Numerical Simulation of Non-steady Heat Conduction during Induction Line Heating Process

N. Osawa[1], K. Hashimoto[1], H. Tanaka[1], M. Ishiyama[2] and Y. Tango[3]

Summary

The nature of the induction current field during a spot heating test is investigated by electromagnetic-transient thermal analysis. It is found that the induction current during spot heating can be given by a function of the location and temperature. The functions which give the initial induction current, I_0 and the current reduction ratio, w, are identified. Plate temperature history during line heating can be estimated by heat conduction analysis when the internal heat generation is evaluated by I_0 and w identified for a spot heating test. Accurate temperature estimation during induction line heating process has becomes possible for the first time.

Introduction

Line heating is one of the most characteristic processes in ship building. This process has not been performed by automation but by skilled workers. It is strongly desired to automate this process because the number of the skilled workers has decreased. To accomplish the automation, it is needed to estimate plate temperature accurately. Line heating has been performed by gas flame or induction heating apparatus. It is needed to establish accurate heat transition simulation techniques for these heating procedures.

In the earlier studies (e.g., Moshaiov and Latorre [1]), it was assumed that the heat flux distribution around the gas torch or induction coil did not change with time. This assumption is not valid when the plate is heated by very slow and repetitive heating. An accurate temperature calculation technique for these procedures has to be established to accomplish the automation of the line heating process. Such technique for gas line heating was developed by the authors (Osawa et al. [2]). However, the technique for induction heating has not been developed. Induction heating is more suitable for the automation than gas heating. It is needed to develop a simulation technique applicable to very slow and repetitive induction heating.

It is possible to estimate the plate temperature during induction spot heating test by electromagnetic-transient thermal multi physics analysis. In the electromagnetic analysis, not only the steel plate but also the heating coil and the air space have to be meshed. The

[1] Dept. Naval Architecture and Ocean Engineering, Osaka University, Suita, Osaka, Japan

[2] IHI AMTEC Co. Ltd., Aioi, Hyogo, Japan

[3] Kure shipyard, IHI Marine United Inc., Kure, Hitoshima, Japan

skin depth of the heat source layer is less than 0.1mm while the model of the air space is of the order of 10m. 3-dimensional analysis is needed when we simulate line heating cases. In this case, ultra fine meshes, whose element size is of the order of 0.01mm, has to be arranged along the plate surface swept by the heating coil. This means that a complicated 3D FE mesh with huge degrees of freedom has to be created. The man-hours needed to create such FE mesh becomes so long that it is impossible to carry out electromagnetic-transient thermal analysis for line heating cases. It is needed to develop an alternative simulation technique.

In this paper, electromagnetic-transient thermal analysis of induction spot-heating test is carried out to examine the nature of induction current field during spot heating. Based on these results, a simplified model for the induction current distribution during spot heating is proposed. Using this model, a transient heat conduction simulation technique for induction line heating process is developed. The validity of the proposed technique is examined by comparing the calculated and measured plate temperature during spot and line heating tests.

The induction heating tests

Figure 1 shows the heating coil. This coil has external and internal diameters of 30mm and 90mm, and it is made of a hollow cupper tube of 6mm diameter. The frequency of induction current is 22KHz, and the excited current is 6000A.

In the spot heating test, a square mild steel plate with edge length 500mm and thickness 25mm is heated by the coil. In line heating tests, a rectangular mild steel plate with length 2000mm, width 1500mm and thickness 25mm is used. Plate temperatures are measured on the heating and back faces.

Line heating is carried out by moving along the center line of the plate at a constant speed. The torch speed is 1000mm/min and 300mm/min. The heating tests are carried out at IHI Marine United Kure Shipyard. Plate temperatures in the transversal cross-section 500mm apart from the plate end are measured on the heating and back faces.

Electromagnetic-Transient Thermal analysis of Spot Heating Tests

The electromagnetic - thermal analyses is carried out by ANSYS8.1. In each time step, a harmonic electromagnetic analysis is performed and the induction current, I, is evaluated. Joule heat, W, is calculated by

$$W = I^2 \cdot R \,, \qquad (1)$$

where, R is the resistance. W is used as the input data in the successive thermal analysis. The temperature dependency of the electromagnetic and thermal material properties are shown in Figure 2 and Figure 3. The dependency of the relative permittivity around Curie temperature was approximated by a kinked line.

Figure 4 shows the axisymmetric FE mesh used for ANSYS’s electromagnetic analysis. Shape of coil is modeled as rectangles. The heating coil is arranged up side down. Figure 5 shows the axisymmetric FE mesh for ANSYS’s thermal analysis.

Figure 6 shows the comparisons of the calculated and measured plate face temperatures during the spot heating test. The calculated temperature almost agrees with the measured one when the elapsed time is less than 7 sec. The maximum temperature doesn’t exceed Curie temperature during this period. After this period, the numerical instability occurs, and the calculated temperatures do not fit the measured ones. It is supposed that the employed temperature dependency of permittivity approximated by a kinked line (Figure 3) caused this instability.

Figure 7 shows the calculated time histories of induction current in the heating layer (depth=0.01mm, Figure 7 (a)) and the deep portion (depth=0.2mm, Figure 7 (b)). The current decreases with time at all points. It is shown that the temperature elevation is very large and the current drops steeply in the heating layer while the changes in the temperature and the current are small in the deep portion. The redaction rate of the current almost equals to each other when the rate of temperature rise is equal.

Simplified Model for Induction Current Distribution

The results of the previous section leads us to an assumption that the induction current can be given by a function of the location in the plate and the temperature, and this function can be expressed by

$$I = I_0\left(r, z\right) \cdot w(T)\ , \tag{2}$$

where, the temperature dependent current reduction rate w is 1.0 at the initial temperature, and it becomes zero when the temperature exceeds Curie temperature, Tc. I_0 is the initial current distribution, and it is a function of r and z, where r is the distance from the plate center, and z is the depth from the heating face. I_0 and w are identified so that the calculated plate temperatures agree the measured ones. When we employ this simplified model for induction current distribution, it becomes possible to calculate the plate temperature solely by heat conduction analysis, and it is not needed to carry out electromagnetic analysis.

I_0 and w are identified in trial and error manner so that the calculated temperatures agrees with the measured ones. Figure 8 shows the axisymmetric FE mesh used for the identification. Figure 9 shows the identified I_0 and w. Figure 10 shows the comparison between the calculated and measured plate temperatures during the spot heating test. It is shown that the calculated temperatures agree well with the measured ones. This demonstrates the accuracy of the identified I_0 and w, and the validity of the proposed technique.

Plate Temperature Estimation during Induction Line Heating Test

In the proposed technique, the initial current, I_0, and the temperature dependent current reduction rate, w, are time independent. Coil moving speed in induction line heating process is slow enough compared with the changing rate of the induction current during a spot heating test. These results lead us to a hypothesis that, the plate temperature during induction line heating test can be calculated when we analyze heat transfer and heat conduction updating the distributions of $I_o(r, z)$ and $w(T)$ at every time step so that their distributions around the coil equal to those of the spot-heating case. In this scheme, the plate temperature can be estimated without electromagnetic analysis.

In order to demonstrate the applicability of the proposed technique, a transient temperature analysis of the line heating tests are carried out. Figure 11 shows the 3-dimensional thermal FE mesh employed in the analysis. Material properties are the same as those for the spot heating analysis, and I_0 and w of Figure 9, which are identified in the spot heating test, are employed.

Figure 12 shows the comparisons of the calculated and measured plate temperatures. It is shown that the calculated temperatures agree well with the measured ones. This indicates that I_0 and w identified in the spot heating test can be used in the line-heating analysis. Also, these results demonstrate the validity of the proposed method.

Reference

1 Moshaiov A. and Latorre R. (1985). "Temperature Distribution During Plate Bending by Torch Flame Heating," *Journal of Ship Research* 29:1, pp.1-11.

2 Osawa N., et al. (2007): ``Development of Heat Input Estimation Technique for Simulation of Shell Forming by Line-Heating", *CMES*, 20, 1, pp. 43-53.

Figure 1: Heating coil.

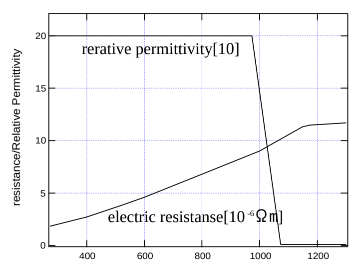


Figure 2: Temperature dependency of the electro magnetic properties.

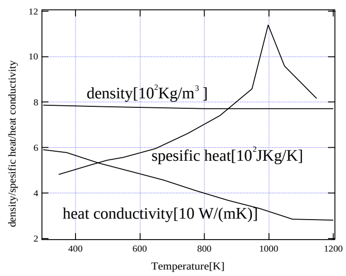
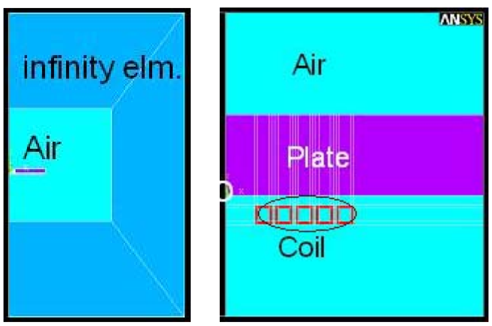


Figure 3: Temperature dependency of the thermal properties.



(a) Global view. (b) Enlarged view around the heating coil.

Figure 4: FE mesh for ANSYS's magnetic analysis.

Figure 5: FE mesh for ANSYS's heat conduction analysis.

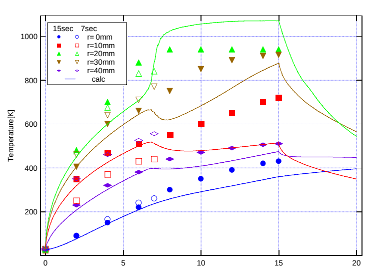
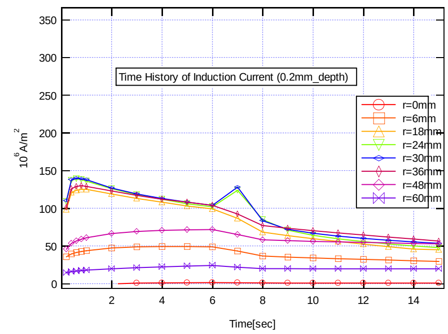
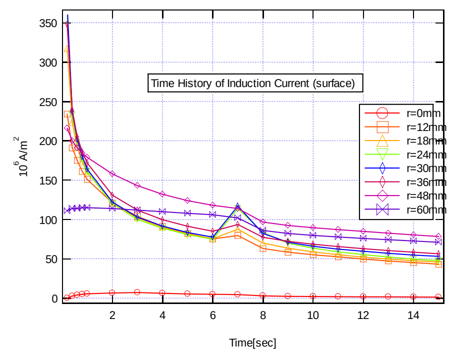


Figure 6: Measured and calculated plate temperature during spot heating test.



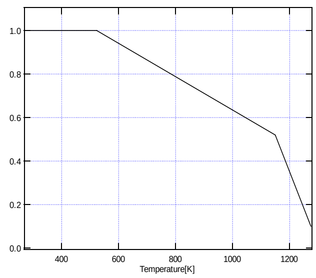
(a) depth = 0.01mm.



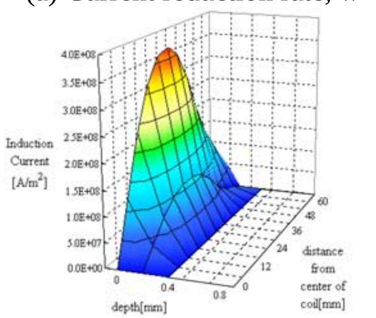
(a) depth = 0.2mm.

Figure 7: Time histories of the calculated induction current.

Figure 8: Axi-symmetric FE mesh used for the identification of I_0 and w.



(a) Current reduction rate, w



(b) Initial current distribution, I_0

Figure 9: I_0 and w identified from the spot heating test.

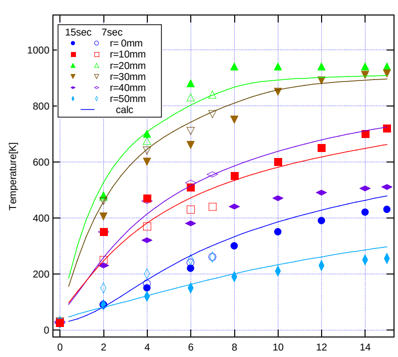


Figure 10: Comparison of the estimated plate temperatures calculated from the identified I0(r,z) and w(T) with the measured ones.

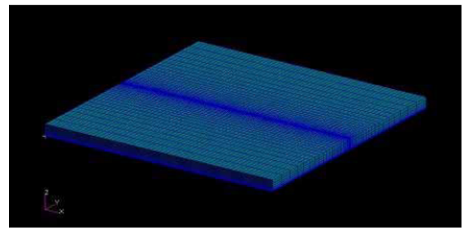
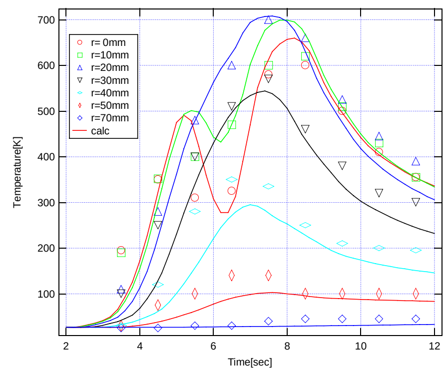
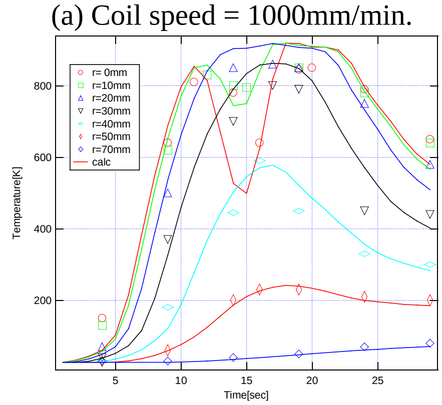


Figure 11: 3-dim. FE mesh used in the line-heating analysis.



(a) Coil speed = 1000mm/min.



(b) Coil speed = 300mm/min.

Figure 12: Comparisons of the measured and calculated plate temperatures during line heating tests.