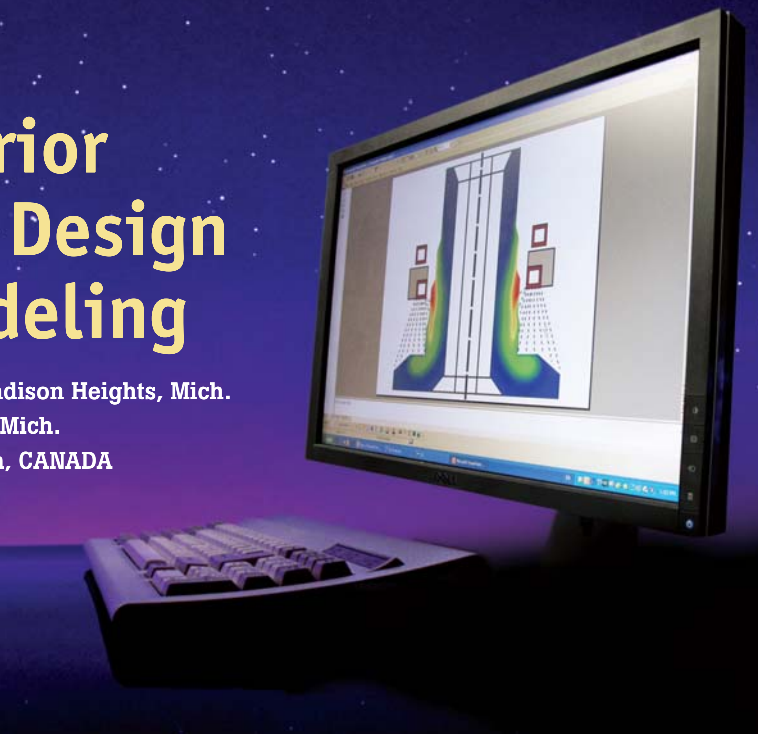
FEATURE | Induction Heat Treating



Unleashing a Superior Induction-Heating Design with Computer Modeling

Valery Rudnev and Don Loveless – Inductoheat, Inc., Madison Heights, Mich.
Carmo Ribeiro – Federal-Mogul Corporation, Plymouth, Mich.
James Boomis – Spinduction Weld Inc., Calgary, Alberta, CANADA

Numerical computer modeling is one of the major factors in successful design of induction-heating systems. In the fast-paced world economy, the ability of induction-heating manufacturers to minimize the development time and shorten the "learning curve" through efficient computer modeling is critical for a company's success.

Induction heating is a complex combination of electromagnetic, heat transfer and metallurgical phenomena involving many factors.[1,2] Heat transfer and electromagnetics are non-linear and tightly interrelated because the physical properties of heated metals depend strongly on both temperature and magnetic-field intensity. The metallurgical phenomenon is also a non-linear function of temperature, heating intensity, cooling severity, chemical composition, prior microstructure and other factors. Computer modeling provides the ability to predict how different, interrelated and non-linear factors may impact the transitional and final thermal conditions of the workpiece and what must be accomplished in the design of the induction-heating system to improve the effectiveness of the process and guarantee the desired temperature profiles, helping to optimize technical pioneering ideas.

Monosteel® Piston's Innovation

Federal-Mogul is one of the largest global suppliers of pistons for both traditional and high-performance engines. The piston's main task is to convert combustion energy into mechanical energy. During this process, substantial pressures exerted on the piston create high rigidity and temperature-resistance demands.[3]

In response to rising performance demands on the piston, Federal-Mogul engineers and technicians have developed the next-generation pistons. The Monosteel® piston's innovative technology, a 2006 *Automotive News* PACE Award recipient and recently featured in its top 25 innovation technology supplement, was developed by Federal-Mogul to address the increasing thermal, mechanical, abrasive and corrosive challenges placed on heavy-duty diesel engines resulting from emissions regulations. It allows for the potential of thinner design sections, closer to aluminum or articulated piston weights, targeted for the higher-volume diesel-engine market.

Advantages include better yield from forgings that are closer to the required final dimensions and improved rough-machining rates. The Monosteel piston has a 300-bar firing-pressure design capability, which meets Euro VI and U.S.10 emissions regulations, and alternative induction solid-state welded design that brings lightweight steel pistons to the light-vehicle diesel, mid-range diesel or natural gas category. Other advantages of the Monosteel piston include:[3,4]

- A large, closed structural gallery with superior fatigue factors in the hottest bowl rim area and highest stiffness, reducing groove distortion and improving oil control and gas sealing
- A large, closed gallery with superior cooling of the piston bowl rim, ring grooves and undercrown
- A profiled, bushingless pin bore
- A full-length skirt for stable piston dynamics, reducing friction and the risk of liner cavitation, piston slap and improving ring sealing
- Process allows material flexibility with crown material options to reduce corrosion or oxidation and/or skirt material options to improve manufacturability

The Monosteel piston starts life as two separate forgings (Fig.1) – a top (crown) forging and a lower (skirt) forging. Before joining, the forged top and bottom halves

Fig. 1. The Monosteel® piston starts life as two separate forgings.

are each prepared with two concentric circular end-face lands, which are simultaneously welded. This mandates a "one-shot" welding process. Complex internal geometry of pistons (Figs. 1 & 2) presents certain challenges for any of the commercially established welding processes. Incremental welding processes, such as arc or laser, or electron-beam welding are precluded mainly because of poor access to the inner concentric end face and also because of lower productivity. All welding processes require some form of energy input. Friction- and inertia-welding processes rely upon kinetic energy being converted to thermal energy via mechanical friction. In doing so, a significant volume of metal is rapidly consumed and ejected from the shear interface as flash.

In an attempt to further enhance the piston's manufacturing technology, Federal-Mogul specialists have combined their efforts with experts from Spinduction Weld Inc., which recently developed a novel welding process – Spinduction™[5,6] – and Inductoheat, Inc., a leader in designing and computer modeling of novel induction-heating systems.[1,2]

Spinduction Welding

The Spinduction welding process[5,6] is the advantageous combination of two long-established welding processes: friction welding and induction pressure welding.

Friction welding is a remarkable welding process because it is nearly instant and produces very high-integrity, consistent-quality welds even with dissimilar metals. It requires one workpiece to be spun at high speed. When scaled up to perform large cross-section welds, it requires a massive machine to furnish the requisite stored mechanical energy. High cooling rates inherent with kinetic heating may be undesirable for certain types of steels because of their hardenability and formation of Widmanstätten structures.

Induction pressure welding is a similarly rapid-welding process that does not require any spinning of workpieces. But it loses reliability when used on large cross sectional areas due to the increased probability of contaminant entrapment and inadequate coalescence.

Fig. 2. Cross-section of a friction-welded piston

Fig. 3. Spinduction™ produces consistently flawless welds at very low rotational velocities with minimum or no flash projection.

Spinduction welding provides relative motion between the joining parts (similar to friction welding) to minimize impurity entrapment in the weld zone and to produce fast, high-integrity welds with consistent quality. The important advantages of Spinduction are that it produces consistent, flawless welds at very low rotational velocities, well below the minimum forging velocity for friction welding with minimum or no flash projection (Fig. 3).

Since the Spinduction process uses very little kinetic energy, the required machinery is more compact and has fewer moving parts than a comparable-capacity friction or inertia welder. The Spinduction process uses induction heating for over 95% of the weld energy input, so when considering very large workpieces, the Spinduction process is more advantageous than inertia welders or friction welders. It is easier and more cost efficient to build a high-power induction system than a mechanical drive line with comparable kinetic energy.

A further advantage of Spinduction is that the loss of length is dramatically reduced. The net result is a weld of comparable quality with conventional friction welds, which already are renowned for their high integrity and repeatability. Since the kinetic energy input is so small, it is very easy to control the final rotational orientation of the parts to within a fraction of a degree.

Unlike other commercial welding processes, most of which are classified as fusion welding because they involve the melting of the item to be welded, Spinduction is a solid-state welding process. This means that there is no liquefaction of the workpiece (or filler metal). This process is, therefore, inherently exempt from many of the defects encountered in conventional welding operations. These defects include porosity, slag inclusions, incomplete fusion, inadequate penetration, undercut, melt through, various weld-metal cracks, etc. Unlike fusion welding and flash welding, there are no sparks or spatter with Spinduction.

Induction Heating

Induction preheating is a critical part of this technology providing the required heat input quickly, efficiently and with required uniformity. Immediately after completion of the heating stage, the inductor is retracted within a fraction of a second and the two piston's halves are rapidly pressed together. Rotation begins just before surfaces of both halves come into contact. Rotational displacement and the axial forging force are simultaneously applied and controlled until required tangential displacement is

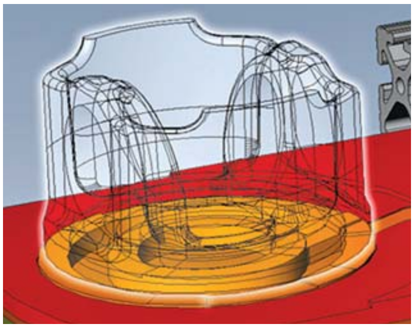


Fig. 4. Inductoheat's inductor was developed using several patented features that allow its withdrawal from piston's pre-heated faces at less than one second if required.

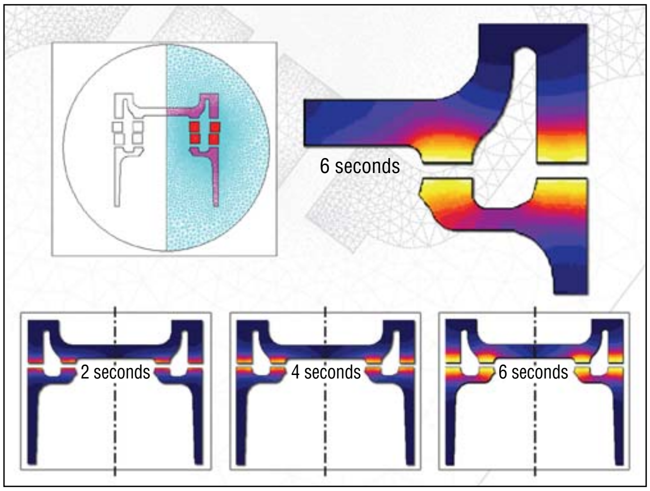


Fig. 5. Inductoheat's computer-modeling capability was a decisive factor in predicting temperature profiles during heating of top and bottom complex-shaped halves (0° cross-section).

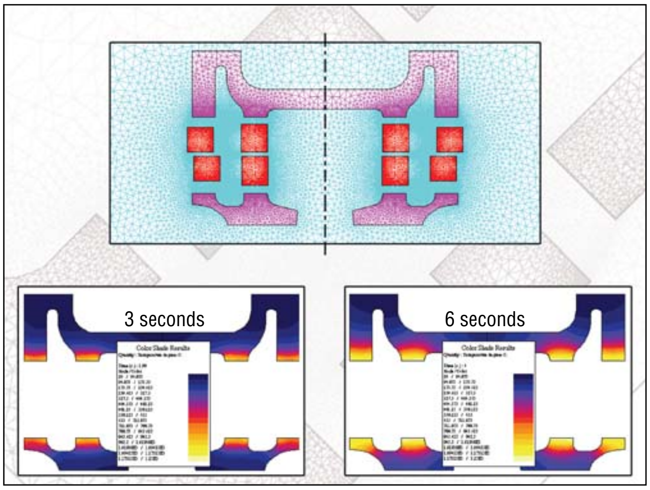


Fig. 6. FEA computer modeling helps determining the transient and final thermal conditions (90° cross-section) of the piston's halves, helping to determine an optimal inductor design and process recipe.

achieved and rotation stops.

Some of the innovations and "know how" of this technology are related to the ability to accurately control heating and cooling stages in order to produce sound welds. There are several phenomena that contribute to a challenge in satisfying required temperature uniformity of joining surfaces and providing a specified heat-affected transition zone beyond those faces. They include:

1. Magnetic-field distortion due to close proximity of heated four circular faces and electrically conductive bodies such as fixture and tooling (i.e. grippers). These conductive bodies located close to the inductor act as Faraday rings.
2. Induced eddy currents have a tendency to take the shortest path of the smallest impedance. This results in an electromagnetic "ring" effect,[1] which causes eddy current to flow non-uniformly across heating faces.
3. Transient time between the end of heating and beginning of bonding should be as short as possible and preferably less than one second. Longer inductor retraction time results in a dramatic reduction of the temperature of joining faces due to thermal conduction towards colder areas and due to thermal surface losses (radiation and convection). If inductor retraction time is greater than 1.5 seconds, the temperature drop can easily exceed 450°C (810°F).
4. The existence of varied background masses behind heating faces (Figs. 5 & 6) leads to appreciably non-uniform "heat sinks" that, depending upon the piston's cross-section, provide substantially different cooling effects during heating and inductor retraction. To complicate matters further, all these factors are nonlinear and multi-dimensional in nature.
5. Thermal profile in the transition zone has a marked effect on the cooling rate of the welded joint, which determines final microstructure and also affects the steel's self-tempering conditions and, therefore, the ductility of the weld.

The mechanics of the process made it difficult to see or measure the temperature of the heated surface, making the old "cut-and-try" method of inductor development impractical. Inductoheat's 2-D and 3-D computer-modeling capability and design experience were decisive factors in the successful development of a novel inductor design (Fig.4).

Modeling results determined not only the subtleties of the inductor's geometry but the process recipe that would guarantee the optimal temperature profiles and superior quality of pistons. Figures 5 and 6 show finite-element mesh and variation of temperature profiles during heating of top and bottom halves at 0° and 90° cross-sections, respectively. Total heat time was six seconds. A novel inductor concept made possible a retraction time of less than one second.

Spinduction welds (Fig.7) look completely different from any known friction, inertia or induction pressure welds – macroscopically and microscopically. Immediately obvious to the unaided eye is the complete absence of centerline grooves or ejected flash. Microscopically, the Spinduction welds are completely devoid of any bondplane artifacts; it is impossible to tell from the microstructure where the prior end faces were located. It is routine to see a uniform grain size with equiaxed grain structure across the entire weld, which eliminates preferential fracture planes.

The Spinduction process provides an

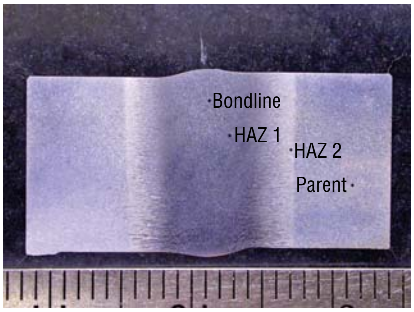


Fig. 7. Spinduction™ welds look completely different from any known friction, inertia or induction pressure welds – macroscopically and microscopically.

added degree of control for moderating the cooling rates, creating a specified heat transition zone upon completion of heating. Residual stresses in Spinduction welds are typically quite low. Even complex parts, such as pistons welded from quench-hardenable steels, often do not require post-weld stress relieving or tempering.

In the presence of oxygen, heated metals react quickly, resulting in the formation of metal oxides on the exposed surfaces with resultant microstructural imperfections in the weld zone. With the Spinduction process, a protective gas environment (i.e. nitrogen) is easily incorporated, forming protective blankets for the joining faces. Induction heating is well suited to work with a protective atmosphere. **IH**

References (online only)

For more information: Contact Dr. Valery Rudnev, Inductoheat, Inc., 32251 North Avis Dr., Madison Heights, MI 48071; tel: 248-629-5055; e-mail: rudnev@inductoheat.com. Don Loveless, Inductoheat, Inc.; tel: 248-629-5054; e-mail: loveless@inductoheat.com. Carmo Ribeiro, Federal Mogul Corporation - Powertrain Energy, 47001 Port Street, Plymouth, MI 48170; tel: 734-254-8225; e-mail: carmo.ribeiro@federalmogul.com. James Boomis, Spinduction Weld Inc.; e-mail: jaboomis@gmail.com

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