Formation of One Pass Fully-Penetrated Weld Bead of Titanium Plate by Fiber Laser and MIG Arc Hybrid Welding

Takahiro Murakami¹⁺, Kazuhiro Nakata¹, Naotsugu Yamamoto² and Jinsun Liao²

¹Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan
²Technology Development Headquarters, Kurimoto Ltd., Osaka 559-0021, Japan

A hybrid welding of high power fiber laser and pulsed metal inert gas (MIG) arc was applied to titanium plate with 6 mm in thickness, and the optimum welding condition to make fully penetrated weld bead as well as the metallurgical and mechanical properties of the welded joint were evaluated. It is found that sound one pass fully penetrated square-groove butt joints without any weld defect can be made by optimizing the welding conditions mainly welding speed, arc current, laser power and laser focus position. The hardness and tensile tests indicate that heat affected zone and weld metal are stronger than base metal. It is considered that the strengthening is attributed to the increment of chemical compositions and substructures. [doi:10.2320/matertrans.M2012044]

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1. Introduction

Titanium and its alloys have been widely applied in aerospace, chemical and medical industries owing to their high specific strength, good corrosion resistance and excellent biocompatibility. Therefore, the welding and joining technology is imperative in order to apply them to various products. A major welding method of titanium and its alloys is tungsten inert gas arc welding, but it is difficult to make one pass fully penetrated weld bead in thick plates. Metal inert gas (MIG) arc welding may increase the weld efficiency, but one pass fully penetrated weld bead is also difficult to be made in thick plates. Besides, one of the drawbacks of MIG arc welding is related to the instability of the arc; however, this drawback of MIG arc welding of titanium is being resolved due to the development of titanium welding wire and the progress of pulsed MIG technology in recent years. In another way, laser beam welding (LBW) enables to make one pass fully penetrated weld bead in thick plate. In the past few years, many works have been conducted to investigate the fusion welding technology of titanium and its alloys, and most have been concentrated on the LBW because of its small welding deformation, narrow softening zone as well as convenient operation compared with electron beam welding, mainly based on the high power energy density and the fast welding speed. However, disadvantages of the LBW are the insufficient gap bringing ability and required precision in positioning. The hybrid welding, which combines LBW and arc welding, has been proven to be able to resolve these drawbacks of LBW, while maintaining the key advantages of laser welding and even improving the welding speed and penetration. Some works about hybrid welding of titanium plate have been conducted, however few works are reported about the hybrid welding of thick titanium plates. In this study, a hybrid welding of high power fiber laser and pulsed MIG arc was applied to pure titanium plate with 6 mm thickness, and the optimum welding condition to make fully penetrated weld bead as well as the metallurgical and mechanical properties of the welded joint have been evaluated.

2. Experimental Procedure

The material used in this study was the grade 2 commercially pure titanium sheet with 6 mm thickness. Filler wire with diameter of 1.2 mm and oxide layer on its surface was used. The chemical compositions of base metal (BM) and filler wire are shown in Table 1. As the hybrid welding heat sources, a 10 kW class IPG fiber laser and Daihen DC 500A pulsed MIG welder were used. The hybrid welding was performed in the combination of the laser at the trailing and the arc at the leading positions. Incident angle of the laser beam was tilted with 10 degrees to vertical direction and the arc torch was tilted with 25 degrees to vertical direction and at the opposite side of laser beam axis as shown in Fig. 1. The laser head with focus length of 310 mm and focus beam diameter of 0.47 mm was used, and the distance between laser and arc was 2 mm on the surface of the titanium plate for welding. During hybrid welding, the laser powers was 10 kW, and the focus position \( f_d \) ranged from bottom \( f_d = -6 \) mm to the top surface \( f_d = 0 \) mm of the plate, welding speed from 1.5 to 3.0 m/min, arc current from 125 to 200 A, root gap from 0 to 1 mm were selected in this investigation. Both the top and bottom surfaces of the welds were shielded using ultrahigh purity argon gas (99.9999%) with a flow rate of 50 L/min in order to minimise the surface oxidation. The welding conditions used in this study are

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Table 1 Chemical compositions of pure titanium and filler wire.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Ti</td>
<td>0.081 0.001 0.0039 0.04 Bal.</td>
</tr>
<tr>
<td>Filler wire</td>
<td>0.120 0.003 0.0050 0.03 Bal.</td>
</tr>
</tbody>
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¹Graduate Student, Osaka University

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shown in Table 2. After welding, the hybrid welds were cross-sectioned perpendicularly to the welding direction (WD) for the metallographic and mechanical analysis by an abrasive cutter. The cross-sections were mechanically polished using water abrasive papers, and then some of them were electropolished at room temperature for 30 s under a potential of 25 V in a solution containing perchloric acid, n-butyl alcohol and methanol at a volume ratio of 1:7:10. The polished cross sections were etched in a solution comprising of hydrofluoric acid, nitric acid and distilled water at a volume ratio of 1:1:8. The etched cross-sections were examined by an optical microscope. Electron backscattering diffraction was used to analyze the grain structure and orientation, using a scanning electron microscope incorporated with a TexSEM Laboratories. The electron backscattering diffraction maps were taken perpendicular to the WD. Small grains comprising fewer pixels were removed using the grain dilation option to ensure reliability, and a 15 degree criterion was used to define the low angle boundaries (LABs) versus the high angle boundaries (HABs). The hardness distribution at the cross-section was measured by a hardness testing machine. The dimensions of the specimen for tensile test are illustrated in Fig. 2. The tensile test was evaluated by means of a tensile test machine at room temperature, and three specimens with flat surfaces were made for each welding condition.

3. Experimental Results and Discussion

3.1 Comparison of welding processes

Bead appearances and cross sections of MIG arc, laser and hybrid welding joints are shown in Fig. 3, for comparison. MIG arc welding produced large weld reinforcement, but didn’t make a fully penetrated weld bead because MIG arc welding didn’t have enough penetration ability, while LBW made a fully penetrated weld bead but without weld reinforcement. Hybrid welding formed both weld reinforcement and a fully penetrated weld bead due to the filler wire addition and the high energy density of laser beam. It was confirmed that hybrid welding was an efficient process which had advantages of both LBW and MIG arc welding, even for the welding of thick plates of pure titanium as for the welding of thick steel plates.[14-20]

3.2 Effect of hybrid welding condition on bead formation

The effects of welding speed, arc current and focus position on bead formation of bead-on-plate welding are shown in Figs. 4(a), 4(b) and 4(c), respectively. Sound fully-penetrated weld beads were obtained at the welding speed of 2 to 3 m/min but large undercut and melt-through occurred because of overmuch heat input at the welding speed of 1.5 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min. Weld bead width became narrower and weld reinforcement became smaller as welding speeds was increased because heat input to workpieces decreased. On the other hand, when arc current was from 125 to 200 A and focus position from top to bottom of the plate, sound fully penetrated weld beads formed, provided that the welding speed was in the range of 2–3 m/min.
3.3 Bead appearance, cross section and microstructure
in square-groove butt weld

The bead appearances, macrostructures of cross section and X-ray radiographs in square-groove butt joint welds are shown in Fig. 6. The welding parameters were the arc current of 150 A, the welding speed of 2 and 3 m/min and the focus position of the plate center. One pass fully penetrated square-groove butt weld beads with silvery white surfaces and smooth reinforcements were obtained. In addition, X-ray radiograph inspection was carried out to evaluate the defect formation in these weld beads. It was confirmed that there was not any defect in these welds. Typical microstructures of base metal (BM), heat affected zone (HAZ) and weld metal (WM) at the welding speed of 2 m/min are shown in Fig. 7. A clear boundary between the BM and HAZ is easily distinguished because of microstructural difference. However, the fusion line is not accurately identified due to the similar microstructures formed in the HAZ and WM, and thus it is approximately asserted according to the location of weld root and weld toe. The equiaxed grains were observed in BM, and granular structures with large amount of substructures were observed in WM and HAZ.

3.4 Mechanical properties

In order to evaluate the mechanical properties of hybrid welded joints, hardness test and tensile test were performed. Figure 8 shows the hardness distributions on cross section of the hybrid welded joint obtained at arc current of 150 A, welding speed of 2 m/min and focus position of plate center. The hardness was measured along straight lines in the upper, middle and bottom parts of the welded joint, namely 0.5 mm below the top surface, plate center and 0.5 mm above the bottom surface. The WM hardness increased up to about 162 HV and also the HAZ hardness increased to about 155 HV in comparison with the hardness of the base metal, about 141 HV. The significant scatter in the hardness distributions was confirmed in the HAZ and WM, but not in the BM. There was no significant difference in the hardness distributions among the three parts.

Tensile test was performed to evaluate the strength of the welded joint obtained under the same welding condition as above. The average tensile strength, average elongation, fracture positions and photographs of tested specimens of the welded joint and BM are shown in Table 3. The average tensile strength of the welded joint was nearly identical with that of the BM. However, the average elongation was lower than that of BM, and all the specimens machined from the welded joint fractured at the BM. The tensile test result suggested that the HAZ and WM were stronger than the BM, which was accordant with the hardness test result.

3.5 Strengthening mechanism in hybrid weld

It is well known that the strength of pure titanium depends on the chemical compositions, especially on the concentration of N and O elements. The active titanium element inevitably absorbs a small quantity of other elements from the surrounding environment during welding, although welds with silvery white surfaces are obtained after welding. The chemical compositions in the weld, which was produced under the welding condition of arc current of 150 A, welding speed of 2 m/min and focus position of center of the plate, are shown in Table 4. The concentrations of O, H and N
elements in the WM were actually higher than those in the BM, and the increment of concentrations of these elements, which can be considered to originate from the air and the filler wire that contains higher concentrations than the BM, is one of the reasons for the strengthening in the WM. Additionally, it has been reported that strengthening in the HAZ and fusion zone is attributed to substructure in the grain in the LBW of pure titanium.9) The grain boundary maps of the various regions in the weld obtained at the same condition are shown in Fig. 9. The HABs (solid black line) were the α grain boundaries, while the LABs (solid grey line) depicted the substructures within the α grains. As seen from the grain boundary maps in Fig. 9, there were many substructures in the HAZ and WM while the substructures in the BM were few. The result was similar to that of LBW, thus it can be considered that the strengthening in the HAZ and WM of the hybrid welds are partly attributed to the substructures, similar to that in LBW welds. In addition, as shown in Fig. 10 where the (0001) pole figures of various regions in the weld are revealed, there was an evident concentration of grain orientation with the basal plane close to the edge part of the pole figure in the BM, but the grain orientation in the HAZ and WM was random. It has been reported that the relatively high hardness is detected when indenting into the basal plane, whereas the low hardness is found when indenting into the prismatic plane, in measuring the hardness of such metals having the hexagonal close packed structure as pure titanium.9,22,23) For the above reasons, the scatters in the hardness distributions occurred in the HAZ and WM of hybrid welded joint.

4. Conclusions

The hybrid welding of pure titanium plate was carried out, and the optimum welding conditions, mechanical properties and strengthening mechanism in the welds were investigated. The results can be summarized as follows.

(1) The one pass fully-penetrated weld beads without any weld defect were obtained at the laser power of 10 kW, welding speed of 2 to 3 m/min, focus position of plate center. The gap allowance was about 1 mm for the hybrid welding.
(2) The average hardness in the HAZ and WM was higher than that in the BM, and the scatters were found in hardness distributions in the HAZ and WM. The tensile strength of hybrid welded joint showed the same value as that of BM under the optimum welding conditions, and the fracture of all the tensile specimens occurred at the BM, implying that the HAZ and WM were stronger than the BM.

(3) The strengthening in the WM was attributed to both the increment of concentrations of O, H and N elements and the substructures within the grains, and the substructures was also the reason for the strengthening of the HAZ. The significant scatter in hardness distribution in the WM and HAZ was caused by the random of grain orientations.

REFERENCES