Effect of applying electrical potential to a CO₂ laser welding of different thickness plates

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Abstract

This study was aimed at developing laser welding with an applied voltage potential to increase the bead root width in laser welding. Also, in order to enhance the welding speed and the butt joint gap tolerance, the influences of the experimental conditions: supplied voltage between plate and backside electrode, welding speed, plasma operate gaseous species, and the butt joint gap, on the bead root width were investigated. Although it is necessary to avoid over heating and melting the plates, it is applicable for higher speed and wider gap butt joint welding than a conventional laser welding. In the case of butt joint welding with a thickness of 2.0 and 0.8 mm steel sheets by using 5 kW CO₂ laser system, it is concluded that this method is effective for increasing of the welding speed from 5 to 8 m/min. Knowledge of optimum conditions and configurations has guided to extend this process to more challenging structural materials such as a tailored blank steel sheet.

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1. Introduction

Tailored Blanks (TBs), consisting of different thickness plates or different strength plate, is newly concept material that can reduce total weight of automobile; thus, it is available to decrease amount of exhaust NOx [1–4] gas. To manufacture the TBs, we have investigated some joining techniques. Laser welding is a promising method of applying to the TBs.

The static strength and fatigue strength of welded joint depend substantially on features, such as bead height, smoothness of the bead surface, under-fill, under-cut and so on, that exist because the amount of molten metal, temperature of molten metal, and gravity relate to the bead morphology complexly. A required minimum bead height is considered to be 70% of plate thickness for the same thickness butt joint. The smoothness of the bead surface and penetration depth of the bead, particularly, is fairly sensitive to the gap at the butt joint between two plates. The bead root, however, is so narrow that accurate beam focusing on the plates and precise setting of the beam are required for butt joint laser welding. It must therefore be preferable to widen the bead root for industrial application of laser welding.

A laser welding with an argon gas shielding is that generated plasma on the plate heats itself [5,6]. The injected argon gas is ionized by the energy of the laser beam passing through the plate. Although this plasma can enlarge the width of bead root, its heat input is not sufficient to increase the bead root width significantly. Additionally, because the laser beam generates plasma on the bead root plate surface spontaneously, its width cannot be controlled affirmatively. A further heat source to heat the bead root is a tungsten inert gas (TIG) arc jet [7]. This TIG arc is superposed with the laser beam onto the weld bead root. In contrast to the spontaneous argon shield plasma, with the TIG arc it is possible to control the input power. The problem associated with this technique is that the tungsten cathode of TIG apparatus is consumed at such a rate that endurance of this process might be too short.

To overcome such problems, we have developed laser welding with an applied electrical potential [8]. H.C.Tse has investigated electric and/or magnetic effect fields on plasma control during laser welding [9,10]. This method, however, applied these filed to the plasma on the side of molten metal.
surface not root surface. In our method, during laser welding, an electrical potential is applied between the plates and a copper electrode, which is set below these plates, with plasma operation gases such as argon, helium, and hydrogen being injected into the space between the plates and electrode. Plasma is generated between the point where the laser beam emerges from the plate and the point where this transmitted laser beam strikes the electrode, because those points are heated and thermally excited, and can therefore function as a cathode spot and an anode spot. Previous our study reports that this method is effective in increasing the root bead width and the melting area for bead on plate welding. Also, even though, it is necessary to avoid overheating and melting of the plates, it is applicable for higher welding speed and wider gap butt joint welding in the same thickness plates.

This paper describes the application of the laser welding with an applied electrical potential to a welding of different thickness plates to increase the bead root width in order to enhance the welding speed and the butt joint gap tolerance. The influences of the experimental conditions: supplied voltage between plate and backside electrode, welding speed, plasma operate gaseous species, and the butt joint gap, on the bead root width were investigated. The difficulty of this method is considered to not only be obtaining the correct energy balance between the transmitted and residual laser beam power and the applied electrical potential, but also plates’ arrangements, gap and beam position, for laser welding in different thickness plates. In order to enhance the butt joint properties, the static strength and fatigue strength of welded joint, bead features must be optimized. Also from viewpoint of industrial application, higher welding speed is preferable. Therefore, supplied voltage between plate and backside electrode, welding speed, plasma operate gaseous species, and the butt joint gap, on root bead were investigated on several plate thickness combination. Knowledge of optimum conditions and configurations has guided to extend this process to more challenging structural materials.

2. Experimental details

Fig. 1 shows experimental configurations for laser welding with applied electrical potential. A CO₂ laser (Mitsubishi-Denki, model 50C) operating at 5 kW was used as the laser beam source. The laser beam, with a focal length of 200 mm and focused-spot diameter of 0.45 mm, was irradiated on the surface of the plate 1 whose thickness was thicker than plate 2. Both plates were mild steel SS45 with a thickness of 0.8, 2.0, or 3.2 mm and the performed thickness combinations of those plate were 0.8:0.8, 2.0:2.0, 3.2:3.2, 3.2:2.0, 2.0:0.8, and 3.2:0.8 in mm. The focus position was varied in the ranges from −1.0 to 1.0 mm. An insulated copper electrode was located below the sheet and a distance, between plate and electrode, of 5 mm. Electrical power, 0–1.4 kW, was supplied by a TIG power supply (Daihen, model ARGO 300P) connected to the sheet plate and the copper electrode. The plasma gas, a mixture of argon (0–20 l/min) and helium (0–20 l/min), was injected from 17 pairs of holes, of diameter 1.5 mm and pitch 10 mm, symmetrically arranged a short distance from either side of the electrode.

The TIG power source operates in current constant power mode; thus, first an applied electrical current value is set between the plates and electrode with the injection of plasma gas. Then, laser beam irradiation is started using the moving plate and electrode. During welding, the voltage between the plates and electrode was measured via a shunt that converted current to voltage (500 A–50 mV). The copper electrode was set as an anode due to the benefit of the stability of the plasma [8]. The welding speed was varied 1–10 m/min and a co-axial shielding argon gas flow rate was 20 l/min. In present work, we expressed a butt gap to be

Fig. 1. Schematic experimental configuration for method of laser welding with an applied electrical potential for butt joint welding; during laser welding, electrical potential is applied between plates and copper electrode with injection of argon, helium, or hydrogen plasma gas.
Gap, controlled by thin foil in the gap, and a out of setting the beam, distance from the beam centerline to the butt root face of plate 1, to be $L_a$. Selected that value was in ranging of 0.0–0.3 mm and of −0.3 to 0.3 mm, respectively. In present work, $L_a$ is expressed with a ratio of $L_a$ to Gap.

For applied this laser welding to the butt joint welding of different thickness plates, for butt joint welding with the same plate thickness, the effects of experimental parameters on the bead stability and bead shape were evaluated, using the bead height which was defined as a thickness of weld metal at bead center, melting area, root bead width and the ratio of bead root width to bead face width. Those factors were estimated from observation of bead face, a bead root surface and three cross-sections for each welded bead. The bead stability was determined by assessing the uniformity of the three cross-sections. If all three cross-sections were almost equal, the experimental condition was defined as stable. If only two of the three cross-sections were equal or all cross-sections were different due possibly to weld bead humping, the conditions were defined to be unstable. An available bead height criterion in this study was set to be more than 70% to the plate thickness. The other observed values were guidelines to evaluate the effect of irradiated plasma on the under surface of the plate to utilize melting it. The root bead width mainly informed added heat input by plasma from under surface of the plate, melting area did from not only under surface but also butt gap. Assumed preferable the ratio of root and surface bead width to be 100 to improve gap tolerance and ease to precise beam setting.

Also, for butt joint welding with different thickness plates, experimental parameters were mainly selected from effective values in cases of both thickness plates condition. In the case of different thickness plates welding, the experimental parameters on the root bead width to effect of plasma as an added heat source, and the existence of under-fill and under-cut, moreover as a criterion determining possible experimental parameters such as a welding speed and butt gap.

3. Results and discussion

3.1. Welding for same thickness plates

Fig. 2 shows comparison of the effect of welding speed on the melting area in the cases of bead on plate welding and that in the case of butt joint welding. As expected, the melting area decreases with increasing welding speed. Also, it is easy to understand that the melting area in the butt joint welding is smaller than that in bead on plate welding, caused by the passing laser beam through the butt gap without absorption into plates. Here, by comparison of the melting area in both cases, an energy loss, $\eta$, useless to melt the plate due to the gap, was defined as;

$$\eta = 100 \left(1 - \frac{S_{\text{Gap}}}{S_{\text{bead on}}} \right)$$

where $S_{\text{Gap}}$: melting area at butt welding with Gap, $S_{\text{bead on}}$: melting area at bead on welding. Therefore, heat conduction or radiation losses were neglected. The estimated loss is shown in Fig. 3. As will be shown, for a welding speed, the energy loss increases up to be around 50%. An objective of our study is to reutilize the loss laser energy that may help to heat and to melt the plates by using applying electrical potential. First, the bead stability was investigated for a butt joint welding of the same thickness plates.

Fig. 4 shows maps of the bead stability in relation to applied electrical potential (represented by TIG current, as elsewhere) and welding speed. In the case of that plasma operated argon flow rate is 10 l/min, shown in Fig. 4(a), it
can be seen that welding with an applied current less than 15 A (14 V) and welding speed greater than 7 m/min is found to be stable. For currents greater than 30 A or welding speed lower than 5 m/min the welding is unstable even though the amount of weld metal is sufficient. Therefore, this process is applicable higher welding condition by selecting the optimized TIG current to enhance amount of weld metal and to prevent from the instability, here humping, of the bead due to overheating and melting. The wider stable TIG range will be more help to utilize this
process. The choice is employing more plasma operate argon gas flow rate is critical to expand the bead stability. Fig. 4(b) presents maps of the bead stability in the case of argon shielding gas flow rate to twice higher than that in Fig. 4(a) case. As shown here, the possible current extends to be 30 A. Although detailed analysis was not carried out in this work, one of the primary possible reason is that, higher gas flow rate decreases plasma temperature and then restrains to overheat the weld metal and to form humped bead.

The effect of the supplied TIG power on the bead shape is shown in Fig. 5, the bead root/surface width ratio, root bead width, melting area, and bead height with a plate thickness of 0.8 mm.

Under conditions with an argon gas flow rate of 0 l/min, it is hard to form spontaneous and/or laser induced plasma, on the under surface of the plate, that attributes to establish the plasma, good electrical conductor, between plate and Copper anode. Thus, even though supplying TIG current between them, no current, actually, was supplied and setting current vale does not affect the bead shape. In this case, 0.10 mm Gap is an almost gap limit for the butt joint welding under conventional laser welding.

In present works, conditions with a TIG current of 0 A with argon gas corresponds to the laser welding only with argon back shield gas, and then is expected to heat from root face by spontaneous argon plasma. It is clear that the

Fig. 6. Effect of the TIG current on the bead root/surface width ratio, root bead width, melting area, and bead height with a plate thickness of 2.0 mm, laser power of 5 kW, the welding speed of 7 m/min, and beam focusing of 0 mm.

Fig. 7. shows the effect of deviation of laser beam irradiation on the root bead width in the case of a conventional butt joint laser welding of plate thickness combination of 3.2 and 2.0 mm. Deviation is determined by the distance from the thicker plate edge and plus direction is defined as thinner plate. Welding speed of 4 m/min.
existence of plasma operated argon gas, spontaneous plasma, critical only increases root bead width, but little affects amount of weld metal. These results mean that the spontaneous plasma could only slightly provide heat input onto the root bead but not enough.

Conversely, the supplying electrical potential to the welding with a gap of 0.1 mm, while increasing the enthalpy due to increased arc power, is found to have unexpected impact on the melting area and bead height for increasing current. However, above 30 A (22 V), the benefit of increased plasma power was apparently offset by the increases the humping caused by exceeded heat input. Furthermore, in the case of gap of 0.15 mm, similar tendency is obtained. At a current of 30 A, bead height is beyond 70% to plate thickness, value to obtain minimum weld joint strength, of plate thickness and it is the very limit of what is permissible. Thus, the optimum currents are around 30 A (22 V) with a gap of 0.10 and 0.15 mm in the butt joint welding of 0.8 mm thickness plates. From the standpoint of bead stability, root gap of 0.15 mm is superior to that of 0.1 mm.

As mentioned above, the tolerance of root gap was 0.10 mm in the conventional welding and that was 0.15 mm in our process. This value therefore must be 1.5 times higher than that of conventional laser welding.

These figures assert that the approximate enhancement of melting area and root bead width, and bead height is 70, 70 and 20%, respectively. Here, expected energy inputs from laser beam and plasma are 5 and 0.7 kW, increased energy input of those cases is below 15% estimated by (0.7)/5. An applied electrical potential therefore must contributes to reutilizing laser beam power in somewhat.

In order to weld different plate thickness combination, the same investigation for another plate thickness was carried out. Fig. 6 shows the effect of the supplied current on the bead shape for the butt joint welding with a gap of 0.10 or 0.15 mm using plates with a thickness of 2.0 mm. For a current, all values increase and possible current also 30 A. The approximate enhancement of melting area and root bead width, and bead height is 50, 40 and 15%, respectively.

The possible current for the butt joint welding of 3.2 mm plates was also almost 30 A, and then it is found that the possible current for each plate thickness is independent of plate thickness. This result inferred that induced plasma affect on only root surface or shallow area on inside gap. Based on these knowledges, we have selected TIG current of 30 A to the welding of different thickness combination.

4. Welding for different thickness plate

Fig. 7 shows the effect of deviation of laser beam irradiation on the root bead width in the case of a conventional butt joint laser welding with a plate thickness combination of 3.2 and 2.0 mm. This figure illustrates the root bead width is maximized at a deviation of −0.04 mm. For a welding of different thickness plates, bead formation
mainly depends on the thicker plate and thus, it is prefer to irradiate laser beam on the thicker plate edge slightly as effective as to be the molten metal moved from thicker plate to the gap.

Fig. 8 shows the cross-sectional photographs of weld bead in the butt joint welding with a deviation of $-0.04$ mm. It is found that, in the case of conventional laser welding, the narrow root bead width and under-cut are observed, and then an available welding speed in this conventional welding is less than 4 m/min. Conversely, in the case of laser welding applied electrical potential, the weld bead assisted by argon plasma has a relatively wider root bead. Moreover, on employing a mixture of 50% helium and 50% argon as a plasma operate gas, it is obtained a sufficient root bead width and no under-cut due to the improvement of heat transfer from root surface to molten metal during welding caused by using helium, higher heat transfer coefficient than argon gas. For a higher welding speed, 4.5 m/s, even adding electrical potential and using argon—helium mixture gas, under-cut is observed.

Fig. 9 demonstrates the effect of welding speed on the root bead width for the butt joint laser welding in shown Fig. 8. As expected, by adding an electrical potential, the root bead width is twice wider than that in conventional laser welding with a welding speed of 4 m/min. With a Gap of 0.3 mm, welding speed is restricted to be 3.5 m/min owing to the ability of bead formation. The choices of Gap to be 0.15 mm contributes to enhancing welding speed up to 4 m/min. Additionally, the choice of deviation to be $-0.04$ mm contributes to the width to be wide.

For a butt joint welding with a plate thickness combination of 3.2 and 2.0 mm and with a Gap of 0.15 mm, an available welding speed, totally, is improved up to be 4 m/min by using our technique.

Similarly, butt joint welding with a plate thickness combination of 2.0 and 0.8 mm has been investigated. Fig. 10 shows cross-sectional photos that express the effect of supplied electrical potential and plasma operated gaseous species on bead shape of laser welding. Welding speeds indicated in this figure are the speed in which under-cut and instability of weld bead can be avoided.

Based on this criterion, the welding speed in the conventional laser welding is 5 m/min and that in our developed process is 8 m/min under optimum conditions such as a helium mixing ratio of 50%, TIG current of 30 A.

Fig. 11 shows the effect of welding speed on the root bead width in the butt joint welding of 2.0 and 0.8 mm in thick plates. At a welding speed of 5 m/min, the electrical potential, with argon gas flow rate of 20 l/min, archives to improve the root bead width to be almost 1.5 times larger than does conventional welding. Even the root bead width, as expected, decreases with increasing welding speed, helium gas, also, contributes to enhancement of the root bead width.

5. Conclusion

The developed laser welding with an applied voltage potential, supplied electrical potential inducing plasma on the root bead surface during welding, can enhance root bead width and melting area under the optimum conditions.
related to supplied voltage between plate and backside electrode, welding speed, plasma operate gaseous species, and the butt joint gap complexity.

The choice of current lower than 30 A was substantial on the bead stability, to avoid over heating and melting the plates. Several other effects such as welding speed, gaseous species and each gas flow rate, were observed that were predictable. The root bead width and melting area increased with adding electrical potential and helium gas indicating higher thermal conductivity. From the standpoints of laser beam deviation, distance from the beam centerline to the butt root face of thicker plate, it was determined that laser beam should be irradiated on approximately 0.04 mm away from gap centerline to thicker plate side.

The possible welding speed, in the case of butt joint welding with a thickness of 2.0 and 0.8 mm steel plates, increases from 5 to 8 m/min, and its gap tolerance is improved to be 1.5 times higher than does a conventional laser welding. Hence, it is applicable for higher speed and wider gap butt joint welding than a conventional laser welding. The surprising results warrant further study if they are deemed to impact the conditions for laser welding.

It should be noted that, to improve the welding speed and gap tolerance, employing a high power CO2 laser system, with a laser power of higher than 5 kW, is effective and common. On the other hand, a commercial maximum laser power of YAG laser is less than 6 kW. In future works, as a laser beam source, YAG laser, with an advantage in transmission of laser beam through fiber and then flexibility of welding position, might be applicable. The disadvantage in employing YAG laser is that the temperature of spontaneous plasma or plume in YAG laser welding is lower than that in CO2 laser system and then the stabilization of induced plasma will be required.

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