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Effect of Pulse Shapes on Weld Defects in Pulsed Laser Welding of Stainless Steel

Jong-Do Kim† · Byung-Lea Kil* · Young-Sik Kim**

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Abstract : This paper describes the effectiveness of laser pulse shaping in eliminating weld defects such as porosity, cracks and undercuts in pulsed Nd:YAG laser welding. A large porosity was formed in a keyhole mode of deeply penetrated weld metal of any stainless steel. Solidification cracks were present in STS 310S with above 0.017%P and undercuts were formed in STS 303 with about 0.3%S. The conditions for the formation of porosity were determined in further detail in STS 316. With the objectives of obtaining a fundamental knowledge of formation and prevention of weld defects, the fusion and solidification behavior of a molten puddle was observed during laser spot welding of STS 310S through a high speed video photographing technique. It was deduced that cellular dendrite tips grew rapidly from the bottom to the surface, and consequently residual liquid remained at the grain boundaries in wide regions and enhanced the solidification cracking susceptibility. Several laser pulse shapes were investigated and optimum pulse shapes were proposed for the reduction and prevention of porosity and solidification cracking.

Key words : Pulsed Nd:YAG Laser, Pulse shaping, Stainless steel, Weld defects

1. Introduction

Laser is a heat source with high power density, and laser welding is receiving a great attention as a high precision, high performance, good flexibility and high speed welding process. Recently, high power Nd:YAG laser apparatuses , such as 800 W pulsed laser with single rod, about 2 kW cascade type CW laser, 3 kW cascade type pulsed laser and 3 kW laser with 3 coupled beams of 1 kW pulsed laser, were developed[1]-[3]. Also, pulse shapable Nd : YAG lasers were developed[4].

Kim and others[5]-[7] have performed a series of studies to clarify the weldability of various alloys and to establish

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† Corresponding Author(Division of Marine System Engineering, Korea Maritime University), E-mail:jdkim@mail.hhu.ac.kr, Tel:051)410-4253

* Division of Marine System Engineering, Korea, Maritime University

** Division of Mechanical & Materials Engineering, Korea Maritime University

Table 1 Chemical compositions of commercially available stainless steels used.

Materials (STS.AISI)	Compositions (mass%)								Creq (%)	Nieq (%)
	C	Si	Mn	P	S	Cr	Ni	Other		
310S(A)	0.063	0.39	1.68	0.027	0.007	24.35	20.26	-	24.94	22.99
310S(B)	0.078	0.93	1.56	0.021	0.007	25.06	20.30	0.1Mo	26.56	23.42
310S(C)	0.07	0.61	1.69	0.017	0.002	25.02	19.16	-	25.94	22.11
310S(D)	0.05	0.75	1.19	0.013	0.001	25.02	19.20	-	26.15	21.30
316(A)	0.078	0.53	1.29	0.032	0.013	17.04	11.03	2.27Mo	20.11	14.02
316(B)	0.05	0.69	1.06	0.031	0.006	16.96	10.38	2.21Mo	20.21	12.41
316(C)	0.05	0.92	1.40	0.030	0.009	17.43	12.01	2.53Mo	21.34	14.21
304	0.07	0.45	0.82	0.025	0.005	18.16	8.63	-	18.84	11.14
309S	0.06	0.76	1.62	0.031	0.002	22.16	14.16	-	23.30	16.77
321	0.05	0.89	1.19	0.029	0.011	17.47	9.43	-	18.80	11.53
347	0.04	0.61	1.26	0.026	0.007	18.18	9.69	0.62Nb	19.40	11.52
303	0.05	0.32	1.96	0.024	0.332	18.18	9.96	0.20Mo	18.86	12.17
329J1	0.02	0.51	0.35	0.029	0.001	24.70	5.35	1.77Mo	17.24	6.2+
430	0.06	0.56	0.56	0.028	0.005	16.49	-	-	17.33	2.08
630	0.05	0.25	0.82	0.024	0.014	15.94	4.56	3.33Cu	16.57	0.5+

optimum pulse shapes for the production of laser welds without defects using a special pulse-shapable Nd : YAG laser apparatus. This study was undertaken to obtain a basic knowledge of pulsed laser welding of stainless steels and related problems. First, the kind and formation conditions of weld defects were investigated in various shallow and deep weld metals. Especially, conditions of porosity formation and hot(solidification) cracking were investigated in STS 316 and 310S, respectively. Also, fusion and solidification phenomena of a molten puddle were observed with a high speed video photographing technique. From these results, optimum pulse shapes for the reduction in porosity and solidification cracking were proposed.

2. Materials and Experimental Procedure

The materials used are various kinds of commercially available stainless steels and Fe-Cr-Ni ternary alloys. The chemical compositions of commercial stainless steels used are shown in Table 1. STS 316 and 310S plates of 5mm thickness are mainly employed in this investigation. The surface of each plate was polished by #400 emery paper and cleansed with acetone before laser welding.

The laser apparatus used is Miyachitechnos′ pulsed Nd:YAG laser, which can control a pulse shape of laser output power. The pulse duration of laser power can be varied from about 2 to 20 ms, and the pulse duraion is divided into 20 equal segmental periods. 7 levels of lamp voltages are selected from 0 to 495 V for each segmental period. A laser beam is delivered through GI fiber 0.8 mm diameter, and is focused by a quartz lens of 150 mm focal length.

Laser spot welding was conducted in argon atmosphere under various irradiation conditions.

The presence of cracks and porosity was examined on the surfaces and polished cross section.

Fusion and solidification behavior during laser spot welding was observed by a high speed color video camera of 1,000 frames per second. **Fig. 1** shows the schematic arrangement for the observation of fusion and solidification behavior.

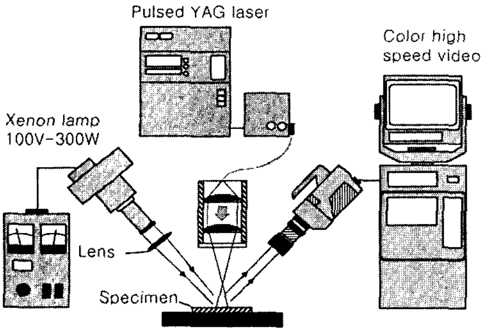


Fig. 1 Schematic arrangement of high speed video photography for observation of fusion and solidification phenomenon occurring during laser spot welding.

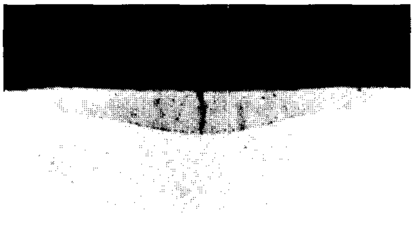
3. Experimental Results and Discussion

3.1 Characteristics of laser spot weld defects

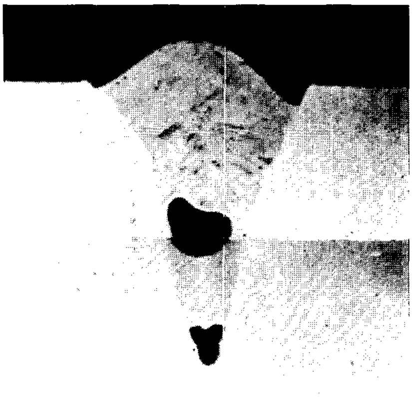
Laser spot welding was performed on each stainless steel plate. **Fig. 2** shows characteristic weld defects in STS 310S and 303 plates subjected to rectangular pulse shapes of 5 ms duration. Large porosities are observed in the central or lower part of deeply penetrated weld fusion zones, as seen in Fig. 2(a) and (c). It was thus found that porosities were easily formed in a key hole mode of deeply penetrated weld fusion zones of all stainless steels.

Solidification cracks were present in laser spot weld metals of STS 310S with 0.017%P or more, as seen in Fig. 2(b). On the other hand, no cracks were detected in weld metals of STS 310S with 0.013%P and 0.001%S, STS 303 with 0.33%S and STS 630 with 3.3%Cu which are sometimes accepted to be susceptible to cracking.

(a) Porosity in STS 310S



(b) Solidification crack in STS 310S



(c) Undercut in STS 303

Fig. 2 Typical weld defects observed in pulse laser-welded stainless steels.

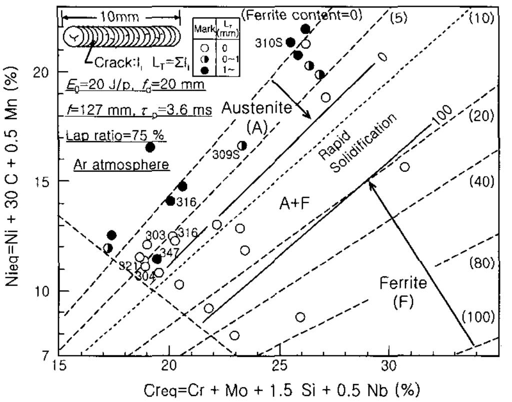


Fig. 3 Crack lengths for various of stainless steels subjected to laser-overlapped welding shown in Schaeffler diagram.

Fig. 3 shows the level of crack lengths for various stainless steels subjected to pulsed laser overlapped (seem) welding (using another laser apparatus with normal pulse shapes), projected in the Schaeffler diagram. The ranges of fully austenitic and ferritic microstructure at room temperature are widened and that of austenitic + ferritic duplex microstructure is narrowed in pulsed laser weld metals due to rapid solidification and quenching in comparison with the Schaeffler diagram. It is shown that cracks occurred in the weld metals (of STS 316, 309S, etc.) containing less than 5% ferrite in the Schaeffler diagram. The weld metals in which cracking takes place are presumed to solidify as primary austenite phase during rapid solidification. Cracks were also found in STS 347, probably because Nb(Cb) might segregate to a higher degree to lower the solidification temperature due to the formation of a larger content of austenite during rapid solidification process. It is concluded that the solidification cracking may occur extremely easily in the weld metals of austenitic single-phase solidification with normally commercial or higher levels of impurities.

Moreover, it was revealed that the STS 303 are very sensitive to undercuts in both shallow and deep weld metals, as observed in Fig. 2(c). This occurrence may be interpreted in terms of the effect of surface tension due to a high level of S content; however, the real cause of undercut formation is not clear at the present. More work will be needed to clarify the undercut phenomenon in laser-welded STS 303.

3.2 Conditions of porosity formation

The influences of welding conditions and weld fusion zone geometries were investigated by irradiating STS 316 plate with a pulsed laser in the rectangular output power shape. **Fig. 4** indicates schematically the shapes and locations of porosity in weld metals exposed to laser beams with different pulse durations at various defocused distances. Porosities were found in the shallow and deep weld

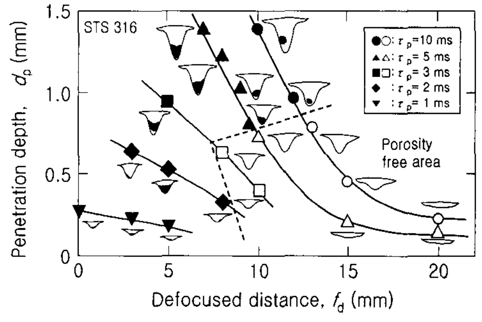


Fig. 4 Effects of penetration depths of weld metals, defocused distance and pulsed length on porosity formation and location in laser spot weld fusion zones.

metals made at high power densities due to short defocused distances and in a keyhole mode of deep penetration weld metals. It is therefore presumed that the formation of porosities has a close correlation with the collapse of a key hole(cavity or beam hole) just after the laser irradiation termination. That is, (1) the keyhole in the liquid metal is hydrodynamically unstable, (2) the keyhole collapses drastically due to rapid reduction in the laser power (density) because of the rectangular pulse shape, (3) the liquid in the upper part of molten puddle flows down to cover the keyhole, (4) the lower part of keyhole can not be filled up by the liquid, resulting in the formation of a bubble, (5) the upper part of liquid solidifies to prevent the bubble from flowing up, and then (6) the bubble remains as a porosity or pore in the weld fusion zone. Accordingly, in the case of short pulse duration at high power density, a narrow cavity (keyhole) must be formed in the shallow fusion zone.

3.3 Effect of pulse shape on prevention of porosity

The presence or absence of porosity was examined by irradiating STS 316 plates with pulse shaped laser beams under various combinations of tailing powers and additional periods. **Fig. 5** shows the measured output power shapes of pulsed laser, indicating the addition of lower (about 4.5 kW) power for 2, 4 and 6 ms after 5 kW level of about 5 ms duration. A slow increase in laser power at the beginning is employed to reduce spattering. **Fig. 6** exhibits the cross sections of STS 316 laser welds produced by the selected power densities shown in Fig. 5. The porosity is located in the upper part as the additional pulse period is longer, and no porosity is seen in deeply-penetrated weld metal at the pulse duration of 16 ms. On the other hand, when the levels of additional tailing powers were not appropriate, porosities could not be eliminated.

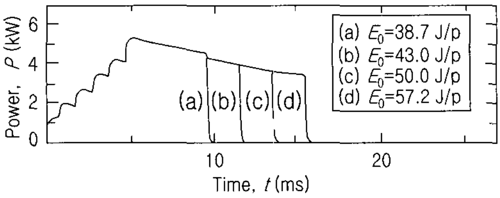


Fig. 5 Controlled power shapes of pulsed laser in 4.5 kW tailing shape for 2, 4 and 6 ms after 5 kW standard pulse for 10 ms.

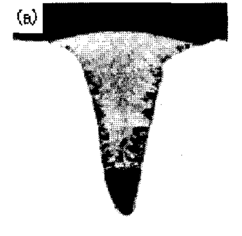
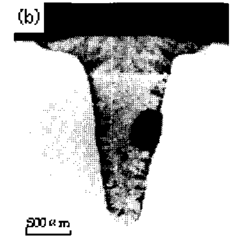
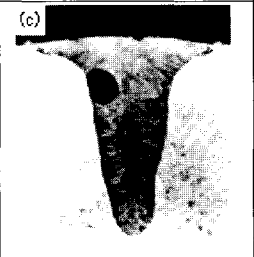
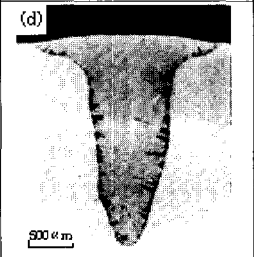
STS316: f=150 mm, f_d=5 mm	
	
τ_p=10 ms, E_0=38.7 J/p	τ_p=12 ms, E_0=40.3 J/p
	
τ_p=14 ms, E_0=50.3 J/p	τ_p=16 ms, E_0=57.2 J/p

Fig. 6 Cross-sectional macrostructures of STS 316 welds produced at various controlled pulse power shapes.

From such experimental results, it was revealed that a keyhole type of deeply penetrated weld metals without porosity could be produced under the proper addition of tailing power by pulse shapable laser apparatus. Such similar tendency is recognized in aluminum alloys[8], although the optimum pulsed laser power shapes are different between stainless steels and aluminum alloys.

3.4 Fusion and solidification behavior of molten puddle

Fusion and solidification behavior on the surface of molten puddle was observed in pulse laser welded STS 310S by a high speed video camera. The photos demonstrating the variation in the molten pool under the conditions of τ_p =5 ms and f_d =15 mm are shown in **Fig. 7**. The generation of plasma plume and the behavior of solidification on the spot weld surface are seen between 3 and 4 ms and between 6 and 13 ms, respectively. Such observation suggests that the temperature of the central surface of a molten puddle was raised up to the boiling temperature during welding even in the case of shallow weld fusion zone.

Three pulse shapes of laser power densities used are shown in **Fig. 8**, and the variations in the radii of spot weld fusion zones during and after laser irradiation under three different pulse conditions are indicated as a function of time in **Fig. 9**. In the case of τ_p =5 ms and f_d =15 mm, cellular dendrite tips solidify so rapidly as to reach the center of weld nugget surface within about 10 ms after the termination of laser irradiation. As the power density is higher, the time required complete the solidification at the central-upper part of a spot weld metal is longer because the deeper weld fusion zone is formed. When the pulse duration is increased, the solidification time is longer due to the increase in the absorbed heat input. The formation of keyhole could not be observed just after the laser irradiation termination. Therefore, it is presumed that the keyhole after laser shot collapses so suddenly and quickly that the deeply penetrated weld metal is liable to form porosity.

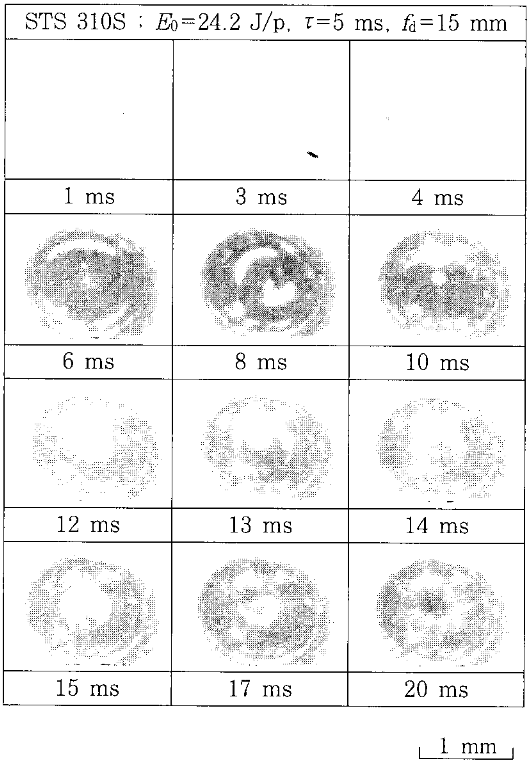


Fig. 7 High speed video pictures showing fusion and solidification behavior during pulsed laser welding of STS 310S.

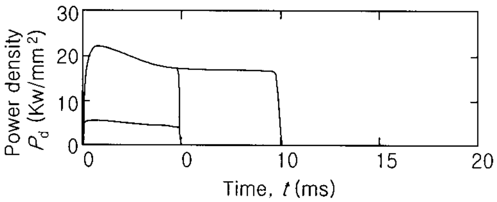


Fig. 8 Three kinds of output power density shapes of pulsed laser used for video observation.

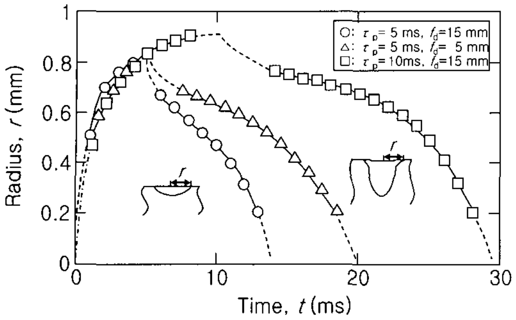


Fig. 9 Variation in radius of laser weld molten puddle of STS 310S as function of time.

3.5 Effect of pulse shaping on reduction in solidification cracking

Based on solidification cracking mechanism in pulsed laser weld metal, the procedure of heat input control to suppress the rapid growth rate of cellular dendrite tips, to narrow the mushy zone or region with residual liquid along grain boundaries and to advance solidification in the peripheral parts of a weld fusion zone more smoothly should be adopted to reduce cracking. Therefore, a laser beam with the tailing low power or subsequent pulsed laser power, which are shown in **Fig. 10** and **Fig. 11**, was irradiated on STS 310S plate containing 0.021%P and 0.007%S with the objectives of eliminating cracking in a heat-conduction mode of shallow weld metal or a keyhole mode of deep weld metal. The photos of spot welds are shown in **Fig. 12** and **Fig. 13**. Compared with Fig. 2(b), the proper tailing of low power is readily judged to be effective to the reduction in cracking, as shown in Fig. 12. Also, by comparison in Fig. 13, the second additional pulse irradiation with lower energy after the main pulse shot appears to exert a beneficial effect on the drastic decrease in large solidification cracks occurring near the fusion boundaries in the upper part if the additional irradiation can be carried out after the peripheral parts near the fusion boundaries have solidified and before the central parts have solidified. This also suggests that the laser-overlapped (seam) welding at the controlled proper repetition rate may be effective to the reduction or prevention of cracking. Therefore, the minimization of solidification cracking is feasible by controlling a pulse shape (and repetition rate) in laser welding. The combination of the first pulse-shaped laser with such an effective tailing power as to prevent porosity as shown in Fig. 5 and the second pulsed laser of relatively lower power will be beneficial to the reduction or prevention of both porosities and cracks in pulsed laser weld fusion zones.

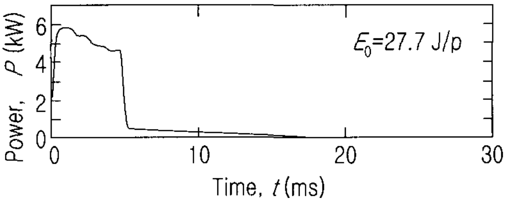


Fig. 10 Output power shape of pulsed YAG laser with tailing of low power, used for heat-conduction mode of spot weld metal.

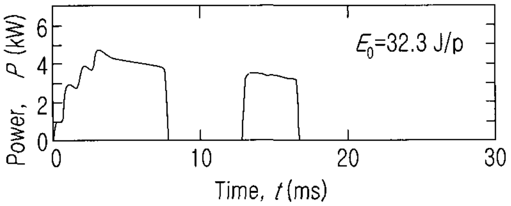


Fig. 11 Output power shape of pulse YAG laser controlled for reducing cracking, showing second pulse after main laser shot.

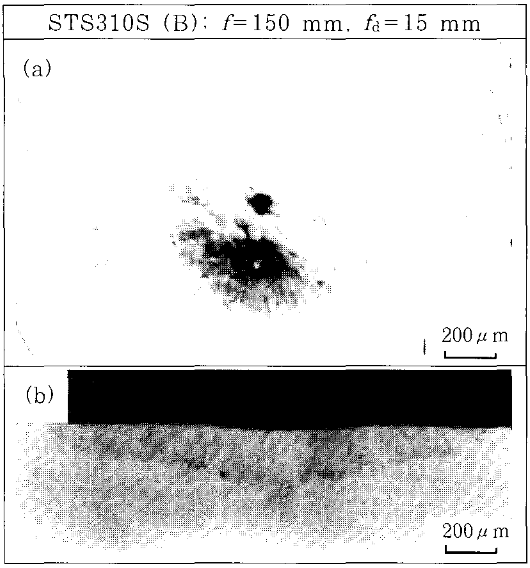
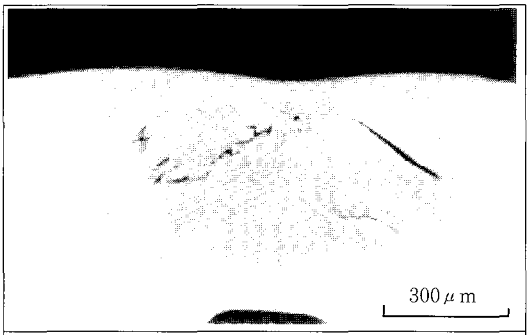
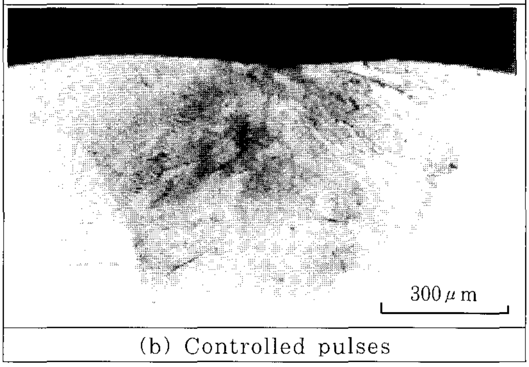


Fig. 12 Surface and cross sectional macrostructure of STS 310S produced with pulsed laser in tailing power shape.



(a) One pulse shot



(b) Controlled pulses

Fig. 13 Cross-sectional macrostructure of laser welded STS 310S, showing effect of second shot of controlled pulse shape on reduction in cracking.

4. Conclusion

1) Porosities were liable to be formed in a keyhole mode of deeply penetrated spot weld metals of all stainless steels subjected to a laser beam with a rectangular pulse shape.
2) Solidification cracks were present along grain boundaries in the weld fusion zones of STS 310S and other stainless steels with commercial or higher levels of P content which solidified as primary austenite phase.
3) Undercuts were formed in the spot weld metals of STS 303 with a considerable content of S.
4) The formation of a porosity was interpreted in terms of a sudden collapse of the cavity or keyhole and a rapid solidification so as to trap a pore.
5) A keyhole mode of deep penetration weld metals without porosity could be produced under the proper addition of tailing power by pulse shapable laser apparatus.
6) On the basis of high speed video observation of a fusion and solidification behavior, it was deduced that cellular dendrite tips grew rapidly from the bottom to the surface, and consequently residual liquid remained at grain boundaries in wide regions, which enhanced the susceptibility to solidification cracking.
7) Pulse shape of laser powers proper for minimizing solidification cracking in STS 310S weld metal were proposed, and the effect was confirmed.

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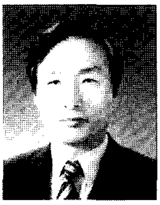
Author Profile

Jong-Do Kim

He received the B.A. degree in Marine Engineering from Korea Maritime University in 1985. And he received the M.Eng. and Ph.D degrees in Laser Welding Engineering from Osaka University in 1995 and 1997. From 1997 to 1998, he was a Research Fellow in JWRI of Osaka University. Since 1998, he has been a professor of Dept. of Marine System Engineering at Korea Maritime University. His research interests are in Laser Precision Processing and Its Automation.

Byung-Lea Kil

He received the B.A. degree in Marine Engineering from Korea Maritime University, and the M.Eng. from Pukyong National University. Since 1996, he has been a professor of Dept. of Marine System Engineering at Korea Maritime University. His research interests include Rotor Dynamics, Machinery Monitoring and Diagnosis.



Young-Sik Kim

He received the B.A. and M.Eng. degrees from Korea Maritime University, and the Ph.D from Tokyo Institute of Technology, Japan. He is currently a professor of Dept. of Mechanic and Material Engineering at Korea Maritime University. His research interests are in Welding Engineering and Material Science.