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An approach to triangular induction heating in final precision forming of thick steel plates

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ABSTRACT

An automatic high-frequency (HF) induction-heating (IH)-based triangular heating process was introduced in order to investigate the influence of designing heating patterns on the permanent deformation behavior of an SS400 thick plate. Temperature distribution and permanent plate deformation during triangular heating were predicted based on electromagnetic–thermal and thermal–structural analyses, respectively. Both analytical and experimental permanent deformation values obtained by zigzag-type triangular heating were significantly higher than those by fan-shaped triangular heating, presumably because of the different temperature gradient along the thickness. Proper design of triangular heating pattern appeared to be the most important factor in determining the final shape of the thick plate. All predicted results were in good agreement with the experimentally observed permanent deformation.

1. Introduction

In recent years, significant effort has been devoted to automating the process in shipbuilding industry for precision forming of the various curved plates with considerable productivity. Shim et al. (2007) suggested a possible automation process using a Line Array Roll Set (LARS) for manufacturing a doubly curved sheet metal. Heo et al. (2010) also introduced a flexible forming machine for manufacturing a prototype of curved metal plate block. Nevertheless, ship manufacturing was still considered a labor-intensive and low-productivity process. Since the curved surfaces were too huge and complex in shape, each ship's hull was produced in a shipyard by means of either mechanical and/or thermal forming processes, by using flat and thick steel plates. Cold mechanical pressing have generally been carried out at an initial forming stage in order to induce a large amount of deformation, whereas permanent curvatures of the initially curved blocks have been realized with flame torches skillfully manipulated by experienced steel craftsmen, as reported by Hemmati and Shin (2007). This implies that it was relatively difficult to manually control the uniformity of heat flux on the curved blocks because craftsmen determine the heating line, moving speed, and position of the gas torch based on their own hands-on experience. Therefore, an inaccurate temperature control across the thickness of the curved plate was probable during lengthy line heating, which resulted in a subsequent loss in the dimensional accuracy as reported by Bae et al. (2008) and Zhang et al. (2011). Furthermore, according to Lee et al. (2011), this process generated a large amount of CO_2 gas and considerable noise, thereby causing severe environmental problems. In order to overcome the aforementioned drawbacks, a few studies dealing with the automation of line heating were reported. For instance, Shin et al. (2003) reported a fully automated line heating (LH) process using gas torch-type heat source. Shin et al. (2004) also extended his previous work and developed a comprehensive algorithm for an automated LH process. Wang et al. (2009) introduced an iterative loop system for automating LH process. Seong et al. (2010) proposed an algorithm for solving the inverse problem of flame forming which was capable of applying to the two-dimensional plate forming by flame heat source. However, the difficulty in reproducing a desired temperature field together with a controlled operation speed was recognized by Imatani et al. (1998) and Lee et al. (2010) when gas torch was utilized as a heat source.

Alternatively, electromagnetic high frequency induction heating-based line heating has emerged as a novel and automated technique to form thick metal plates. In the deformation process by high-frequency induction heating, thick steel plates could be heated to a target temperature through the desired depth in a very short time, making this technique a suitable substitute for conventional line heating using a flame torch. Lee et al. (2006) and Shen et al. (2006) established computational and mathematical

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models for simulating the temperature profile generated by simple LH using high frequency inductor. In practice, the effect of process parameters using simple line heating (i.e., heat input, moving speed, etc.) was relatively well investigated with respect to generating symmetric cross sections of the metal plates. For example, Reutzel et al. (2006) provided a computationally efficient differential geometry to analyze the thermal forming process generated by line heating patterns. Lee et al. (2013) also studied the influence of input power of HF inductor on the temperature distribution and the permanent deformation of the thick metal plate. However, only few reports have been published by Nguyen et al. (2009) and Bae et al. (2012) on the deformation behavior of high-frequency (HF) induction-heating (IH)-induced curve-bending of asymmetric-shaped thick plates by triangular heating.

The focus of this work was to introduce a newly designed laboratory-scale high-frequency induction-based line heating apparatus capable of fast and precise generation of asymmetric curvature for mild steel plates by triangular heating. To verify the influence of pre-designed heating paths on the temperature distribution alongside plate thickness direction and its subsequent permanent deformation, three-dimensional electromagnetic–thermal and thermal–structural finite element numerical analyses were first performed to predict temperature distribution and permanent deformation, respectively. Then, experiments with the same induction heating-based triangular heating parameters were carried out in order to obtain experimentally determined profiles of permanent deformation with respect to different plate positions and to compare them with numerical predictions. The relationship between the distributions of the effective heat-penetration depth, e.g., in the case of a heat-affected zone (HAZ), and the microstructural evolution was also discussed.

2. Numerical procedure and experimental

2.1. Bending mechanism for thick metal plates

The two most extensively reported mechanisms for describing triangular heating-induced forming are bucking mechanism and temperature gradient mechanism. Bucking mechanism is dominant when temperature gradient across the thickness is relatively small. Kim et al. (2009) introduced this mechanism using a gas torch as a heat source. On the other hand, Imatani et al. (1998) reported that the temperature gradient mechanism dominates when the temperature gradient is relatively high. The thermal expansion of the locally heated surfaces of the plate closer to the HF IH source causes the plate to bend away from the inductor direction during triangular heating. However, during cooling, the plate bends in reverse toward the inductor direction because of the thermal contraction of the top surface. The latter concept is adopted in this study for numerical simulations.

2.2. Modeling and numerical analysis

As with other HF IH-based processes such as heat treatment, HF induction-based thermomechanical forming is dependent on many non-linear physical phenomena like eddy current, temperature, and stress–strain fields, which are strongly correlated. These were accounted for when using commercially available finite element package program ANSYS (version 14.5). The operating system and running platform for modeling and numerical analysis was Windows 7 Professional 64 bit and 8-core Intel Xeon X5560 2.6 GHz pair, respectively. The sample was a 500 mm × 500 mm × 20 mm mild SS400 steel plate. Basically, this workpiece plate was assumed to be isotropic, perfectly flat, and free of residual stresses. Further, the time-dependent electromagnetic, thermal, and structural properties of SS400 as a function of temperature were used as a materials database for numerical analysis from the previous report by Lee et al. (2011).

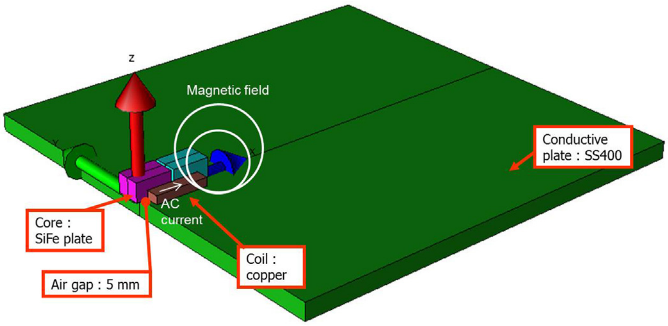

Fig. 1. Schematic diagram of a thick SS400 steel plate line heated by high-frequency inductor.

Fig. 1 shows a schematic diagram of the high-frequency (HF) induction-heating (IH) process. Based on the induction heating principle, eddy current is induced by a magnetic field on the electrically conductive metallic workpiece. The distribution of electromagnetic field and eddy current density could be obtained by solving the well-known Maxwell's equation, as described by Rudnev et al. (2003) and Sadeghipour et al. (1996). Then, the Joule heat and temperature distribution could be calculated by electromagnetic–thermal coupling analysis. Three-dimensional, initial meshed model for this coupling analysis is illustrated in Fig. 2. This model consists of a conductive steel plate, a square-shaped high conductivity copper coil, Si–Fe electrical steel cores covered with just two sides of square coil, and air atmosphere. Twenty-node hexahedral elements SOLID236 were used to mesh for the solid-state materials such as coil, core, and workpiece plate for electromagnetic analysis. As the air zone adjacent to the solid became highly distorted during the simulation, a sufficient number of tetrahedral meshes were simultaneously

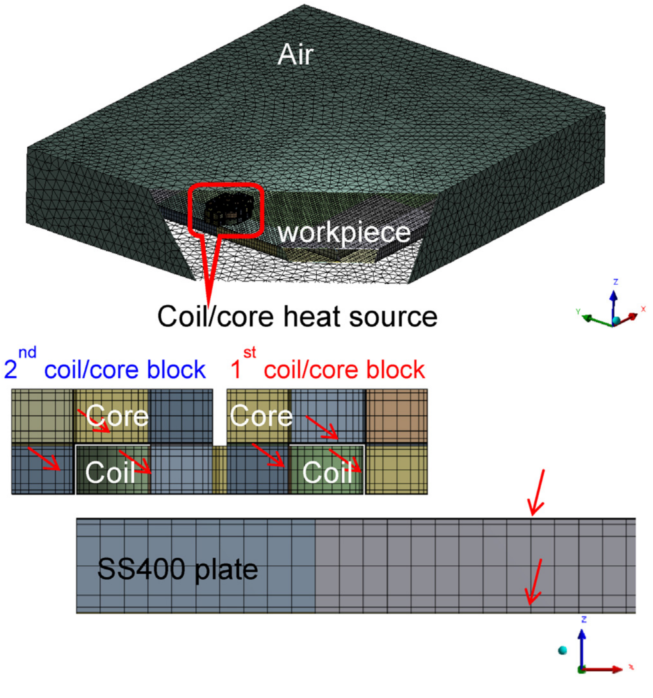

Fig. 2. Mesh shape for electromagnetic–thermal coupling analysis of high-frequency induction heating.