Abstract
This paper describes the use of computational simulation to examine the heat transfer properties and resulting residual stress obtained by quenching a standard probe into various quench oils. Cooling curves (time-temperature profiles) were obtained after immersing a preheated 12.5 mm dia × 60 mm cylindrical Inconel 600 (Wolfson) probe with a Type K thermocouple inserted into the geometric center into a mineral oil quenchant. Different quenching conditions were used, as received (“fresh”) and after oxidation. Surface temperatures at the cooling metal–liquid quenchant interface and heat transfer coefficients are calculated using HT-Mod, a recently released computational code. Using this data, the temperature distribution was calculated. The corresponding distortion and residual stresses were calculated using ABAQUS. This work illustrates potential benefits of computational simulation to examine the expected impact of different quenchants and quenching conditions on a heat treatment process.

Key words: heat transfer, thermal stress, computational simulation.

Introduction
Comparisons of different quenchants and quenching conditions in heat treatment processes of steels are of great usefulness to control residual stresses, cracking and distortion. Mathematical modeling of these processes is an indispensable tool for that purpose.

Simulating a quenching process requires a detailed knowledge of the heat transfer coefficients, $htc$, at the hot-metal/quenchant interface. Various methodologies for obtaining these coefficients have been described (Sarmiento et al., 2000).

The effect of different quench oils and bath temperatures (40, 60, 80 and 100°C) on cooling time-temperature performance using a so-called Wolfson Inconel 600 probe according to ASTM D 6200 is described in this paper. The data obtained was analyzed using the Finite Element Software HT-MOD (Heat Treating Modeling) and the general purpose Finite Element System Analysis ABAQUS.

HT-MOD (Heat Treating Modeling) (Sarmiento et al., 1998a, 1998b, 2000, 2001; Gustón et al., 1999; Samiento & Vegas, 2000; Felde et al., 2001) is a program used to simulate heat treatment processes. It is also used to calculate the heat transfer coefficients as function of time solving an inverse heat transfer problem. The model is based on a numerical optimization algorithm which includes a finite element module for calculating with respect to time and space the temperature distribution and its coupled micro-structural evolution. The transformation from austenite to ferrite, perlite and martensite is governed by the appropriate CCT or TTT curves and by Avrami’s approximation. ABAQUS/CAE (2004) is a finite element program, used in this work to simulate the residual stresses due quenching, and calculate the superficial temperature. These calculations
are based on heat transfer coefficients obtained with HT-MOD.

**Experimental Procedure**

The quenchants used for this work included a fresh, as-received commercial mineral oil, and a sample of this quench oil obtained from a heat treating facility after normal use.

Cooling curve analysis was performed without agitation according to ASTM D 6200. An Inconel alloy 600, cylindrical probe, of 12.5 mm diameter and 60 mm length, was heated at a temperature of 850°C. This probe was equipped with a Type K thermocouple inserted into the geometric center, which was connected to a computer for cooling curve data acquisition. The probe was quenched in both fresh and oxidized mineral oil at 40, 60, 80 and 100°C. Interfacial temperatures at the cooling metal–liquid quenchant interface and heat transfer coefficients are obtained with HT-MOD. (Heat flux values may be computed as well but for this work, only heat transfer coefficients were used.)

The cooling curves obtained from fresh and oxidized oils are shown at Figures 1 and 2 respectively, for each temperature.

![Figure 1](image1.png)  
**Figure 1**  Cooling curves obtained for fresh mineral sample oil, at 40, 60 80 and 100°C.

![Figure 2](image2.png)  
**Figure 2**  Cooling curves obtained for oxidized mineral sample oil, at 40, 60 80 and 100°C.
Modeling with HT-MOD

The simulations performed with HT-Mod Code use a finite element mesh containing 11 nodes along the radial direction and 3 nodes along the longitudinal direction, as shown in Figure 3. Although the INCONEL probe does not undergo transformation upon quenching, it is used to approximate conventional steel cooling which does undergo transformation. Most of the microstructural transformations of conventional steel with this cross-section occurs during the first minute, therefore these were the times taken into account for the simulations. For the discretization of the time variable during 50 seconds, 180 time steps were selected.

The total time of each process was divided into a sufficient number of time intervals where the linear variation of the heat transfer coefficient can be assumed. The selection of the initial values for these coefficients and of the quantity and length of the time intervals depended on each sample.

The mean square difference between the measured and calculated temperatures obtained after optimization of the heat transfer coefficients was about 1°C. Figure 4 shows the calculated heat transfer coefficients as a function of temperature, comparing the quenching power of the two quenchants at the four quenching conditions studied.

Temperatures at nodes in the core and surface were calculated as a function of time and are shown in Figures 5 and 6 for new and used mineral oil, respectively. It is interesting and important to note that the variation of cooling performance with respect to quench oil bath temperature is fundamentally different when fresh, as-received quench oil is compared to the same quench oil after use. Figures 1 and 5 show that the quenching performance of fresh oil is relatively insensitive to bath temperature variation but after use, there is a significant variation of cooling performance with variation of the bath temperature (Figure 6).

![Figure 3](image1.png) Infinite element mesh used to calculate $h$.

![Figure 4](image2.png) Heat transfer coefficient variation as a function of temperature as determined by HT-Mod for all conditions studied.
Calculations of Thermal Residual Stresses

The heat transfer coefficients obtained from HT-MOD, for all studied situations were used as input for ABAQUS/CAE to calculate the superficial temperature and the corresponding distribution of thermal stresses depending on time during the heat treating process, solving the corresponding thermal-elastic-plastic problem. (Note: the test specimen (probe) used for this work is Inconel 600 and therefore there are no transformational stresses.)

A comparison of longitudinal and hoop stresses at nodes in the core and surface were calculated for new and used mineral oil, at 40, 60, 80 and 100°C. These data are plotted in Figures 7, 8, 9 and 10, respectively. Calculations showed that in all cases the stresses were sufficiently high to generate residual stresses.
**Figure 7**  Longitudinal and hoop stresses at the core and surface calculated for new and oxidized oils at 40°C.

**Figure 8**  Longitudinal and hoop stresses at the core and surface calculated for new and oxidized oils at 60°C.

**Figure 9**  Longitudinal and hoop stresses at the core and surface calculated for new and used oils at 80°C.
Longitudinal and hoop stresses are compared for fresh and oxidized mineral oil in Tables 1 and 2, respectively. Predicted hoop residual stresses along the radius for each sample and temperature are illustrated in the figure below. In all cases residual stresses are tensile in core and compressive in surface. As can be observed at 60 and 80°C the residual stresses increase. This range of temperature can be consired the working zone of quenching oil. For both samples at 40 and 100°C there are lower degrees for residual stresses.

Table 1 Comparison of longitudinal and hoop stresses for fresh mineral oil quenchant at different bath temperatures.

<table>
<thead>
<tr>
<th></th>
<th>40°C</th>
<th>60°C</th>
<th>80°C</th>
<th>100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\theta$ [MPA]</td>
<td>–146</td>
<td>–157</td>
<td>–158</td>
<td>–141</td>
</tr>
<tr>
<td>Max. $\sigma_\theta$ [MPA]</td>
<td>181</td>
<td>181</td>
<td>181</td>
<td>181</td>
</tr>
<tr>
<td>$\sigma_z$ [MPA]</td>
<td>–118</td>
<td>–128</td>
<td>–129</td>
<td>–115</td>
</tr>
<tr>
<td>Max. $\sigma_z$ [MPA]</td>
<td>186</td>
<td>186</td>
<td>186</td>
<td>186</td>
</tr>
</tbody>
</table>

Table 2 Comparison of longitudinal and hoop stresses for used mineral oil quenchant at different bath temperatures.

<table>
<thead>
<tr>
<th></th>
<th>40°C</th>
<th>60°C</th>
<th>80°C</th>
<th>100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\theta$ [MPA]</td>
<td>–120</td>
<td>–172</td>
<td>–176</td>
<td>–162</td>
</tr>
<tr>
<td>Max. $\sigma_\theta$ [MPA]</td>
<td>180</td>
<td>179</td>
<td>179</td>
<td>180</td>
</tr>
<tr>
<td>$\sigma_z$ [MPA]</td>
<td>–96</td>
<td>–140</td>
<td>–144</td>
<td>–132</td>
</tr>
<tr>
<td>Max. $\sigma_z$ [MPA]</td>
<td>185</td>
<td>187</td>
<td>187</td>
<td>186</td>
</tr>
</tbody>
</table>
Conclusions

Mineral oils are the most commonly used liquid quenchants worldwide. To achieve ever-increasing quality control specifications it is becoming increasingly important to appropriately qualify the quenching performance expected from as-received quench oils and to monitor the changes in this performance with use. Conventional cooling curve analysis does not adequately provide the user with the expected impact of variations in standard cooling curve performance on his process. Computational simulations, although conducted on small, simple shapes, do provide considerably greater information than observable with a simple cooling curve analysis. This increased insight into the consequences of process variations provides the heat treater with additional and important parameters for better process control.

The results of numerical analysis of the heat transfer properties using HT-MOD of the fresh and used oil quenchants conducted for this study confirm that bath temperature and quenchant oxidization produce substantial impact on the heat transfer properties. Furthermore, using ABAQUS to compute the comparative residual stress profiles and predicted surface temperatures and heat transfer coefficients (of the as-quenched Inconel 600 probe) showed that, as expected, fluid oxidation produced a substantial increase in residual stresses and distortion when compared to fresh.

This work illustrates the enormous insight that numerical analysis of the heat transfer and residual stress properties exhibited by a quenchant can provide relative to the rather limited analysis provided by conventional cooling curve analysis using a procedure such as ASTM D 6200.

Acknowledgement

The authors acknowledge and appreciate the financial support of FIPAI (Fundação para o Incremento da Pesquisa do Aperfeiçoamento Industrial) and RNA (Rassini NHK Autupeças Ltda). Without their support, this work would not have been possible.

References


