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Research Paper

Numerical and experimental investigation of induction heating process of heavy cylinder

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HIGHLIGHTS

- The electromagnetic-temperature-stress multi-field coupling model of heavy cylinder induction heating was established.
- The solution for acute angle effect problem of heavy cylinder induction heating was proposed.
- The heating effects of traditional resistor furnace and induction heating were compared.

ARTICLE INFO

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Induction heating
Acute angle effect
Rapid heat treatment

ABSTRACT

In this work, the induction heating of heavy cylinder is numerically and experimentally studied. The electromagnetic-temperature-stress multi-field coupling simulation are performed, using the ANSYS software in order to investigated the induction heating process of heavy cylinder, simulation results show that the end of heavy cylinder would be overheating and burning because of the acute angle effect and the high magnetic flux density when the rectangular coil is used. And then, the acute angle effect problem of heavy cylinder in the induction heating process is investigated, a solution of welding heat treatment ring at the end of the heavy cylinder and adding the magnetizer at the end of coil is proposed, and the acute angle effect can be eliminated. Furthermore, the heating effects of heavy cylinder by traditional heating method and induction heating method proposed are compared, simulation results show that the heating efficiency and the energy saving of induction heating are improved greatly. Finally, the heat treatment experiment of heavy cylinder material based on induction heating is investigated, experiment results show that the mechanical properties of the heavy cylinder can meet the application requirements.

1. Introduction

The heavy cylinder is the basic component of heavy pressure vessel, which is widely used in nuclear power, petrochemical, coal liquefaction and aerospace industry [1,2]. The size of heavy cylinder is huge, and the diameter can reach to 10 m, the height is about 3 m, the wall thickness is more than 0.3 m [3]. In order to improve the mechanical properties of products, the multiple normalizing and tempering processes after heavy cylinder forging are applied, the heat process is usually carried out in a bogie-hearth resistance furnace [4], and the heating rate of heavy cylinder is very slow, the heating time is dozens of hours, then the energy consumption and the production cycle increase [5,6]. Induction heating is a more efficient and environmentally friendly heating method, the induction heating process of heavy cylinder is studied in this paper.

Induction heating is a complex process of electromagnetic-temperature-stress multi-field coupling process, it has been widely used in industrial products such as crankshafts, sprockets, steel tubes and slabs, many studies have been performed on the aspects of theory and experiment of induction heating, but mainly used in the integral heating of the small parts and the surface heating of large axial forgings [7–9]. Tsopelas, et al. [10] studied the influence of plate shape, coil shape, plate position in the coil, and magnetic flux in the induction coil on the induction heating efficiency at low frequency. Han et al. [11] studied the induction heating process of large chain wheel under circular coil and copying coil, the results showed that the copying coil could effectively improve the heating uniformity and improve the performance of chain wheel products. The induction heating of heavy cylinder is more similar to the induction heating of pipe, crankshaft and rolls. Garbulsky et al. [12] established the numerical simulation model of the induction

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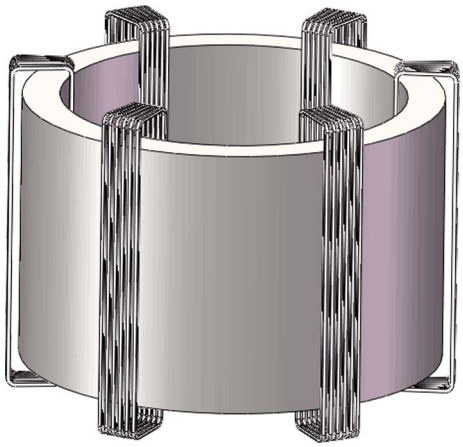

Fig. 1. Three-dimensional model for induction heating of heavy cylinder.

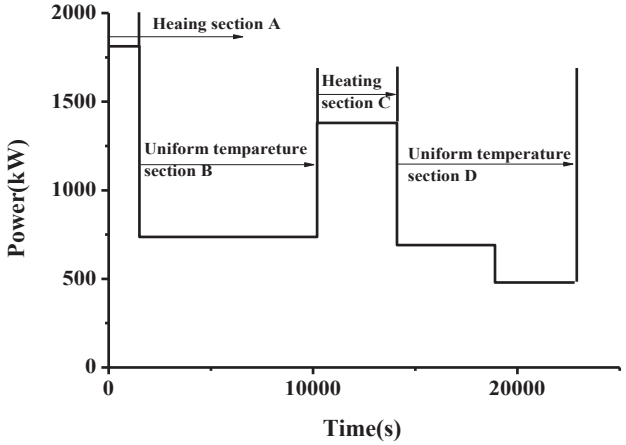

Fig. 3. Power change of the rectangular coil inductor.

Table 1
The material parameters of 2.25Cr1Mo0.25 V steel.

T (°C)	Relative permeability	Electrical resistivity (10^{-6} Ωm)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)
300	178.1	0.435	38.45	519
400	167.1	0.541	37.98	544
500	154.9	0.656	35.16	599
600	137.8	0.790	33.57	630
700	92.5	0.949	32.99	664
720	33	0.982	32.43	672
740	11	1.019	31.86	680
760	1	1.042	31.30	688
800	1	1.080	30.17	706
900	1	1.162	28.29	758
1000	1	1.20	32.47	904

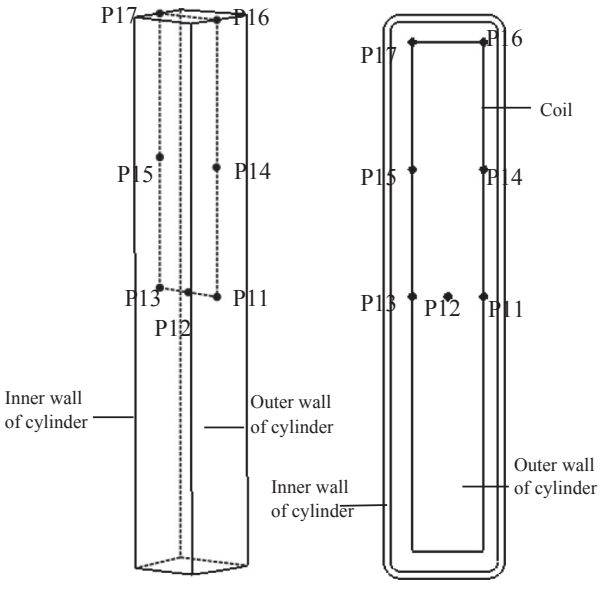

Fig. 2. The sketch of finite element geometric model of heavy cylinder unit.

heating process of the steel pipe which takes into account magnetic induction saturation and temperature dependence of material properties. Ganesan et al. [13] studied the small scale steel pipes induction heating instead of large scale steel piles induction heating, the results has demonstrated that a small scale specimen can establish thermo-mechanical conditions similar to those of a large scale tubular end forging given that the shape of the specimen is fine-tuned to the temperature distribution for the small scale specimen. Song et al. [14] proposed an equivalent circuit model, which 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, simulation and experimental results suggested analysis method can be a practical tool to predict the temperature distribution in the induction heating for the forging of heavy marine crankshafts. Hong-Seok et al. [15] studied the induction heating process of the crankshaft before forging and proposed that the heat loss could be reduced by 9% and the heating efficiency could be increased by adding an insulating system between the adjacent heaters. Xu [16] verified the engineering feasibility of the adjustable roller induction heating device based on Finite element method analysis. The above studies provided important reference to the induction heating device design and optimization of heavy cylinder.

Although many studies have used the induction heating to investigate heating process of small parts, there is little research work concentrating on induction heating of heavy cylinder. Jang et al. [17] carried out the simulation and experimental research for the electromagnetic and temperature field distributions of cylindrical steel members based on segmented induction heating, the error between simulation and experiment was less than 15%. Kranjc et al. [18] studied the induction heating of temperature dependent material cylinder and temperature independent material cylinder, the results showed that the heating effect was very different, and the temperature dependent material had universal applicability. Jiang et al. [19] studied the continuous induction heating process of thick wall cylinder piece, obtained the temperature and micro-structure distributions. Cho [20] took account of parameter nonlinearity, proposed an induction heating model that the cylindrical blank moved relative to induction coil at constant velocity, the results showed that the dynamic model was more accurate than the traditional static model. China First Heavy Industries developed a heavy cylinder induction heating furnace [21], in which the spiral coil was twined on the outer surface of the heavy cylinder, but the spiral coil can only heat the heavy cylinder of the specified size, meanwhile the heating surface is only the outer surface, so the heating efficiency is limited. Due to the diameter, wall thickness and height of the heavy cylinder are very huge, many problems such as the control of non-uniform temperature distribution, the mechanism and solution of acute angle effect are different from those of small cylindrical parts, the mechanism of induction heating process of heavy cylinder need to be investigated.

Therefore, in this paper, an electromagnetic thermal coupling model of induction normalizing heating was established based on finite element method; the problem of acute angle effect in the cylinder induction heating process was studied, the parameters of coil were optimized; the induction heating and electric resistance furnace heating of