Enabling optimized performance and quality of case-hardened steel parts

O A A T   A C C O M P L I S H M E N T S

Intelligent Induction-Hardening

Challenge

Minimizing product design lead times, manufacturing energy consumption, and costs of powertrain components – while simultaneously improving performance and quality – are critically important drivers in the automotive industry. Performance improvements can be used to avoid component redesign or to decrease weight. Automotive powertrain parts are typically surface hardened for use in high-stress, high-wear environments, normally by induction hardening or carburizing. However, these parts are not usually optimized for performance, due to inadequate understanding of materials-processing-performance relationships, and a lack of closed-loop process control for use in the manufacturing environment. The electromagnetic, thermal, and structural responses of the part being induction hardened are all highly non-linear, which makes optimization and control of the process highly difficult to simulate accurately and control precisely. The lack of closed-loop control necessitates quality control by destructive testing.

Technology Description

Induction hardening is an energy-efficient, in-line, heat-treating process widely used in the automotive industry to surface-harden these kinds of parts at the lowest possible cost. The substitution of induction heating/hardening for furnace heating/hardening can lead to savings of up to 95% of the energy used in heat-treating operations, in addition to the energy savings enabled by optimization and lightweighting of automotive powertrain components.

Induction hardening is accomplished by passing an alternating current through a water-cooled copper coil that is coupled to the part by the induced magnetic field. The alternating magnetic field induces eddy currents that resistively heat the outer surface of the part. The part is then quenched to martensite, a strong, wear-resistant phase, when the austenitized layer becomes sufficiently thick.

Examples of automotive parts typically induction hardened, including axle shaft components, a steering rack, and miscellaneous pump shafts.

A multidisciplinary team was formed to improve and optimize the induction-hardening process. Three primary objectives were established: 1) to develop a rigorous computational model of the process; 2) to develop science-based sensors and closed-loop control algorithms applicable to a broad range of steels, processes, and component geometries; and 3) to use these tools to develop steel components with optimized strength-to-weight ratios.

For a given induction-heating process, steel composition, and part/coil geometry, the process simulation code which was developed predicts the thermal cycle, final microstructure distribution, dimensional changes, and the residual stress distribution. The computational code has been structured to utilize advanced parallel computing platforms as they become mainstream, enabling dramatic reductions in computational time and speeding the design cycle.

Passive and active electromagnetic sensors were developed to accurately monitor the depth of heating by tracking the depth of the surface layer that reached the Curie temperature and the resistivity of the surface layer. Since parts are processed iteratively, an adaptive process control algorithm was developed, capable of updating the control parameters – heating time, heating power, or scan speed – for the next part.

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Accomplishments

The program developed a state-of-the-art computational simulation code package for the induction-heating/hardening process. Simulations for static and scanning heating problems are possible. Phenomenological sub-routines for on-heating phase transformation kinetics and hysteretic heating were developed and validated. The code package predicts final microstructural and residual stress distributions and geometry distortion. Science-based passive and active electromagnetic sensors were developed to monitor the depth of heating over time. A model-based adaptive control code for the induction-hardening process was also developed. These tools were validated for bar steels used for automotive powertrain components (shafts, bearings, gears) having ferrite-pearlite microstructures and related microstructures of importance to the automotive industry.

Benefits

- Improved modeling and process control capability enables the manufacture of components with a higher strength-to-weight ratio, reducing component weight and contributing to improved fuel economy. It is estimated that a 20-30% increase in strength-to-weight ratio over existing applications can be achieved with optimization of the induction-hardening process, at lower cost compared to carburizing. The improvement will be needed to minimize powertrain mass in future vehicles, regardless of the propulsion systems used.
- Validated simulation capabilities provide a way to dramatically shorten product development times for these kinds of components.
- Electromagnetic sensors that enable precise control of the induction-heating process were developed. This allows higher-quality parts to be made at lower cost, eventually reducing the cost of scrapped parts and manufacturing support.
- The system enables closed-loop, on-line monitoring of the parts being case-hardened, which eliminates the costly destructive testing associated with open-loop control.
- The use of computational modeling and closed-loop control technology allows the use of existing materials and manufacturing infrastructure in "smarter" ways to produce lighter parts. It also enables the development of optimized materials for inductive processing.
- The substitution of induction heating/hardening for furnace heating/hardening can lead to savings of up to 95% of the energy used in heat-treating operations, because energy is used only when and where it is needed. The process is environmentally benign compared to furnace heat treating as it does not require cleaning, plating, or stripping tanks that use acids or other harmful chemicals.

Commercialization

The process simulation code, as well as the electromagnetic and on-heating transformation kinetics sub-routines, are currently available for license. Discussions with a number of potential licensees have occurred. The science-based sensors and adaptive control algorithms have been demonstrated for potential licensees. Plans to commercialize these technologies are being developed. Delphi Saginaw Steering Systems used an older version of the control algorithm to produce intermediate axial shafts for General Motors Saturn vehicles for a period of time.

Future Activities

The induction-hardening simulation code will be validated against the manufacturing process. Additional projects to add features and refine the accuracy of the code are being pursued. The simulation models will be assessed for utilization of other manufacturing processes – resistance welding, forging, forming processes utilizing localized heating, and other non-equilibrium thermal processes. The applicability of this technology to improve other industrial sectors – steel, heavy vehicle, and industrial equipment manufacturers – is ongoing. Additional projects to commercialize the electromagnetic sensors and conduct research into other types of advanced sensors for induction-heating surface property tailoring are being pursued.

Partners in Success

- AISI Bar Applications Group
- DaimlerChrysler Corporation
- Delphi Saginaw Steering Systems
- Ford Motor Company
- General Motors Corporation
- Sandia National Laboratories