MULTIPHYSICS MODELING OF INDUCTION HARDENING OF RING GEARS

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ABSTRACT. Induction surface hardening of low-alloy carbon steel is increasingly used for high stressed components in the automotive and aeronautical industry sectors \([1]\). The process is known to offer some advantages with respect to conventional surface treatments (e.g., case-hardening) like the high fatigue strength improvement, the “greener” approach, and higher energy efficiency. However, mechanical part designers are sometime reluctant to switch to this technology as some aspects of the process seem less predictable than in other hardening processes. Poor understanding of all concurrent physical phenomena occurring within the work-piece during the hardening process requires the development of reliable simulation tools which would thus lead to better control of the design together with faster optimization of the manufacturing process parameters.

INTRODUCTION

Induction heating has been widely used for heat treating and especially surface hardening for a broad variety of applications, ranging from the automotive to the renewable energy market. However, the lack of precise knowledge about the interrelation between all the concurrent physical phenomena occurring within the part during the heating cycle has confined this technology in the hands of few experienced technicians, restricting its use to mass production items (mostly gears). The benefits of this technology, which is clean, repeatable and cost-effective, could boost its introduction into more conservative industry sectors, such as aerospace, where furnace-based treatments (e.g., carburizing) represent the golden standard \([2]\). The major limitation is related to the optimization of the induction hardening process, which usually requires significant material know-how and thus can be very long and expensive \([3]\). Moreover, the limited production rates and demanding quality requirements in terms of mechanical properties (e.g., case/core hardness) would not be worth the effort. For these reasons, computer simulation could provide a general tool for understanding and improving the critical aspects of each phase, thus helping and speeding up the re-engineering of the whole process and the spreading of the induction technology into new markets.

NUMERICAL MODELING OF THE HARDENING PROCESS

Problem description

Heat treatments are well known and codified procedures for causing desired changes in the metallurgical structure of metal parts and thus in their mechanical properties \([4]\). The main goal of heat treatments is thus to improve these properties, in order to increase overall performances. Hardening of steels is commonly done to increase their strength and wear properties and consists of two main steps, the heating above the austenitization temperature...
A$_3$ (in Fe-C diagram), followed by a rapid cooling in order to create a very hard martensitic structure (quenching). During the first step, known as austenitizing, the material undergoes a phase transformation, while the atomic lattice rearranges from body-centered cubic (BCC) to face-centered cubic (FCC) configuration (in some case the initial structure is a tempered martensite). This process is usually fully accomplished (i.e., 99% of transformed austenite is achieved) by uniformly heating the work-piece above a critical temperature around 850 °C. Once a fully austenitic structure is obtained (and hopefully the carbides precipitates has dissolved inside the lattice), the material is rapidly cooled, in order to trap atoms inside the crystal structure and create a martensite structure, sort of ferrite with supersaturated solid solution of carbon. After this step, known as quenching, the transformed regions are very hard and brittle [5]. In some materials, very high cooling rates must be imposed on the part to achieve a fully martensitic superficial structure, in order to avoid the presence of intermediate transformation products like pearlite and bainite. Continuous cooling transformation (CCT) diagrams can tell how the selected steel is sensitive to cooling and represent a good tool for material selection [6].

Although these concepts usually hold true for conventional hardening processes (e.g., case-hardening by carburizing or nitriding), they must be carefully extended to induction hardening. In fact, this process is characterized by a very fast electromagnetic heating which originates directly within the work-piece. Due to the elevated power densities (almost 90% of the induced power is allowed on the skin depth layer) a much higher heating rate of the order of 1,000 °C/s can be obtained. In these conditions, carbon just hasn’t enough time to uniformly diffuse into an FCC lattice and inhomogeneous austenite can be obtained, thus requiring either longer heating time, or higher temperature (i.e., more energy) to accomplish the transformation. On the other hand, some austenite may retain after the heating cycle and this so-called retained austenite is a major aspect to take into consideration. While it directly reduces the percentage of transformed martensite after quenching, it may affect the resulting surface hardness value and actual fatigue performance of the part.

The industry demands for high-quality gears, meeting severe specifications both in terms of performances (high strength, long life) and costs. This can be attained by combining a very hard, wear-resistant surface layer with a softer, tougher core. Case-hardening seems to represent nowadays the most widely used technique for guaranteeing such requirements, but it is quite costly, time-consuming, polluting, and labor-intensive. In fact, it requires both hard-machining and long carburizing times in order to ensure the desired case depth and rectify the dimensions due to part distortion during quenching [7]. Induction hardening is an alternative technology which is rapidly spreading and could represent a cost-effective solution for heat treating gears. It allows a rapid contour-heating of the tooth surface, without the need for carbon enrichment (since the desired carbon content is already present in the raw material) and subsequent grinding or lapping operations (since the transformed regions are small so that the distortions are minimal and predictable).

Gear contour-hardening usually requires that a thin case depth is obtained all along the profile of the tooth, without affecting much its core. Thus, very high power densities together with very short heating times are mandatory in order to guarantee the desired hardening profile on the tip, flank, and root of the tooth. This provides excellent wear and fatigue resistance together with a high bending strength, thus extending gear durability and life [8].

The choice of a suitable steel for induction hardening must take into account the requested properties of the final product, in terms of required hardness and default working conditions: in fact, hardenability (i.e., the depth to which the steel may be hardened during quenching) is greatly influenced by the chemical composition and should be tightly controlled in order to achieve reproducible results; moreover, a homogeneous, fine-grained (i.e., quenched and tempered) initial microstructure should be used to avoid incomplete phase transformation and retained austenite formation after the heat treatment. In this paper, a low-alloy, medium-
carbon chromium steel with 0.50% carbon content (AISI/SAE 6150) is used in the course of the simulations, which exhibits a good hardenability, high hardness (53 HRC), an average grain size (ASTM No. 5), and a sufficient cold-drawn hardness (30-36 HRC).

As a reference work-piece, we use a 45 teeth spur gear test-case (Figure 1-a). The original circular geometry is first reduced exploiting the tooth periodicity and its symmetry along the middle radial plane; secondly, it is further sliced into a 0.1 mm layer, in order to contain the total number of elements and reduce the computation time. It must be pointed out that this simplification doesn’t allow to take into account the real field behavior at the end-extremities of the gear (the so-called edge-effects); however, it can provide a good approximation of the real power (and heat) distribution along its inner cross-sections. The resulting geometry is finally imported into a 3D finite element software able to carry out coupled simulations (Cedrat Flux). A single-turn, induction coil encircling the gear is added in order to impose the given current source. The inductor is modeled as a coil conductor, which enables the representation of non-magnetic, conducting regions with sources. This solution doesn’t account for the real current density distribution within the coil region, which is higher on the inner profile, due to the electromagnetic ring effect. Moreover, since no internal water cooling is taken into account, the thermal computation is only performed within the magnetic regions (i.e., within the work-piece). Though, these assumptions allow faster computations without affecting the resulting power density profile, which remains qualitatively unaltered. All the noticeable parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>No. teeth</td>
<td>45</td>
</tr>
<tr>
<td>Module (mm)</td>
<td>2.54</td>
</tr>
<tr>
<td>Pitch diameter (mm)</td>
<td>114</td>
</tr>
<tr>
<td>Face width (mm)</td>
<td>6</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>22°30'</td>
</tr>
<tr>
<td>Coil outer diameter (mm)</td>
<td>128</td>
</tr>
<tr>
<td>Airgap (mm)</td>
<td>4</td>
</tr>
</tbody>
</table>

The described geometry is meshed using both tetrahedral and brick elements of the first order, obtaining the discretization shown in Figure 1-b. The resulting mesh consists of 8,688 volume elements and 11,924 nodes. We would like to stress the importance of having a finer mesh on
the tooth profile region, where the induced currents localize within few hundredths of millimeter, due to the very low skin depth, especially at higher frequency values (i.e., above 100 kHz). In this case, a progressive layered mesh is used, accounting for at least three elements per penetration depth.

**Problem formulation**

The presented problem can be analyzed in two main steps, the heating phase, consisting of a fast electromagnetic heating caused by the current induced inside the work-piece, and the cooling phase, during which a quenching fluid is sprayed directly over the heated profile, in order to rapidly cool it down and obtain the hardened martensitic structure. A fully coupled 3D magneto-thermal simulation is performed, which updates the steady-state magnetic solution at each time-step of the thermal transient problem.

The 3D eddy current problem is solved by means of a T-T₀ϕ formulation [9], which expresses the magnetic vector field $\mathbf{H}$ (or equivalently the magnetic flux density $\mathbf{B}$) within the conducting regions as follows:

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0 \mu_r} = \mathbf{T} + \mathbf{T}_0 - \nabla \Phi,$$

where $\mathbf{T}$ (A/m) is the unknown electric vector potential and $\Phi$ (A) is the total magnetic scalar potential. $\mathbf{T}_0$ (A/m) represents the given imposed electric vector potential, which describes an arbitrary current distribution equal to the prescribed value. In this case, the real B-H curve relationship is taken into account by defining a non-linear dependence of the relative magnetic permeability $\mu_r$ with the applied field $H$. This allows to accurately model the effects due to magnetic saturation at high field strengths. The current density $\mathbf{J}$ can then be derived from the Ampère’s law, thus yielding:

$$\mathbf{J} = \nabla \times (\mathbf{T} + \mathbf{T}_0).$$

Despite its overall worse average accuracy within the single element, compared to the vector potential formulation (e.g., A-V), the scalar model allows for faster computations, thanks to the reduced number of variables required to describe non-conductive regions (e.g., air) [10]. This type of formulation has been recently implemented in Flux, and may be coupled with an external circuit in order to take into account the real current distribution within the coil due to the ring effect. The main advantage of this type of formulation is its reduced memory occupancy compared to the A-V and faster transient resolution time. [11]

The thermal transient problem is described by the well-known heat diffusion equation:

$$\gamma C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = \rho J^2,$$

where $T$ (K) is the temperature, $k$ is the thermal conductivity (W/m.K), $\rho$ the mass density (kg/m³), $C_p$ the specific heat capacity (J/kg.K), and $\rho$ the resistivity (Ω.m). Here, a linear temperature dependence for both the thermal conductivity and the resistivity is considered. The volumetric heat capacity $\gamma C_p$ (J/m³.K) is modeled with a gaussian model, taking into account the 2nd order phase transition in proximity of the Curie temperature. Moreover, a temperature dependence for the relative magnetic permeability $\mu_r$ is considered, by means of an exponential function which progressively decreases as the temperature increases and
approaches the Curie value of 760 °C (Figure 2). All the parameters used in the course of the simulation are listed in Table 2.

Table 2. Material properties of AISI/SAE 6150 steel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{sat} (T)</td>
<td>saturation magnetization</td>
<td>2</td>
</tr>
<tr>
<td>μ_0</td>
<td>initial permeability</td>
<td>600</td>
</tr>
<tr>
<td>ρ (Ω·m)</td>
<td>electrical resistivity</td>
<td>21e-8</td>
</tr>
<tr>
<td>α_ρ (K^{-1})</td>
<td>temperature coefficient ρ</td>
<td>2.5e-3</td>
</tr>
<tr>
<td>k (W/m·K)</td>
<td>thermal conductivity</td>
<td>46.7</td>
</tr>
<tr>
<td>α_k (K^{-1})</td>
<td>temperature coefficient k</td>
<td>-2.5e-4</td>
</tr>
<tr>
<td>γC_p (J/m³·K)</td>
<td>volumetric heat capacity</td>
<td>3.3e+6</td>
</tr>
</tbody>
</table>

The heat exchange through the free surfaces of the gear can be represented by combining the losses due to both convection and radiation at the given boundaries:

$$\varphi = k \frac{\partial T}{\partial n} = -h(T - T_a) - \sigma \varepsilon (T^4 - T_a^4),$$ (4)

where $\varphi$ is the heat flux (W/m²) normal to the surface, $T_a$ is the temperature of the surrounding fluid, $h$ (W/m²·K) is the convection heat exchange coefficient (HEC), $\sigma$ is the Stephan-Boltzmann constant (5.675e-8 W/m²·K⁴), and $\varepsilon$ is the emissivity. During the heating phase, we consider 1.5 W/m²·K for convection and 0.8 W/m²·K⁴ for radiation. The cooling phase at the end of the heating is represented by means of a sudden change in the HEC, in order to account for the effect of the quenchant.

The mechanism of quenching is affected by many factors, which significantly influence the performance obtained from this process. In general, cooling occurs in three different stages: the early vapor phase, governed by convection and conduction through a vapor film around the work-piece; the main boiling phase, ruled by conduction between the hot surface and the cool quenchant; the late convection phase into the liquid. Moreover, the cooling rate of polymer-based (polyalkylene glycols, PAG) quenchants, which are the most commonly used for gear hardening applications, depends on the concentration of the solution, the quenchant
temperature, and the degree of agitation. Based on the above considerations, the coefficient $h$ results to be greatly dependent on the superficial temperature of the metal part and is thus modeled accordingly.

A single-shot induction hardening simulation is performed [12], using a frequency of 170 kHz and an equivalent magnetic field strength of 315 kA/m. The maximum induced power within the gear is 360 kW. A heating time of 120 ms is selected in order to achieve a temperature above 950 °C within few millimeters below the tooth profile. Afterwards, the quenching phase is simulated, by switching the power off and adjusting the heat transfer coefficient on the surface of the tooth in order to fit the behavior of the quenchant. In this case, a high-cooling rate fluid with 8% polymer concentration and a temperature of 30 °C is considered. The characteristic cooling curve and HEC evolution with temperature as provided by the manufacturer are depicted in Figure 3.

![Figure 3. Cooling curve (a) and HEC evolution (b) of the given quenchant.](image)

Model implementation and results

In order to translate the above considerations into Flux, its multiphysics capabilities must be fully exploited. A stand-alone model is built for simulating each of the main concurrent stages involved in the hardening process (i.e., eddy current losses, heating and cooling phases) and a scripting procedure is written in order to couple the different phenomena (i.e., magnetic and thermal). In practice, by means of a continuous data exchange and synchronization between the applications, the thermal variations of the main electric and magnetic parameters of the gear are taken into consideration. This process is carried out in 2 steps, which are iterated until a specific precision of the residual is reached: first, the coordinates of the nodes of the mesh are transferred through a data-exchange text file; the physical quantities of interest are then synchronized and updated.

Particular care must be taken in handling the sudden change in the HEC value resulting from the beginning of the quenching phase. In fact, an abrupt increase of such coefficient requires a refinement of the time-stepping in order to accurately describe the thermal dynamics at the end of the heating phase. Moreover, the average temperature over the tooth profile is evaluated at each time-step and used to update the current value of the HEC. All the computations are performed on a modern 64 bit workstation (2.54 GHz, 4 GB RAM) and take about 35 minutes for solving the coupled electromagnetic problem during the heating phase; 5 minutes are required to evaluate the solution of the cooling phase.

The thermal distribution at the end of the heating is illustrated in Figure 4. It can be noticed that the 950 °C contour follows the tooth profile, thus satisfying usual hardening requirements, which demand a higher case depth on the tip and a smooth transition along the
flank down to the root of the tooth. A better understanding of the resulting temperature chart can be obtained by inspection of Figure 5, where the time evolution during the heating phase and spatial distribution after 120 ms are depicted.

Figure 4. Temperature map after 120 ms of heating (frequency: 170 kHz, H-field: 315 kA/m): complete distribution with evaluation paths (a) and 950 °C contour with sensor locations (b).

Figure 5. Thermal profiles on the tooth (frequency: 170 kHz, H-field: 315 kA/m): temperature evolution at a depth of 0.25 mm below the surface during the heating phase (a) and depth of heating after 120 ms (b).

Figure 6. Thermal history of the work-piece (frequency: 170 kHz, H-field: 315 kA/m): temperature evolution at a depth of 0.25 mm below the surface.
If we consider the temperature evaluation paths P1–P5 and the depth at which the austenitization temperature is reached, we obtain an hardening depth higher than 1 mm on the tip (P1, P2), between 0.6 and 0.7 mm on the flank (P3, P4), and of 0.25 mm on the root (P5). The cooling curves obtained during quenching and evaluated over the temperature sensors T1–T5, show a rapid cooling below the martensite start temperature Ms (which for the given steel is approximately 270 °C) within the first 5 seconds for T5 (Figure 6). This would result in a very fast cooling rate and avoiding the formation of softer intermediate products such as bainite and perlite.

CONCLUSIONS

In this paper a multiphysics approach for modeling the gear induction hardening process is presented. Some novelties are taken into account with respect to similar contributions presented in the past. In particular, a fully non-linear magnetic behavior is considered for the given steel, taking into account both magnetic saturation and Curie transition effects. Furthermore, the full thermal history of the work-piece can now be computed, featuring the real cooling rate of the quenchant. The collected data are valuable and may be used in future to predict the resulting hardness and residual stresses originated within the work-piece during and after the heat treatment.

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REFERENCES