A study on an efficient prediction of welding deformation for T-joint laser welding of sandwich panel PART I : Proposal of a heat source model

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ABSTRACT: *The use of I-Core sandwich panel has increased in cruise ship deck structure since it can provide similar bending strength with conventional stiffened plate while keeping lighter weight and lower web height. However, due to its thin plate thickness, i.e. about 4~6 mm at most, it is assembled by high power CO₂ laser welding to minimize the welding deformation. This research proposes a volumetric heat source model for T-joint of the I-Core sandwich panel and a method to use shell element model for a thermal elasto-plastic analysis to predict welding deformation. This paper, Part I, focuses on the heat source model. A circular cone type heat source model is newly suggested in heat transfer analysis to realize similar melting zone with that observed in experiment. An additional suggestion is made to consider negative defocus, which is commonly applied in T-joint laser welding since it can provide deeper penetration than zero defocus. The proposed heat source is also verified through 3D thermal elasto-plastic analysis to compare welding deformation with experimental results. A parametric study for different welding speeds, defocus values, and welding powers is performed to investigate the effect on the melting zone and welding deformation. In Part II, focuses on the proposed method to employ shell element model to predict welding deformation in thermal elasto-plastic analysis instead of solid element model.*

KEY WORDS: Sandwich panel; Laser welding; Heat transfer analysis; Thermal elasto-plastic analysis.

INTRODUCTION

Application of sandwich panel has been recently increasing in shipbuilding. The sandwich panel have proven to have many advantages over traditional plates; low weight, modular prefabrication, decrease of labor demand. The panels are used in production of walls, decks, bulkheads, staircases and deckhouses on the ships. One of the popular uses is a vehicle deck in RoPax vessel or an upper deck in cruise ship due to the merits of ship stability, crashworthiness and noise & vibration. I-core sandwich panel is composed of two face sheet plates and web plates (called cores) welded perpendicular to the face sheet plates as depicted in Fig. 1. CO₂ laser welding is utilized for welding web plates to face sheet plates due to its merits of narrow heat affected zone, small welding deformation, and deep penetration capability. However, even if CO₂ laser welding induces less welding deformation than other conventional welding methods, the deformation level is still not negligible in the sandwich panel assembled by quite thin plates of 3-5 mm thickness.

Fig. 1 Shape of I-core sandwich panel.

Web plate is welded to face sheet plate by shooting laser on the face sheet plate at the joint of the face sheet plate and the web plate. The laser penetrates the face sheet plate and reaches upper part of the web plate and the molten zone joins as it cools down. The area where heat energy is imposed is completely different from fillet welding using conventional arc welding method. The resultant welding deformation is much less than the fillet welding due to smaller heat input. Fig. 2 simply shows the procedure of making I-core sandwich panel with one core.

Fig. 2 Process of sandwich panel production with laser welding.

Assumption of a proper heat source in a thermal elasto-plastic analysis is essential to the correct prediction of welding deformation. Meanwhile, researches on the heat source model of laser welding has been focused on only butt welding and any model for T-joint has not been reported. Existing researches on laser welding can be divided into two groups. One is related to the estimation of keyhole shape formed during the welding process and the other one is the assumption of heat source model. As representative studies on the estimation of keyhole shape, Cho and Na (2006) employed a ray-tracing method and Pablo and Guillermo (1997) took into account ever-changing shape which seems to 'hook' according to laser processing of materials. In order to observe transient keyhole shape inside the material, a few methods were suggested (Bardin et al., 2005; Arata et al., 1976; Jin et al., 2002). The initial research of laser heat source is limited to the assumption of line heat source through material depth (Rosental, 1941; Swift-Hook and Gick, 1973). Because of the difficulty in observing how deeply the material is penetrated, those researches could not consider the changes of penetration depth versus heat source power and welding velocity. As efforts to predict the shape of heat affected zone, 2D heat flux equations for low power welding have been proposed (Mazumder and Steen, 1980; Zacharia et al., 1989). However, such a 2D Gaussian distribution heat source model cannot appropriately represent deep penetration of high power heat source. As an improvement, Lee et al. (2005) proposed heat source with laminated Gaussian distribution. It also has deficiency in developing a correct temperature gradient through thickness. Additionally these heat sources don't provide any consideration of defocus effect.

This study proposes a simple volumetric heat source model of laser welding for I-core sandwich including the defocus phenomenon. For a verification of the proposed model, heat transfer analysis and thermal elasto-plastic analysis using solid element model are performed to investigate heat distribution in the thickness direction and the resultant welding deformation, respectively. Both analysis results are compared with experimental results for heat transfer analysis and thermal elasto-plastic analysis. A parametric study for different laser powers, welding speeds, and defocus values is carried out to identify their influences on welding deformation and melting zone size through a series of heat transfer analyses and thermal-elasto plastic analysis. The melting zone size can be used as an indicator of weldability of the T-joint. This study utilizes commercial finite element analysis program, ANSYS version 13.0.

PROPOSAL OF HEAT SOURCE

Keyhole phenomenon occurred by laser welding

Keyhole phenomenon which is shown Fig. 3 is one of main characteristics of the laser welding. When power density of

laser welding is over 10^5 W/cm^2 (Lee et al., 2005), keyhole-shaped zone composed of vaporized material and plasma starts to form by vapor pressure. The temperature of plasma is known to be over $3,500^\circ\text{C}$. This zone plays a role of transferring the laser energy into the deep area of the vertical web plate. This cone-shaped keyhole induces multiple-reflection effect which leads to high welding efficiency. Multi-reflection effect is a phenomenon that most laser beam reflecting perpendicular to incidence angle remains inside keyhole.

Fig. 3 Laser welding and keyhole phenomenon.

Volumetric heat source model considering defocus

The principle of laser welding is concentrating the light through the focusing lens to get a high dense heat source to increase the material temperature. After melting and vaporization of the material, the keyhole phenomenon occurs and vapor pressure maintains keyhole volume as mentioned before. It is known that it takes just dozens of micro seconds for keyhole to form due to high power of CO_2 laser welding. Because keyhole exists as a heat source which propagates heat to surrounding inside the material, and keyhole is defined as the laser welding heat source of T-joint structure in this paper. Detail content will be presented later. Following Fig. 4(a) shows the principal of laser welding and mechanism of keyhole creation.

Another thing to be taken into account in the heat source is defocus. A negative defocus enables deeper penetration of laser as shown Fig. 4(b). There are important factors to be considered in laser welding process. Defocus is one of those factors and it also needs to be taken into account in the assumption of welding heat source. The defocus is defined as the location of laser beam waist from the top surface welding material. For instance, if defocus is $+1 \text{ mm}$, the beam waist is located above the base material at a distance of 1 mm and if 0 mm , it is on the top surface of material. If the defocus has minus value, the beam waist is located inside the material.

In this study, dimension of keyhole is determined from experimental results and laser energy input to volume of determined keyhole. When the defocus is 0 mm , the shape of keyhole is assumed triangular prism and defined by two variables: radius ($= R_0$) and depth ($= D_0$) as shown in Fig. 4(a). The radius is the laser radius at the beam waist and depth is assumed to be equal to the value of penetration depth (Lee et al., 2005) i.e. melting depth. In this experiment, the radius of beam waist is 0.5 mm .

Fig. 5 shows welding sections with different defocus values. The figures show the cutting section after some inspection called macrocosm testing. The relatively dark part in the material is the melting part where the temperature is over 1500°C . The power of laser welding is 8.9 kW and its speed is 4 m/min . As shown in Fig. 5, the melting area is strongly dependent on defocus value. Negative defocus leads deeper penetration.

Fig. 4 Defocus of laser welding.

Fig. 5 Experimental results for different defocus values.

Most of existing laser welding heat source models have been developed for butt welding where the negative defocusing is not necessary. This study proposes an additional assumption to incorporate the negative defocus into the volumetric heat source model as shown in Fig. 6. It shows how to extend the proposed heat source model considering the negative defocus. In the proposed method, when defocus is zero, the heat source is assumed as a circular cone whose radius is R_0 , and depth is D_0 . When defocus ($= D_{df}$) is given, the radius of heat source ($= R_1$) is defined in the following formula.

Fig. 6 Extension of the proposed heat source for negative defocus.

$$R_1 = \left| R_0 - \frac{(R_f - R_0)}{L_f} \times D_{df} \right| \quad (1)$$

where, R_1 : Radius of heat source for negative defocus.

R_0 : Radius of heat source for zero defocus (= Radius of laser beam waist = 0.5 mm).

R_f : Radius of focusing lens (= 15.5 mm).

L_f : Focal length (= 150 mm).

Penetration depth is determined from experiment results. Fig. 7 displays penetration depth versus welding speed for two laser power cases. Depth of molten zone is reported to be the same as depth of keyhole and it is also assumed to be equal to the value of penetration depth and melting depth. Experiment is performed to investigate the depth of molten zone with varying the welding speed.

Fig. 7 Experimental results for determination of depth of heat source.

Regression formulas for the depth of heat source for zero defocus ($= D_0$) versus welding speed ($= V_{weld}$) are suggested for power of 6.0 kW ($D_{0,6.0kW}$) and 8.9 kW ($D_{0,8.9kW}$), respectively as follows.

$$D_{0,6.0kW} = 9.7752 \times V_{weld}^{-0.689} \quad (2)$$

$$D_{0,8.9kW} = 16.772 \times V_{weld}^{-0.793}$$

From the above-defined D_0 , the depth heat source for negative defocus (D_1) can be simply calculated as the following formula.

$$D_1 = D_0 - D_{df} \quad (3)$$

Power density of the proposed heat source model

Laser heat energy multiplied by total welding efficiency ($= \eta$) is uniformly distributed over the keyhole volume. Here, total welding efficiency of 0.5 is assumed since it has been used for typical laser welding (Lee et al., 2005). This volumetric heat source distribution is assumed to be developed right after material inside keyhole changes into plasma condition. The keyhole forming process can be skipped since it happens in tens of micro seconds. The duration can be regarded nearly instantaneous compared to the time required for structural deformation induced by the heat load around the keyhole.

The power density (Q) can be defined as

$$Q = \frac{\eta \cdot P}{V} \quad (4)$$

P is the power of welding and V is the volume of heat source. When defocus is 0 mm, V is

$$V_{defocus=0} = \frac{1}{3} \pi R_0^2 D_0 \quad (5)$$

When defocus is negative, V is

$$V_{defocus \neq 0} = \frac{1}{3} \pi \left\{ R_1^2 D'_1 - R_0^2 \left(D'_1 - |D_{df}| \right) + R_0^2 D_0 \right\} \quad (6)$$

where, $D'_1 = |D_{df}| \left(1 + \frac{R_0}{R_1 - R_0} \right)$

As illustrated in Fig. 8, D'_1 is the depth of the circular cone of which base radius is R_1 .

Fig. 8 Definition of D'_1 value.

VERIFICATION OF PROPOSED HEAT SOURCE THROUGH HEAT TRANSFER ANALYSIS

In this section, the proposed heat source model is verified by comparing heat distribution on the cross section of welding joint obtained from heat source model with experiment results. For a comparative purpose, heat transfer analysis for other heat source models is also carried out.

Comparison proposed heat source with two types of Gaussian distributed heat sources

Heat transfer analysis for zero defocus is performed for three cases summarized in Table 1.

Table 1 Three heat sources.

Case	Description
1	The proposed heat source
2	Gaussian distributed 2D heat flux
3	Gaussian distributed 3D heat flux

Case 1: The proposed volumetric heat source defined by Eq. (4) and (5).

Case 2: A 2D heat flux distribution on the surface. It has a Gaussian distribution around the center of laser beam waist.

$$P(x, y) = \frac{\eta \cdot P}{\pi \cdot r_0^2} \cdot e^{\left(-\frac{2r^2}{r_0^2}\right)} \quad (7)$$

where r_0 is the radius of laser beam waist ($=0.5 \text{ mm}$) and r is the distance from its center.

Case 3: The equation defines 3D distribution of power density. In Eq. (8), r_0 is the radius of laser beam waist and α is power density distribution factor ($=0.8$). Additionally $u(z)$ is step function and is D_0 is the depth of key hole i.e. molten zone. The same welding efficiency ($\eta=0.5$) as Case 1 and Case 2 is applied.

$$Q(x, y, z) = \frac{2\eta \cdot P}{\pi \cdot r_0^2 \cdot D_0} \cdot e^{-2r^2/r_0^2} \cdot \left(1 - \frac{\alpha \cdot z}{D_0}\right) \cdot u(z) \quad (8)$$

where, $u(z) = 1$, if $z < D_0$ and $u(z) = 0$, if $z > D_0$

Fig. 9 plots heat distribution of the proposed heat source and 3D Gaussian heat source model. The proposed heat source has constant value across the volume, but 3D Gaussian heat source model has Gaussian distribution in transverse direction and the distribution linearly decreases with the penetration depth.

(a) Proposed heat source.

(b) Gaussian distributed 3D heat flux.

Fig. 9 3D plot of the proposed heat source and Gaussian distributed 3D heat source.

Heat transfer analysis is performed for three cases. Laser power and speed are 8.9 kW and 6 m/min , respectively. The power multiplied by efficiency (ηP) is evenly distributed to nodes located inside the keyhole volume which is depicted in Fig. 9(a). That is, the power is divided by the number of the nodes and the value is applied to the nodes. The room temperature of analysis is supposed to 20°C . Fig. 10 shows the analysis results. The shaded part indicates the area of which temperature goes beyond $1,500^\circ\text{C}$. The volume of proposed heat source in Fig. 9(a) is marked black in Fig. 10(b). From these analysis results, it can be regarded that the proposed heat source model shows a good agreement with the experimental result. On the other hand the considerable difference is observed for Case 2. Case 3 also shows insufficient penetration depth.

(a) Experimental result.

(b) Case 1.

(c) Case 2.

(d) Case 3.

Fig. 10 Results of heat transfer analysis with three cases of heat source.

Heat transfer analysis using the proposed method for different defocus values

The proposed heat source model with different defocus values is verified. Four defocus values are considered: -2 mm , -1 mm , $+1\text{ mm}$ and $+2\text{ mm}$. The laser power is 8.9 kW and welding speed is 6 m/min . Fig. 11 shows the melting zone for different defocus values. As the defocus goes positive, the depth of melting zone gets smaller and the power density becomes larger. When defocus is $+2\text{ mm}$, the depth is too shallow to join the plate and the core. Thus, an application of proper negative defocus is essential for T-joint welding. The proposed heat source model is identified to also match well for different defocus values. It proves that the approach to extend the original heat source model considering the defocus is reasonable.

(a) Defocus = -2 mm . (b) Defocus = -1 mm . (c) Defocus = $+1\text{ mm}$. (d) Defocus = $+2\text{ mm}$.

Fig. 11 Results of heat transfer analysis based on four different defocus.

In Fig. 12, the experimental result and analysis result are compared by plotting three dimensions of melting zone versus defocus : width at the top of core ($= M_{wc}$), width at the top of face plate ($= M_{wf}$), and height ($= M_h$) of melting zone. On the whole, the analysis results are in good agreement with experiment results. Comparison results are shown Fig. 13 with graph.

Fig. 12 Three parameters defining melting zone.

(a) Comparison of M_{wc} .

(b) Comparison of M_{wf} .

(c) Comparison of M_h .

Fig. 13 Comparison of melting zone parameters four different defocus values.

VERIFICATION OF PROPOSED HEAT SOURCE THROUGH THERMAL ELASTO-PLASTIC ANALYSIS

This section compares welding deformation obtained from thermal elasto-plastic analysis with that from experiment. The existing heat source models as well as the proposed method are compared together.

Experimental welding conditions and Finite Element (FE) modeling

A laser welding experiment is performed for a sandwich panel composed of one face plate and four cores. Table 2 contains details of laser welding condition. Fig. 14 depicts details of model. Welding sequence and direction are shown Fig. 15.

Table 2 Laser welding condition.

Power (kW)	Velocity (m/min)	Shielding gas	Plate & core thickness (mm)	Defocus (mm)
8.9	6	He	3	-2

Fig. 14 Details of experimental model.

Fig. 15 Welding sequence and direction.

Fig. 16 shows FE model built using solid elements. The number of elements is 35,226. Temperature dependent material properties summarized by Ha (2006) are used in the analysis. All translational degrees of freedom of nodes located at the center are restrained as shown in Figs. 16 and 17 depicts deformed sandwich panel after the welding. Four edges are deflected upward slightly.

Fig. 16 Boundary conditions for thermal elasto-plastic analysis.

Fig. 17 Welded sandwich panel.

Results of thermal elasto-plastic analysis

Beside the proposed heat source model, additional analyses with Gaussian distributed 3D heat source models addressed in the previous section are performed. Heat source models of three cases are defined in Table 3. Original Gaussian distributed 3D heat source model doesn't include the defocus effect, that is, the model is applicable only to zero defocus. However, this study applied the same approach to the model for an extension of the melting zone for the negative defocus, which corresponds to Case 3 in Table 3.

Table 3 Heat sources of three cases.

Case	Description
1	Proposed heat source (defocus = -2 mm)
2	Gaussian distributed 3D heat source (defocus = 0 mm)
3	Gaussian distributed 3D heat source (defocus = -2 mm)

Case 1: Proposed heat source model defined by Eqs. (4) and (6). Depth of heat source ($=D_1$) is 6 mm, and radius at top surface ($=R_1$) is 0.7 mm.

Case 2: Gaussian distributed 3D heat source with zero defocus defined in Eq. (8). Depth of heat source ($= D_0$) is assumed 4 mm and radius at top surface ($= R_0$) is 0.5 mm.

Case 3: Gaussian distributed 3D heat source with defocus of -2 mm. The same formula as Case 2 is employed with increased depth ($= D_1$) of 6 mm and radius ($= R_1$) of 0.7 mm.

Fig. 18 Thermal elasto-plastic analysis results of three different heat sources.

Fig. 18 shows distribution plots of vertical deflection obtained from three analysis results. Vertical welding deflections along four lines are compared with experiment result as depicted Fig. 19. ‘Proposed HS’, ‘Gaussian Df0’ and ‘Gaussian Df-2’ indicate Case 1, Case 2 and Case 3 respectively.

Fig. 19 Comparison of vertical welding deformations for a verification of the proposed heat source model.

On the whole, Case 1 and Case 3 show a good agreement with experiment result. As identified in Fig. 10, two cases provide similar temperature distribution at the cross section of welding joint, especially at face plate zone. This leads to similar welding

deformation of the face plate. On the other hand, Case 2 shows a big difference with experimental result and it is due to not consideration of negative defocus. Case 3 provides a good prediction of welding deformation, however, it has a limitation in estimating weldability since there is considerable difference in the melting zone resulted from heat transfer analysis differently from Case 1.

PARAMETRIC STUDY OF LASER WELDING CONDITIONS

Definition of the parametric study

The melting zone size is a crucial indicator to judge whether the plate and the core plate is correctly welded or not. As the laser power is raised and the welding speed is lowered, the resultant welding zone gets deeper and wider, that is, welding quality becomes better. However, it can cause larger welding distortion due to excessive heat energy applied to the welding trajectory. Thus, it is necessary to identify the effects of each parameter of welding condition, such as laser power, welding speed, and defocus value, on the melting zone and welding deformation. It is also expected to find out an optimal welding condition in terms of weldability and welding deformation.

In the above sections, it is identified that melting zone size and welding deformation can be accurately predicted using the suggested heat source model. Therefore, it is expected to utilize the proposed heat source model for the above-mentioned exploration. A parametric study is conducted for three welding parameters, i.e. laser power, welding speed and defocus value. The values of the parameters are summarized in Table 4 and total 48 cases are treated. Fig. 20 shows the FE model used in the parametric study. The width of melting zone at the top core ($=M_{wc}$) obtained from heat transfer analysis is selected as an indicator of the weldability since it determines the width of connecting area between the face plate and core plate. Welding deformation is quantified by the maximum deformation at the edge of the plate.

Table 4 Summary of values of parameters to be explored.

Welding parameter	Values
Laser power (kW)	4.5, 6.0, 7.5, 8.9
Welding speed (m/min)	2, 4, 6, 8
Defocus (mm)	-2, -1, 0

Fig. 20 FE Model of parametric study.

Results of parametric study

Heat transfer analysis and thermal elasto-plastic analysis are performed for the above-defined total sixteen (16) cases with zero defocus value. Fig. 21 shows plots of the width of melting zone (M_{wc}) at the core plate versus laser welding power and

welding speed. It is observed that the width becomes larger as the welding power increases and the welding speed decreases. For lower welding power and higher welding speeds, the width has zero value, which means the melting zone doesn't reach to the top of core due to low applied heat energy. From this result, it can be identified that the weld ability can be improved by raising laser power and lowering welding speed.

Fig. 21 Lots of melting zone width (M_{wc}) versus (a) laser power and (b) welding speed.

The maximum welding deformations at the edge of the face plate obtained from a thermal elasto-plastic analysis are plotted over different laser powers and welding speeds in Fig. 22. Here, this calculation is made only for 2 m/min and 4 m/min of welding speed since the melting zone doesn't reach the top of core plate for the other two speeds. The welding distortion grows as the welding power gets higher and welding speed lower. This can be explained by the fact that the more the heat energy is applied to unit welding length, the larger welding distortion results in.

Fig. 22 Welding deformation according to welding power and welding speed.

The effect of welding power and speed on melting zone is identified while the effect of the defocus is relatively small. A new criterion, energy per unit length, is suggested to take into account the combined effect of two parameters.

$$\text{Energy per unit length (J/m)} = \text{Power (J/s)} / \text{Welding speed (m/s)}$$

In Table 5, energy per unit length is calculated for each case and listed in descending order. The width of welding zone at the top of core and the welding deformation can be plotted over the energy per unit length in Fig. 23 and Fig. 24, respectively. The results of different defocus values are plotted together. M_{wc} is observed to be proportional to energy per unit length. This means the energy per unit length can be a good criterion to judge weldability between the core and the face plate and the welding distortion. The effect of defocus on the M_{wc} is relatively smaller than the other two parameters.

Table 5 Energy per unit length for each case.

Power (kW)	Speed (m/min)	Energy per unit length (J/m)
8.9	2	267.0
7.5	2	225.0
6.0	2	180.0
8.9	4	133.5
7.5	4	112.5
6.0	4	90.0
8.9	6	89.0
7.5	6	75.0
4.5	4	67.5
8.9	8	66.8
6.0	6	60.0
7.5	8	56.3
4.5	6	45.0
6.0	8	45.0
4.5	8	33.8

Fig. 23 Melting zone width of M_{wc} according to energy per unit length.

Fig. 24 Welding deformation according to energy per unit length.

Fig. 25 Low welding deformation according to weldability.

The correlation between the weldability and the level of flatness can be identified by collecting M_{wc} and welding deformation in a graph as depicted in Fig. 25. Here, weldability is represented by M_{wc} and the level of flatness by the reciprocal of the maximum deformation at the plate edge. Two are identified to have conflicting relationship as expected from Figs. 23 and 24. For a good welding quality, high energy per unit length should be selected, however, it leads to large welding distortion and vice versa. Thus, the selection of laser welding condition requires a proper compromise between the weldability and the welding deformation.

CONCLUSION

The method and important findings of this paper can be summarized as follows.

- First, a circular cone shaped volumetric heat source model is proposed for a laser welding of T-joint. Depth of the circular cone is measured from an experiment and the radius of the base is assumed to be the radius of beam waist. The model is extended to consider negative defocus which is essential to the T-joint welding. Heat transfer analysis is performed for various cases and the resultant melting zones are compared with experiment results. Compared to other existing methods developed for butt welding, the proposed volumetric heat source provides the most satisfying results.
- Second, thermal elasto-plastic analysis is carried out using the proposed heat source model and vertical welding deformation is compared with experimental results for further verification. Additional assumption is suggested to consider negative defocus. The resultant welding deformation coincides well with experimental results.
- Third, a parametric study to investigate the influences of laser power, welding speed and defocus values is performed. From the study, it is identified that the higher laser power and the lower welding speed leads to the wider melting zone but the larger welding deformation at the face plate edge. The relationship is well summarized when they are plotted over energy per unit length which is introduced to combine the effects of laser power and the welding speed. The defocus gives relatively little influences on the two, while it has a large effect on the height of the melting zone. It is also observed that the laser welding deformation and weldability have conflicting relationship.

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