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Verification of Possibility for Controlling Welding Distortion Generated by Laser-Arc Hybrid Welding

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Abstract

For predicting welding distortion and residual stress generated by laser-arc hybrid welding (HYBW) with high accuracy by the 3D thermal elastic-plastic analysis based on FEM, a heat input model considering the dual heat source of HYBW was proposed. By using the proposed model, welding distortion and residual stress generated by HYBW on the general structural steel under several welding conditions, in which the heat input ratio of laser and arc were variously changed, were obtained. Comparing with the results obtained by experiments and analyses, the validity and generality of the proposed heat input model could be verified. The tendency and magnitude of welding distortion varied with the heat input ratio of laser and arc. The results indicated the possibility for controlling welding distortion generated by HYBW with the optimum heat input ratio of laser and arc.

Keywords: laser-arc hybrid welding, welding distortion, residual stress, heat input ratio, thermal elastic-plastic analysis

1. Introduction

Application of laser beam welding (LBW) has been tried as a new joining method for achieving the joints with high performance and high quality. Due to the deep penetration, the narrow bead and the high speed welding by LBW, it has been confirmed that the welding distortion and residual stress were largely improved (Inose *et al*., 2008). However, LBW requires quite severe control of the root gap of welded plates for avoiding generation of under fill (Kim *et al*., 2011a). To this problem, application of laser-arc hybrid welding (HYBW) has been investigated for improving manufacture efficiency. By supplying deposit metal by arc welding, the control of the root gap of HYBW is expected to be easier than that of LBW without deposit metal.

Because HYBW uses the dual heat source, the characteristics such as heat input and bead shape extremely differ from those of existing welding by using only laser or arc. Therefore, it is unknown how distortion and residual stress are generated by HYBW.

For predicting welding distortion and residual stress generated by HYBW with thermal elastic-plastic analysis based on FEM, a heat input model considering the dual heat source of HYBW was proposed. By using the model treating the dual heat source separately, the welding distortion and residual stress generated by HYBW on the high strength steel could be simulated with considering the phase transformation at the relatively low temperature in the cooling stage (Kim *et al*., 2011b).

In this paper, for verifying the validity and the generality of the proposed heat input model for HYBW, a series of welding experiments are carried out on the general structural steel in which the phase transformation in the cooling stage little affects the generation of welding distortion and residual stress. The experiments are simulated by the 3D thermal elastic-plastic analysis. It is examined whether the welding distortion and residual stress are accurately obtained by the proposed heat input model even if the welding conditions such as the heat input ratio of laser and arc are variously changed.

Furthermore, the possibility for controlling welding distortion generated by HYBW with the optimum heat input ratio of laser and arc is investigated.

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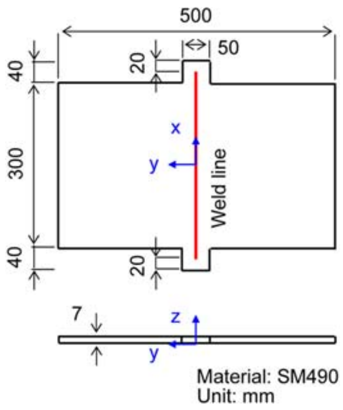


Figure 1. Test specimen.

2. Welding Experiment

2.1. Experimental procedures and specimens

Figure 1 shows the shape and dimension of the specimen.

In order to obtain distortion and residual stress generated by butt welding with high accuracy, it is necessary that a specimen is made so that a linear misalignment due to tack welding does not occur (Lee *et al.*, 2010). Therefore, welding by using dual heat source of fiber laser and CO_2 MAG arc is performed on the specimen made by one plate with I-shape slit (groove) of which the width is 0.1 mm.

The material is a general structural steel of which tensile strength is over 490 MPa (SM490). The thickness is 7mm. The filler wire used for arc welding is 490 MPa class (JIS Z 3312 YGW16). Table 1 shows the chemical compositions and the mechanical properties of the materials.

Table 2 shows the welding conditions.

One of the main objectives of this study is to verify the validity and the generality of the proposed heat input model for HYBW. For this objective, the heat input ratio of laser and arc are variously changed.

The heat input ratio of laser and arc is around 5:5 in Basic specimen. That is around 7:3 in L.E. (Laser Emphasis) specimen. That is around 3:7 in A.E. (Arc Emphasis) specimen. However, the total heat inputs by the dual heat source of these conditions are almost the same.

Thermo couples are attached to 2 points (y=15, 30 (mm)) of the upper side of the specimen (z=7 (mm)) in the center of the welding direction (x=10 (mm)) and the temperature histories are measured. Because of the size of HYBW system, the thermo couples could not be attached near the weld line (y<15(mm)).

Table 2. Welding conditions

	Energy (kW)		Heat input (J/m)			Speed (m/min)
	Laser	Arc	Q_L: Laser	Q_A: Arc	Q_T: Total	
Basic	4.8	4.4	290	265	555	1.0
L.E.	6.8	2.8	410	169	579	1.0
A.E.	2.9	6.7	173	403	576	1.0

After welding, the penetration shapes are confirmed by obtaining macrographs. They are also used for making a grid in simulating the experiment by FEM. The welding distortion is measured and residual stress is obtained by a stress relaxation method. In the stress relaxation method, the specimens are tried to be cut to the small cubic of which the edge length is around 15 mm.

2.2. Experimental results

Figure 2 shows the macrographs of the welds of each specimen. Due to the difference of the heat input ratio, the penetration shapes of the three specimens are variously changed.

The shape of the weld metal of Basic specimen is equal at the upper and lower surfaces. In the case of L.E. specimen, the weld metal at the upper surface does not rise up at all although that at the lower surface sags largely. This is because of the deep penetration by laser beam. On the other hand, the weld metal at the upper surface of A.E. specimen is extremely large. That at the lower surface is not shaped.

Figure 3 shows the welding distortion of each specimen.

The angular distortion of Basic specimen (the circular symbols in Fig. 3(a)) is V-shape. The magnitude is 0.28 mm. That of L.E. specimen (the triangle symbols) is inverted V-shape. The magnitude is 0.52 mm. In the case of A.E. specimen (the square symbols), although that is V-shape as well as Basic specimen, the magnitude is considerably large (1.9 mm).

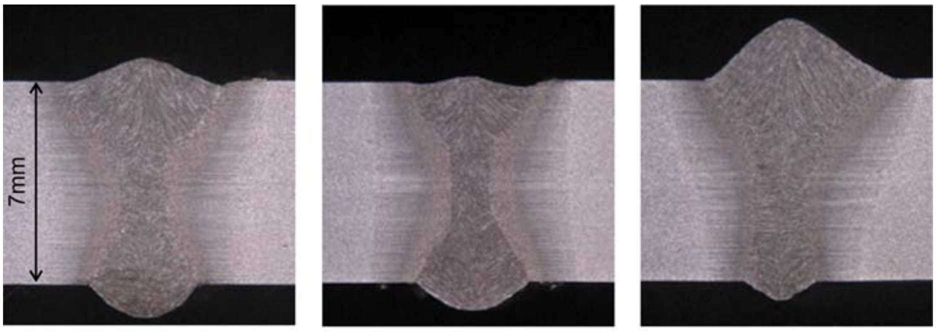
The longitudinal bending distortions of the three specimens are extremely small (Fig. 3(b)).

The angular distortion is caused by the difference of temperature between the upper and lower surfaces of the

Table 1. Chemical compositions and mechanical properties

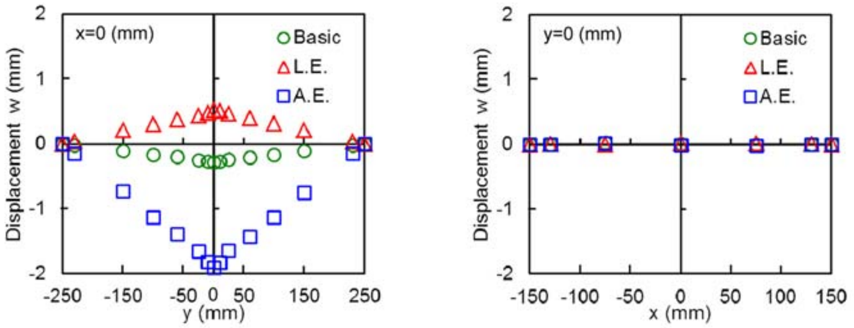
	Chemical compositions (mass%)					Mechanical properties (MPa)	
	C	Si	Mn	P	S	Yield stress	Tensile strength
Base metal	0.17	0.40	1.41	0.015	0.004	436	535
Consumable*	0.10	0.72	1.36	0.010	0.012	490	590

*catalog values (JIS Z 3312 YGW 16)



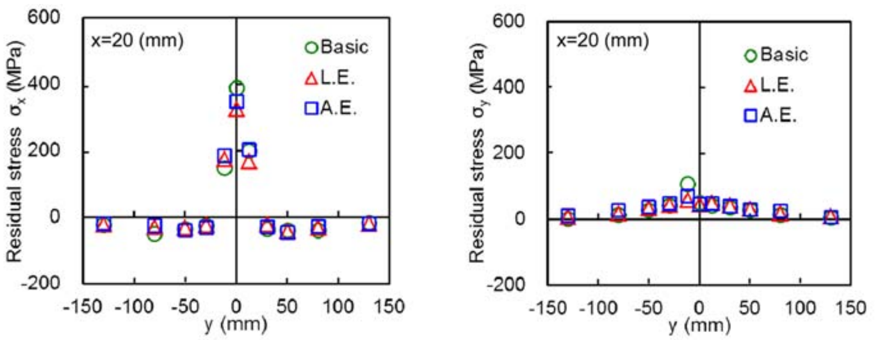
(a) Basic specimen (b) L.E. specimen (c) A.E. specimen

Figure 2. Macrographs of specimens.



(a) Angular distortion (b) Longitudinal bending distortion

Figure 3. Welding distortion obtained by experiment.



(a) Stress component along the weld line (b) Stress component perpendicular to the weld line

Figure 4. Residual stress obtained by experiment.

plates. It can be confirmed that the tendencies and the magnitudes of the angular distortions are variously changed with the heat input ratio of laser and arc.

Figure 4 shows the residual stress obtained by the stress relaxation method.

The residual stress distributions at the upper and lower surfaces are almost the same because the thickness is thin. Therefore, the stress distributions in the figures are the averages of the upper and lower surfaces. By the way, when obtaining the stress at the weld metal (y=0(mm)), the strain gages are attached after removing the weld reinforcement.

The stress component σ_x along the weld line is noted (Fig. 4(a)).

The stress distributions of the three specimens are almost the same. The tensile stress from 330 to 390 MPa is generated at the weld metal. The compressive stress from 30 to 40 MPa is generated at the base metal for balancing with the tensile stress.

The stress component σ_y perpendicular to the weld line is noted (Fig. 4(b)).

The stress distributions of the three specimens are almost the same as well as the cases of σ_x. The tensile stress at the weld metal is from 60 to 110 MPa.

It can be said that the difference of the heat input ratio of laser and arc does not affect the distributions of the

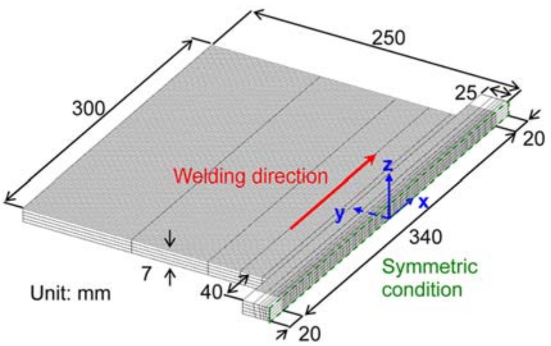


Figure 5. View of simulation model.

residual stress when the total heat input by laser and arc is almost constant.

3. Numerical Simulation of Welding Experiment

3.1. Models for simulation

The welding experiments are simulated by the 3D thermal elastic-plastic analysis.

Figure 5 shows the view of the model.

The 8-nodes solid elements are used. The half model is adopted with considering the symmetric conditions at the weld line. The heat input elements are decided by referring to the macrograph (Fig. 2) (Kim *et al.*, 2010). By the way, in FEM modelling, physical constants and mechanical properties of the materials consider temperature dependence. Specially, Young's modulus of the weld metal over 1400 degrees Celsius is made to be constant at 20 MPa (Kim *et al.*, 2007).

The heat input model for HYBW was proposed in which the dual heat source of HYBW was treated separately. It was confirmed that the welding distortion and residual stress generated by HYBW on the high strength steel could be simulated with considering the phase transformation at the relatively low temperature in the cooling stage (Kim *et al.*, 2011b). The validity and the generality of this heat input model are verified by comparing the following two types of treatment of heat input by HYBW.

Figure 6 shows the types of the heat input models.

In the case of Model A, the sum of the magnitude of heat input by laser and arc (q_T) is given inside the penetration shape. By dividing the total heat input; Q_T by the area of the weld metal, q_T is obtained. On the other hand, in the case of Model B, the penetration shapes are separated by laser and arc. This is the proposed heat input model. In each part, the magnitude of heat input by laser (q_L) and arc (q_A) are given respectively. They are obtained by dividing the heat input of laser; Q_L and arc; Q_A by the area of the weld metal of them each other.

3.2. Results of analysis

The non-steady heat conduction analysis is carried out on the three models by using the two types of the heat inputs.

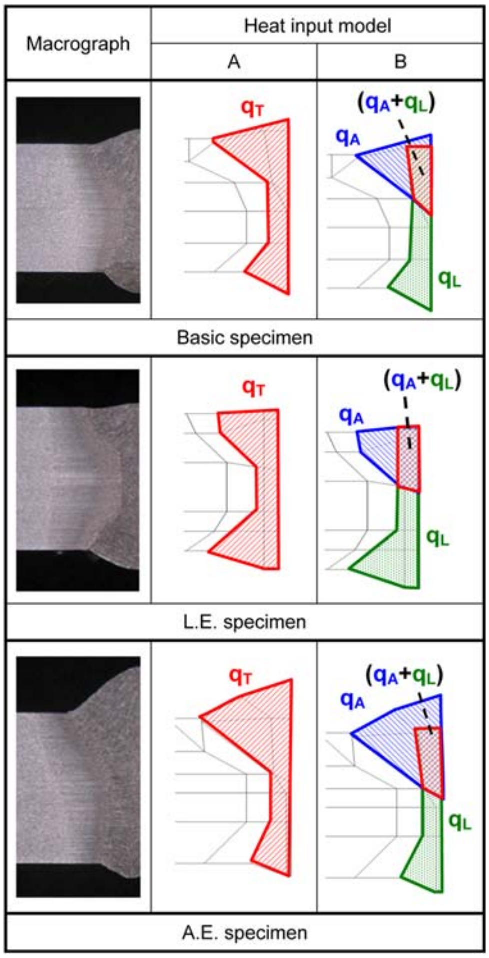


Figure 6. Heat input models.

Figure 7 shows the temperature histories.

They are measured on the upper side at the cross-section of x=10(mm). The distances from the weld line are 15 and 30 (mm), i.e., y=15 and 30 (mm). The symbols represent the results obtained by the experiment and the lines represent those obtained by the analysis.

In both cases of the heat input models A (the broken line) and B (the solid line), the temperature histories obtained by the analysis successfully agree with those by the experiment in the all specimens.

When comparing the temperature histories of the three specimens, the differences between them are small because the total heat inputs of them are almost the same.

The 3D thermal elastic-plastic stress analysis is carried out with using the temperature histories obtained by the heat conduction analysis.

Figure 8 shows angular distortion obtained by the experiment and the analysis.

The results obtained by the analysis without separating the penetration shape by laser and arc (Model A; the broken line) differ from the experimental results in the all

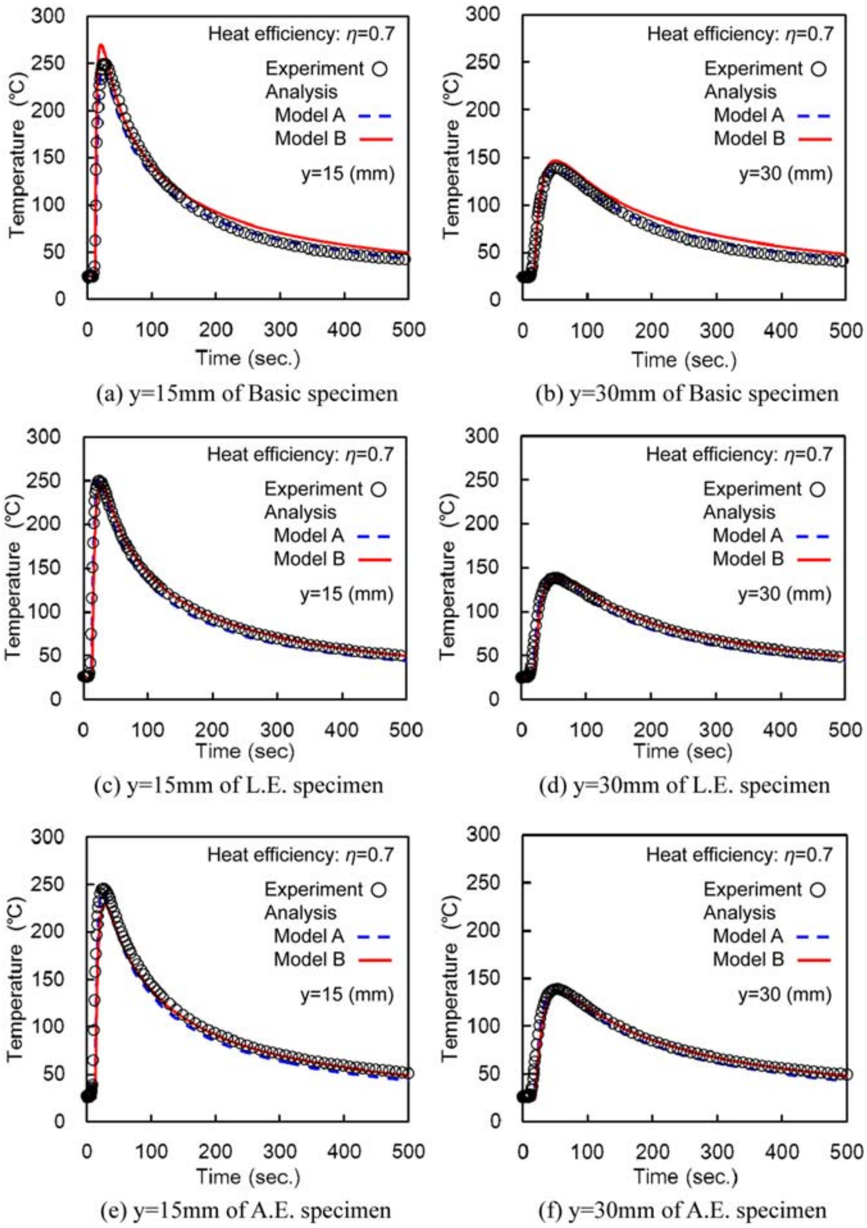


Figure 7. Temperature histories.

cases of Basic (Fig. 8(a)), L.E. (Fig. 8(b)) and A.E. (Fig. 8(c)) specimens (the circular symbols). Especially, even the tendency of the welding distortion cannot be simulated in the case of Basic specimen.

On the other hand, the results obtained by the analysis with separating the penetration shape by laser and arc (Model B; the solid line) agree with those obtained by the experiments in the all specimens.

Figure 9 shows longitudinal bending distortion of L.E. and A.E specimens obtained by using Model B.

Longitudinal bending distortion tends to be large a little comparing with that of L.E. specimen as anticipated from the macrograph (Fig. 2).

Figure 10 shows the distribution of residual stress component in the welding direction; σ_x, obtained by the experiment and the analysis.

The results obtained by the analysis without/with separating the penetration shape by laser and arc (Model A; the broken line, Model B; the solid line)) are almost the same. They agree with the experimental results in the all cases of Basic, LE. and A.E. specimens (the circular symbols).

The differences between three specimens are small because the total heat inputs of them are almost the same and specimen size (mechanical situation) is the same.

Welding distortion and residual stress generated by HYBW under several conditions could be simulated by the proposed numerical modeling of the heat input. These

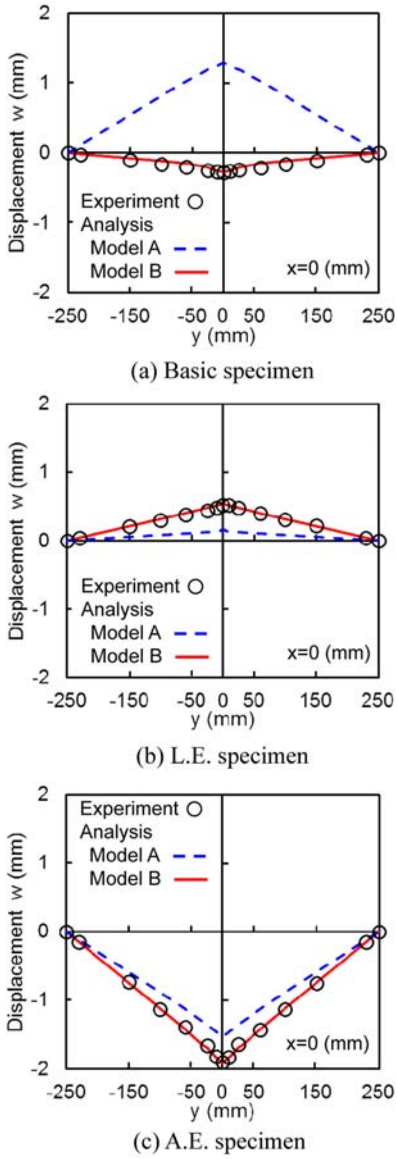


Figure 8. Angular distortion obtained by analysis.

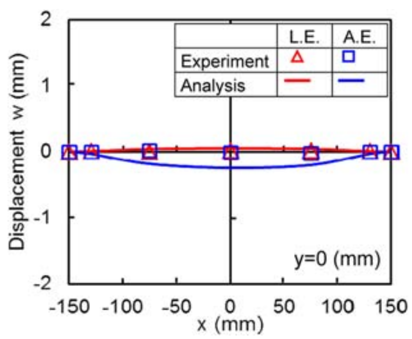


Figure 9. Longitudinal bending distortion obtained by using Model B.

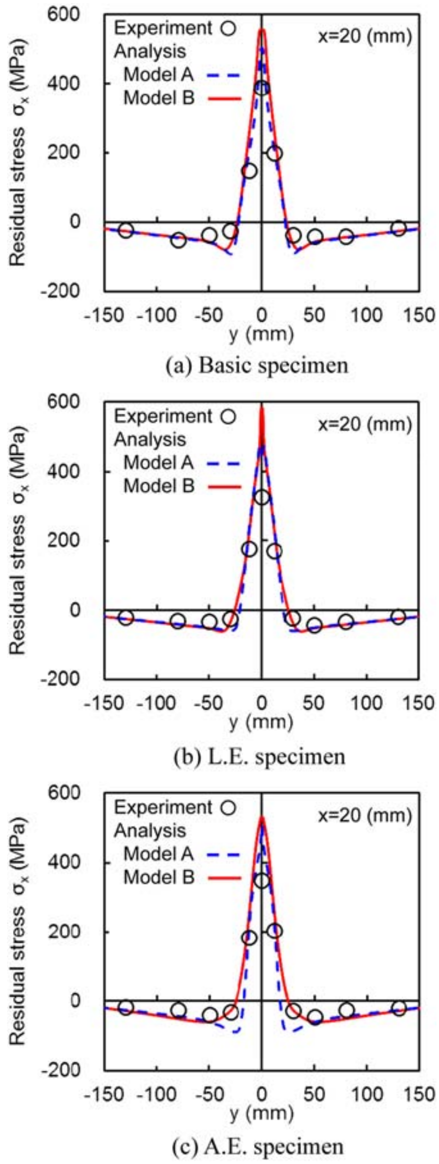


Figure 10. Residual stress component along the weld line obtained by analysis.

results indicated the validity and the generality of the proposed heat input model.

4. Possibility of Controlling Welding Distortion by HYBW

Welding distortion and residual stress are inevitably generated in constructing steel structures such as bridges, ships and so on. Welding distortion is generally corrected from the view point of the accuracy of fabrication and the appearance. Correction of welding out-of-plane distortion is one of processes not to be ignored.

In fact, from three results of the experiment and the analysis mentioned in the above section, the magnitude of angular distortion of Basic specimen (the heat input ratio of laser and arc was almost equal) and L.E. specimen (the heat input of laser was about 2.4 times larger than that of arc) is small. On the other hand, although total heat input was almost equal, the magnitude of angular distortion of A.E. specimen (the heat input of arc was about 2.3 times larger than that of laser) was large as anticipated from the macrograph (Fig. 2).

Considering from the production mechanism of welding out-of-plane distortion, a temperature gradient through the thickness largely affects it. Unless there is a temperature gradient, no welding out-of-plane distortion is generated. At any rate, if the heat input ratio is controlled so as to make a temperature gradient through the thickness as small as possible, welding out-of-plane distortion becomes small to infinity.

From the consideration above, the results of the experiment and the analysis indicated that there is a possibility that the process to correct welding out-of-plane distortion, which cannot be ignored in constructing steel structures, can be omitted by controlling the heat input ratio of laser and arc.

5. Conclusions

A series of welding experiments was carried out on the general structural steel under the several heat input ratios of laser and arc. Simulating the experiments by 3D thermal elastic-plastic analysis, the validity and the generality of the proposed heat input model for laser-arc hybrid welding were verified. Then, the possibility for controlling welding distortion was considered.

The obtained main results are as follows.

From the experimental results:

(1) Although the tendency and the magnitude of angular distortion were variously changed with the heat input ratio of laser and arc, the magnitude of longitudinal bending distortions were extremely small regardless of the heat input ratio of laser and arc.

(2) Even though the heat input ratio of laser and arc varied, the distribution and the magnitude of welding residual stress were almost the same.

From the results of the analysis:

(3) By using the heat input model treating the dual heat source by laser and arc separately, the tendency and the magnitude of angular distortion variously changed with the heat input ratio of laser and arc could be simulated with high accuracy.

(4) The magnitude of angular distortion of Basic specimen (the heat input ratio of laser and arc was almost equal) and L.E. specimen (the heat input of laser was about 2.4 times larger than that of arc) was small, and longitudinal bending distortion of two specimens was extremely small. On the other hand, the magnitude of angular distortion of A.E. specimen (the heat input of arc was about 2.3 times larger than that of laser) was large, and longitudinal bending distortion tended to be large a little.

(5) The distribution and the magnitude of the residual stress could also be simulated with high accuracy by the above heat input model. The above-mentioned results indicated the validity and the generality of the proposed heat input model.

(6) The possibility for controlling welding distortion generated by laser-arc hybrid welding was shown.

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