journal of materials processing technology 209 (2009) 2693–2698

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Effect of temperature on plastic deformation of sheet by electromagnetic force

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ARTICLE INFO

Article history:
Received 10 June 2007
Received in revised form
27 April 2008
Accepted 7 June 2008

Keywords:
Plastic deformation
Electromagnetic force
Temperature
Sheet
Simulation

ABSTRACT

Based on the new method of controlling welding distortion with trailing electromagnetic force, the electromagnetic force and the plastic deformation of sheet by electromagnetic force at different temperature was simulated by ANSYS. The circuit–electromagnetic–structural coupling was carried out with physical environment method. The results show that the magnitude of peak axial force decreases and the magnitude of peak radial force increases with increasing temperature. The variation of electromagnetic force with temperature is nonlinear. The variation rate of axial force decreases and the variation rate of radial force increases with increasing temperature. The driving force of sheet deformation decreases with increasing temperature because the axial force is larger than radial force so much. But the plastic strain of sheet by electromagnetic force increases with increasing temperature due to the decreasing yield strength. Compared with the post-welding processing, the energy supplied to processing is reduced when the electromagnetic force is applied to the controlling of welding distortion as an impactive source during welding.

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1. Introduction

Welding residual distortion is a common problem in welding (Tian, 1982). So the method of controlling welding distortion with trailing electromagnetic force (TEMF) is put forward. Its characteristics are as follows: applied the force without contacting, easily controlled energy and flexible operated equipment (Zhou and Yang, 1996). The principle of controlling welding distortion during welding is that the metal of weld and near weld at high temperature is extended by mechanical method or other methods to compensate the compressive strain (Fan et al., 2004; Guo et al., 2004). Because the metal at high temperature has lower yield strength, the sheet would deform under the smaller energy. However, when the electromagnetic force is applied to control welding distortion, it decreases due to the decreased resistivity with increasing temperature, which is against to the deformation of sheet. Therefore, the electromagnetic force and the plastic deformation of sheet by electromagnetic force at different temperature were simulated by means of software ANSYS in this study. It is the base of the following work for TEMF. The hot cracking can be inhibited by dint of the electromagnetic force (Xu et al., 2007). The electromagnetic force was applied in the area with high temperature near brittle temperature range (BTR). Thus, the work is meaningful for controlling hot cracking by electromagnetic force. Otherwise, there are contradictory viewpoint about that whether increasing temperature is beneficial to the electromagnetic forming (EMF) of metal (Zhang and Lu, 2005; Ou-Yang and Hang, 2005). Therefore, this study is referential for EMF at higher temperature.

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doi:10.1016/j.jmatprotec.2008.06.023

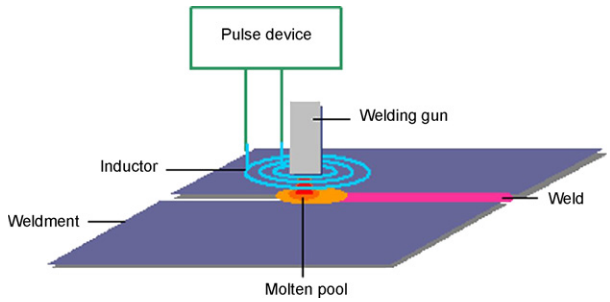

Fig. 1 – Schematic configuration of TEMF.

2. Primary principle of controlling welding stress with trailing electromagnetic force

As the thermal expansion of metals of weld and near weld is constrained, the plastic compression occurs in welding joint. And the plastic tension occurs during following cooling because thermal shrinkage of metals of weld and near weld is constrained. The tension deformation can not counteract the compression deformation, and then the compression strain remains, which leads to residual strain in the weldment after welding (Guo et al., 2001). According to the above analysis, the residual distortion is induced by the plastic compression deformation of the weld metal. Consequently, the residual strain will decrease if the compression of the weld metal is impeded (Masubuchi, 1991).

The idea of controlling welding distortion based on electromagnetic force during welding is as follows: the inductor is located near the welding torch over the weldment and moves with the torch during welding, as shown in Fig. 1. There is rapidly varying current with high peak value in the inductor, and then there is varying magnetic flux and eddy current in the weldment. Therewith, the electromagnetic force is generated between inductor and weldment. Welding distortion will be controlled if the weld metal and the metal near weld at high temperature can be extended by the electromagnetic force.

3. Finite element analysis

3.1. *Finite element model*

When the welding process comes into the quasi-stable state, the temperature of area in which the electromagnetic force is applied is stable. So the relative movement between coil and weldment is not taken into account. The flat spiral coil is modeled, which can be regarded as an axisymmetric model. Otherwise, the dimension of sheet is far larger than the dimension of coil, so the sheet can also be simplified to an axisymmetric model.

As the parameters in the practical discharging circuit can be measured and the electromagnetic-circuit coupling analysis can be carried out in ANSYS, the electromagnetic–circuit model is built, as shown in Fig. 2. There are capacitor C_d, resistor R_d and inductor L_m in the electric circuit part; coil *CL*, sheet S, near field air region N and far field air region F in the magnetic circuit part. The coupling process is completed

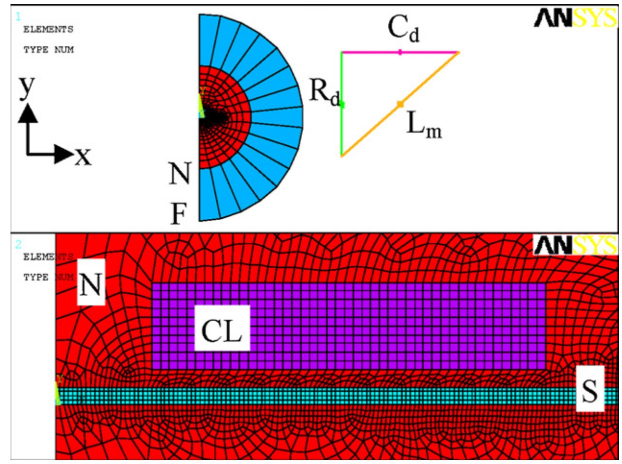

Fig. 2 – Electromagnetic–circuit model.

by means of that any node in the element of coil is built as the node "*K*" of the inductor in circuit. The circuit equivalent of the electromagnetic–circuit model consists of two circuits: discharging circuit and sheet circuit, as shown in Fig. 3. There L_s is the inductance of sheet and R_s is the resistance of sheet in Fig. 3. There is the mutual-inductance M between coil and sheet. M and self-inductances of coil and sheet can be calculated with the energy method (Oliveira et al., 2001). The circuit–electromagnetic coupling analysis follows the governing equation:

$$\frac{d^2I(t)}{dt^2} + 2\xi\omega\frac{dI(t)}{dt} + \omega^2 I(t) = 0 \quad (1)$$

where $I(t)$ is the discharging current, ζ is the damping term given by $\xi = 1/2R\sqrt{C/L}$, ω is the natural angular frequency given by $\omega = \sqrt{1/LC}$. It can be obtained from Eq. (1) that

$$I(t) = \frac{V_0\sqrt{C/L}}{\sqrt{1-\xi^2}} e^{-\xi\omega t}\sin(\omega t) \quad (2)$$

where V_0 is the original voltage across capacitor. It can be seen that the discharging current can be calculated if the inductance, capacitance and resistance in circuit are known. The parameters are shown in Table 1. The calculation of electromagnetic force is based on Maxwell's equation. The relative displacement between coil and weldment is not taken into account in the calculation and the displacement current is ignored. Therewithal, the following equation can be deduced:

$$\nabla \times (\upsilon\nabla \times \vec{A}) + \sigma\frac{\partial \vec{A}}{\partial t} = \vec{J}_s \quad (3)$$

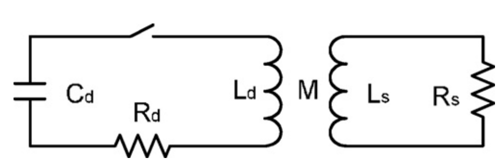

Fig. 3 – Circuit equivalent of the electromagnetic–circuit model.

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