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Numerical and Dimensional Analysis for Prediction of Line Heating Residual Deformations

Pankaj Biswas*, Nisith Ranjan Mandal and Om Prakash Sha

Department of Ocean Engineering and Naval Architecture, IIT, Kharagpur 721302, India

Abstract: Line heating process is a very complex phenomenon as a variety of factors affects the amount of residual deformations. Numerical thermal and mechanical analysis of line heating for prediction of residual deformation is time consuming. In the present work dimensional analysis has been presented to obtain a new relationship between input parameters and resulting residual deformations during line heating process. The temperature distribution and residual deformations for 6 mm, 8 mm, 10 mm and 12 mm thick steel plates were numerically estimated and compared with experimental and published results. Extensive data generated through a validated FE model were used to find co-relationship between the input parameters and the resulting residual deformation by multiple regression analysis. The results obtained from the deformation equations developed in this work compared well with those of the FE analysis with a drop in the computation time in the order of 100 (computational time required for FE analysis is around 7 200 second to 9 000 seconds and where the time required for getting the residual deformation by developed equations is only 60 to 90 seconds).

Keywords: dimensional analysis; 3-D finite element analysis; elasto-plastic analysis; residual deformations; multiple regression analysis; *oxy*-acetylene gas flame

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1 Introduction

Line heating is a method of plate forming by means of local heating in linear segments. It can be gainfully utilized in shipbuilding industry, and other relevant plate forming operations in allied industries. Despite its possibility of gainful utilization, the process is still not developed for successful implementation in shipyards. When a plate is heated on one side, the temperature gradient across the thickness of the plate generates different expansion across the thickness of the plate, thereby causing the plate to bend. Plastic deformation occurs in the region directly under the heat source where the temperature is high and yield stress of the metal is low. After the plate cools down, as a result of compressive plastic strains, the heated area shrinks, causing the plate bend reversely.

Investigation on the mechanism of the line heating process aims to predict the final shape of the metal plate, given the heating conditions and mechanical properties of the metal plate to be heated. Finite element method or simplified beam or plate theory is usually applied. Research on design of the proper heating and cooling processes is based on the experience on forming simple shape surfaces from rectangular plates.

No general process planning scheme for general curved shapes nor automatic control of the forming process is available.

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***Corresponding author Email:** panu012@yahoo.co.in

Until today, quite a few researchers have addressed the topic of line heating in the search for better control of the process. A range of different methods which help to understand the mechanism has been developed, among others beam analysis approximations, equivalent force calculation and three dimensional finite element analyses.

Ueda *et al*. (1993) proposed a similarity rule for the line heating process and derived two parameters governing the residual deformation. Their experimental results showed a limited amount of data and extrapolated those to general cases.

Ueda *et al*. (1994) investigated the development of a computer-aid process planning system for plate bending by line heating. They computed the strains using large deformation elastic finite method and decomposed strains into in-plane and bending components. They then chose regions with large in-plane strains as heating zones and selected heating directions normal to the principal strain. Their work in line heating provides relevant information for the Laser forming process design. However, their approach to heating path determination is not well explained. Further more, they did not deal with how to determine the heating conditions.

There have been many attempts to understand the mechanism of the line heating process numerically (Shin *et al*., 1995; Clausen, 1999; Ishiyama *et al*., 1999; Yu *et al*., 2001). However, none of them proved their numerical assessments by experiments and did not derive the relations from their analysis results. Furthermore, they did not deal with how to determine the heating condition.

Jang and Moon (1998), developed an algorithm to determine heating lines for plate forming by line heating method. They first calculated the lines of curvature of a prescribed surface and evaluated the points of extreme principal curvature along the lines. They then classified and grouped them based on their principal directions and distances between. The heating lines are obtained by 3 linear regressions on the grouped points. However, this method only used straight heating lines, which are inappropriate for more complicated shapes. Also, it did not address the heating condition determination.

A theory where a strip perpendicular to the heating line supported by springs represents the heated plate is developed by Moshaiov and Vorus (1987) and Moshaiov and Shin (1991). This is successfully applied to the elastic case, but when plasticity is included it is difficult to determine the spring constants.

The works of above investigators indicate that the thermal history and distortion in Line heating process is strongly affected by many parameters and by their interactions. The FE analysis carried out involves nonlinear transient thermal analysis followed by mechanical analysis. In analyzing real life structures, this method is not fully effective. Prime reason is, such analyses are extremely time consuming requiring prohibitively high number of elements and nodes for modeling. Therefore an attempt has been made in this work to develop simple equations by dimensional analysis for prediction of deformations due to Line heating. Once established the same equations can be extended to real life situations of Line heating.

2 Dimensional analysis

2.1 Basic Principals

If the numbers of variable involved in a physical phenomenon are known, then the relation among the variables can be determined by the following two methods:

1) Rayleigh's method.
2) Buckingham's Π - theorem.

Two methods have slightly different formulations, but provide the same result, in most cases. Here the Rayleigh's method (Bansal, 2007) has been used for finding out the co-relationship between input parameters and output parameters. This method is used for determining the expression for a variable which depends upon other variables. Lets X is a variable, which depends on X_1, $X_2, \cdots$, X_n variables. Then according to Rayleigh's method, X is a function of $X_1, X_2, \cdots, X_n$ and mathematically it is written as $X= f(X_1, X_2, \cdots, X_n)$. This can also be written as $X= K\cdot X_1^{a}\cdot X_2^{b}\cdots X_n^{m}$. Where, K is a constant and $(a, b, \cdots, m)$ are arbitrary powers. The values of $(a, b, \cdots, m)$ are obtained by comparing the powers of the fundamental dimensions on both sides. Thus the expression is obtained for dependent variable.

2.2 Dimensional analysis of line heating

There are many factors in the line heating process that affect the final deformation of a plate. These include torch speed, torch height above the plate surface, amount of heat flux, number of passes, material properties, heating and cooling location, heating order, dimensions of a plate, fixture conditions and initial imperfections. Environmental and human factors, such as humidity and wind at line heating workshops, and the level of a worker's skill also come into play.

A method of dimensional analysis was employed to deduce major parameters in nondimensionalized forms among many factors. The method dissolved the complexity of a phenomenon at the initial stage of investigations. If variables are properly chosen, the dimensional parameters can be used to make certain logical deductions about the phenomenon.

Application of dimensional analysis enabled the interpretation of numerical and experimental data of line heating. This section presents the functional relations between heating conditions and residual deformations.

Physical quantities involved in the line heating process can be expressed dimensionally in terms of three fundamental quantities, i.e., mass [M], length [L], and time [S], or force [F], length [L], and time [S]. In a heat transfer problem temperature is one of the main factors. The material properties, residual deformation *etc* are dependent on temperature which is represented here by [θ]. The plate undergoing line heating was assumed to have zero initial deformation. A list of the various quantities involved in line heating with their dimensions is as follows

$$\begin{gathered} T=[\theta],\quad Q=[FLS^{-1}]=[ML^2S^{-3}] \\ [q_{\max}]=[FL^{-1}S^{-1}]=[MS^{-3}] \\ [s]=[LS^{-1}],[\delta]=[L] \\ k=[FS^{-1}\theta^{-1}],[C]=[FL^{-2}\theta^{-1}] \\ [Q_0]=[F]=[MLS^{-2}] \\ [E]=[FL^{-2}]=[ML^{-1}S^{-2}] \\ [W]=[L],[l]=[L],[t]=[L] \end{gathered} \tag{1}$$

where Q the heat input rate, $C=\rho c_p$ the heat capacity per unit volume, s (m/s) the moving speed of heat source, k (W/m$\cdot$K) the heat conductivity, T (℃) is the temperature, δ the residual deflection, $Q_0=Q/s$ the heat input per unit length, $q_{\max}=Q\gamma/\pi$ (cal/s) the maximum heat input rate on surface, W the width of plate, and l the length of plate. ρ, c_p and γ represent density (kg/m^3), specific heat (J/kg$\cdot$K), and concentration coefficient of torch (W/m$^2\cdot$K), respectively. E Young's modulus, t the thickness of plate, and h the torch height from the top surface of the plate.

2.3 Dimensional analysis of temperature distribution

The temperature distribution in a plate during the line heating process depends on *k*, *C*, *h*, *Q*, *s*, *t* and the maximum surface temperature $T_{\max}$. Considering Raleigh's method, a relation of the parameters can be formulated in an exponential form

$$[T] = f[kChQtsT_{\max}] \tag{2}$$

This can also be written as

$$T = K \cdot k^a \cdot C^b \cdot h^c \cdot Q^d \cdot t^e \cdot s^f \cdot T_{\max}^g \tag{3}$$

where, *K* is a constant and (*a*, *b*, *c*, *d*, *e*, *f*, *g*) are arbitrarily powers.

The exponent must be adjusted to make the above equation dimensionally homogeneous.

$$\begin{aligned}[\theta] = K[(FS^{-1}\theta^{-1})^a \cdot (FS^{-2}\theta^{-1})^b \cdot \\ (L)^c \cdot (FLS^{-1})^d \cdot (L)^e \cdot (LS^{-1})^f \cdot (\theta)^g]\end{aligned} \tag{4}$$

The values of *a*, *b*, *c*, *d*, *e*, *f*, *g* are obtained by comparing the powers of the dimension on both sides. Hence

$$\begin{cases} F(a+b+d) = 0 \\ S(-a-d-f) = 0 \\ L(-2b+c+d+e+f) = 0 \\ \theta(-a-b+g) = 1 \end{cases} \tag{5}$$

Eq.(5) consists of four equations with seven unknowns. The system is indeterminate. Eq.(4) can be solved for the remaining four unknowns. These 4 unknowns i.e. *d*, *e*, *f* and *g* is represented by *a*, *b*, *c* as follows,

$$d = -(a+b)$$

$$e = (a+2b-c)$$

$$f = (a+d) = b$$

$$g = (1+a+b)$$

Therefore Eq.(3) becomes,

$$T = K \cdot k^a \cdot C^b \cdot h^c \cdot Q^{-(a+b)} \cdot t^{(a+2b-c)} \cdot s^b \cdot T_{\max}^{(1+a+b)} \tag{6}$$

or

$$\frac{T}{T_{\max}} = K\left[\left(\frac{ktT_{\max}}{Q}\right)^a \left(\frac{Ct^2sT_{\max}}{Q}\right)^b \left(\frac{h}{t}\right)^c\right]$$

The nondimensional parameters $T/T_{\max}$ can be expressed as

$$\frac{T}{T_{\max}} = K\left[\left(\frac{ktT_{\max}}{Q}\right)\left(\frac{Ct^2sT_{\max}}{Q}\right)\left(\frac{h}{t}\right)\right] \tag{7}$$

Eq.(7) shows nondimensional parameters for the temperature distribution due to a line heating operation. Generally the line heating residual deformation depends on heat input rate and the resulting maximum peak temperature. By keeping the constant torch height from the plate top surface the rate of heat input can be varied. Considering thermal properties for a given material under a prescribed maximum temperature and also considering a constant torch height from the plate top surface (i.e. *h*) Eq.(7) gives the following parameters as shown in below.

$$\left[\left(\frac{t}{Q}\right)\left(\frac{t^2s}{Q}\right)\left(\frac{1}{t}\right)\right] \tag{8}$$

2.4 Dimensional analysis of residual deformation

It is reasonable to treat bending and in-plane deformations separately. For a given material, deformations are affected by the plate dimension as well as heating conditions.

$$\delta = f(Q_0 l, D, W) \tag{9}$$

where, $D = Et^3/12\left(1-\nu^2\right)$ is bending rigidity of a plate and ν is Poisson's ratio. The heat input supplied to the length of heating line is $Q_0 l$. By substituting the dimensional formulae for the variables, from Eq.(9) one obtains,

$$[L] = [(FL)^a (FL)^b (L)^c] \tag{10}$$

Hence, for *F*, the following equation must be satisfied

$$a + b = 0 \tag{11}$$

Since deflection is proportional to the load and is inversely proportional to bending rigidity, therefore the exponent of *D* can be chosen as negative unity. Therefore from Eqs.(10) and (11) one obtains, *b* =−1, *a* =1, *c* =1.

Hence the dimensionless equation of residual deflection can be rearranged as given by Eq.(12).

$$\delta = f\left(\frac{Q_0 Wl}{D}\right) = f\left(\frac{QWl}{Est^3/12(1-\nu^2)}\right) \tag{12}$$

Considering unit length, for a given material Eq.(12) can be simplified as

$$\frac{\delta}{W} = f\left(\frac{Q}{st^3}\right) \tag{13}$$

The in-plane deformation can be written as

$$\delta_c = f(Q_0, D_c) \tag{14}$$

where, $D_c = Et/12\left(1-\nu^2\right)$ represents the in-plane stiffness of a plate. It should be noted that the in-plane deformation is measured for unit length and has nothing to do with the breadth of a plate. From the dimensional analysis, the following relationship can be obtained.

$$\delta_c = f\left(\frac{Q_0}{D_c}\right) = f\left(\frac{Q}{st}\right) \tag{15}$$

2.5 Major line heating parameters

Two output variables were selected are selected to describe the residual deformation of a plate due to line heating. These are the residual deformations in the direction of the heating path $\delta_y(m)$ and the residual deformations in the direction perpendicular to heating path $\delta_y(m)$. The target surface thus can be described with two deformation variables as given by Eq.(16).

$$\delta_j^{\mathrm{Res}} = \{\delta_x, \delta_y\} \qquad j = 1,2 \tag{16}$$

From Eqs.(8), (13), and (15), the variables that determine the temperature distribution and the residual distortion

$$X_i = \left\{\frac{t}{Q}, \frac{t^2 s}{Q}, \frac{1}{t}, \frac{Q}{st^3}, \frac{Q}{st}\right\} \qquad (i=1,2,\cdots,5) \tag{17}$$

Therefore, the desired functional relationship can be expressed in the following form

$$\delta_j^{\mathrm{Res}} = f_j(X_i) \tag{18}$$

where specific form of each function f_j can be determined from the result of numerical simulation and multiple regression analysis.

2.6 Functional relations of residual deformations

The fundamental relation of Eq.(18) can be expressed by the multiple linear regressions as follows.

$$\delta_j^{\mathrm{Res}} = a_{j0} + \sum_i a_{ji} X_i' \tag{19}$$

$$\begin{cases} \delta_x = a_{10} + a_{11}\dfrac{t}{Q} + a_{12}\dfrac{t^2 s}{Q} + a_{13}\dfrac{1}{t} + a_{14}\dfrac{Q}{st^3} + a_{15}\dfrac{Q}{st} \\ \delta_y = a_{20} + a_{21}\dfrac{t}{Q} + a_{22}\dfrac{t^2 s}{Q} + a_{23}\dfrac{1}{t} + a_{24}\dfrac{Q}{st^3} + a_{25}\dfrac{Q}{st} \end{cases} \tag{20}$$

The coefficient of different deformation equations can be obtained by multiple regressions analysis.

The dependent variables in Eq.(20) are the residual deformations along *X* and *Y* directions. The co-efficients (i.e. a_{10}, a_{11}, *etc*) have been calculated by multiple regression analysis.

3 Results and discussion

3.1 Prediction of residual deformations through regression analysis

After validation of a 3-D FE model comparing with the experimental results and published results (Clausen, 2001) extensive data were generated by varying the process parameters (i.e. heat input, torch speed, plate thickness). These data were used for finding out the co-efficients of residual deformation equations by regression analysis

3.1.1 Deformations along X-axis

Variations of residual deformation at location A_4 i.e.120 mm away from heating line (Fig.1) with various parameters and their trendlines of Eq.(20) are shown in Figs.2~6.

Similarly the deformations at other locations i.e. A_1, A_2 and A_3 i.e. 15 mm, 35 mm and 65 mm away from heating line were also estimated with respect to the independent variables. The regression analysis results and different coefficients of residual deformation equation for different control points are shown in Tables 1 and 2.

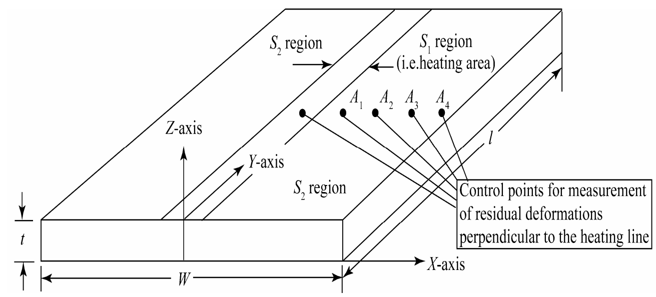

Fig.1 Control points along *X*-axis for measurement of residual deformation

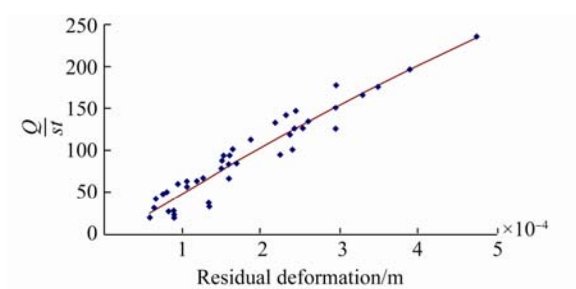

Fig.2 Residual deformation vs. parameter $\frac{Q}{st}$

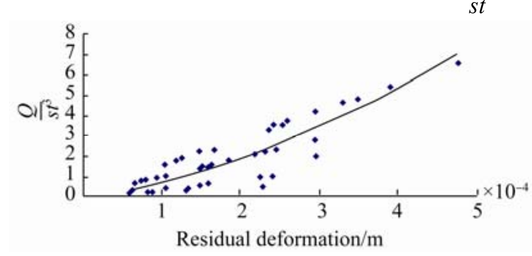

Fig.3 Residual deformation vs. parameter $\frac{Q}{st^3}$

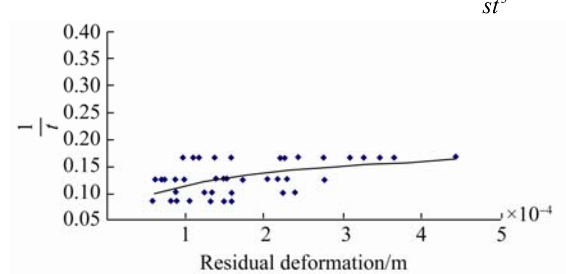

Fig.4 Residual deformation vs. parameter $\frac{1}{t}$

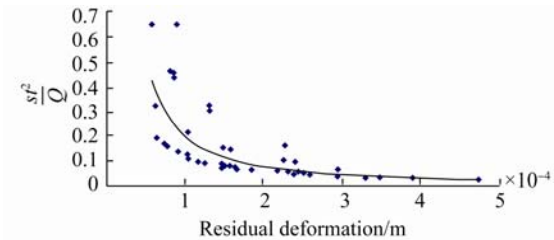

Fig.5 Residual deformation vs. parameter $\frac{t^2 s}{Q}$

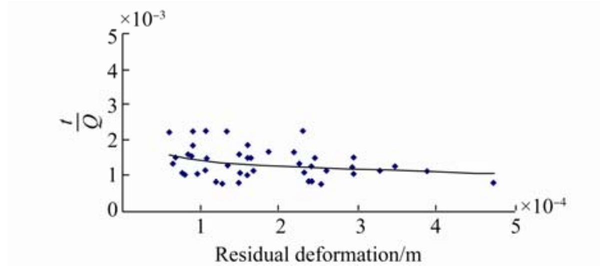

Fig.6 Residual deformation vs. parameter $\frac{t}{Q}$

Table 1 Regression statistics for various points along *X*-axis (perpendicular to the heating line)

Regression Statistics	Multiple R	R Square	Adjusted R Square	Standard Error
15 mm away from heating line	0.981 795	0.963 922	0.959 627	3.98E-06
35 mm away from heating line	0.971 299	0.943 422	0.937 135	1.21E-05
65 mm away from heating line	0.964 497	0.930 255	0.921 537	1.8E-05
120 mm away from heating line	0.965 758	0.932 688	0.924 48	2.56E-05

Table 2 Coefficients of residual deformation's equation for various points along *X*-axis (perpendicular to the heating line)

Coefficients	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
Coefficients at 15 mm away from heating line	-1.7E-5	1.173E-3	1.29E-5	9.37E-5	3.67E-6	3.14E-7
Standard error	1.14E-5	2.205E-3	9.54E-6	6.8E-5	2.27E-6	5.71E-8
Coefficients at 35 mm away from heating line	-1.4E-5	4.107E-3	1.06E-5	4.3E-5	1E-5	6.8E-7
Standard error	3.3E-5	6.464E-3	2.89E-5	1.92E-4	6.4E-6	1.69E-7
Coefficients at 65 mm away from heating line	9.23E-5	2.068E-3	-3.1E-5	-6.4E-4	3.09E-5	6.74E-7
Standard error	5.29E-5	1.027 7E-2	4.37E-5	3.12E-4	1.03E-5	2.6E-7
Coefficients at 120 mm away from heating line	2.05 E-4	5.736E-3	-7.1E-5	1.38E-3	5.06E-5	7.05E-7
Standard error	7.53E-5	1.417 2E-2	6.36E-5	4.35E-4	1.4E-5	3.7E-7

3.1.2 Deformations along Y-axis (i.e. parallel to the heating line)

Fig.7 shows the control points along *Y*-direction for estimation of residual deformations. The relationship between the residual deformation at location B_3 and independent parameters and their trendlines obtained from dimensional analysis shown in Figs.8~11.

For each control point residual the regression analysis results and the different coefficients of residual deformation equation are shown in Tables 3 and 4.

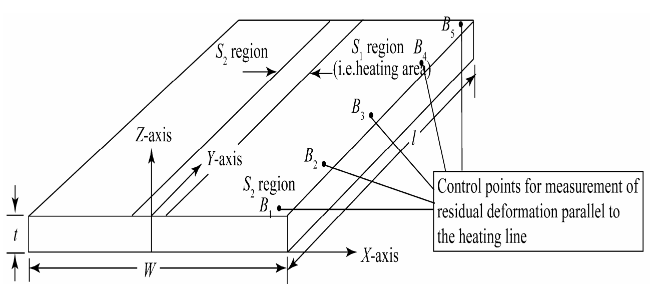

Fig.7 Control points along *Y* axis for measurement of residual deformation

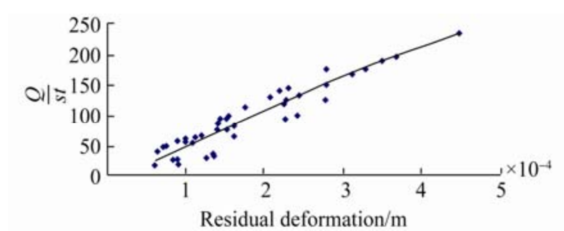

Fig.8 Residual deformation vs. parameter $\frac{Q}{st}$

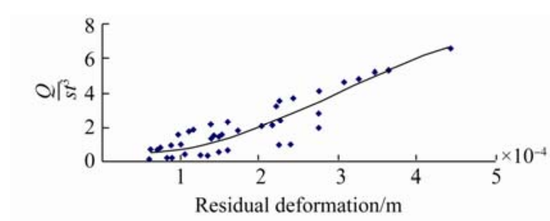

Fig.9 Residual deformation vs. parameter $\frac{Q}{st^3}$

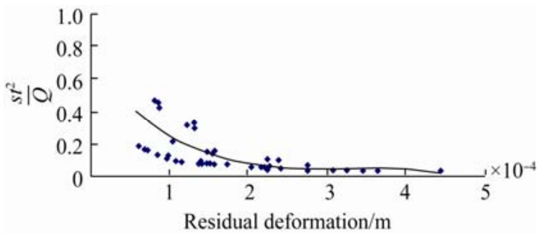

Fig.10 Residual deformation vs. parameter $\frac{t^2 s}{Q}$

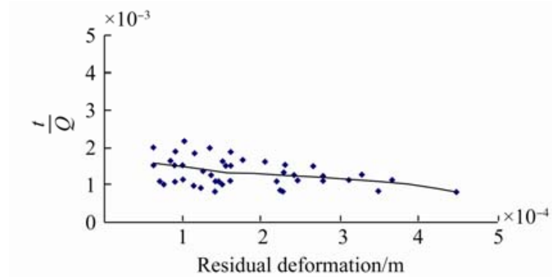

Fig.11 Residual deformation vs. parameter $\frac{t}{Q}$

Table 3 Regression statistics for various points along *Y*-axis (parallel to the heating line)

Regression statistics	Multiple R	R Square	Adjusted R Square	Standard error
B_1 (y=0 mm)	0.966 679	0.934 468	0.926 277	2.21E-05
B_2 (y=90 mm)	0.966 033	0.933 219	0.924 871	2.39E-05
B_3 (y=150 mm)	0.965 834	0.932 836	0.924 44	2.45E-05
B_4 (y=210 mm)	0.966 538	0.934 196	0.925 97	2.41E-05
B_5 (y=300 mm)	0.968 045	0.937 111	0.929 25	2.25E-05

Table 4 Coefficient of deformation equation for various points along *Y*-axis (parallel to the heating line)

Coefficients	a_{20}	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}
Coefficients at B_1 (y=0 mm) position	0.000 225	-0.010 57	-4.0E-5	-0.001 41	4.61E-5	5.39E-7
Standard Error	6.46E-05	0.0128 04	5.70E-5	0.000 374	1.21E-5	3.23E-7
Coefficients at B_2 (y=90 mm)	0.000 237	-0.011 69	-4.2E-5	-0.001 48	4.86E-5	5.92E-7
Standard Error	7.00E-05	0.013 883	6.19E-5	0.000 406	1.31E-5	3.50E-7
Coefficients at B_3 (y=150 mm)	0.000 239	-0.011 42	-4.2E-5	-0.001 49	4.91E-5	6.18E-7
Standard Error	7.18E-5	0.014 227	6.34E-5	0.000 416	1.34E-5	3.59E-7
Coefficients at B_4 (y=210 mm)	0.000 234	-0.010 69	-4.2E-5	-0.001 47	4.85E-5	6.24E-7
Standard Error	7.06E-05	0.013 997	6.24E-5	0.000 409	1.32E-5	3.53E-7
Coefficients at B_5 (y=300 mm)	0.000 219	-0.008 68	-3.9E-5	-0.001 4	4.57E-5	6.17E-7
Standard Error	6.58E-05	0.013 037	5.81E-5	0.000 381	1.23E-5	3.29E-7

3.2 Comparison of deformation results

Results obtained from the developed deformation equations were compared with those of transient nonlinear elasto-plastic thermo-mechanical FE analysis (Biswas *et al*., 2007; Biswas *et al*., 2009). In FE analysis for evaluating the residual deformation pattern of a line heated plate, heat transfer analysis is first carried out to find the nodal temperatures over a time domain. Then in the second part elasto-plastic analysis is carried out using the results obtained from the heat transfer analysis as inputs. The structural analysis involved thermo-elasto-plastic material model with temperature dependent material properties incorporated into the modelling. Rate independent plasticity, Kinematic hardening together with Bilinear von Mises yield criterion was assumed in the analysis (Biswas *et al*., 2007; Biswas *et al*., 2009).

The plate thickness and line heating parameters used are shown in Table 5. The residual deformation along *X*-direction (i.e. perpendicular to the heating) is shown in Fig.12 and the residual deformation along *Y*-direction near the plate edge is shown in Fig.13.

Table 5 Plate thickness and line heating parameters

Sample No.	Plate thickness /mm	Torch speed /($mm \cdot s^{-1}$)	Heat input /W
1	12	0.6	7 245

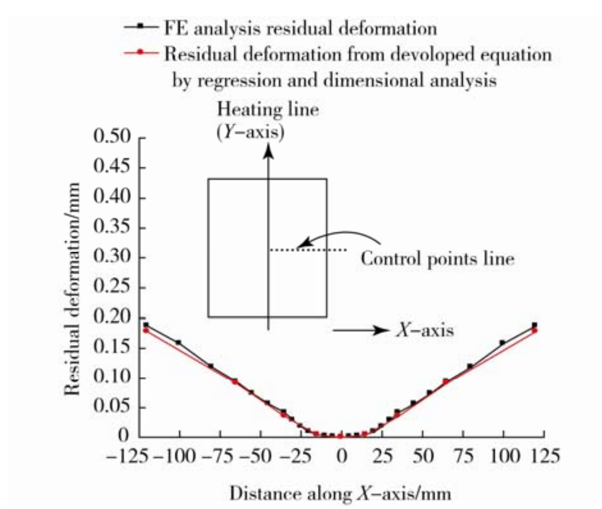

Fig.12 Residual deformation along *X*-direction

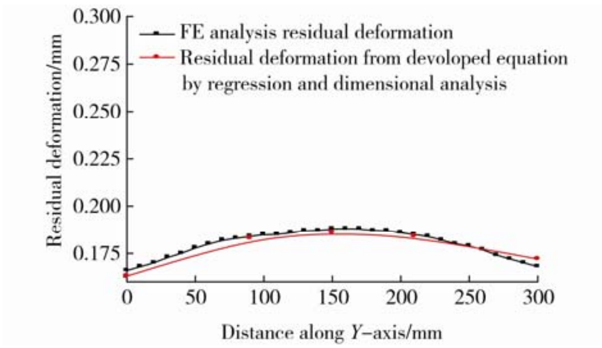

Fig.13 Residual deformation along Y-direction

Similarly, the residual deformations of pate thickness 6 mm and 8 mm obtained from the developed deformation equations were compared with those of transient nonlinear elasto-plastic thermo-mechanical FE analysis are shown in Figs.14~16. The plate thickness and line heating parameters used are shown in Table 6. The residual deformation for plate thickness 8 mm along X-direction (i.e. perpendicular to the heating) is shown in Fig.14 and the residual deformation for plate thickness 6mm along X-direction (i.e. perpendicular to the heating) is shown in Fig.15. The residual deformation for plate thickness 6 mm and 8 mm along Y-direction near the plate edge is shown in Fig.16.

Table 6 Plate thickness and line heating parameters

Sample No.	Plate thickness /mm	Torch speed /(mm·s^{-1})	Heat input /W
1	6 and 8	10	7 400

The agreements in all the cases as can be observed from Figs.12~16 were found to be excellent. Since the deformation equations were developed from a data set of plate thicknesses varying from 6mm to 12 mm with various heating conditions, these can be used for prediction of deformation within this thickness range due to line heating.

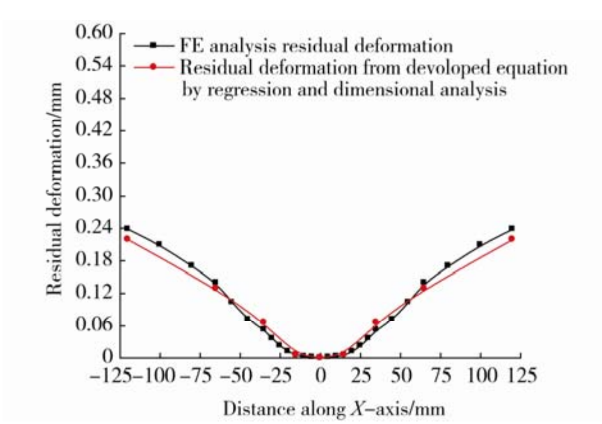

Fig.14 Residual deformation along X-direction for 8 mm thick plate

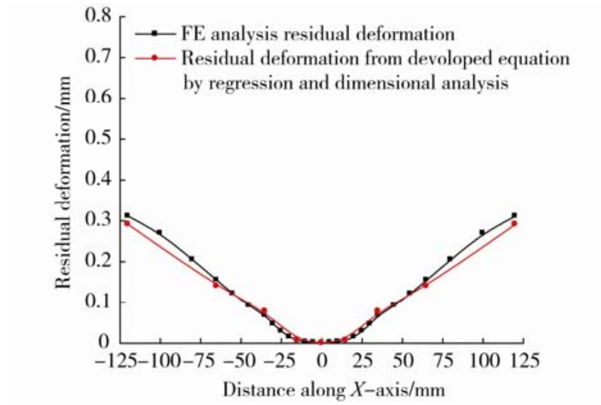

Fig.15 Residual deformation along X-direction for 6 mm thick plate

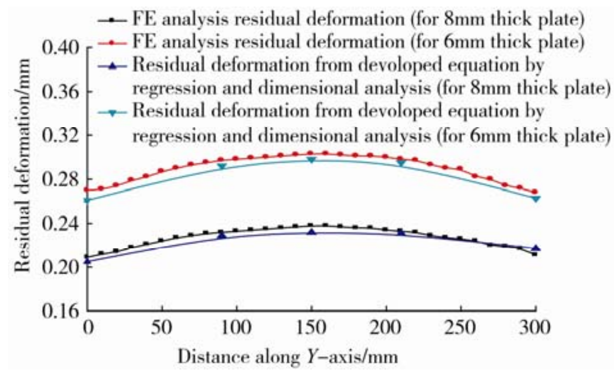

Fig.16 Residual deformation along Y-direction for 6 mm and 8mm thick plate

4 Conclusions

From the preceding investigation the following conclusions can be drawn:

1) Five nondimensional parameters affect residual deformations in line heating. Bending and in-plane deformation along and perpendicular to the heating direction are included in the formulation.

2) An explicit relationship is proposed between heating conditions and residual deformations.

3) Non dimensional formulation using Raleigh's method for prediction of different type of residual deformation has been successfully achieved.

4) For prediction of coefficients of different distortion equations Multiple Regression analysis has been successfully completed.

5) Results obtained from dimensional analysis matched fairly well with experimental results.

6) In the present investigation a simplifying methodology for line heating residual deformation prediction was

developed which is computationally feasible and efficient method compare to the extensive numerical analysis. The computational time required for analysis of the line heating using FE transient nonlinear elastoplastic thermomechanical analysis is around 7 200 second to 9 000 seconds and where the time required for getting the residual deformation by developed methodology is only 60 to 90 seconds.

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Pankaj Biswas was born in 1979. He is a research associate of IIT Kharagpur, Dept. of OE&NA. His current research interests include welding and ship production, line heating, structural analysis, *etc*.

Nisith Ranjan Mandal was born in 1954. He is a professor of IIT Kharagpur, Dept. of OE&NA. His current research interests include ship production, ship design, line heating, Welding distortion of large stiffened structures and welding techniques, *etc*.

Om Prakash Sha was born 1958. He is a professor of IIT Kharagpur, Dept. of OE&NA. His current research interests include marine design and production, line heating, CAD/CAM, *etc*.