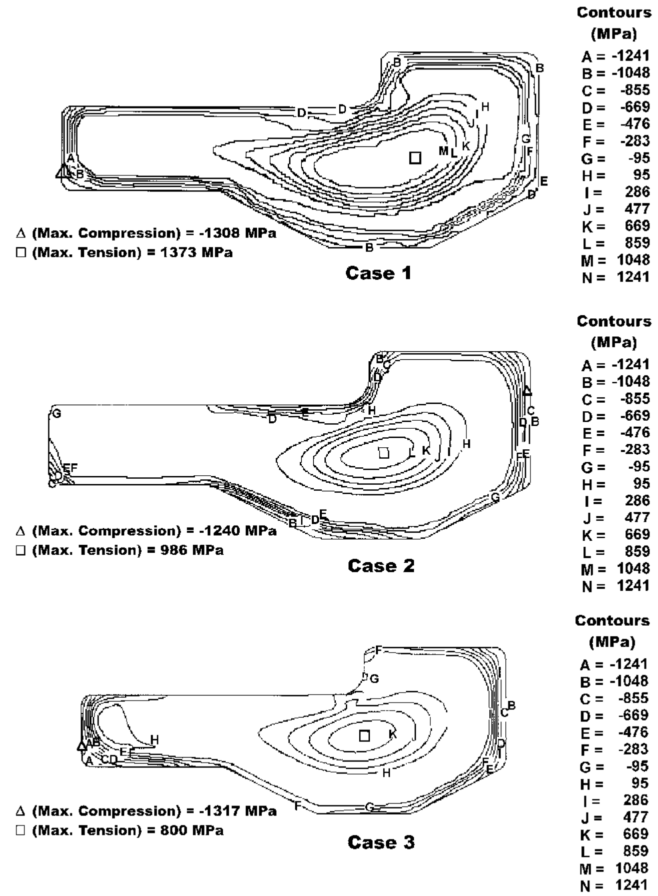


Fig. 10 Residual stress distributions

The magnitude of the large compressive stresses near the surface of the component are relatively unaffected by the nonuniformity of spray cooling so that the maximum compressive residual stress only ranges from 1240 to 1317 MPa. However, the maximum tensile residual stress in the interior of the component exhibits a much greater variation ranging from 800 to 1373 MPa. In addition, Fig. 10 clearly shows that nonuniform sprays can disturb the resultant distribution of compressive residual stress. In the uniformly sprayed forging, the compressive residual stress contours form a thin relatively uniform "skin" near the surface. Distortion of the component during machining is thus relatively predictable and repeatable and can partially, at least, be accommodated. The nonuniform sprays disturb this "skin," and the compressive residual stresses vary considerably over the near surface layers of the forging although the maximum value remains approximately constant. Thus, the residual stresses and, hence, the resultant distortions appear to be sensitive to spray nonuniformity and may be more difficult to predict and take into account. Consequently, it may be necessary to pay careful attention to the spray arrangement (nozzle pitch and nozzle to forging spacing) to obtain a relatively uniform water flux distribution over the surface of the forging in an industrial installation.

5. Conclusions

The experimental measurements reported in this article provide basic heat transfer data for air-assisted, atomized water sprays over a wide range of water flow rates and at surface temperatures up to approximately 850 °C. The heat transfer coefficients are heavily dependent on both these variables because the mechanisms of boiling vary during the quenching process. The strength of superalloy forgings is largely determined by the cooling rate at high temperatures. In this temperature range, the measured heat transfer coefficients were virtually independent of the water mass flux for inundation rates above 2 $kg/m^2 \cdot s$ so that there is little point in using high water flows with consequent savings in water and energy costs. Moreover, at these temperatures, the variation of heat transfer coefficient at low water flow rates can provide a reasonable range of heat extraction rates falling between those normally associated with air cooling or oil quenching.

The heat transfer rates can be affected by the presence of a recess or cavity in the surface. At lower temperatures, there is often a substantial reduction in heat transfer. However, generally the difference in heat transfer characteristics between the two surfaces is reduced at the high temperatures of particular interest in superalloy quenching.

Simulations of residual stress formation in a typical forging indicate that spray nonuniformities can substantially disturb the resultant residual stress patterns. These, in turn, may result in less predictable distortions during final machining so that it may be necessary to pay particular attention to the arrangement of the spray nozzles in a large scale installation.

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