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Investigating a Die Quench Cracking Problem in 52100 Steel Bearing Rings with Computer Simulation

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KEYWORDS

Press quenching, heat treatment, residual stress, phase transformation, quench cracking, bearings, distortion.

Abstract

Quenching using a press with controlled die loads, commonly referred to as press quenching, is a specialized technique used to minimize distortion of critical components such as gears and high quality bearing races. Improper press load magnitudes or timing of the load application may restrict part movement during quenching to the point of imposing stresses that cause cracking, especially in a common bearing steel such as AISI 52100, high carbon, high strength steel. This paper applies a finite element based heat treat simulation tool, DANTE®, to investigate the sensitivity of cracking to press quenching process parameters.

The typical method for designing a press quench process to control flatness, out-of-round, and taper is by experience coupled with trial-and-error. This is accomplished by adjusting oil flow rates, flow directions, die loads, and the timing of die loads. Metallurgical phase transformations occur during the quenching process as austenite transforms to martensite and possibly to diffusive phases. Thermal contraction due to cooling and volumetric expansion due to the phase changes therefore occur simultaneously during the heat treating process. A constantly changing stress state is present in the part, and improperly applied die loads, oil flow or oil flow rate can add additional stress to result in cracking.

An inconsistent cracking problem in an AISI 52100 bearing ring was evaluated using production trials, but the process statistics were not conclusive in identifying the source of the problem. Heat treatment process modeling using DANTE was used to investigate the effects of quench rate, die load pulsing, and several other process variables to determine how these parameters impact the resulting stresses generated during the press quenching operation.

Introduction

Components such as spiral bevel gears and bearing races for the automotive and aerospace industries requiring high precision dimensional tolerances often distort during unconstrained immersion quenching in oil or polymer solutions. Size change is unavoidable due to the metallurgical phase transformations that occur during hardening, and consistent size change can be accounted for by proper part design. Nonuniform conditions introduce shape change in addition to size change, and this can also be accommodated during design if conditions are consistent. However, inconsistent conditions, whether they are uniform or nonuniform, result in inconsistent dimensional changes, and this inconsistency is the source of undesirable distortion. The purpose of quenching using dies, pressure, and controlled oil flow as is done in press quenching is to achieve dimensional consistency in the quench hardened part.[1,2]

An inner bearing race is shown in Figure 1. This part is made from AISI 52100 steel, and the steel chemistry specification is given in Table I. This bearing ring cross section dimensions and a finite element mesh are shown in Figure 2. While the ring is axisymmetric, the cross section is asymmetric, with the thin top section and a thick bottom section. This difference in section thickness causes nonuniform cooling during quenching, even under uniform heat transfer conditions, and the radial dimensional change of the top section will be different from the radial dimensional change of the bottom section. The designed action of the press quench is to mitigate this difference.

Table I. Chemistry Specification for AISI 52100 Steel

C, w/o	Mn, w/o	Si, w/o	Cr, w/o	Ni, w/o	Mo, w/o	Fe
0.93/ 1.05	0.25/ 0.45	0.15/ 0.35	1.35/ 1.60	0.25 max.	0.10 max.	Bal.

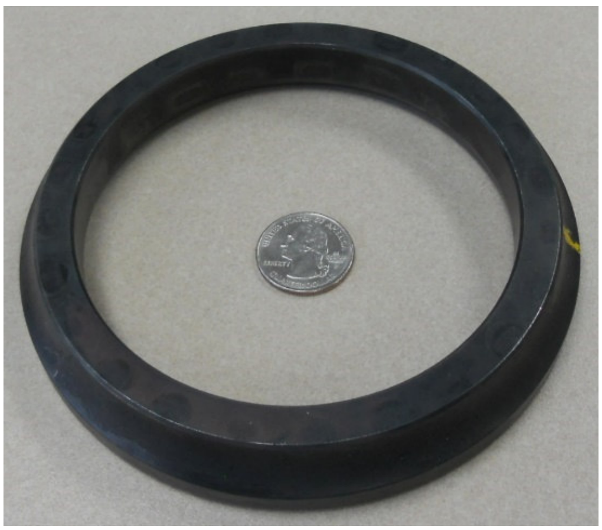


Figure 1 – Inner bearing race.

During press quenching the austenitized bearing ring is placed onto a lower die assembly, as shown in Figure 3. The die assembly is quickly positioned at the center of the press bed, and an outer containment shell is lowered around the lower die assembly. This shell contains the oil that will be pumped through the tooling to quench the part and to cool the dies. An internal expander is activated to maintain ring roundness, and an upper die assembly is lowered to contact the ring top surface and apply pressure. The expander, bottom die and upper die are castellated, meaning the contact between the ring and tooling is not contiguous. The gaps in the tooling facilitate oil flow and also minimize die chill of the part, thus allowing the oil to control heat extraction from the part during quenching. By utilizing this specialized quenching technique, the stringent geometrical tolerances required for these high precision components can be satisfactorily and consistently met. However, if the localized stresses generated during quenching are severe enough, cracking can result in these asymmetric geometries.

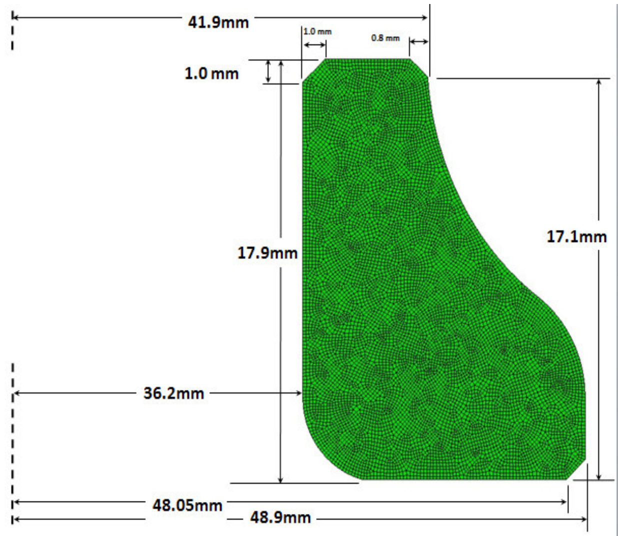


Figure 2 – Cross-sectional profile of the asymmetrical inner bearing ring geometry that was studied during this investigation. The profile area was divided into 9,367 nodes and 9,188 elements for finite element modeling purposes.

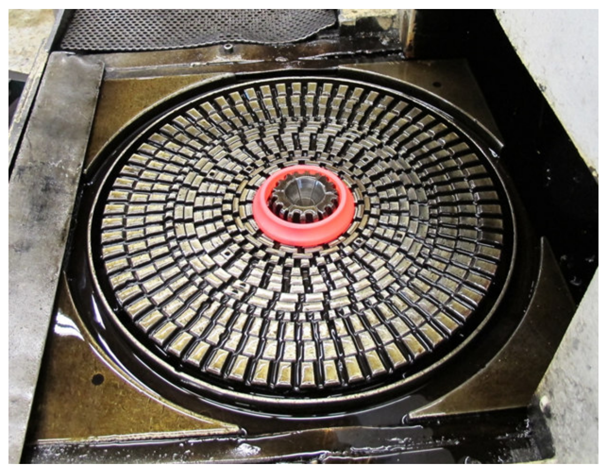


Figure 3 – The hot inner bearing ring is shown positioned on the lower die assembly of a quenching machine just prior to quenching. Note the segmented lower die tooling and the individual slotted rings. These rings can be rotated independently to meter the flow of oil over the part being quenched.

Bearing Race Cracking in Press Quenching

Some 209 inner bearing rings manufactured from the same heat of AISI 52100 steel were processed through heat treatment. Each ring was magnetic particle inspected (MPI) in the as-received condition prior to heat treatment, and no cracks were found. Four furnace loads of approximately 50 rings each were processed consecutively over the course of a standard 8 hour shift by a single operator. Each furnace load was austenitized at 1570°F for approximately 1 hour under a protective endothermic atmosphere in a rotary hearth furnace. The furnace had already been equalized at the soak temperature when the rings were manually loaded into it. The heated bearing ring shown in Figure 3 was part of these trials. The rings were quenched one at a time in a Gleason quenching machine using Houghton 105 quench oil. The quench oil is drawn from a 10,000 gallon (37,854 l), temperature controlled central reservoir that maintains the oil temperature at 130°F ± 10°F (54°C ± 6°C). The maximum oil flow rate of 210 gal/min (795 l/min) was used during quenching, and each part remained in the quenching machine for an average of 47 seconds, at which time its temperature was approximately 137°F (58°C). The quenched 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. Rings with cracks were placed in a separate basket from crack-free rings. Both baskets were then tempered in a furnace preheated to 450°F (232°C). The delay time from quenching, inspection, 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 basket to enter the furnace received a temper that was longer than the second basket of that load. The minimum temper time was 4½ hours. The bearing rings were tempered only once. After the tempering operation was completed, the crack-free bearing rings from the second basket were re-inspected using MPI.

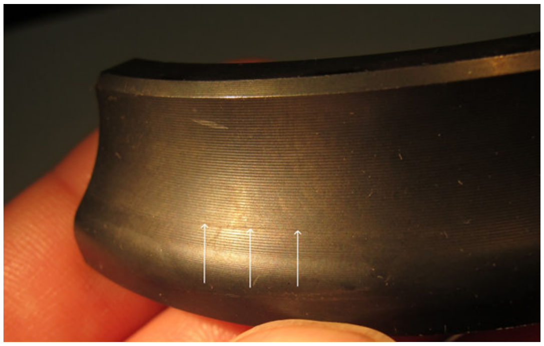
The production runs for the four loads were identical in terms of temperatures, timing, oil flow, and die pressure application except for pressure pulsing during the press quench. No pulsing of the die pressure was used during runs 1 and 3, and pulsing was used during runs 2 and 4. Pulsing periodically eases the applied pressure exerted by the inner and outer upper dies over the course of the quenching cycle, allowing the component to contract normally as it is quenched, while still maintaining the desired part geometry. When the pulsing mode is not activated the stresses introduced from frictional contact between the dies and the part being quenched may prevent normal contraction and expansion as the part cools. 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 physical contact with the part throughout the entire course of the quenching cycle. 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.

Table II contains data pertaining to numbers of cracked rings discovered for each production run after the press quench operation and after tempering. For the initial run, 29 of the 52 inner bearing rings exhibited MPI indications after press quenching, and 4 more rings from this batch were found to have cracks after tempering, for a total of over 63% of the first batch of rings had cracks on the race. For run #3, which also did not use pressure pulsing during the press quench, 59% of the rings had cracks on the race. For runs which used pulsing, no cracks were found after press quenching, and only 4 rings in run #2 were found to have cracks after tempering. The combined two runs that used pulsing had only 4 out of 103 rings, or 4%, of rings with cracks.

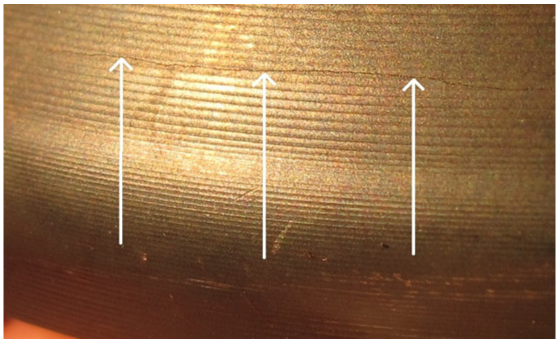
Table II. Numbers of Inner Bearing Rings with Cracks after Heat Treatment

Furnace Load	Number of Bearing Rings	Press Quench Setting	Number of Cracked Rings After Press Quench	Number of Rings Cracked After Tempering
1	52	No pulse	29	4
2	51	Pulse	0	4
3	51	No pulse	19	11
4	52	Pulse	0	0

A typical example of one of these cracked rings is shown in Figure 4a and b.



(a) Low Magnification of Crack.



(b) Higher Magnification of Crack.

Figure 4 – One of 29 inner bearing rings from the first furnace load 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.

Machining marks are pronounced, and the crack can be seen running in a direction roughly parallel to the machining grooves. 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.

Modeling Using DANTE Heat Treatment Simulation

Even before these four production trials were conducted, a decision was made to model the press quench step of the heat treatment to investigate the sensitivity of part stress to various process parameters. A series of twelve (12) heat treatment computer simulation models for this bearing ring were run using the DANTE program. [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 and typically encountered die wear 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 ring axially. Pulsing will relieve the radial constraint on the top and bottom die surfaces caused by the sticking. The model should show how much additional stress such sticking excursions in-process produce in the part. The phenomenon was studied using three (3) different models:
    a. Restricting radial movement of both top and bottom ring surfaces
    b. Restrict radial movement of the top ring surface
    c. Restrict 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 beneficial in Gleason’s practice, as the high tensile stresses produced by transient sticking are relieved by the pulsing.

Quantifying and predicting residual stress remains a substantial challenge to the metallurgical process engineer. 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 model 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 (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.

<u>Heat Transfer</u>

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

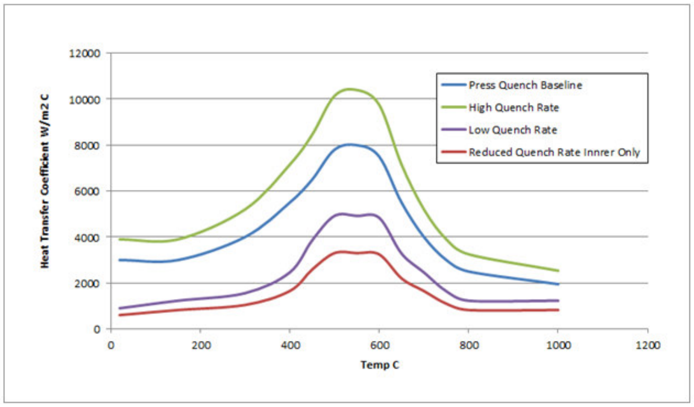


Figure 5 – Heat transfer coefficient as a function of temperature for the four (4) quenching scenarios examined in this investigation.

Table III. Nine (9) press quench process conditions examined in the modeling parametric study

CASE	FRICTION COEF.	AUST TEMP	QUENCH PRACTICE	PRESS LOAD
1	0.05	854.5°C	Standard Press Quench	17,800 N
2	0.05	854.5°C	Low Flow Press Quench	17,800 N
3	0.2	854.5°C	Standard Press Quench	17,800 N
4	0.5	854.5°C	Standard Press Quench	17,800 N
5	0.05	854.5°C	High Flow Press Quench	17,800 N
6	Sticking – Both Top and Bottom Dies	854.5°C	Standard Press Quench	Not Applicable
7	Sticking Top Die	854.5°C	Standard Press Quench	Not Applicable
8	Sticking Bottom Die	854.5°C	Standard Press Quench	Not Applicable
9	0.05	854.5°C	Reduced Quench on Inside Ring Surface; Standard Quench on Outside Surface	17,800 N

Loading and Simulation of Die Pulsing

Die loading and friction boundary conditions were applied as shown in the schematic in Figure 6. Mechanical loading was applied from the top die, as shown. Die frictional effects were considered from the top and bottom dies only. For the expander 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 7 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.

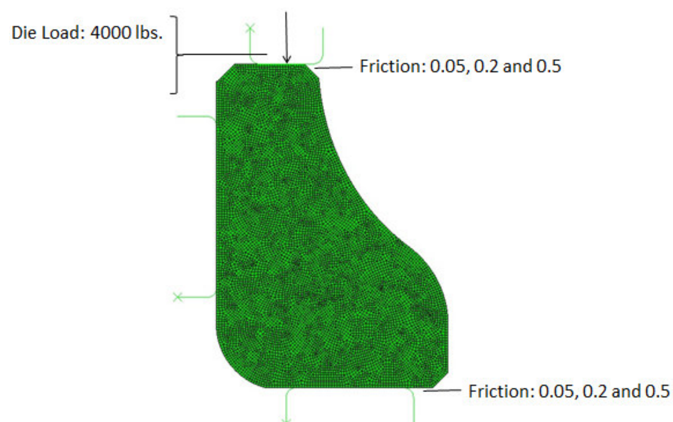


Figure 6 – Schematic illustrating press quench loading and frictional boundary conditions applied to the 52100 ring heat treatment model.

Results and Discussion of the Press Quench Modeling

For the cases examined (Table III), the maximum tensile stress was predicted to occur during the press quench consistently at a location 9mm from the ring base on the OD surface (ball raceway). This predicted location is precisely where production trials were found to crack, as discussed in the previous section and shown in Figure 4. It was this location that was chosen the reference for quantitative stress comparisons in this study.

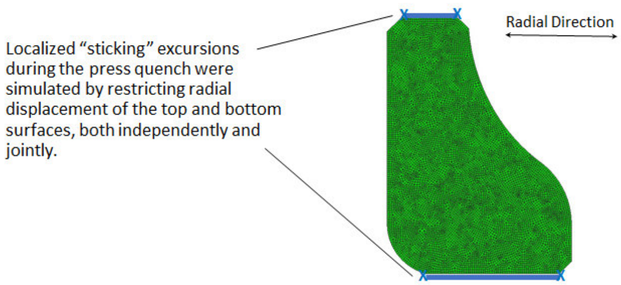


Figure 7 – Benefit of pulsing the dies was determined by modeling sticking friction during the press quench by restricting radial displacements of the top and bottom surfaces of the ring.

Table IV provides a comparison of predicted maximum principal stress for the 9 processes modeled, 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.

Stress contour plots, showing both the maximum in-process stress state and final stress state for the indicated conditions are shown in Figures 8 – 14. The results summarized in Table IV, along with the details in the stress contour plots, indicate that a primary driver for increased surface tensile stress in the part is sticking of the press quench dies during processing. In particular, sticking of the bottom die produces a predicted surface tensile stress of 860 to 880 MPa which is about 220 to 242 MPa higher than 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 stress on the ring outer ball groove surface. The predicted stress magnitudes from these nine cases agreed qualitatively with the Gleason plant experience cited in this paper.

Additionally, comparison of the model results in Table IV shows that reducing the applied quench rate decreases both the in-process and final surface stresses at the critical cracking location (Table IV; Compare Figures 9 and 10). With a 35% reduction in the quench heat transfer, the models predict a reduction in the maximum in-process surface stress from a baseline level of 642 MPa to 400 MPa. Conversely, increasing the quench rate by ~35% over the baseline rate was predicted to increase the in-process surface tension from 642 MPa to 746 MPa.

The effect of local quench application modifications on the stress response in the ring was also examined by modeling. In Case #9 the quench cooling on the bore of the bearing was reduced to a level ~60% lower than the baseline condition, while the quench cooling applied to the outer surface was kept at the baseline condition – see Figure 5 for the heat transfer coefficient values. Comparing Figures 8 and 14, the stress on the outer bearing surface is reduced from the baseline value of 642 MPa to 325 MPa. The exercise shows the utility of heat treatment modeling to investigate key process modifications virtually. The modeling tool can be used to design focused plant trials for quench press process optimization.

Table IV. 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	Friction Coef.	Press Quench Practice	Press Load (lbs)	Max. In-Process Stress	Final Max. Stress
1	0.05	Std Press Quench	17,800	642 MPa at 14 sec	400 MPa
2	0.05	Low Flow Press Quench	17,800	400 MPa at 22 sec	236 MPa
3	0.2	Std Press Quench	17,800	668 MPa at 12 sec	403 MPa
4	0.5	Std Press Quench	17,800	691 MPa at 14 sec	422 MPa
5	0.05	High Flow Press Quench	17,800	746 MPa at 14 sec	472 MPa
6	Sticking – Both Top and Bottom Dies	Std Press Quench	Not Applicable	882 MPa at 14 sec	338 MPa
7	Sticking Top Die	Std Press Quench	Not Applicable	680 MPa at 14 sec	393 MPa
8	Sticking Bottom Die	Std Press Quench	Not Applicable	860 MPa at 14 sec	371 MPa
9	0.05	Reduced Quench on Inside Ring Surface; Std Quench on Outside Surface	17,800	325 MPa at 22 sec	230 MPa

It is important to note that modeling 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 martensite phase transformation in the core of the ring, 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. Each figure plots the maximum principal stress in the race surface vs. time and the martensite phase fractions in the core and the surface vs. time for the press quench operation. 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 due to martensite formation in the core produces tension on the race 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 and thermal factors (e.g. from a press quench process).

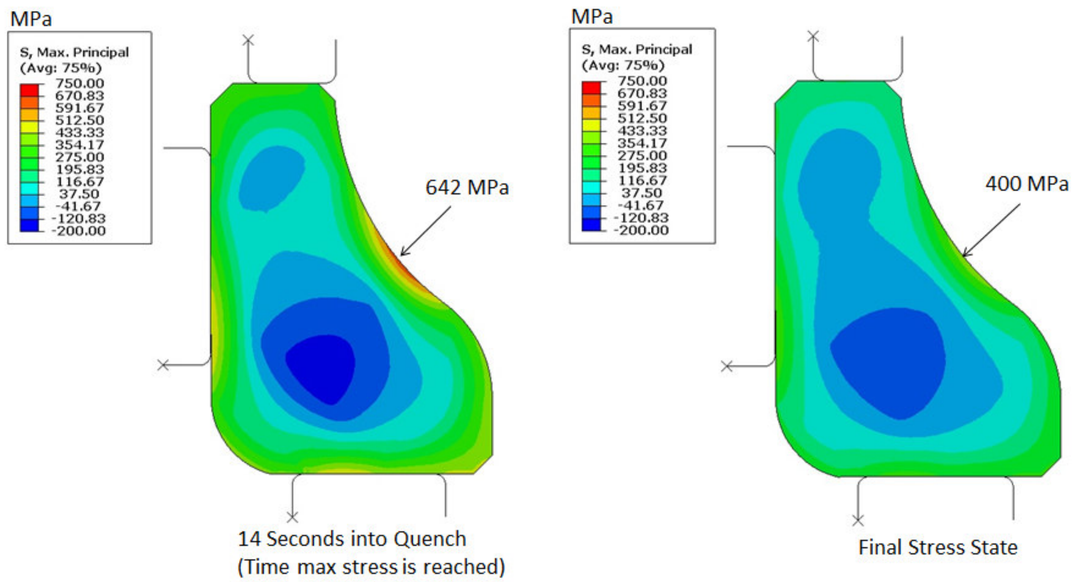


Figure 8 – Maximum principal stress at 14 seconds into press quench and at the end of the press quench for the baseline condition (Case #1 in Table IV)

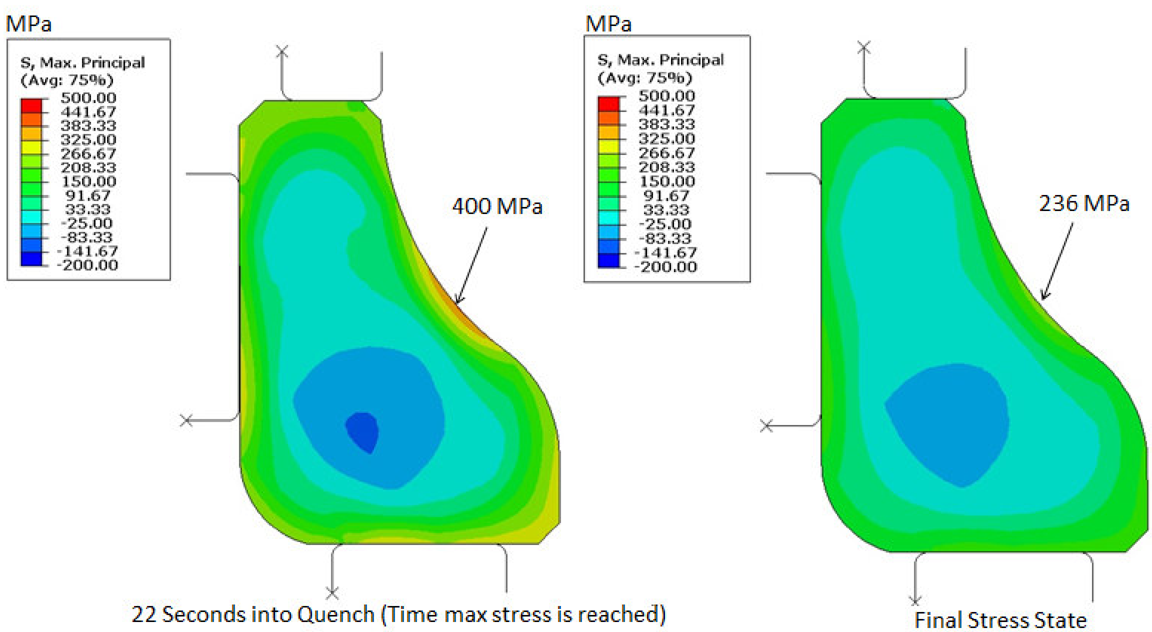


Figure 9 – Maximum principal stress at 22 seconds into press quench and at the end of the press quench, for the low heat transfer quench condition. (Case #2 in Table IV)

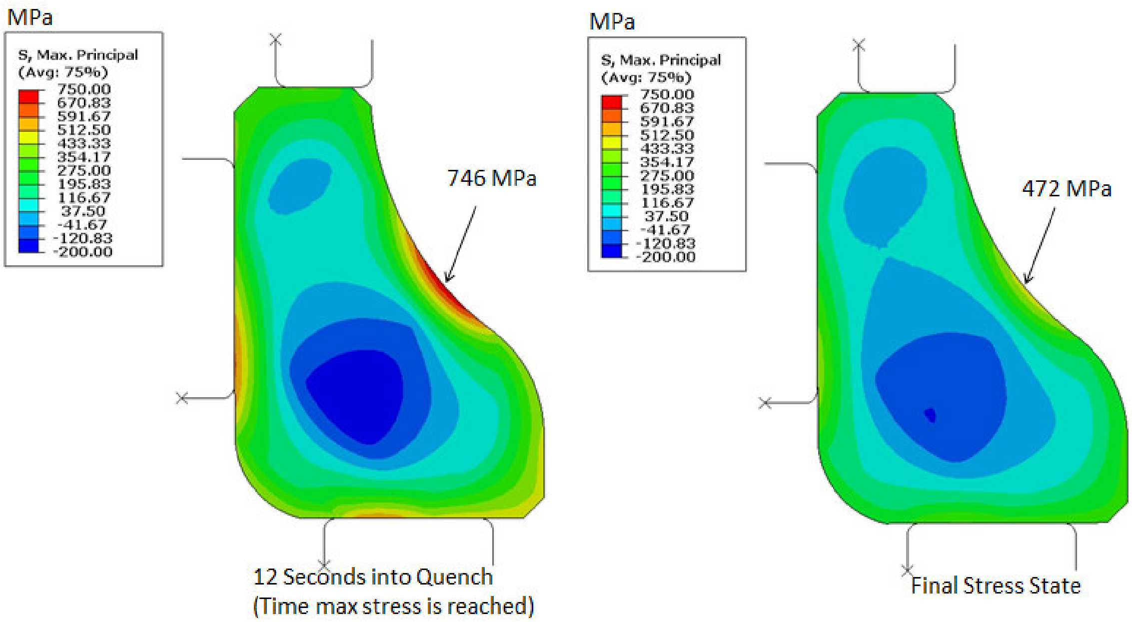


Figure 10 – Maximum principal stress at 12 seconds into press quench and at the end of the press quench, for the high heat transfer quench condition. (Case #5 in Table 2.)

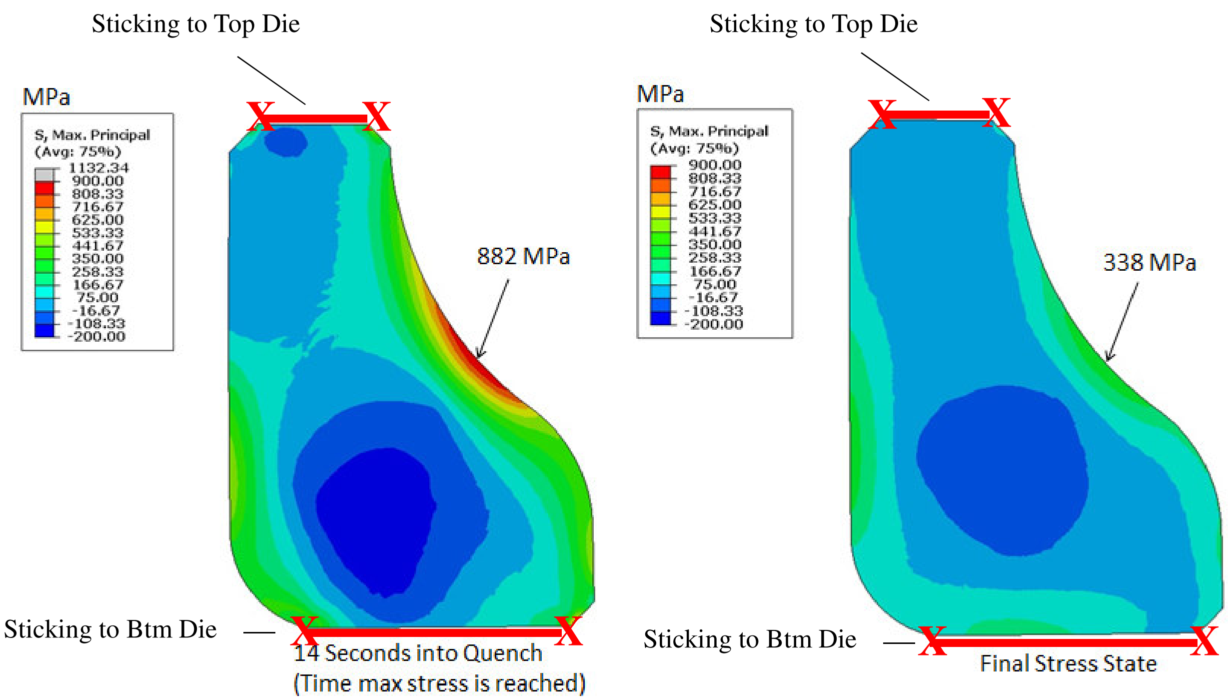


Figure 11 – Maximum principal stress at 14 seconds into press quench, with "Sticking" of both the top and bottom ring surfaces (radial displacement restriction). (Case#6 in Table IV)

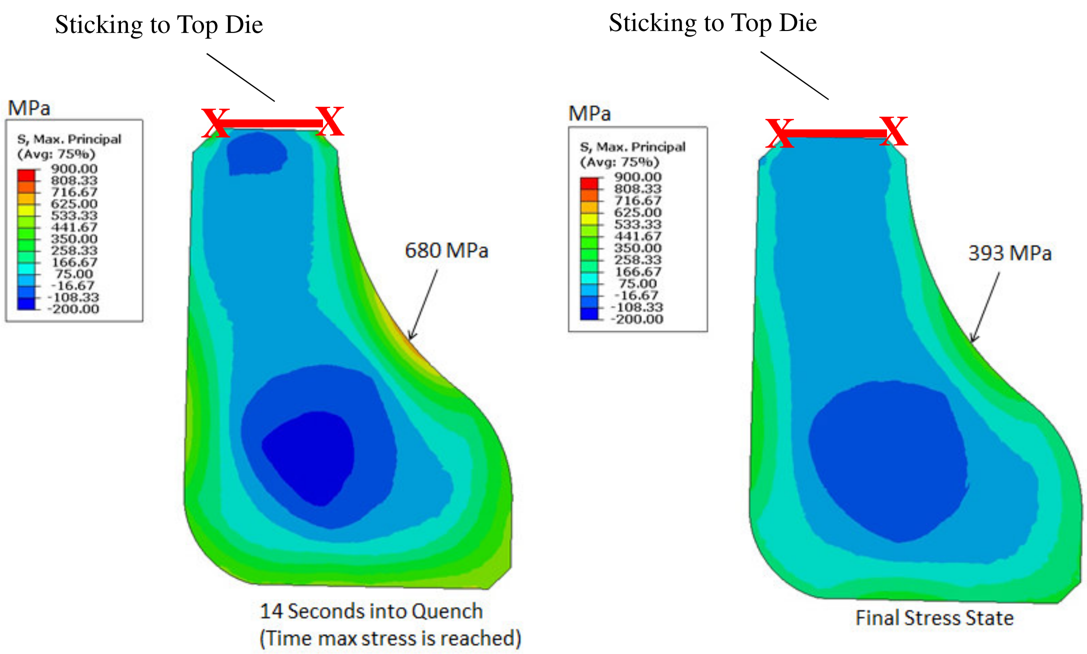


Figure 12 – Maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring top surface (radial displacement restriction). (Case #7 in Table IV)

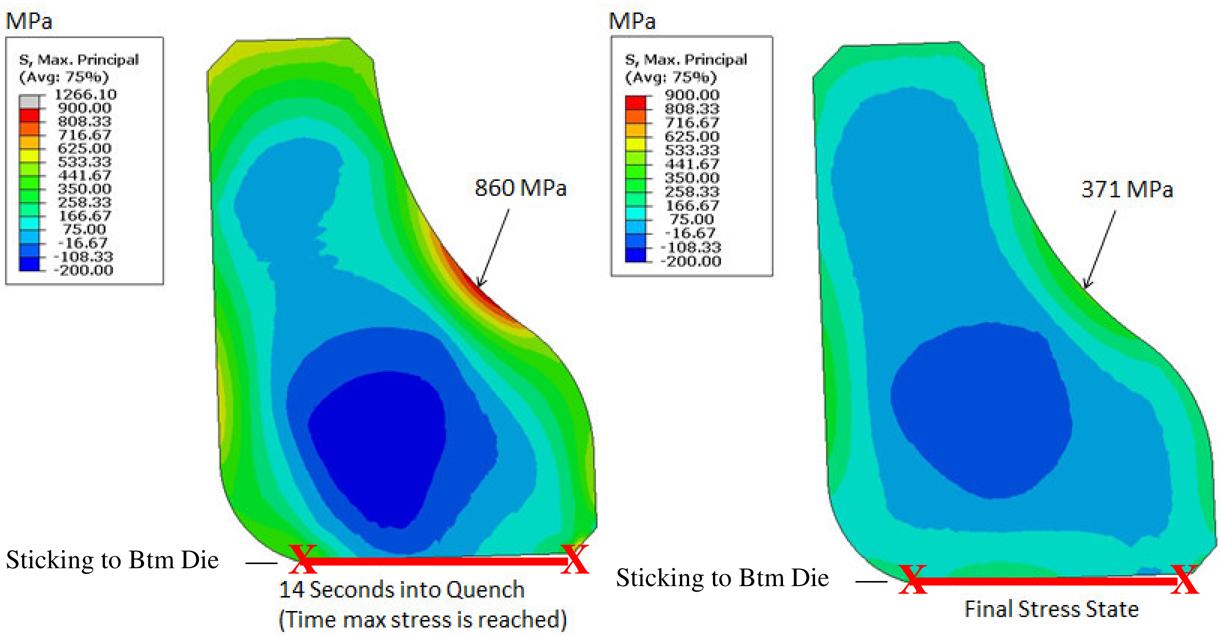


Figure 13 – Maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring bottom surface (radial displacement restriction). Case #8 in Table IV)

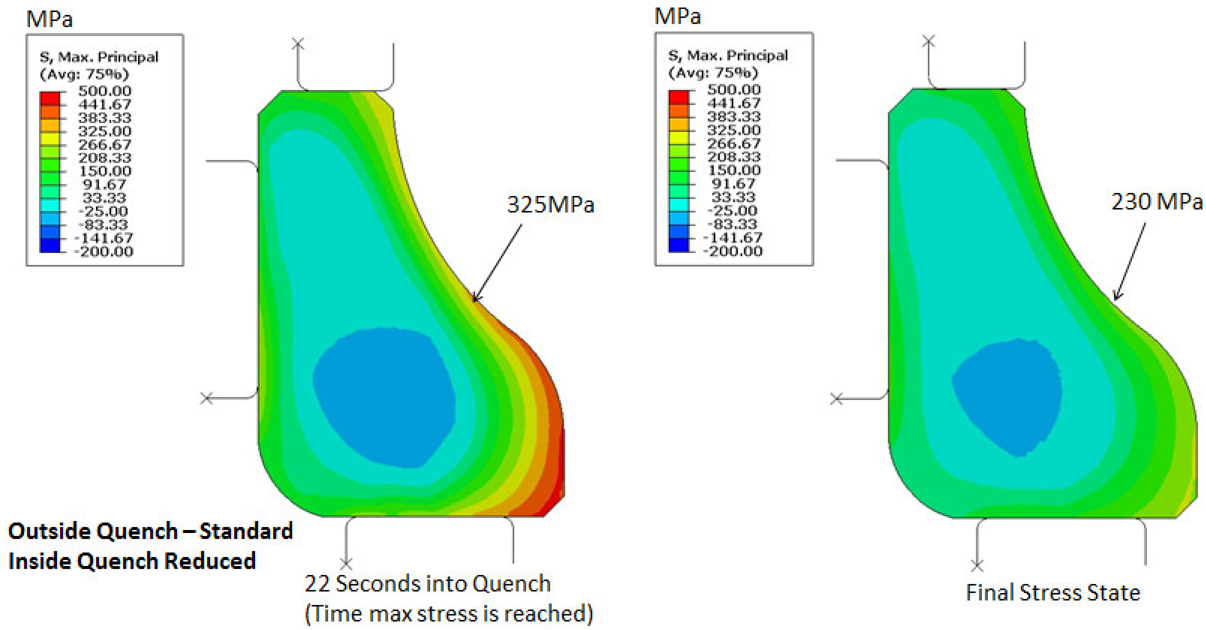


Figure 14 – Maximum principal stress at 14 seconds into press quench, with "Sticking" of the ring bottom surface (radial displacement restriction). (Case #9 in Table IV)

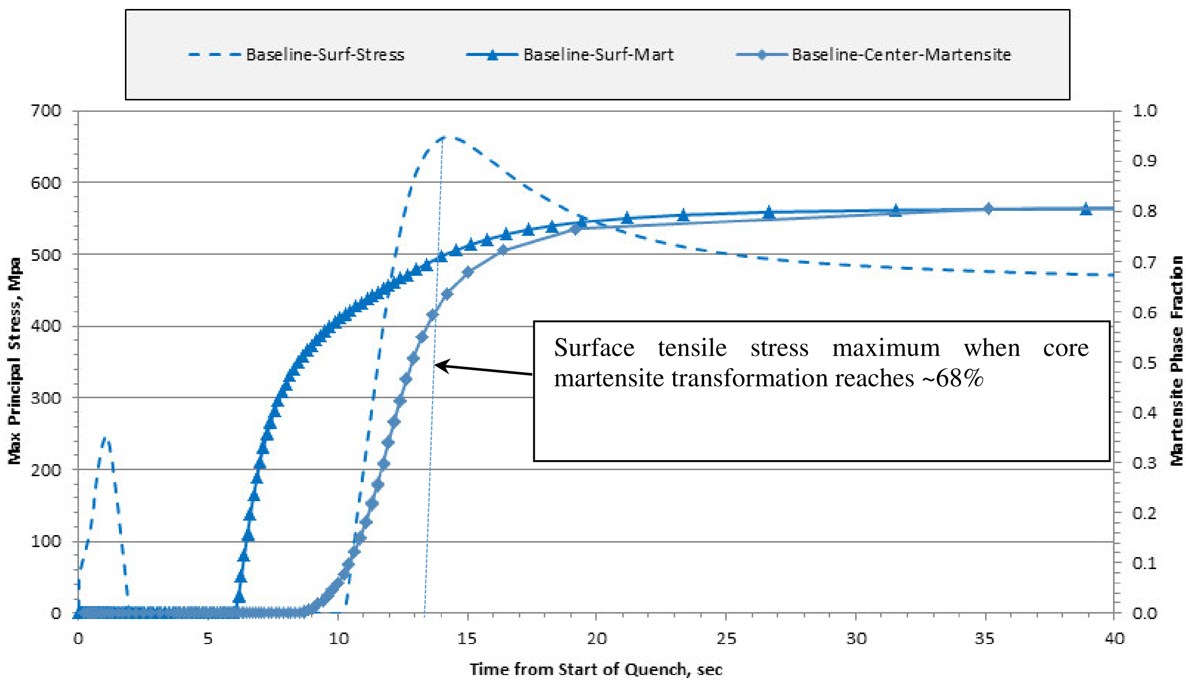


Figure 15 – Stress-Martensite-Time plot for the baseline press quench (Case #1), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

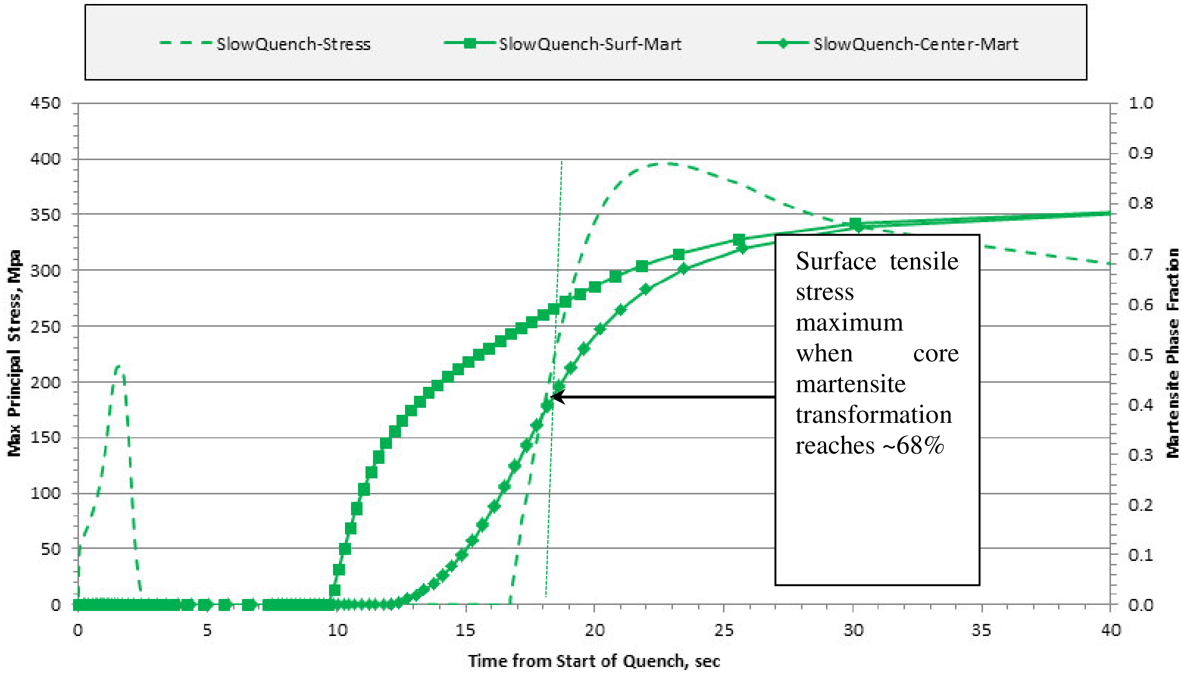


Figure 16 – Stress-Martensite-Time plot for the low heat transfer press quench (Case #2), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

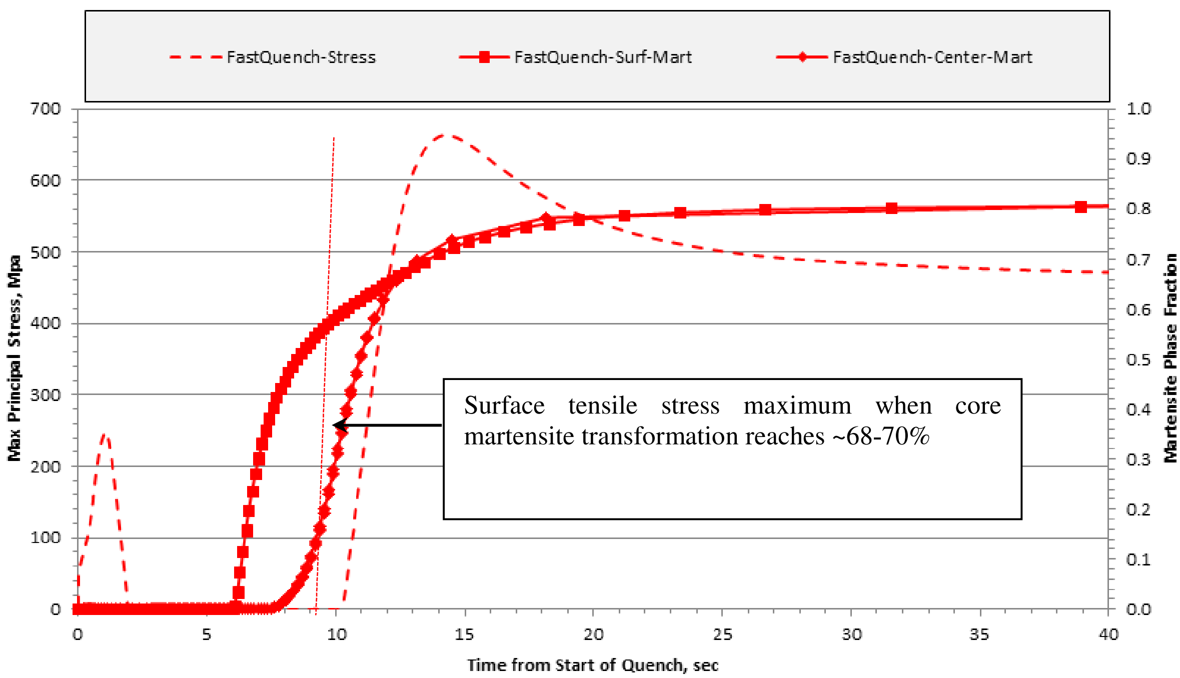


Figure 17 – Stress-Martensite-Time plot for the high heat transfer press quench (Case #5), showing how the delayed core transformation produces the transient tensile stress "spike" on the outer ring surface.

Conclusions

Experience with press quenching of 52100 bearing inner rings has demonstrated that a pulsing practice is beneficial in reducing cracking tendency on the raceway during the process. DANTE heat treating and loading models were useful tools in determining why the pulsing practice was beneficial, and also in examining additional process sensitivities such as the heat transfer during the press quench. For the bearing ring investigated in this study the following process sensitivities are 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 bore provided a significant reduction in both the in process and final stress at the critical outer raceway location.

- Surface sliding 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 simulation provides a means of investigating key press quench quenching 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 affect meaningful process improvement with respect to reduced stresses in quench pressed parts.

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