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3D modeling of induction hardening of gear wheels

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ABSTRACT

Induction hardening of gear wheels is modeled. The model consists of two nonlinear partial differential equations describing the distributions of magnetic and temperature fields in the system. All material parameters are supposed to be functions of temperature. The model is then solved numerically in the 3D hard-coupled formulation using the professional code FLUX3D supplemented with a number of own scripts and procedures. The methodology is illustrated with a typical example whose results are discussed.

1. Introduction

Induction hardening is a heat treatment process whose purpose is to bring about local changes in the crystalline structure of surface layers of steel bodies resulting in their higher hardness [1–3]. The required external parts of the body are first heated somewhat above temperature Ac_3 securing their uniform internal austenitic structure. Then, after optional homogenization of their temperatures (on the order of seconds or less), the body must be intensively cooled in a suitable quenchant (water, spray, oil or polymer liquid). The result is a harder, but more brittle martensitic structure of the hardened layers. The structure of the other parts of the body (its interior) remains practically unchanged.

The principal aspects of the process can be explained in terms of Figs. 1 and 2. Fig. 1 shows several curves (full lines) of cooling of a typical carbon steel (50 CrMo 4) from the starting temperature T_{start} exceeding the value of Ac_3. Hardness HV (here given in Vickers) is a function of the time t_c of cooling to the temperature T_{finish} below the martensite temperature M_s. The higher the velocity of cooling, the harder the structure we obtain (see the leftmost curve). The other curves (in the right part of the figure) pass, however, through the area of bainite (B), pearlite (P) or ferrite (F), which leads to an incomplete hardening process.

The same can be seen in Fig. 2 that can be derived from Fig. 1. The resultant hardness obviously decreases with the time of cooling.

The process of heating itself may be realized in two basic ways, namely by means of gas or electricity. This paper investigates the process of hardening of a gear wheel where heat is produced by magnetic induction. Its advantages are summarized, for example, in [4–8]. It provides a lot of variations, such as hardening by parts (several teeth at a time), spin hardening (simultaneous hardening using a ring inductor) and also heating by two frequencies, which allows obtaining the required temperature profile in particular teeth with a substantially higher accuracy.

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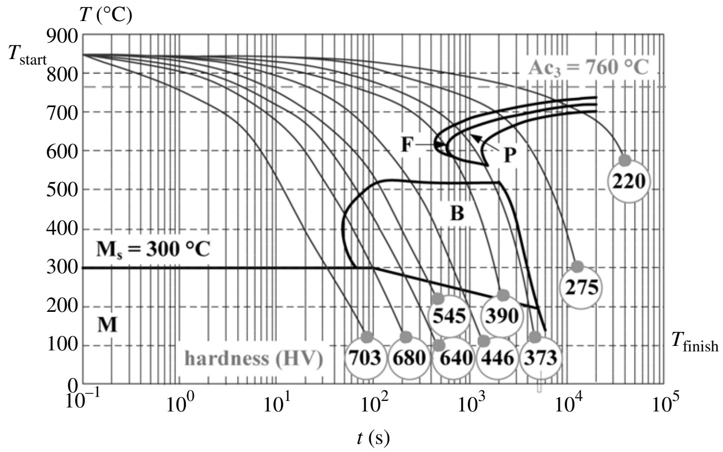

Fig. 1. CCT diagram of steel 50 CrMo 4: temperature $Ac_3 = 760$ °C.

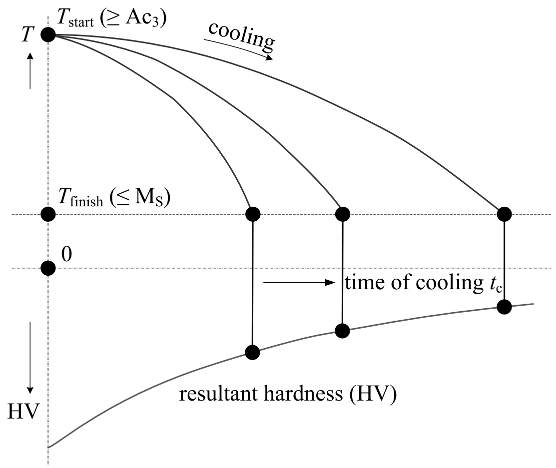

Fig. 2. Dependence of hardness on time of cooling.

Modeling of the process is an essential prerequisite for the anticipation of numerous mechanical properties of the gear wheel in the stage of design. Nevertheless, it is still a challenge. From the physical viewpoint, induction heating is characterized by a mutual interaction of the magnetic and temperature fields influencing one another through the physical parameters (electric and thermal conductivities, magnetic permeability, heat capacity or specific mass) of the heated material, that are generally nonlinear functions of temperature. Another problem is that the austenitization temperature Ac_3 generally depends not only on the chemical composition of the processed steel, but also on the velocity of heating (higher velocity of heating results in the growth of Ac_3, as is shown in the diagram for typical CrMo steels in Fig. 3). Further difficulties accompany the modeling of the process of cooling: merging of the hot work-piece into the quenchant first results in the production of a thin vapor layer around the work-piece and the relevant heat transfer is governed by the convection and conduction of heat through this layer. In the subsequent phase, the principal role is played by the heat conduction between the work-piece and quenchant and, finally, after vanishing the vapor layer by the direct heat convection between them. All these mechanisms of heat convection and conduction are extremely uneasy to quantify. That is why the process of cooling is mostly modeled by a generalized convection (substituting both the real conduction and convection) whose coefficient depends on the actual temperature of the surface of the work-piece.

Although the heating of gear wheels by induction was proposed and tested already in the thirties of the last century [9], its parameters were recommended for a long time only on the experimental basis. Numerical and computer modeling of the typically 3D process started developing only in the late nineties and even so, the first attempts were based on strongly simplified non-realistic 2D models. The significance of these pioneering works did not consist in the results achieved, but just in showing the ways of further research in the domain. More sophisticated and also more realistic 3D models started appearing only several years after. First, they also suffered from numerous simplifications (such as simplified geometries or independence of the physical parameters on temperature). That is why the relevant works were usually published in the form of conference presentations and not in scientific journals.