Prediction of Geometric Distortions and Residual Stresses on Heat Treated Hot Rolled Rings

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By
Jose L. Gonzalez-Mendez
Graduate Program in Mechanical Engineering

The Ohio State University
2011

Master's Examination Committee:
Taylan Atan, Advisor
Jerald Brevick
Abstract

After being rolled at forging temperature most rings are heat treated (i.e. normalized, quenched and tempered). Due to this processing some rings, especially those with a large outer diameter to wall thickness ratio, distort and become oval, i.e. out of tolerance. This distortion is not the only problem resulting from this phenomenon. Even if the finished rings meet dimensional tolerances and are shipped to the final costumer, residual stresses resulting from heat treatment may become a problem during subsequent machining causing additional deformation and distortion.

Understanding this problem is a challenging task considering the three triggering mechanisms (thermal, metallurgical and mechanical) that affect the ring during heat treatment causing the undesired results. This study covers the prediction of geometric distortion and residual stresses in rolled and heat treated rings. Due to its versatility, accuracy and efficiency, the Finite Element Model technique was used to simulate the heat treatment process of a large ring, resulting in the prediction of geometric distortion and residual stress distribution in the ring under certain conditions for heat treatment.
This document is dedicated to my family.
Acknowledgments

The success of this research has been due to the invaluable contribution of various individuals. First and foremost, I would like to express my gratitude to my advisor Dr Taylan Altan. This research work would not have been possible if not for his trust, guidance and insight throughout my graduate studies.

I would also like to thank Dr. Jerald Brevick for serving on my thesis committee and providing valuable suggestions and guidance. Special thanks go to Ms. Carola Sekreter, Technical Director at the Forging Industry Association (FIA) for the given opportunity to participate in this project.

My heartfelt acknowledgements go to: Alisson Duarte-Da Silva and Xiaohui Jiang, who worked with me in this study and helped me more than they can possibly imagine. Sincere thanks are extended to all the students and staff of the Engineering Research Center for Net Shape Manufacturing (ERC/NSM).
Vita

November 30, 1983........................................... Born Puebla, Mexico

2005........................................ B.S. Mechanical Engineering, ITESM, Mexico

2008........................................ M.S. Manufacturing Systems, ITESM, Mexico

2009 to present ....................... Graduate Research Associate, Center of
                                  Precision Forming (formerly known as
                                  ERC/NSM), The Ohio State University,
                                  Columbus, OH.

Fields of Study

Major Field: Mechanical Engineering
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Chapter 1: Introduction

Ring rolling process

The ring rolling process commonly follows the following steps (Figure 1). The starting round billets are sawed based on the target ring size. Usually, the surfaces of the billets are not machined. The sawed billets are then heated and soaked in a furnace for at least two hours. Additional heating may be needed depending on the billet size. The heated billets are upset, punched and pierced to obtain doughnut shaped pre-forms for the ring rolling machine. The pre-forms are then re-heated to reach the temperature necessary for the ring rolling operation.

![Figure 1. Process sequence in ring manufacturing [Ajax Ring, 2011]](image)
Heat treatment of rolled ring

After rolling, the rings undergo heat treatment. The steps commonly followed in heat treatment are: normalizing, air cooling, austenitizing, quenching, and tempering. Figure 2 shows a schematic of the most common heat treatment steps that may cause distortion and lead to the development of undesired residual stresses in the ring.

Figure 2. Most common steps used in heat treatment of hot rolled rings
Chapter 2: Geometrical distortion and residual stress development during heat treatment of large rolled rings.

After being rolled at forging temperature most rings are heat treated in stacks of 4 to 6 rings (i.e. normalized, quenched and tempered). Due to this processing some rings, especially those with a large outer diameter to wall thickness ratio, distort and become oval, i.e. out of tolerance. This distortion is not the only problem resulting from this phenomenon. Even if the finished rings meet dimensional tolerances and are shipped to the final costumer, residual stresses resulting from heat treatment may become a problem during subsequent machining causing additional deformation and distortion.

As a result of these workpiece alterations, corrective measures have to be taken. Thus, increasing manufacturing costs of industries such as energy and automotive.

Understanding and ultimately solving this problem is a challenging task considering the three triggering mechanisms (thermal, metallurgical and mechanical) that affect the ring during heat treatment causing the undesired results. Due to its versatility, accuracy and efficiency, the Finite Element Model technique is a viable and cost effective tool for conducting this study.

Normalizing (heating and cooling)

In this study, we assume the ring has the nominal dimensions after cooling from ring rolling and ignore, if existent, the distortion and residual stress generated before heat treatment. Normalizing is conducted to achieve uniformity in grain size and composition throughout an alloy. The target temperature will depend on the composition of the steel.
This process may be omitted in case the microstructure is considered to be uniform enough after rolling process.

After heating for normalizing, the ring is air cooled. At the end of this cooling step, no significant distortion of the ring was observed according to the sponsor companies, this statement is also validated by our simulation results.

Convection, conduction and radiation are the heat transfer mechanisms that act during air cooling. This study considers the case in which after heating for normalizing, two rings are individually placed one next to the other on a resting surface. The heat transfer coefficient with environment was selected considering still air, while the conduction coefficient was chosen upon free resting conditions on the surface. The radiation phenomenon was modeled taking into account the proximity effect of a cooling ring that emits heat and affects the cooling of an adjacent ring, as seen in Figure 10.

Quenching (Austenitizing and quenching)

Prior to the quenching process, the ring is heated up to Austenitizing temperature. The purpose for this process is to achieve a uniform Austenite phase in the ring, necessary for the initial step during quenching.

Quenching is defined as the rapid cooling of metals from a suitable elevated temperature. This is generally accomplished by immersion in water, oil, polymer solution, salt although forced air is sometimes used [Davis, 1992]. This process results in maximized metal hardness. Quenching also imparts a fine grain structure to the metal which increases its qualities of hardness and toughness. Cooling rate is the most critical factor in this process since it will determine the capacity of Martensite transformation. However,
as seen in this study, the thermal shock causes undesirable geometric distortion and residual stresses development in the ring.

The heated rings are submerged in a quenching tank with agitated solution. The different conditions inside the quenching tank (i.e. quenchant temperature, agitation level, stacking conditions, tank size) will affect the resulting geometric distortion and the development of residual stresses. An accurate calculation of heat transfer conditions during quenching may be achieved. However, such calculation depicts specific quenching conditions for one case (location in the tank and in the stack, propeller proximity and orientation) and cannot be standardized for any given ring that is quenched in this tank. Alternative quenching processes have been developed to reduce the effect of thermal shock. For instance, intermittent quenching intends to reduce the thermal shock by submerging and extracting the ring into and out the tank intermittently. Nevertheless, this alternative process is also affected by the same irregular parameters in continuous quenching and its modeling is difficult. According to the material, the behavior during quenching may vary. However, [Shuhui, 2002] has classified this process in three stages as follows.

*Film boiling phase*

The first stage of quenching, which is shown as stage A in Figure 3, is characterized by the formation of a vapor film around the component [Houghton 2000]. This vapor blanket develops and is maintained while the supply of heat from the interior of the part to the surface exceeds the amount of heat needed to evaporate the quenchant and maintain the vapor phase. This is a period of relatively slow cooling during which heat transfer occurs by radiation and conduction through the vapor blanket.
The wetting process occurs during the transition from film boiling to nucleate boiling. It occurs in repetitive waves that “rewet” the surface. The transition temperature from A to B stage cooling is independent of the initial temperature the metal being quenched.

![Cooling mechanisms during quenching](image)

Figure 3. Cooling mechanisms during quenching [Houghton, 2000]

**Nucleate boiling phase**

Upon further cooling, the nucleate boiling stage (Stage B) begins. This cooling mechanism is characterized by violent boiling at the metal surface. The stable vapor film eventually collapses and cool quenchant comes into contact with the hot metal surface resulting in nucleate boiling and high extraction rates.

**Convection phase**

Stage C, or the convective cooling stage in Figure 3, begins when the metal cools just below the boiling point of the quenching fluid [Georgy, 1993]. As cooling continues, the
temperature of the ring surface decreases below the boiling point of the quenchant and
the metal surface is completely wetted by the fluid. At this point, the cooling rate
decreases and is determined by the convection rate and the viscosity of the quenching
fluid. Heat transfer rates in this region are affected by various process variables, such as
agitation, quenchant viscosity and bath temperature. The rate of cooling in the convection
phase is also important since it is generally within this temperature range that martensitic
transformation occurs and it can, therefore, influence residual stress, distortion and
cracking.

Tempering

In heat treatment, tempering consists in reheating hardened steel to some temperature
below the eutectoid temperature for the purpose of decreasing hardness and increasing
toughness [ASM, 1993]. This is done by transforming brittle Martensite or Bainite into
tempered Martensite or a combination of Ferrite and Cementite. The brittle Martensite
becomes tough and ductile after it is tempered. During quenching, Carbon atoms are
trapped in the Austenite, forming Martensite. This phase becomes tough and ductile when
reheated, since the microstructure rearranges and the Carbon atoms diffuse out of the
distorted body-centered-tetragonal (BCT) structure [Todd, 1994].
Chapter 3: FE modeling of heat treatment process for rolled rings.

Case study

An AISI 4140 ring was selected for this study. This ring is named Ring A and is described in Table 1 and Figure 4. This specific geometry is obtained from one of the sponsor companies. However, for the case of any generic ring, it should be noted that the degree and type of the quenching effects (e.g. distortion, residual stresses or cracking) will be directly related to the ratio given below. The smaller the ratio \( \rho \), geometrical distortion is more probable to occur, and the larger the ratio \( \rho \), cracking is more prone to happen.

\[
\rho = \frac{\text{Outer Diameter (OD)}}{\text{Outer diameter (OD)} - \text{Inner diameter (ID)}}
\]  \hspace{1cm} (1)

The heat treatment steps modeled are normalizing (heating and air cooling) and quenching (austenitizing and quenching). In order to save computation time, the FE models for heat treatment will consider symmetry (1/4th of the ring) unless otherwise mentioned. The geometry and boundary conditions are shown in Figure 5.

![Figure 4](image)

Figure 4. Top view and cross section view of a ring
### Table 1. Ring dimensions

<table>
<thead>
<tr>
<th>Dimensions in mm</th>
<th>Ring A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter (OD)</td>
<td>1296.2</td>
</tr>
<tr>
<td>Inner Diameter (ID)</td>
<td>1163.8</td>
</tr>
<tr>
<td>Height (H)</td>
<td>163.6</td>
</tr>
</tbody>
</table>

Initially, for this study it was considered that the residual stresses and distortion were only caused by the mechanical and thermal properties of the material. However, it was observed that the results are highly sensitive to the accuracy of the material data input in the FE code. And in the case of ring distortion, it is important to consider phase
transformation since the total strain is not only defined by elastic, plastic and thermal terms but also phase transformation and transformation plasticity.

The prediction of geometrical distortion and residual stresses during quenching of steels requires detailed material data for each metallurgical phase formed during heat treatment, all of which are a function of alloy composition, heat treatment procedures (microstructure) and temperature. The information on materials properties necessary to predict geometrical distortion and residual stresses is listed below [Guo et al., 2009]: phase transformation kinetics, i.e., TTT (time-temperature transformation) and CCT (continuous cooling transformation) diagrams;

- temperature dependent mechanical properties of each phase formed, including tensile strength, yield strength and hardness;
- temperature dependent thermo-physical properties of each phase formed, such as density, Young’s modulus, thermal expansion coefficient, and thermal conductivity;

The latter category can be categorized and described as follows:

**Plastic properties.**

The flow stress (true stress vs. true strain, Units: MPa) governs deformation and flow behavior for any object undergoing permanent deformation. The flow stress for each phase is characterized by strain, strain rate and temperature. The hardening rule should also be addressed. This rule defines the type of hardening that occurs in the material under an applied load. All phases are governed by the isotropic hardening rule, which assumes that the Von Mises yield surface expands uniformly as the material is stressed into the plastic regime. [SFTC, 2010].
Elastic properties

The Young’s Modulus (Units: MPa) is a measure of the stiffness of a material and is only valid in the linear region of the stress-strain diagram. This Modulus is closely related to Poisson's ratio, which is defined as the negative ratio of lateral and axial strains that result from an applied axial stress. Both elastic properties are defined for each phase and are temperature dependant [SFTC, 2010].

The thermal expansion coefficient is also considered an elastic property. It is used to determine the amount an elastic object expands due to temperature change. The temperature change is defined as the difference between nodal temperatures and a specified reference temperature (usually 20°C). However, in case of heat treating, the thermal expansion coefficient is derived by using each phase's volume fraction [SFTC, 2010]

Thermal properties

The thermal properties also change according to the microstructure phase and are temperature dependant. The thermal conductivity may be specified as a set of discrete temperature/conductivity data pairs, as well as the heat capacity. The emissivity, in the case of radiation, will have a constant value for the whole body.

For this study, we have used that material data for AISI 4140 with phase transformation consideration provided by JMatPro (Java-based Material Properties). This material database is defined as a mix of phases, these being: Austenite, Banite, Pearlite and Martensite for AISI 4140. Each phase will have a set of material properties of its own. The material data is obtained based on expensive and long experimental tests in laboratories with appropriate equipments. Also, the data accuracy depends on each
laboratory equipments precision and procedures. The material database used in this study was validated with a case found in literature. Please refer to 0 for a detailed description.

Kinetics of phase transformation

The time-temperature transformation diagram (TTT diagram), helps to predict the post-heat treating microstructure based on the cooling rate (quench severity). [Rudnev, 2003]. These diagrams are used for Austenite to Pearlite, Austenite to Bainite and Austenite to Ferrite transformations. The transformation start and end curves are inputted by the time in the logarithmic value at some temperature and carbon content. In the case of Austenite to Martensite transformations, the necessary input is the martensitic data (TMS =340 °C, TM50 =290 °C), which are the transformation start and 50% level temperatures. Figure 6 exemplifies the importance of the cooling rate during phase transformation of AISI 4140 alloy steel. At high cooling rate (20 °C/s) Martensite is formed at high volume fraction. Meanwhile, at slow cooling rate (5 °C/s) Bainite dominates the phase transformation and Martensite, Pearlite, and Ferrite are formed in small proportions. DEFORM™ considers the TTT diagrams for the phase transformation kinetics. Figure 7 shows the TTT diagram for the mentioned steel. Please note that the chemical composition (%wt) of AISI 4140 is:

Fe – 0.98Cr – 0.77Mn – 0.21Mo – 0.04Ni – 0.15Si – 0.37Cr.
Figure 6. Microstructure evolution in a 4140 steel during cooling at (a) 20 °C/s and (b) 5 °C/s [Guo et al., 2009]

Figure 7. TTT curves of steel 4140, corresponding to 10% and 90% of the transformation [Guo et al., 2009]

The thermo-physical and mechanical properties of steel vary as a function of cooling rate. Figure 8 shows linear expansion and 0.2% proof stress for the AISI 4140 as function of
temperature, considering several cooling rates. On the other hand, the yield stress is shown as a function of temperature and material phase for AISI 4140 in Figure 9.

Figure 8. Examples of properties calculated for a 4140 steel at cooling rates from 0.01 °C/s to 100 °C/s [Guo et al., 2009]

Figure 9. Yield stress for each phase during cooling of 4140 steel [Guo et al., 2009]

It is also important to consider that during phase transformation, the dimensions of a specimen are affected by the presence of an applied stress during the transformation, as if
the material had been subject to plastic deformation. This effect is referred to as ‘transformation plasticity’ which occurs even at low stresses below the yield stress of the material [SFTC, 2010]. To account for this material behavior during the transformation, the following form is used:

\[
\dot{\epsilon}_{ij}^p = \frac{3}{2} \sum K_I h (\xi_1) \hat{\epsilon}_{I} \hat{\epsilon}_{ij}
\]

Where \(\dot{\epsilon}_{ij}\) is the strain rate caused by transformation plasticity, the constant \(K_I\) is the intensity of transformation plasticity and depends on the material, \(s_{ij}\) is the deviatoric stress, and \(h = 2(1-\xi)\). The units for transformation plasticity are 1/s.

The latent heat released when one phase transforms into another should also be considered among the kinetics of phase transformation. This is a constant value depending on the phase. Finally, the volume change, the fractional length change that occurs when one phase transforms to another, is used to determine the amount of volume change that occurs during transformation [SFTC, 2010].

FE modeling of heating process (normalizing heating)

For this study, it is assumed that the furnace conditions are ideal to have a uniform heating in all ring surfaces. The heating process is simulated in DEFORM™ with the parameters shown in Table 2. The material data used for the heating simulations does not consider phase transformation for the following reasons:

In case of considering phase transformation, the volume fraction of each phase should be initially defined. However, determining these values prior to heating is impractical and difficult.
It is assumed that once the ring is heated above Austenitizing temperature, the volume fraction of austenite in the ring is 1.0.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>DEFORM-3D™</td>
</tr>
<tr>
<td>Material</td>
<td>AISI 4140 no phase transformation</td>
</tr>
<tr>
<td>Material properties (function of temperature)</td>
<td>DEFORM-3D Library:</td>
</tr>
<tr>
<td></td>
<td>Plastic properties (Flow stress data)</td>
</tr>
<tr>
<td></td>
<td>Elastic properties (Young's Modulus, Poisson's ratio, Thermal expansion)</td>
</tr>
<tr>
<td></td>
<td>Thermal properties (Thermal conductivity, heat capacity)</td>
</tr>
<tr>
<td>Normalizing heating temperature</td>
<td>927°C</td>
</tr>
<tr>
<td>Normalizing heating time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Symmetry</td>
<td>¼ of ring with symmetry planes</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Elastic-plastic</td>
</tr>
</tbody>
</table>

Table 2. Normalizing heating – FE parameters

Based on this, it was decided for heating stages Normalizing and Austenitizing, to use the AISI 4140 material database with no phase transformation found in DEFORM™ library to capture the expanded geometry of the ring when the target temperature is reached. Then, when the air cooling simulation is carried out the volume fraction is set to Austenite -1.0 and the material data for AISI 4140 with phase transformation (JMatPro database) can be applied.
Since the ring is elasto-plastic there will be a thermal expansion. The results for radial expansion, $\Delta$(Outer Diameter) and $\nabla$(Inner Diameter) of ring A after heating for normalizing are listed in Table 3. Note that this thermal expansion is purely elastic.

<table>
<thead>
<tr>
<th>Ring A</th>
<th>$\Delta$(Outer Diameter) (mm)</th>
<th>$\nabla$(Inner Diameter) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~9</td>
<td>~8</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Ring radial expansion after normalizing-heating

FE modeling of non-uniform air cooling

In practice, after heating for normalizing during 2 hours and reaching a uniform temperature of 927°C, the ring is air cooled individually or in stacks of 4-6 rings and placed on gravel. In the case when several rings are stacked, spacers may be used as a separation method between rings. However, the use of spacers changes from company to company.

This document reports the results on air cooling for ring A. The mechanisms that trigger heat transfer during air cooling are: convection with environment, conduction with bottom surface and radiation with a surrounding ring. Convection with environment is governed by following the equation:

$$q_c = A \cdot C_{nvcof} \cdot (T_s - T_{temp})$$  \hspace{1cm} (3)

where:
$q_c$ = heat transfer associated with convection
A = convection heat transfer area
$C_{nvcof}$ = convection coefficient
$T_s =$ surface temperature

$T_{temp} =$ environmental temperature

$C_{conv}$ is a constant value, which for free air convection ranges between $5 \times 10^{-3} - 25 \times 10^{-3}$ N/sec/mm/$^\circ$C. We have selected the value $20 \times 10^{-3}$ N/sec/mm/$^\circ$C for the air cooling simulation.

Modeling the conduction of the ring with a surface during air cooling is a critical step since this phenomenon causes the highest heat transfer during this stage. The value of conduction heat transfer coefficient will be determined based on the pressure of the ring on the surface or in the case of a stack, the pressure of the rings on the bottom ring. In [Hora, 2008], conduction heat transfer coefficients are defined as a function of pressure. The pressure caused by a single ring is calculated as 0.012 MPa, while a stack of four rings will result in a pressure of 0.05 MPa with the bottom surface. Based on [Hora, 2008], the heat transfer coefficient due to conduction for both cases is practically the same, 1.302 N/Sec/mm/$^\circ$C. For this reason we concluded that the influence of the stack weight (4 rings) in conduction between the bottom ring and the surface is not significant and only the single ring case is simulated.

Once that individual cooling (no stacking) has been selected, it is important to consider that rings are air cooled one next to another. Since the radiation of a neighboring ring (ring II) may affect the heat transfer phenomenon of a ring (ring I) according to the relative distance between the surfaces of both rings, as seen in Figure 10, we have called this phenomenon as non-uniform cooling. The sponsoring companies have reported in average a separation of 254 mm between two rings during air cooling.
DEFORM\textsuperscript{TM} takes into account the radiation of two bodies located with a certain distance between them that could affect heat transfer. This technique is based in the view factor theory described by [Incropera, 2003]. To evaluate this process, two rings, I and II, are positioned side by side exchanging heat with environment by convection. Both bodies will be affected by radiation. DEFORM\textsuperscript{TM} considers the bodies’ geometries and distance between them to calculate a view factor, $F$, which will be used at the radiation heat flow equation. The view factor is defined as the fraction of the radiation leaving a body $i$ that is intercepted by a body $j$. Please refer to 0 for further detail on the view factor.

The Stefan-Boltzmann equation for the radiation heat calculation is modified as follows to include the view factor.

$$q_r = B \ A_s \ \text{Emiss} \ F(T^4 - E_{\text{temp}}^4)$$  \hspace{1cm} (4)

where

$q_r$=heat associated with radiation

$B$= Boltzmann constant $(5.669 \times 10^{-11} \ \text{N/sec/C}^4)$

$A_s$= surface area

Figure 10. Schematic of two rings showing radiation received by Ring I from Ring II
Emiss = emissivity factor

\( F \) = view factor

\( T_s \) = surface temperature

\( E_{\text{temp}} \) = environmental temperature

In order to emulate the real boundary conditions, the FE model was built based on Figure 10 with 254 mm distance between the two rings. Symmetry was considered, and 1/2 of the ring was used during the simulation. Figure 11 shows a comparison between the real set up and its respective FE model with symmetry.

![Symmetry plane](image)

**Figure 11.** Layout of non-uniform air cooling. (a) Original setting and (b) 1/2 of geometries.

The rings (ring I and ring II) were modeled with an elasto-plastic behavior, characterized by AISI 4140 material data considering phase transformation. Both rings have a starting homogeneous temperature (927°C). Therefore, both rings have a volume fraction of Austenite – 1.0. According to Figure 10, the rings are positioned beside each other with a distance between them of 254 mm. The heat transfer with environment is caused by radiation, convection and conduction. The radiation effect is modeled by the modified Stefan-Boltzman equation that includes the view factor feature. The view factor value is calculated by DEFORM™ based on the proximity of the two bodies. The convection
coefficient with still air has a constant value of 0.02 N/mm/sec/°C. Finally, the conduction of the bottom face with the surface has the heat transfer coefficient obtained previously. In Table 4 the FE setup parameters are given.

| Parameters                      | Values
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetry for ring A</td>
<td>1/2 of ring. See Figure 11</td>
</tr>
<tr>
<td>Material properties.</td>
<td>AISI 4140 (JMatPro)</td>
</tr>
<tr>
<td>Set of properties for each phase formed.</td>
<td>Plastic properties (Flow stress data)</td>
</tr>
<tr>
<td></td>
<td>Elastic properties (Young's Modulus, Poisson's ratio, Thermal expansion)</td>
</tr>
<tr>
<td></td>
<td>Thermal properties (Thermal conductivity, heat capacity)</td>
</tr>
<tr>
<td></td>
<td>Phase transformation kinetics</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>927°C</td>
</tr>
<tr>
<td>Initial phase</td>
<td>Austenite (Volume fraction 1.0)</td>
</tr>
<tr>
<td>Environment temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Elastic-plastic</td>
</tr>
<tr>
<td>HTC for bottom surface</td>
<td>1.302 (N/Sec/mm/°C)</td>
</tr>
</tbody>
</table>

Table 4. Normalizing – air cooling. FE parameters

As mentioned before, the heating simulation was conducted with no phase transformation material data to avoid the phase fraction calculation, due to the lack of information on initial volume fraction. At the start of air cooling, the ring has a uniform temperature of 927°C, meaning that the ring is in austenite phase at 100%. This assumption allows us to use the phase transformation material database for the air cooling simulation.
FE results for non uniform air cooling

The results presented in this section concern the Ring I (Figure 10). Two cross sections, A-A’ and B-B’, were selected to summarize the results (Figure 12, Figure 13 and Figure 14). Section A-A’ in ring I shows the farthest area to ring II, meaning that section A-A’ is the least affected by radiation of ring II, whereas section B-B’ is the closest area to Ring II (separation of 254 mm between rings) and therefore the most influenced by radiation of the surrounding ring. Figure 12 shows the temperature distribution of both sections after 5 minutes of air cooling. Note that the aspect ratio of the ring diameter is modified for presentation purposes. The bottom face of the ring shows the highest heat transfer due to conduction with the surface. However, the effects of radiation of the surrounding ring (ring II) can be observed in the point tracked on section B-B’ outer surface where the temperature is slightly higher (644°C) than in section A-A’ (642°C). In other words, temperatures are higher in the area where the distance between rings is minimum (254 mm). However, the temperature gradients with the rest of the rings are small during the entire air cooling process.

Figure 12. Temperature distribution of Ring I after 5 minutes of air cooling simulation
Figure 13 presents the effective stresses of both sections of ring I after the first 5 minutes of air cooling. Maximum level of stress is developed at 5 minutes. It can be seen that section B-B’ is more influenced by radiation from the surrounding ring than section A-A’ due to the surrounding ring proximity. Section B-B’ presents a smaller development of effective stress due to the slower cooling rate. Nonetheless, the difference between section A-A’ and B-B’ is about 4 MPa and can be neglected.
Figure 14. Effective stresses for Ring I at room temperature (25°C) after air cooling simulation.

Figure 15. Final displacement of ring A in non-uniform cooling.

Figure 14 shows the effective stress distribution in ring I after reaching room temperature (approximately 2 hours and 40 minutes). The maximum residual stress in non-uniform
cooling is around 131 MPa. During non uniform air cooling, the ring contracts towards its nominal dimensions. However, there is some resulting distortion. When the ring has reached room temperature there is a rotation in the z-r plane as shown in Figure 15. Also, the ring does not recover its original dimensions in the r direction. There is a distortion of about +2mm in the r direction as shown in Figure 15.

**FE modeling of quenching**

In almost all of the heat treatment simulations, it is assumed that the total strain, which governs part of the FE calculation, is the sum of the strains from different physical events, namely, temperature variation and phase transformations [Gur, 2008].

\[
de_{ij}^T = de_{ij}^e + de_{ij}^p + de_{ij}^{th} + de_{ij}^{tr} + de_{ij}^{tp}
\]  

(5)

Where the subscripts e, p, th, tr, and tp represent the entities for elastic, plastic, thermal, phase transformation, and transformation plasticity, respectively, occurring from a phase i to another phase j.

The transformation induced volume change, \(de_{ij}^{tr}\), occurs due to the volume changing of the material when the phase transformation induces a change in the lattice structure of the material. This volume change may induce stress in the transforming part and will certainly affect the final dimensions after processing. The transformation plasticity, \(de_{ij}^{tp}\), represents sharp reductions in plastic strains resistance that accompanies phase transformation. The change of the dimensions of a part due to transformation plasticity occurs is combined with the dimension changes due to the transformation induced volume change. [Gur, 2008]
Assumption of Heat transfer coefficient during quenching

For the FE model of quenching we have considered the following scenario: the heated rings are submerged in a quenching tank with agitated solution as seen in Figure 16. This arrangement is a common practice in the sponsor companies. One of the most critical parameter to be input into the FE quenching simulation is the heat transfer coefficient which depends on: temperature, agitation and stacking conditions. Some tools such as Computational Fluid Dynamics tool (CFD) can depict in detail the heat transfer conditions for a particular quenching setting. This approach has been developed for academic purposes with some limited commercialized applications. Another option is the inverse analysis of temperature experimental data in order to obtain heat transfer coefficient.

It is important to note that both methods CFD and inverse analysis capture the specific quenching conditions (ring geometry, location in the tank and in the stack, propeller proximity and orientation) and cannot be standardized for any given ring that is quenched in the tank. This makes both methods impractical and expensive from an industry point of view. Therefore, we have adapted the FE tool to achieve a close to reality and practical quenching simulation.
Figure 16. Typical arrangement of ring stacks in the quenching tank.

Figure 17. Heat transfer coefficient for quenching from Houghton [Houghton, 2011]
It was mentioned that the heat transfer is not uniform in all the ring surfaces since it depends on several factors such as ring and propeller location and agitation. We have defined a methodology to roughly approximate the non-uniform heat transfer behavior inside the tank. In this methodology the ring has been divided in four sections, each section will have a different quenching severity, meaning that the heat transfer coefficient as a function of temperature will be different for each segment.

The quenchant supplier for one of the sponsor companies has provided us with the heat transfer coefficient \( H_q \) as a function of temperature for a solution with no agitation conditions (Figure 17). This data is the base for the different heat transfer functions used for the sectioned ring. As seen in Figure 18, the left most section of the ring is assumed to have the highest quenching severity, therefore it is assumed that the heat transfer...
coefficient is 8 times larger than the reference given in Figure 17. The two middle sections are assumed to have a medium agitation, resulting in heat transfer coefficient function 2 times larger than the reference. On the other hand, the right most section and the inner surface of the ring are assumed to have the lowest quenching severity, close to no agitation.

FE setup of quenching simulation

For the FE setup, convection is the only heat transfer mechanism considered active during quenching. And it is modeled by applying the heat transfer coefficient as a function of temperature. In order to characterize the non-uniform quenching conditions, the heat transfer coefficients are input according to the assumptions already mentioned.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>DEFORM™</td>
</tr>
<tr>
<td>Material properties.</td>
<td>AISI 4140 JMatPro</td>
</tr>
<tr>
<td>Set of properties for each phase formed.</td>
<td>Plastic properties (Flow stress data) Elastic properties (Young's Modulus, Poisson's ratio, Thermal expansion) Thermal properties (Thermal conductivity, heat capacity) Phase transformation kinetics</td>
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<tr>
<td>Initial temperature</td>
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<td>Quenchant temperature (target temperature)</td>
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<td>Symmetry</td>
<td>1/2 ring</td>
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<td>Elements</td>
<td>3500 brick elements</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Elastic-plastic</td>
</tr>
</tbody>
</table>

Table 5. FE modeling-parameters setup
The Austenitizing process prior to quenching creates a uniform Austenite microstructure in the ring. Hence, the volume fraction is set as 1.0 for Austenite. The phase transformation is calculated based on the transformation kinetics from the material database JMatPro. The FE setup parameters are presented in Table 5. It's important to note that considering the distribution of heat transfer coefficient functions as seen in Figure 18 the FE model can be set as half ring due to symmetry.

FE results for quenching simulation

Figure 19 and Figure 20 show examples of the distortion evolution through time during quenching and the final estimated distortion after heat treatment simulation, respectively. Here, different values of the heat transfer coefficient were assumed at various locations in the quenched rings. The reliability of a quenching simulation is conditioned to mostly two things: the precision with which the quenching tank conditions are emulated, in other words, how reliable the heat transfer calculations are, and the accuracy of the mechanical (elastic and plastic), thermal and metallurgical properties of the material to be simulated. Figure 19 shows that after the quenching simulation there is a distortion of approximately 7.2 mm. This value is calculated by comparing the outer diameter of the now distorted ring in the maximum dimension versus the minimum dimension. The FE setting of the heat transfer coefficient for this simulation is described in Figure 18. The severity of the distortion will vary according to the heat transfer coefficient setting used. In our case, it will depend on the different proportions given to each section in which the ring was divided. Figure 20 presents the effective stress distribution after quenching. The heat transfer coefficient distribution around the ring assumed to emulate agitation conditions results, as expected, in big differences in the temperature and stress history at
different areas of the ring. To exemplify this, three points in the ring were selected. Each point represents an area of the ring exposed to a particular agitation level (quenching severity) as described in Figure 18. Point 1 represents the most severe quenching (8XHₖ), Point 2 corresponds to a medium agitation (2XHₖ) and Point 3 represents the lowest agitation level (1XHₖ). Figure 21 shows that the cooling rate at the three different points is directly proportional to the agitation level assumed. Point 1 shows the largest cooling rate while temperature at Point 3 decreases at the slowest rate. Figure 21 covers the results only until 600 seconds since temperatures at the three points are below 150°C and decrease towards quenchant temperature at a low stable pace. Therefore, no phase transformation will take place.

The residual stress development is shown in Figure 22. The irregular behavior in stress observed during the first 150 seconds of quenching is a consequence of the rapid phase transformation phenomenon where each phase involved comprises a different set of material properties. As the cooling rate reduces, the stress development tends to stabilize and the effect of the heat transfer coefficient distribution is clearly seen. Point 1 presents the highest stress approximately at 450 MPa, while Point 3 presents the lowest value at 100 MPa. As the ring reaches the quenchant temperature, the stresses stabilize and maintain the residual stress value. Hence, Figure 22 only shows the residual stress history up to 600 seconds.
Figure 19. Example of distortion evolution during quenching (diameter comparison between maximum and minimum dimension)

Figure 20. Resulting geometrical distortion and residual stresses after FE simulation of heat treatment
Figure 21. Temperature tracking during quenching simulation at three ring points with different assumed agitation (different heat transfer coefficient proportion)

Figure 22. Effective stress tracking during quenching at three ring points with different assumed agitation (different heat transfer coefficient proportion)
Summary of quenching simulations

Quenching process is quite complex because heat transfer varies with location and temperature. In addition, the phase transformation happens during all the cooling process which increases the difficulties of FE simulation. In order to obtain more accurate distortion, heat transfer coefficient and material properties are typical and should be achieved for FE modeling setup. From the simulations we have done, the following conclusions could be summarized:

- Different steps of heat treatment (up to quenching) have been simulated in a commercial FE code in order to predict ring distortion and residual stresses distribution.
- Heat transfer variation during quenching as a function of temperature, tank and stack location, and agitation is the key factor to calculate distortion. Hence, it is important to correctly model the heat transfer coefficient.
Chapter 4: Effect of heat transfer in quenching

Two factors are critical in the prediction of distortion and residual stresses of a ring during FE quenching simulations: 1. accurate material properties, 2. heat transfer coefficient between the quenchant and ring. The heat transfer coefficient can be calculated using different methodologies, one of them being the inverse heat transfer analysis from experimental temperature measurements, as will be seen in this section. This method is accurate but impractical from an industry point of view since it only pertains to the specific quenching conditions of such experiment.

An accurate modeling of the heat transfer conditions is a critical factor for the FE quenching simulation of steel alloys (e.g. AISI 4140, AISI 4340). The development of residual stresses and geometric distortion of a heat treated ring will depend on the cooling rate assigned to the quenching solution by means of the heat transfer coefficient (HTC) input in the FE code. Several methods can be used to approximate the real heat transfer conditions in a quenching tank such as Computational Fluid Dynamics (CFD), lumped analysis model, inverse analysis from experimental temperatures. It is important to note that the approximation to heat transfer coefficient will only pertain to a specific setup of quenching conditions (i.e. agitation, ring geometry, stacking conditions, etc). Therefore, most methods of calculation of heat transfer may be impractical for industrial purposes.

Discussion on the heat transfer assumption for this study.
It has been already stated that the heat transfer during quenching of a ring will depend in a number of parameters that are difficult to model and predict (i.e. tank size, concentration of quenchant solution, bath temperature, ring size, propeller location, etc.). For that reason, this study, in an attempt to approximate the non-uniform heat transfer conditions during quenching, assumed the heat transfer coefficient seen in Figure 18. The simplicity and coarseness of this assumption is a clear limitation that should be addressed.

The different proportions of heat transfer coefficients applied to the ring (1XH_q, 2XH_q and 8XH_q) were selected to create a distribution of high stresses that would cause plastic strain in different patterns, resulting in distortion and non-homogeneous residual stresses. The objective of this study is to obtain a methodology for quenching simulations that would provide distortion and residual stress distribution realistic enough. The results may be considered acceptable since the distortion value falls within the distortion range reported by one of the sponsors companies. This data is omitted due to confidentiality. Nonetheless, this assumption should be improved as experience and knowledge in the FE modeling of quenching is gained.

Inverse heat transfer analysis in DEFORM™.

The Center of Precision Forming (CPF) decided to exemplify the inverse analysis technique to approximate the heat transfer coefficients for a specific quenching process. Experimental data was received from one of the sponsor companies, consisting of temperature measurements during a quenching process. These measurements were obtained by thermocouples located in different parts of the ring cross section. The experimental data covers the time range from furnace exit to the end quenching.
The selected ring was arranged at the bottom of a 4-ring stack. The temperatures for this ring were tracked during the quenching process. This stack is dipped into the quenching tank along with other three stacks. Four cross sections were picked from the ring, with a separation of 90° between each cross section as seen in Figure 23. Five thermocouples were located under the surface close to the top, bottom, left edge, right edge and center of the cross section.

![Diagram of thermocouple location](image)

Figure 23. Schematic of thermocouple location in experiment conducted by the sponsor company

For illustration purposes, only the measurements at cross section 1 in the heat treated ring were chosen. The temperature history of the 5 thermocouples located in this cross section
was tracked and is shown in Figure 24. The received raw data included the quenching delay time right before quenching. This initial part was neglected. Once the temperature vs. time data for quenching was analyzed, two clear cooling rate behaviors were identified. Based on this, the inverse heat transfer analysis was divided in Region A and Region B (Figure 24). In region A, the cooling rate is high due to the thermal shock. On the other hand, the region B presents a slight increase in temperature caused by the microstructure change, and a consequent slower cooling rate.

![Figure 24](image.png)

**Figure 24.** Temperature measurements during quenching for cross section 1. Source: sponsor company

In order to facilitate the inverse calculation by DEFORM™, two analyses were conducted according to the different cooling rates, region A and region B. Once each
analysis was carried out, the results were combined to summarize and present the heat transfer coefficient (HTC) as a function of temperature.

**FE set up of inverse analysis simulation**

The inverse analysis conducted with the FE commercial code DEFORM™ presents the following limitation: the material data used for the inverse analysis is only a function of temperature and strain rate, and does not consider thermal and mechanical properties per each phase. Therefore, it neglects the energy dissipated due to phase transformation, which can be observed in the form of temperature changes in the experimental data.

<table>
<thead>
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<th>Parameters</th>
<th>Value</th>
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<td>Initial temperature</td>
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</tr>
<tr>
<td>Quenchant temperature</td>
<td>confidential</td>
</tr>
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</table>

Table 6. Inverse analysis- FE parameters

For this report only the results for section 1 are presented. Some of the important parameters for the FE setup are shown in Table 6. The FE inverse analysis requires the user to input the temperature data obtained from experiments into the mesh in the exact position where the thermocouples were located (Figure 25). The quenching conditions cause the heat transfer to be non-uniform in the ring surfaces. For this reason, the user discretizes the ring surfaces in zones. For each zone the code calculates a heat transfer coefficient as a function of temperature. In this case four zones were defined in the ring:
inner face (zone 1), top face (zone 2), outer face (zone 3), and bottom face (zone 4), as seen in Figure 26.

![Figure 25. FE Input of temperature measurements](image)

Validation and modification of heat transfer coefficient (HTC) from inverse analysis Figure 27 presents the results from the heat transfer inverse analysis for region A and region B (Figure 24). Initial results showed a rough approximation to the heat transfer coefficient (HTC) function. This is caused by numerical errors that occur during the inverse analysis. The initial results were manually modified to smooth the function and present a more realistic behavior of the heat transfer. Figure 27 shows both, the coarse approximation to HTC (black line) and the modified smooth HTC (red dotted line).
Figure 26. Definition of heat transfer zones for the FE inverse analysis

Figure 27. Heat Transfer Coefficient (HTC) approximation by inverse analysis for Zone 1 of Figure 26

A quenching simulation of the previously evaluated ring (section 1) was conducted in DEFORM™ using the calculated heat transfer coefficient in order to validate the results from the inverse analysis. Some of the parameters used in the FE set up are listed in
Table 7. For the heat transfer calculation, the mesh that represents the ring was divided into the same zones as in the inverse analysis. Then, the heat transfer coefficient obtained from the inverse analysis was input as a function of temperature. It is important to note that during this validation simulation the input material data considers phase transformation and therefore the mechanical-metallurgical-thermal effects resulting from this phenomenon are considered.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<td>Material properties.</td>
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<td>Set of properties for each phase formed.</td>
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<td>Elastic properties (Young's Modulus, Poisson's ratio, Thermal expansion)</td>
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<tr>
<td></td>
<td>Thermal properties (Thermal conductivity, heat capacity)</td>
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<td></td>
<td>Phase transformation kinetics</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>After air cooling 80s for transferring to tank</td>
</tr>
<tr>
<td>Quenchant temperature</td>
<td>Confidential</td>
</tr>
<tr>
<td>Quenching heat transfer coefficient (HTC)</td>
<td>From DEFORM™ Inverse analysis</td>
</tr>
<tr>
<td>Object type</td>
<td>Elastic-plastic</td>
</tr>
</tbody>
</table>

Table 7. HTC Validation- FE parameters

The temperature distribution of point 1 in section 1 was extracted from the DEFORM™ simulation and compared with the experimental data (Figure 28). The predicted phase volume fraction was also evaluated. Ferrite and Bainite dominated the phase transformation. Meanwhile, the Martensite formation was not significant.
High Martensite formation is expected from the fast cooling rate in quenching. Since the heat transfer-inverse analysis did not achieve a significant amount of Martensite, CPF considered two alternative heat transfer coefficient functions, HTC-Alternative 1 and HTC-Alternative 2. These alternatives were selected upon two criteria: to achieve significant Martensite formation and to match the experimental temperature distribution from the sponsor company. The alternatives, seen in Figure 29, are based on the inverse analysis results. Heat transfer coefficient was increased in the temperature range where Martensite transformation starts and finishes (2 times increment for Alternative 1 and 3
times increment for Alternative 2). The rest of the FE setup remains the same as in the previous simulation.

![Figure 29. Modification of the Heat transfer Coefficient obtained from FE inverse analysis](image)

The FE results in temperature distribution are improved with both alternatives, HTC-Alternative 1 and HTC-Alternative 2 as seen in Figure 30. HTC-Alternative 2 option presents the best approximation to experimental results. However, this heat transfer coefficient has to be further modified in order to improve the approximation of temperature changes during phase transformation (detailed area in Figure 30), and to improve the temperature prediction from 500 seconds to 1000 seconds where the FE simulation presents a higher cooling rate than the experiment.
Based on the discussions above, using inverse analysis to calculate heat transfer coefficient (HTC) and quenching simulations in DEFORM™ to validate this data, some conclusions could be drawn as follows:

- By using DEFORM™ the experimental temperature distribution was inversely analyzed and heat transfer coefficient functions, according to the ring surface, were approximated.
- To validate the approximated heat transfer coefficient, FE quenching simulations were conducted and the calculated temperature distribution was compared with the experimental data.

Summary of inverse analysis

Figure 30. Temperature comparison of experimental data with FE results from alternative Heat Transfer Coefficients
- The resulting Martensite formation from the FE quenching simulation was not as expected. Therefore, the approximated heat transfer coefficient is modified to provoke Martensite transformation and to improve the temperature estimation. These modifications improved the results from the FE quenching simulation.

- Understanding the kinetics of phase transformation during quenching is critical. It is necessary to confirm the accuracy of the material data used in the FE simulation, specifically the data that dictates the energy dissipation during phase transformation.
Chapter 5: Conclusions and future work

Conclusions

- For this study, the FE commercial code DEFORM™ was used to model several heat treatment processes: normalizing (heating and air cooling), austenitizing, and quenching.
- The material database with phase transformation used for this work was provided by JMatPro (Java-based Material Properties).
- Simulation of heating stages (normalizing heating and austenitizing) was conducted in order to obtain the expanded geometry.
- For the air cooling FE simulation, the mechanisms that trigger heat transfer were modeled: convection with environment, conduction with bottom surface and radiation effect of a surrounding body.
- During non-uniform air cooling, the maximum level of stress is developed at 5 minutes. The ring section (section B-B’) that is closest to a surrounding ring will be the most affected by radiation, showing a slower cooling rate and smaller stress levels. However, the difference in temperature and stress between section B-B’ and the area least affected by radiation (section A-A’) is not significant. The maximum residual stress in non-uniform cooling is around 131 MPa. However this stress vanishes during Austenitizing.
- During non uniform air cooling, there is some resulting but not significant distortion of +2mm in the radial direction.
- The heat transfer during quenching of a ring will depend in a number of parameters that are difficult to model and predict (i.e. tank size, concentration of quenchant solution, bath temperature, ring size, propeller location, etc.).

- Two factors are critical in the prediction of distortion and residual stresses of a ring during FE quenching simulations: 1. accurate material properties, 2. precise modeling of heat transfer between the quenchant and ring.

- Several methods can be used to approximate the real heat transfer conditions in a quenching tank such as Computational Fluid Dynamics (CFD) and inverse analysis from experimental temperatures. However, most heat transfer approximation methods may be impractical for industrial purposes.

- For the FE quenching simulation, a supposed proportion of heat transfer coefficients were applied to the ring (1XH_q, 2XH_q and 8xH_q) distributed in three different sections. This assumption should be improved as experience and knowledge in the FE modeling of quenching is gained.

- After conducting the FE quenching simulation, there is a distortion of approximately 7.2 mm. This value is calculated by comparing the outer diameter of the now distorted ring in the maximum dimension versus the minimum dimension.

- The objective of this study is to obtain a methodology for quenching simulations that would provide distortion and residual stress distribution realistic enough. The results may be considered acceptable since the distortion value falls within the distortion range reported by one of the sponsors companies.
Future work

- The future work focuses on the mechanical methods (e.g. compression or expansion) applied to correct geometrical distortion and relieve residual stresses. These methodologies although already used by ring rolling companies are not well understood, in our opinion, since most knowledge is built upon trial and error.

- It is the study’s objective to establish a structured physics based methodology that will optimize the procedure used for mechanical correction, i.e. minimum time and best achievable tolerances in concentricity.

- The approach intends to find a relation between the distortion to diameter ratio and the compression stroke needed to reach the geometrical tolerances for the ring.

- Future work will also cover the FE simulation of other alternatives such as intermittent quenching (martempering), which alters the quenching conditions by alternating the ring submersion into the bath and extraction several times. This process has already been explored by the sponsor companies but has not been quantitatively analyzed or optimized. There are myriads of examples of intermittent quenching for heat treating specific parts in the literature to control distortion, but none has been tried in large rings of the size the sponsor companies produce.
References


1989.


Appendix A: View Factor for radiation calculations

The general integral to calculate view factor $F_{ij}$ for surface $i$ to surface $j$ is given by the following equation.

$$F_{ij} = \frac{-1}{A_i \pi} \int \int \frac{n_i \cdot r \cdot n_j \cdot r}{(r \cdot r)^2} \, dA_i \, dA_j$$

Where $n_i$, $n_j$ are surface unit normal vectors, $r$ is a vector from a point on surface $i$ to a point on surface $j$. The integration is taken over areas of the surfaces that are viewable from the other surface. The negative sign accounts for the reversal of $r$ when viewing $dA_j$ from $dA_i$. There are two important view factor relations suggested by the equation above. The reciprocity relation $A_i F_{ij} = A_j F_{ji}$, which helps to determine one view factor when the other is known. The enclosure relation, when a surface is enclosed the summation of view factors should equal 1. In the case of cylinders, we present the view factor formulas for a 2-D case as described by [Incropera, 2003].
Figure 31. View factor calculation for cylinders of different radii

\[ F_{ij} = \frac{1}{2\pi} \left[ \pi + \left( C^2 - (R + 1)^2 \right)^{1/2} \right. \\
\left. - \left( C^2 - (R - 1)^2 \right)^{1/2} \right. \\
+ (R - 1) \cos^{-1} \left[ \left( \frac{R}{C} \right) - \left( \frac{1}{C} \right) \right] \\
\left. - \left( R + 1 \right) \cos^{-1} \left[ \left( \frac{R}{C} \right) + \left( \frac{1}{C} \right) \right] \right] \]

\[ R = r_j/r_i, \; S = s_i r_i, \]
\[ C = 1 + R + S \]
Appendix B: Validation of quenching simulation using DEFORM™

Before starting the heat treatment FE simulations for the hot rolled rings. The material data and the FE set up used in DEFORM™ had to be validated with literature and/or experiments.

- Case study from literature

The case used to validate the material data and FE setup was selected from [TOTTEN et al., 1993] and [HARDIN et al., 2005], where an AISI 4140 steel C-ring is heated at 900 °C and quenched in petroleum oil at 65 °C. Figure 32 shows the dimensions of the specimen.

![Figure 32. C-ring test specimen used for quench distortion studies [TOTTEN et al., 1993]](image)

In [HARDIN et al., 2005], a quenching simulation for the Navy C-ring geometry was performed to investigate the resulting distortion (Figure 32). The simulations were carried out in ABAQUS (FE commercial code) with DANTE subroutines (CFD commercial...
Experiments mentioned in [TOTTEN, 1993] are conducted with carburized test pieces, but [HARDIN, 2005] considered a non-carburized SAE 4140 steel specimen for the simulation. Regardless of this fact, experimental results and simulation results were still compared.

Figure 33. Finite element model used to simulate the Navy C-ring [HARDIN et al., 2005]

Figure 33 shows the finite element mesh used in [HARDIN et al., 2005]. The mesh has 750 elements and 1116 nodes, and one-quarter symmetry is assumed for the analysis.

FE modeling of C-Ring quenching simulation

CPF (Center for Precision Forming) has simulated the described case using the FE commercial code DEFORM™ in order to validate the applied methodology to calculate distortions and residual stresses caused by heat treatment. The finite element mesh used in [HARDIN, 2005] was exactly replicated and the same boundary conditions were applied (Figure 33). The material properties described in 0 and 0 were obtained from JMatPro and input into the FE code.

The FE-CFD study by [HARDIN, 2005] was divided in two stages. The first one covers a 1000-second heating process, while the second stage simulates the quenching in oil during 1000 seconds. The CFD study with a DANTE subroutine was conducted to calculate the heat transfer coefficient as function of temperature.
Figure 33. Finite element model used to simulate the Navy C-ring [HARDIN et al., 2005]

Figure 34. Heat transfer coefficient as a function of surface temperature for several heating and cooling conditions [HARDIN et al., 2005]
Figure 34 shows the calculated heat transfer coefficients for several environment situations. For our validation case, the “Furnace” values were used for Heating and “Oil Quenching” data for Quenching. Once the heat transfer coefficients were obtained, the FE study was carried out with ABAQUS, simulating the two heat treatment stages.

FE results for C-Ring simulation and comparison with literature. Figure 35 shows the C-ring displacement in x direction during the heat treatment process (heating and quenching) using ABAQUS [HARDIN, 2005]. Figure 36 shows the CPF results for the same FE simulation using DEFORM™. It was observed that the displacement after quenching is overall higher in the [HARDIN, 2005] study.

Figure 37 shows the displacement in X direction for a selected point in the ring (Point B). The DEFORM™ – JMat Pro data simulation indicates that the X-displacement of node B is 0.20 mm while the ABAQUS simulation results in 0.28 mm displacement [HARDIN, 2005]. Figure 38 shows the X-displacement for another selected point in the ring, Point C, where the DEFORM™ – JMat Pro data simulation predicts a 0.11 mm X displacement and [HARDIN, 2005] presents a 0.09 mm distortion. Based on the validation study of C ring, DEFORM™ is capable to predict distortion during quenching. Furthermore, it was also found that results on distortion are very sensible to the accuracy of material data.
Figure 35. FEA x-displacement (ABAQUS). Displacements (30X)

Figure 36. FEA x-displacement (DEFORM\textsuperscript{TM}). Displacements (30X)
Figure 37. X-displacement comparison between ABAQUS and DEFORM™ simulations at point B

Figure 38. X-displacement comparison between ABAQUS and DEFORM™ simulations at point C
Appendix C. Heat transfer inverse analysis results

The heat transfer coefficients as function of temperature calculated from inverse analysis with DEFORM™ are presented below:

Figure 39. Heat transfer coefficient (HTC) output setup of different zones

Figure 40. Heat transfer coefficient for different ring surfaces