

Simulation of plate deformation due to line heating considering water cooling effects

Dae-Eun Ko^{1*} and Yun-Sok Ha²

¹Department of Naval Architecture and Ocean Engineering, Dong-Eui University

²Department of Welding Research, Samsung Heavy Industries Co., Ltd.

수냉 효과를 고려한 선상가열에 의한 판 변형의 시뮬레이션

고대은^{1*}, 하윤석²

¹동덕대학교 조선해양공학과, ²삼성중공업(주) 산업기술연구소 용접연구파트

Abstract Inherent strain method, a hybrid method of experimental and numerical, is known to be very efficient in predicting the plate deformation due to line heating. For the simulation of deformation using inherent strain method, it is important to determine the magnitude and the region of inherent strain properly. Because the phase of steel transforms differently depending on the actual speed of cooling following line heating, it should be also considered in determining the inherent strain. A heat transfer analysis method including the effects of impinging water jet, film boiling, and radiation is proposed to simulate the water cooling process widely used in shipyards. From the above simulation it is possible to obtain the actual speed of cooling and volume percentage of each phase in the inherent strain region of a line heated steel plate. Based on the material properties calculated from the volume percentage of each phase, it should be possible to predict the plate deformations due to line heating with better precision.

요약 실험적인 방법과 수치적인 방법의 장점을 취한 고유변형도법은 선상가열에 의한 판의 변형을 예측하는데 매우 유용하다. 고유변형도법을 이용한 선상가열에 의한 판 변형의 예측을 위해서는 고유변형도의 크기와 영역을 적절하게 결정하는 것이 중요한데, 선상가열 후의 실제 냉각속도에 따라 강의 상변태 특성이 달라지므로 이 또한 고유변형도 결정에 있어서 고려되어야 한다. 조선 현장에서 많이 사용되는 수냉과정을 모사하기 위해 충돌제트, 막비등, 복사 효과를 포함하는 열전달 해석법을 제안하였으며, 이를 통해 고유변형도 영역의 실제 냉각속도와 상변태 분율을 구할 수 있다. 상변태 분율에 따른 재료의 물성치를 반영함으로써 선상가열에 의한 판의 변형을 보다 정도 있게 예측하는 것이 가능하다.

Key Words : Inherent strain method, Line heating, Water cooling effect, Phase transformation, Plate deformation

1. Introduction

The line heating process has long been used in plate forming of streamlined hull surfaces, and has been dependent on skillful workers due to difficulties in its automation. Line heating work must be improved to attain higher productivity.

As the first step in the automation of hull forming using line heating, it is most important to develop an efficient method for precisely predicting plate deformations. Nomoto et al. conducted experiments to obtain the forces and moments that cause shrinkage and bending deformation of a plate [1]. By replacing the detailed thermal elastoplastic analysis with experiments,

This work was supported by Dong-Eui University Grant.(2009AA198)

*Corresponding Author : Ko, Dae-Eun(deko@deu.ac.kr)

Received April 28, 2011

Revised (1st May 31, 2011 2nd June 7, 2011)

Accepted June 9, 2011

the computing efficiency was improved. Ko et al. developed a simplified thermal elasto-plastic analysis method, based on the inherent strain method, for the real-time simulation of plate deformation due to line heating [2]. As the shrinkage forces and moments are determined by integration of the inherent strains, various deformations can be simulated. Jang et al. included the phase transformation of steel in their inherent strain analysis method. They considered the volume expansion of martensite when calculating the inherent strains using a modified temperature dependent coefficient of thermal expansion [3].

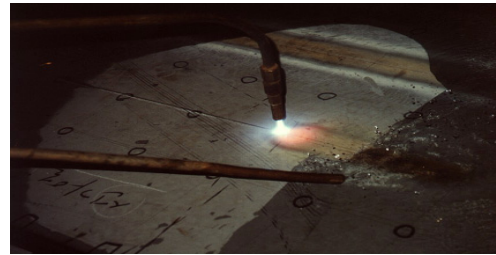
In this study, our focus was on the effect of water cooling in the line heating process to improve the predictability of plate deformation. In shipyards, water cooling is widely used in the line heating process for both efficiency and safety. However, from the viewpoint of plate deformation, the effect of water cooling has previously been unclear. In order to realistically simulate the water cooling process, a heat transfer analysis was performed on the effects of the impinging water jet, film boiling, and nucleate boiling. Using the determined cooling speed and volume percentage of each phase of the inherent strain region, the plate deformations were calculated based on the inherent strain method proposed in [3] and compared with those obtained experimentally.

2. Heat transfer in water cooling process

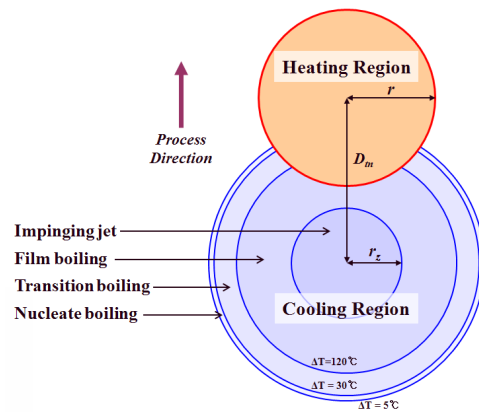
Line heating in shipyards should be followed by water cooling as shown in Fig. 1. Heat transfer generally occurs via conduction, convection, and radiation. However, in the case of the water cooling process of line heating, most heat transfer occurs via convection and radiation.

2.1 Definition of cooling region

The cooling area by water cooling can be divided into the impinging jet region, boiling region, and laminar flow region. The boiling region can be subdivided according to boiling modes, as shown in Fig. 2.



[Fig. 1] Water cooling after line heating in shipyards



[Fig. 2] Boiling modes in line heating with water cooling

2.2 Heat transfer by convection

Convection due to the movement of fluid particles is composed of free convection and forced convection. It is sufficient to consider only forced convection because the effect of free convection is negligible in the case of the water cooling process during line heating.

The cooling process can easily be simulated once the convection coefficients have been calculated, because the boiling regions are defined by the excess temperature over the boiling point of water.

The convection coefficient for the laminar flow region can be represented as a function of the plate surface temperature, as shown in equation (1) [4].

$$h^c(T_s) = 0.332 \frac{k(T_f)}{2r_{wet}} Pr(T_f)^{1/3} \frac{u_\infty}{\nu(T_f)} \times \int_{r_{wet}}^{3r_{wet}} \frac{1}{\sqrt{x}} dx \quad (W/m^2 K) \quad (1)$$

The convection coefficient for the nucleate boiling region can be represented as a function of the plate surface temperature by considering the roughness of the

plate surface, as shown in equation (2) [4].

$$h^c(T_s) = 1424670 \times \mu_l(T_s) h_{fg}(T_s) \times \frac{\sqrt{\frac{\rho_l - \rho_v}{\sigma_f(T_s)} \left(\frac{c_{p,l}(T_s) T_e}{h_{fg}(T_s) Pr_l(T_s)} \right)^3}}{T_s - T_i} \quad (W/m^2 K) \quad (2)$$

The film boiling region accounts for a large amount of heat transfer due to convection. The experimental equation proposed by Hatta and Osakabe can be applied for the convection coefficient of this region [5].

$$h^c(T_s) = \frac{158500}{(T_s - 95)^{0.8}} \quad (W/m^2 K) \quad (3)$$

The central area of the cooling circle in Fig. 2 is called the impinging jet region, as the cooling water vertically hitting the plate surface causes a significant cooling effect. Convection in this area is much more affected by the nozzle diameter, nozzle height, and flux of the coolant rather than by the excess temperature over the boiling point of water.

In a simulation of the cooling process, the convection coefficient of this region should be considered as being distance dependent. For the convection coefficient of the impinging jet region, equation (4) is applied [6].

$$h^c(T_s, r_w) = \frac{2Pr^{0.42}(T_i)k(T_i)(1-1.1\frac{D_w}{r_w})}{r_w(1+0.1(\frac{H_w}{D_w}-6)\frac{D_w}{r_w})} \times \sqrt{\frac{4W_f}{\pi D_w \nu(T_i)} + 0.043 \left(\frac{W_f}{\pi D_w \nu(T_i)} \right)^{1.55}} \quad (4)$$

$$\left[\begin{array}{l} 2,000 \leq \frac{4W_f}{\pi D_w \nu(T_i)} \leq 400,000 \\ 2 \leq \frac{H_w}{D_w} < 5 \\ 2.5 \leq \frac{r_w}{D_w} \leq 7.5 \end{array} \right]$$

2.3 Heat transfer by radiation

Radiation governed by Stefan-Boltzmann law, is one of the important heat transfer factors in the cooling process

during line heating, which becomes a dominant cooling factor when the temperature of the plate is over 800°C. As the temperature range governing the phase transformation of steel during the cooling stage is 800~500°C, the effect of radiation should be considered in any heat transfer analysis.

With the exception of the film boiling region, the total heat transfer coefficient can be represented by equation (5), which includes the effect of radiation.

$$h(T_s) = h^c(T_s) + h^r(T_s) = h^c(T_s) + \varepsilon\sigma(T_s^2 + T_i^2)(T_s + T_i) \quad (5)$$

With the actual water cooling process in shipyards, critical cooling mostly occurs in the film boiling region, because the cooling water nozzle follows the heating torch at a distance of about 10cm. For the film boiling region, the total heat transfer coefficient can be represented by equation (6), which considers the effect of radiation on the film thickness [7].

$$h(T_s) = \left(h^c(T_s)^{\frac{4}{3}} + h^r(T_s)h^c(T_s)^{\frac{1}{3}} \right)^{\frac{3}{4}} \quad (6)$$

3. Examination of heat transfer analysis

In this chapter, the heat transfer analysis based on the heat transfer coefficients obtained in chapter 2 is performed using ANSYS and examined.

A heat transfer analysis was performed under the line heating experimental conditions, which will be described later in chapter 4. From the result of the temperature distribution, the boiling region can easily be found as it is defined by the excess temperature over the boiling point of water.

Mitsutake and Monde investigated the heat transfer during the transient cooling of a high temperature surface using an impinging jet, and measured the radius of the boiling region for various plate roughnesses [8]. The maximum radius of the boiling region can be represented by equation (7) from the experimental results.

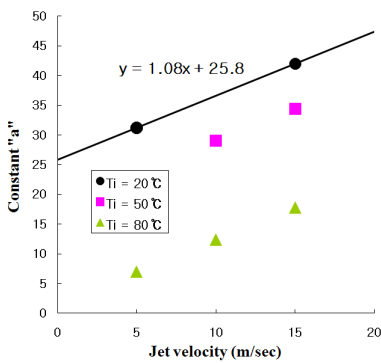
$$r_{wet} = a t^{1/2} - t \sqrt{u_{\infty}^2 + 19.6H_w} \quad (mm)$$

$$\left[\begin{array}{l} 2 < \sqrt{u_{\infty}^2 + 19.6H_w} < 3.4 \\ T_{sat} - T_i = 80^{\circ}C \\ T_{max} = 900^{\circ}C \\ C = 0.45\% \end{array} \right]$$

$$= \frac{a^2}{40\sqrt{u_{\infty}^2 + 19.6H_w}}$$

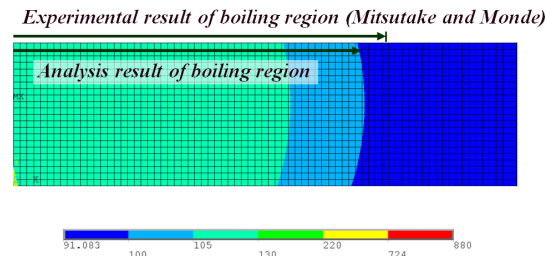
$$at \quad t = \frac{a^2}{400(u_{\infty}^2 + 19.6H_w)} \quad (\because \frac{dr}{dt} = 0) \quad (7)$$

The relation between the coefficient “a” in equation (7) and the jet velocity is shown in Fig. 3. It is known that the slope of this relationship curve is irrelevant to the coolant temperature.



[Fig. 3] The relation between constant “a” and jet velocity

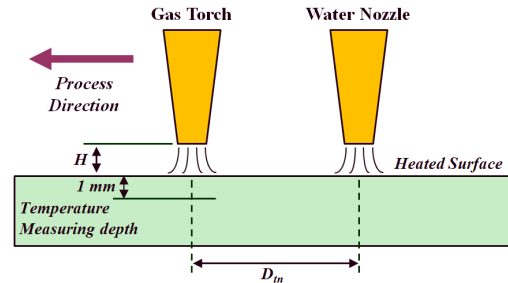
The boiling region determined from the heat transfer analysis method proposed in this study was in close agreement with the result from equation (7), as shown in Fig. 4.



[Fig. 4] Boiling region determined by heat transfer analysis

4. Prediction of plate deformation

In this chapter, the results of the analysis were compared with those obtained experimentally by Chung et al. [9]. Chung et al. conducted line heating experiments under different cooling conditions to investigate the relationships between the plate deformation and phase transformation of steel. The variable for different cooling conditions was the distance between the gas torch and water cooling nozzle, as shown in Fig. 5. The line heating conditions are listed in Table 1. Two different cooling conditions were also considered, as listed in Table 2. Table 3 shows the chemical compositions of the 50kg/mm² high tensile steel plate used in the experiment.



[Fig. 5] Sketchy drawing of line heating experiment

[Table 1] Line heating conditions

Item	Conditions
Nozzle moving speed	3.15 mm/sec
Height of nozzle	20 mm
Water flow	2.1 liter/min
Max. Temp. 1 mm depth from plate surface	870~880 °C

[Table 2] Two cases of different cooling conditions

	Distance (D _m)
Case(I)	50 mm
Case(II)	35 mm

[Table 3] Chemical compositions of test plate

Chemical composition (%)					
C	Si	Mn	Mo	P	S
0.18	0.27	1.54	0.01	0.017	0.007

The volume percentages of each phase transformed by the line heating with water cooling are affected by the speed of cooling of the heated region. The plate deformations are also determined by the inherent strains by considering the volume percentages of each transformed phase [3]. Therefore, to predict the deformations of plate, it is important to obtain details on the cooling speed, which can be achieved using the heat transfer analysis method described in chapter 2.

The martensite ratio, which is the rate of martensite in phase transformed steel, is a major parameter in calculating the plate deformation. The martensite ratio generally increases under rapid cooling conditions and decreases under slow cooling conditions. According to the distance between the torch and nozzle, there would be a difference in speed of cooling, which will cause a difference in the martensite ratio. Two different cooling conditions, Case(I) and Case(II) outlined in Table 2, can be regarded as the case for the main cooling in the film boiling region (i.e. slow cooling) and the impinging jet region (i.e. rapid cooling), respectively.

For predicting the plate deformation due to line heating, it was assumed that the inherent strains were distributed in the region with a half-elliptical shape [2]. The speed of cooling at the centroid of the half-elliptical inherent strain region was used as a representative value.

The material properties of phase transformed steel were calculated using the function shown in equation (8), where the martensite ratio was determined based on equation (9) [10].

$$f_C(T) = \sum_i^n X_i(T) \cdot f_{C,i}(T)$$

$i \rightarrow \text{Ferrite, Austenite, Pearlite, Bainite, Martensite}$

(8)

$$X_M = 1 \text{ when,}$$

$$V_M > 10^{8.6424 - (4.62C + 1.05Mn + 0.50Cr + 0.66Mo + 0.54Ni)}$$

$$X_M = 0.9 \text{ when,}$$

$$V_M > 10^{7.5924 - (4.04C + 0.96Mn + 0.58Cr + 0.97Mo + 0.49Ni)}$$

$$X_M = 0.5 \text{ when,}$$

$$V_M > 10^{7.3324 - (4.13C + 0.86Mn + 0.41Cr + 0.94Mo + 0.57Ni)}$$

$$X_M = 0 \text{ when,}$$

$$V_M > 10^{4.5113 - (0.43C + 0.49Mn + 0.26Cr + 0.38Mo + 2\sqrt{Mo} + 0.78Ni)}$$

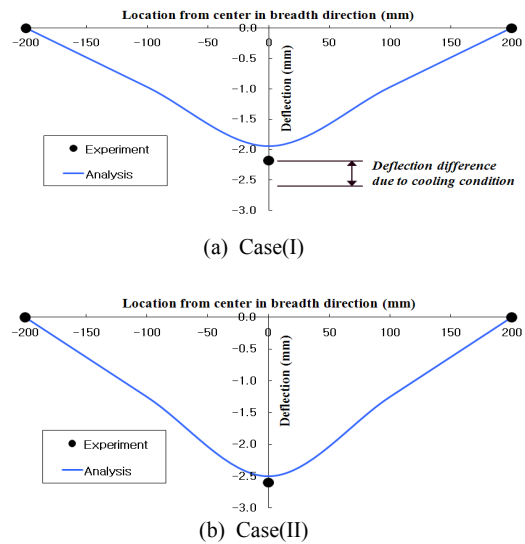
(9)

Table 4 shows the critical cooling speeds and martensite ratios for Cases(I) and (II), which were calculated at 700°C during the cooling stage.

[Table 4] Critical cooling speed and martensite ratio

	Critical cooling speed (°C /sec)	Martensite ratio (%)
Case(I)	71.325	65.8
Case(II)	196.875	100.0

Using the speed of cooling and volume percentage of each phase determined for the inherent strain region, the plate deformations were calculated based on the inherent strain method proposed in [3], the results of which are shown in Fig. 6, and compared with the experimental results.



[Fig. 6] Comparison of plate deformation results

5. Conclusions

In this study, our focus was on the effect of water cooling during the line heating process to improve the predictability of plate deformation. A heat transfer analysis was performed on the effects of the impinging water jet, film boiling, and radiation. From this analysis the actual cooling speed and the volume percentage of each phase in the inherent strain region were achieved. Based on the material properties calculated from the

volume percentage of each phase, it should be possible to predict the plate deformations due to line heating with better precision. Compared to the line heating experimental results, the simulation method of the water cooling process was verified to improve the predictability of the plate deformation due to line heating.

Nomenclature

c_p : specific heat (J / g K)
 $c_{p,l}$: specific heat of liquid (J / g K)
 C : carbon in steel (%)
 D_m : distance between torch and nozzle
 D_w : nozzle diameter (m)
 f_c : material property of steel during cooling
 $f_{c,l}$: material property of i-phase during cooling
 h : total heat transfer coefficient
 h^c : heat transfer coefficient by convection
 h_{fg} : evaporation heat (J / kg)
 h^r : heat transfer coefficient by radiation
 H_w : nozzle height from plate surface (m)
 k : fluid heat transfer coefficient (W / m sec °C)
 Pr : Prandtl number
 Pr_l : Prandtl number of liquid
 r : radius of heat flux by torch
 r_c : radius of impinging jet region
 r_w : distance from nozzle center (m)
 r_{wet} : radius of film boiling region (m)
 T_e : temperature difference between plate and boiling water (°C)
 T_f : average temperature between plate and fluid (°C)
 T_r : room temperature (°C)
 T_{max} : maximum temperature of plate (°C)
 T_s : temperature of plate surface (°C)
 T_{sat} : saturation temperature of water (°C)
 u_∞ : fluid velocity (m / sec)
 V_M : critical cooling speed of martensite (°C/sec)
 W_f : fluid flow of coolant (m³ / sec)
 X_l : ratio of i-phase
 X_M : ratio of martensite
 ϵ : emissivity of plate surface
 μ_l : dynamic viscosity coefficient of liquid (N sec / m²)
 ν : Poisson number
 ρ : density (kg / m³)
 ρ_l : density of liquid (kg / m³)
 ρ_v : density of vapor (kg / m³)
 σ : Stefan – Boltzmann constant
 σ_f : surface tension (N / m)

References

- [1] T. Nomoto, S. Takechi, K. Shouki, K. Aoyama, M. Enosawa, and M. Saitoh, "Development of Simulator for

Plate by Line Heating Considering In-Plane Shrinkage", *J. of SNAJ*, 170, 1991.

- [2] D. E. Ko, C. D. Jang, S. I. Seo, and H. W. Lee, "Realtime Simulation of Deformation due to Line Heating for Automatic Hull Forming System", *J. of the SNAK*, 36 (4) pp. 116-127, 1999.
- [3] C. D. Jang, Y. S. Ha, and D. E. Ko, "An Improved Inherent Strain Analysis for the Prediction of Plate Deformations Induced by Line Heating Considering Phase Transformation of Steel", *ISOPE*, IV pp.147-152, 2003.
- [4] F. P. Incropera and D. P. Dewitt, *Fundamentals of Heat and Mass Transfer*, WILEY, 5th Edition, 2003.
- [5] N. Hatta and H. Osakabe, *ISIS Int.*, 29 (11) pp. 919, 1989.
- [6] H. Martin, "Heat and Mass Transfer between Impinging Gas Jets and Solid Surfaces", *Jr., Eds., Advances in Heat Transfer*, Academic Press, New York, 1977.
- [7] L. A. Bromley, "Heat Transfer in Stable Film Boiling", *Chem. Eng. Prog.* 46, pp. 221, 1950.
- [8] Y. Misutake and M. Monde, "Heat Transfer during Transient Cooling of High Temperature Surface with an Impinging Jet", *Heat and Mass Transfer*, 37, pp. 321-328, 2001.
- [9] N. H. Chung, B. K. Choi, and J. E. Park, "Distortion and Transformation of High Tensile Strength Steel Plate of 50kg/mm² Grade due to Line Heating", *J. of KWS*, 3 (1) pp. 11-21, 1985.
- [10] M. Atkins, "Atlas of CCTD for engineering steels", *British Steel Corp*, 1977.

Dae-Eun Ko

[Regular member]



- Feb. 1993 : Seoul National Univ., NAOE, MS
- Aug. 1998 : Seoul National Univ., NAOE, PhD
- Jul. 1998 ~ Feb. 2008 : Samsung Heavy Industries Co., Ltd., Senior Manager
- Mar. 2008 ~ current : Dong-Eui Univ., Dept. of NAOE, Assistant Professor

<Research Interests>

Ship/Offshore Structural Design, Welding Design and Deformation Control

Yun-Sok Ha

[Regular member]



- Feb. 2001 : Seoul National Univ., NAOE, MS
- Feb. 2006 : Seoul National Univ., NAOE, PhD
- Mar. 2006 ~ current : Samsung Heavy Industries Co., Ltd., Senior Researcher

<Research Interests>

Thermal Distortion Analysis, Aluminum Welding