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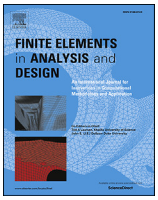

Modelling of induction hardening in low alloy steels

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ABSTRACT

Induction hardening is a useful method for improving resistance to surface indentation, fatigue and wear that is favoured in comparison with through hardening, which may lack necessary toughness. The process itself involves fast heating by induction with subsequent quenching, creating a martensitic layer at the surface of the workpiece. In the present work, we demonstrate how to simulate the process of induction hardening using a commercial finite element software package with focuses on validation of the electromagnetic and thermal parts, together with evolution of the microstructure. Experiments have been carried out using fifteen workpieces that have been heated using three different heating rates and five different peak temperatures resulting in different microstructures. It is found that the microstructure and hardening depth is affected by the heating rate and peak temperature. The agreement between the experimental and simulated results is good. Also, it is demonstrated that the critical equilibrium temperatures for phase transformation is important for good agreement between the simulated and experimental hardening depth. The developed simulation technique predicts the hardness and microstructure sufficiently well for design and the development of induction hardening processes.

1. Introduction

Hardening of steel is performed with the purpose to obtain certain properties such as high wear resistance, strength, etc. It may be performed throughout the cross section of the workpiece, so called through hardening, or on the surface only, so called case hardening. The latter is favourable when parts are subjected to contact with hard and abrasive materials, since the soft core can absorb stresses without cracking. Typically, surface hardening is performed by carburising the outer layer of a mild steel, or by rapidly heating the surface of steel with sufficiently high carbon content. Flame or induction heating are two common processes for this. Please see, e.g., Kalpakjian and Schmid [1] for more information.

Induction heating is a non-contact heating process. Heating of any electrically conductive material through joule heating from the eddy currents created in the outer layer of the workpiece, whenever subjected to an alternating electromagnetic field is possible. The depth of the heated layer depends on many factors, such as the frequency of the electromagnetic field source, the thermal and electrical properties of the workpiece, and other factors. In the process of induction hardening, the heated surface of the metallic workpiece is transformed into austenite. Subsequent quenching, usually done by spraying a mixture of water and polymers onto the surface, creates a hard martensitic layer. The process appears to be very straight forward, but deals with a number of complexities such as metallurgical phenomena and the temperature distribution in the workpiece resulting in difficulties predicting the thickness of the martensitic layer. Modelling this is challenging, since changing material properties must be accounted for, as well as a material model accounting for phase changes must be included. In addition, induction hardening concerns ferromagnetic materials, which may require a cumbersome electromagnetic transient solution [2].

Simulating the process of induction heating has been performed by a number of researchers: a high-frequency induction heating system was simulated and verified with a series of experiments by Ref. [3]; in Bay et al. [2] a mathematical and numerical model developed for coupling the electromagnetic, thermal and mechanical phenomena during induction heating is presented. Cajner et al. [4] takes the problem one step further and simulates the phase transition, computes the hardness and compares the results with experiments. Hömberg et al. [5], simulate the temperature for discs and gears using a dual frequency inductor

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Table 1
Chemical composition in wt% for AISI 4150 steel.

Fe	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
Balance	0.53	0.24	0.74	0.008	0.001	1.12	0.18	0.22	0.17	0.026

and compare the depth of hardness and peak temperature. Magnabosco et al. [6], compute the hardness profile and compare the results with experiments. In the work of Schwenk et al. [7], the temperature and hardness profile for single and dual frequency inductors are simulated. The temperature surface profile and hardening depth profile are compared with experiments. All these are examples of work in which the process has been investigated, but not the peak temperature and heating rate influence on the microstructure.

The surface temperature, hardness profile and final microstructure are simulated and compared with experimental results for the process of induction hardening in this work. It is concluded that the final microstructure, and as a result the hardness profile, is strongly influenced by the heating rate. This phenomena is captured in the modelling of the hardness profile. The agreement between computed and measured hardness profile is very good in general. In addition, the influence of the phase transformation equilibrium temperatures on the hardness profile and the computed microstructure is presented. It is found that the critical equilibrium temperature influences on the depth of hardness, and is crucial for a good agreement. The developed technique for simulating the hardness profile and depth of hardness are sufficiently good for design and development the process of case hardening using induction heating.

2. Induction heating experiments

Experiments have been carried out on cylindrical workpieces with a dimension of 100 mm in length and 40 mm in diameter. The workpieces were heat treated at a temperature of 880°C for 2 h, quenched in oil holding a temperature of 80°C, and tempered for 4 h at 650°C before any induction heating experiments were carried out. This results in a homogeneously tempered martensitic microstructure consisting of uniformly dispersed cementite particles embedded within a continuously ferrite matrix of the workpieces. The final hardness throughout the diameter of the cylindric workpiece was 280 – 300 HV 0.5. The chemical composition of the steel is given in Table 1. In total were 15 induction hardening experiments performed: five workpieces were heated with a rate of approx. 260 K/s, five with a rate of 150 K/s, and five with a rate of 50 K/s. For each heating rate, each workpiece was heated to a different peak temperature, namely 940°C, 1000°C, 1050°C, 1100°C and 1150°C, respectively. Thus, each experiment resulted in a typically hardening depth.

The induction heating was carried out using a voltage-feed series load with a capacitor at the input of the inverter, and a series-connected output circuit. The inductor was a five-turned coil with a coupling distance of 5 mm. The inner diameter of the coil was 50 mm and the outer 66 mm. At the primary side of the converter, the voltage, current, frequency of the current, and power were recorded with a sample frequency of 25 Hz. Using an infrared IMPAC ISQ 5 pyrometer with a measuring range of 700 – 2500°C, the temperature was recorded during the heating process at the half-length of the workpiece with the same sample frequency. Immediately after the power had been turned off, a mixture of water and 8% of commercial polymer (Aqua-Quench 365) was sprayed onto the workpieces with a flow rate of 110 l/min. The temperature of the mixture before quenching was around 20°C. The workpiece was rotated during the quenching and the heating process. Fig. 1 shows the experimental setup after a complete induction heating cycle. Table 2 shows the range in data for each workpiece. As an example, the measured current, frequency and temperature during heating of workpiece number 8 is shown in Fig. 2. After quenching the workpiece was tempered at 160°C for 2 h. The microstructure model does not include the tempering effect.

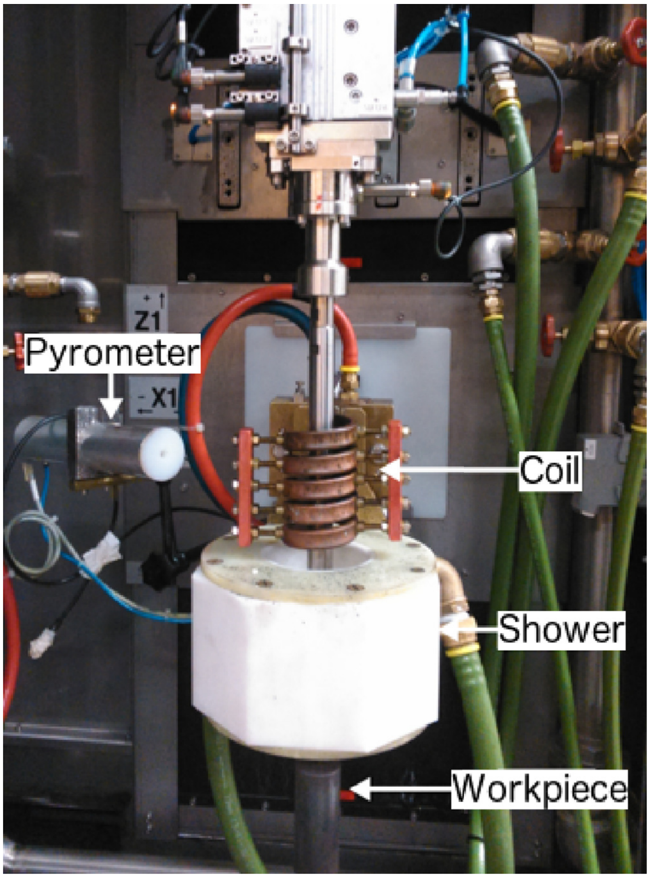

Fig. 1. Experimental setup of the induction heating experiment after a complete induction heating cycle. The workpiece was rotating during the heating and quenching stages. The temperature was not measured during quenching of the workpiece.

After quenching, the austenitised layer is transformed into martensite. For penetration depth detection, the workpiece was cut half-length and micro-hardness Vickers (HV0.5) profile measurements were performed out in the radial direction on each sample. For microstructural information, the surface of each sample was investigated using light microscopy. Before pictures of the microstructure were taken, each sample was mounted using a resin, polished and etched using nital. The analysis was carried out half-lengthwise of the workpiece in order to avoid boundary effects, such as non-uniformly heating and quenching [8].

3. Material properties

To model the induction heating process, electrical and thermal material properties as a function of temperature must be known. The temperature dependency of the specific heat, and the thermal and electrical conductivity was extracted from JMatPro version 8 [9] for the austenite, ferrite, pearlite, bainite and martensite phases. Also, the magnetic permeability as a function of temperature must be known. The magnetic hysteresis curve is measured in this work and the result are described in section 3.1.