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Understanding Process Sensitivities in Press Quenching: An Integrated Approach

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Abstract

Press quenching is a specialized quenching technique used in heat treating operations to minimize the distortion of complex components such as spiral bevel gears and high quality bearing races. The quenching machine is designed to control the geometrical characteristics of components such as out-of-round, flatness, and (if the tooling is designed to accommodate it) taper. The achievement of final dimensional tolerances is accomplished through a trial and error process where the incoming machined sizes of the components are adjusted based upon measurement data taken from the initial sets of quenched and tempered components that have already been processed through the press quenching operation. Oil flow rates can be altered during the different stages of the quenching cycle, and through the use of specialized tooling the oil flow pathways can be selectively adjusted to meter the oil flow towards specific areas of the part surface while baffling it away from others in order to provide a more uniform overall quench. Complex metallurgical changes take place during austenitizing and quenching, resulting in corresponding mechanical property changes. Accompanying these changes are the generation of thermal and transformation induced stresses, which produce in-process and final residual stresses. During press quenching, dimensional restrictions add additional complexity to the combined effects of thermal and mechanical process sensitivities on these stresses. And if the stresses are severe enough, quench cracking can result. In this investigation the quench cracking of an asymmetrical AISI 52100 bearing ring is evaluated through physical experiments and through corresponding heat treatment process modeling using DANTE. The effects of quench rate, die load pulsing, and several other process variables are examined experimentally and/or analytically to illustrate how they can impact the resulting stresses generated during the press quenching operation.

Introduction

Components requiring high precision dimensional tolerances such as spiral bevel gears and bearing races used in the automotive and aerospace industries can often distort appreciably during heat treatment as they undergo open tank oil quenching. Heat should be extracted from the component in as uniform a manner as possible in order to minimize distortion related issues during quenching. But this can be difficult to achieve in parts that are designed with sudden changes in geometry where heavy or thick sections are located adjacent to thinner sections. A good example of this is the asymmetrical inner bearing ring geometry shown in Figures 1 and 2. As the part is submerged into the quenching medium, the thinner walled section cools and contracts more rapidly than the adjacent heavier section. Due to this varying quench rate, the outcome of quenching such components is the generation of temperature gradients and non-uniform thermal and transformation induced stresses. Press quenching can help to minimize the distortion of such components by utilizing specialized tooling for generating concentrated forces at key

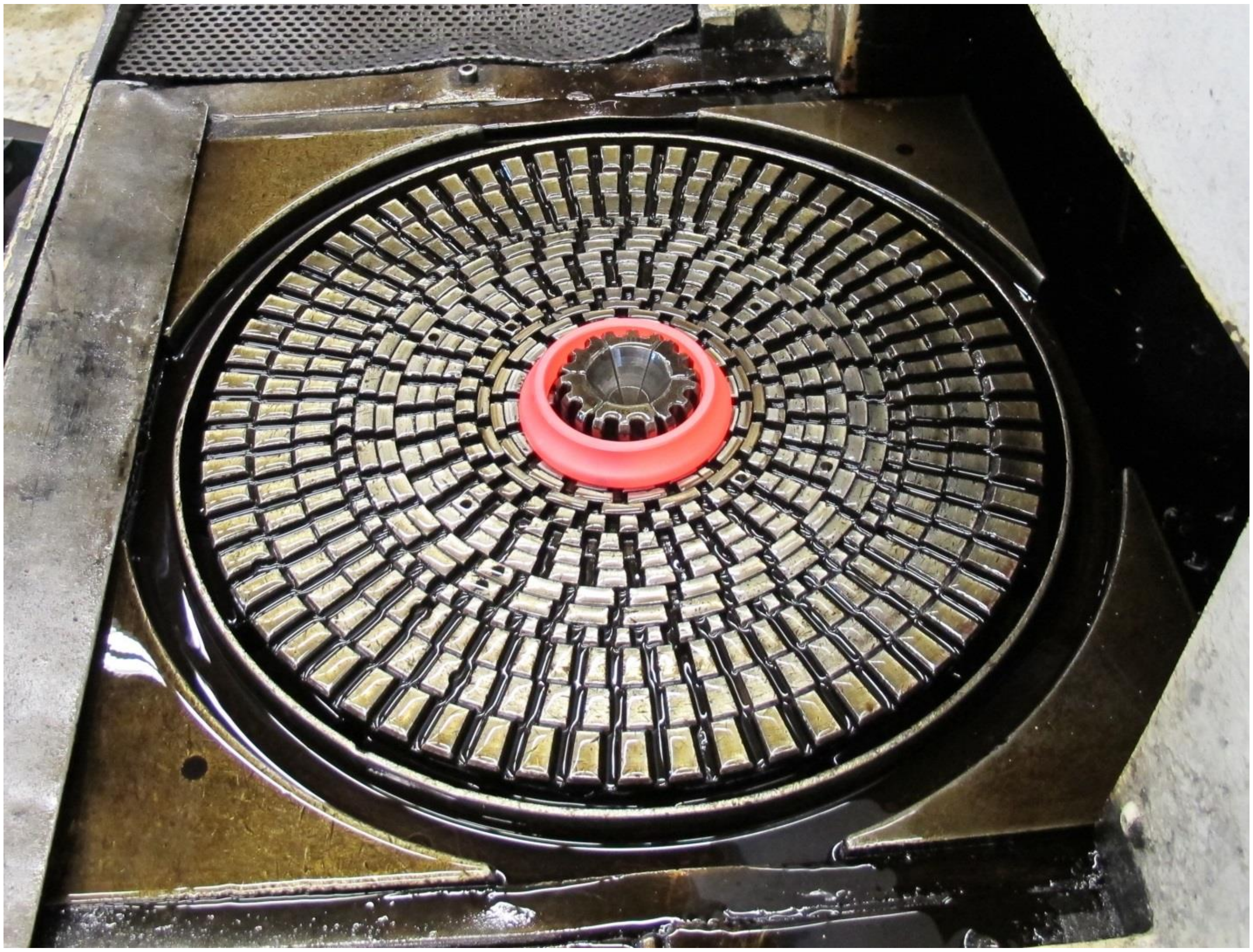

Figure 1. The hot inner bearing ring is shown positioned on the lower die assembly of a quenching machine just prior to quenching. This ring served as a part of the pulsing trials conducted during this investigation. Note the segmented lower die tooling and the individual slotted rings. These rings can be rotated independently to meter the flow of oil over the part being quenched.

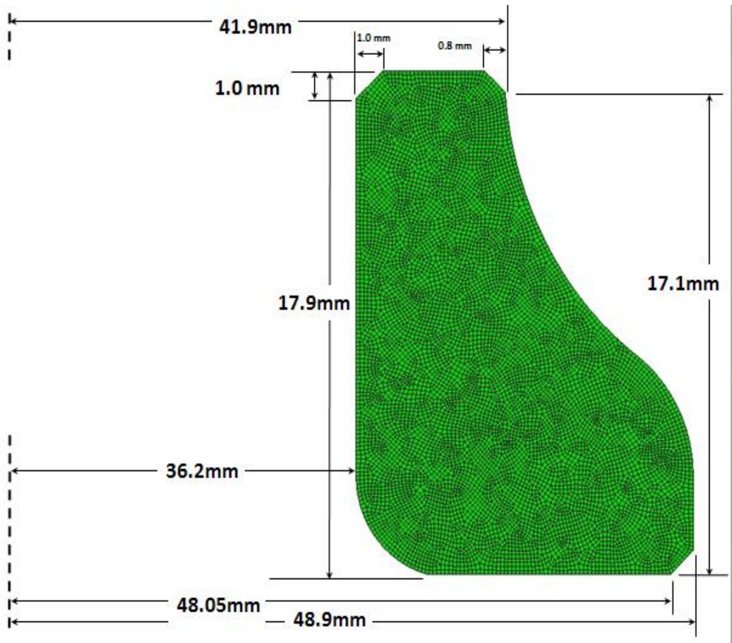

Figure 2. Cross-sectional profile of the asymmetrical inner bearing ring geometry that was studied during this investigation. The profile area was divided into 9,367 nodes and 9,188 elements for finite element modeling purposes.

locations in order to carefully control the movement of the component during quenching [1,2]. By utilizing this specialized quenching technique, the stringent geometrical tolerances that are often required for these high precision components can be satisfactorily and consistently met. However, if the localized stresses that are generated during quenching are severe enough, cracking can result in these asymmetric geometries.

Cracking In Press Quenching

In the experimental stage of this investigation a total of 209 inner bearing rings manufactured from the same heat of AISI 52100 tool steel were processed through heat treatment. All of the rings were magnetic particle inspected (MPI) in the as-received condition prior to the execution of any thermal treatment operations, and no cracks were identified in the as-received rings. Four furnace loads of approximately 50 rings each were processed back to back over the course of a standard eight hour shift by a single operator. The initial furnace load that was processed utilized the standard processing parameters of a normal production cycle. The bearing rings were austenitized at 1570ºF in a rotary furnace with a protective endothermic atmosphere. The furnace had already been equalized at the soak temperature when the rings were manually loaded into it. They were heated for a total of approximately 1 hour and then individually press quenched. A representative bearing ring that served as a part of these trials is shown in Figure 1 immediately after it was removed from the austenitizing furnace, just prior to quenching in a Gleason quenching machine using Houghton 105 quench oil. The quench oil is drawn from a 10,000 gallon (37,854 l) central reservoir containing a chiller that maintains the oil temperature at 130°F ± 10°F (54°C ± 6°C). An oil flow rate of 210 gal/min (795 l/min) was used during quenching, and the parts remained in the quenching machine for an average of 47 seconds each. After quenching to a final temperature of approximately

137°F (58°C), the bearing rings were manually wiped to remove any remaining oil and then placed into a steel mesh basket. Once the basket was filled, the parts were re-inspected using MPI.

In the as-quenched condition a total of 29 inner bearing rings from the initial furnace load of 52 rings exhibited MPI indications. Visual inspection confirmed the presence of quench cracks in the affected rings. A typical example of one of these cracked rings is shown in Figures 3a and 3b.

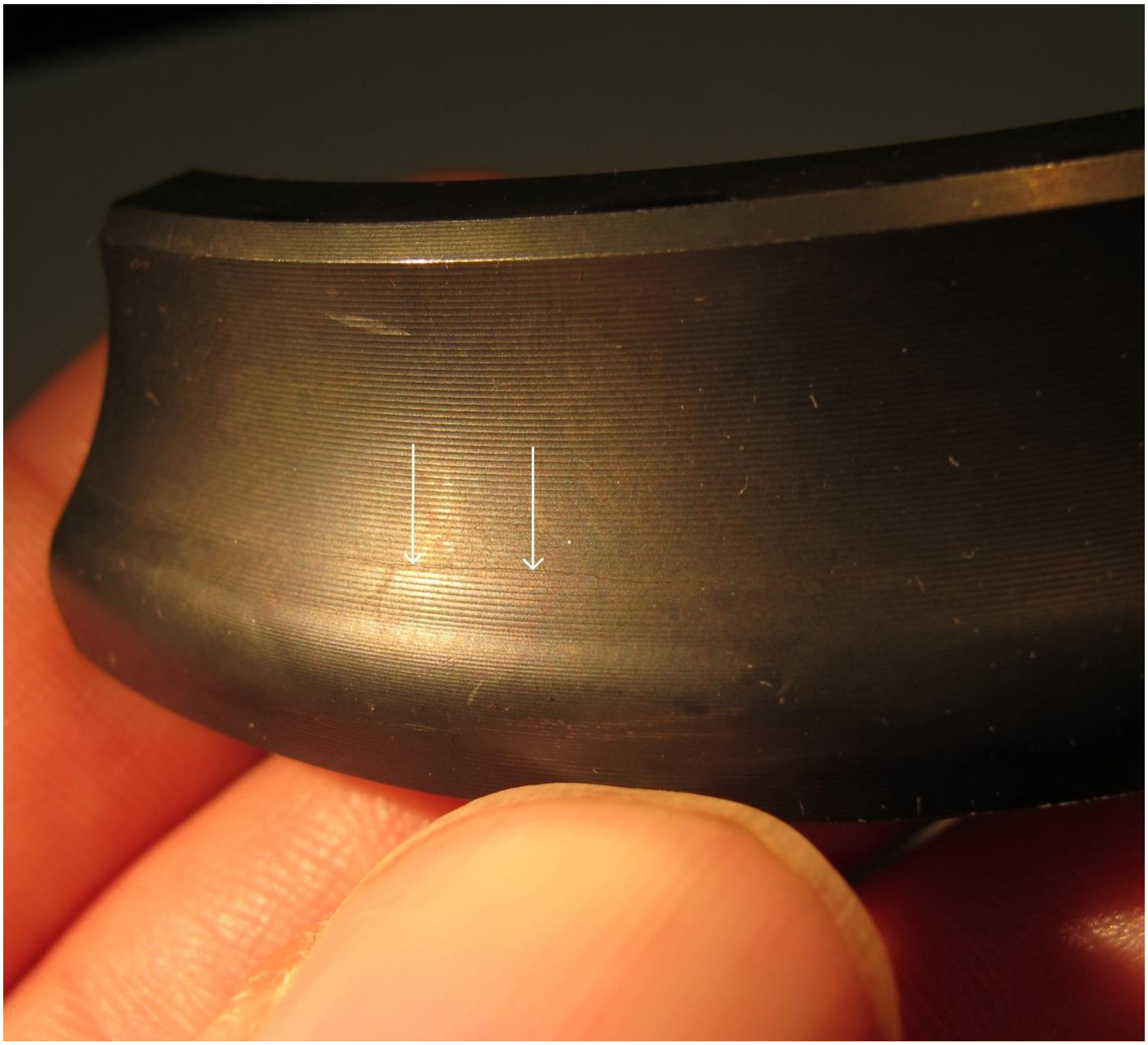

Figure 3a. This is one of 29 inner bearing rings from the first furnace load of parts that cracked in the as-quenched condition. The part is shown after temper, and the white arrows identify the circumferential crack that was found during MPI inspection.

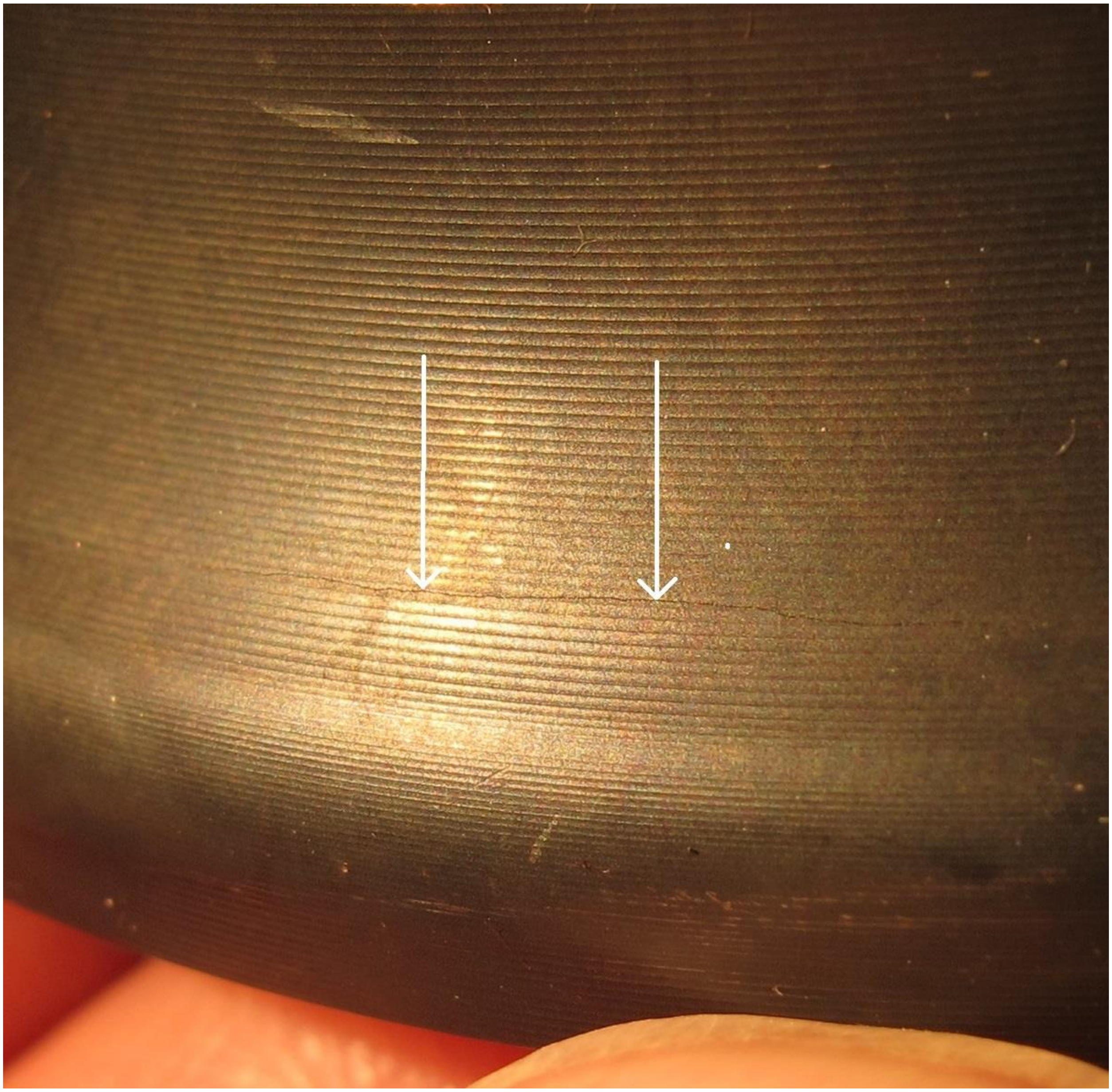

Figure 3b. This is a higher magnification view of the circumferential crack that formed in the 52100 bearing ring during quenching.

The circumferential cracks all formed in the raceway at the junction where the thin and thick sections of the bearing ring come together. On some rings the crack propagated around the entire circumference of the part while on others it only propagated about 25% around the circumference. The crack orientation, geometry, and depth were very consistent from part to part. After MPI inspection the rings were segregated into two separate baskets with the first basket containing the 29 rings that exhibited quench cracks, and the second basket containing the balance of the rings which did not exhibit any MPI indications after quenching. The baskets were subsequently placed into a tempering furnace that was preheated to a temperature of 450°F (232°C). The delay time from quench and into the temper furnace was 3 hours, which is the maximum delay time allowed during normal production runs. Since the baskets were placed into the furnace sequentially, the first baskets to enter the furnace received a temper that was longer than the remaining baskets. The minimum temper time was 4½ hours. The bearing rings were tempered only once. After the tempering operation was completed, the bearing rings from the second basket were re-inspected using MPI. Four additional cracked rings were identified. The total fallout due to cracking in the initial furnace load of 52 rings was 63.5%.

During processing of the initial furnace load the pulsing mode in the quenching machine was not activated. Pulsing periodically eases the applied pressure exerted by the inner and outer upper dies over the course of the quenching cycle, allowing the components to contract normally as they quench while still maintaining the desired part geometry. When the pulsing mode is not activated the stresses that are introduced from frictional contact between the dies and the parts being quenched may prevent the parts from contracting normally as they cool. Pulsing effectively reduces the magnitude of this frictional force, helping to minimize distortion related issues due to eccentricity and out-of-flatness. During pulsing the dies maintain intimate physical contact with the part throughout the entire course of the quenching cycle while the applied pressure is substantially reduced and then re-applied approximately every two seconds. The inner and outer upper dies are typically cycled in this manner, but the central expander is not normally pulsed. Due to the restrictions imposed by the geometry of this component, only the inner upper die was utilized during press quenching.

After the initial furnace load of bearing rings had been processed through quenching, a second group of 51 inner bearing rings were loaded into the austenitizing furnace. These rings were heat treated and press quenched using the same parameters that were used to process the initial furnace load, but with one important exception: the pulsing mode was now activated in the quenching machine. These rings were also MPI inspected in both the as-quenched and the quenched and tempered conditions. No MPI indications were found in the as-quenched rings, indicating that no quench cracking had occurred. After tempering, a total of four cracked rings were identified. This represents an overall fallout of only 8% for the second furnace load of heat treated bearing rings, a substantial improvement over the initial furnace load that was not pulsed.

The third and fourth furnace loads of bearing rings were heat treated using the same process parameters as those used to process the first and second furnace loads, respectively. The objective was to determine if the test results could be replicated. During processing of the third furnace load of 51 rings, the pulsing mode was deactivated so that the processing parameters that were used were identical to those used in processing the initial furnace load of rings. In the as-quenched condition, MPI inspection revealed that 19 rings were cracked. After temper, an additional 11 rings were found to contain cracks. This represents an overall fallout of 59%, which is very close to that observed on the initial furnace load of bearing rings. Within acceptable tolerances, the results replicated for the non-pulsed rings. For the fourth furnace load of 52 inner bearing rings, the pulsing mode was activated again and the rings were heat treated and press quenched using the same process parameters as those used for the second furnace load of rings. In the as-quenched condition no MPI indications were found, indicating that no quench cracking had occurred. In the as-quenched condition the MPI results on the pulsed rings replicated identically. After temper, MPI inspection was again performed and no indications were identified. No cracked rings were found in the final furnace load. It should be noted that dimensional measurements between the pulsed and non-pulsed groups showed no significant differences – both were acceptable. Subsequent modeling of the press quenching operation was undertaken in order to identify the reason(s) why activation of the pulsing mode in the quenching machine produced such a dramatic reduction in the propensity for cracking, and to determine the contribution of several of the other processing parameters to the cracking issue.

Modeling using DANTE Heat Treatment Simulation

In order to investigate how several metallurgical and mechanical factors combine during press quenching to influence quench cracking, a series of twelve (12) heat treatment computer simulation models were run using the DANTE program for the subject part [3]. The following primary process sensitivities were examined:

- Cooling rate sensitivity during the quench
    a. Comparison of three general cooling (quench) rates to determine if reducing or increasing the quench rate would reduce the in-process and/or final residual tensile stresses in the part.
    b. Examine a practice where the quench rate applied to the inner surface is reduced with respect to the outer ring surface.

- The effect of pulsing was simulated by constraining the top and/or bottom ring surfaces in the dies to simulate sticking friction. It is postulated that frictional effects from die wear that are normally encountered may contribute to over constraint (i.e. "sticking") of the ring surfaces in the die during quenching. The purpose of the quench dies is to only constrain the axial movement of the ring. Pulsing helps to relieve the radial constraint on the top and bottom die surfaces caused by the sticking. The model should show how much additional stress is generated in the part during processing. This phenomenon was studied using three (3) different models:
    a. Restricting radial movement of both top and bottom ring surfaces
    b. Restricting radial movement of the top ring surface
    c. Restricting radial movement of the bottom ring surface

  Each of the sticking models was conducted using the baseline quenching heat transfer assumption. As will be seen, the models illustrated precisely why pulsing was found to be beneficial in Gleason's practice. The high tensile stresses produced by transient sticking are relieved by the pulsing.

Predicting and quantifying the residual stresses in these components represented a significant challenge. Recent advancements in quantitative process simulation (modeling) have made it possible to study in situ the combined effects of carbon mass diffusion, heat treatment thermal strains, and strains produced from metallurgical phase changes. The DANTE heat treatment software is a finite element based tool that calculates the residual stress, dimensional change, hardness and metallurgical phase volume fractions of steel parts as a result of heat treatment [4]. The DANTE database includes mechanical and thermal property data for steel microstructural phases as functions of temperature and rate, as well as the necessary phase transformation kinetics parameters to address both heating and cooling transformations [5].

<u>DANTE Model Set-Up</u>

Figure 2 (referenced previously) shows a schematic of the model set-up with ring dimensions and mesh. The model was constructed as a 2-D axisymmetric framework for capturing the heat treatment thermal stress effects, including those from die loading. The part cross section was meshed using 9,367 nodes and 9,188 quadrilateral elements.

The DANTE model was used to assess nine (9) process conditions, including the effects of varied quench application and pulsing/frictional effects from the press quench. Three friction levels in the die (static coefficient of friction values 0.05, 0.2 and 0.5) were also investigated to gauge general sensitivity to non-sticking levels of friction in the dies. Table 1 summarizes the conditions examined.

Heat Transfer

Cooling behavior and variation in quenching conditions within the dies were modeled through application of varying surface convection heat transfer boundary conditions. These included a "baseline" condition that simulated the cooling response as observed in the Gleason equipment, as well as three hypothetical quench conditions from which a parametric examination of quenching response could be made. The conditions examined were:

- **Quench Press Baseline:** This is the baseline oil / die quenching convection heat transfer applied to all the ring surfaces – assuming standard Gleason practice. This also serves as the mean heat transfer condition for the variation studies.
- **High Quench Rate:** Assumed increased convection cooling to gauge stress sensitivity.
- **Low Quench Rate:** Assumed decreased convection cooling to gauge stress sensitivity.
- **Reduced Quench Rate Inner Only:** Trial conducted to assess effect of adjusting surface cooling locally. A reduced convection cooling was applied to the inner ring surfaces while keeping the outer surfaces cooled as per the baseline.

Figure 4 shows a plot of the respective heat transfer coefficients for each case as a function of temperature.

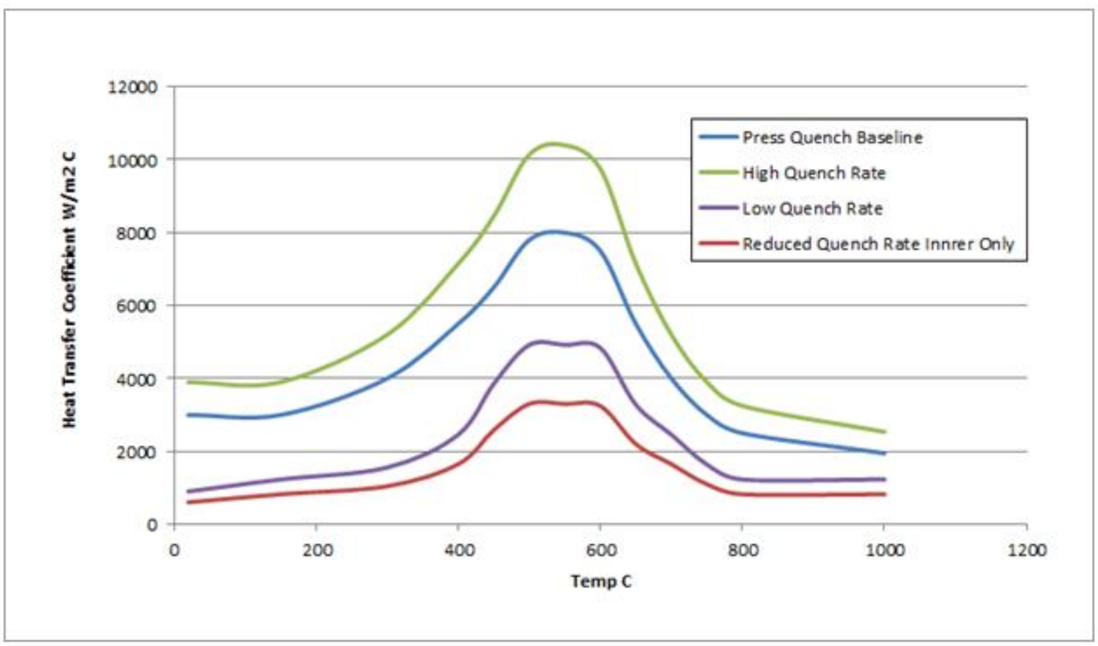

Figure 4. Heat transfer coefficient as a function of temperature for the four (4) quenching scenarios examined in this investigation.

Table 1. Nine (9) press quench process conditions were examined in this parametric modeling study.

Case	Static Coefficient of Friction	Aust. Temp.	Quench Practice	Upper Die Press Load
1	0.05	1570°F	Standard Press Quench	4000 lbs
2	0.05	1570°F	Low Flow Press Quench	4000 lbs
3	0.2	1570°F	Standard Press Quench	4000 lbs
4	0.5	1570°F	Standard Press Quench	4000 lbs
5	0.05	1570°F	High Flow Press Quench	4000 lbs
6	Sticking – Both Top and Bottom Dies	1570°F	Standard Press Quench	Not Applicable
7	Sticking Top Die	1570°F	Standard Press Quench	Not Applicable
8	Sticking Bottom Die	1570°F	Standard Press Quench	Not Applicable
9	0.05	1570°F	Reduced Quench on Inside Ring Surface; Standard Quench on Outside Surface	4000 lbs

Loading and Simulation of Die Pulsing

Die loading and friction boundary conditions were applied as shown in the schematic in Figure 5. Mechanical loading was applied from the top die, as shown. Die frictional effects were considered from the top and bottom dies only. For the plug on the ring inner diameter, frictionless contact was assumed.

Model results from examination of frictional sensitivity, discussed in the 'Results' section of this paper, indicated that intermittent and localized tensile stress excursions may be the result of radial sticking of the top and/or bottom ring surfaces in the dies during quenching. Pulsing would act to alleviate these excursions. Consequently to examine the effects of pulsing, three combined heat treatment/loading models were run to evaluate the sensitivity of stresses to sticking of the top and bottom die surfaces of the ring. These cases used the following mechanical boundary conditions:

1. Restricting radial displacement of both the top and bottom surfaces
2. Restricting radial displacement of the top surface only; permitting only the part bottom surface to slide
3. Restricting radial displacement of the bottom surface only; permitting the part top surface to slide

Figure 6 schematically illustrates the application of the sticking boundary conditions. The results of the models employing the sticking excursions indicate the potential transient stress increases which are relieved by the die pulsing practice.

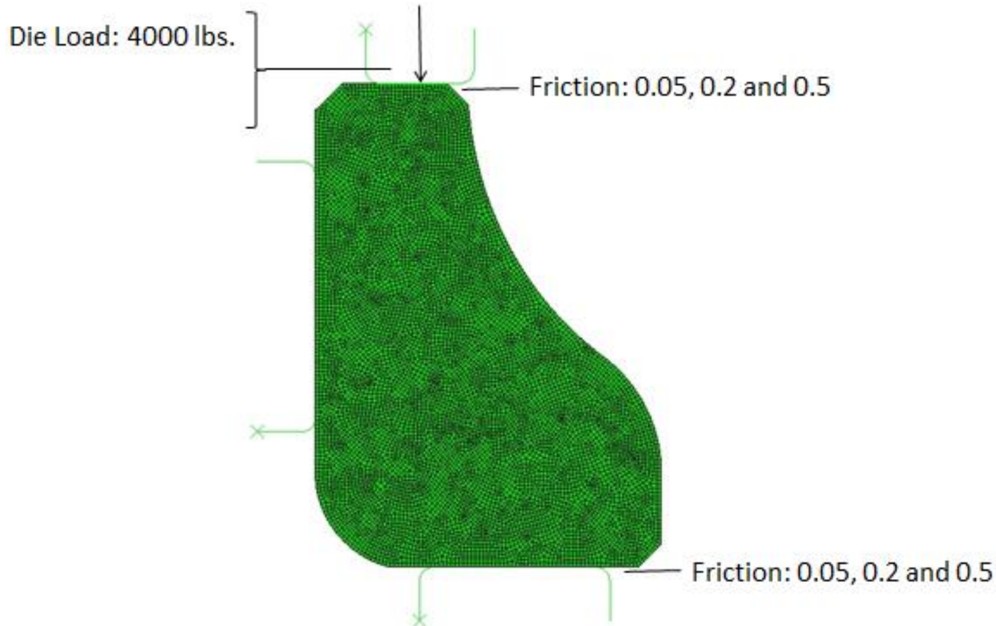

Figure 5. Schematic illustrating press quench loading and frictional boundary conditions applied to the 52100 ring heat treatment model.

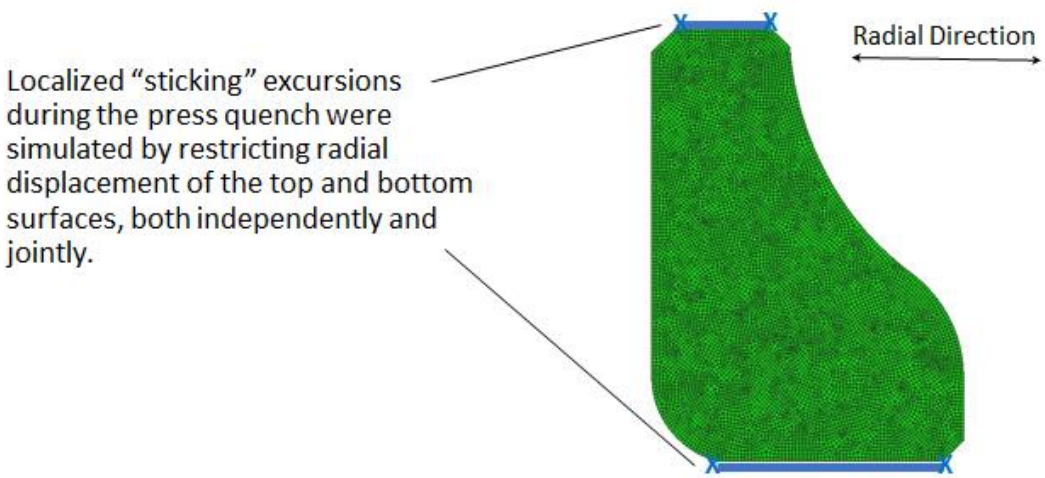

Figure 6. Benefit of pulsing the dies was determined by modeling sticking excursions during the press quench by restricting radial displacements of the top and bottom surfaces of the ring. Pulsing acts to relieve such excursions, and the stresses resulting from them.

Results and Discussion of the Press Quench Modeling

For all of the cases examined (Table 1), the models showed the maximum tensile stress to occur in-process (during quench) consistently at a location 9mm from the ring base on the OD surface (ball raceway). The composite in Figure 7 shows the in-process maximum principal stress at key times for Cases #1, #2, #5 and #6 for example purposes. The highest tensile stresses are indicated by the red contour, and the illustration is provided to show that the models predict precisely where the greatest crack sensitivity occurs – as validated with Gleason's experience as discussed in the previous section and shown in Figure 3. Note that the location of the maximum surface stress on the outer raceway is consistent in each case. It was this location that was chosen as the reference for quantitative stress comparisons in this study.

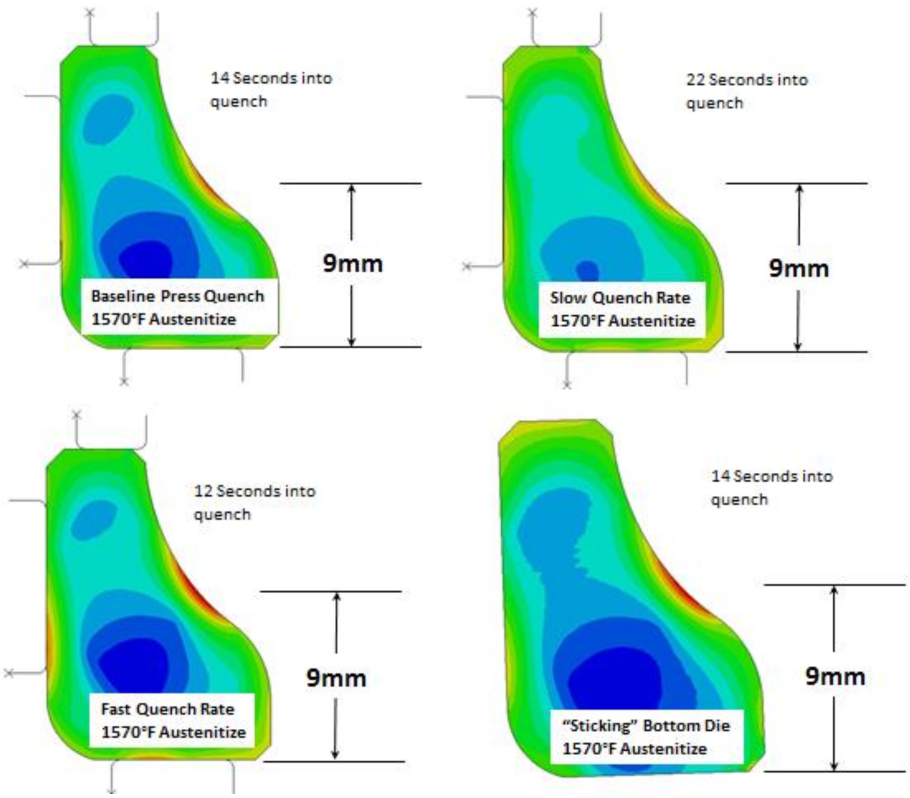

Figure 7. Composite showing location of maximum surface tensile stress in four (4) example cases for the press quench processing of the 52100 ring. Location of the maximum stress is consistent between each case.

Table 2 provides a general comparison of resulting maximum principal stress for the 9 processes examined, including both the highest in-process stress (with corresponding time) and the final stress at 9mm from the base, ball raceway location. The table indicates the primary process sensitivities to be ring sticking on the top and bottom die surfaces, and quenching rate. A minor effect was seen from the sliding frictional variations. Die loading was found to have negligible effect; however, higher die loads increase the friction effect which would increase the tensile stress magnitude during quenching.

Table 2. Summary of max. in-process stress and final max. residual stress at the key outer bearing race location. Nine (9) press quench process conditions are compared.

Case	Static Coefficient of Friction	Quench Practice	Upper Die Press Load	Max In-Process Stress (MPa)	Final Maximum Stress (MPa)
1	0.05	Std Press Quench	4000 lbs	642	400
2	0.05	Low Flow Press Quench	4000 lbs	400	236
3	0.2	Std Press Quench	4000 lbs	668	403
4	0.5	Std Press Quench	4000 lbs	691	422
5	0.05	High Flow Press Quench	4000 lbs	746	472
6	Sticking – Both Top and Bottom Dies	Std Press Quench	Not Applicable	882	338
7	Sticking Top Die	Std Press Quench	Not Applicable	680	393
8	Sticking Bottom Die	Std Press Quench	Not Applicable	860	371
9	0.05	Reduced Quench on Inside Ring Surface; Std Quench on Outside Surface	4000 lbs	325	230

Stress contour plots, showing both the maximum in-process stress state and final stress state for each condition, are shown graphically in Figures 8 – 14. Reviewing the results summarized in Table 2, along with the details in the stress contour plots, indicates that a primary driver for increased tensile stresses in the part is sticking of the press quench dies during processing. In particular, sticking of the bottom die produces a predicted increase in surface tensile stress of ~220 to 242 MPa (32 – 35 ksi) over the baseline case. Sticking of the bottom die, and bottom die in combination with the top die, produce the greatest transient increase in local tensile stresses on the ring outer ball groove surface.

Additionally, comparison of the various quench practices shows that reducing the applied quench rate decreases both the in-process and final surface stresses at the critical cracking location (Table 2; Compare Figures 1 and 3). With a 35% reduction in the quench heat transfer rate, the models predict a reduction in the max in-process surface stress from a baseline level of 642 MPa to 400 MPa (93 to 58 ksi) with the reduced quench rate. Conversely, increasing the quench rate by ~35% over the baseline rate increases the in-process surface tension from 642 MPa to 746 MPa (93 to 108 ksi).

An exercise was also undertaken to examine the effect of local quench application modifications on the stress response in the ring. Reducing the quench cooling on the inner surface to a level ~60% lower than the baseline quench applied to the outer surface (Figures 4, 8 and 14), the stress on the outer bearing surface is reduced from the baseline 642 MPa to 325 MPa (93 to 47 ksi). Though hypothetical, the exercise shows the utility of heat treatment modeling to investigate key process modifications virtually. In this regard, the modeling tool can be used to design focused in-plant trials for quench press process optimization.

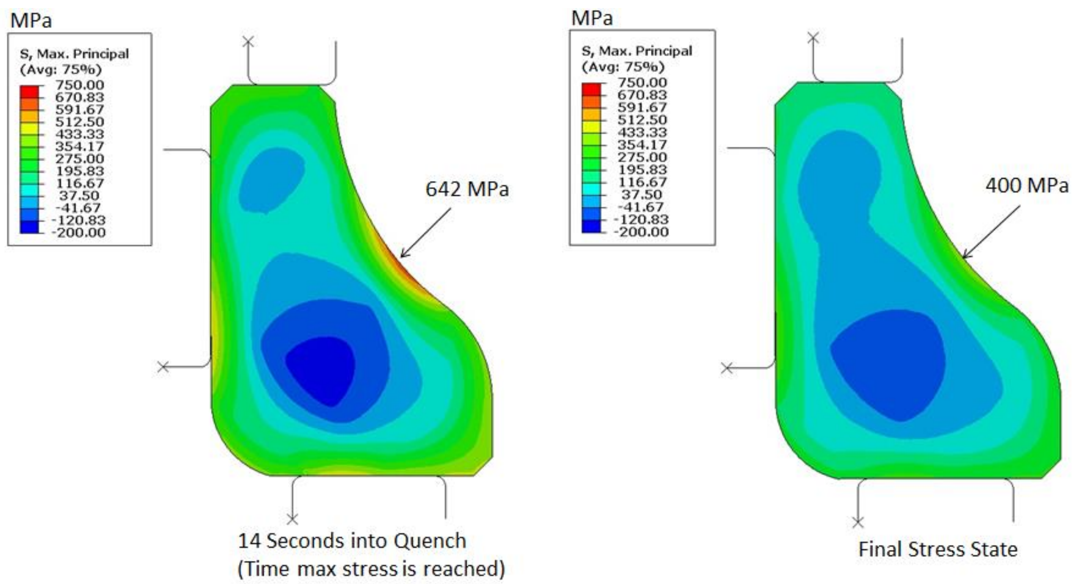

Figure 8. Illustration of the maximum principal stress 14 seconds into the press quench cycle, and at the end of the quench cycle for the baseline condition (Case #1). See Table 2.

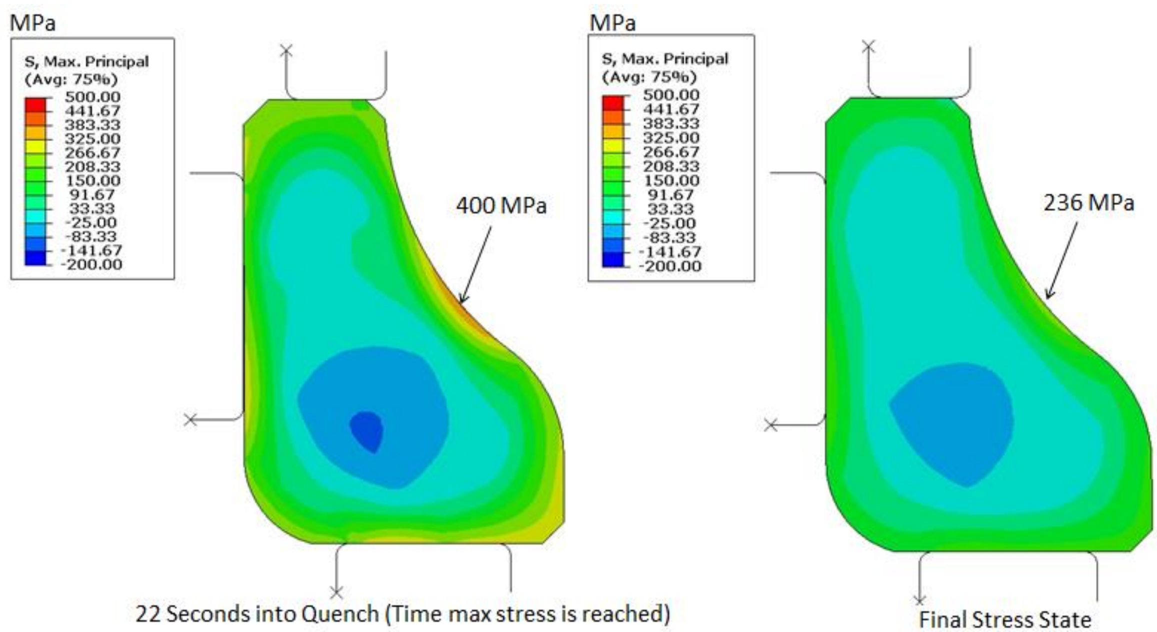

Figure 9. Illustration of the maximum principal stress 22 seconds into the press quench cycle, and at the end of the quench cycle for the low heat transfer quench condition (Case #2). See Table 2.

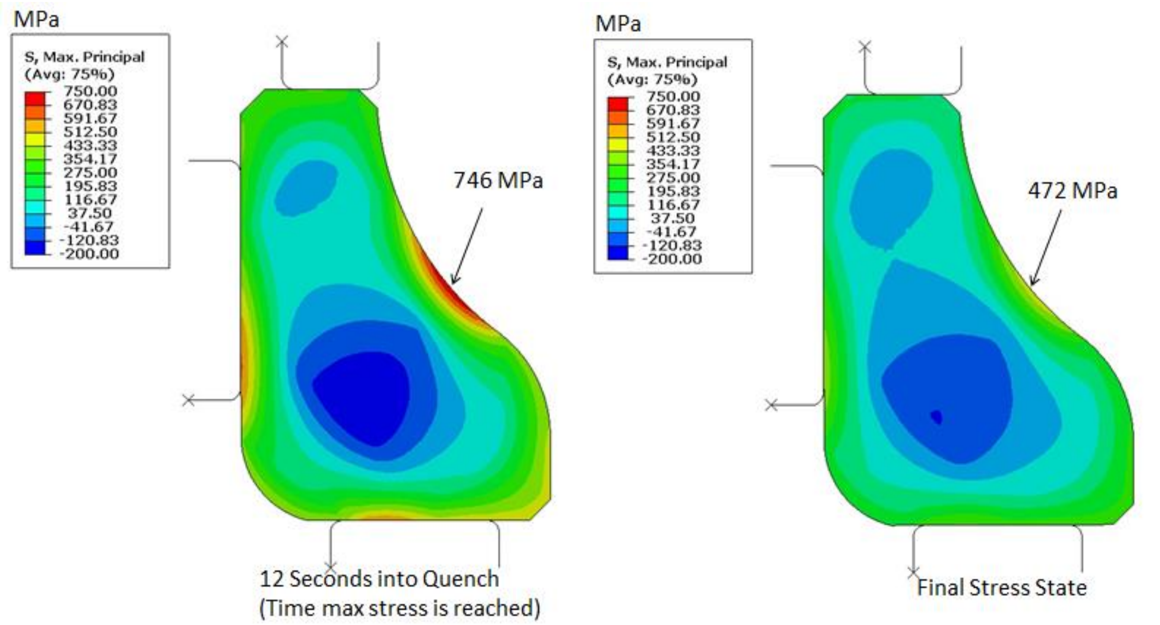

Figure 10. Illustration of the maximum principal stress 12 seconds into the press quench cycle, and at the end of the quench cycle for the high heat transfer quench condition (Case #5). See Table 2.

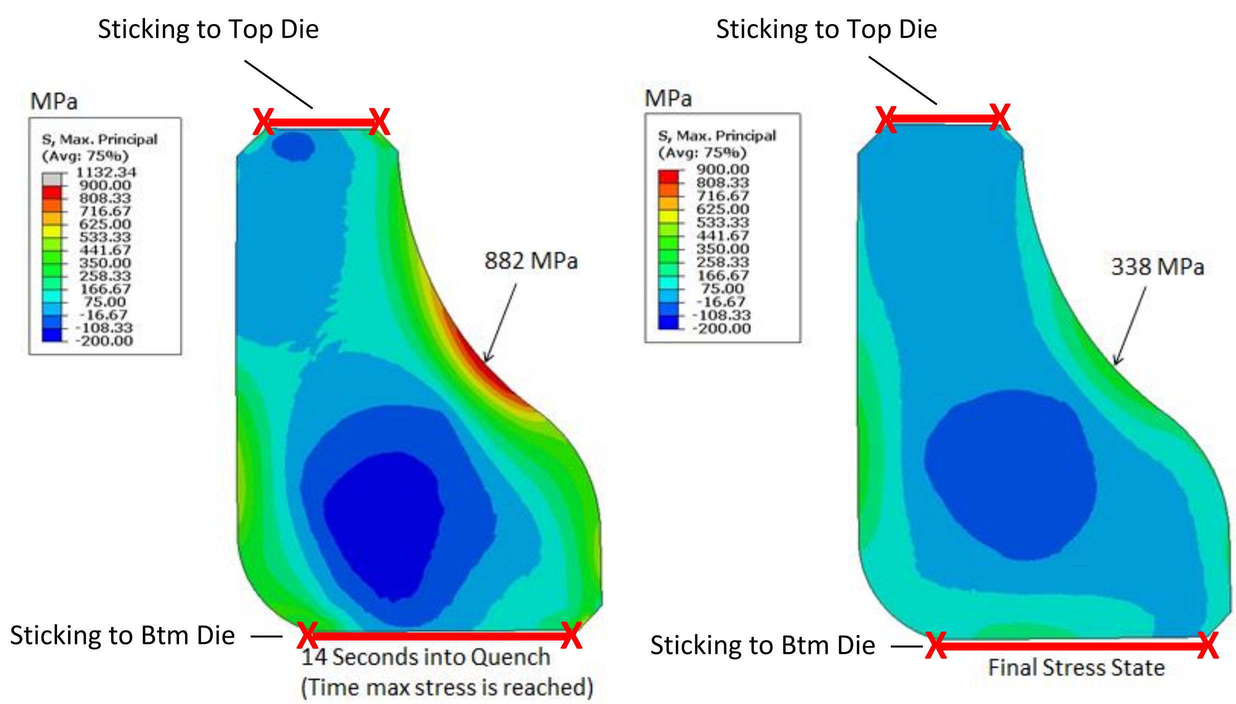

Figure 11. Illustration of the maximum principal stress 14 seconds into the press quench cycle, with "sticking" of both the top and bottom ring surfaces (radial displacement restriction). – see Figure 6.

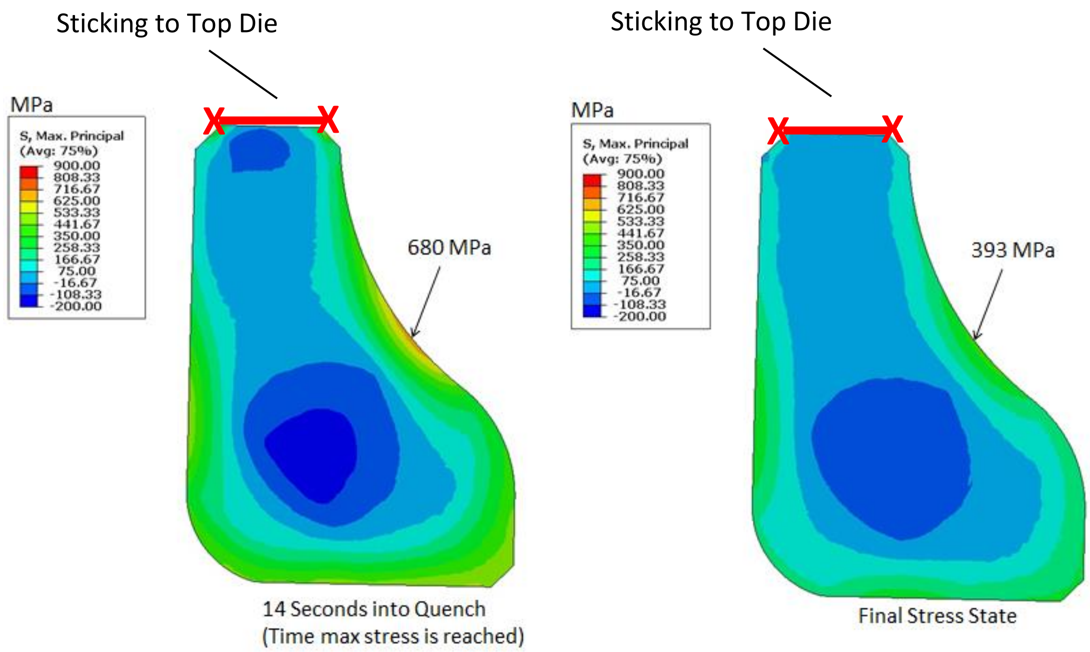

Figure 12. Illustration of the maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring top surface (radial displacement restriction). – see Figure 6.

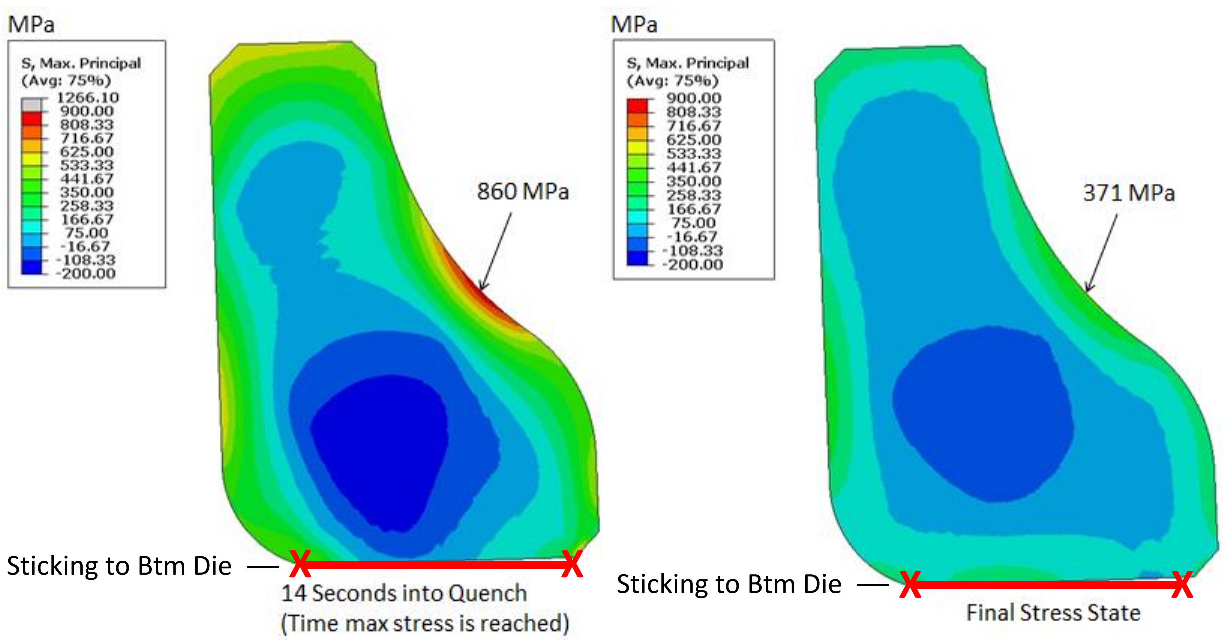

Figure 13. Illustration of the maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring bottom surface (radial displacement restriction). – see Figure 6.

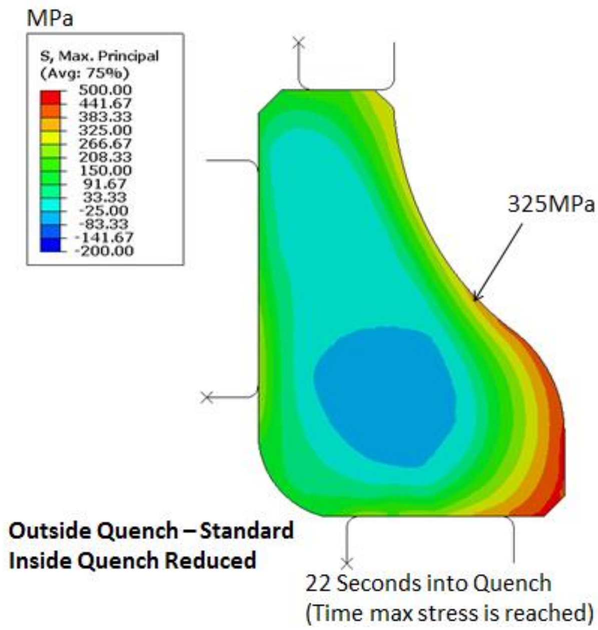

Figure 14. Illustration of the maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring bottom surface (radial displacement restriction). – see Figure 6.

It is important to note that proper modeling of the transformation strains associated with the martensite transformation is critical in establishing the correct in-process and final stress distributions. The primary driver for the maximum in-process tensile stress "spike" is the ring core martensite phase transformation, and the corresponding volumetric expansion in the core relative to the already transformed surface. Stress-Transformation-Time plots for the baseline, low and high quench cooling scenarios are shown in Figures 15 – 17, and clearly indicate the importance of accounting for the martensitic transformation strains in characterizing stress effects during heat treatment. Note that in each case, the in-process tensile stress "spike" occurs consistently when the core martensite volume fraction reaches 65-70%. This directly indicates that the volume increase from the transformation strain in the core produces tension on the surface as the hardened martensite surface layer resists the expansion. It is therefore critical that a heat treatment simulation be able to account for such metallurgical phenomena, in addition to the pure mechanical factors (e.g. from a press quench process).

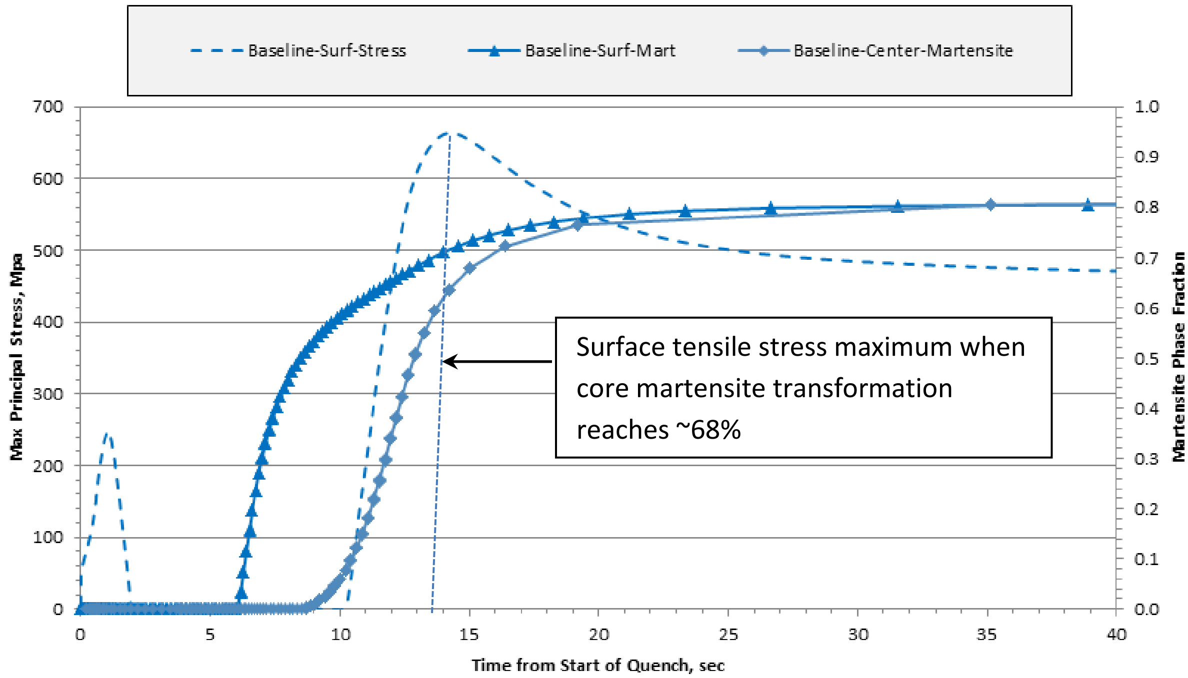

Figure 15. Stress-Martensite-Time plot for the baseline press quench (Case #1), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

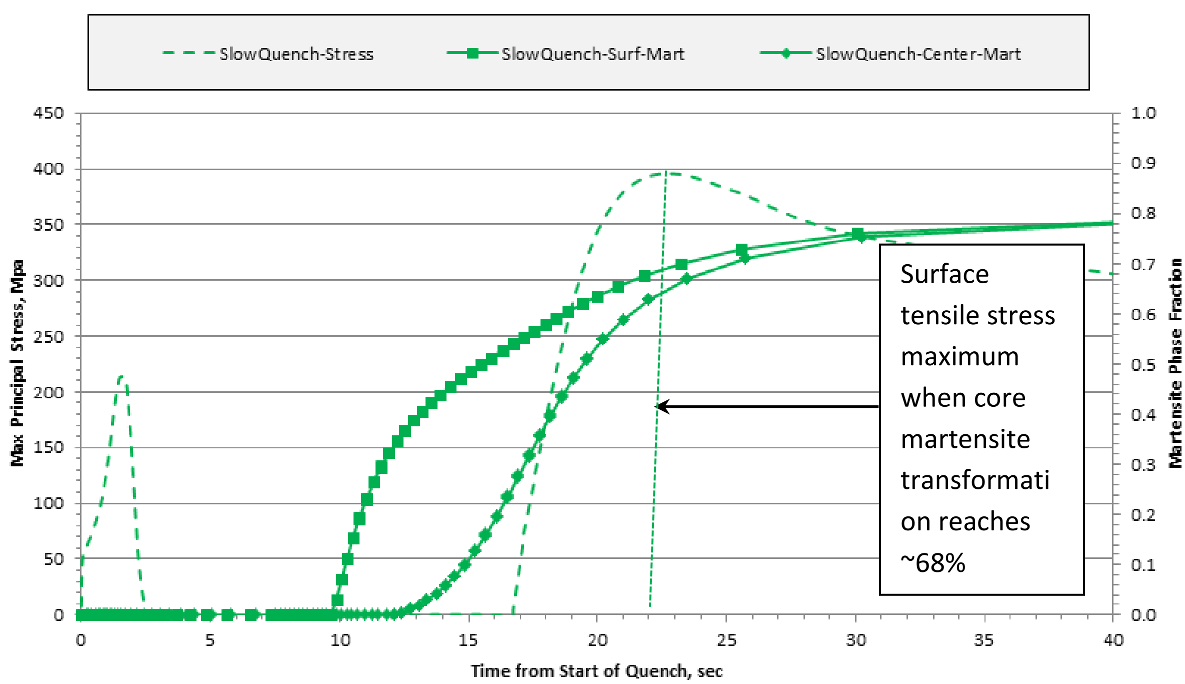

Figure 16. Stress-Martensite-Time plot for the low heat transfer press quench (Case #2), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

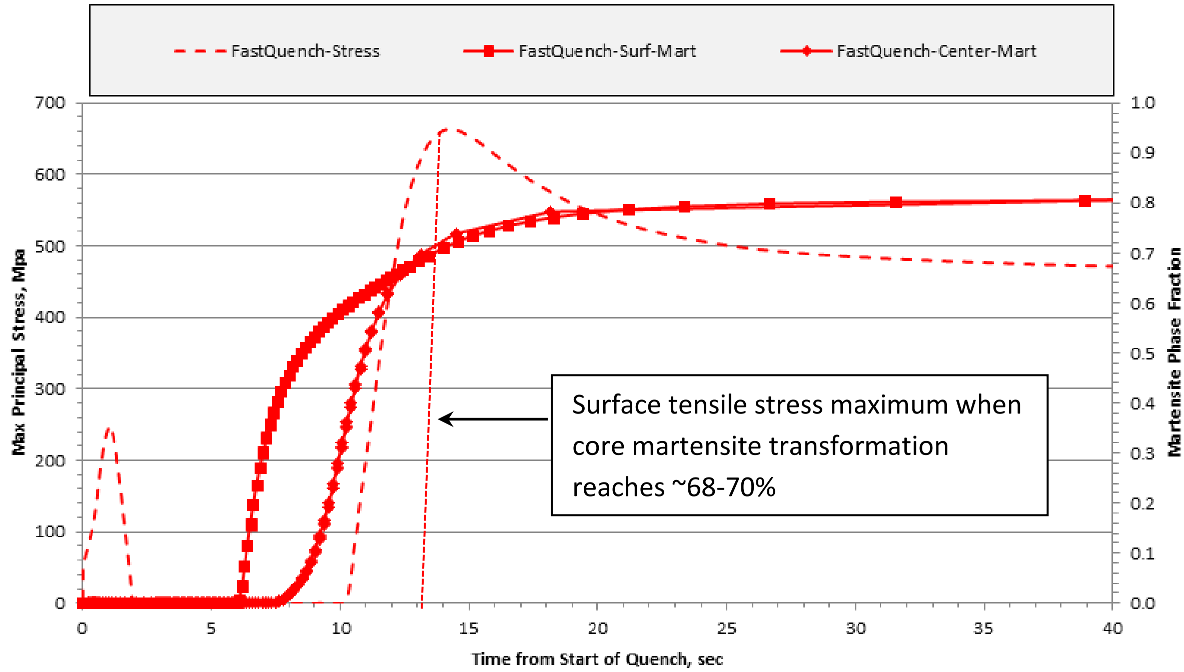

Figure 17. Stress-Martensite-Time plot for the high heat transfer press quench (Case #5), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

Conclusions

Experience with press quenching of 52100 bearing rings has demonstrated that a pulsing practice is beneficial in reducing the probability for cracking on the inner bearing ring raceways. DANTE heat treating and loading models were useful tools in demonstrating why the pulsing practice was beneficial, and also in examining additional process sensitivities such as the heat transfer rate during press quenching. For the bearing ring geometry investigated in this study the following process sensitivities were noted:

- The reduction in cracking propensity during pulsing of the quench dies may be due to release of intermittent radial displacement restriction ("sticking) of bottom or both bottom/top ring surfaces of the die. The models show a significant increase in local in-process tensile stress at the critical outer race location when such restriction in radial displacement occurs.
- Reducing the quench rate also shows a significant effect in reducing the maximum in-process tensile stress at the critical outer raceway location, as well as a reduction in the final tensile stress. Conversely, increasing the quenching rate shows an increase in both the maximum in-process tensile stress and final tensile stress at the critical raceway location.
- Reducing the quench rate in the ring interior provided a significant reduction in both the in process and final stress at the critical outer raceway location.

- Surface friction increases at the ring/die interface were found to have a small effect on stress response, with increasing friction found to increase the resulting in-process stresses. This was seen as an indicator for potential intermittent part-die "sticking" excursions potentially leading to increased cracking propensity.
- Heat treatment simulations provide a means of investigating key press quench cracking sensitivities with respect to in-process and final residual stresses. The simulation tool DANTE can be effectively used to conduct virtual experiments to characterize these sensitivities and to identify appropriate adjustments in the relevant processing parameters helping to mitigate these cracking issues.

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