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Three-dimensional analysis of medium-frequency induction heating of steel pipes subject to motion factor

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ABSTRACT

As hydrocarbon resource exploration will extend towards deep sea and alpine cold areas in future, the corresponding welded pipes for oilfield use will face increasingly adverse operating environment. Acquisition of more precise heat source for medium-frequency heat treatment of welded pipes is fundamental to postweld residual stress analysis, weld microstructure improvement and performance research. However, as a pipe billet is subjected to movement factor, it is very tough to solve for a three-dimensional heat source closer to real pattern with complex process parameters. In this paper, the authors utilized a computing method of sequential coupling combining electromagnetic-thermal coupling and relative motion between steel pipe and coils, and designed the corresponding computation flowchart, and by computing pipe billet heat treatment process, they found that the steady-state temperature field formed around a weld appears double ellipsoidal. Further analysis shows that the root cause of the double ellipsoidal temperature field is asymmetric distribution of magnetic flux density and induction current, generated in the weld zone due to electromagnetic effect, within the steel pipe in axial direction. Moreover, stability and hysteresis of pipe billet temperature field were studied. It's found that there is a certain hysteresis between the maximum temperature of inner surface and that of outer surface, because of two different heat sources undergone by the inner and outer surfaces of the weld, as well as relative motion between induction coil and welded pipe. The unique heat transfer process and temperature distribution pattern in wall-thickness direction is the immediate cause of the double ellipsoidal three-dimensional temperature field. This study offers a referenceable analysis method for further exploring steel pipe induction heating process under complex process parameters and optimization of the process parameters.

1. Introduction

Oil well pipes are cornerstone of petroleum industry, accounting for about 60% of oilfield equipment assets. And among oil well pipes, casing consumption is above 70%, and their service condition is harsh, usually they have to withstand internal and external pressures of hundreds of atmospheric pressures, tensile load of hundreds of tons and so on. As hydrocarbon resource exploration will further develop towards harsh areas in future, such as deep sea, alpine cold areas and remote areas, steel pipes call for higher safety and stability. Meanwhile, more stringent requirements are put forward for material [1], molding [2], welding [3,4] and heat treatment process of steel pipes [5].

Electromagnetic induction heating technology not only merits in high performance and environment friendliness, but also precise electromagnetic heating is increasingly valued by people with continuous progress being made in computer digitization technique [6,7], and it, therefore, has been widely applied in a number of sectors [8–10]. For a welded steel pipe, high-frequency welding is subjected to skin effect, temperature difference between inside and outside surfaces of the steel pipe is very great, prone to plate edge overheat and cold weld core, and the higher the wall thickness, the more pronounced the overheat and cold weld phenomena [11]. High-frequency heating of welds of a steel pipe results in temperature gradient distribution in proximity to edges of the pipe billet, and forms characteristic zones such as molten zone, normalized zone, incompletely normalized zone, and tempered zone. As electromagnetic heating is fast, austenitic grains grow larger drastically, and when cooled, will form hard and brittle coarse-grained zone, besides, existence of large temperature gradient will lead to postweld residual stress [12]. Hence, there comes a circumstance that mechanical properties of a weld zone are inferior to those of the base metal. Using a medium-frequency heat treatment

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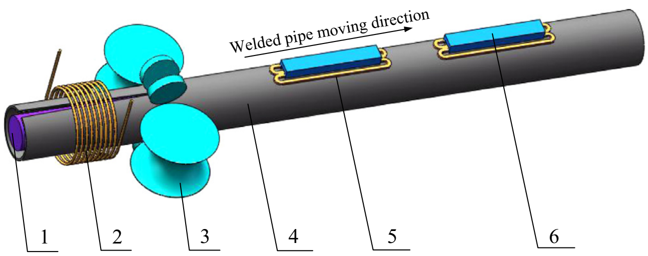

Fig. 1. Schematic of HFIW pipe production process. (1) Magnetic rod (2) high-frequency induction coil (3) squeezing rollers (4) welded pipe (5) medium-frequency induction coil (6) magnetic conductor.

device, one can soften and refine the microstructure of local normalized zone of a weld and lower postweld residual stress to some extent, so as to improve overall mechanical performance of heat-affected zone of a weld, which is very necessary to improve weld quality [13]. In local heating, temperature shall be tightly controlled; too low temperature would fail to achieve the desired heat treatment effect, while too high temperature would make the grains grow larger again, hampering the effect of local heat treatment. Therefore, to improve weld quality of a steel pipe, it is imperative to control heating temperature tightly [14]. To acquire more accurate induction heating temperature distribution has always been one of the objectives pursued by related scholars [15–17]. This can not only offer theoretical basis for multi-parameter optimization under complex process condition, but also has positive practical implication to further improving safety and reliability of welded pipe quality.

Utilizing ANSYS finite element software, the authors established a three-dimensional electromagnetic-thermal coupling computing model in consideration of pipe billet motion. Through dynamic simulation of medium-frequency heat treatment process for a longitudinally-welded pipe, a three-dimensional "double ellipsoid" shaped temperature field was obtained. And root cause and immediate cause of it were analyzed.

2. Mathematical model

In dynamic simulation of medium-frequency heat treatment process for a high-frequency induction welded (HFIW) pipe, a sequential electromagnetic-thermal coupling approach was employed, in other words, electromagnetic field analysis was carried out first, then the Joule heat arising from induced eddy current calculated on the basis of electromagnetic field served as the heat source of thermal analysis.

The differential forms of Maxwell equations are:

$$\begin{array}{l} \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \\ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{D} = \rho \end{array}, \tag{1}$$

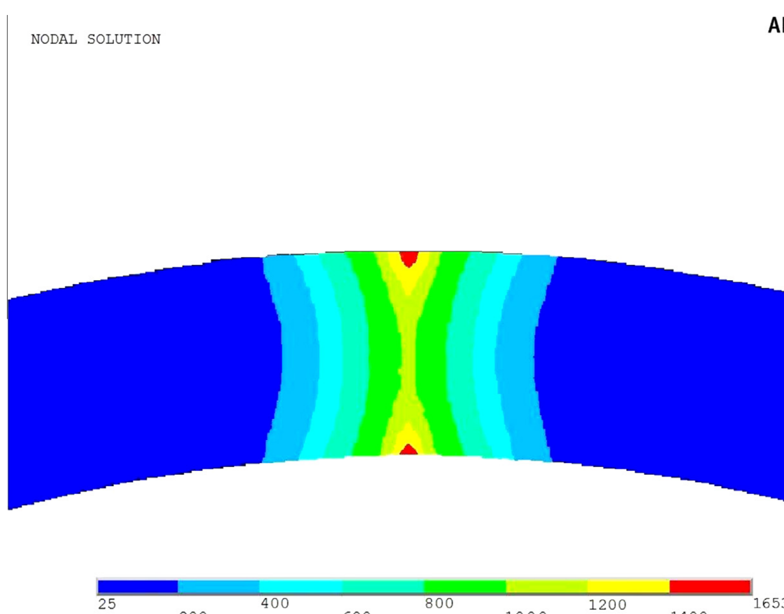

Fig. 2. The "sandglass" shaped temperature field of high-frequency welding.

Table 1
Calculated basic parameters.

Parameter	Value	Parameter	Value
Outside diameter of steel pipe (mm)	406.4	Coil cross-section (mm^2)	30×20
Coil-to-weld spacing (mm)	4.5	Production rate of steel pipe (mm/s)	63.6
Coil length (mm)	270	Wall thickness of steel pipe (mm)	16.66
Spacing from the first heater to high-frequency welding point (mm)	640	Spacing between induction heaters (mm)	260
Current density of the first heater (A/m^2)	8.5×10^7	Current density of the second heater (A/m^2)	9.0×10^7
Frequency of the first induction heater (Hz)	1150	Frequency of the second induction heater (Hz)	900