Ocean Systems Engineering, *Vol. 16, No. 2 (2026) 129-138*
https://doi.org/10.12989/ose.2026.16.2.129

Techno-Press

A research note on analysis of pulse heating strategy in line heating for shipbuilding applications

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(Received November 25, 2025, Revised February 22, 2026, Accepted March 26, 2026)

Abstract. Line heating is a popular technique used in the ship building and related structures that involves bending of plates using a heat source, the path of which is determined by the final shape required. Numerical techniques such as Finite Element Analysis (FEA) is popularly used to investigate the various aspects of the process that significantly reduces the time and cost involved with the experimental analyses. Based on the numerical studies, a novel strategy of heating termed here as 'pulse heating strategy' is proposed primarily for thicker plates that is expected to reduce the overall production time. Furthermore, the effect of pulse amplitude in the residual deformation of the plate subjected to line heating as per the novel heating strategy is numerically investigated in the present study.

Keywords: finite element analysis; flame bending; line heating; numerical techniques; ship building; transient thermal analysis

1. Introduction

Line heating commonly known as flame bending is a plate forming process involving thermo-elastic-plastic bending of plates using a heat source such as oxy-acetylene gas flame, laser and induction heating, etc. It is widely used in the production of ship hulls and parts of other off shore structures including double curvature surfaces. When a heat source such as oxy-acetylene flame is made to travel across the plate length, a temperature gradient will be developed across the plate thickness which is considered as the driving force for the process. The temperature gradient thus developed results in variations in the expansions across the plate thickness. The resulting expansion followed by cooling lead to plastic deformation and bending of plates. The hot zone near the heating line experiences compressive stresses from the comparatively cooler zone away from the heating line leading to an initial thermo-elastic bending. Subsequent cooling of the plate leads to thermo-plastic bending in the reverse direction developing a permanent bending angle. The region directly under the heat source experiences plastic deformation due to the high temperature and reduction in the yield stress of the material there [3].

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ISSN: 2093-6702 (Print), 2093-677X (Online)

Maximum temperature, the heating and cooling rate, and width and depth of the heated zone are the primary factors that influence the amount of deformation. Plate dimensions, the heated length, the plate restraint and state of pre-strain in the plate are considered to be secondary factors [5]. Line heating problem may be divided into two problems:one involving the heat transfer problem and the other involving the elasto-plastic deformation problem [9]. As the temperature distribution is assumed to be independent of stresses and strains, the line heating is treated here as a weakly coupled problem. This enables us to import the thermal distribution obtained from the thermal analysis as thermal load into mechanical analysis to obtain strains and residual deformations [10]. Line heating is considered to be a difficult process to control. The curvatures have specific local characteristics, as in case of ships [7]. Moreover, the non-linear behaviour of the materials in the transient thermal field makes line heating a difficult process to analyse [6]. Early researchers alanayzed the line heating problem using simplified beam model normal to the heating line. Temperature dependent material properties were used in these studies. However, the model was inadequate to predict the plate behavior as line heating is predominantly a three dimensional problem. The problem was three dimensionally approached by Moshaiov et al. [6] in which a theory for thermo-elastic-plastic bending of plates was developed and solved the governing equation using boundary element method. However, the main limitation of this method is that it considers only small deflections. As the line heating is highly intricate process owing to its material non linearity and spatial and time dependent temperature distribution researchers started using numerical simulations based on finite element technique. The advancement in computer technology made this feasible. A 3D finite element code was developed by Ueda et al. [8] incorporating large deformations to study the plate behavior during induction heating and subsequent cooling and the same was validated using experimental results. Using a validated finite element model, the correlation between the peak temperature developed and the plate thickness is established with the heat source travelling in a straight line. It is observed that an increase in the plate thickness leads to a decrease in the final peak temperature developed when the plate is subjected to line heating keeping all the other parameters unchanged [1]. As a result the extend of bending gets adversely affected for thicker plates as the primary driving force for line heating is the temperature gradient across the plate thickness. The method of reducing the flame velocity to raise the temperature for the same heat input may be adopted in case of thick plates. However reduction in the flame velocity will lengthen the process duration and hence may raise the production cost.

Herein, we suggest a new strategy of heating, termed here as '*pulse heating strategy'*. The pulse heating pattern as opposed to straight line heating is illustrated in Fig. 1. When other parameters are kept constant, it is assumed that the amplitude (a), pulse width (w) and the flame velocity are the major factors that decide the peak temperature developed.

2. Methodology

ANSYS*TM Mechanical APDL solution system is used for developing the numerical model and the different elements available in its element library is used to model the rectangular plate with required dimensions. The determination of residual deformation of the thermally formed plates using finite element method involves two steps.

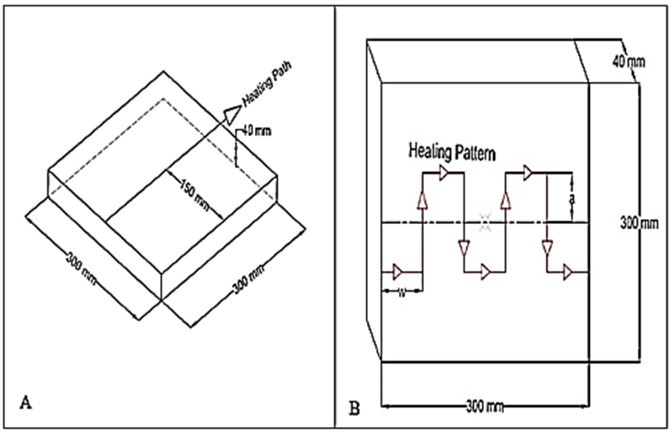

Figure 1. (a) Straight line heating and (b) Pulse heating

In the first step, temperature distribution in the plate undergoing line heating is determined via the thermal analysis done using the plate model uniformly discretised using eight node brick thermal element available in the Ansys*TM Mechanical APDL element library. Structural analysis performed to determine the inherent deformations of the plate using the temperature field obtained from the thermal analysis is the second step. For structural analysis, the plate is uniformly meshed using eight node structural brick element available in the Ansys*TM Mechanical APDL element library. 30000 elements are used in the present study beyond which not much variations are found. Temperature dependent properties are used in this study (Fig. 2). The methodology adopted in the current study is illustrated in Fig. 3. [1].

The three dimensional heat conduction equation (Eq. (1)) and the Newton's law of cooling (Eq. (2)) are the governing equations adopted for thermal analysis. Eq. (3) gives the thermal boundary conditions

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho c\frac{\partial T}{\partial t} \tag{1}$$

$$q_{conv} = h_f(T - T_\infty) \tag{2}$$

$$\begin{gathered} At\ time, t = 0, Temperature\ T = T_\infty \\ At\ t > 0, q_n = -q_{sup,} along\ the\ heating\ region \\ At\ t > 0, q_n = h_f(T - T_\infty), for\ regions\ away\ from\ the\ heating\ line \end{gathered} \tag{3}$$

Heat source in the present study is oxy-acetylene gas torch and is modelled as a Gaussian distribution as given in Eq. (4). Total heat input is calculated using Eq. (5) [4]

$$Q_p = Q_{max}e^{-\gamma r^2} \tag{4}$$

$$Q_{total} = \int_0^{2\pi}\int_0^{\infty} Q_p r\, dr\, d\theta = \frac{\pi Q_{max}}{\gamma};\ \gamma = \frac{ln100}{r_{torch}^2} \tag{5}$$

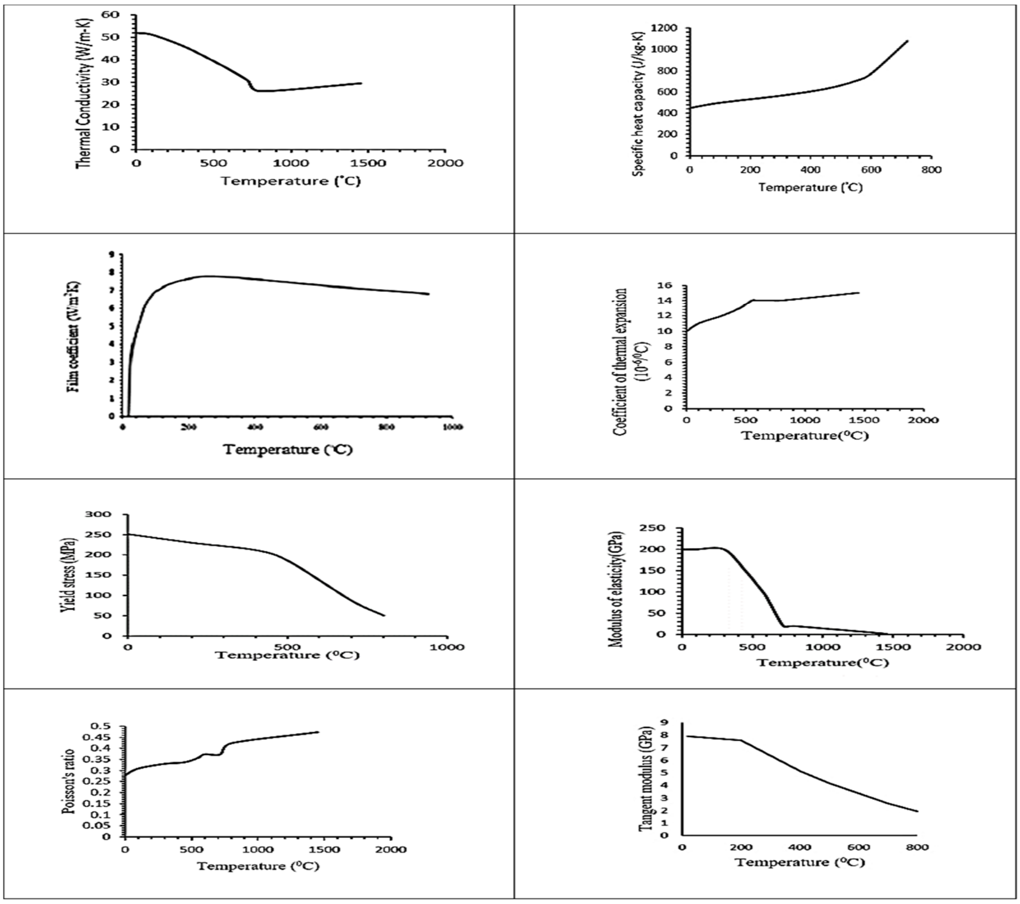

Figure 2. Temperature dependent properties

We note that in the present study heat transfer via radiation mode is not considered as its effect is considered to be negligible as compared with the other two modes. However, this simplication causes minor discrepancies between the simulated and experimental results, e.g., exclusion of radiative heat transfer. Equilibrium equations (Eq. (6)), stress-strain relations (Eq. (7)) and thermal elastic-plastic strain relations (Eq. (8)) are used as the governing equations for structural analysis. Isotropic hardening with uniform yield surface expansion is used in this study and it is defined

$$\nabla\sigma + F = 0 \tag{6}$$

$$\{\sigma\} = [D]\{\varepsilon\}, \text{ and} \tag{7}$$

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_t. \tag{8}$$

The FE model developed is validated using the experimental results by Biswas et al. [2]. The heating parameters adopted by Biswas et al. [2] are reported in Table 1.

Fig. 4 compares the numerical and experimental results and it is observed that both align well. Subsequent analyses are performed using the validated FE model.

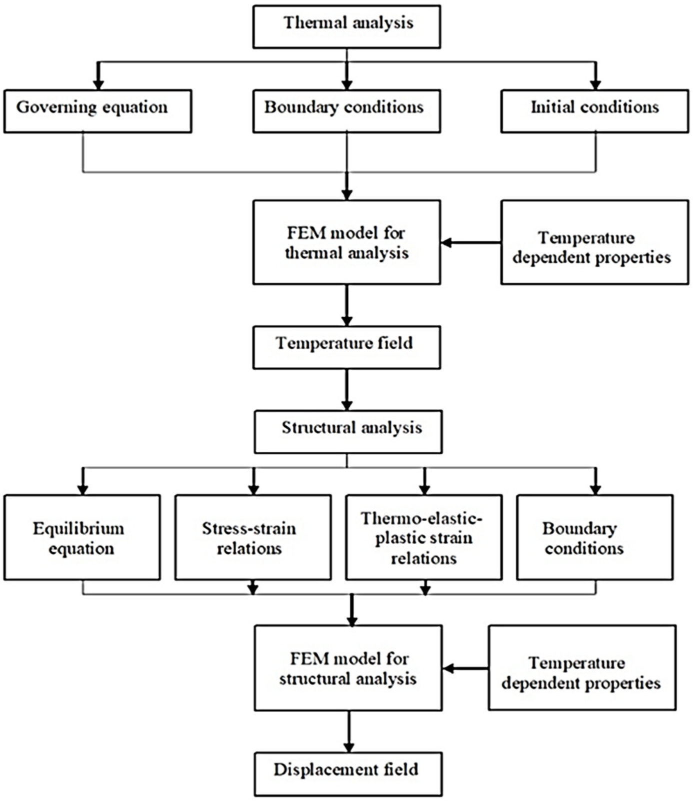

Figure 3. Methodology for FE thermo-mechanical analysis of plate bending

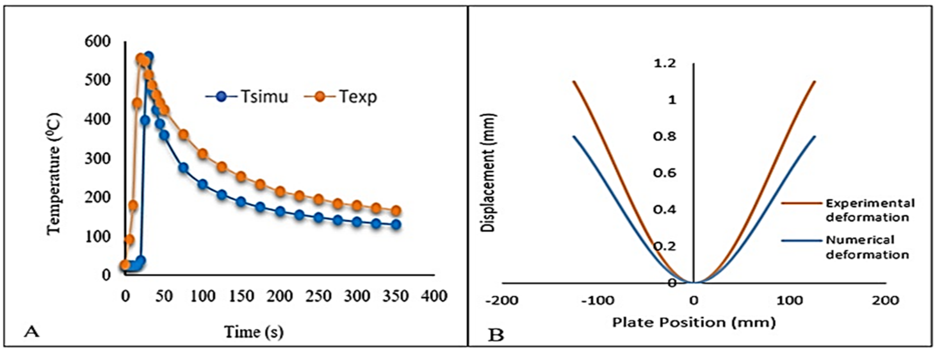

Figure 4. (a) Thermal history and (b) Residual deformation

Table 1. Experimental parameters

Plate thickness (mm)	Torch speed (m/min)	Torch height (mm)	O_2 cylinder pressure (kg/cm^2)	O_2 cylinder working pressure (kg/cm^2)	C_2H_2 cylinder pressure (kg/cm^2)	C_2H_2 cylinder working pressure (kg/cm^2)
6	0.36	35	82	0.92	8.5	0.31

Table 2. Numerical parameters for straight line heating

Heating type	Flame type	Flame velocity	Flame radius	Heat input	Plate dimension
Straight Line	oxy-acetylene	2.5 mm/s	4 cm	6350 watts	300x300x40 mm

Table 3. Numerical parameters for pulse heating

Heating type	Flame type	Flame velocity	Flame radius	Pulse amplitude	Pulse width	Heat input	Plate dimension
Pulse	oxy-acetylene	35 mm/s	4 cm	10 mm	5 mm	6350 watts	300x300x 40 mm

3. Results and discussions

Idea here is to develop a pulse heating strategy that will develop nearly the same peak temperature as that obtained through straight line heating with the same heat input and increased flame speed. The numerical parameters used in case of straight line heating for a comparative study with pulse heating is given in Table 2.

Through numerous simulations, the pulse heating parameters that will develop the peak temperature approximately similar to straight line heating as per Table 2 are identified and listed in Table 3.

3.1 Time temperature history and inherent deformation of straight line heating and pulse heating

The time- temperature history in both cases is depicted in Fig. 5 and the residual deformation in case of straight line heating with that of pulse heating is compared in Fig. 6. Note here that TCP and BCP stands for Top Central Point and Bottom Central Point respectively of the plate. In our reported results, we note that the peak temperature in case of pulse heating is slightly lower than that of straight line heating (in reference to Fig. 5) and this is primarily because in the pulse heating, in general, a lower bending angle is obtained as against the straight line heating (in

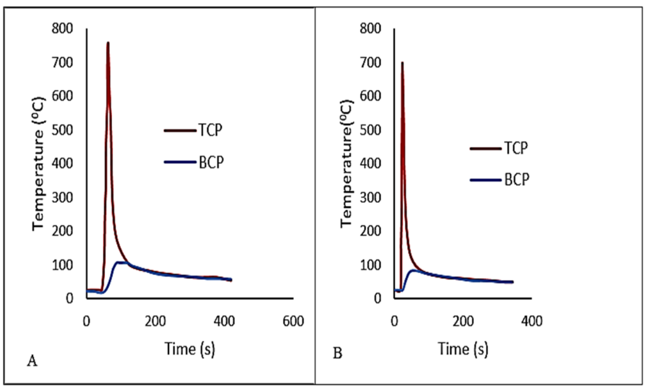

Figure 5. (a) Time-Temperature history for straight line heating and (b) Time-Temperature history for pulse heating

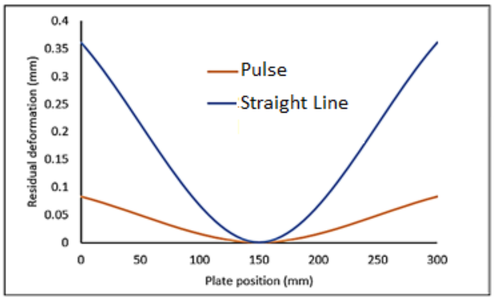

Figure 6. Residual deformation-Pulse heating & straight line heating

Table 4. Numerical parameters for studying the effect of pulse amplitude

Heating type	Flame type	Flame velocity	Flame radius	Pulse width	Heat input	Plate dimension
Pulse	oxy-acetylene	35 mm/s	4 cm	5 mm	6350 watts	300x300x40 mm

reference to Fig. 6). However, it can be expected that through rigorous optimization driven approach, the pulse heating velocity will be calibrated allowing the peak temperature to match with that obtained in straight line heating. This application of an optimization based approach will effectively minimize the variance between the two. As a limitation of our work, we note that this optimization driven approach has not been implemented, so far, and it is being investigated at present.

3.2 Effect of pulse amplitude on residual deformation in pulse heating

Herein, an attempt is made to study the effect of pulse amplitude on residual deformation obtained through line heating that adopts pulse heating strategy using numerical techniques based on FEA. Here we compare the effects of 5 mm and 10 mm amplitudes keeping the other parameters unchanged. The parameters adopted for the present study are given in Table 4. Residual deformations in both cases are reported in Fig. 7. Analysing the results, it may be concluded that an increase in the amplitude in case of pulse heating, tends to raise the residual deformation.

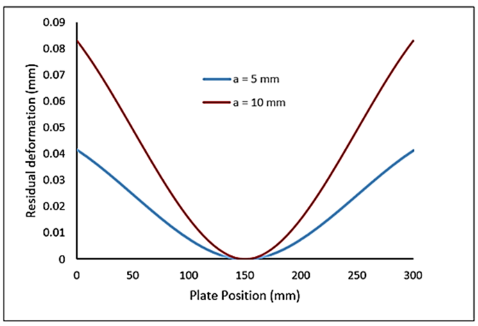

Figure 7. Residual deformation for a = 5 mm and a = 10 mm for pulse heating

4. Conclusions

Concept of pulse heating strategy aims to accelerate the line heating process of thick plates by increasing the flame speed. Achieving this objective is impractical with line heating along a straight path, as the resulting temperature and temperature gradient are inadequate to produce appreciable deformation or bending angles in thick plates. Although, the proposed pulse heating has the distinct advantage of fastening the line heating process in case of thick plates, it is relatively difficult to achieve precise bending with pulse heating. This limitation can be addressed through the application of rigorous optimization driven approach. When other parameters are kept unchanged, flame velocity, pulse amplitude and pulse width are assumed to be the major factors that determine the maximum temperature and extend of residual deformation in the plate. FEA based technique can be used to identify the pulse width and flame velocity that can replace the straight line flame heating.

Studies have been performed and reported on a 40 mm thick plate and detailed numerical simulations have been conducted to explore the impact of pulse amplitude on the residual deformation obtained in the plate. We compared the results of pulse heating with amplitudes of 5 mm and 10 mm and cautiously we note that since results presented here are based on numerical studies, we shall require detailed experimental validations before proposing the industry applicable guidelines. Our future work will go in these directions and some of these are currently under investigation.

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Nomenclature

$a = Pulse\ amplitude$

$w = Pulse\ width$

$k - Thermal\ conductivity\ of\ the\ plate\ material$

$T - Temperature\ of\ the\ plate\ surface$

$T_\infty - Ambient\ temperature$

$\rho - Density\ of\ the\ plate\ material$

$c - Specific\ heat$

$x, y, z - position\ coordinates$

$q_{conv} - Convection\ heat\ loss\ from\ the\ plate\ surface$

$h_f - Heat\ transfer\ coefficient$

$t - time$

$q_n - Component\ of\ the\ conduction\ heat\ flux\ vector\ normal\ to\ the\ plate\ surface$

$q_{sup} - heat\ flux\ supplied\ to\ the\ plate\ surface\ from\ oxy - acetylene\ flame$

$Q_p - Pointwise\ heat\ flux\ distriution$

$Q_{max} - Maximum\ value\ of\ the\ distributed\ heat\ flux$

$r - Distance\ from\ oxy - acetylene\ flame\ center$

$r_{torch} - Oxy - acetylene\ flame\ radius$

$\gamma - Width\ factor$

$\{\sigma\} - Stress\ vector$

$F = Body\ force\ vector\ per\ unit\ volume$

$[D] - Stifness\ matrix$

$\{\varepsilon\} - Strain\ vector$

$\varepsilon_e, \varepsilon_p, \varepsilon_t - Elastic, plastic\ and\ thermal\ strains\ respectively$