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ADVANCED ELECTROMAGNETIC-THERMAL CO-SIMULATION FOR INDUCTION HEATING

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Induction heating is an important heat treatment process that is commonly utilized for components, such as for gear teeth and cams, which require localized heating [1]. Induction heating is carried out as follows. Eddy currents are induced in a metal workpiece when it is placed within a time-varying magnetic field. The time-varying magnetic field is usually generated by a coil, which carries alternating current at a known frequency, and is placed close to the workpiece. Joule heating arises when the energy dissipated by the eddy currents flowing through the workpiece is converted into thermal energy. This results in induction heating of the workpiece. The ability to model [2] the induction heating process is very important from the point of view of optimizing the process parameters.

Simulation of induction heating requires the ability to model multiple physical fields. Thus, modelling the generation of eddy current requires an electromagnetic solution, which results in a Joule heat distribution in the workpiece. The latter is used as a body heat source to drive a transient thermal analysis, in order to get the temperature distribution in the workpiece. The process is often further complicated by the fact that the electromagnetic properties of the workpiece are strongly temperature-dependent, requiring that the electromagnetic solution be recomputed based on an updated set of material properties. The temperature field also affects the stresses in the workpiece through the thermal expension coefficient, and possibly through temperature-dependent mechanical properties.

The induction heating process also involves multiple time and length scales. For example, the time scale associated with the electromagnetic solution depends on the frequency of the alternating current in the coil, while the time scale associated with transient heat transfer in the workpiece is determined by its thermal properties and size. Generally, the time scale associated with heat transfer is significantly longer than the time scale associated with electromagnetism. Likewise, a length scale that is important for the electromagnetic solution is the so-called *skin depth* [3] of the workpiece, which determines the extent to which the electromagnetic fields have penetrated into the workpiece. The electromagnetic fields (eddy currents, for example) are mostly confined within the skin depth. As a result, the Joule heating is also initially confined within the skin depth, and subsequently diffuses throughout the workpiece. The treatment of the disparate time and length scales requires special attention, as outlined next.

In this paper, induction heating is simulated using the finite element procedure, and utilizing built-in, but relatively new capabilities of Abaqus/Standard [4, 5]. In particular the co-simulation technique, which provides *run-time coupling* between two separate Abaqus analyses, is utilized to couple a time-harmonic low-frequency electromagnetic analysis and a transient heat transfer analysis. To capture the skin-depth accurately, both the electromagnetic and the heat transfer analyses use a fine mesh at the surface of the workpiece, and relatively coarser mesh elsewhere. Because the associated time-scales are very different, a solution approach that treats both the electromagnetic and the heat transfer procedures as transient would be very expensive (potentially hundreds of cycles of the electromagnetic solution may need to be simulated to cover the time scale of heat diffusion). To account for the disparate time scales, the electromagnetic analysis directly computes the steady-state time-harmonic (as opposed to transient) solution for a given alternating current in the coil, and provides the time-averaged (over a cycle) Joule heat as output. The Joule heat is imported (mapped over) to a new mesh and serves as a body heat source for the transient heat transfer analysis. Thus, the co-simulation technique is used to couple a *time-harmonic* and a *transient* procedure (as opposed to two transient procedures).

The whole process is automated; in particular, the mapping capability is built into the co-simulation interface, and does not require any additional user intervention. The electromagnetic analysis always computes a time-harmonic solution, based on the current values of the material properties, while the heat transfer analysis uses the latest results for Joule heat to march forward to the next time increment. A sequential explicit coupling scheme is used in which the two analyses may be set up to exchange data at the end of each time-increment of the transient heat transfer analysis, or after a fixed time period. The difference in the results between these two approaches is dependent upon how strongly the material properties are temperature dependent. An iterative coupling scheme that supports a fixed number of exchanges at the end of each time-increment in the heat transfer analysis is also available to ensure that the correct solution is reached after each exchange.

The whole workflow is illustrated using an example. While the application discussed in this paper is induction heating, similar approaches may also be utilized for other kinds of induction workflows, such as induction hardening and induction sealing.

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