Distortion in Rolled and Heat-Treated Rings

Forged rings with high outer-diameter to wall-thickness ratios are most prone to stresses from manufacturing and heat-treating processes. *Photo courtesy of Scot Forge.*

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The rolling and thermal treatment of forged rings sometimes leaves residual stresses that cause dimensional distortion. Corrective measures in industry are often based on trial-and-error techniques. Ongoing research seeks to base corrective actions on the laws of physics.

After being rolled at forging temperature, most rings are heat treated (i.e. normalized, quenched and tempered, see Figure 1). Because of this processing, some rings, especially those with a large outer-diameter to wall-thickness ratio, distort and become ovular (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 customer, residual stresses resulting from heat treatment may become a problem during subsequent machining, causing additional deformation and distortion.

A study on control of distortion and residual stresses in rolled and heat-treated rings is being conducted by the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) in partnership with the Forging Industry Association (FIA/FIERF), Education and Consulting LCC and four forging companies supplying the energy and aerospace industries. 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 and cause the undesired results.

In light of the complexity of the problem, most ring-rolling companies approach it with corrective rather than preventive measures. Some manufacture the ring with large tolerances so it can be machined to final dimensions. Others correct the ring distortion by a mechanical method (compression or expansion), which also partially relieves the residual stresses. However, mechanical methods are fairly empirical, and there is a need for a physics-based understanding and methodology to produce rings with minimal distortion at an acceptable cost and lead time.

The Process

Ring rolling is conducted at a temperature around 2200°F (1204°C). This leads us to an important assumption: the high temperatures at which the ring is being formed will not create any major residual stresses unless the rolling process itself is not well controlled and leads to nonconcentric rings. Consequently, the scope for this project does not include the Finite Element Analysis (FEA) of the ring-rolling process and focuses only on the heat-treatment steps.

Before heat treatment, the rings are either arranged individually or stacked in groups of four to six units. Then they are normalized at approximately 1700°F (925°C) for two hours, then air cooled. Industry experience indicates that, although ring stacking will cause nonuniform cooling, the observed distortion is not significant due to the slow cooling rate. Furthermore, the residual stresses developed will vanish in the next heating stage.

Prior to quenching, austenitizing is typically carried out at 1515°F (850°C) with the same stack used during normalizing. After exiting the furnace, the rings are submerged into a quench tank. The cooling rate at which the rings reach the bath temperature

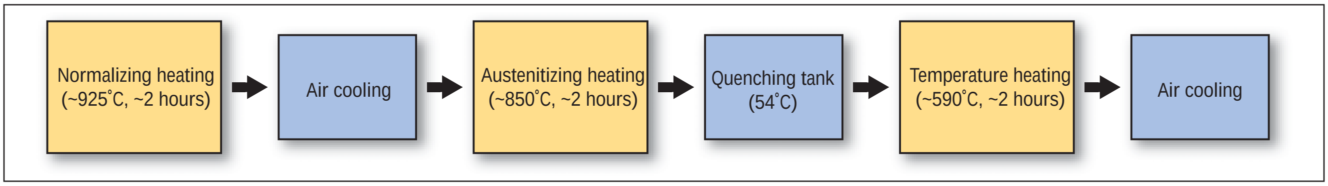

Figure 1. Commonly used procedures in heat treatment of hot-rolled rings.

An operator in a control room oversees the ring-rolling line. Photo courtesy FRISA Industries.

should be fast enough to generate martensitic microstructure that will harden the ring material.

Microstructural Issue

A microstructural change takes place during quenching. Ideally, the ring has a homogeneous austenitic microstructure at the beginning of this step. Depending on the cooling rate, the microstructure will change to pearlite, bainite or martensite (Figure 2). The amount of transformation will not be the same along the cross section of a ring.

How will this affect the distortion and residual stresses development?

The strain and stress fields vary with time depending on the thermal and mechanical properties of each phase, which are, in turn, functions of temperature and cooling rate. Also, the volume change at each phase and transformation plasticity during phase transformation should be taken into account. All these factors act together and cause the undesired phenomena, namely that the stresses may exceed the yield point at various locations in the ring. Thus, non-homogeneous plastic flow occurs, causing distortion.

Heat Treatment Finite Element Analysis

The commercial modeling program used for this project is DEFORM from Scientific Forming Technologies of Columbus, Ohio. This software allows us to conduct a thermomechanical and metallurgical analysis to predict microstructural changes and geometrical variations. The phase-transformation model of the material is determined by the cooling rate and phase-transformation kinetics. Since each phase carries particular thermal and mechanical properties, these factors are integrated into the model and calculated accordingly. The thermal component considers the heat transfer between the ring and the environment, whether it is air or a quenchant. Finally, the calculation of stresses and strains through each phase constitutes the mechanical model.

For this project we selected an AISI 4140 ring that is geometrically similar to rings produced and heat treated by the sponsoring companies. The dimensions are given in Table 1. To simplify our calculations, we assumed that a single ring is heat treated. In actual industrial settings, only large rings are thermally treated individually, while smaller rings are heat treated in stacks.

Table 1. Ring Dimensions

	Dimensions in mm
Outer Diameter (OD)	1,296
Inner Diameter (ID)	1,164
Height (H)	163

Heating Stages for Normalizing and Austenitizing

The heating operations for normalizing and austenitizing were simulated for two reasons. First, volumetric expansion of the ring prior to cooling was captured. Second, to corroborate that the heating time is sufficient to achieve homogeneity at the desired temperature. We assumed that at the end of every heating stage and before quenching austenite was formed with volume fraction 1.0 in the ring.

Air Cooling

Convection, conduction and radiation are the heat-transfer

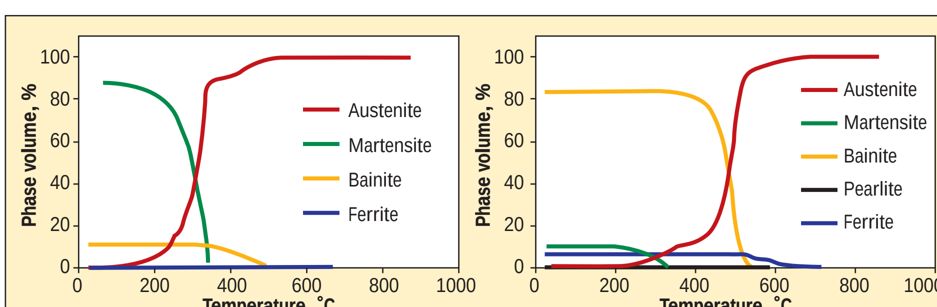

Figure 2. Microstructure evolution in 4140 steel during cooling at: a) 20°C/s and b) 5°C/s.

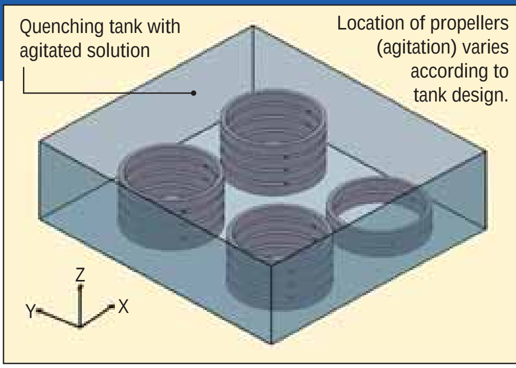

Figure 3. Typical arrangement of ring stacks in the quenching tank.

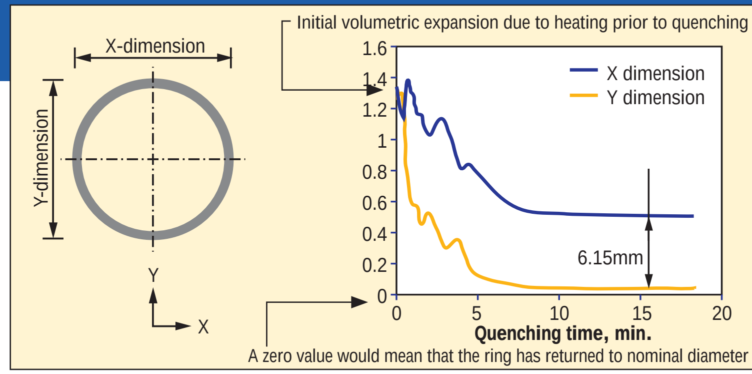

Figure 4. Example of distortion evolution during quenching (diameter comparison between X and Y direction).

mechanisms that act during air cooling. The finite element (FE) simulation conducted considers that after heating for normalizing, two rings are individually placed one next to another on a resting surface. The heat-transfer coefficient with the environment was selected assuming still air, while the conduction coefficient was chosen upon free resting conditions on the surface. The radiation phenomenon was modeled by the Boltzman equation, considering also the proximity effect of an adjacent cooling ring that emits heat.

Quenching

The heated rings are submerged in a quenching tank with agitated solution (Figure 3). In order to simulate the quenching, heat conduction of the ring with the quenchant should be carefully modeled. A computational fluid dynamics (CFD) tool depicts the heat-transfer conditions for a particular quenching system. This approach, developed for academic purposes, has some limited commercial application. On the other hand, from an industrial point of view, the number of possible quenching settings and ring geometries make the CFD analysis impractical and expensive. Therefore, we adapted a finite element tool to achieve a close-to-reality and practical quenching simulation.

The most critical parameter during quenching is the heat-transfer coefficient, which depends on temperature, agitation and stacking conditions. Some companies participating in this project conducted temperature measurements on the ring during quenching. This data was later analyzed to calculate the heat-transfer coefficient. It is noteworthy that this calculation depicts the specific quenching conditions (location in the tank and in the stack, propeller proximity and orientation) for this ring and cannot be standardized for any given ring that is quenched in this tank. Figures 4 and 5 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 first is the precision with which the quenching tank conditions are emulated (in other words, how reliable the heat-transfer calculations are). The second is the accuracy of the mechanical (elastic and plastic), thermal and metallurgical properties of the material to be simulated.

Summary

As progress is made, the ERC/NSM is building its knowledge in heat-treatment simulations and recognizing the importance and intricacies of an integrated metallurgical, mechanical and thermal analysis. We can summarize our progress as follows:

- Different steps of heat treatment (up to quenching) have been simulated in a commercial FE code in order to predict ring distortion and distribution of residual stresses.
- According to FEA results, air cooling will not create any significant distortion (ovality).
- Heat-transfer variation during quenching as a function of temperature, tank and stack location, and quenchant agitation is the key factor in calculating distortion, hence the importance of correctly modeling the heat-transfer coefficient.
- Through FEA, distortion and residual-stress distribution have been predicted assuming certain quenching conditions.

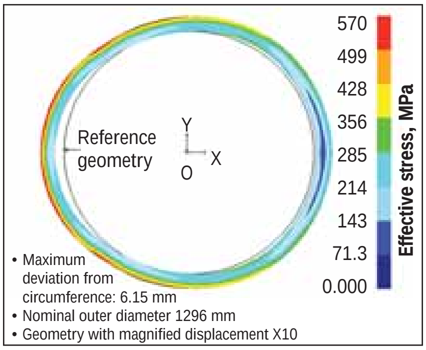

Figure 5. Resulting geometrical distortion and residual stresses after FE simulation of heat treatment (original ring dimensions are given in Table 1).

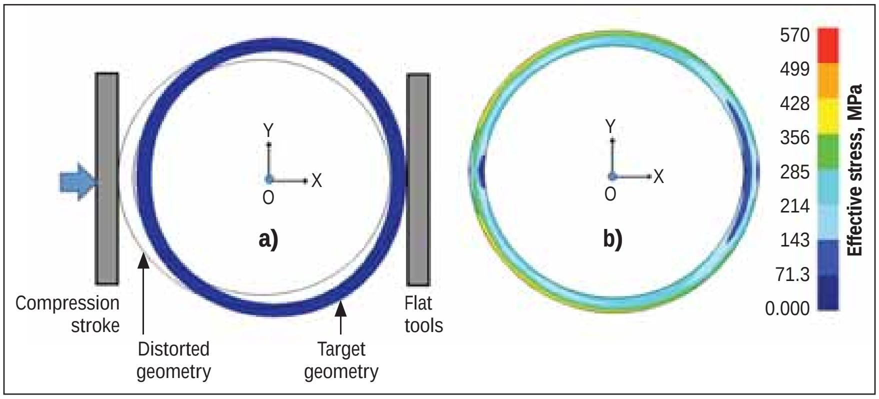

Figure 6. Preliminary results for FEA of mechanical correction method (compression): a.) FE setup; and b.) residual stress distribution after corrective method.

Our ongoing work focuses on the mechanical methods (e.g., compression or expansion) used by ring-rolling companies to correct geometrical distortion and relieve residual stresses. Our goal is to establish a physics-based methodology that will optimize the procedure used for mechanical correction, i.e. minimum time and best achievable tolerances in concentricity. To this end, we considered the distorted ring geometries obtained from quenching simulations to investigate the compression method by corrective tools already in use. These, in our opinion, are not well understood, since most of this experience is built on trial and error. Our intent is to find a relationship between the distortion-to-diameter ratio and the compression stroke needed to achieve the geometrical tolerances for the ring. Preliminary results (Figure 6) show that a number of compression steps at different locations of the ring will correct ovality and residual stresses are relieved through this plastic strain. Further work needs to be conducted to optimize the process.

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