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Process Innovation to Eliminate Cracking Problems in Large Diameter Parts with Nonuniform Wall Thickness

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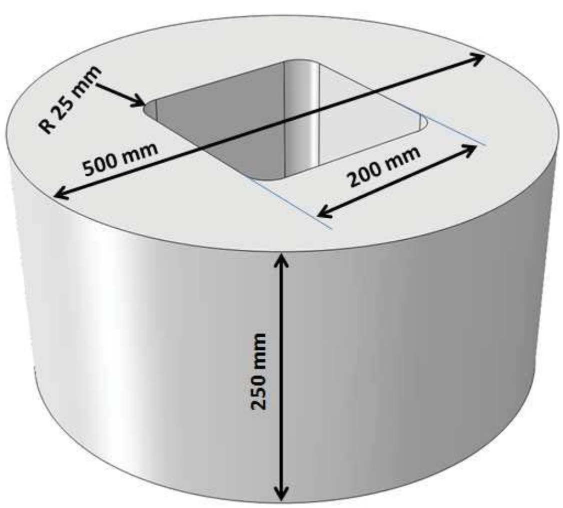
Introduction

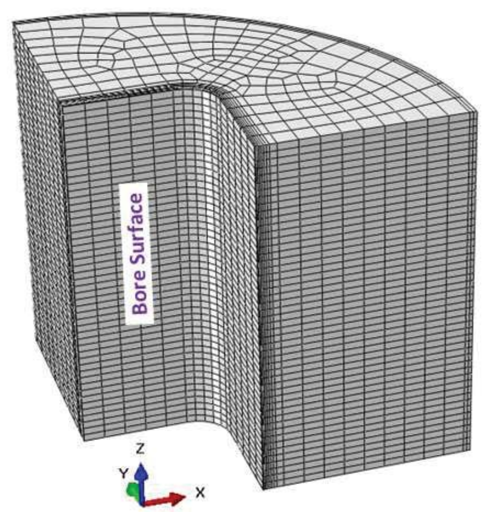
The induction hardening process has been widely adopted in the heat treatment industry due to its energy efficiency, process consistency, and clean environment. Compared to traditional furnace heating and liquid quenching processes, induction hardening is more flexible in terms of process adjustment for improved results. The commonly modified process parameters are frequency and power of the inductor, method and timing of power application, and spray quench rate. In this study, a scanning induction hardening process of a generic coupler made of AISI 4150 is investigated by heat treatment process modeling using DANTE. The corner of the non-axisymmetric bore experiences high tensile stresses during the hardening process, which leads to a high possibility of cracking during quenching. The model is used to explain why and how the high tensile stresses are generated. To reduce cracking potential, an innovative process is proposed that reduces the high tensile stresses at the corner, which is demonstrated and validated by modeling. This process modification not only reduces the magnitude of the tensile stress at the corner during induction hardening, but also converts the surface residual stresses at the corner from tension to compression. The residual compression on the bore surface provides improves fatigue performance for the coupler during service.

Descriptions of Coupler Geometry, FEA Model and Hardening Process

The generic coupler is made of AISI 4150, and the dimensions are shown in Figure 1(a). The bore is a square shape, so the wall thickness varies. One quarter of the coupler is modelled to represent the whole part due to its symmetric geometry. The mesh for finite element model has 19,074 nodes and 16,850 hexagonal linear elements, as shown in Figure 1(b), with the inner and outer regions having finer mesh than the part interior.



(a)



(b)

Figure 1: (a) Geometry of the generic coupler, and (b) finite element mesh.

A scanning induction hardening process is applied to harden the bore of the coupler. The width of the inductor is 50.8 mm, and the scanning speed is 1.27 mm/s. The scanning process starts from the bottom of the coupler and travels upward. The spray quench follows the inductor, with a gap of 12.7 mm. Therefore, there is a 10 second delay before being quenching. The minimum case depth is 6.5 mm. The entire scanning process takes 236.85 seconds. Once the spray is completed, the coupler is cooled to room temperature in air.

Snapshots of temperature, stress, phase distributions at 136.6 second of the hardening process are shown in Figure 2.

A portion of the model is removed so the stresses under the surface of the corner fillet can be viewed. Displacements are magnified 10 times. The stress contour in Figure 2(b) is plotted using a local cylindrical coordinate system, so the hoop stress at the corner fillet is in the tangential direction. Figures 2(c) shows the austenite phase that is produced by the heating at this time, and Figure 2(d) shows the martensite that has formed as a result of the spray quenching. The stress state in Figure 2(b) is a combined effect due to both the thermal gradient and phase transformations.

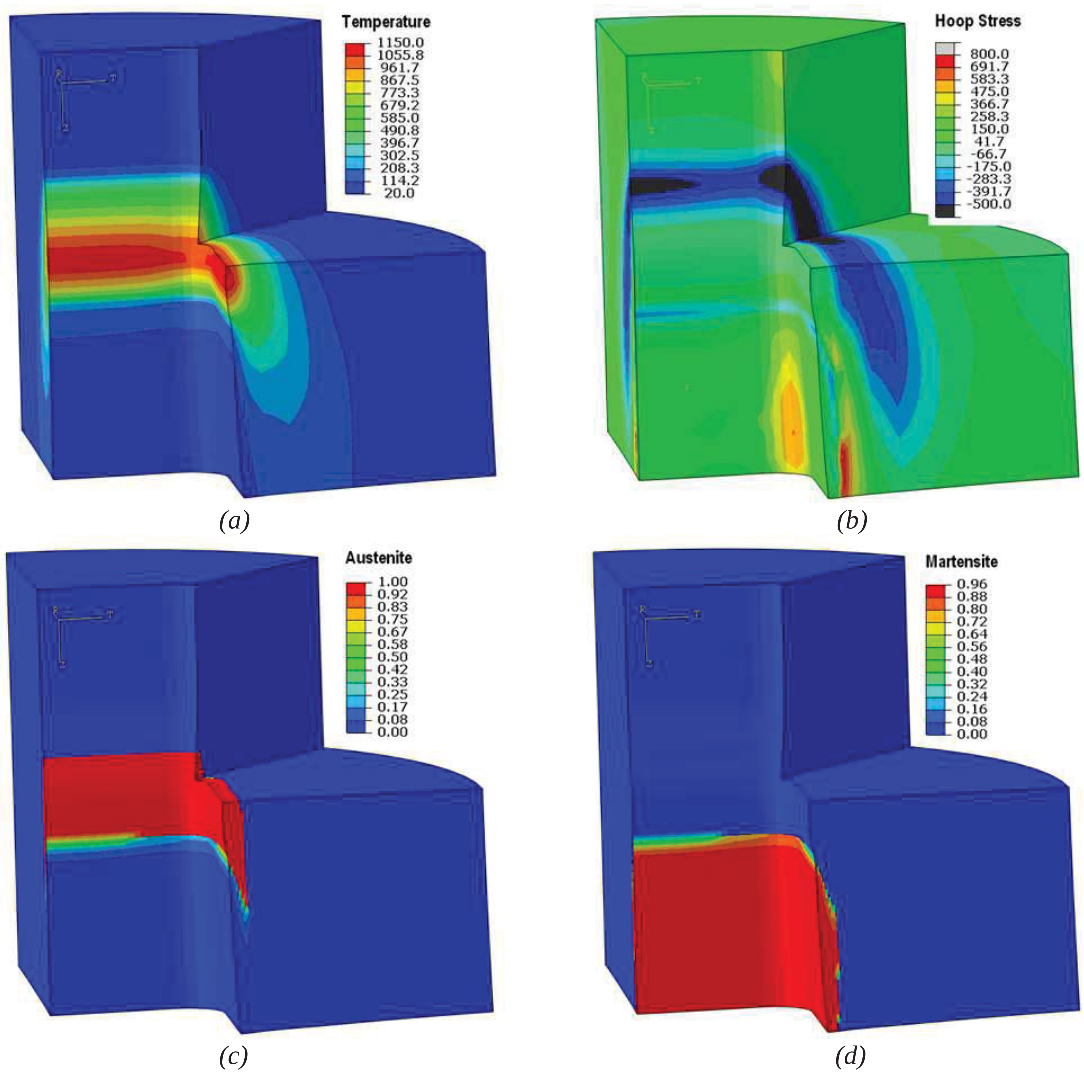


Figure 2: (a) Temperature, (b) hoop stress, (c) austenite, and (d) martensite distribution at 136.6 second during induction hardening process.

The predicted axial stress, hoop stress, martensite and radial displacement at the end of the hardening process (as-quenched condition at room temperature) are shown in Figure 3. The case depths are 8 mm and 10 mm, respectively at the corner fillet and flat bore surfaces, as shown in Figure 3(c). The predicted residual stresses in the axial direction, Figure 3(a), at the flat bore surface are compressive and range from about -100 MPa to -350 MPa. These values compare to residual tension about 250 MPa at mid-height of the corner fillet surface. In Figure 3(b), the predicted hoop stress at mid-height of the corner fillet surface is around 1000 MPa, which has a high potential for cracking. High residual tension at the fillet surface also increases the cracking possibility during service as the fatigue performance is reduced. Under the hardened case, residual tension is predicted in both the hoop and axial directions. However, the cracking potential under the case is low relative to the surface location because of greater energy required to initiate a sub-surface crack. Radial displacement is shown in Figure 3(d) using the cylindrical coordinate system. Radial shrinkage is predicted, with around 80 um to 100 um for the OD surface, and 200 μm for the bore. Over 300 um radial shrinkage is predicted at the middle height of the corner fillet. Because this is a scanning process, residual stress, phase and displacement are different between the top and bottom of the coupler.

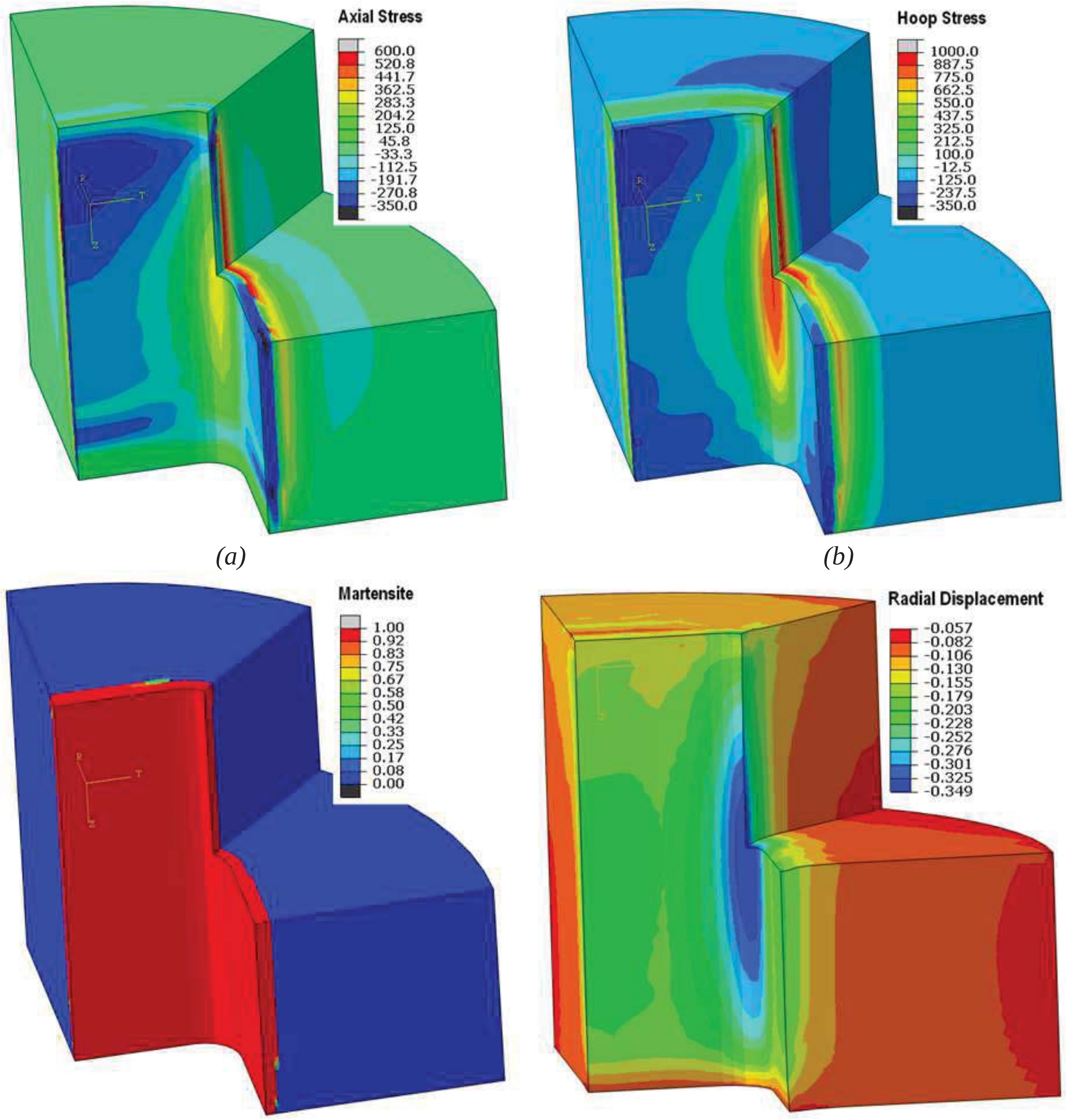
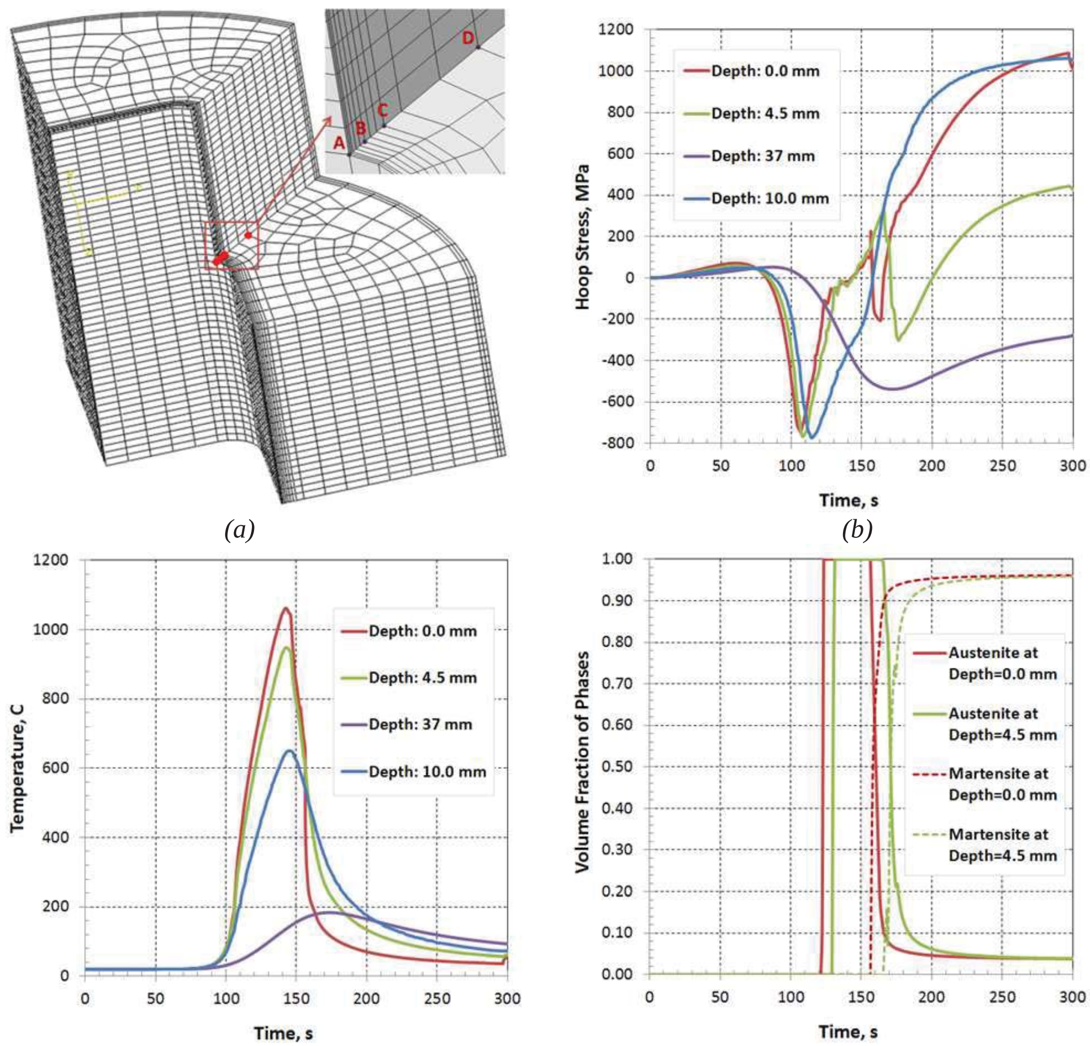


Figure 3: (a) Axial stress, (b) hoop stress, (c) martensite, and (d) radial displacement distributions at the end of induction hardening process.

During the induction hardening process, both the thermal gradient and phase transformations contribute to the stress state. Four points shown in Figure 4(a) are selected to understand the stress evolution process. The four points, A, B, C, and D, are located at mid-height of corner fillet, with depths of 0.0, 3.5, 10.0 and 37.0 mm, respectively from the surface. Points A and B are in the hardened case, point C is under the case, and point D is in the core. During heating, the bore surface experiences compression due to the surface thermal expansion and constraint by the cold body. When austenite forms at the bore surface, compression drops because of the phase change. There is a gap between the inductor and the spray, and the surface temperature at point A drops from 1050 to 800 °C due to the 10 second dwell before being spray quenched. The main reason for the temperature drop is thermal conduction from hot section into the cold body. The gap between the inductor and the spray, or dwell time, can have significant effect on the quenching results. After martensitic transformation is completed along line A-D, the hoop stresses at the surface point A and inner point C increase significantly by stress concentration due to temperature balance. An axial surface crack is expected to form near mid-height of the corner fillet, and similar cracks have been observed during bore hardening of parts with non-uniform wall thicknesses.

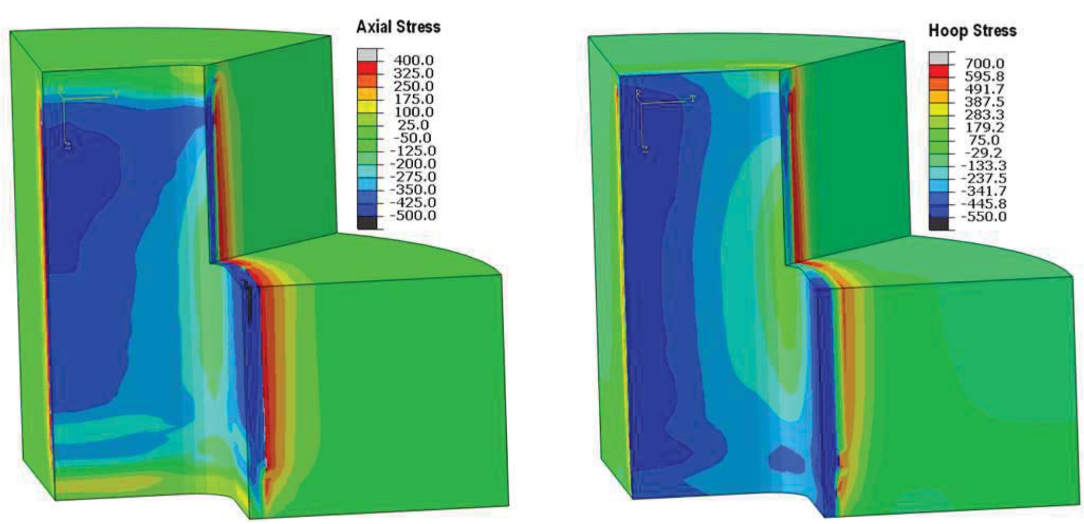
An innovative induction hardening process was designed using virtual DANTE models. The tensile stress at the corner fillet was greatly reduced, as shown in Figure 5, to eliminate fillet cracking issues and to improve fatigue performance of the component. The innovative induction hardening process makes it possible to control the in-process and residual stresses at critical locations of the part. Residual compression at the corner fillet can be obtained with this innovation process.



(a) *(b)*

(c) *(d)*

Figure 4: Evolution of temperature, hoop stress, and phase transformation during induction hardening process.



(a) Axial Stress *(b) Hoop Stress*

Figure 5: Residual stress distributions produced by the innovative induction hardening process.