Basic Numerical Study on Gap Influence of Residual Stress and Distortion during High-Brightness Laser Butt Welding †

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Abstract

High-brightness laser such as fiber laser or disk laser is expected to minimize the total heat input energy in welding due to its high beam quality, and the welding residual stress and distortion also seem to be reduced as a result. However, the diameter of high-brightness laser beam is less than 0.6 mm and it is difficult to set the beam position to contact face between two parts because in general there would be a gap due to quality of parts. In this study, in order to reveal the effect of gap on the residual stress and the welding distortion during fiber laser welding, the butt welding of two plates were examined through the thermal elastic-plastic analysis with a new gap element. From the result of thermal analyses, it was found that the homogeneous ellipsoid body could be applicable to model the shape of heat source for the fiber laser and the gap width would not influence the penetration shape when the gap width was changed from 0.1 to 0.25 mm. In addition, the elastic-plastic analyses indicated that the transverse shrinkage slightly increased with increasing the gap width, while this shrinkage without gap was much smaller than that with gap. Also, it was revealed that the welding speed largely affects both the welding residual stress and distortion. Moreover, it was found that the residual stress was almost independent of the jig position, while the position of fixtures slightly affected the transverse shrinkage.

KEY WORDS: (Fiber Laser), (Butt Welding), (Gap), (Thermal Elastic Plastic Finite Element Analysis), (Residual Stress), (Welding Distortion)

1. Introduction

The international thermonuclear experimental reactor (ITER) has been constructed at Cadarache in France as the world's largest experimental fusion facility in order to examine the possibility of fusion reactor as one of the future electric power generator[1,2]. Various types of test blanket module (TBM) are planned to be installed in ITER for demonstrating the engineering technologies required for utilization of fusion energy[1,3,4]. The first candidate system of the Japanese ITER-TBM is a water cooled solid breeding blanket system, where a well-perceived reduced activation ferritic/martensitic steel F82H is considered as one of the most candidate structural materials for the Japanese ITER-TBM[2,4-6]. **Figure 1** shows the schematic illustration of Japanese ITER-TBM where thickness of plates or pipes are varied from 1.0 to 90 mm and the appropriate joining methods have to be selected for each plate or pipe.

As the preliminary studies about the weldability of F82H, the butt-joined F82H produced by tungsten inert gas (TIG) welding and electron beam (EB) welding has been evaluated and it was found that EB welding seems to be preferable because the heat affected zone (HAZ) of joint was smaller so that the risk of degradation of mechanical properties would become little[2]. In addition to these ordinary joining techniques, the applicability of advanced joining methods such as high-brightness laser welding, the plasma metal inert gas (MIG) hybrid welding, and friction stir welding to F82H has been studied[7,8]. Because the recent high-power fiber laser can produce MW/mm^2 class power density similar to EB[9], the fiber laser welding is expected to minimize the total heat input energy during the welding and to reduce the

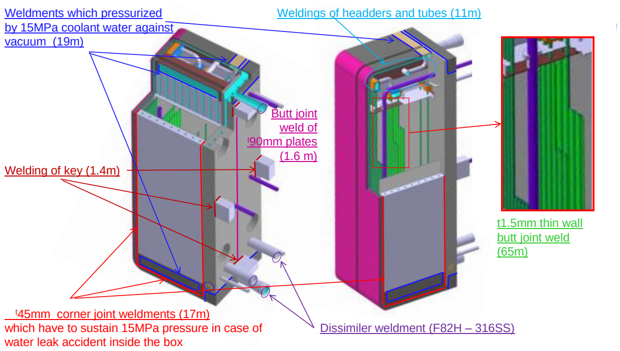

Fig. 1 Schematic illustration of Japanese ITER-TBM.

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Table 1 Experimental welding conditions of fiber laser butt welding for F82H plates.

Power (kW)	Beam Spot (mm)	GAS Flow (L/min)	Focal Length (mm)	Plate Thickness (mm)	Shift (mm)	Welding Speed (m/min)
4	0.2	40	0	4	0	3

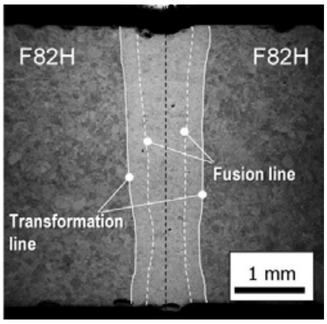
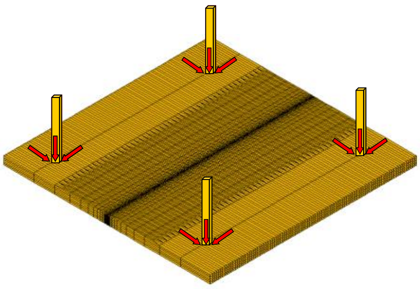
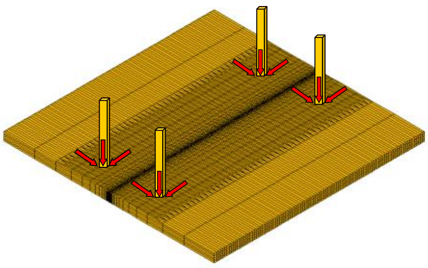


Fig. 2 Microstructural image of penetration obtained by butt welding without gap.

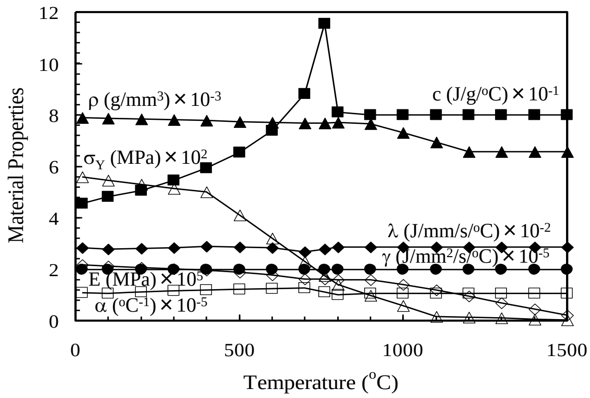


(a) Experimental mechanical boundary condition



(b) Mechanical tight boundary condition

Fig. 3 Finite element mesh and boundary conditions for but welding.



c : Specific heat	E : Young's modulus
ρ : Density	σ_Y : Yield stress
λ : Thermal conductivity	α : Thermal expansion coefficient
γ : Heat transfer coefficient	(ν : Poisson's ratio = 0.3)

Fig. 4 Temperature dependent material properties of F82H.

welding distortion and the residual stress in comparison with TIG welding. Also, the fiber laser welding can be conducted in an inert gas atmosphere although the environment of joint has to be a vacuum during the EB welding.

On the other hand, because the diameter of high-brightness laser beam is less than 0.6 mm and there would be a gap between parts due to the quality of parts, it is difficult to set the beam position to contact face between two parts during the practical butt-joint using the high-power fiber laser. In addition, although the gap between parts are generally reduced or controlled by using tack welds or jig, it is unrealistic to set a gap to zero along all the welding line of butt-joint and the gap seems to affect the welding distortion and the residual stress. So, in this research, as a basic study of gap influence on the welding residual stress and distortion of butt-joint welded by high-power fiber laser, thermal elastic-plastic finite element analyses were conducted by changing the gap width, beam position, welding speed, and position of jig. In addition, in order to demonstrate the change of gap width during the welding, a new finite element was developed.

2. Method of Analysis

2.1 Model for analysis

According to our experimental tests using 4kW fiber laser, butt welding of two plates was modeled for this analysis[10-12]. Where the size of plate was 100 mm in length, 50 mm in width and 4 mm in thickness, and the material of plates was set as F82H. In the experiment, butt welding without gap was conducted and **Fig. 2** shows the penetration shape, where the welding conditions are summarized in **Table 1**. As shown in Fig. 2, the two plates were fully penetrated through the thickness without cracks and pores. Because the diameter of fiber laser at the focal position was only 0.2 mm as shown in Table 1, the gap width was varied from 0.1 to 0.25 mm. In order to study the effect of total heat input on the welding distortion and the residual stress, the welding speed was changed from 2 to 4 m/min. In addition, the influence of beam position was studied by setting the beam to the edge of plate and changing the gap width from 0.1 to 0.3 mm. Also, as a preliminary study for the influence of jig position, the position of fixture during welding was varied. One was the condition as same as the experiment, while the fixtures were set near the weld line in another condition as shown in **Fig. 3**. The total number of elements and nodes are 56,400 and 64,230, respectively. The temperature dependent material properties of F82H were summarized in **Fig. 4**.

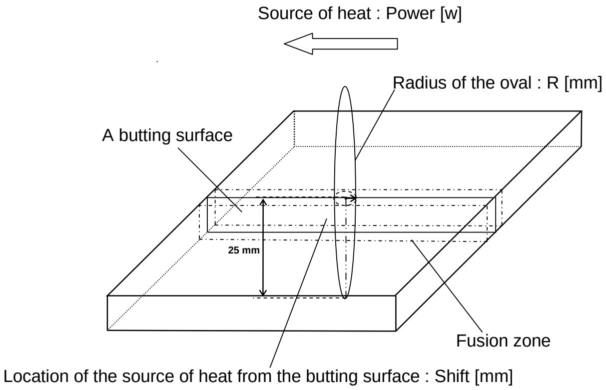


Fig. 5 Schematic illustration of ellipsoid body heat source model.

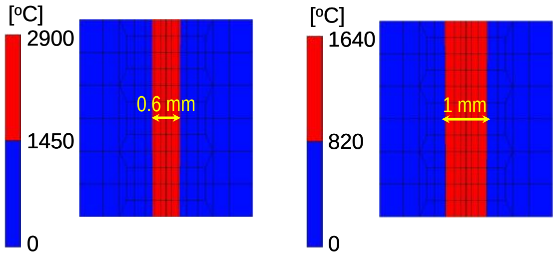
2.2 Heat source model

Recently, thermal elastic-plastic finite element analyses have been conducted in order to predict the welding residual stress and distortion[13-15], where the transient temperature histories are obtained through the thermal analysis and then the elastic-plastic analysis are conducted in general. So, in order to predict the welding residual stress and deformation precisely, the transient temperature histories have to be demonstrated accurately. However, because the temperature histories were not measured in our experiment, an appropriate heat source model was decided so that the penetration shape could be demonstrated. In this research, a volumetric heat source model, whose shape was an ellipsoid body, was employed.

2.3 Gap element

During the butt welding, the gap width between two plates seems to change before the weld heat source comes, while the distance between two plates would be fixed by the weld metal after passing the heat source. However, this distance between two plates might change before the temperature of weld metal is higher than the mechanical melting point since its rigidity is much smaller than that of plates. So, in this study, a new gap element was developed for demonstrating such change of gap width in the finite element method.

Before the weld heat comes, the elastic modulus of gap element is assumed to be much smaller than that of ordinary finite element to demonstrate the change of gap width, meanwhile the modulus of gap element changes to be much lager than that of ordinary element when the strain of gap element achieves to be -1 in order to prevent the collision of two plates. On the other hand, after passing the heat source, although the gap is considered to be filled by the weld metal, the gap width might change before cooling to the mechanical melting point. So, after cooling to the mechanical melting point, the change of gap width is prevented with the exception of thermal shrinkage. In other words, the gap element changed to be the ordinary finite element after cooling to the mechanical melting point.



(a) Weld Metal (b) Weld Metal & HAZ

Fig. 6 Maximum temperature distributions at center of weld line without gap.

3. Results and Discussions

3.1 Thermal analysis

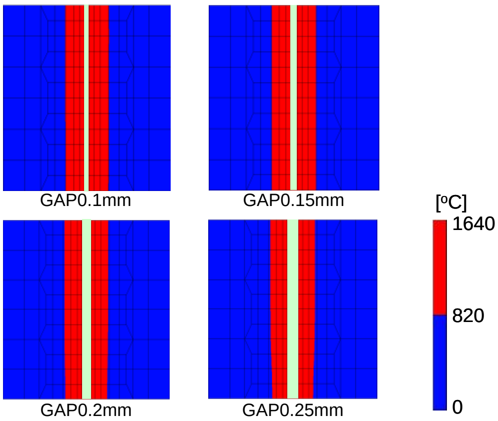
In order to estimate the penetration shape and the temperature history during the laser welding, the total heat input energy in the welding has to be precisely defined. However, since the thermal efficiency of fiber laser welding is unknown, the shape of ellipsoid body and the total heat input were decided through the serial computations. Where, the radiuses of ellipsoid body parallel and transverse to the weld line were set to be same because the shape of fiber laser spot is a circle. In addition, since the focal position of fiber laser was the specimen surface as shown in Table 1, a bottom half of ellipsoid body was selected as the heat input area and the density of heat input in ellipsoid body was assumed to be homogeneous.

From the result of serial analyses, the radius of ellipsoid body parallel to the weld line was decided to be 0.15 mm while the depth of ellipsoid body was selected as 25 mm as shown in **Fig. 5**. Also, the power of ellipsoid body was defined to be 1.5 kW. **Figure 6** shows the maximum temperature distributions at the center of weld line. Both the widths of weld metal and heat affected zone have the good agreements with the experimental result shown in Fig. 2. Then, by using this heat source model, the influence of gap width, beam position and welding speed on the penetration shape was examined. The maximum temperature distributions calculated were summarized in **Fig. 7**, where the red area indicates both weld metal and heat affected zone. In the thermal analyses, the ordinary finite elements passing through the heat source were assumed to be heated meanwhile the gap elements were not heated according to the practical laser welding without any weld wires. So, in the cases of gap width and beam position effects, the total width of red area in two plates did not change regardless of gap width. On the other hand, the width of red area increased with decreasing the welding speed because the total heat input increased.

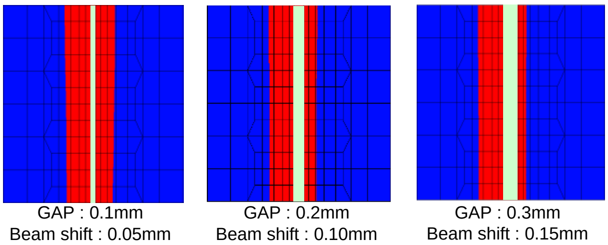
3.2 Elastic-plastic analysis

3.2.1 Effect of gap width

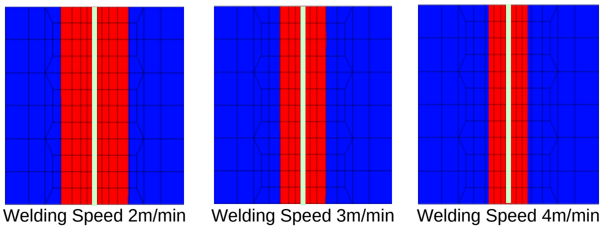
By using the transient temperature histories, the elastic-plastic analyses were conducted, where the mechanical boundary conditions demonstrating the experimental fixtures were applied. The influence of gap



(a) Influence of gap width



(b) Influence of beam position



(c) Influence of welding speed

Fig. 7 Maximum temperature distributions at center of weld line with gap.

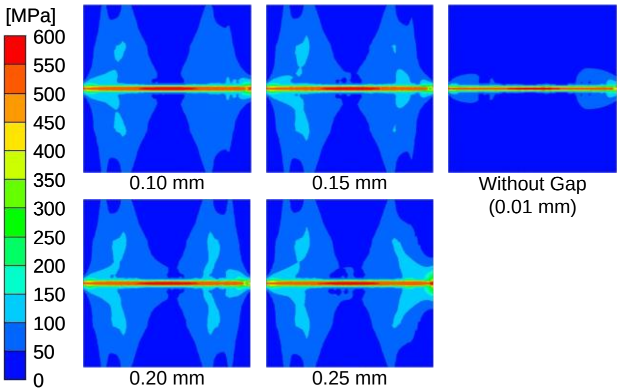


Fig. 8 Effect of gap width on von Mises residual stress before releasing fixtures.

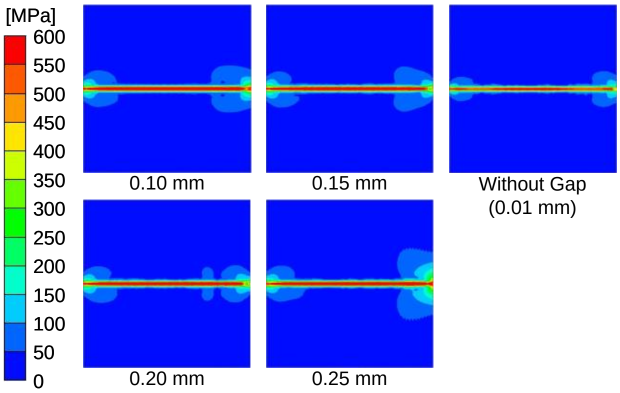


Fig. 9 Effect of gap width on von Mises residual stress after releasing fixtures.

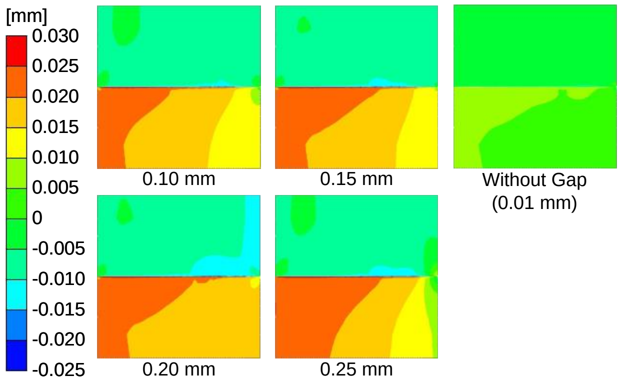


Fig. 10 Effect of gap width on transverse shrinkage after releasing fixtures.

width on the von Mises residual stress distribution is summarized in **Fig. 8**. Also, the result demonstrating without gap is shown in this figure, where a gap width was set as 0.01 mm not 0.00 mm in order to avoid the numerical instability. From this figure, it is considered that the fixtures would affect these residual distributions in the cases with the gap. So, the additional computation demonstrating the free of fixtures was conducted and the results are summarized in **Fig. 9**. This figure indicates that the von Mises residual stress seems not to be influenced by the gap width although the little differences can be seen at both beginning and ending edges. As same as the von Mises residual stress, the longitudinal and transverse residual stresses were found to be almost independent of the gap width. In addition, there were not seen any large differences between the longitudinal distributions, while the transverse shrinkage was affected by the gap as shown in **Fig. 10**. With increasing the gap width, the transverse shrinkage slightly increased, while the transverse shrinkage without gap is much smaller than that with a gap as shown in this figure. One possible reason of this difference seems to be caused by the shrinkage of gap during the welding in the cases with the gap. On the other hand, the reason why the gap width did not affect the transverse shrinkage might be caused by the fixture during the welding.

3.2.2 Effect of beam position

In the practical butt welding with fiber laser, the laser beam would be shifted from the central line to the edge of one plate in order to prevent the passing of laser beam through the gap. So, the influence of laser beam position was examined by changing the gap width where the beam position was fixed to the edge of one plate.

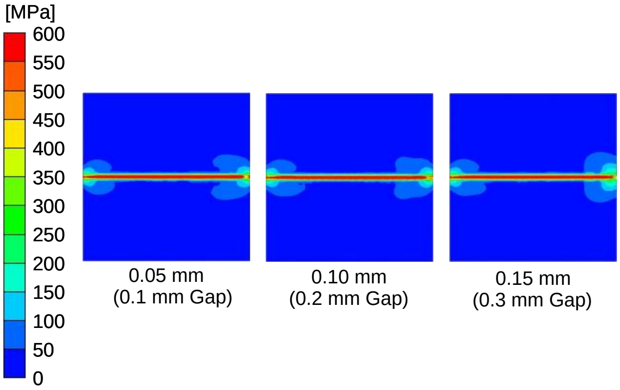


Fig. 11 Effect of beam position on von Mises residual stress after releasing fixtures.

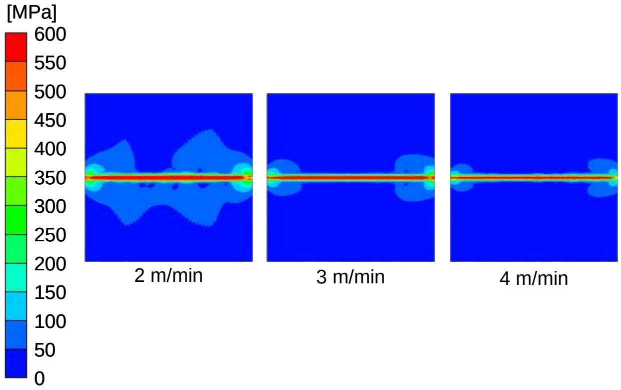


Fig. 14 Effect of welding speed on von Mises residual stress after releasing fixtures.

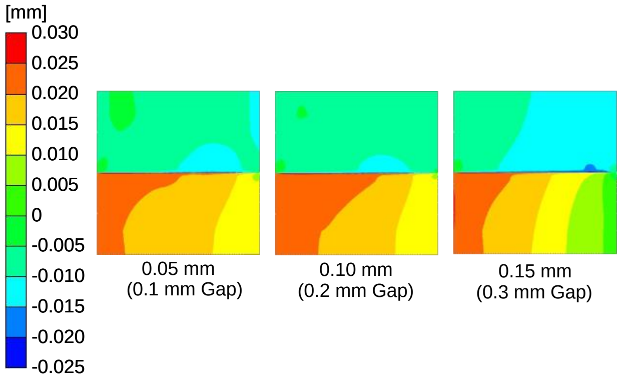


Fig. 12 Effect of beam position on transverse shrinkage after releasing fixtures.

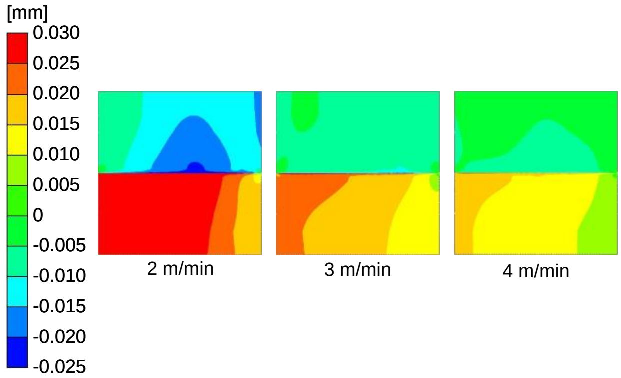


Fig. 15 Effect of welding speed on transverse shrinkage after releasing fixtures.

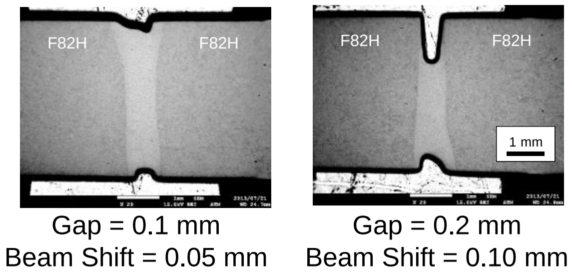


Fig. 13 Microstructural images of penetration obtained by butt welding with gap.

Figures 11 and **12** show the distributions of von Mises residual stress and transverse shrinkage in the cases with the laser beam shift after releasing the fixtures. As same as the results of gap width influence, there are not any large differences in the residual stress distributions, while the transverse shrinkage slightly increased with increasing gap width. In addition, from the comparison between Figs. 10 and 12, it was found that the laser beam position also slightly affected the transverse shrinkage. However, these figures indicated that the influence of beam position on the transverse shrinkage would be smaller than that of gap width.

Figure 13 shows the penetration shapes of laser butt welding with a gap conducted as our trial experiment where the beam position was set to the edge of plate. This figure indicates that an additional weld metal should be supplied during the welding in order to obtain the sound penetration when the gap width becomes larger than 0.2 mm. However, it was found that although the diameter of spot diameter was 0.2 mm, the good penetration in the butt welding with 0.1 mm gap can be produced by controlling the beam position precisely.

3.2.3 Effect of welding speed

The influences of welding speed on von Mises residual stress and transverse shrinkage are summarized in **Figs. 14** and **15**. With decreasing the welding speed, the residual stress increased and the large residual stress widely distributed along the weld line in the case of 2 m/min welding speed. A little difference of residual stress between 3 and 4 m/min seems to be caused by a little difference of maximum temperature distributions as shown in Fig. 7. On the other hand, the maximum temperature distributions of 2 m/min drastically changed so that the residual stress became larger. In addition, the transverse shrinkage obviously increased in the case of 2 m/min. According to the welding mechanics, the transverse shrinkage seems to increase proportionally with increasing the total heat input and the total heat input is inverse proportional to the welding speed[16]. So, the total heat input of 2 m/min is twice as large as that of 4 m/min, while that of 3 m/min is about 1.3 times as large

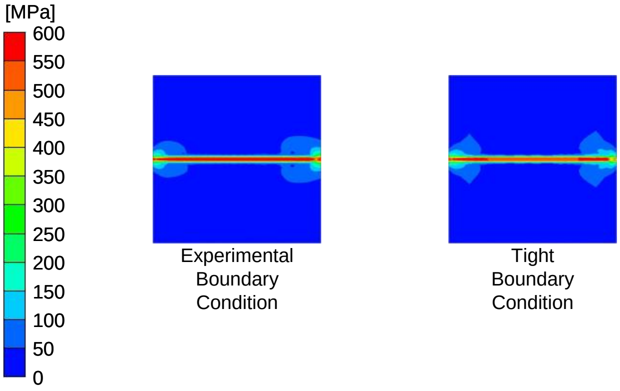


Fig. 16 Effect of jig position on von Mises residual stress after releasing fixtures.

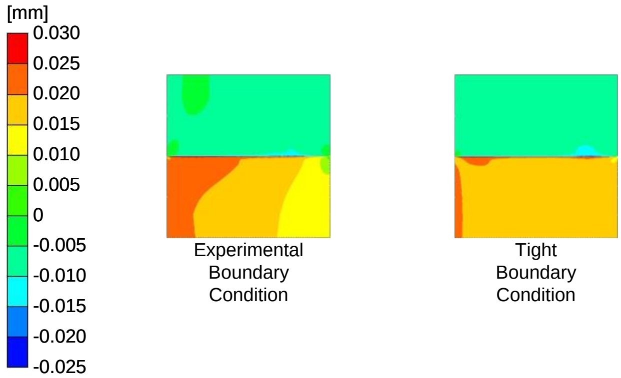


Fig. 17 Effect of jig position on transverse shrinkage after releasing fixtures.

as that of 4 m/min. However, the width of red area in 2 m/min was about 1.73 times as wide as that in 4 m/min, and that in 3 m/min was about 1.14 times as wide as that in 4 m/min as shown in Fig. 7. In addition, the total transverse shrinkage of 2 m/min, which is obtained from the difference between maximum and minimum values, was about 2.27 times as large as that of 4 m/min, and that of 3 m/min was about 1.29 times as large as that 4 m/min. Namely, the influence of welding speed on the transverse shrinkage in the butt welding of two plates with gap could not be explained by the ordinary theory of welding mechanics. Then, in order to reveal this effect, more additional experimental and numerical studies have to be needed.

3.2.4 Effect of jig position

In the practical welding process, various types of fixture are employed during the laser welding in order to control and/or to close the gap between parts. So, the influence of jig position on the welding residual stress and distortion was examined by assuming two types of mechanical boundary conditions as shown in Fig. 3. **Figures 16** and **17** show the distributions of von Mises residual stress and transverse shrinkage. From these figures, it was found that the residual stress was almost independent of the jig position, while the position of fixtures slightly affected the transverse shrinkage. In addition, by moving the fixture near the weld line, the transverse shrinkage became almost homogeneous along the weld line. So, it can be concluded that the jig position should be placed near the welding line for making the homogeneous welding deformation along the weld line.

4. Conclusions

In order to examine the gap influence of the welding residual stress and distortion during the fiber laser butt welding of two plates, the thermal elastic-plastic finite element analyses were conducted by changing the gap width, beam position, welding speed, and position of jig. The conclusions can be summarized as follows.

(1) By using the homogeneous ellipsoid body heat source model, the penetration shape of fiber laser butt welding can be demonstrated.
(2) The change of gap width during the welding can be simulated by developing a new gap element.
(3) From the serial computational results, it was found that the gap width seems to slightly affect only the transverse shrinkage under the same heat input, while this shrinkage without gap was much smaller than that with gap.
(4) The results of welding speed effect indicated that both von Mises residual stress and transverse shrinkage were influenced due to the change of total heat input.
(5) As a result of jig position influence, it was revealed that the residual stress was almost independent of the jig position, while the position of fixtures slightly affected the transverse shrinkage.

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