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Research Paper

Coupled electromagnetic and thermal analysis of induction heating for the forging of marine crankshafts

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HIGHLIGHTS

- FE analysis combined with equivalent circuit model (ECM) for induction heating has been developed.
- The efficiency and coil current for various conditions have been determined.
- An iterative method is proposed for the evaluation of the relative magnetic permeability.
- The proposed numerical technique was validated by comparison of the model results with experiments.

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ABSTRACT

The induction heating of heavy marine crankshaft preforms has been analyzed to evaluate the temperature distribution prior to forging. The preform has a cylinder shape with a ring groove region and is heated in sections by induction. Each section is then forged to produce a crankshaft pin journal and a web region with continuous grain flow using vertical and horizontal compressions. Since induction heating of the preform needs precise temperature control to prevent process-induced defects such as overheating or insufficient heating, an equivalent circuit model was adopted in conjunction with a coupled electromagnetic and thermal analysis to evaluate the coil current induced in preforms with various dimensions, power levels, and frequencies. The magnetic permeability, which depends on temperature and magnetic field, was evaluated in an iterative manner and also considered in the analysis. The temperature distribution of the preform was numerically predicted and compared with experimental values. The experimental validation confirms that the suggested analysis method can be a practical tool to predict the temperature distribution in the induction heating for the forging of heavy marine crankshafts.

1. Introduction

The crankshaft for heavy marine diesel engine is generally manufactured by a continuous grain flow (CGF) forging process. Fig. 1 shows the preform of the crankshaft for CGF forging. The preform is a round bar with ring grooves and undergoes a multiple step forging after heating of each section individually. To achieve accuracy in the final product, it is very important to control the temperature distribution within the part during each section forging.

The induction has been most commonly used as the heating method for CGF forging of crankshafts due to the high productivity with lower oxidation loss. Induction is a heating method that uses an induced current within the workpiece in a time varying magnetic field. However, the induction heating method has some limitations in achieving an even temperature distribution for large sized preforms, since the temperature gradient between the surface and the center of the preform increases significantly as the diameter of the preform is increased.

As the heating for forging requires precise temperature control to prevent the defects such as overheating or under-filling due to insufficient heating, an accurate prediction of the preform temperature prior to each forging step is essential.

Induction heating is a complex process combining electromagnetic and thermal phenomena. Moreover, induction heating analysis becomes more complex due to the nonlinearity of relative magnetic permeability of ferromagnetic materials such as steel.

Lavers [1] provided an excellent review of numerical techniques for induction heating from the classical papers to the current state of the art. The first paper focused on numerical solutions of induction heating was provided by Holmdahl and Sundberg [2]. They suggested a numerical solution for the prediction of the temperature increase for a ferromagnetic cylinder using the FDM (Finite Difference Method) considering temperature dependent material properties except for the relative magnetic permeability. Using this

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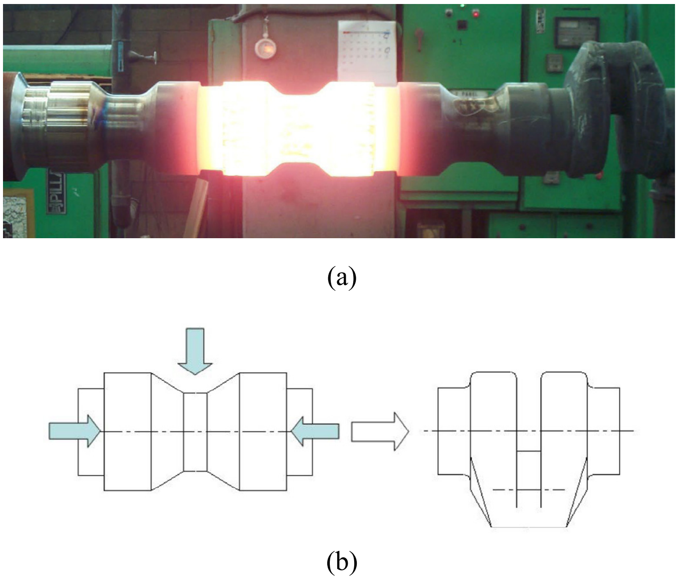

Fig. 1. Induction heating and forging steps to make on a section of the crankshaft: (a) local induction heating, (b) vertical and horizontal compressions.

methodology, Lavers [3] provided one of the first solutions to a 2D induction heating problem involving a ferromagnetic, square cross section conductor. Massé et al. [4] described a finite element prediction correction scheme that allowed a time step refinement during the critical Curie transition. Ida [5] provided one of the first attempts at modeling velocity effects in induction heating. Nakata et al. [6] investigated the effect of relative magnetic permeability on the error of numerical solutions. They found that the error increased exponentially with an increase in the relative magnetic permeability. Adly [7] presented a numerical approach for solving induction heating problems involving relatively long rods that exhibit hysteresis. Recently, a meshless method called the element-free Galerkin method for electromagnetic field computations was developed to overcome the re-meshing of the analysis domain involving moving geometry. Čingiski et al. [8] provided one of the first attempts at the meshless method. Urbanek et al. [9] investigated the effect of the frequency on the induction heating efficiency for ferromagnetic hollow cylinders considering a relative magnetic permeability that was dependent on both the magnetic field intensity and temperature. Sadeghipouir et al. [10] compared finite element analysis and experimental results of induction heating for heat treatment of carbon steel tubes with a flange. The temperature dependence of resistivity was considered but the change of relative magnetic permeability was not part of their finite element analysis. Kranjc et al. [11] and Cho [12] also conducted induction heating analysis for steel cylinders with an emphasis on the temperature dependency of material properties. Most of previous studies are for the cases with constant diameter of the workpiece or a constant power or constant frequency. According to the recent studies for the numerical simulation and experimentation of induction heating, investigations with constant current and frequency are not significantly different from the studies described above. Han et al. [13] conducted numerical analysis with a fixed current and frequency to find the proper heat treatment conditions for a welded pipe. Lee and Hwang [14] performed numerical simulations and experiments for a fixed input power of 40 kW for the induction heating during the forming of thick steel plate. Bui and Hwang [15] studied the working coil with magnetic flux concentrators for the barrel induction heating in an injection molding machine. The operating conditions for induction heating in their study were also for a fixed power and frequency. Although induction heating simulations need the coil current as an input for the analysis, a detailed description for the determination of coil current has not been provided in these recent studies.

Since the induction heating efficiency and coil current depend on many variables such as diameter, frequency, power level, coil turns, and material properties, improvement of versatility of the analysis method is needed to provide a comprehensive understanding of the various variables involved in induction heating. Furthermore, the relative magnetic permeability has normally been considered as a function of temperature only or as a constant in most previous studies. Since relative magnetic permeability of ferromagnetic material like steel is dependent on both temperature and magnetic field intensity, it is important to develop an evaluation method that considers relative magnetic permeability as a function of these variables during induction heating.

The purpose of the current study is to develop an analysis method for induction heating that can handle various forging preform sizes and process variables like power, frequency and coil turns etc. An equivalent circuit model that reduces the workpiece and coil to equivalent resistances and inductances respectively is used in the current study to evaluate the effects of induction heating variables on the efficiency and coil current. The coil current from the equivalent circuit model is used as input to a finite element analysis of induction heating. Since relative magnetic permeability has an interdependent relationship with magnetic field intensity, it is evaluated in an iterative manner. Based on the results, a coupled electro-magnetic and thermal analysis was conducted to predict the temperature distribution of induction heating for workpieces with various dimensions. The results of finite element analysis are compared with experimental results to verify the validity of the suggested analysis method.

2. Experiments

The heated workpiece in the current study has a cylindrical shape with a ring groove and this section of the preform is heated locally by induction heating using a solenoid as shown in Fig. 2. The heated workpiece (i.e. the forging preform) is heated up to approximately 1200 °C. The workpiece is comprised of two pre-web regions with relatively large diameters and a pin region with a small diameter between the webs (i.e. the ring groove). The two pre-web regions are the main focus for heating prior to forging. Fig. 3 shows the location of temperature measurements in the heated workpiece. A 6 mm diameter hole was drilled from surface to the target depth to measure the internal temperature of workpiece. The temperatures at 0.5 relative radius and center of the section of the pre-web were measured at one second interval using a K type thermocouple that was certified in accordance with Korean standard (KS C 1602). The allowable tolerance of KS C 1602 is within 0.75% of the measured temperature. The K type thermocouple was enclosed by stainless tube with a diameter of 5 mm. The end part of the thermocouple was bended into "L" shape and was inserted into the hole to the target depth. Then, the thermocouple was fixed by wiring steel wire around the workpiece to prevent movement of the thermocouple as shown in Fig. 2(b). The location of the measurement point was verified by comparing the inserted length of thermocouple with the depth of the hole. Since the heated workpiece is symmetric about the center line as shown in Fig. 3, the coil turns were selected to achieve a symmetric temperature distribution with consideration of the workpiece length.

Table 1 shows the size of heated workpieces, range of input power, frequency and coil turns used in the experiments. The temperature during induction heating was measured for four preforms with different diameters and lengths. Low frequency with a range from