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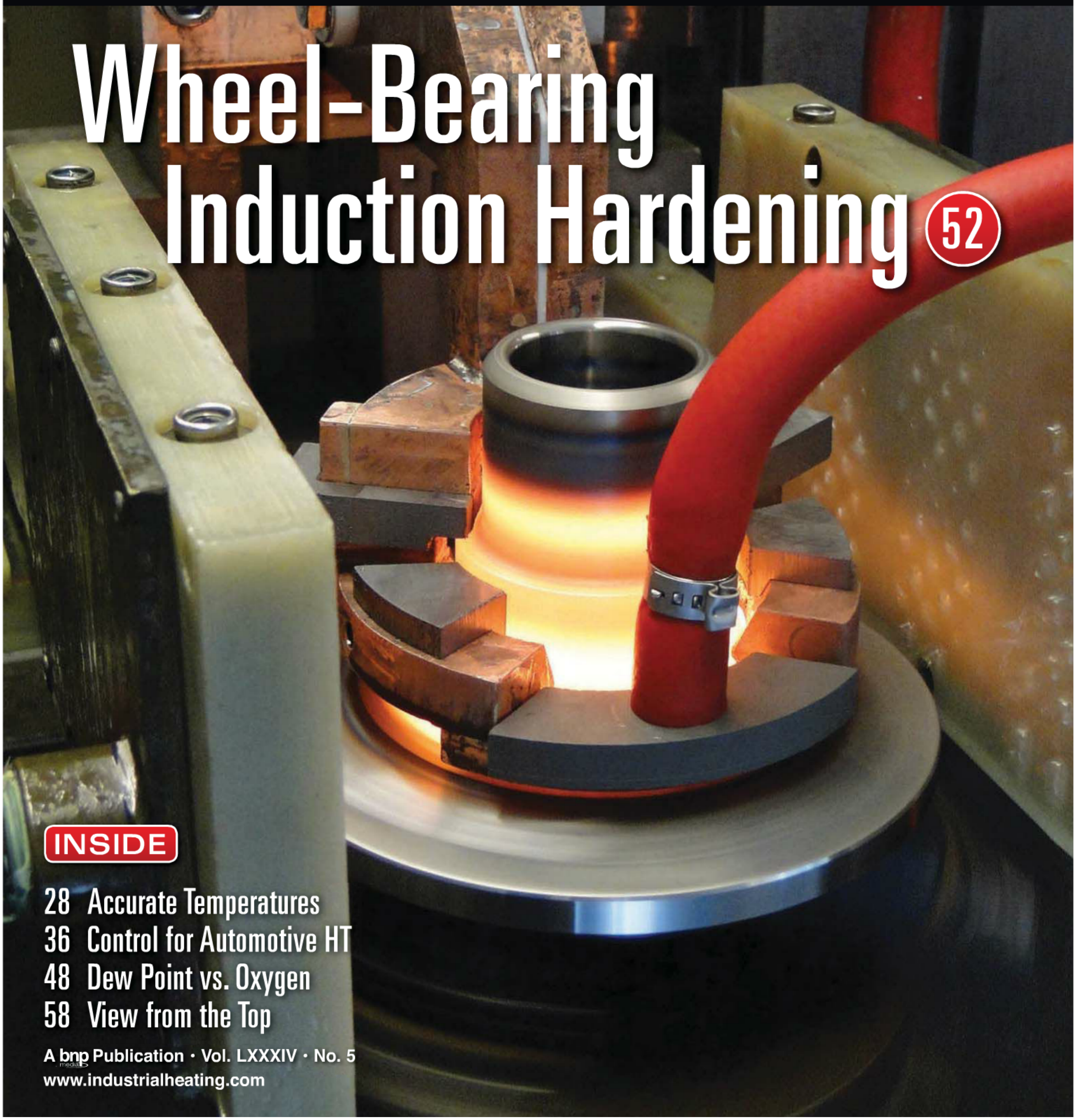

Wheel-Bearing Induction Hardening 52

INSIDE

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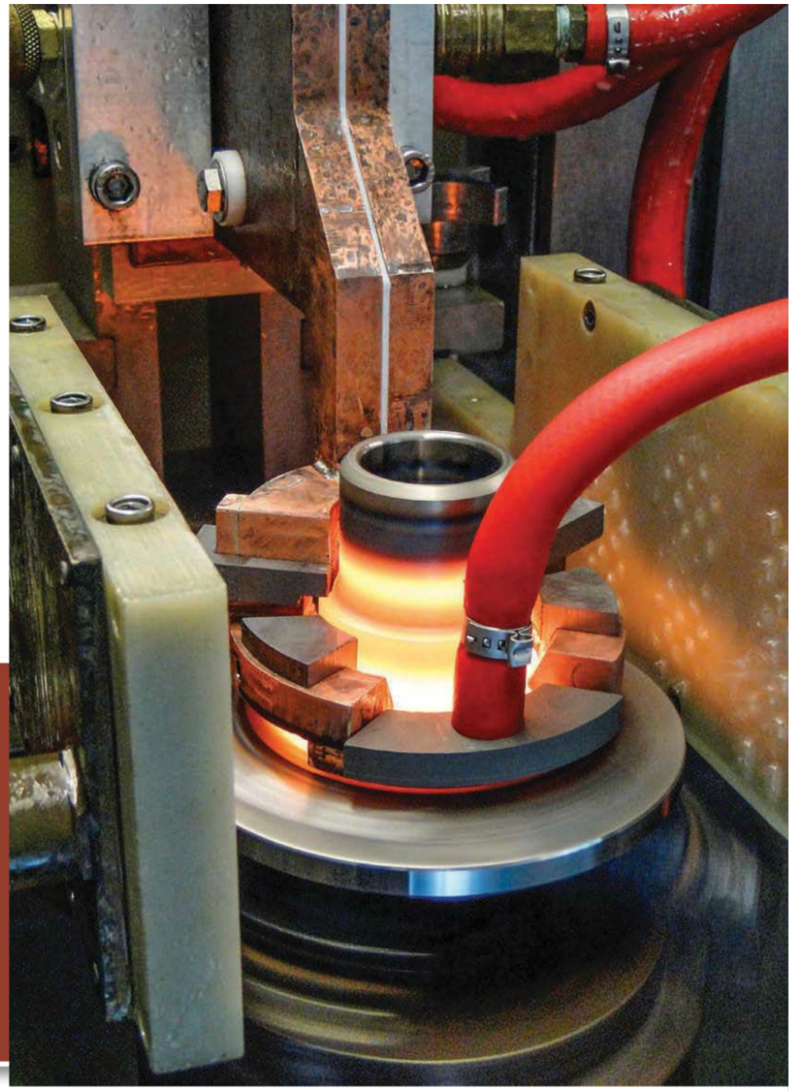
Design and Development of PPAP-Ready Wheel-Bearing Inductors



Sandra J. Midea – Induction Tooling Inc.; North Royalton, Ohio

Did you know induction hardening (IH) requires a six-degree design equation to predict how a wheel bearing will respond in an induction field? Although great strides are being made to simulate induction patterns, most of today's inductor design and validation is still done through experience and experimentation. Our objective in this article is to show how a wheel-bearing inductor is designed, fabricated and validated to be ready for Production Parts Approval Process (PPAP) and integration into robust manufacturing.

First, consider a wheel bearing. From a heat-treater's perspective, a wheel bearing consists of two parts: the inner ring, or spindle, and the outer ring, or hub. Together, these components form the raceway for the wheel bearings. While each part has unique challenges for hardening, we will concentrate our discussions on the spindle (inner ring).

Each aspect of the hardening inductor is critical for it to be capable of meeting engineering drawing requirements and be ready for the PPAP process at the supplier facility. This includes:

- Inductor design
- Fabrication
- Characterization and process development
- Metallurgical validation
- Finalizing the inductor for production

Inductor Design

Design begins with analysis of the engineering specifications and process constraints. The engineering design framework includes the required hardening pattern with case depths, runouts and metallurgical requirements. It also incorporates manufacturing needs such as throughput, frequency and power limitations, and material-handling abilities (Fig. 1). Most production is run on current equipment, so the inherent limitations of existing generators and material-handling equipment must be taken into account during the inductor design.

John Gadus, design specialist at Induction Tooling Inc., commented on the spindle inductor design process. "Overall, spindle geometries are very similar as they often share many of the same features. Typically, the main difference is the physical size of the part. Scaling an existing inductor to match the size of a new part might seem like a simple approach, but it's not usually the best approach. Subtle differences in the geometry or mass of the part may create unexpected results that need to be addressed during process development. My goal during the design process is to anticipate how the tooling will perform and to quickly and efficiently achieve results that meet or exceed customer expectations. Our extensive library of proven inductor designs and years of design experience help us to achieve this goal (Fig. 2)."

Inductor Fabrication

The rigorous environment of automotive manufacturing requires inductors designed and fabricated to withstand abuse. From the beginning, we develop methods to reinforce braze joints for maximum life and use pressure testing to verify integrity of the cooling passages. Solid CNC-machined components (Fig. 3) allow repeatability when manufacturing spare/replacement coils and provide superior rigidity for

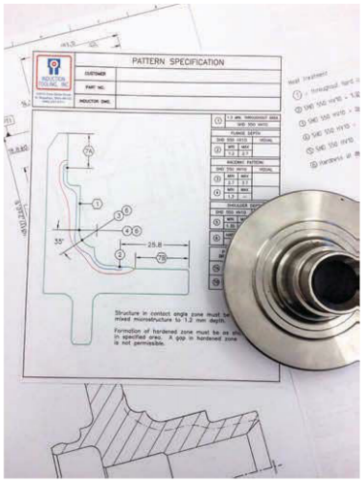


Fig. 1. Incoming design requirements and prototype parts

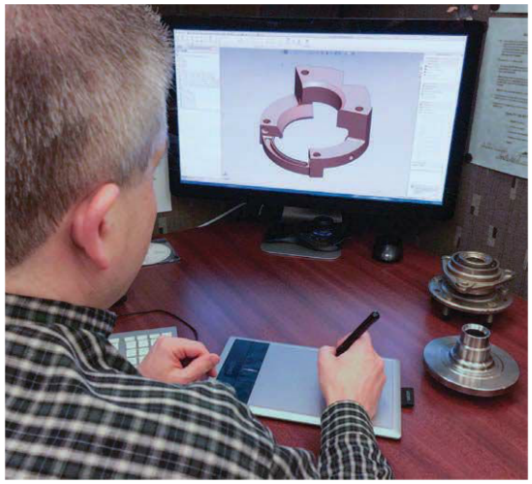


Fig. 2. A design specialist uses SolidWorks CAD program to design an inductor loop.

Fig. 3. CNC machining a copper loop to precise dimensions

enhanced process consistency. Our inductors (Fig. 4) are made by toolmakers, all of whom undergo an extensive apprenticeship training program within our facility.

Characterization and Process Development

An inductor design that has been in production for an extended time can be reproduced from existing drawings. A coil for a new part lacks production history and will need to be characterized so that the inductor produces the required hardening pattern. Small changes in angles, chamfers and air gaps have a tremendous effect on the IH pattern. Making these changes and validating the effect is called characterizing the inductor. In the past, characterizing was performed in the following sequence.

- Fabricate the inductor.
- Ship to heat treat (HT).
- HT breaks into production to try the inductor.
- Check the results.
- Ship the inductor back to the fabricator
- Fabricator makes changes and returns coil to HT.
- HT breaks into production to try the inductor.
- Check the results.
- Reiterate until an acceptable pattern is achieved.

The opportunity for improvement of this iterative process goes well beyond cycle time and lost production. This sequence does not allow additional manipulation of the inductor to optimize the IH pattern.

Induction Tooling Inc.'s Induction Development Laboratory offers the ability to significantly shorten this cycle by developing the process, characterizing the inductor and

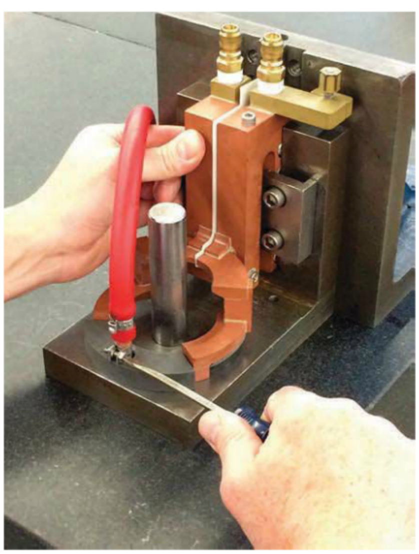


Fig. 4. Dimensional check of inductor during characterization

Fig. 5. Spindle hardening process development

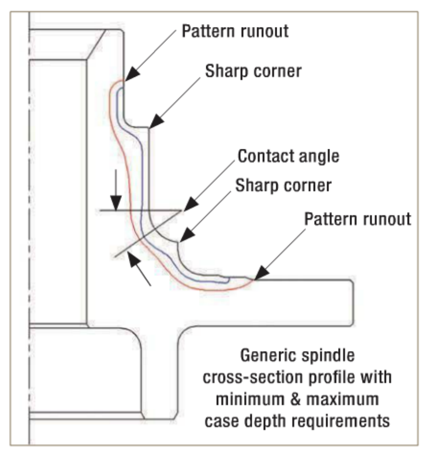


Fig. 6. A generic spindle cross section (black) showing the minimum (blue) and maximum (red) allowable case depths. Sharp corners, pattern runouts and required quench angles demand particular design attention *(courtesy of John Gadus).*

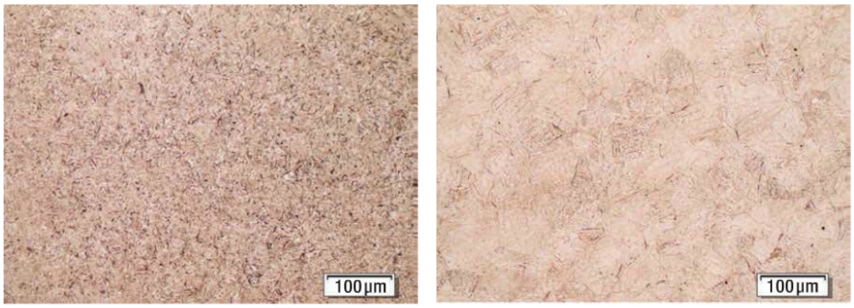


Fig. 7. Martensite formed during induction hardening (2% Nital etch, original magnification 200x). a. AISI 1080 properly IH with grain size ASTM 6. b. 4140 alloy overheated with grain size ASTM 4.

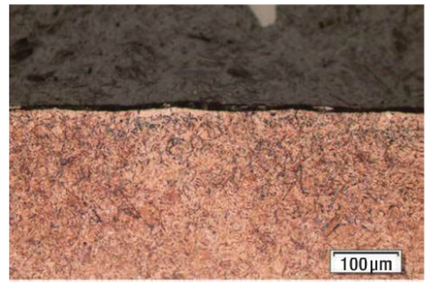


Fig. 8. Bainite formed at the critical-angle surface due to ineffective quenching (2% Nital etch, original magnification 200x).

evaluating the part in our accredited metallurgical laboratory – all located under one roof.

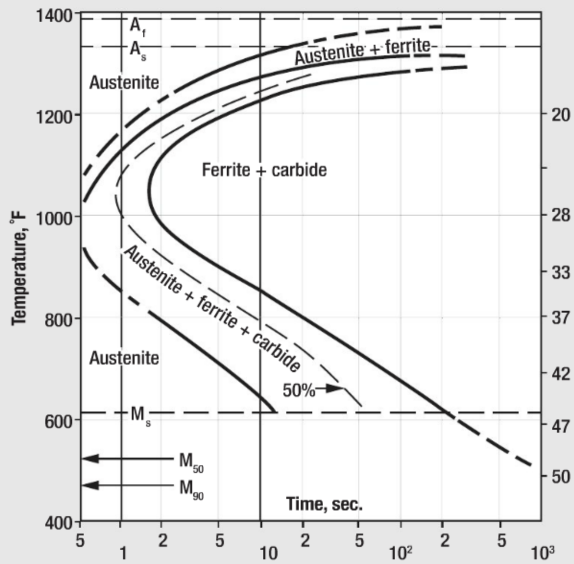
"The concept behind our induction lab is to reduce the time required to get a capable process that is ready for PPAP," said Bill Stuehr, ITI president and CEO. "We don't have the luxury of a blueprinted case-depth range. We must target the nominal values, that is, between maximum and minimum, so that our customer has the full flexibility of range for their process."

ITI's induction development lab, coupled with a fully ISO 17025-accredited commercial testing lab, is a unique asset. Using nine different generators from a variety of companies, some specifically designed for development, gives the capability to mimic production process settings found in most commercial and captive operations. For spindle inductor development, the objective is to provide an inductor and process details so the required IH pattern is produced with only minor adjustments to cycle time and power (Fig. 5).

Since each generator/workstation combination has different system losses, the power settings or cycle time may need to be increased or decreased at the heat-treater's location. The inductor has been validated, however, and will produce the required pattern and meet metallurgical requirements once the corresponding power setting is found. In addition, once the correlation offset is identified, it will be consistent for other inductors developed.

Let's examine a cross section of a generic spindle (Fig. 6). While all design criteria are critical, particular attention is given

Bainite (blue-gray phase) in martensitic matrix formed due to insufficient quenching during induction hardening. The part is an AISI 1055 steel forging. Original magnification: 1000x with 2% Nital etch, taken with an Olympus GX-41 (courtesy of Induction Tooling Inc.).
Editor's note: Although not part of the article investigation, the author submitted this photograph for reader reference. It is an excellent depiction of bainite in martensite as the result of an insufficient quench. The quench rate was unspecified, but induction quenching is typically quite rapid. The 1055 grade has good forgeability. Without the alloying elements to assist with the quench, however, this medium/high-carbon forging is made from what is considered to be a "low-hardenability" steel. It is virtually impossible to fully miss the nose of the cooling-transformation curve. Thanks, Sandra, for submitting this excellent and instructional photo.



Isothermal transformation diagram for 1055 steel. Austenitzed at 1670°F (910°C). Grain size, 7 to 8. Martensite temperatures estimated. *(Source: Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1977)*

to areas shown in the figure that pose the biggest issues in IH.

- Pattern run-out and the end of the hardening pattern
- Overheating at sharp corners
- Quenching in the contact angle

Pattern Runout

Pattern runout is controlled by balancing sufficient heat to fully transform the microstructure without creating excessive heat by induction or conduction. Deep case-depth requirements adjacent to short runouts have inductor design constraints working in opposition to each other, making it difficult to produce the required pattern. Magnetic-field controllers, commonly called intensifiers (e.g., Fluxtrol's Ferrotron®), may be required for pattern control.

Overheating at Sharp Corners

Corner overheating results in enlarged grain size and poor microstructure. Large grains yield reduced fatigue life and make great crack initiation sites. Overheating typically occurs at corners for two reasons. First, the electrical field coalesces around sharp geometrical features, and second, energy is introduced from two faces.

Whenever practical, the addition of increased radii and chamfers at corners and fillets make a significant difference in response to the induction field. Overheating can be seen in the microstructure. Differences between a properly hardened part (Fig. 7a) versus an overheated microstructure (Fig. 7b) are evident in the grain size and coarseness of the martensite.

Quenching

Quenching, or rapidly cooling the part, is a balancing act. Quench too aggressively and quench cracking is possible. Quench too slowly and unintended steel transformations occur. The raceway contact angle is generally specified to be fully transformed martensite without any non-martensitic transformation products visible to a specified depth. Full martensitic transformation requires both heating to the austenitic transformation temperature and effective quenching.

Spindle inductors generally do not have integrated quenches. Nevertheless, quenching is critical to getting the desired final microstructure. Figure 8 shows bainite that formed on the contact-angle surface when flood quenching was used. Adding quench nozzles focused into this area alleviated the issue. Quench flow rate and configuration are specified as part of the development program.

Fig. 9. Products of a typical development project

Validation of the Metallurgy

As the inductor is being characterized by changing the inductor geometry, the metallurgy is validated for correct case depth, hardness and microstructure.

Metallurgical analysis begins by determining the visual (total) case depth. After sectioning the spindle with a metallurgical saw, the surface can be macro-etched with 10% nitric acid in water to reveal the case/core interface. Visual case depth is measured from the surface to the end of the case that can be seen visually using an optical comparator. The visual case depth is deeper than the effective case depth (ECD). ECD is the perpendicular distance below the surface to reach a specific hardness as measured via microhardness. In spindle inductor characterization, visual case depth should target deeper than the required nominal ECD to obtain the required case.

Further evaluation requires mounting and polishing of the sample for metallurgical examination. This includes microstructural evaluation to verify no overheating at the surface or corners; grain-size requirements; fully transformed structure with no prior structure (untransformed core microstructure from before IH); no incorrect structure (typically bainite); and microhardness traverses to verify the effective hardness. These results are transmitted to the customer for approval. Typically, a couple of additional samples are heat treated for the customer's use as samples or for evaluation. After the customer's approval, the inductor drawings are updated, and the inductor goes through a process called finalizing.

Finalizing for Production

During development, the inductor is configured so changes can be readily made. For production, the inductor must be assembled for production usage. This includes permanent silver brazing with intensifiers secured in position. The inductor is plated, epoxied, pressure tested and cleaned for shipping. Each inductor is labeled, and a durable storage box is provided.

Conclusion

Performing inductor characterization and metallurgical validation at the inductor fabricator significantly reduces the product-development cycle and leads to more capable induction tooling and processes. A typical development program yields a fully characterized inductor, process parameters, validated ISO 17025-compliant metallurgical report and additional prototype pieces for our customer to evaluate or use in their sales efforts (Fig. 9).

The author would like to thank Bill Stuehr, John Gadus, Mike Ziebert and John Kobus for their outstanding contributions for this article.

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