

# A study on the simulation of water cooling process for the prediction of plate deformation due to line heating

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## Abstract

In a line heating process for hull forming, the phase of the steel transforms from austenite to martensite, bainite, ferrite, or pearlite depending on the actual speed of cooling following line heating. In order to simulate the water cooling process widely used in shipyards, a heat transfer analysis on the effects of impinging water jet, film boiling, and radiation was performed. From the above simulation it was 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. Compared to the line heating experimental results, the simulated water cooling process method was verified to improve the predictability of the plate deformation due to line heating.

**Keywords:** Line Heating Process; Heat Transfer Analysis; Cooling Speed; Phase Transformation; Inherent Strain; Plate Deformation

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## 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. Since reducing production costs is a major concern of shipbuilding companies, 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 [9]. By replacing the detailed thermal elasto-plastic analysis with experiments, 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 [1]. They considered the volume expansion of martensite when calculating the inherent strains using a modified temperature-dependent coefficient of thermal expansion.

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### 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
- $f_{c,i}$  : 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)
- $T_i$  : room temperature (°C)
- $T_{max}$  : maximum temperature of plate (°C)
- $T_s$  : temperature of plate surface (°C)
- $T_{sat}$  : saturation temperature of water (°C)
- $u_\infty$  : fluid velocity (m / sec)
- $V_M$  : critical cooling speed of martensite (°C/sec)
- $W_f$  : fluid flow of coolant (m<sup>3</sup> / sec)
- $X_i$  : ratio of i-phase
- $X_M$  : ratio of martensite
- $\varepsilon$  : emissivity of plate surface
- $\mu_l$  : dynamic viscosity coefficient of liquid (N sec / m<sup>2</sup>)
- $\nu$  : Poisson number
- $\rho$  : density (kg / m<sup>3</sup>)
- $\rho_l$  : density of liquid (kg / m<sup>3</sup>)
- $\rho_v$  : density of vapor (kg / m<sup>3</sup>)
- $\sigma$  : Stefan – Boltzmann constant
- $\sigma_f$  : surface tension (N / m)

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 radiation. 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 [1] and compared with those obtained experimentally.

## 2. Heat transfer in water cooling process of line heating

Heat transfer generally occurs via conduction, convection, and radiation. However, in the case of a plate in the water cooling process of line heating, most heat transfer occurs via convection and radiation.

### 2.1 Definition of cooling region

The cooling area of a plate during line heating with water cooling is shown in Fig. 1. The cooling area can be divided into three regions, i.e. the impinging jet region, pool boiling region, and laminar flow region. The pool boiling region was subdivided according to boiling modes, as shown in Fig. 2.

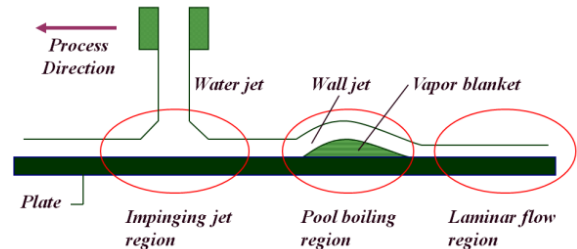


Fig. 1 Cooling regions in line heating with water cooling

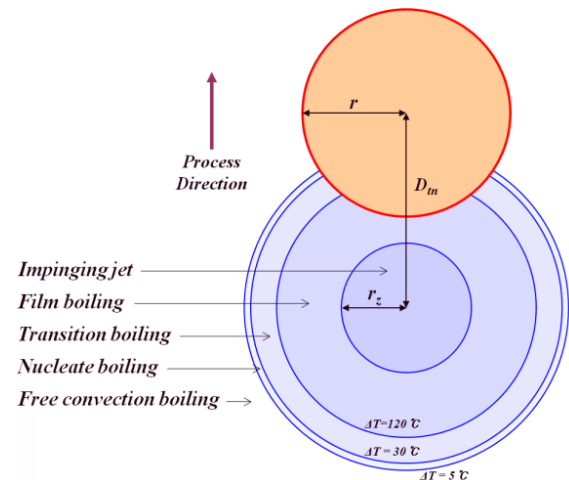


Fig. 2 Boiling modes in line heating with water cooling

**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) [3].

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

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) [3].

$$h^c(T_s) = 1424670 \times \mu_l(T_s) h_{fg}(T_s) \times \sqrt{\frac{\rho_l - \rho_v}{\sigma_f(T_s)}} \left( \frac{c_{p,l}(T_s) T_e}{h_{fg}(T_s) Pr_l(T_s)} \right)^3 \frac{1}{T_s - T_i} \quad (W / m^2 K) \quad (2)$$

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 [8].

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

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 [4].

$$h^c(T_s, r_w) = \frac{2Pr^{0.42}(T_i)k(T_i)(1-1.1\frac{D_w}{r_w})}{r_w(1+0.1(\frac{H_w}{D_w}-6)\frac{D_w}{r_w})} \times \sqrt{\frac{4W_f}{\pi D_w v(T_i)} + 0.043 \left( \frac{W_f}{\pi D_w v(T_i)} \right)^{1.55}} \left[ \begin{array}{l} 2,000 \leq \frac{4W_f}{\pi D_w v(T_i)} \leq 400,000 \\ 2 \leq \frac{H_w}{D_w} < 5 \\ 2.5 \leq \frac{r_w}{D_w} \leq 7.5 \end{array} \right] \quad (4)$$

**2.3 Heat transfer by radiation**

Radiation governed by Stefan-Boltzmann’s 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 [5].

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

**3. Examination of heat transfer analysis result**

In this chapter, the heat transfer analysis method based on the heat transfer coefficients obtained in chapter 2 is 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 [10]. The maximum radius of the boiling region can be represented by equation (7) from the experimental results.

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

$$\left[ \begin{array}{l} 2 < \sqrt{u_{\infty}^2 + 19.6H_w} < 3.4 \\ T_{sat} - T_i = 80^{\circ}C \\ T_{max} = 900^{\circ}C \\ C = 0.45\% \end{array} \right] \quad (7)$$

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

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

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.

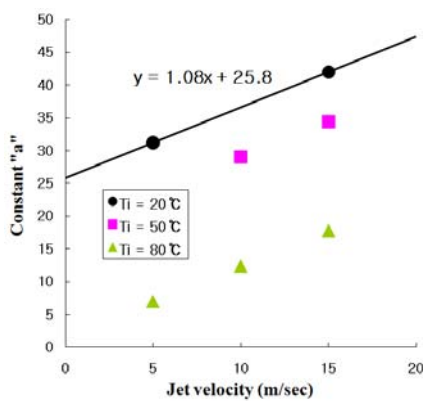


Fig. 3 The relation between constant “a” and jet velocity

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.

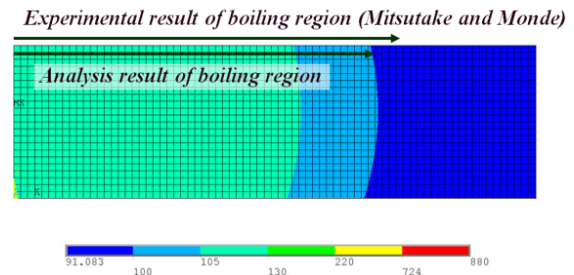


Fig. 4 Boiling region determined by heat transfer analysis

#### 4. Prediction of plate deformation

In this chapter, the results of the analysis were compared with those obtained experimentally by Chung et al. [7]. 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, which is the drawing schematics of their experiments. 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/mm<sup>2</sup> high tensile steel plate used in the experiment.

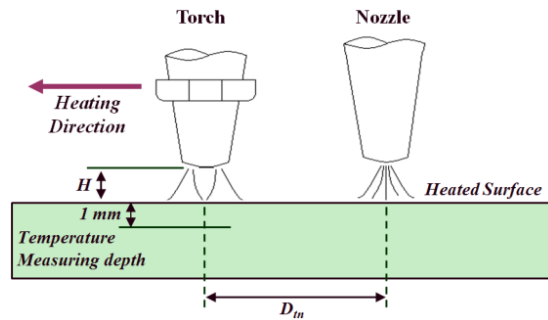


Fig. 5 Sketchy drawing of line heating experiment

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 [1]. Therefore, to predict the plate deformations, it is important to obtain details on the speed of cooling, 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 due to line heating. 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. Fig. 6 shows the two different cooling conditions outlined in Table 2. Case(I) and Case(II) 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.

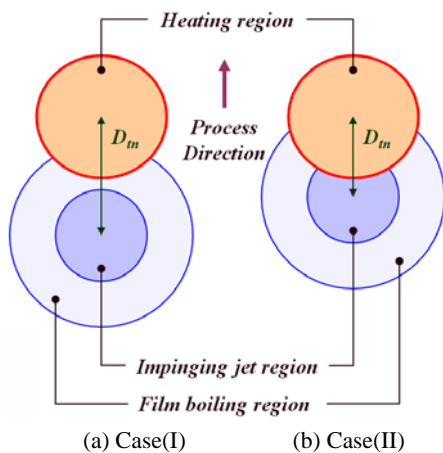


Fig. 6 Cooling conditions of Case(I) and Case(II)

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-elliptic 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) [6].

$$f_C(T) = \sum_i^n X_i(T) \cdot f_{C,i}(T) \tag{8}$$

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

$$X_M = 1 \text{ when, } V_M > 10^{8.6424 - (4.62C + 1.05Mn + 0.50Cr + 0.66Mo + 0.54Ni)} \tag{9}$$

$$X_M = 0.9 \text{ when, } V_M > 10^{7.5924 - (4.04C + 0.96Mn + 0.58Cr + 0.97Mo + 0.49Ni)}$$

$$X_M = 0.5 \text{ when, } V_M > 10^{7.3324 - (4.13C + 0.86Mn + 0.41Cr + 0.94Mo + 0.57Ni)}$$

$$X_M = 0 \text{ when, } V_M > 10^{4.5113 - (0.43C + 0.49Mn + 0.26Cr + 0.38Mo + 2\sqrt{Mo} + 0.78Ni)}$$

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 [1], the results of which are shown in Fig. 7, and compared with the experimental results.

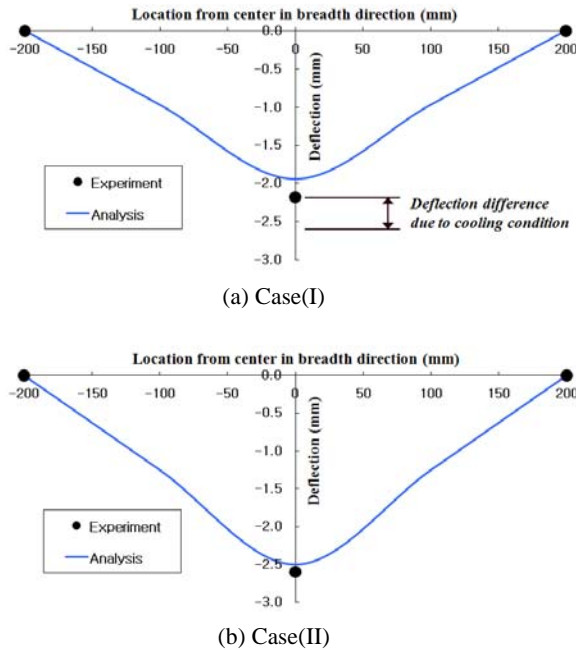


Fig. 7 Comparison of plate deformation results

## 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 speed of cooling 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.

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