FATIGUE STRENGTH AND ANGULAR DISTORTION OF THE FULL-PENETRATION TEE TYPE JOINT FABRICATED BY ONE-SIDE SINGLE-PASS LASER-ARC HYBRID WELDING

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ABSTRACT

Laser-arc hybrid welding is a high-quality welding technology and is expected to improve the productivity of manufacturing hull and offshore structures. Application of this technology allows the replacement of fillet-welded joints in structures with full-penetration welded joints. The fatigue performance and deformation caused by welding will be improved by this replacement. The present study experimentally investigates the fatigue performance and deformation due to welding. Two types of tee joints, which penetrate from one side and both sides, were applied. The investigations confirm the superiority of full-penetration tee joints fabricated by laser-arc hybrid welding over conventional fillet-welded joints.

INTRODUCTION

The application of advanced welding technology is important to improving the efficiency of hull construction and to reducing production costs. Laser-arc hybrid welding technology, which has the advantages of laser and normal arc welding, provides high-quality welds and is expected to improve productivity [1, 2]. A strong advantage of laser-arc hybrid welding is its low heat input compared with current arc welding methods. Large reductions in residual welding deformation are expected when applying laser-arc hybrid welding. Such improvements will increase the productivity of hull construction and permit structural styles that reduce hull net weight.

The present study highlights the full-penetration tee-type joint fabricated by one-side single-pass laser-arc hybrid welding. This joint can replace the fillet-welded tee joint, which is widely used for ship hull structures, and improve the integrity of hull structures. However, a number of difficulties must be overcome to replace the fillet-welded tee joint by the full-penetration joint in hull structures.

1) Applicable plate thickness extension. The plate of the stiffener is expected to have thickness of at least 10~15 mm. Such plates are often used for general cargo ships. To date, applicable plate thicknesses of laser-arc hybrid welds are about 10 mm.
2) Omission of the precise treatment of groove cutting. In general, mechanical cutting is required. Thermal cuttings are suitable for groove cutting during hull construction.
3) Pure CO_2 shield gas should be applied in the place of MAG (CO_2 and argon mixed gas) to reduce the construction cost.

The present study investigates the fatigue performance and angular distortion of the full-penetration tee joint fabricated by one-side single-pass welding and confirms the superiority of such joints by comparing with fatigue-strength design curves and measured angular distortions of fillet-welded joints.

FABRICATION OF THE FULL-PENETRATION TEE JOINT BY ONE-SIDE SINGLE-PASS WELDING

Fabrication conditions

Steel with a shipbuilding grade KD36 produced by ClassNK is used for the welded joints. Plate thicknesses of the stiffener and base plate are 14 and 21 mm, respectively. The filler wire is MG-50, which is solid wire and satisfies YGW 11 of Japan Industrial Standards JIS Z 3312 [3]. The chemical compositions and mechanical properties of plate and filler wire are given in Tables 1 and 2. Other welding conditions are given in Table 3.

TABLE 1 CHEMICAL COMPOSITION OF TESTED MATERIALS [mass%]

Material	C	Si	Mn	P	S	V	Cu	Nb	Ni	Ti	Cr	Mo	Al	CE
KD36 (14 mm)	0.15	0.27	1.08	0.018	0.002	0	0.01	0.01	0.01	0.02	0.01	–	0.0027	0.33
KD36 (21 mm)	0.15	0.27	1.08	0.018	0.002	0	0.01	0.01	0.01	0.02	0.01	0	0.0027	0.33
MG-50	0.08	0.51	1.10	0.01	0.01	–	–	–	–	–	–	–	–	–

Note: CE = C + Mn / 6 + (Cu + Ni) / 15 + (Cr + Mo + V) / 5

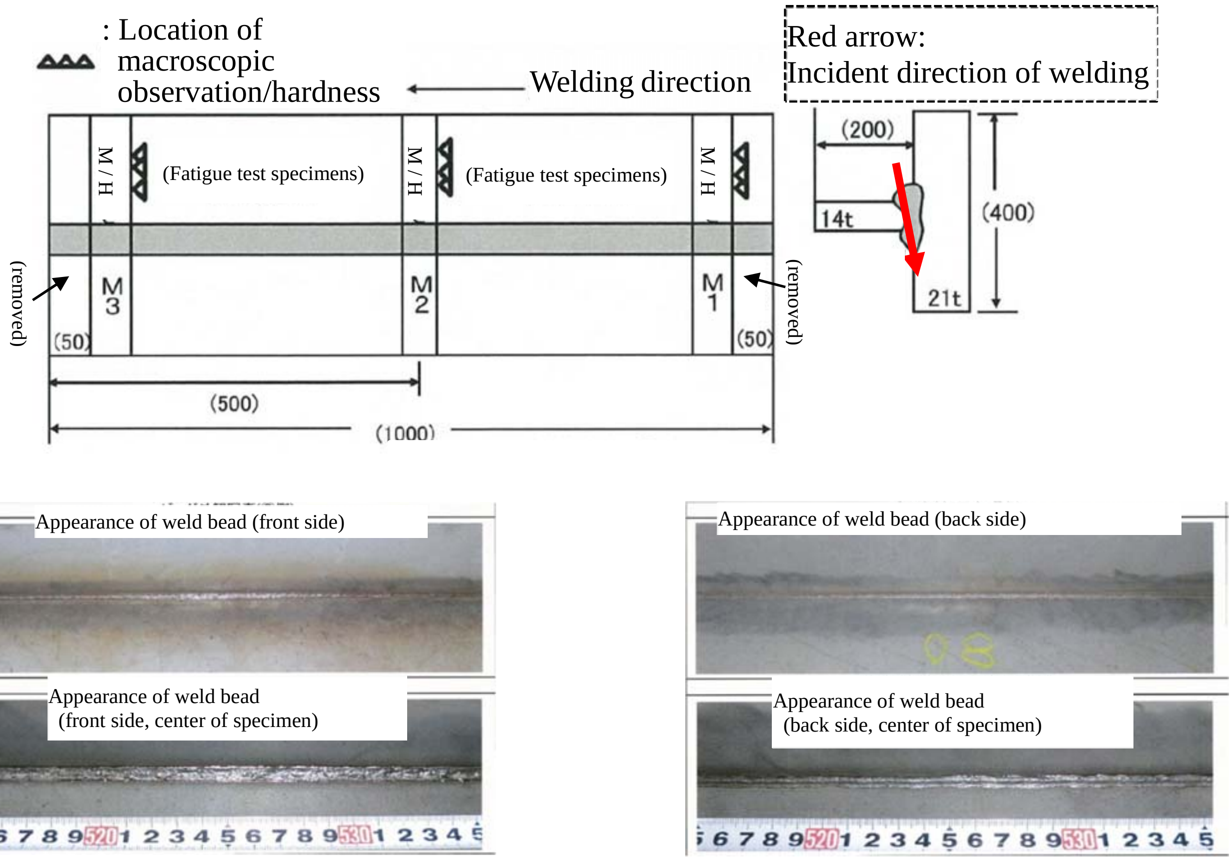


FIGURE 1 FABRICATED FULL-PENETRATION TEE JOINT AND APPEARANCE OF WELD BEADS.

TABLE 2 MECHANICAL PROPERTIES OF TESTED MATERIALS

Material	Y. S. [MPa]	T.S. [MPa]	El. [%]	Absorbed Energy [J] at –20 °C
KD36 (14 mm)	426	516	24	253
KD36 (21 mm)	443	546	19	294
MG-50	490	570	31	–

TABLE 3. WELDING CONDITIONS (SINGLE-PASS WELDING)

Parameter	Set value
Laser power [kW]	20.0
Arc current [A]	425
Arc voltage [V]	27.3
Travel speed [mm/min]	900
Shield gas of arc welding	CO_2

Tack welding

Tack welding was employed to fix the stiffener. Tack welding was also conducted over the back side of the welding incident. Laser irradiation without filler wire was applied to melt the region of connection between the stiffener and base plate. The travel speed and laser power of tack welding were 600 mm/min and 3 kW, respectively. Figure 2 is a macroscopic observation of the cross section of tack welding. This tack welding technique has been detailed in the literature [4].

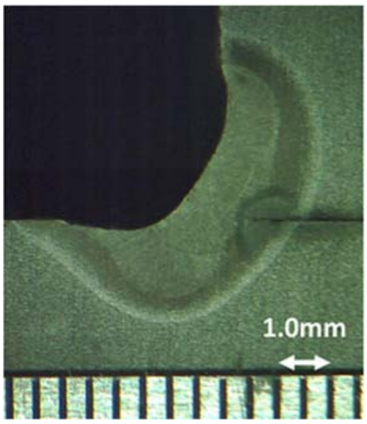


FIGURE 2 MACROSCOPIC OBSERVATIONS OF TACK WELDING.

Results of welding qualification procedure tests

Visual inspections of weld beads are shown in Fig. 1. The figure confirms that full-penetration weld joints were fabricated. In addition, radiographic testing, ultrasonic testing and magnetic particle testing found no weld defects. Moreover, a macroscopic cross-section observation and Vickers hardness test were conducted according to *Guidelines on Laser-Arc Hybrid Welding* issued by ClassNK [5]. Photographs of the macroscopic observation and measurements of the Vickers hardness test (with a test load of 10 kgf) are shown in Figs. 3 and 4, respectively. No weld defect is seen in Fig. 3. The maximum measured HV value is 258. This value is below the maximum allowable HV value of 380 [5].

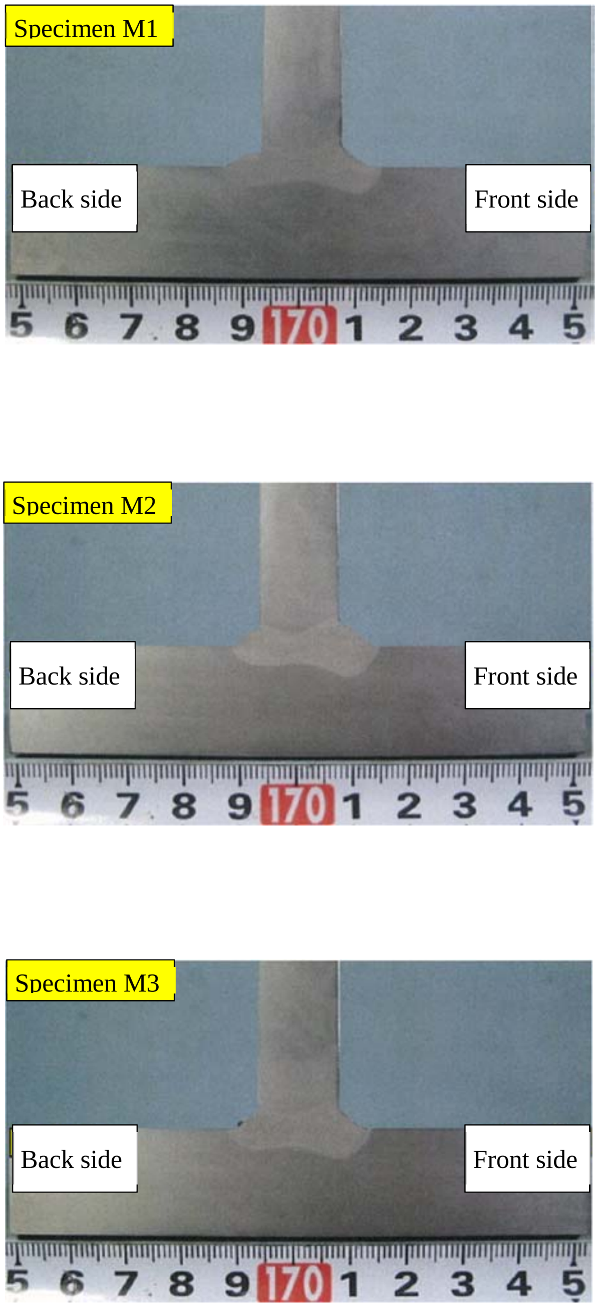
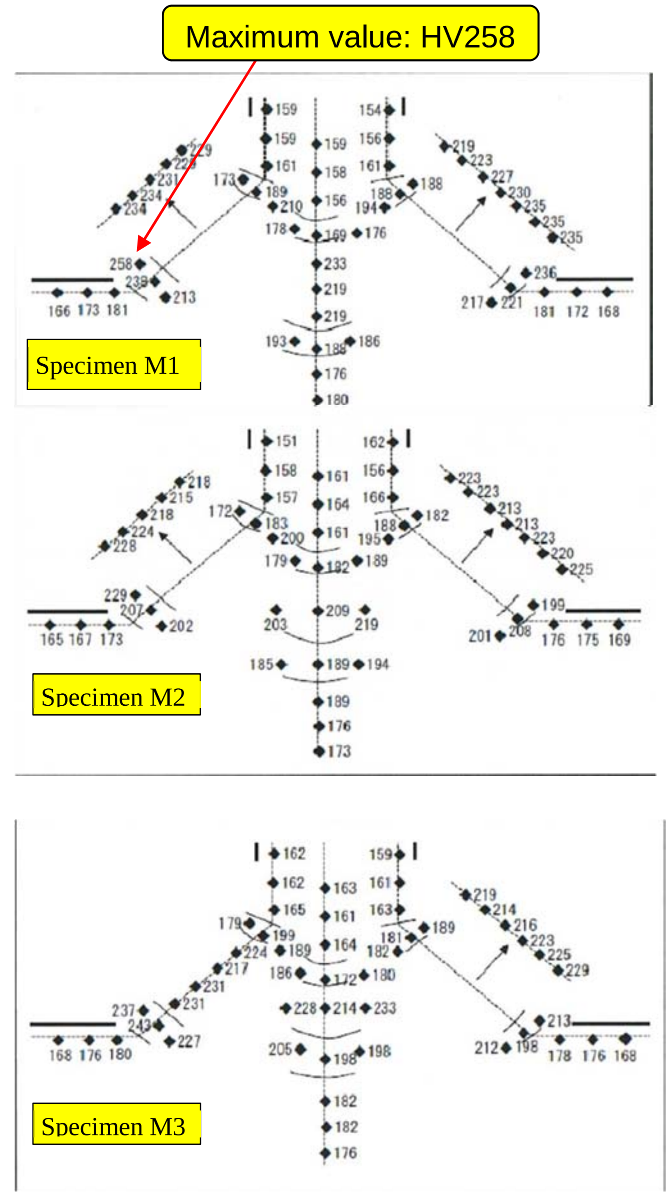


FIGURE 3 MACROSCOPIC OBSERVATIONS.



(Notes)

- Measured cross sections are shown in Fig. 1.
- Measured pitch is 1 mm and the location is 2 mm from surfaces.

FIGURE 4 VICKERS HARDNESS DISTRIBUTIONS.

FATIGUE STRENGTH

The fatigue strength of welded joints is important in terms of ensuring the integrity of ship hull structures. The fatigue strength of full-penetration tee joints produced by one-side single-pass welding is investigated by conducting three-point bending fatigue tests with a zero stress ratio according to ISO TR14345-2002 [6]. Specimens were arranged as non-load-carrying joints.

Measured curves of stress versus the number of cycles to failure (S–N) curves are shown in Fig. 5. Fatigue-strength design curves provided by IIW [7] and JSSC [8] and the measured fatigue strengths of tee joints fabricated by twin-pass welding [9][10] are also shown in the figure. Conditions for twin-pass welding are given in Table 4.

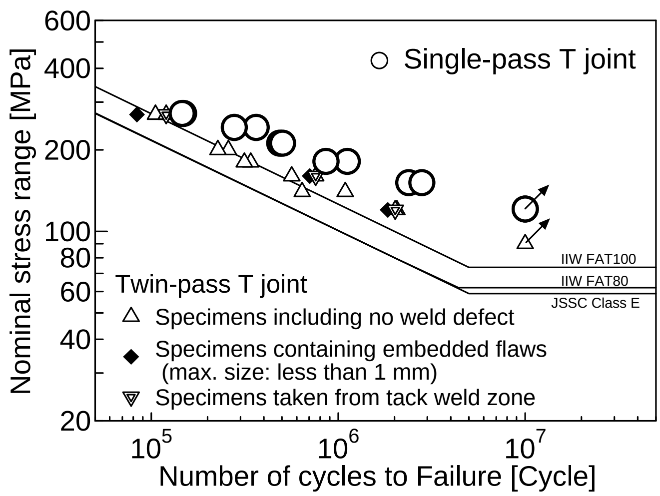


FIGURE 5. S–N CURVES

TABLE 3. WELDING CONDITIONS (TWIN-PASS WELDING) [10]

Parameter	Set values	
	First pass	Second pass
Laser power [kW]	8.0	5.0
Arc current [A]	450	457
Arc voltage [V]	29.0	30.5
Travel speed [mm/min]	1000	1000
Shield gas of arc welding	CO_2	

Although some fatigue test specimens fabricated by twin-pass welding contained small embedded flaws or a tack weld region produced by semi-automatic CO_2 arc welding, test results were not affected by these defects or tack weld.

Figure 5 confirms that the fatigue performance of full-penetration tee joints is superior to the design curves of IIW FAT80 and JSSC Class E (for the as-welded fillet-welded tee joint) and IIW FAT 100 (for the toe-grounded fillet-welded tee joint). It is expected that conventional fillet weld tee joints in hull structures could be replaced with full-penetration tee joints by introducing laser-arc hybrid welding in the stage of hull construction.

The fatigue performance of the full-penetration tee joint produced by one-side single-pass welding is higher than that for twin-pass joints. In particular, the slope of S–N curves for the one-side single-pass joint is more gradual than that for the twin-pass joint or fillet-welded joint. One reason that the single-pass welding joint has high fatigue performance is the difference in the stress concentration factor at the weld toe. The average value of the stress concentration factor of single-pass welding joints applied in fatigue tests was about 1.9 while that of twin-pass welding was about 2.5, because of the different shapes of the weld bead. Examples of the cross section of each welded joint are shown in Fig. 6. These stress concentration factors were calculated by finite element analysis. The average measured weld toe radius, leg length and Frank angle given in Table 5 were used in creating finite element meshes. MSC. Marc 2013 was used for these calculations.

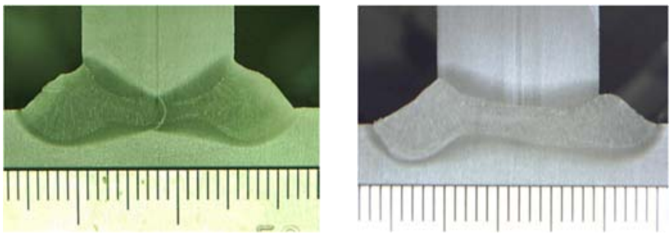


FIGURE 6. Examples of the cross section of each welded joint

TABLE 5. GEOMETRY OF THE WELD BEAD SHAPE

	Single pass	Twin passes
Weld toe radius [mm]	2.2	0.78
Leg length on the base plate [mm]	4.70	5.37
Frank angle [deg.]	45.7	51.9

From the above results, it is concluded that the one-side single-pass welded tee joint has excellent fatigue performance.

ANGULAR DISTORTION

Reducing the angular distortion of welded joints is important to realizing accurate hull construction. It is expected that that such a reduction can be achieved by introducing laser-arc hybrid welding.

The angular distortions of tee joints fabricated by conventional fillet welding, single-pass full-penetration laser-arc hybrid welding and twin-pass full-penetration laser-arc hybrid welding are compared in Fig. 7. Full-penetration joints having a weld length of 300 mm and comprising the same materials listed in Tables 1 and 2 were fabricated to measure angular distortion. Welding conditions were the same as those in the fatigue test specimen fabrication.

The angular distortion of the fillet weld joint was estimated by applying an approximation curve and a procedure used by Satoh and Terasaki [11, 12].

Categories F0, F1 and F2 in Fig. 7 correspond to the fillet-welded joints having a leg length that satisfies the Common Structural Rules for Bulk Carriers (CSR-B) [13]. Category F0 is required for primary members; e.g., deck plates, shell plates, inner bottom plates and bulkhead plates. Heat input for each joint was estimated using the regression formula of heat input and leg length [14].

Figure 7 confirms that the angular distortions of full-penetration tee joints are smaller than those of the fillet-welded joint of category F0, although full-penetration joints are stronger than fillet-welded joints. The superiority of the single-pass full-penetration joint produced by laser-arc hybrid welding is also confirmed from the viewpoint of welding deformation.

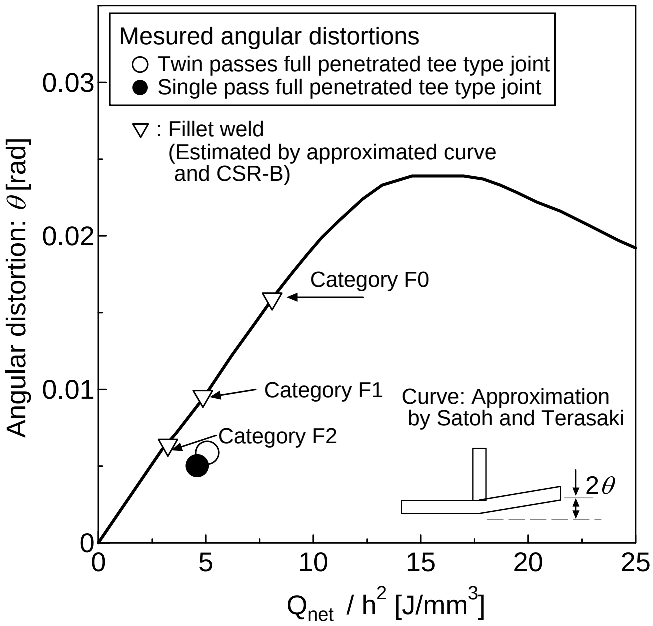


FIGURE 7. COMPARISON OF ANGULAR DISTORTIONS

CONCLUSION

The fatigue performance and angular distortion of full-penetration tee joints fabricated by one-side single-pass and twin-pass welding were investigated. The superiority of single-pass full penetration welded joints fabricated by laser-arc hybrid welding was confirmed.

Future challenges related to this study are as follows.

1) The expansion of the applicable plate thickness of the stiffener.
2) Investigation of the fatigue performance of single-pass full-penetration welded joints carrying a load.
3) Expansion of applicable groove cutting methods. Single-pass full-penetration tee joints are expected to be applicable to plasma or gas cutting.

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