Prediction of Geometric Distortion and Residual Stresses In Hot Rolled and Heat Treated Large Rings Through Finite Element Modeling

da Silva, Alisson Duarte[1]
Guo, Zhanli[2]
Schillé, Jean-Philippe[2]
Altan, Taylan[3]
Cetlin, Paulo Roberto[1]

Abstract

During quenching, hot rolled steel rings, especially those with a large outer diameter to wall thickness ratio, distort and develop undesired residual stresses. These phenomena are the result of three major mechanisms: metallurgical, mechanical and thermal. This paper presents the result of a comprehensive study on the heat treatment of rings by modeling via Finite Element Analysis. The simulation is carried out with coupled analysis of heat transfer, deformation mechanics and phase transformations. The material data required for the simulation of distortion during heat treatments, including TTT/CCT phase transformation diagrams, temperature dependent physical and thermophysical properties, as well as temperature and strain rate dependent mechanical properties are calculated by computer models.

Key words: rings; material properties; quench distortion; computer simulation; JMatPro; DEFORM.

1. Introduction

Heat treatments are performed to assure high quality and reliability of steel components. As long as parts have been heat-treated, distortion has been a concern [1]. Since distortion is unavoidable, the main focus is therefore to account for the distortion during design and manufacturing. If the new shape of a part after heat treatments could be accurately predicted, then compensation measures could be included in the design stage prior to manufacturing [2].

Metallic parts such as rings, especially those with a large outer diameter to wall thickness ratio, distort and become oval, *i.e.*, out of tolerance. In addition, even if the rolled and heat treated rings meet dimensional tolerances and are shipped to

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1. School of Engineering, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, 31270-901, Brazil;
2. Sente Software Ltd., The Surrey Research Park, Guildford GU2 7YG, U.K.;
3. College of Engineering, The Ohio State University, Columbus, Ohio, 43210-1271, U.S.A..

the final customer, residual stresses resulting from heat treatment may become a problem during subsequent machining, causing additional deformation and distortion.

Thus, corrective measures have to be taken, increasing manufacturing costs. 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 technique is a viable tool for conducting this study.

1.1. Heat treatment

In industrial practice, before heat treatment, the rings are either stacked in groups of 4 to 6 rings or arranged individually. To facilitate the analysis in this study we have selected the case where a single ring is heat treated. Initially, normalizing is conducted to achieve uniformity in grain size and composition throughout an alloy. However, this process may be omitted in case the microstructure is uniform enough after the rolling process. After rolling, the ring is air cooled, where no significant distortion is observed, and the residual stresses developed vanish during re-heating before quenching. Prior to quenching, the rings are heated uniformly above austenitizing temperature. Depending on the cooling rate during quenching the microstructure will change to ferrite, pearlite, bainite and/or martensite. The amount of transformation will not be the same throughout the cross section of the ring, affecting the strain and stress fields which depend on the thermal and mechanical properties of each phase. Also, the volume change and transformation plasticity during phase transformation should be taken into account. All these factors act together and cause the undesired phenomena, namely the stresses may exceed the yield point at various locations of the ring. Thus, inhomogeneous plastic flow may occur, causing distortion.

1.2. Prediction of distortion

The prediction of distortion is difficult because it requires reliable material data, including phase transformation kinetics, physical and thermophysical properties, and mechanical properties. The traditional way of obtaining such data is via experimentation, which is not only expensive but time-consuming, because of their dependence on alloy composition, temperature, and/or strain and strain rate. Thus, lack of material data has been a common problem for such simulation, in spite of the availability of many CAE packages. To overcome this problem and provide reliable and cost effective data for process simulation, computer-based material models have been developed so that such properties can be readily calculated [3,4]. These material models have been implemented in computer software JMatPro [4]. To make the calculated material data more easily used by modellers, the data can now be organised in user-defined formats.

One of the available JMatPro formats can be directly read by DEFORMTM [5], a processing simulation package based on the Finite Element Method. DEFORMTM-HT module establishes a coupling between all of the involved phenomena as shown in Figure 1. The part distortion was predicted taking into account the deformation based on the following strain components:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{tp} ,$$

where *e*, *p*, *th*, *tr*, and *tp* represent the contributions from elastic, plastic, thermal, phase transformation and transformation plasticity, respectively.

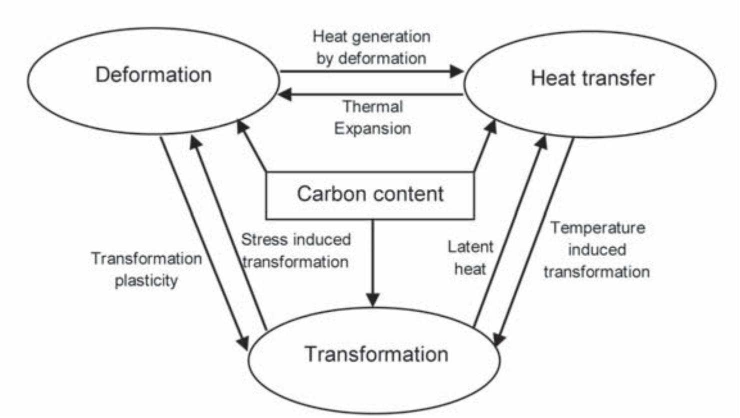

Figure 1 – Coupled phenomena considered during the quenching simulations.

This paper is based on a validated model [2,6] to define a methodology to predict the distortion of hot rolled and heat treated large rings (the so-called ring ovality). The material data is calculated using the JMatPro software, which is used as input to the finite element package DEFORM-HT.

2. Modeling of materials properties

Any simulation involving heat treatment must be able to deal with heat transfer, phase transformation and material deformation in a coupled fashion. Simulation of heat transfer requires the knowledge of thermal conductivity and heat capacity. Deformation simulation requires elastic modulus, Poisson's ratio, thermal expansion coefficient, strength and flow stress curves. Phase transformation simulation requires the knowledge of transformation kinetics, as well as heat evolution and volume change during transformations.

The material properties required for distortion simulation were calculated using JMatPro [3,4,7,8,9]. The material of interest is an AISI 4140 steel with nominal composition (wt.%): Fe-0.40C-0.20Si-0.85Mn-0.95Cr -0.20Mo. The TTT curves of the 4140 steel are given in Figure 2, where the austenite grain size is taken as ASTM 9 and austenisation temperature as 900°C.

JMatPro's ability to calculate physical and thermophysical properties has been well documented in previous work for various metallic systems [4,7,8,10]. The calculation of strength and hardness of an alloy during cooling has been described previously [11]. Figure 3 displays the calculated proof stress for each phase in the material during cooling at 10°C/s. The linear expansion of alloy 4140 during a thermal cycle plays an important role, and is shown in Figure 4 as an example, where both heating and cooling rate are set as 10oC/s.

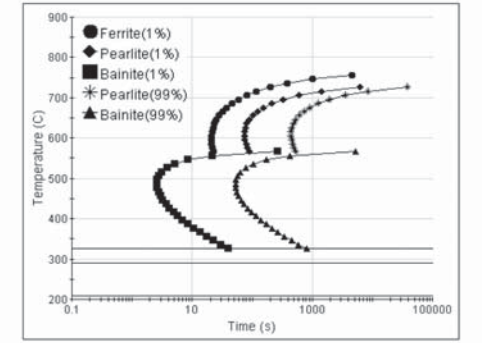

Figure 2 - TTT diagram of 4140 steel calculated by JMatPro.

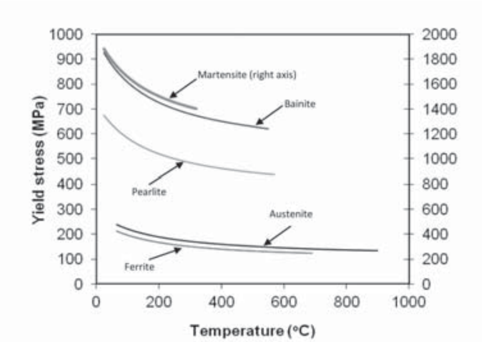

Figure 3 - Proof stress of various phases during cooling at 10°C/s.

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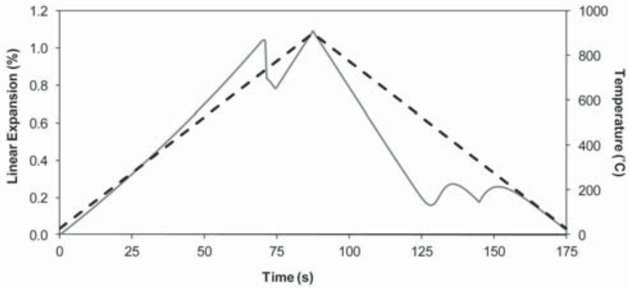


Figure 4 - Linear tendency (dashed line) expansion of alloy 4140 during a heating and cooling cycle, both at 10°C/s.

3. Numerical simulation

A case study was used to approach the objective of defining a methodology to predict ovality. Figure 5 gives the dimensions of the AISI 4140 steel ring used as a case study. Due to the part symmetry, only half of the part was simulated. Brick elements were used (7,000), as shown in Figure 6.

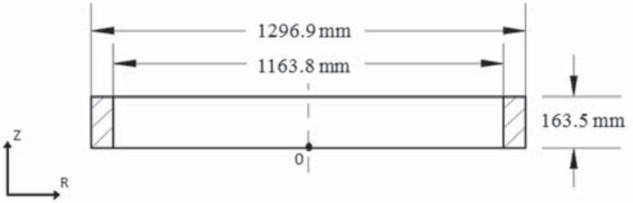


Figure 5 – Thin-walled ring to be used as a case study (cross section).

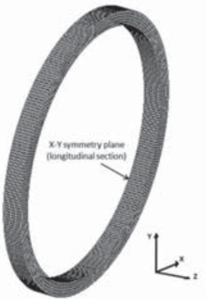


Figure 6 – Meshed ½ ring symmetric geometry used for the simulation.

In order to simulate the quenching, heat conduction of the ring with the quenchant solution should be carefully modeled. The quenchant supplier for one major ring rolling company provided the heat transfer coefficient (*Hq*) as a function of temperature for a solution with no agitation conditions (Figure 7)[12].

However, the heat transfer coefficient on the ring's surface is too complex, being a function of many factors, *e.g.*, quenchant agitation, concentration and temperature, geometry of the ring and the tank, and position of the ring and propellers inside the tank [13]. Therefore, a hypothetical heat transfer coefficient profile around the ring's surface was assumed in order to obtain realistic distortion magnitudes, considering that a propeller is positioned beside the ring, flowing the quenchant against the outside surface of the ring [14]. The case study was divided in four sections as seen in Figure 8. Each section had a different quenching severity, meaning that the heat transfer coefficient (*Hq*) as a function of temperature was different for each segment. For the inside surface of the ring (green line), the heat transfer coefficient was applied as it is (Figure 5). For external, top and bottom surfaces, the heat transfer coefficient was applied as shown in Figure 8: for region DA (green color), the heat transfer coefficient was applied as it is; for regions AB and CD (yellow color), the heat transfer coefficient was increased two times; and for region BC (red color), it was increased eight times. Figure 9 shows a schematic drawing of the ring's cross section indicating the heat transfer coefficient for all surfaces.

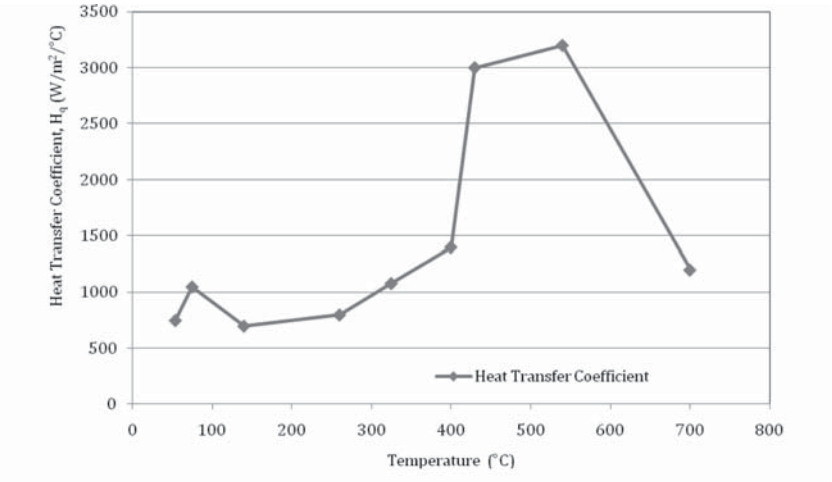


Figure 7 – Heat transfer coefficient for quenching solution from supplier company [12].

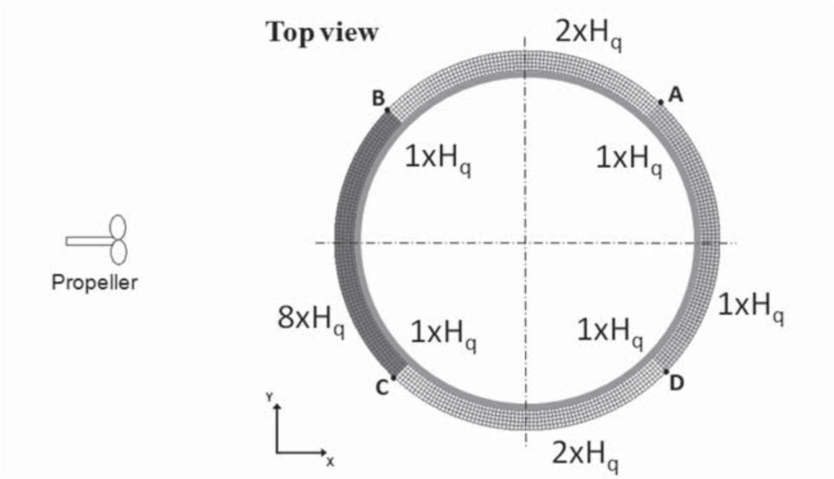


Figure 8 – Heat transfer coefficient distribution on the ring surface. Inside surface is represented by a green line; and regions DA (green), AB and CD (yellow), and BC (red) represent the surface regions referred to top, bottom and outside surfaces.

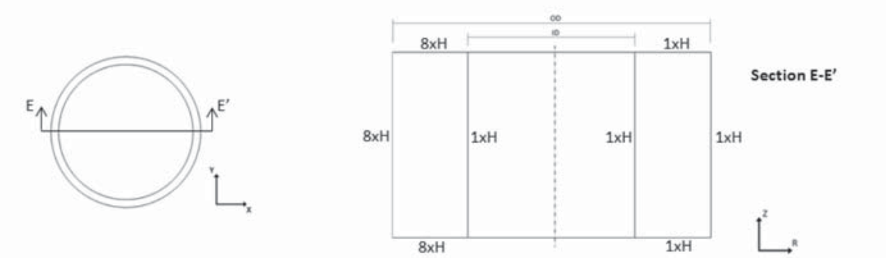
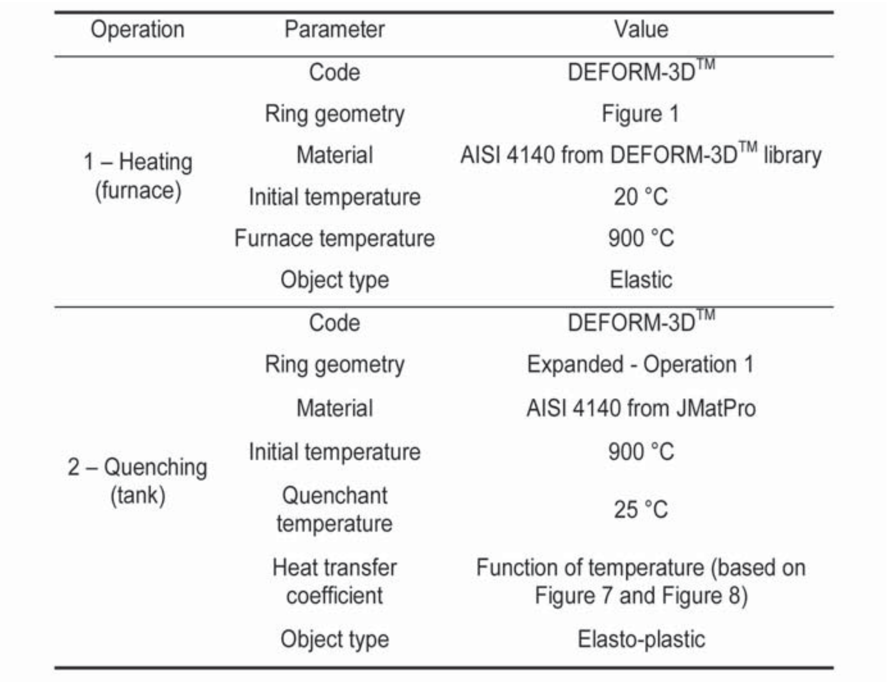


Figure 9 – Schematic drawing of the ring's cross section showing the heat transfer coefficient distribution on the surface.

The simplicity and coarseness of the heat transfer assumption during quenching simulation (Figure 8) is a clear limitation that should be addressed. Two factors are critical in the accurate prediction of distortion and residual stresses of a ring during FE quenching simulations: 1. accurate material properties, 2. heat transfer coefficient (in function of time and location) between the quenchant and ring. Some other FE parameters are listed in Table 1.



Operation	Parameter	Value
1 – Heating (furnace)	Code	DEFORM-3D^{TM}
	Ring geometry	Figure 1
	Material	AISI 4140 from DEFORM-3D^{TM} library
	Initial temperature	20 °C
	Furnace temperature	900 °C
	Object type	Elastic
2 – Quenching (tank)	Code	DEFORM-3D^{TM}
	Ring geometry	Expanded - Operation 1
	Material	AISI 4140 from JMatPro
	Initial temperature	900 °C
	Quenchant temperature	25 °C
	Heat transfer coefficient	Function of temperature (based on Figure 7 and Figure 8)
	Object type	Elasto-plastic

Table 1 – FE setup for the simulation of quenching process.

4. Results and discussion

As a sequence of the hot rolling and normalizing processes, the rings are hardened through quenching. Since there is no ovality due to the normalizing process, the quenching process was simulated considering a ring with no initial residual stresses. The ring was heated to 900 °C, expanding its geometry and increasing 14 mm in the ring OD (outside diameter).

For the simulation of the quenching process, the heated ring is considered completely austenitized at 900 °C. For the fast cooling stage, the heat transfer coefficient was applied to the ring surface as a function of temperature and position on the surface, following the hypothetical configuration defined in Figure 8. The ring was measured at the end of the quenching simulation. The maximum and minimum dimensions were 1304.2 mm and 1291.4 mm, respectively. As a result, the obtained ovality was 12.8 mm. Figure 10 shows the simulated oval ring after the quenching process. The blue geometry (dark) has its displacement magnified 10x, and is superimposed on the “reference geometry” with no magnification.

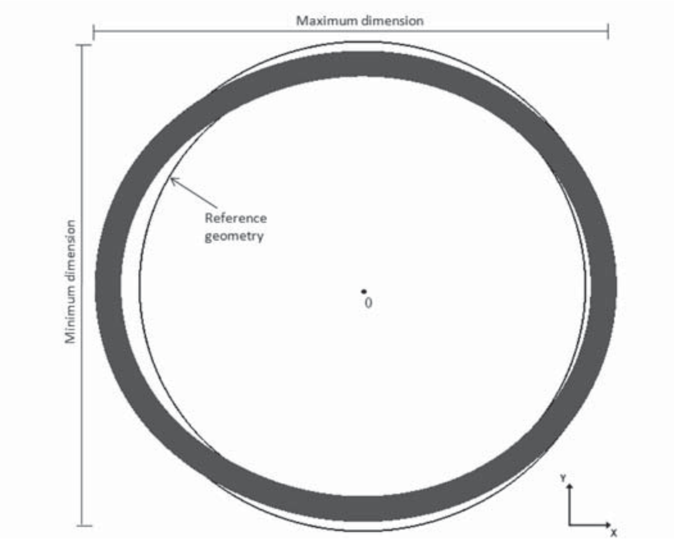


Figure 10 – Quenched distorted ring for hypothetical case (displacement magnified 10x).

The reason for the obtained distortion is the residual stress distribution in the ring. As shown in Figure 11, the residual stress is non-homogeneous along the ring circumference. However, it is necessary to conduct a more specific analysis of the residual stress in the ring in order to understand more clearly the ovality formation.

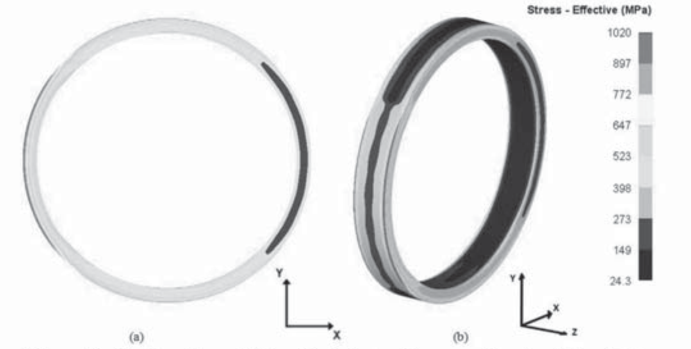


Figure 11 – Residual stress in the distorted ring after quenching simulation: (a) top and (b) 3D views.

The hypothetical case considers a heat transfer distribution along the ring surface as shown in Figure 8 and Figure 9. A schematic drawing of the ring cross section is shown in Figure 12, indicating a center-line for measuring the results. The volume fraction of martensite and bainite along the center-line is shown in Figure 13. The right side of the ring has the same heat transfer coefficient for all the four surfaces (1xHq), and 100% of bainite along the center-line. On the other hand, the left side has the heat transfer coefficient eight times higher for the outside, top and bottom surfaces. As a consequence, there is a formation of martensite in the region closer to the outside surface.

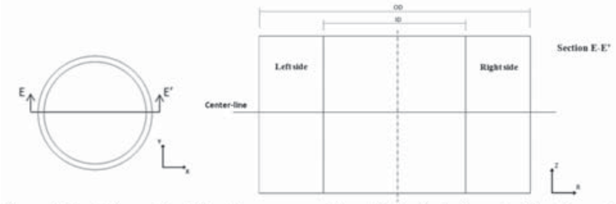


Figure 12 – Schematic of the ring cross section: the indicated center-line is used to analyze the simulation.

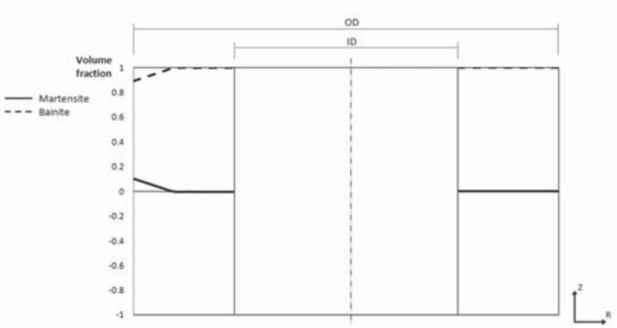


Figure 13 – Volume fraction of bainite and martensite on the center-line of the ring cross section.

Analyzing Figure 14, it is possible to verify that the circumferential stress profile on the right side of the ring is nearly-symmetric. This characteristic is related to the homogeneity of the heat exchange around the ring at that region, where the heat transfer coefficient is the same for all the four surfaces. On the other hand, the left side displays a non-symmetric circumferential stress profile due to the martensite formation closer to the outside surface, which expands this portion of material, creating compressive stresses on the outside surface and tensile stresses on the inside surface. The result is the ovality distortion already shown in Figure 10.

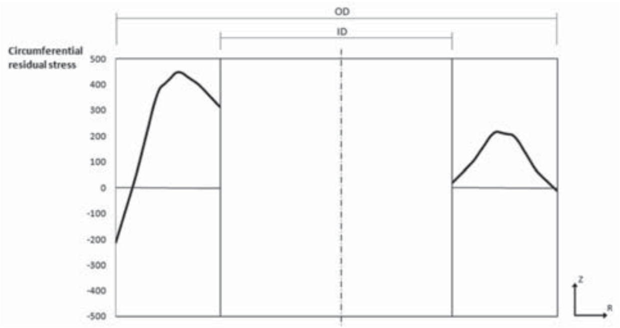


Figure 14 – Circumferential stress on the center-line of the ring cross section.

5. Conclusions and future work

5.1. Conclusions

The methodology developed in previous work [2,6], considering the material data provided by JMatPro [4] and the numerical simulation through DEFORMTM [5], was applied to the prediction of the ovality (distortion) of hot rolled and heat treated large rings. A hypothetical and simplified model was assumed and a realistic ovality value was obtained.

The distortion origin was discussed based on the circumferential residual stresses in the ring after the simulation of the quenching process, caused by the heat transfer coefficient variation on the ring's surface.

5.2. Future work

The industry of hot rolled rings conducts a straightening process after heat treatment in order to correct the ring ovality. A wide range of ovality values is a possibility, and the assumed model based on the variation of the heat transfer coefficient on the ring's surface will be varied and correlated for different ovality values.

Based on the ovality predicted in this study, the straightening process will be defined. This process is nowadays empirically performed in the industry.

The methodology to predict and correct ring ovality will also be applied(?) for rings with different geometries and alloys other than steel, *e.g.*, nickel, titanium and aluminum alloy rings used in aerospace industry.

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