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Research Paper

Electromagnetic heating and motion mechanism for contact welded pipes based on a node sequential number method

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HIGHLIGHTS

- Expounds a calculation method for heating of relatively complex workpieces.
- The axial temperature field in pipe blank exhibits an asymmetric sandglass.
- Temperature difference in the wall thickness direction can be decreased.

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ABSTRACT

In recent years, welded pipes have been used widely in deepwater and polar regions. The electromagnetic heating for contact welded pipes is a key process for producing high-quality piping. The understanding of an accurate three-dimension profile of welding heat sources and evolution have been a subject for decades. In this paper, based on the features of mobile electromagnetic heating, a node sequential number method is proposed to equivalently characterize the motion of the loaded pipe blank. The axial temperature of the pipe blank is found to exhibit an asymmetric-sandglass typed distribution. This can be interpreted by the observation that the inlet side of the welded V point depends strongly on the thermal effect of the eddy current, while the other side is mainly affected by the motion of the pipe blank. The study verifies a calculation method for the moving electromagnetic heating imposed by a node sequential number method and, also, is expected to assist in promoting the intensive applications of the electromagnetic heating in the future.

1. Introduction

Hydrocarbon resources are crucial in various industries to boost economic growth [1,2], and the exploitation of the resources has been developed gradually toward deepwater and polar regions [3–5]. In particular, the hydrocarbon exploitation in harsh environments has become one of the frontier fields of scientific innovation [6,7]. For a contact welded pipe, the metal temperatures on both sides of the weld joint are rapidly raised to the welding temperature using the skin and proximity effects of current, and the areas to be welded are squeezed together by the squeezing rollers. Because of the continuous improvement in production quality as well as the advantage in the transport cost benefited by the large conveying capacity [8], the applications of contact welded pipes have been enlarged gradually, including hydrocarbon transport in important occasions. However, accidents like water-pressure-caused leakage and bursting occur occasionally. The causes usually point to the structural defects in the welded pipes involving cold welds, pinholes [9,10], cavity [11], and inclusions [12] existing in the weld joint as well as the environment factors [13].

The contact welding has the outstanding advantage of efficient energy, where the electrode and the welded areas directly form a current loop, and high-frequency current is directly inputted from the electrode to heat the edge of the pipe blank, as shown in Fig. 1. The contact welding is suitable for the production of large-diameter and heavy-wall pipes [14], and has been viewed as a key process in the whole production, due to its strong impacts on the production efficiency and the quality of weld joints [15]. Most of theoretical model or numerical simulation that has been done so far is for the applications in the stationary high-frequency induction systems [16,17]. However, the electromagnetic heating also shows disadvantages such as high heating rate [18], small heating area and high temperature gradient and, consequently, the control of a desirable heating temperature distribution profile is still a challenge [19]. It will be the essential to control and detect heating temperature distribution [20,21]. To date, a systematic

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Nomenclature

$\boldsymbol{H}$	the strength of magnetic field, A/m	q_v	the intensity of internal heat source, W/m^3
$\boldsymbol{J}$	the density of current, A/m^2	k	the thermal conductivity of isotropy material, W/(m·°C)
$\boldsymbol{D}$	the displacement of electric, C/m^2	ζ	density, kg/m^3
$\boldsymbol{E}$	the strength of electric field, V/m	c	specific heat capacity, J/(kg·°C)
$\boldsymbol{B}$	the density of magnetic flux, Wb/m^2	t	time, s
ε	the constant of dielectric, F/m	n	the normal direction of the boundary surface
μ	permeability, H/m	q_n	the heat flow in the direction of the vector, W/m^2
σ	conductivity, 1/(Ωm)	T_w	the surface temperature of solid, °C
ρ_0	the resistivity of welded pipe, Ωm	T_f	air temperature, °C
j_0	the surface density of induced current, A/m^2	F_{12}	the coefficient of radiation angle
T	temperature, °C	T_1, T_2	the surface temperature of objects 1 and 2, °C
		h	convective heat transfer coefficient, W/m^2·°C

and thorough study is not available on the heating mechanism for the high-frequency contact welded pipes. Taking the dynamic effect of moving workpieces into account for an induction furnace system is necessary, in order to obtain results that are more accurate than those calculated from previous works on electro-magnetic field and temperature distribution of workpieces [22].

Improving the accuracy of the electromagnetic heating has been focused in this research community [23,24]. The mechanism of mobile electromagnetic heating has greatly improved the accuracy of calculations [25,26]. In this paper, aiming at identifying the temperature distribution and evolution in the contact welded pipes during the electromagnetic heating, the mechanism of heating the pipe was deeply analyzed. The node sequential number (NSN) method provides a solution for establishing the three-dimensional motion model through ANSYS finite element software during the electromagnetic heating process and improves computational efficiency [27]. It is not only to optimize the electromagnetic heating parameters and heat precisely, but also provide reference for the establishment and calculation of other involved motion models.

2. Establishment of a finite element model of the contact welded pipe

2.1. Mathematical model

Electromagnetic field: It can be seen from the electromagnetic theory that the core composition formula of the electromagnetic field is Maxwell's equations.

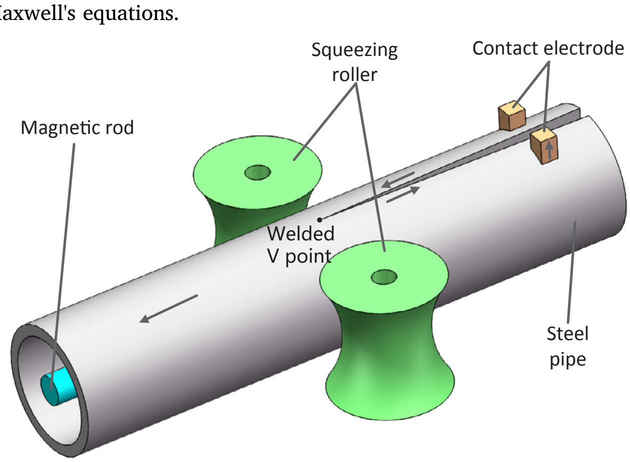

Fig. 1. Schematic diagram of the production process for contact welded pipe.

$$\left.\begin{array}{r}\nabla\times\boldsymbol{H}=\boldsymbol{J}\\ \nabla\times\boldsymbol{E}=-\frac{\partial\mathbf{B}}{\partial t}\\ \nabla\cdot\boldsymbol{D}=0\\ \nabla\cdot\boldsymbol{B}=0\end{array}\right\} \tag{1}$$

The above equation contains five independent vector functions. In order to obtain a definite solution, we also need to increase the structural equation.

$$\left.\begin{array}{r}\boldsymbol{D}=\varepsilon\boldsymbol{E}\\ \boldsymbol{J}=\sigma\boldsymbol{E}\\ \boldsymbol{B}=\mu\boldsymbol{H}\end{array}\right\} \tag{2}$$

The amount of Joule heat which generated in per unit volume and per unit time because of the induced current is called the internal heat generation rate and can be obtained from the results of the eddy current field analysis:

$$q_v=\rho_0|\boldsymbol{j}_0|^2 \tag{3}$$

Temperature field: the corresponding thermal differential equation in the cylindrical coordinate system.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(k\frac{\partial T}{\partial\theta}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v=\zeta c\frac{\partial T}{\partial t} \tag{4}$$

The boundary conditions of temperature field:

During the heating process of the welded pipe, the commonly used boundary conditions are expressed by the following equation:

Table 1
Parameters for the production of the contact welded pipe.

Parameters		Parameters	
Steel pipe diameter (mm)	335.6	Steel pipe wall thickness (mm)	12.7
Distance from electrode to welded V point (mm)	270	Opening angle (°)	5
Electrode length (mm)	20	Length of welded pipe (mm)	200
Electrode width (mm)	20	Length of pipe to be welded (mm)	320
Distance from electrode to middle of weld joint (mm)	21	Current (A)	5400
Magnetic rod diameter (mm)	80	Frequency (kHz)	290
Distance from magnetic rod to welded V point (mm)	0	Speed (mm/s)	62.5