COMPUTER MODELING SINGLE-SHOT INDUCTION HARDENING OF A POWER TRANSMISSION SHAFT

Computer modeling is used in induction hardening process design to improve component quality including hardness, beneficial stress distributions, and reduced distortion.

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The automotive industry is implementing lightweighting initiatives in vehicle design to meet more stringent federal Corporate Average Fuel Economy regulations. New component designs involve material removal resulting in complex geometries containing longitudinal and/or transverse holes, grooves, shoulders, flanges, diameter changes, undercuts, teeth, splines, and more. Many of these components with complex shapes are surface hardened using induction hardening (Fig. 1). Four induction methods routinely used are scan, continuous or progressive, static, and single shot hardening[1].

Irregularities in component geometry distort the magnetic field generated by an inductor, which can cause temperature deviations, hot and cold spots, excessive shape distortion, undesirable microstructures, grain boundary liquation, and cracking. For example, scan hardening shafts with large shoulders, multiple-diameter changes of appreciable size, and other irregularities can produce severe nonuniform hardened patterns. Eddy current flow and temperature fields should be evaluated to determine appropriate process parameters and coil design to prevent cracking and minimize distortion.

Steel shafts and shaft-like components are traditionally induction surface hardened using scanning and single-shot methods. In the single-shot method, the part rotates rather than the shaft or coil moving relative to each other. The entire region to be hardened is heated at the same time. Single-shot inductors typically control hardness pattern and distortion better than scan and static hardening, particularly for stepped shafts. A single-shot inductor consists of two legs and two crossover segments. Crossover segments encircle only half of the workpiece circumference, and induced eddy currents primarily flow along the length of the part. An exception is crossover segments where eddy current flow is half circumferential. Longitudinal leg sections are profiled by relieving selected regions of the copper inductor to accommodate workpiece geometrical features, such as changes in diameter and undercuts.

Inductor configuration depends on factors such as workpiece geometry, temperature uniformity, required hardness pattern, and production rate. The design must take into account the tendency of certain geometrical features to produce heat surpluses and/or heat deficits upon induction heating. Required heat source control can be achieved by adjusting the current-carrying face of the appropriate inductor section, applying flux concentrators, and by varying the inductor-to-workpiece gap. Determining the appropriate inductor profile might be cumbersome and time-consuming.

Fig. 1 — Variety of complex geometry components that are routinely induction hardened.

For critical applications, single-shot inductors are CNC machined from solid copper to conform to the area of the part to be heated. This type of inductor requires the most care in fabrication because it usually operates at high power densities, and workpiece positioning is critical with respect to coil profile. Single shot hardening is also the preferred

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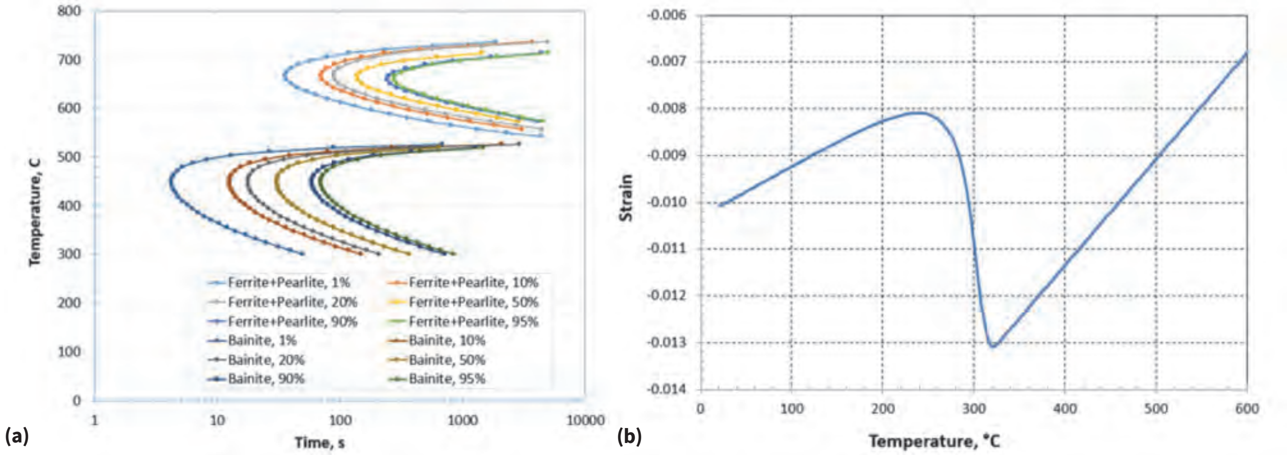

Fig. 2 — TTT diagram (a) and dilatometry strain curve (b) of martensite transformation for AISI 4140 generated from Dante database.

choice when shorter heat times/high production rates are desired. Heating time can be as short as two seconds, but is typically four to eight seconds. Sufficient rotation is critical with single-shot inductor design; at least 10 full rotations per heat cycle is desired. Spray quenching can begin immediately after austenitization is complete, or after a short delay. The duration of quench delay can range from a fraction of a second to a few seconds depending on the geometry of the component, material chemical composition, and hardness pattern specification.

COMPUTER MODELING SPECIFICS

The current production environment does not allow the luxury of process design via trial and error. Computer simulation enables induction heating specialists to quickly determine process details, which could be costly, time consuming, and difficult or impossible to resolve experimentally. Simulation enables prediction of how different interrelated and nonlinear factors could impact the transitional and final thermal conditions of the heated component. It also helps determine what must be accomplished to improve process effectiveness to establish the most appropriate process recipes. Computer modeling provides a comfort factor when designing new systems, avoids unpleasant surprises, shortens the learning curve, and reduces development time.

Today, most software programs are not capable of modeling single shot hardening. However, FEA software developed by Dante Solutions in combination with proprietary subroutines for Flux-3D developed by Inductoheat enable taking into consideration all critical features of the induction hardening process[2].

MODELING INDUCTION HARDENING OF A STEEL SHAFT

Consider a case study of induction hardening of an AISI 4140 alloy steel shaft with shoulders and numerous changes in diameter. Phase transformations occur during induction heating and spray quenching. The surface of the part transforms to austenite during heating, and during quenching, austenite can transform to ferrite, pearlite, bainite, or martensite depending on the cooling rate. Accurate descriptions of phase transformations and mechanical properties of individual phases are required for thermal stress analysis[3]. Figure 2(a) shows the TTT diagram of 4140 generated from the Dante database. The TTT diagram is not used in Dante models directly, but the analytical phase transformation models and database contain all TTT diagram information. Figure 2(b) shows a dilatometry strain curve during martensite formation under continuous cooling. The curve provides the martensite start temperature (M_s), martensite finish temperature (M_f), transformation strain, and coefficients of thermal expansion (CTE) for austenite and martensite. Because

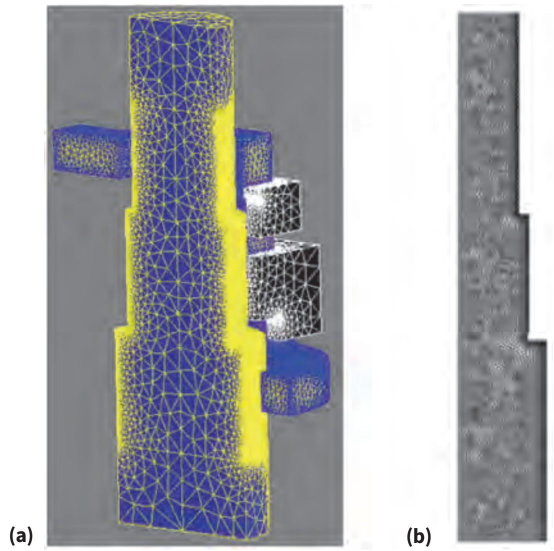

Fig. 3 — Finite element models: (a) electromagnetic model used by Flux-3D, and (b) 2D axisymmetric model used by Dante.

the cooling rate during spray quenching is severe, the main transformation in this study is austenite to martensite.

Using Flux-3D, the electromagnetic problem was solved and 3D heat source distribution was obtained at different heating stages. The finite element model is shown in Fig. 3(a). Calculated power distribution from the Flux-3D model was mapped into the Dante model for thermal, phase transformation, and stress analyses; the Dante mesh is shown in Fig. 3(b). After induction heating, the shaft was spray quenched using a polymer solution without delay. Different finite element meshes were used for the Flux and Dante models.

MAPPING FROM FLUX-3D TO DANTE

Copper inductor profiling was optimized and the most appropriate locations for magnetic flux concentrators were determined to address changes in shaft geometry. During the hardening process, the shaft was positioned inside the inductor with a rotation rate of five rotations/second, and a total heating time of five seconds, which translates into 25 full rotations during the heating cycle.

Because temperature distribution is relatively uniform circumferentially in the shaft, a 2D axisymmetric model was used in Dante to model temperature, phase transformation, and stress evolution during heating and quenching. Power distribution in terms of time predicted by Flux-3D was mapped into the Dante heat treatment model. A special mapping subroutine was developed because different finite element meshes were used in the Flux-3D and Dante models. A comparison of temperature profiles projected by Flux-3D and Dante reveals good correlation (Fig. 4).

STRESS AND PHASE TRANSFORMATION MODELING USING DANTE

Temperature, austenite pattern, axial displacement, radial displacement, and hoop stress distributions after two seconds of heating are shown in Fig. 5. At the early stage of heating before the surface transforms to austenite, the surface is under compression due to thermal expansion. After the surface transforms to austenite, the stress decreases to a magnitude close to neutral. Compression occurs under the austenite layer due to thermal expansion, with tensile stress in the core to balance the stress.

Figure 6 shows predicted results at the end of the five seconds of heating; the austenite layer is approximately 5 mm deep. Surface temperature is about 1100°C, and the radial displacement of the heated region is about 0.2 mm.

After heating is complete, the shaft is spray quenched using a 6% polymer solution; a convection coefficient of 15 KW/(m^{2}K) is applied on the shaft surface of the FEA model to represent the spray quench. After two seconds of quenching, surface temperature is about 204°C, which is below the M_s (320°C) of AISI 4140, and martensite formation started on the surface (Fig. 7). Surface stress shifts from tension to compression due to the volume expansion that accompanies martensite formation. Surface stress is tensile due to thermal shrinkage caused by quenching prior to martensite formation.

At about 10.4 seconds of quenching, almost all of the austenite layer transforms to martensite (Fig. 8). The surface temperature is about 70°C and core temperature is about 306°C. Hoop stress on the surface is about −310 MPa under compression, a tensile stress of about 390 MPa is observed under the austenitized layer, and the core is under slight compression of -80 MPa.

Cooling of the core after phase transformation is completed has a significant effect on the change in stresses in the shaft. Hoop stresses are −700 MPa at the surface, +450 MPa at the case-core location, and +150 MPa in the core after the shaft cools to room temperature (Fig. 9). Residual stress distribution affects shaft fatigue performance.

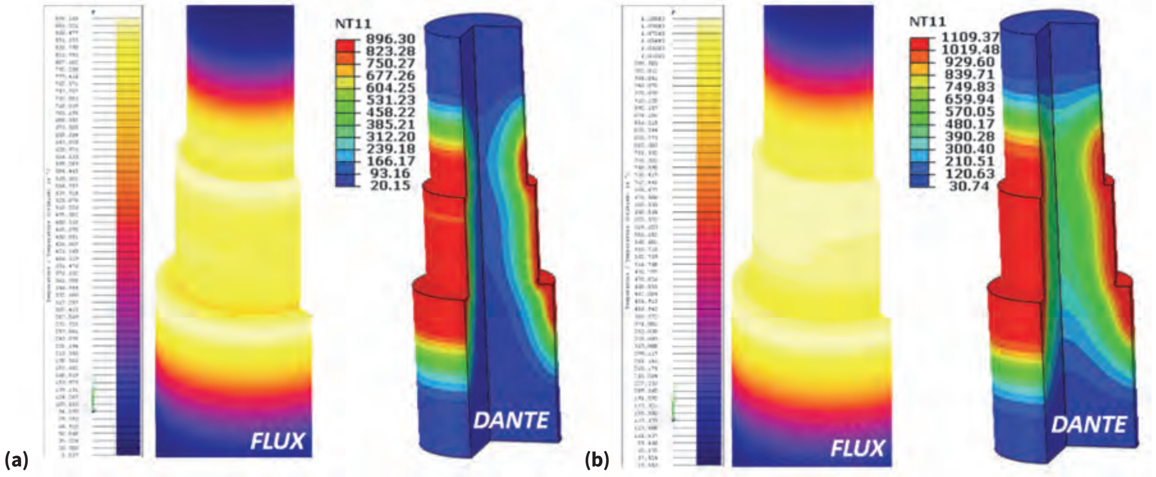

Fig. 4 — Predicted temperature distributions between Flux-3D and Dante during induction heating at 2 s (a) and 5 s (b).

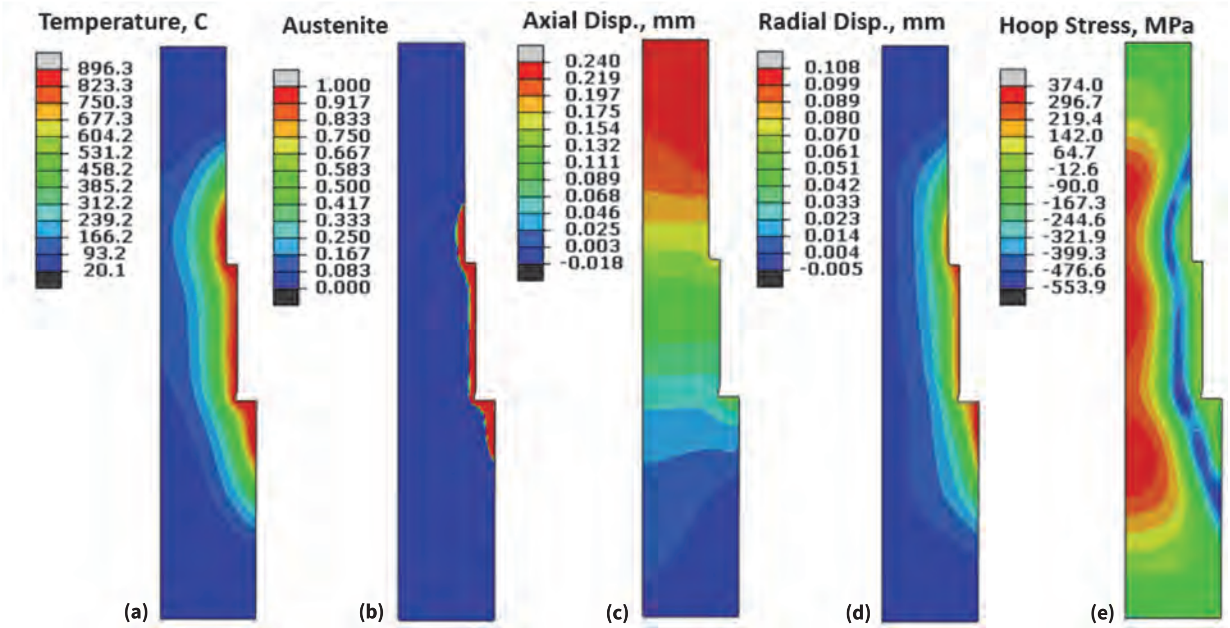

Fig. 5 — (a) Temperature, (b) austenite phase, (c) axial displacement, (d) radial displacement, and (e) hoop stress distributions at 2 s of heating.

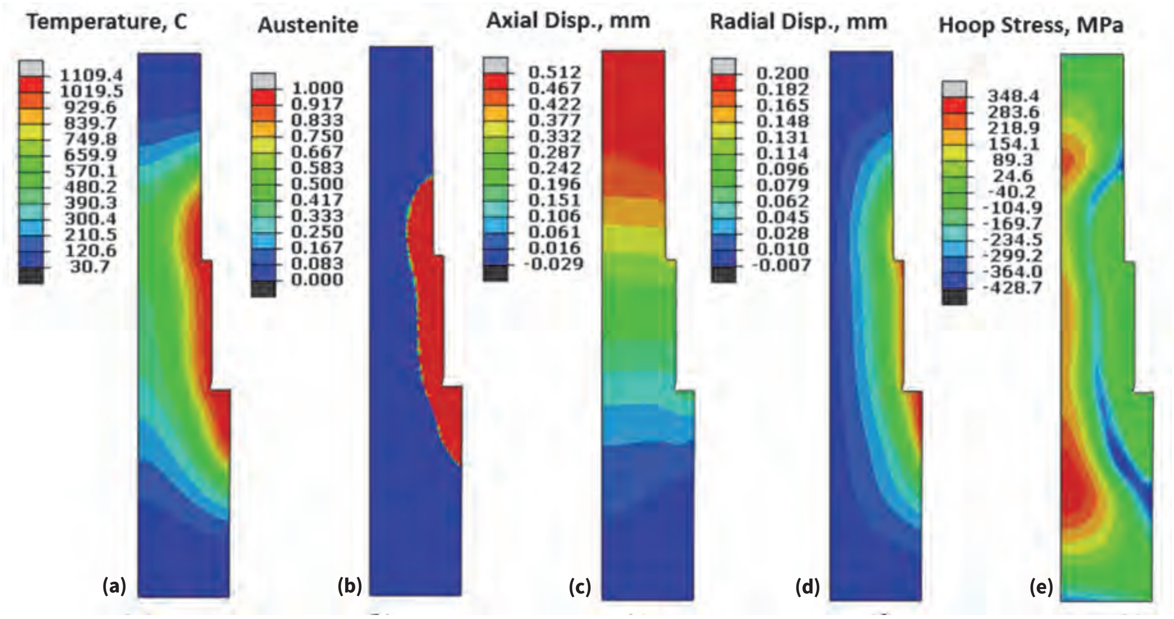

Fig. 6 — (a) Temperature, (b) austenite phase, (c) axial displacement, (d) radial displacement, and (e) hoop stress distributions at 5 s of heating.

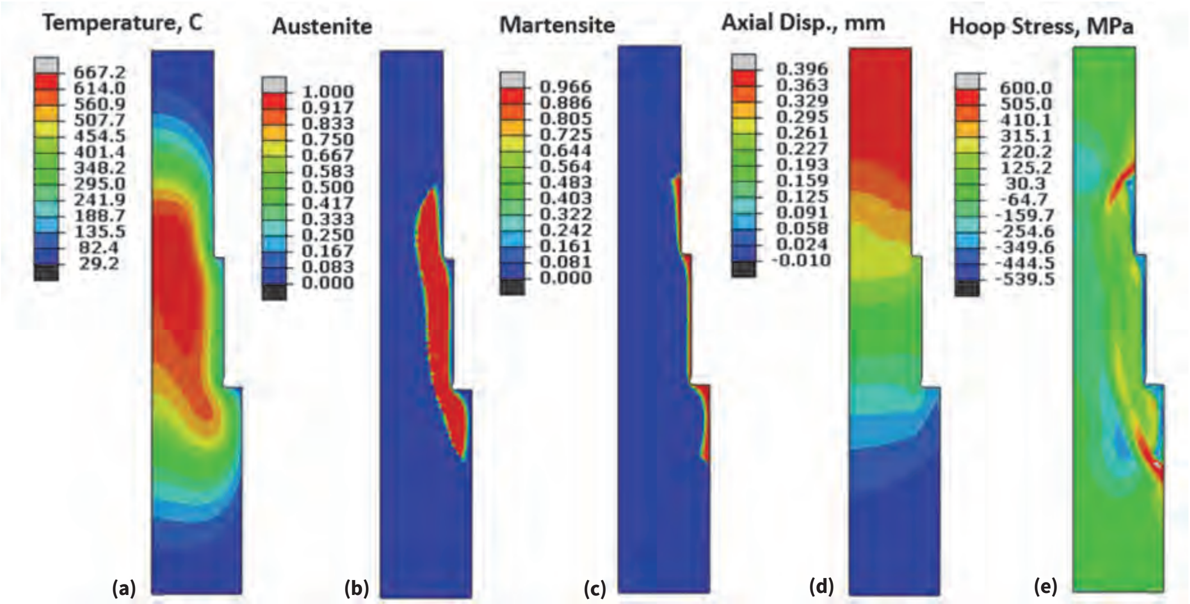

Fig. 7 — (a) Temperature, (b) austenite phase, (c) martensite phase, (d) axial displacement, and (e) hoop stress distributions at 2 s of quenching.

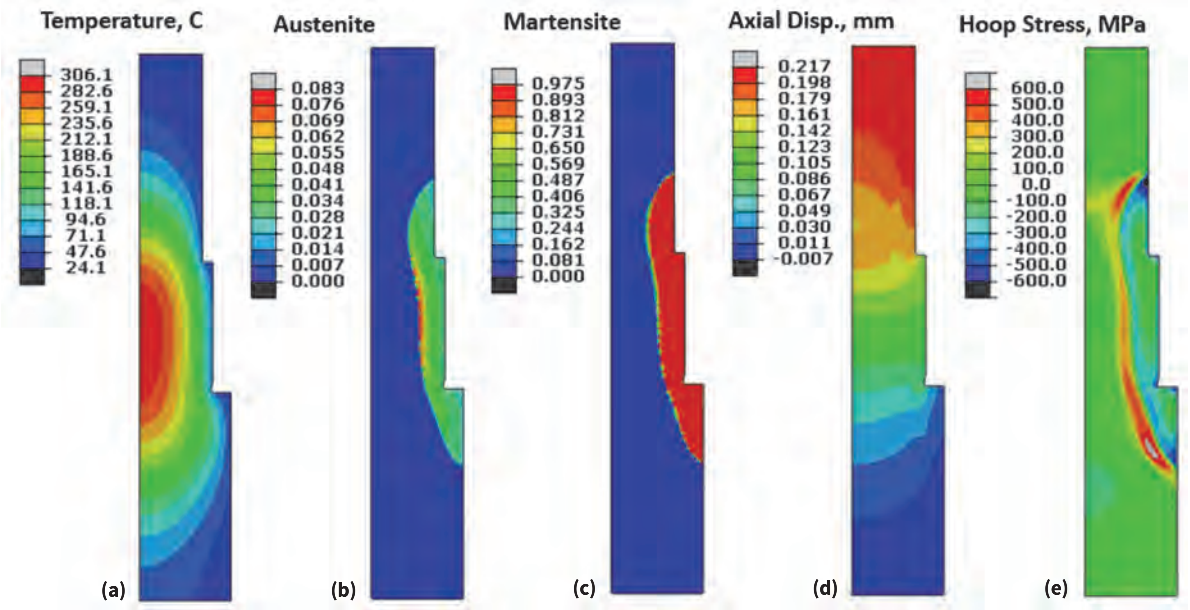

Fig. 8 — (a) Temperature, (b) austenite phase, (c) martensite phase, (d) axial displacement, and (e) hoop stress distributions at 10.4 s of quenching.

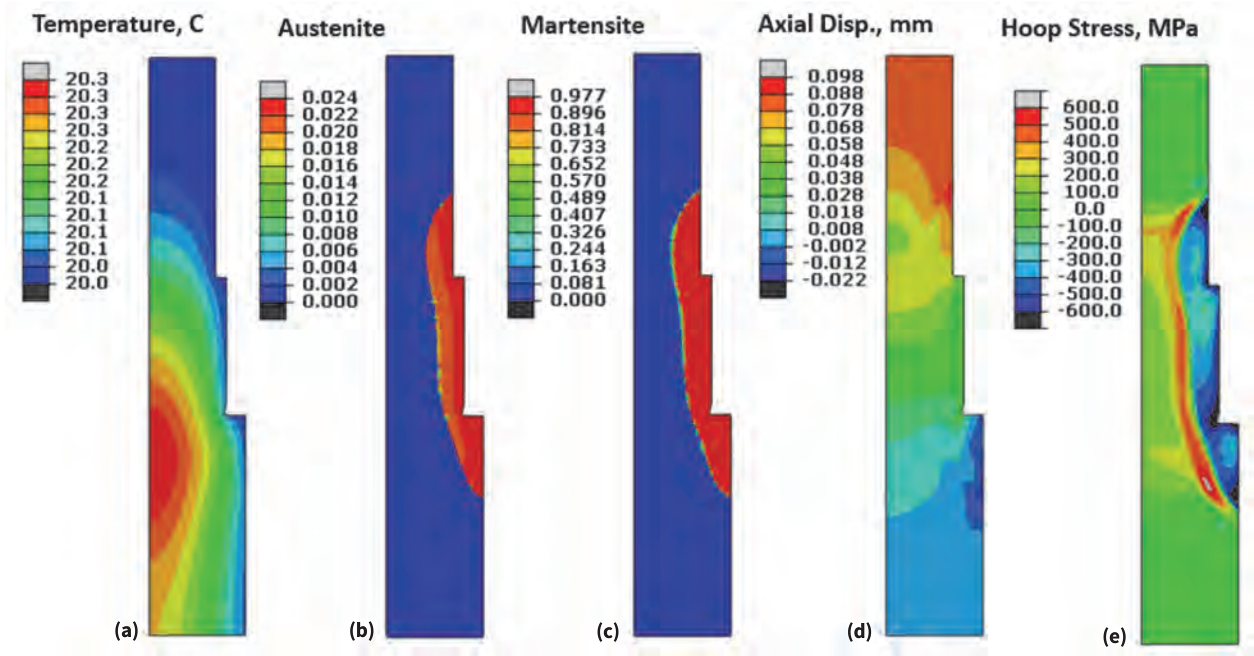

Fig. 9 — (a) Temperature, (b) austenite phase, (c) martensite phase, (d) axial displacement, and (e) hoop stress distributions at the end of quenching.

Compressive residual stresses are preferred on the surface. However, to balance surface compression, tensile stresses exist under the case or at the core, which may lead to failures if the material at those locations exhibits metallurgical or microstructural irregularities (e.g., material is not clean) or if the applied load is too high. Process optimization based on computer modeling is a critical factor to optimize the stress and hardness distribution in specific applications.

CONCLUSION

Years of experience, leveraged by advancements in high performance computers, have improved the cost effectiveness of applying computer simulation during the design and development stages for induction hardening processes. This shortens the learning curve, reducing development time and enabling accurate inductor design and process optimization.~**HTPro**

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