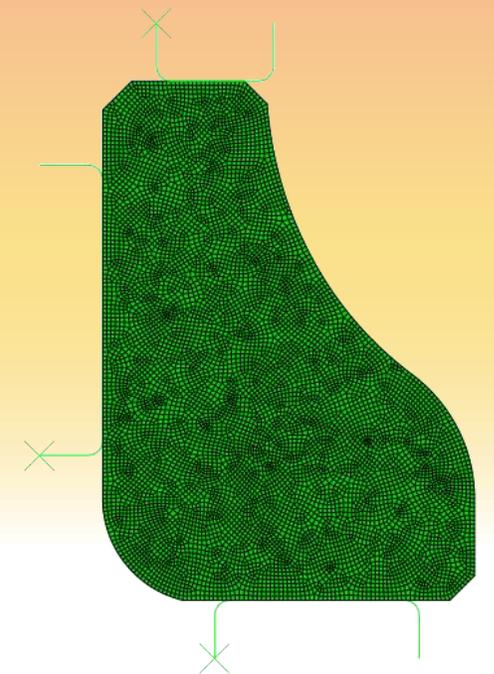
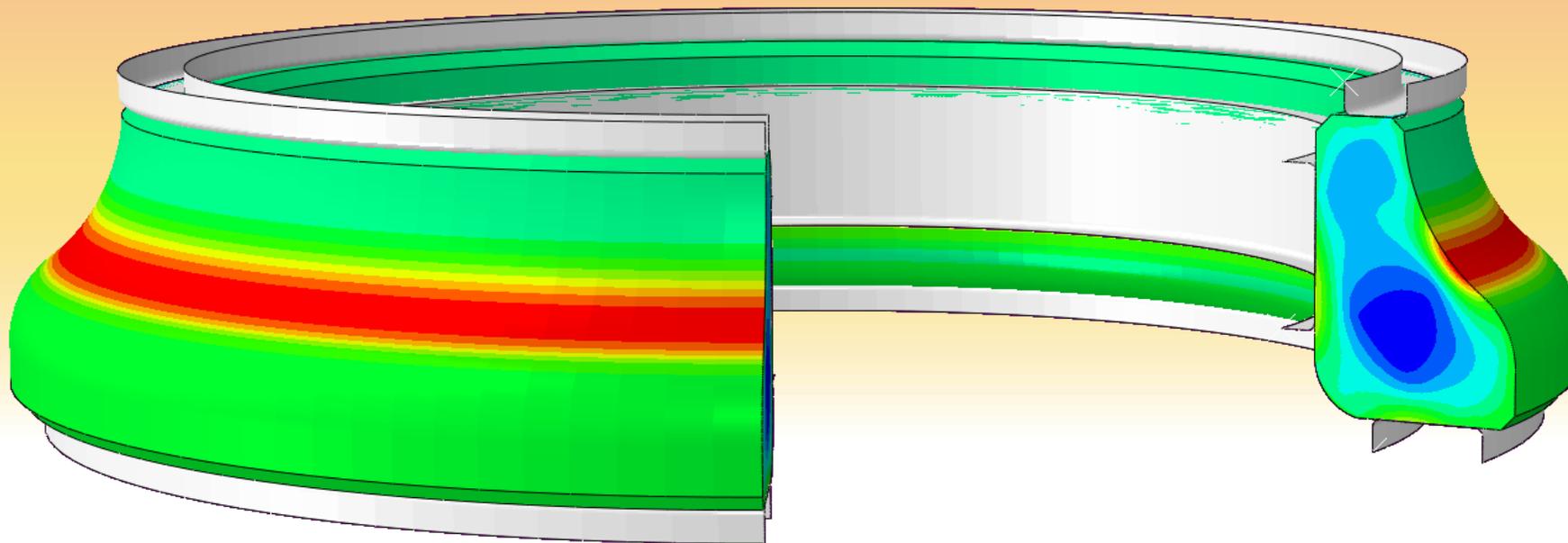




Understanding Process Sensitivities in Press Quenching



Introduction

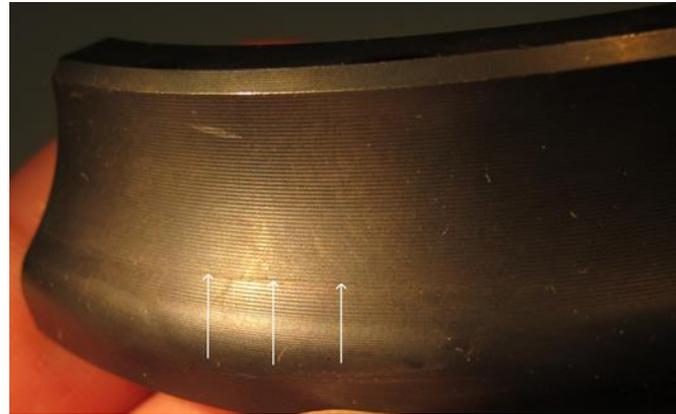
Press quenching is a highly specialized quench hardening technique for components which cannot be held in tolerance during a standard free quenching operation, such as spiral bevel gears and bearing races used in automotive and aerospace applications. The press quench operation aims to control the distortion of the part by applying loads to critical locations of the component while it is being rapidly cooled. The quench machines are highly adaptable to handle any given geometry and distortion mode; such as flatness, taper, and out-of-round. The quench flow rate can be further controlled by rotating the slotted rings to either constrict or liberate the flow of quenchant to different areas around the part. The restricting elements, coupled with thermal and transformation induced dimensional changes, create in-process and residual stresses, adding complexity to the existing process sensitivities present in other quenching processes.

In order to reduce the impact of in-process stresses and distortion, heat should be extracted from the part as uniformly as possible. This can be a challenge when part geometry is not symmetric, as larger mass/lower surface area regions will cool slower than lower mass/higher surface area regions. This leads to non-uniformities in phase transformation timing and stresses, and consequently distortion. The press quench tooling is designed to reduce the displacement caused by these non-uniformities, but it likewise has an impact on residual stresses and in-process stress magnitudes.



Part and Problem Definition

The basis of this study is a 4" OD bearing ring, made of AISI 52100 steel. A large number of these bearing rings were failing during the press quenching process, as seen in the table. Large circumferential cracks could be seen in the bearing race in over half of the parts after quench and temper. The quick solution was to pulse the die during the quench to periodically ease the pressure on the part. Quickly relieving and reapplying the load allowed the part to contract more naturally, while still maintaining the desired final shape. When pulsing was not used, frictional forces from the upper and lower dies contacting the part added stress to the process by not allowing the part to contract freely.



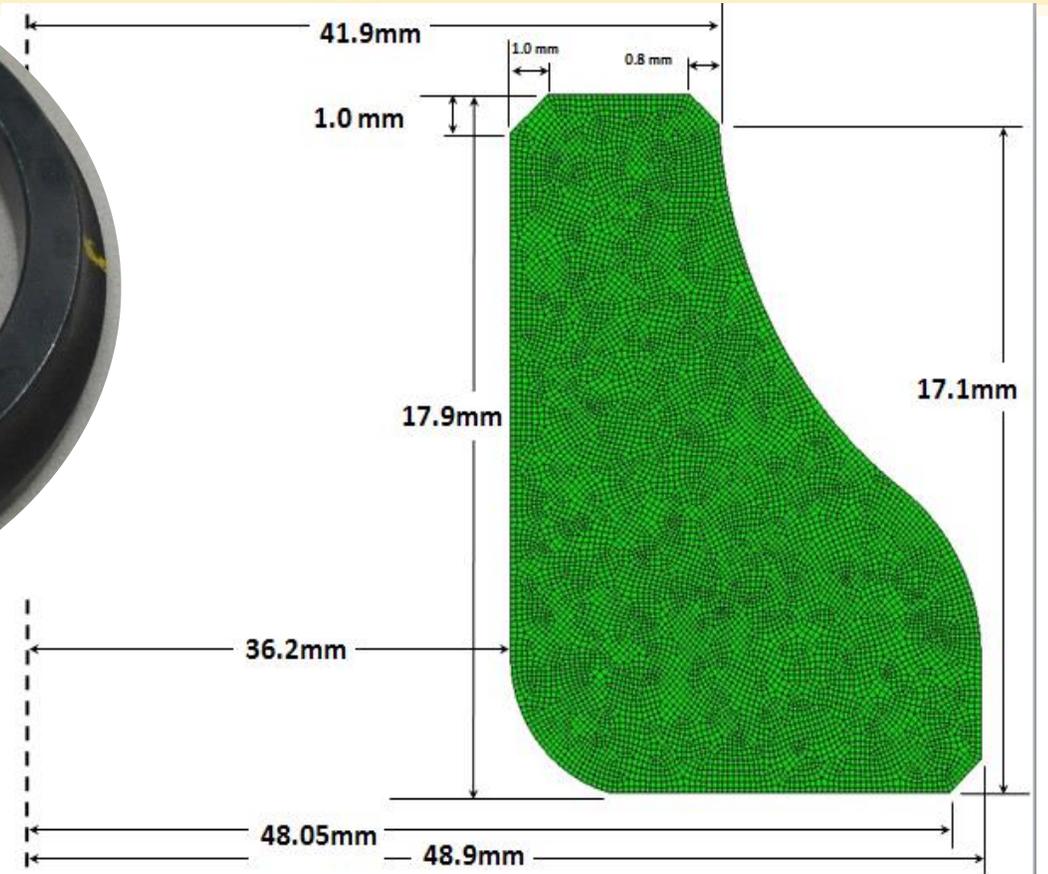
Furnace Load	Number of Bearing Rings	Press Quench Setting	Number of Cracked Rings After Press Quench	Number of Rings Cracked After Tempering
1	52	No Pulse	29	4
2	51	Pulse	0	4
3	51	No Pulse	19	11
4	52	Pulse	0	0



Magnified view of bearing race crack

Model Definition

In order to have a full understanding of the mechanisms at work in the stated problem, an FE model was developed to examine several process sensitivities. A fine mesh was applied to a 2D, axisymmetric cross section of the bearing race to accurately capture the heat transfer and stresses leading to the failures. The figure to the right shows the meshed FE model consisting of 9,367 nodes and 9,188 linear elements. The table below the figure shows the chemistry for AISI 52100 steel. The DANTE heat treatment simulation software has 52100 steel in its material database and was used for the following analyses.



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

Chemistry Specification for AISI 52100 Steel

Process Definition

Frictional Effects

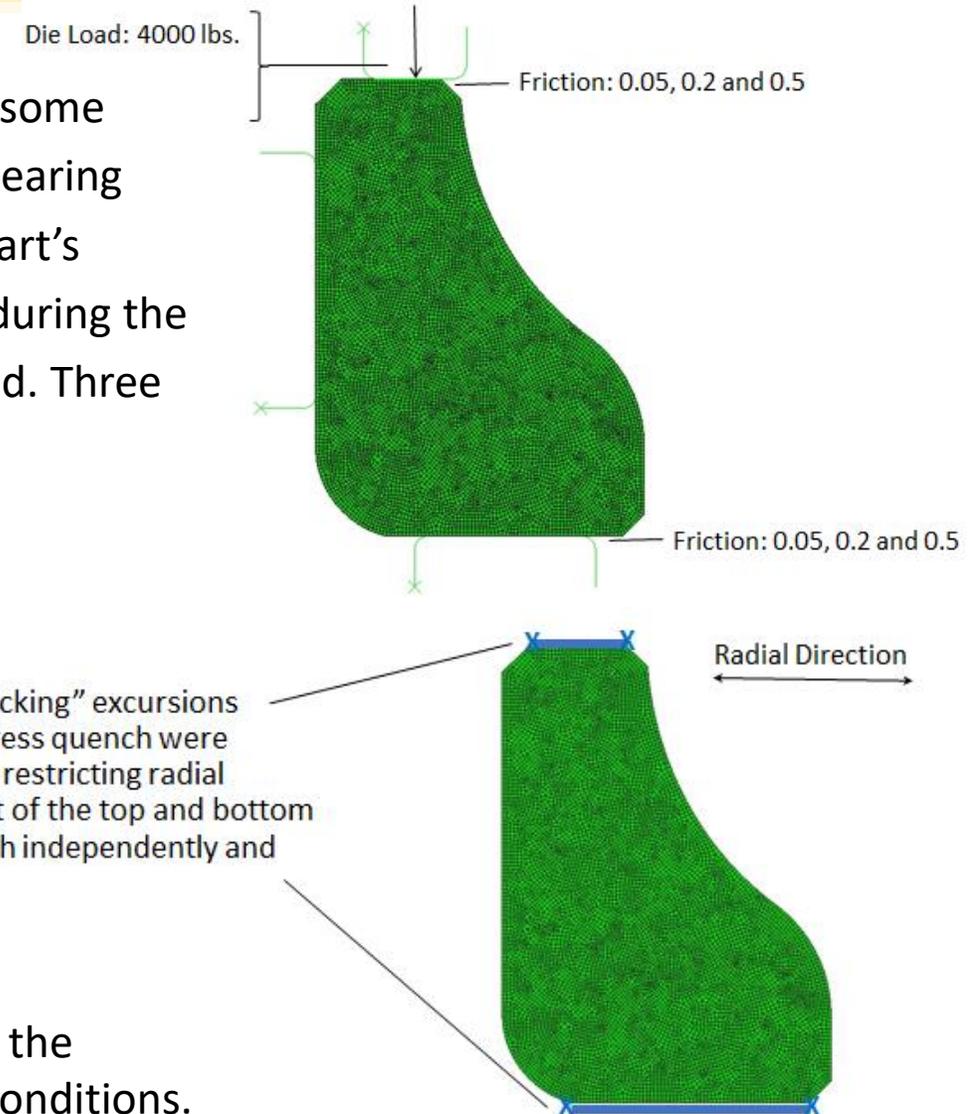
Frictional forces from the press quenching process will be examined, and how they affect residual stresses. As the part cools and shrinks, there will be some friction between the part and the quench dies as the dies work to keep the bearing race flat. In some cases the part will stick to the quench dies, impeding the part's ability to contract naturally. This can lead to undesirable stresses in the part during the quench process. In this study, six different friction conditions will be evaluated. Three conditions will use a constant friction coefficient and they are:

- 0.5
- 0.2
- 0.05

Several conditions of sticking between the dies and the part will also be explored:

- Upper die to top of part
- Lower die to bottom of part
- Upper and lower dies

The sticking was modeled by fixing the selected areas in the radial direction, restraining the bearing race's natural contraction, as if the part were stuck to the quench die. To the right is the die placement and loads prescribed by these conditions.

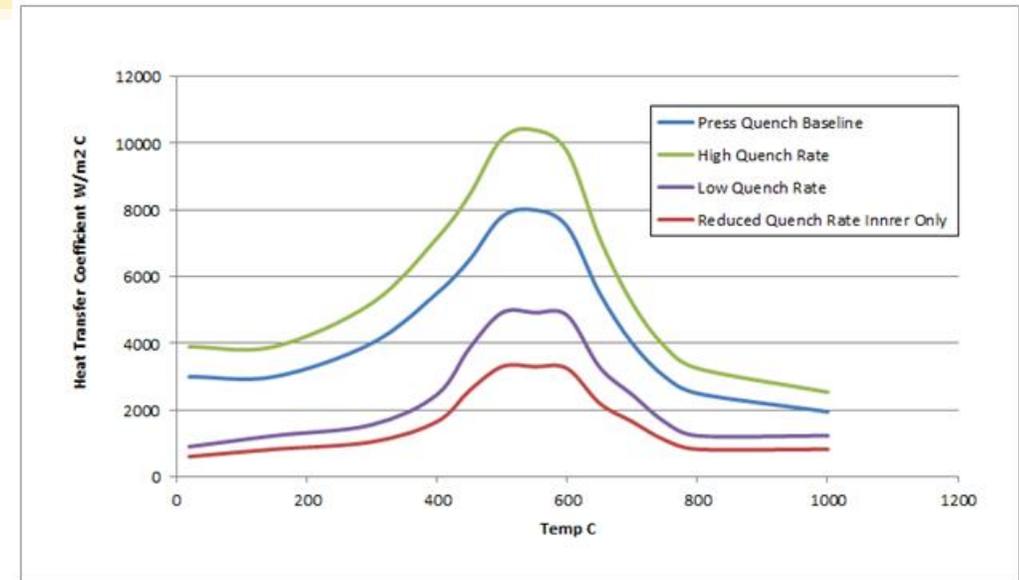


Process Definition

Quench Rate Effects

In addition to the six friction conditions, four quench rates were also examined to evaluate their effect on stress development. They are:

- Standard Press Quench profile, used as a baseline representing the current process
- High Flow Press Quench
- Low Flow Press Quench
- Reduced Quench On Inner Ring Surface
- The three additional quench rates were modeled as factors of the baseline. The plot of each of these heat transfer coefficients vs. temperature can be viewed to the right. Bottom right is the full 9-case test matrix used for this parametric study.
- The standard, low, and high quench rates are evaluated with the lowest friction coefficient, while the standard quench rate is used for the two higher friction coefficients and the sticking conditions. The final case uses the lowest friction coefficient, along with a reduced ID quench rate and a standard quench rate on the OD.



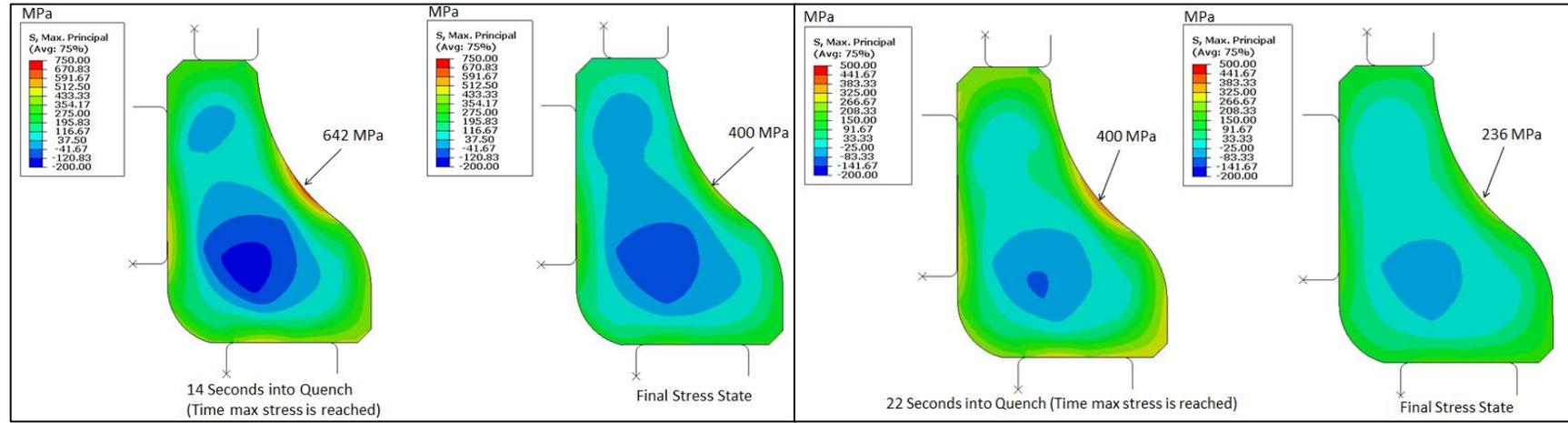
CASE	FRICTION	AUST TEMP	QUENCH PRACTICE	PRESS LOAD
1	0.05	1570°F	Standard Press Quench	4000 lbs
2	0.05	1570°F	Low Flow Press Quench	4000 lbs
3	0.2	1570°F	Standard Press Quench	4000 lbs
4	0.5	1570°F	Standard Press Quench	4000 lbs
5	0.05	1570°F	High Flow Press Quench	4000 lbs
6	Sticking – Both Top and 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

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

Vary Quench Results

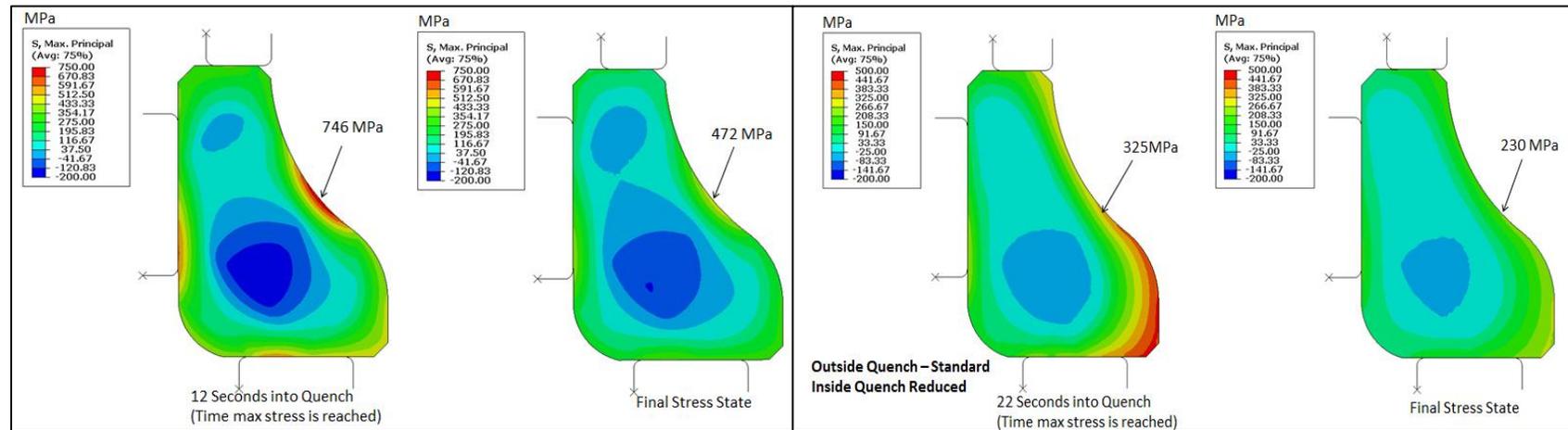
The peak in-process stress, and residual stress states of the four quench rate conditions are shown in the contours to the right. A few observations from the figures:

- All three of the equal ID and OD quench rates show an in-process spike of tensile stresses in the region where the cracks were forming.
- The high flow quench displayed the highest tensile stress at 746 MPa, occurring 12 seconds into the quench
- The low flow max tensile stress was 400 MPa, occurring 22 seconds into the quench.



Standard Quench Rate

Low Flow Quench Rate



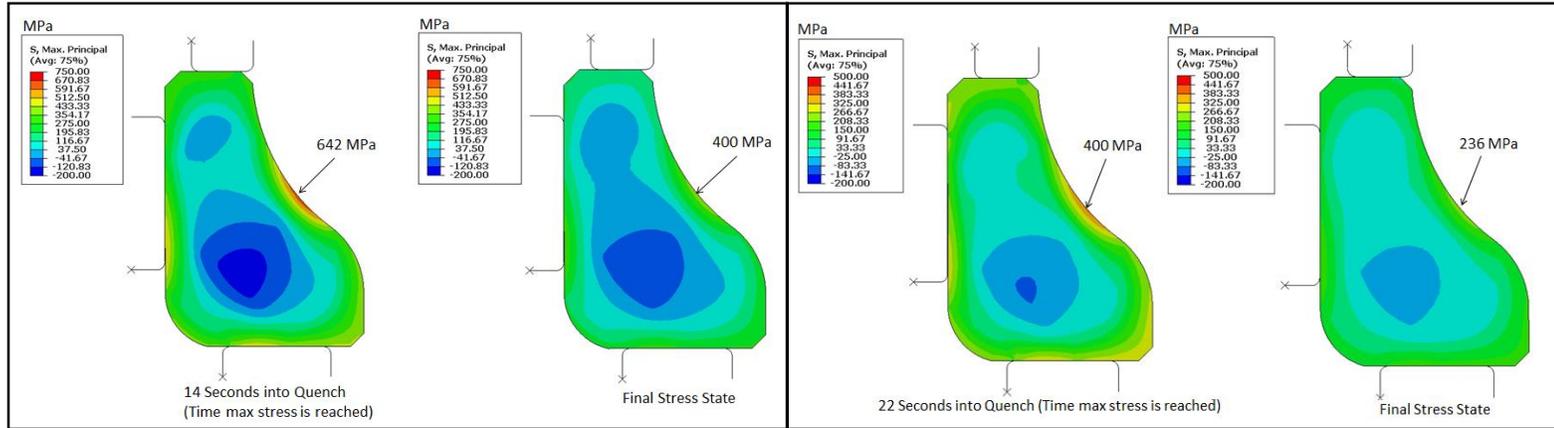
High Flow Quench Rate

Reduced Inner Ring Quench Rate

Vary Quench Results, cont'd

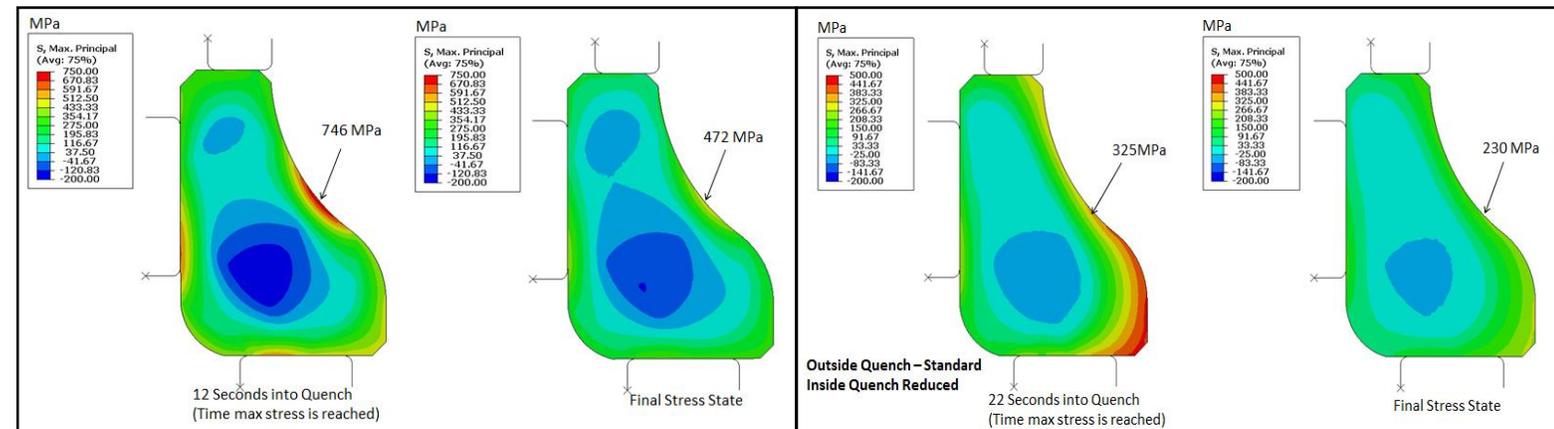
A few closing remarks on the quench rate sensitivity study:

- While varying the quench rate does show a change in the magnitude of in-process tensile stresses, the location of this stress does not change if the quench rate on the ID and OD are equivalent.
- The last quench case, however, shifts the max in-process stress to the bottom of the part due to slower cooling on the ID, and reducing the problem region tensile stress significantly.
- The standard quench rate in-process stress is not likely to cause the cracking consistency seen.



Standard Quench Rate

Low Flow Quench Rate



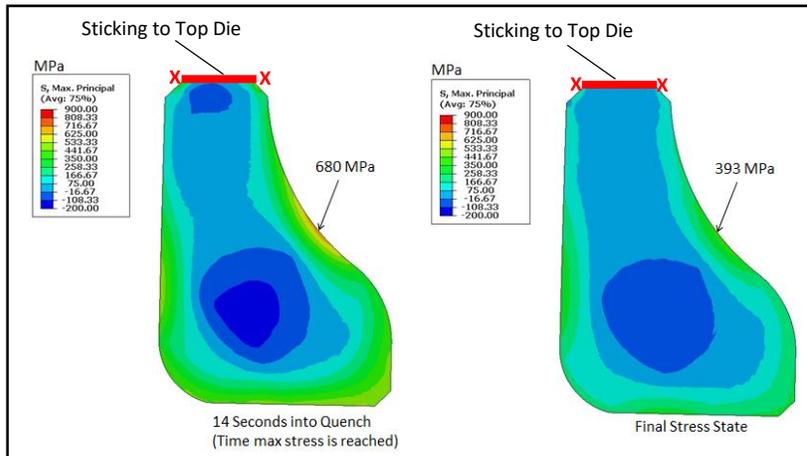
High Flow Quench Rate

Reduced Inner Ring Quench Rate

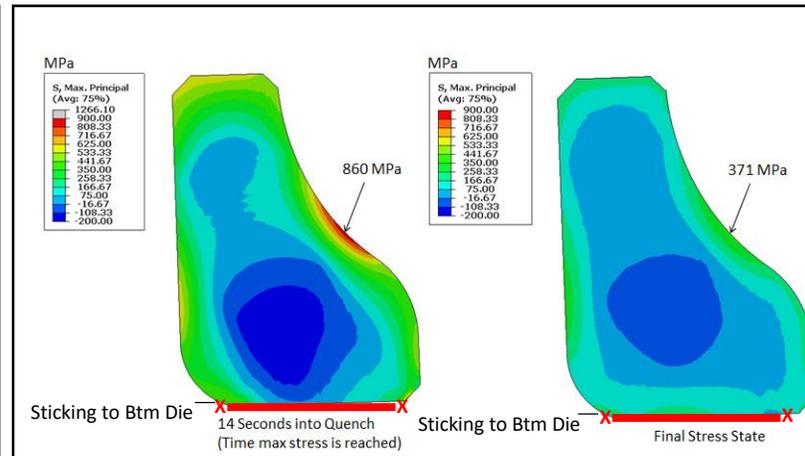
Friction Sticking Results

The contours below demonstrate the effect of the three sticking conditions. A few observations from the contours:

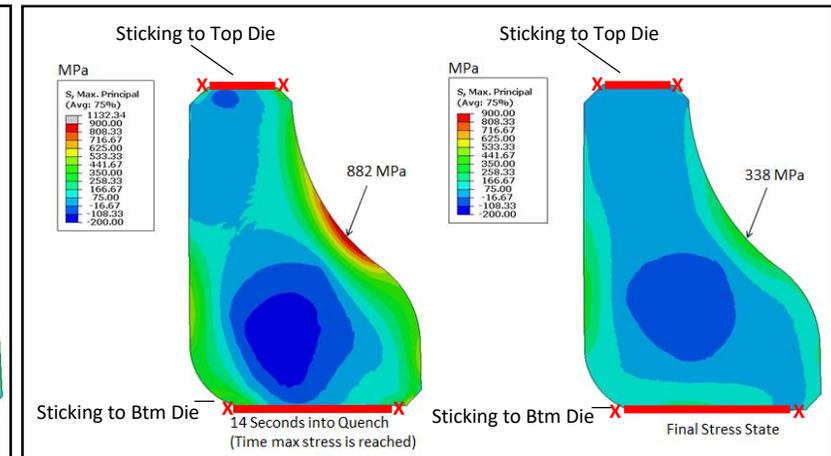
- The bottom die sticking exhibits the largest in-process stress: 882 MPa with top die sticking also and 860 MPa without the top die sticking.
- Top die sticking alone presents a max in-process stress of only 680 MPa, slightly higher than the standard quench rate model.
- Comparing the max in-process stress of the bottom die sticking models to the standard quench model, the sticking model stress is over 200 MPa greater in magnitude.
- This shows the importance of pulsing and its significant effect on stress formation. The mechanism behind the large stress formation in the bearing race is due to a late phase transformation in the larger mass region of the ring. The volume expansion of this phase, coupled with frictional sticking at the base, transfers the stress concentration to the bearing race.



Frictional sticking on top surface



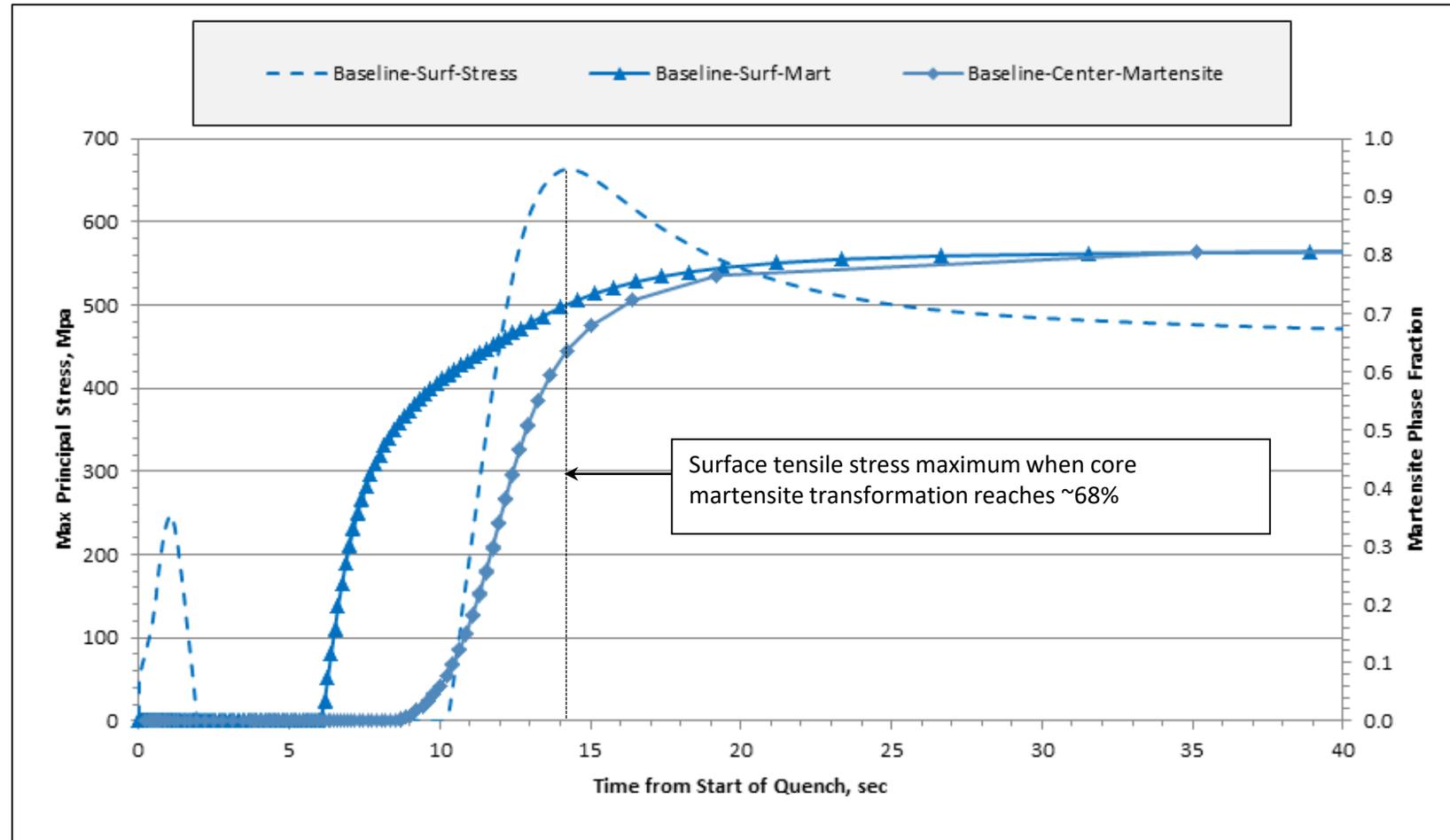
Frictional sticking on bottom surface



Frictional sticking on top and bottom surfaces

Results - Summary

- The timing of the martensite transformation in the larger mass region of the bearing ring is the main cause for the spike in tensile stresses during quenching.
- The graph shows stress at the bearing surface spike as the martensite in the core forms.
- The volume expansion from this transformation forces the top of the part to move up and the base to move out radially, pulling the bearing race apart and into tension.
- Pulsing ensures that this tension does not reach failure by allowing the part to move in response to the increased stresses.



Results – Summary, cont'd

The table shows the maximum in-process and maximum residual stress at the problem location for each of the nine testing conditions. The following conclusions can be drawn from this work:

- An increase in the friction coefficient increases the max stress magnitudes only slightly.
- If the part gets stuck to the bottom quench die, a dramatic increase of in-process stresses occur.
- The high in-process stress when the bottom die sticks is expected to cause cracking issues, particularly with any surface stress raisers.
- Varying the quench rate shows some change in stress levels, with lower quench rates giving lower max stresses, and higher quench rates producing larger magnitudes of stress.

Summary of max in-process and final residual stresses at the bearing race location

CASE	FRICTION	QUENCH PRACTICE	PRESS LOAD	MAXIMUM IN-PROCESS STRESS (MPa) – TIME IN QUENCH WHEN OCCURS	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

Links to Relevant Case Study Material

Material related to this Case Study

[Understanding Process Sensitivities in Press Quenching: An Integrated Approach \(2015\)](#)

[Investigating a Die Quench Cracking Problem in 52100 Steel Bearing Rings with Computer Simulation \(2016\)](#)

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