# Effect of Quenching Variables on the Residual Stress and Distortion of a Heat Treated Disk

**D. Scott MacKenzie, PhD**
Houghton International, Inc., Valley Forge PA

**B. L. Ferguson**
Deformation Control Technology, Inc., Cleveland, OH
**Z. Li**
Deformation Control Technology, Inc., Cleveland, OH

## Abstract

Heat-treaters have long relied on experience to assess the impact of part shape on distortion and residual stress due to quench hardening. Using DANTE®, the residual stress and distortion response of a heat-treated disk was examined. The effects of section thickness and immersion rate were examined.

## Introduction

Heat-treating is a complex process. Modern practice is to minimize the amount of stock for correct for distortion. An understanding of the mechanism of quenching is important to control distortion and residual stresses. It also gives a clue how to properly rack parts so that properties can be met, and achieve minimal distortion.

When a hot component comes in contact with the liquid quenchant, there are normally 3 stages of quenching.[1] The 3 stages of quenching are:[2]

- **Vapor Stage** (Stage A or Vapor Blanket Stage)
- **Boiling Stage** (Stage B or Nucleate Boiling Stage)
- **Convection Stage** (Stage C)

The vapor stage is encountered when the hot surface of the heated component first comes in contact with the liquid quenchant. The component becomes surrounded with a blanket of vapor[2].

In this stage, heat transfer is very slow, and occurs primarily by radiation through the vapor blanket. Some conduction also occurs through the vapor phase. This blanket is very stable and its removal can only be enhanced by agitation or speed improving additives. This stage is responsible for many of the surface soft spots encountered in quenching. High-pressure sprays and strong agitation eliminate this stage. If they are allowed to persist undesirable micro-constituents can form.

The second stage encountered in quenching is the boiling stage[2]. This is where the vapor stage starts to collapse and all liquid in contact with the component surface erupts into boiling bubbles. This is the fastest stage of quenching. The high heat extraction rates are due to carrying away heat from the hot surface and transferring it further into the liquid quenchant, which allows cooled liquid to replace it at the surface. In many quenchants, additives have been added to enhance the maximum cooling rates obtained by a given fluid. The boiling stage stops when the temperature of the component's surface reaches a temperature below the boiling point of the liquid. For many distortion prone components, high boiling temperature oils or liquid salts are used if the media is fast enough to harden the steel, but both of these quenchants see relatively little use in induction hardening.

The final stage of quenching is the convection stage[2]. This occurs when the component has reached a point below that of the quenchant's boiling temperature. Heat is removed by convection and is controlled by the quenchant's specific heat and thermal conductivity, and the temperature differential between the component's temperature and that of the quenchant. The convection stage is usually the slowest of the 3 stages. Typically, it is this stage where most distortion occurs. An example showing the three stages of quenching is shown in Figure 1.

Obtaining properties and low distortion is usually a balancing act. Often, optimal properties are obtained at the expense of high residual stresses or high distortion. Low distortion or residual stresses are usually obtained at a sacrifice in properties. Therefore, the optimum quench rate is one where properties are just met. This usually provides the minimum distortion[3].

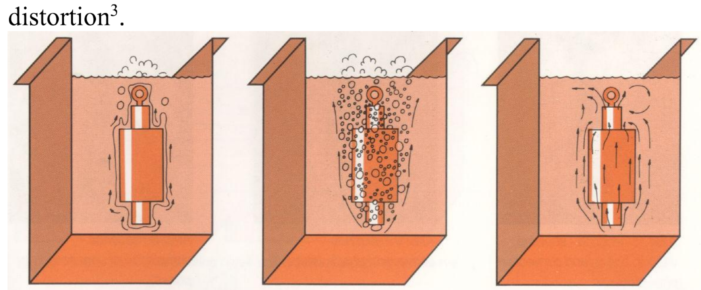

**Figure 1 - Schematic of the 3 primary stages of quenching (from left to right): (a) vapor phase; (b) nucleate boiling; and (c) convection[2].**

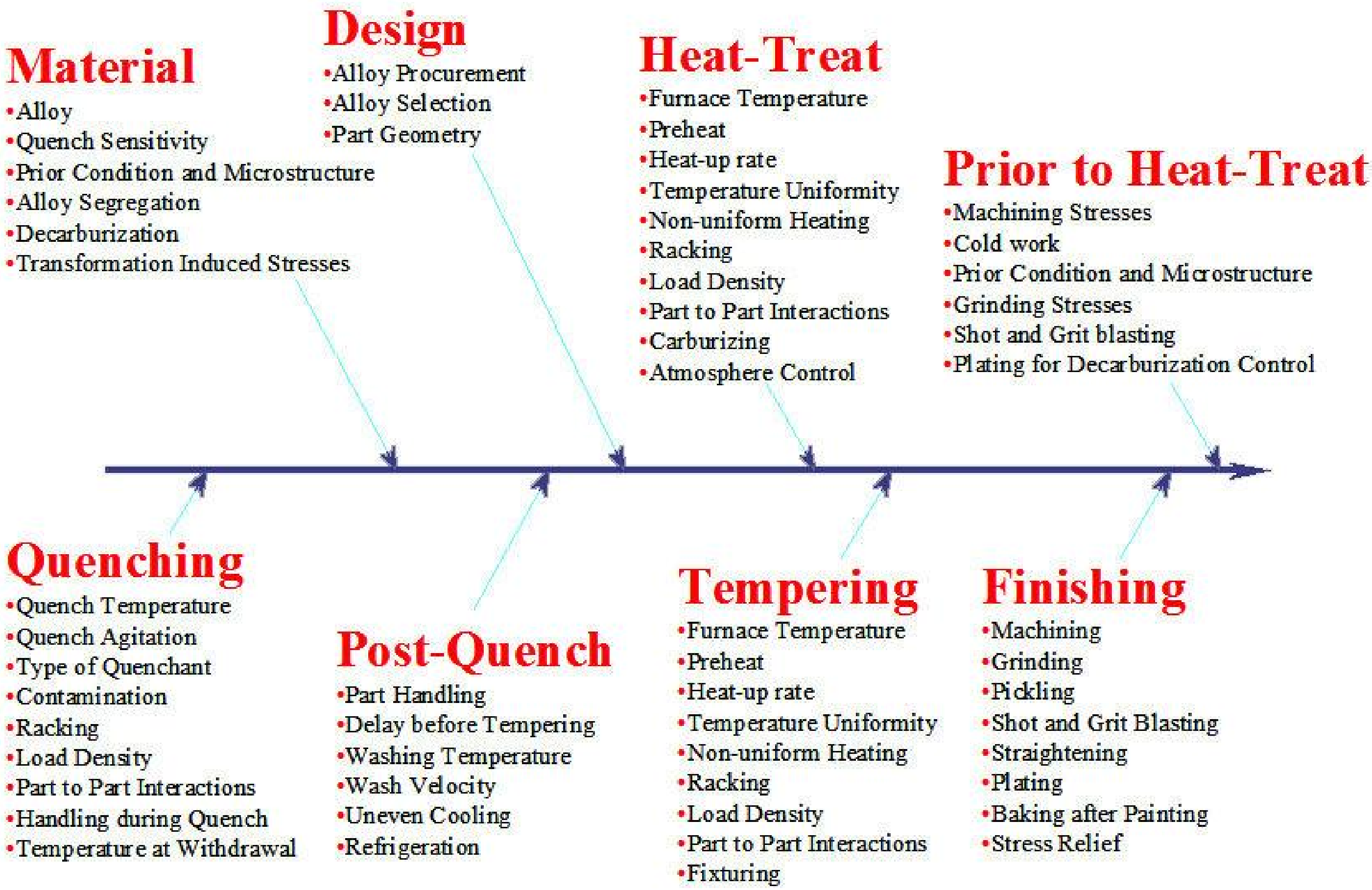


**Figure 2 - Distortion fishbone diagram showing the many sources of distortion and residual stresses in heat-treated parts.**

### Control of Distortion and Residual Stresses

By far the largest source of problems for heat treaters is distortion of parts after heat treatment[4]. Distortion causes excessive noise in the gear drive train, and potentially early failure due to high residual stresses[5]. It also contributes to high grinding costs[6].

However, the source of distortion and residual stresses are not limited to either the Martensite Start Temperature, the oil used, or the alloy content. There are a number of sources of residual stresses, and not all of them are heat-treating related. A schematic of some causes of distortion and residual stresses are illustrated in Figure 2. It can be seen that many of the sources of residual stress and distortion occur before heat treatment and quenching, yet it is often the heat treater that gets the blame for a distorted part.

Distortion is measured in many ways. First there are linear measurements, where rulers; calipers; a straight edge and a flat plate, with feeler gages; or by profilometer traces, measure the displacement in one axis. For 2D measurements, you have a mixture of the linear methods, and include circularity, angularity and parallelism. For 3D measurements, a mixture of linear and 2D measurements is required. Often times coordinate measuring machines and complex software is used.

Simulations, like Finite Element Analysis (FEA) provide displacement data (x,y,z) data for specific locations at node points. This data can be examined in terms of contour plots and line maps. Detailed analysis is required to accurately compare the simulation and actual results.

The characterization of distortion of circular objects like a disk is achieved by either flatness or ovality measurements. Flatness is the displacement of actual surface points from an ideal plane. From the finite element model, the initial and final location (x, y, z) is known. This indicates the location of the un-heat treated and heat-treated surface locations. The geometry equations of the part prior to heat-treatment and after heat treatment are determined, and the deviations from the mathematical plane position are computed (flatness). Normals to the un-heat treated plane and the heat-treated plane can also be computed to determine perpendicularity. The measurement of flatness is illustrated in Figure 3.

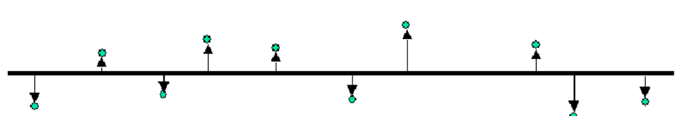

**Figure 3 - Schematic showing linear displacements from a plane.**

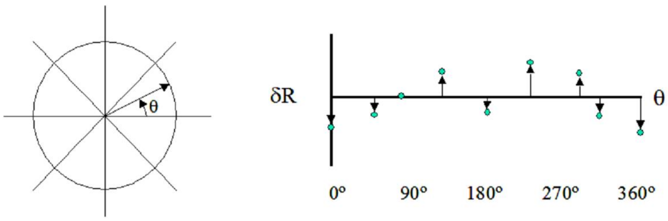


**Figure 4 - Schematic showing the radial or angular displacement of a disk.**

The distortion measurement of ovality, or the non-uniform change in radius or diameter, is achieved by calculating the radial change at each point. The change in size (growth or shrinkage) and the ovality are calculated from the displacements of the node positions (x, y, z). This is illustrated in Figure 4.

**Problem Statement and Overview**

Many parts, such as gears, clutch plates, etc., have a disk-hub type of geometry, and distortion is a serious issue. These issues include flatness and ovality. A typical configuration of racked disk-shaped parts is shown in Figure 5. It is the purpose of this paper to assess the effect of immersion rate and the disk-hub geometry on distortion and final residual stress state. This examination was to accomplished using DANTE™, a finite element based software tool.

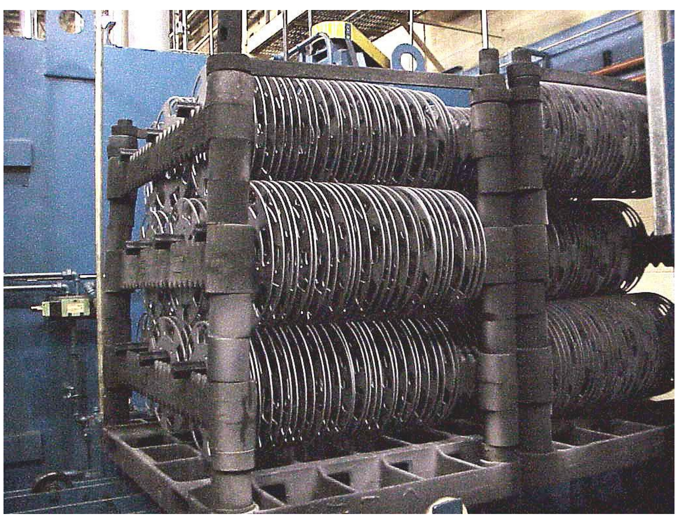

**Figure 5 - Typical load of disk-shaped parts, racked vertically to minimize distortion.**

Determining the distortion of a part during heat-treating, or predicting the microstructure of a part, has been a long-held goal of the heat-treating industry. However, this goal has been elusive. The use of Finite-element-analysis (FEA) has been used extensively to solve structural and performance issues of components for a long time. It has only recently been used in predicting part distortion or part microstructure.

To accurately predict distortion or the formation of residual stresses in a part requires and understanding of many factors. These factors include heat transfer, elastic-plastic stress and strain behavior and microstructure.

Heat transfer is not a steady-state condition. It requires the determination of heat-transfer coefficients as function of fluid properties, geometry, surface condition, and agitation. It is also time and location dependant

Elastic-plastic stress strain behavior requires detailed constitutive models of stress and strain as a function of strain rate, location and temperature.

Knowledge of the diffusion transformations (Pearlite and Bainite) occurring in the component, as well as the non-diffusion transformations (Austenite to Martensite transformation, recrystallization, grain growth, etc.) is necessary to accurately predict the microstructure development, and its contribution to distortion and residual stresses.

All of these factors (heat transfer, microstructure and elastic-plastic strains) are necessary to effectively model the residual stresses and distortion occurring in a component. The interrelationship of these factors is shown in Figure 6.

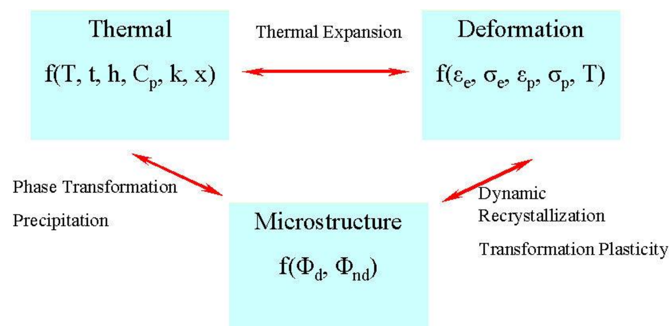


**Figure 6 - Inter-relationship of heat transfer, geometry and microstructure.**

Advantages of FEA modeling of part distortion are many. These include:

- Enabling the distortion and residual stresses in a heat-treated part to be quantified.
- Examining the effect of part geometry and racking on the development of distortion and residual stresses. Alternative part geometries and racking techniques can be examined prior to part creation or heat treatment.
- Examining causes of failure due to quench cracking or high residual stresses.

Disadvantages of this technique include:

- The technique is computationally intensive
- Detailed heat transfer, elastic-plastic and microstructure constitutive models must be known. This may require extensive laboratory and field-testing for the initial model and verification.
- Difficult to measure and verify residual stresses.
- Prior process influence results. These previous processes complicate the model creation, and cause additive errors.

In any finite element analysis (FEA), the necessary data includes the material, the geometry and boundary conditions. The information needed for material includes the many relationships describing the phase transformations and the volume changes associated with the phase transformations. These constitutive equations are material dependant and often are held proprietary with the software or are independently determined. CAD programs define the geometry. Boundary conditions are dependant on the quenchant, and change as a function of time and surface temperature.

**Material and Heat Treat Cycle**. The material used is AISI 4140, austenitized at 850ºC, and transferred to the quenchant. The immersion rate was varied from 10 mm/s to 400 mm/s. The quenchant used was Houghton Houghto-Quench G, which is a high quality, medium speed (9-11 GMQS) with a viscosity of 110 SUS. The basic heat transfer coefficients are shown in Figure 7. The standard cooling curve data for AISI 4140 steel was used.

This heat-treating cycle is common for this material, and will generally generate fully martensitic structures in thin (25 mm) sections.

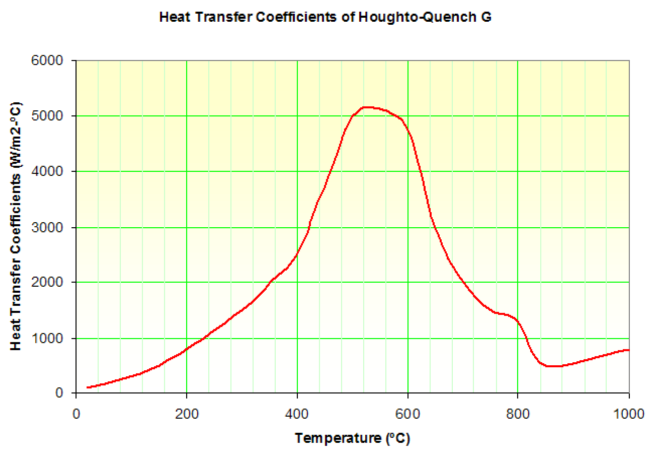


**Figure 7 - Heat transfer coefficients of Houghto-Quench G used in this simulation.**

**Geometry**. The geometry of the disk and hubs was asymmetrical, with a fixed bore of 30mm. The outside diameter was fixed at 100 mm, and the thickness of the disk was varied between 10 and 40 mm. The hub had a constant thickness of 14 mm (Figure 8).

Because of the symmetry of the part examined, only half the part was meshed, and the boundary conditions applied uniformly as a function of the surface temperature. The meshed part is shown in Figure 9.

The material constitutive equations were applied to the meshed disk. Once accomplished, the heat transfer boundary conditions were applied to the part, and the immersion rate was varied. Because of the direction of immersion, the part would be partially immersed, and have the region not immersed at the austenitization temperature (850ºC). Heat transfer in general proceeded from bottom to top.

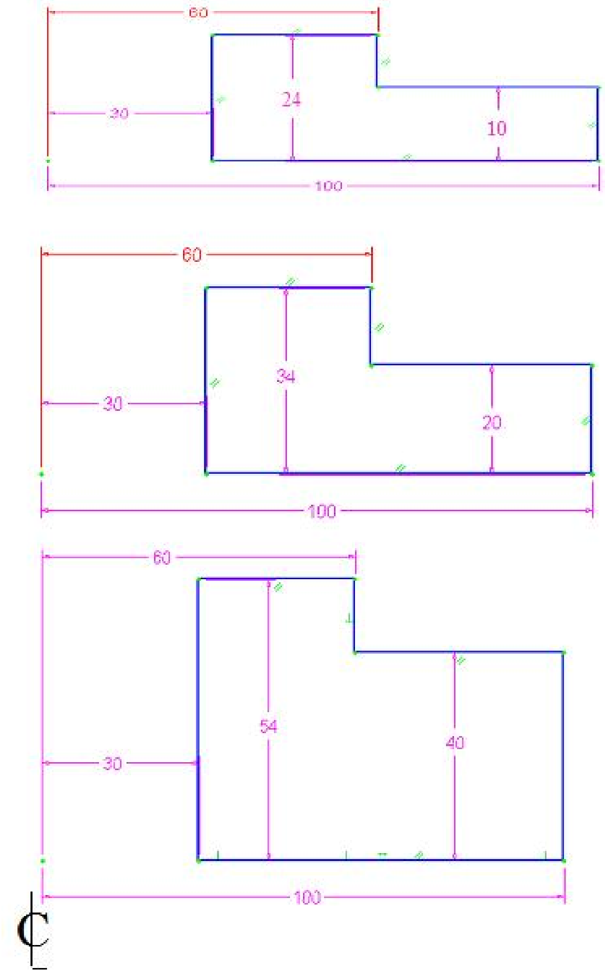


**Figure 8 - Basic geometry of the disk and hub that was used in this investigation.**

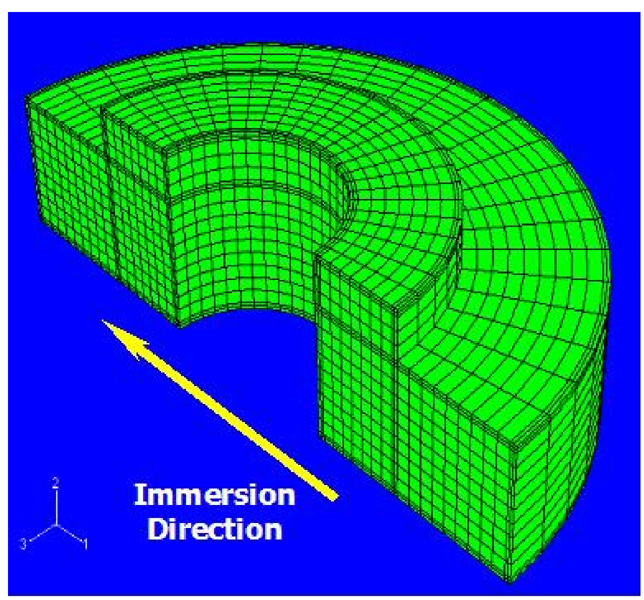


**Figure 9 - Meshed part used in this investigation. Because the 3D model was symmetrical, half boundary conditions were applied.**

## Results

The initial results of the FEA examination of the disks showed substantial differences as the immersion rate and thickness increased. Figure 10 and Figure 11 show the distortion evident in the bottom displacement and the axial displacement. As the thickness increased, the amount of lower bainite increased (Figure 12). However the percentage remained the same, indicating that the thickness was responsible, not the changes in immersion rate.

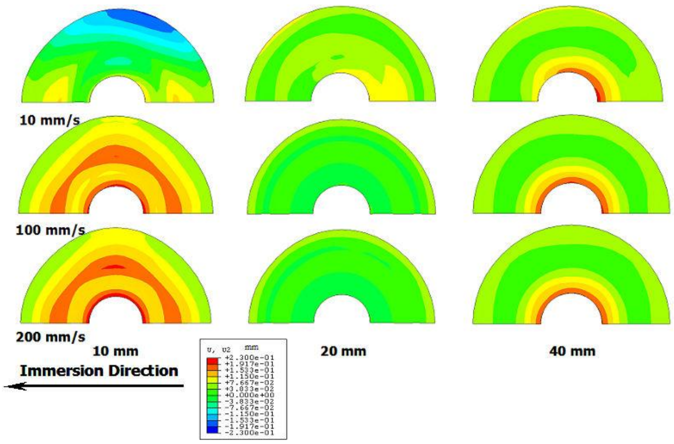


**Figure 10 - Bottom displacement of the disks.**

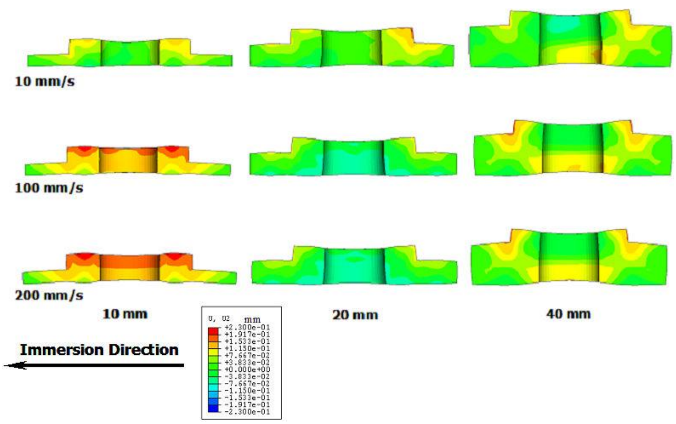


**Figure 11 - Center plane axial displacement**

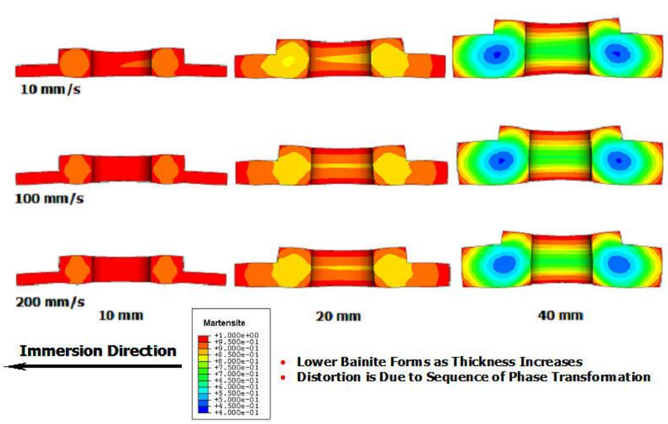


**Figure 12 - Martensite fraction.**

An anomalous behavior was detected in the 10mm thick disks quenched at an immersion rate of 10 mm/sec. It was noticed that the first immersed section had a greater fraction of lower bainite. The nodes of interest are shown schematically in Figure 13. The resultant Bainite percentages are shown in Figure 14.

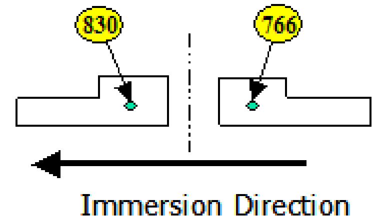


**Figure 13 - Specific nodes in the disks.**

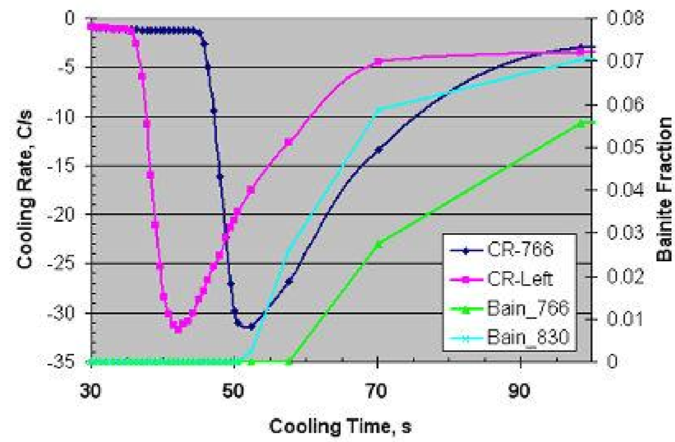


**Figure 14 - Comparison of bainite percentages at nodes 830 and 766 as a function of cooling time.**

This behavior suggested that the cooling rate at the upper node was faster than the lower node (830) at the lower node. Examination of the cooling curve behavior of the two nodes showed that the cooling rate of the lower node was slower through the critical range of 400-300ºC, thus allowing lower bainite to form.

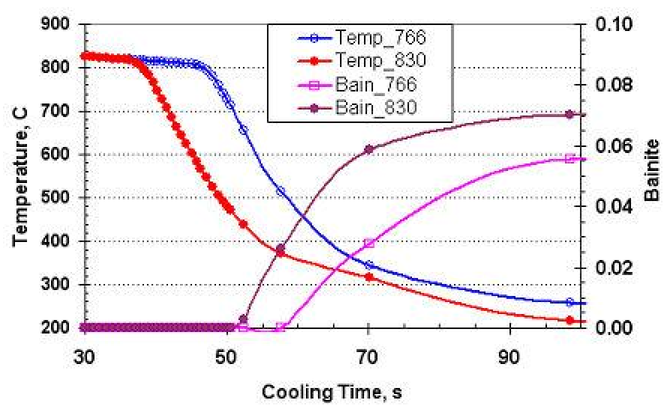


**Figure 15 - Comparison of cooling rates at nodes 766 and 830.**

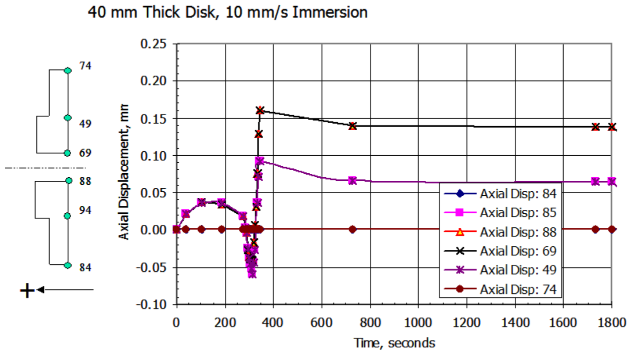


**Figure 16 - Displacement of the 40mm thick disk during heat-up. Disk "cups" during heat treatment.**

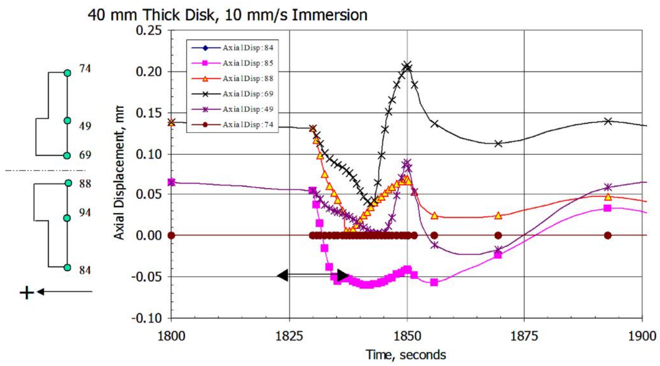


**Figure 17 - Displacement of the 40 mm disk during quenching. Disk bows during quenching.**

As the part heats, the differential temperature causes the disks to "cup" during heat-up. During quenching, the "cup" is removed, and the part "bows" in the opposite direction.

Examination of the effects of immersion rate on the amount of distortion occurring in the disk was performed. The results are shown in Figure 18 - Figure 24.

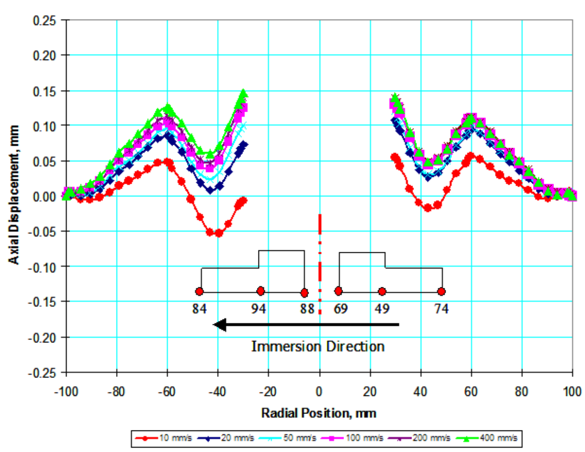


**Figure 18 - Effects of immersion rate on the 10mm thick disk.**

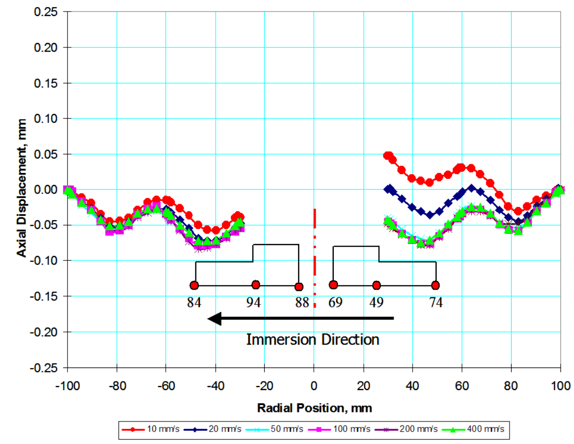


**Figure 19 - Effects of immersion rate on the 20mm thick disk.**

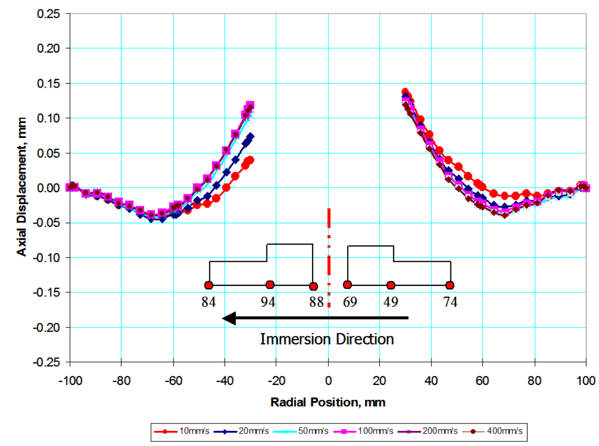


**Figure 20 - Effects of immersion rate on the 40mm thick disk.**

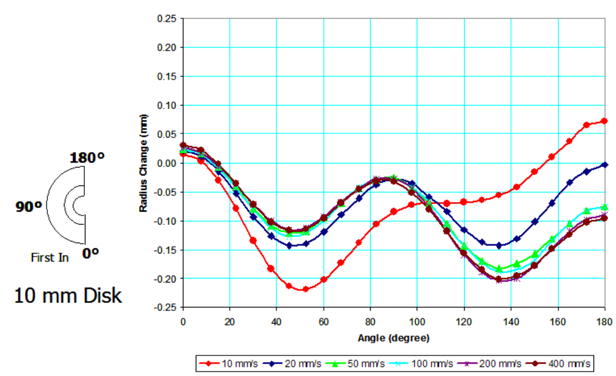


**Figure 21 - Changes in radial displacement as a function of immersion rate for the 10 mm disk.**

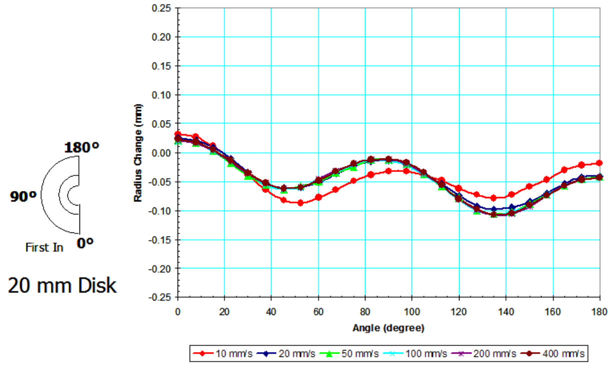


**Figure 22 - Changes in radial displacement as a function of immersion rate for the 20 mm disk.**

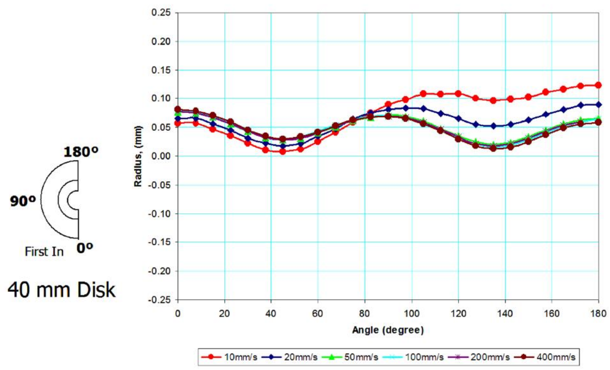


**Figure 23 - Changes in radial displacement as a function of immersion rate for the 40 mm disk.**

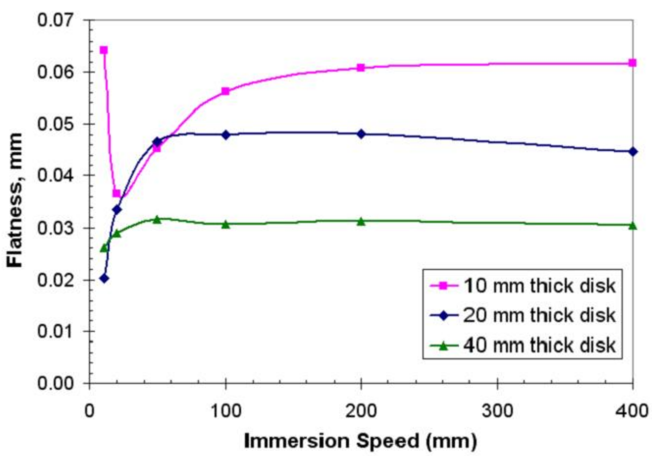


**Figure 24 - Overall flatness of the disks as a function of immersion rate.**

This shows that as the immersion rate is increased, the distortion increases rapidly. However, the distortion becomes more consistent as the immersion rates exceed approximately 50 mm/sec. Thin disks are more prone to distortion. Thick disks do not distort as much, but have higher constraint, and higher residual stresses.

## Conclusions

In general, the prediction of residual stress and distortion is a complex process – even for relatively simple shapes. Both the thickness and the phase transformations occurring in the disk affect the amount of residual stresses and distortion present in the part. This is compounded by the stress state prior to the heat treat cycle. In the case of disks quenched vertically, several general conclusions can be drawn:

- In general, distortion is greater for a thin disk geometry than for a thick disk of similar geometry;
- As the disk thickness decreases, the immersion rate should be faster to achieve more consistent distortion and desired hardness;
- At immersion speeds greater than 50 mm/s, distortion is more consistent; and
- At immersion speeds less than 50 mm/s, the distortion is highly erratic, with thin disks exhibiting the greatest non-uniformity in distortion

## Acknowledgements

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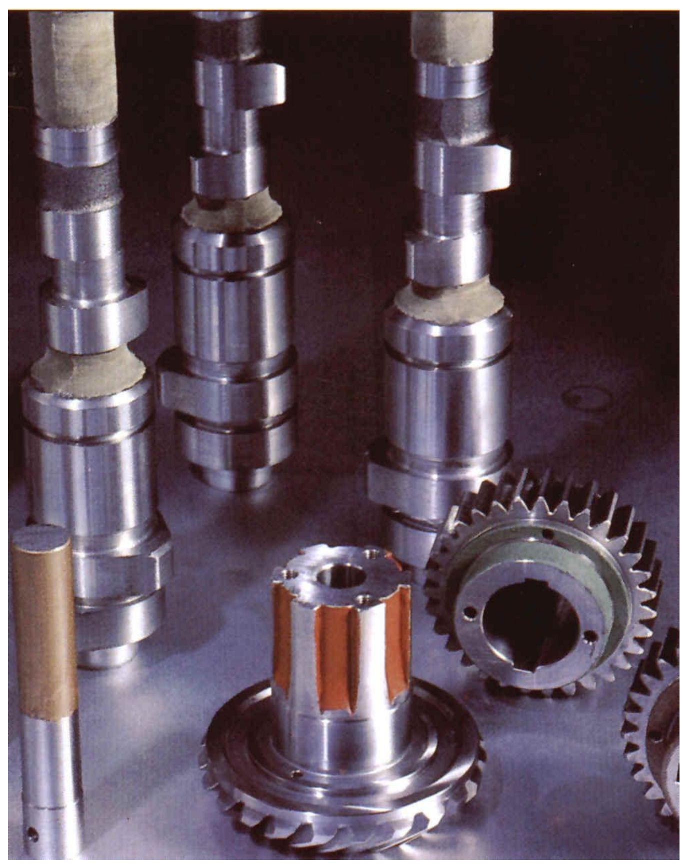

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