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Effects of laser beam energy on the pulsed Nd:YAG laser welding of thin sheet corrosion resistant materials

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Abstract. The aim of this study was to value the possibility to join, for pulsed Nd:YAG laser welding, thin foils lap joints for sealing components in corrosive environment. Experimental investigations were carried out using a pulsed neodymium: yttrium aluminum garnet laser weld to examine the influence of the pulse energy in the characteristics of the weld fillet. The pulse energy was varied from 1.0 to 2.5 J at increments of 0.25 J with a 4 ms pulse duration. The base materials used for this study were AISI 316L stainless steel and Ni-based alloys foils with 100μm thickness. The welds were analyzed by electronic and optical microscopy, tensile shear tests and micro hardness. The results indicate that pulse energy control is of considerable importance to thin foil weld quality because it can generate good mechanical properties and reduce discontinuities in weld joints. The ultimate tensile strength of the welded joints increased at first and then decreased as the pulse energy increased. In all the specimens, fracture occurred in the top foil heat-affected zone next to the fusion line. The microhardness was almost uniform across the parent metal, HAZ and weld metal. A slight increase in the fusion zone and heat-affected zone compared to those measured in the base metal was observed. This is related to the microstructural refinement in the fusion zone, induced by rapid cooling of the laser welding. The process appeared to be very sensitive to the gap between couples.

Introduction

Typical problems in lap joint welding of thin foils include excessive distortion, absence of intimate contact between couples; melt drop-through and high levels of residual stress. Laser beam welding is used widely as an important manufacturing process. Pulsed laser processing is expected to be the method of choice because it allows more precise heat control compared with continuous laser processing.

Monel 400, an important nickel-copper alloy, and Hastelloy C-276, a nickel-based alloy with high concentrations of Cr and Mo, are more corrosion resistant than stainless steels. This characteristic together with their good ductility and easy of cold working make them generally very attractive for a wide variety of applications; nearly all of which exploit their corrosion resistance in atmospheric, salt water and various acid and alkaline media. Ni-alloys are used for marine engineering, chemical and hydrocarbon processing equipment, valves, pumps, sensors and heat exchangers. Nickel, the principal constituent metal of the alloys is less corrosion resistant than Monel 400 and Hastelloy C-276 under reducing and oxidizing conditions, respectively [1].

Welding thin foil materials is very important in many industrial applications. The need for joints between thin foils often appears in complex components, especially the combination with a more corrosion resistant material. Due to differences in thermal conductivity, fusion temperature and solubility of the materials, brittle phases can appear and deteriorate the tensile strength of the joint. Pulsed laser systems have the capability to weld different materials without filler metal (autogenous welding), high energy density and low heat-input. Industrial components are being made smaller to reduce energy consumption and save space, which creates a growing need for microwelding of thin foil less than 100 μm thick. For this purpose, laser processing is expected to be the method of choice because it allows more precise heat control com-pared with arc and plasma processing [2].

Materials play an important role in manufactured goods. Materials must possess both acceptable properties for their intended applications and manufacturability. These criteria hold true for micromanufacturing, in which parts have overall dimensions of less than 1 mm. The wide range of materials that can be processed by lasers includes materials for micro-electronics, hard materials such as tungsten carbide for tool technology and very weak and soft materials, such as polymers for medical products. Even ceramics, glass and diamonds can be processed with laser technology to an accuracy better than 10 μm. In comparison with classical technologies, laser processes are generally used for small and medium lot sizes but with strongly increased material and geometric variability [3].

Welding with pulsed Nd:YAG Laser System is characterized by periodic heating of the weld pool by a high peak power density pulsed laser beam incident that allow melt-ing and solidification to take place consecutively. However, due to very high peak power density involved, the solidification time is shorter than continuous laser and conventional welds. Combination of process parameters such as pulse energy [Ep], pulse duration [tp], repetition rate [Rr], beam spot size [Φb] and welding speed [v] determines the welding mode, that is, conduction or key-hole [4, 5].

Research examining the Nd:YAG laser for continuous welding, pulsed welding, dissimilar sheet welding and coated sheet welding has been published. Kim et al.[6] reported successful welding of Inconel 600 tubular compo-nents of nuclear power plant using a pulsed Nd:YAG laser. Ventrella et al.[7,8] using a homemade Nd:YAG Pulsed Laser System studied thin foil welding of Ni-based alloys. Ping and Molian [9] utilized a nanosecond pulsed Nd:YAG laser system to weld 60 μm of thin AISI 304 stainless steel foil.

The present work has been carried out to investigate the influence of the pulse energy on neodymium: yttrium aluminum garnet (Nd:YAG) laser welding of AISI 316L stainless steel and nickel-based alloys (Monel 400 and Hastelloy C-276) thin foil and its effect on weld joint characteristics.

2. Experimental Procedure

This study used a pulsed Nd:YAG laser system. The experimental setup of the laser system is shown in Fig. 1.

AISI 316L austenitic stainless steel, Monel 400 and Hastelloy C-276 with thickness of 100 μm were used as base metals. Table 1, Table 2 and Table 3 show the detail chemical compositions of the base metals, respectively. Before welding, the specimens were prepared and cleaned to ensure that all samples presented the same surface conditions with a homogeneous finish.

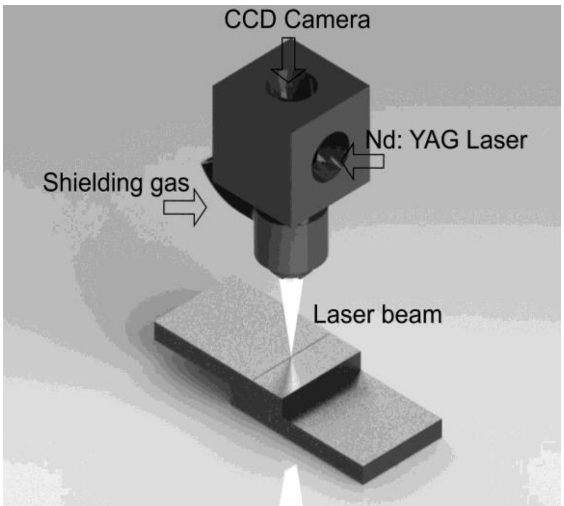


Fig. 1 Experimental setup of the laser system.

Table 1. Chemical compositions of AISI 316L (wt %)

C	Cr	Ni	Mn	Si	P	S	Mo
0.03	17.3	13.0	0.80	0.75	0.75	0.003	2.3

Table 2. Chemical compositions of Monel 400 (wt %)

C	Ni	Cu	Fe	Si	Mn	S
0.30	66	Rem	2.5	0.50	2.0	0.024

Table 3. Chemical compositions of Hastelloy C-276 (wt %)

C	Ni	Cr	Mo	Mn	Fe	Co	W
0.01	Rem	15.9	15.6	0.52	5.35	1.51	3.38

To evaluate the influence of the pulse energy, welding was performed using specimens positioned as lap joints. They were welded with a beam spot size (Φb) and beam angle (Ab) of 0.2 mm and 90 degrees, respectively. The focus point was fixed on the surface of the work-piece. The welding speed (v) and repetition rate (Rr) were fixed at 500 mm/min and 39 Hz, respectively. The pulse energy (Ep) varied from 1.0 to 2.25 J at increments of 0.25 J with a 4 ms pulse duration (tp). Thus, there was one controlled parameter in this process: the pulse energy. The specimens were held firmly using a jig, to fixture and prevent ab-sence of contact and excessive distortion. Fixturing is extremely important for thin-section laser welding. Toler-ances were held closely to maintain joint fitups without allowing either mismatch or gaps.

The specimens were laser-welded in an argon atmosphere at a flow rate (Fr) of 12 l/min. Back shielding of the joint was not necessary because AISI 316L and Ni-based alloys, Monel 400 and Hastelloy C-276, are not oxidizable metals like Al and Ti. None of the specimens were subjected to any subsequent form of heat treatment or machining. After welding, the specimens were cut for the tensile-shear tests, as shown in Fig. 2.

Finally, part of the cut surfaces was prepared for metallo-graphic inspection by polishing and etching to display a bead shape and microstructure. The bead shape measure-ments were made using an optical microscope with an image analysis system. Figure 3 shows a schematic illus-tration of the transverse joint section with the analyzed geometric parameters.

The strength of the welds was evaluated using tensile shear strength tests and Vickers microhardness. For the tensile shear test, specimens were extracted from welded samples, and the width of the samples was reduced to 10 mm to lower the load required to fracture them. Micro-hardness tests were performed on a transverse section of the weld bead, parallel to the surface of the thin foils, in the region next to the connection line of the top foil. Microhardness tests identify possible effects of microstruc-tural heterogeneities in the fusion zone and in the base metal. The reported data were the average of five individ-ual results.

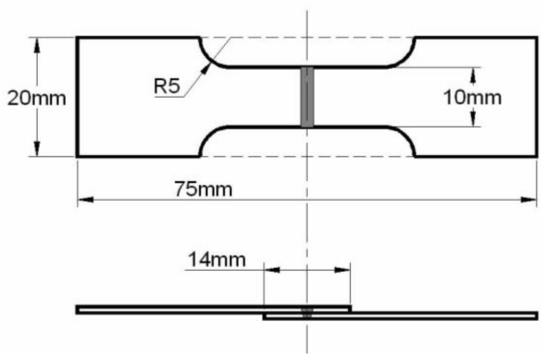


Fig. 2 Schematic diagram of tensile test specimen design [mm].

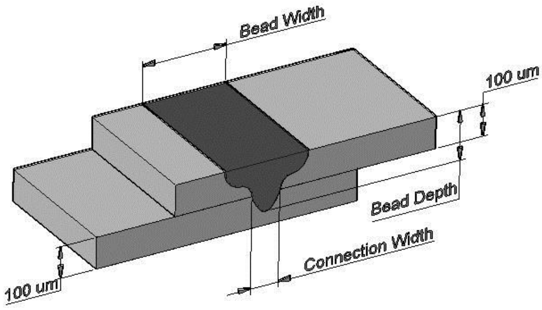


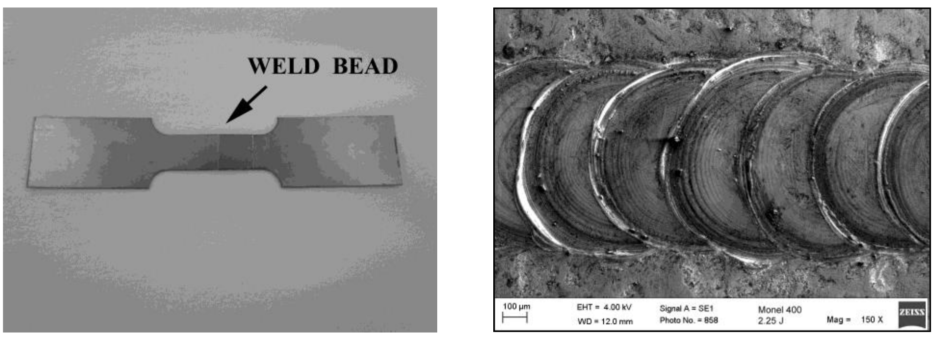
Fig. 3 Schematic of the joint transversal section showing the analyzed geometric parameters.

3. Results and Discussion

The weld beads showed characteristic of pulsed laser welding. No welding cracks were found in any of the welds; this may be partly due to the good crack resistance of base the metals and the correct welding parameters. No discontinuities were observed in the fusion metal of the beads, which demonstrates the efficiency of the shielding gas in preventing oxidation, large porosities and gas inclusions, which cause poor weld quality. All specimens were welded in the conduction mode.

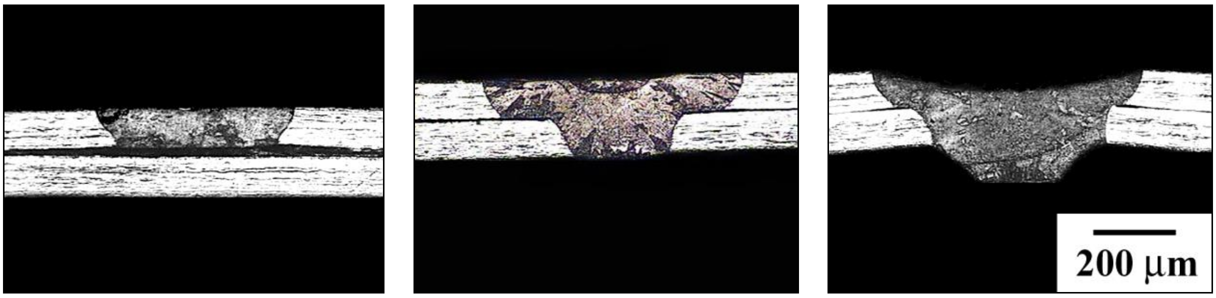
Figure 4a shows a specimen welded with 2.25 J pulse energy for the tensile shear test and Fig. 4b shows a top view of the weld bead. It is clearly noticeable in Fig. 4b no detectable defect existed on the surface of the weld bead or adjacencies.

The cross section macrostructures of AISI 316L stainless steel, Monel 400 and Hastelloy C-256 lap laser welds as a function of pulse energy (Ep) are summarized in Fig. 5, Fig. 6 and Fig. 7, respectively. In Figs. 5a, 6a and 7a (specimens with 1.0J pulse energy) no penetration at the bottom sheet and no depression at the top of the bead was observed, probably due to insufficient laser energy to bridge the couple. Due to the thin thickness, low pulse energy of the laser beam and the presence of a small gap, the molten pool just grew in the radial direction of the top foil resulting in a no bonded joint with the weld morphology observed in Figs. 5a, 6a and 7a. Gaps between foils and gaps in the connection line increase stress and thus are detrimental to weld quality in terms of mechanical properties. When the pulse energy was increased on the other specimens, a connection region between the foils was observed, as shown in Fig. 5b, Fig. 6b and Fig. 7b. Specimens welded with 2.25 J pulse energy, Fig. 5c, Fig. 6c and Fig. 7c , an increase occurred with a depression at the top and a penetration bead. The concavity increased proportionally to the pulse energy (Ep). Moreover, it was evident that specimens welded with 2.25 J pulse energy undergo deformation during joint welding, which causes a large bending moment. Areas near the heat source of the upper foil are heated to higher temperatures and thus expand more than areas away from the heat source or regions of the lower foil. After the foil cools to the initial temperature, the final deformation remains. Like the material heated by the laser beam, the irradiance did not cause the material reach its boiling point; no significant amount of surface material was removed.



(a) (b)

Fig. 4 Tensile shear test specimen (a) and a top view of the weld bead (b). Monel 400. Ep = 2.25 Joules.



(a) (b) (c)

Fig. 5 Cross sections of AISI 316L lap joints made with pulsed Nd:YAG laser welding with different pulse energies (Ep): a) 1.0 J, b) 1.75 J and c) 2.25 J. All figures have the same magnification as shown in (c).

(a) (b) (c)

Fig. 6 Cross sections of Monel 400 lap joints made with pulsed Nd:YAG laser welding with different pulse energies (Ep):): a) 1.0 J, b) 1.75 J and c) 2.25 J. All figures have the same magnification as shown in (c).

(a) (b) (c)

Fig. 7 Cross sections of Hastelloy C-276 lap joints made with pulsed Nd:YAG laser welding with different pulse energies (Ep):): a) 1.0 J, b) 1.75 J and c) 2.25 J. All figures have the same magnification as shown in (c).

The relationship between pulse energy and weld metal geometry is summarized in Fig. 8, Fig. 9 and Fig.10. The bead width increased as pulse energy varied from 1.0 to 2.0 J. This indicated that when the laser beam interacts with the specimen, it creates a liquid melt pool by absorb-ing the incident radiation. This bead width variation is a result of the higher pulse energy; a high amount of material is molten and then propagates through the base material. In the presence of high pulse energy, part of the melt material passed through the joint, which increased the concavity at the top of the weld, the excess of weld metal at the root and the heat-affected zone extension. On the other hand, at pulse energy of 2.25 J, the molten metal volume decreased, and deep concave underfills occurred.

These macrostructural results indicate that weld metal characteristics are sensitive to pulse energy variation. To obtain an acceptable weld profile, intimate contact be-tween couples is necessary. The presence of an air gap in the weld joint restringes heat transfer between the workpieces. This results in a lack of fusion of the bottom element or the formation of a hole on the superior element of the joint. As the pulse energy increases, the concavity at the top of the weld and the excess of material at the weld root increase; consequently, the weld joint is weakened. Moreover, higher pulse energy extended the heat-affect zone.

The macroscopic examination of the cross sections of all specimens also indicated that the weld pool morphology is essentially symmetrical about the axis of the laser beam. This symmetry at the top and bottom was observed in all joints independent of the pulse energy, which suggests a steady fluid flow in the weld pool; however, as the pulse energy increased, a high depression formed at the top.

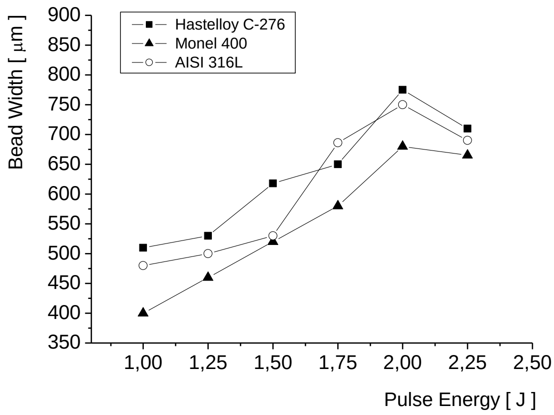


Fig. 8 Bead Width as a function of pulse energy [Ep].

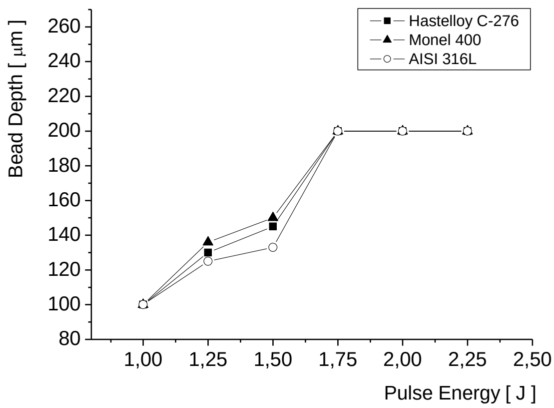


Fig. 9 Bead Depth as a function of pulse energy [Ep].

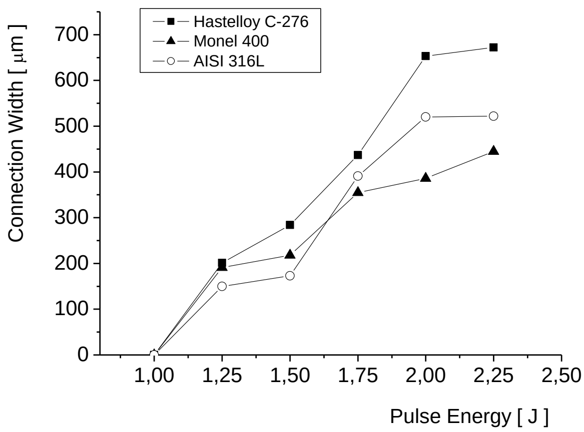
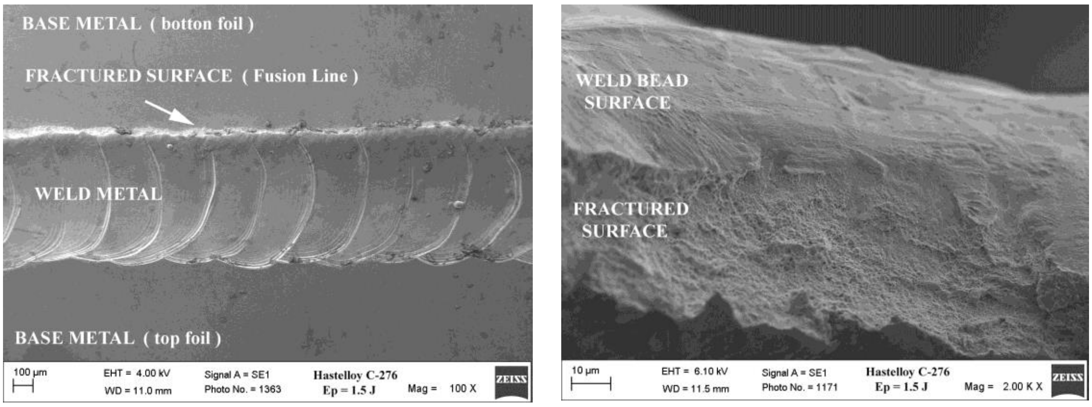


Fig. 10 Connection Width as a function of pulse energy [Ep].

The failure of all specimens occurs in the region next to the fusion line of the top foil. This is expected because hardness and tensile strength values are known to be related. Moreover, the thickness of the top foil is reduced as pulse energy increases. Figure 11 shows a top view of the region fractured resulting from the tensile shear tests of the sample (Hastelloy C-276). All samples ruptured in the fusion line. It was observed, in all of them, a thickness reduction of the sheet.



(a) (b)

Fig. 11 Top view of the joint region fractured (a) and sur-face fractured (b) from the tensile shear tests. Hastelloy C-276. 1,5 Joules.

The ultimate tensile strength (UTS) tends to increase at first and then decrease as the pulse energy (Ep) increases. The relationship between pulse energy and tensile shear strength of welded joints is summarized in Fig. 12. Specimens welded with a pulse energy lower than 1.25 J were not bonded because the pulse energy was too low, and the molten pool did not have enough time to propagate to the bottom foil; incomplete penetration occurred. Otherwise, when the specimens were welded with pulse energy greater than 1.75 J, excessive underfilling and burnthrough was observed. Perforations in the weld bead were observed with pulse energy higher than 2.25 J.

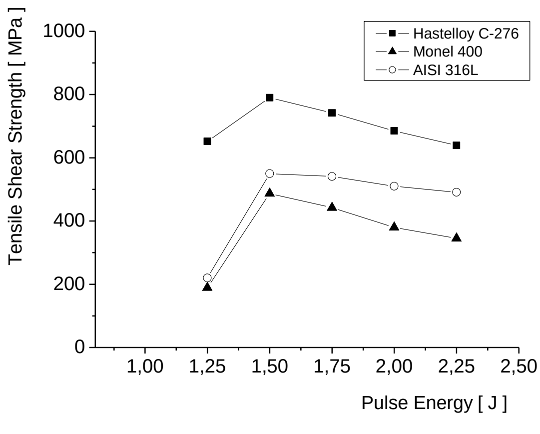


Fig. 12 Relationship between pulse energy and tensile shear strength.

The tensile properties of the welded joint affected by pulse energy (Ep) can be explained by macro and microstructural analyses. When the pulse energy is too low, the welding molten pool has not enough time to form, and incomplete penetration is formed. As the pulse energy increases, the grains in the weld metal and in the HAZ become coarser. The heat-affected zone extension increases too. Discontinuities become more severe. Some precipitates can be present intergranularly and even continuously along the grain boundary. These microstructures changes contribute to a weakness of the weld joint, which reduces the tensile properties as reported in the literature [10]. Finally, the decrease in the UTS may be related to the change of the microstructures and HAZ extension. Therefore, based on the above analyses it can be concluded that the lower the pulse energy, provided complete penetration occurs, the higher the tensile properties of welded joints.

No significant difference between hardness of weld metal and the heat-affected zone was obtained; the hardness of the heat-affected zone was slightly higher than that of the weld metal regardless of the pulse energy. Base metal hardness was always lower than that of HAZ and weld metal. These results are valid for all joints. This is expected because the mechanical properties, in general, are based on its microstructures [11].

4. Conclusion

The results obtained from this study demonstrate that is possible to weld 100 μm thickness of corrosion resistant materials AISI 316L austenitic stainless steel, Monel 400 and Hastelloy C-276 thin foils, in terms of microstructural and mechanical reliability, by precisely controlling the laser pulse energy. The better performance was due to the high quality joint; a joint marked by good penetration, no underfill and free from microcracks and porosity. This was obtained, in all of them, at an energy pulse of 1.5 J, a repetition rate [Rr] of 39 Hz and a 4 ms pulse duration. This reflects one of the most notable features of pulsed laser welding compared with other processes; welding with low heat input. The work also shows that the process is very sensitive to the gap between couples which prevents good heat transfer between the foils. The shape and dimensions of the thin foil weld bead observed in the present work depended not only on the pulse energy, but also on the presence of gaps between foils. Bead width, connection width and bead depth increased as the pulse energy increased. The ultimate tensile strength (UTS) of the welded joints initially increased and then decreased as the pulse energy increased. The specimens welded with 1.5 J attained the maximum tensile shear strength. In all the specimens, fracture occurred in the top foil weld metal next to the fusion line. The microhardness was almost uniform across the parent metal, HAZ and weld metal. A slight increase in the fusion zone compared to those meas-ured in the base metal was observed. This is related to the microstructural refinement in the fusion zone, induced by rapid cooling

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