Trans. JWRI, Vol. 27,(1998), No. 2

Laser Beam Welding of Lap Joints of Dissimilar Materials

Akira Matsunawa*, Abdel-Monem El-Batahgy** and Bahaa Zaghloul**

Abstract

This investigation has been concerned with CO_2 laser welding of austenitic stainless steel in lap joints with Zn-coated carbon steel. The focus was made on weld joint quality in terms of weld profile, porosity in the weld zone and liquid metal embrittlement (LME) cracking of the austenitic stainless steel base metal. The influence of type and flow rate of shielding gas, gap between the sheets, and Zinc removal prior to welding was clarified. Complete weld joint penetration with acceptable weld profile free from pores can be made without a gap between the sheets providing a relatively high flow rate, 30 l/min of Argon or Helium is used as a shielding gas. Welds made at higher flow rates showed unacceptable weld profile. Shielding gas flow rate can be reduced to 15 l/min by using a preset gap of 0.025-0.05 mm between the sheets. Welds made by larger gap showed excessive drop-through of the weld metal into the gap. However, LME cracking induced in the austenitic stainless steel base metal by molten Zinc cannot be avoided, regardless of the type and flow rate of shielding gas and gap distance between the sheets. The only way to produce high quality lap welds of these dissimilar materials to avoid both porosity in the weld zone and LME cracking in the austenitic stainless steel is the complete removal of Zinc coating from the joint area prior to welding.

KEY WORDS : (CO_2 laser welding)(Dissimilar lap welds)(Shielding gas type and flow rate)
(Gap between the sheets)(Porosity)(Liquid metal embrittlement cracking)

1. Introduction

Because of its excellent corrosion resistance, austenitic stainless steel has found widespread use in the paper making equipment, including pressure vessels, storage tanks, piping, hopper, bins, chutes and structural components. For all of these applications, attachments such as access platforms, catwalks, stiffeners, column supports, stairways, washers and pipe hangers are welded to the outside surfaces of the equipment. Zn-coated carbon steel is often specified for these attachments due to its good corrosion resistance and lower cost. Lap weld joints of Zn-coated steel to austenitic stainless steel are used also in other fields such as plate-tube joints, radiators, washing machines as well as some components in the aeronautic field[1)].

Although welding of Zn-coated steel to austenitic stainless steel is a common practice, it presents serious problems of weld zone porosity and LME cracking of austenitic stainless steel base metal due to Zinc vaporization. These welding problems have been studied in the case of conventional metal arc welding processes [2)]. It is reported that joining gaps between the sheets to be lap welded are adjusted in order to allow the degasification of Zinc vapour.

On the other hand, laser butt and lap weld joints of both similar and dissimilar materials are being used in many industrial applications. The proportion of laser welding in all industrial applications is about 15-25% and varies from country to country[3-5)]. The most notable features of laser welding compared with other conventional welding processes are the high weld quality and high welding speed. These together with its low heat input makes the laser a most hopeful candidate for thin sheet metal welding.

However, similar problems as in conventional metal-arc-welding of Zn-coated steel to austenitic stainless steel are expected also in case of laser beam welding. Therefore, more work is required for understanding these problems and the factors affecting them.

The present investigation aims at defining the parameters affecting laser weld quality of Zn-coated steel in lap joints to the austenitic stainless steel. Quality of weld joints was evaluated as a function of weld zone shape, porosity and LME cracking of austenitic stainless steel base metal.

2. Experimental Procedure

Commercial types of ASTM A36, 0.7 mm thick carbon steel sheet coated with 10 μm Zinc on both sides and ASTM A240 Type 304L, 1mm thick stainless steel sheet were used for dissimilar lap joints. **Table 1** shows

---

† Received on Dec. 8, 1998

* Professor
** Associate Professor and Professor, Welding Research Dept., Central Metallurgical R & D Institute, Cairo, Egypt.

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

Table 1 Chemical composition (wt %) and mechanical properties of used base metals

Base Metal	C	Mn	Si	S	P	Cr	Ni	YS (N/mm^2)	UTS (N/mm^2)	Elong. (%)
Zn-coated	0.04	0.35	0.26	0.01	0.02	-	-	245	377	27
304L	0.04	1.70	0.35	0.01	0.03	18.2	8.5	359	558	32

Table 2 Laser welding parameters

P (kW)	S (m/min)	D_d (mm)	Shielding gas		Gap between Sheets (mm)	Zinc Removal Prior to Welding
			Type	Flow rate (l/min)		
2.5	3	-0.1	Argon	15-30	No	No
2.5	3	-0.1	Helium	15-30	No	No
2.5	3	-0.1	Argon	15	0.025-0.3	No
2.5	3	-0.1	Helium	15	0.025-0.3	No
2.5	3	-0.1	Argon	15	No	Yes
2.5	3	-0.1	Helium	15	No	Yes

P: Laser power, S: Welding speed, D_d: Defocusing distance,
Working distance: 10 mm at D_d=0 mm, Nozzle diameter: 4 mm

their chemical composition and mechanical properties.

Pairs of these dissimilar steel sheets of 150 x 150 mm were welded with an overlap of 50 mm and with the weld bead at the middle of the overlap. Zn-coated steel sheet was upper-most and the joint was clamped 15 mm on both sides of the weld line along its entire length. Configurations of laser lap weld specimens are shown in **Fig. 1**. All specimens were ultrasonically cleaned to remove dirt and oil prior to welding.

Welding was performed using a CO_2 laser with a maximum output of 3 kW operating in multi-mode. The beam was focused using a parabolic mirror with 150 mm focal length. Laser beam welding parameters used are summarized in **Table 2**. Optimizing laser power, welding speed and focal point position is of considerable importance for weld quality in terms of fusion zone size and profile. In order to clarify the influence of shielding gas, gap between the sheets and pre-weld Zinc removal on weld quality, laser power, welding speed, and defocusing distance (focal point position) were optimized and kept constant at 2.5 kW, 3 m/min, and 0.1 mm below specimen surface respectively. Shielding was done using Argon or Helium with flow rates of 15-30 l/min. Prescribed gaps ranging from 0.025 to 0.3 mm was introduced between the sheets along the clamped areas of the welding fixture. Pre-weld Zinc removal from the weld area was done by grinding.

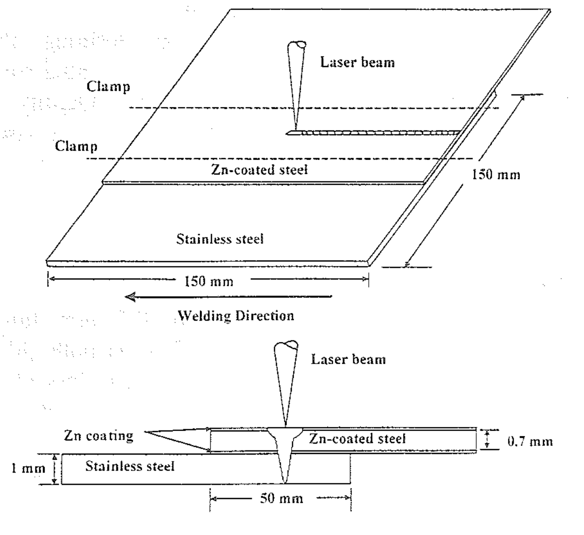

Fig. 1 Configurations of the used laser lap weld specimen

After welding, the specimens were subjected to non-destructive testing including visual and dye penetrant test methods then, sectioned transverse to the welding direction. Three sections of each seam weld were prepared for metallographic examinations using standard technique. Quality of the dissimilar lap joints was evaluated as a function of weld profile, porosity level in fusion zone, LME cracking in austenitic stainless steel base metal. Tensile shear tests were carried out for all laser lap welded joints and the data reported are the average of three individual results.

3. Results and Discussion

3.1 Effect of Shielding Gas

Examples of macro-graphs of laser welds produced using Argon and Helium as a shielding gas with a flow rate of 15 l/min are shown in **Fig. 2(a)** and **(b)** respectively. It is clear that non-uniform weld beads with large pores were obtained in both cases. However, wide seam width combined with an increase of the frequency of pores was obtained with Argon (Fig. 2(b)). In other words, the number of pores was much less with using Helium as a shielding gas (Fig. 2(b)). This means that shielding gas type is an essential factor to improve weld quality since it is used to protect the molten metal against oxidation and blow the plasma away from the beam path.

Generally, when welding Zinc coated steel with stainless steel there is a very strong plasma formation due to the low boiling point of Zinc (906 °C) and it's high vapour pressure, which is about eight orders of magnitude greater than that of Fe [6]. The high vapourization rate of Zinc increases the pressure of the vapour, which is transformed to plasma in the laser beam, and expand further into the free space above the metal surface. This will affect the absorption and fluctuation of the plasma and in practice this is shown as increased spattering and porosity in the weld. This plasma effect was reduced as a result of the higher ionization potential of Helium then, weld quality was improved.

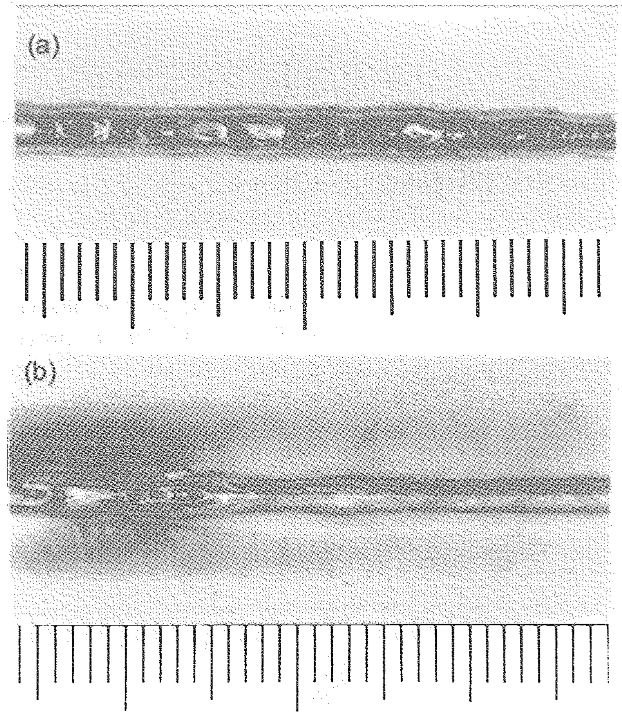

Fig. 2 Macrographs of laser welds produced using (a) Argon and (b) Helium as a shielding gas with 15 *l*/min flow rate

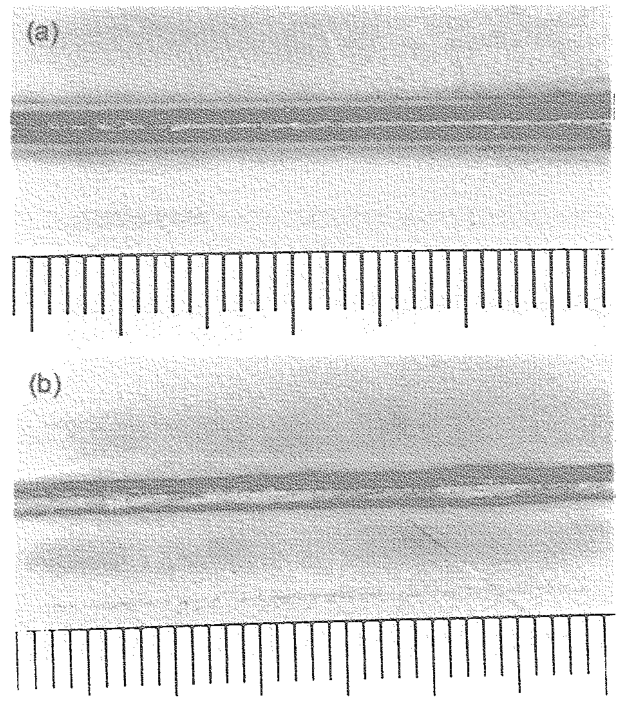

Fig. 3 Macrographs of laser welds produced using (a) Argon and (b) Helium as a shielding gas with 30 *l*/min flow rate

With this relatively low flow rate, the process seemed to change swiftly between deep penetration welds and vapour assisted welds. This may be explained by the presence of Zinc, which makes the process unstable due to plasma fluctuation as has reported in a prior investigation[7]. Consequently, optimized shielding gas flow rate makes the difference between a good or poor weld.

With increasing shielding gas flow rate above 15 *l*/min, the number of pores in seem welds decreased and weld pool penetration was increased. Examples of macro-graphs of laser welds produced using higher flow rate, i.e., 30 *l*/min of Argon and Helium as a shielding gas are shown in **Fig. 3(a)** and **(b)** respectively. It is obvious that smooth and homogeneous seam welds free from pores were obtained in both cases. The increase in penetration depth obtained in this case is consistent with the expected effect of increased plasma suppression with increased flow rate, i.e., more of the beam is allowed to reach the work-piece. However, there appeared to be a trade-off between plasma suppression effects and weld pool stability with increase shielding gas flow rate.

Turning to shielding gas type, it was found to remarkably affect weld zone profile. Low magnification stereoscopic photographs of cross sections taken from laser welds of Fig. 3(a) and (b) are shown in **Fig. 4(a)** and **(b)** respectively. The use of Helium has resulted in complete penetration with higher depth/width ratio and a slight taper configuration which means minimum fusion zone size (Fig. 4-(b)) in comparison with that obtained using Argon (Fig. 4-(a)). In other words, Helium has a more favorable effect on the molten metal than Argon at optimized flow rates, which make the welds more homogeneous and free from pores. A flow rate of 22 *l*/min for Helium was found to be satisfactory in comparison with 30 *l*/min for Argon. These results do conform with prior results of other investigators where they have shown that the weld defects, due to the vapourization of Zinc, can be reduced by optimizing shielding gas parameters [8-10].

On the other hand, it is found that both type and flow rate of shielding gas have no effect on LME cracking of austenitic stainless steel. **Figure 5** shows a typical example of optical micro-graph of a cross section taken from lap weld produced using Helium with its optimum flow rate, i.e., 30 *l*/min. In spite of obtaining homogeneous, sound, complete penetration and acceptable weld profile with such high flow rate, the noticeable feature is the formation of severe cracking at the stainless steel base metal. These cracks extended for a distance of about 0.7 mm around both sides of lap weld joints and propagated on grain boundaries. This type of cracking is typical LME cracking of the austenitic stainless steel which occurs above 750 °C when it is exposed to molten Zinc and tensile stresses. Molten Zinc can be produced by the heat of welding and tensile stresses can be generated from the heating and cooling cycles during welding. This cracking type is characterized by extremely rapid crack propagation perpendicular to the applied stress[11]. It should be mentioned also that similar results were obtained for lap weld joints produced using Argon gas shielding.

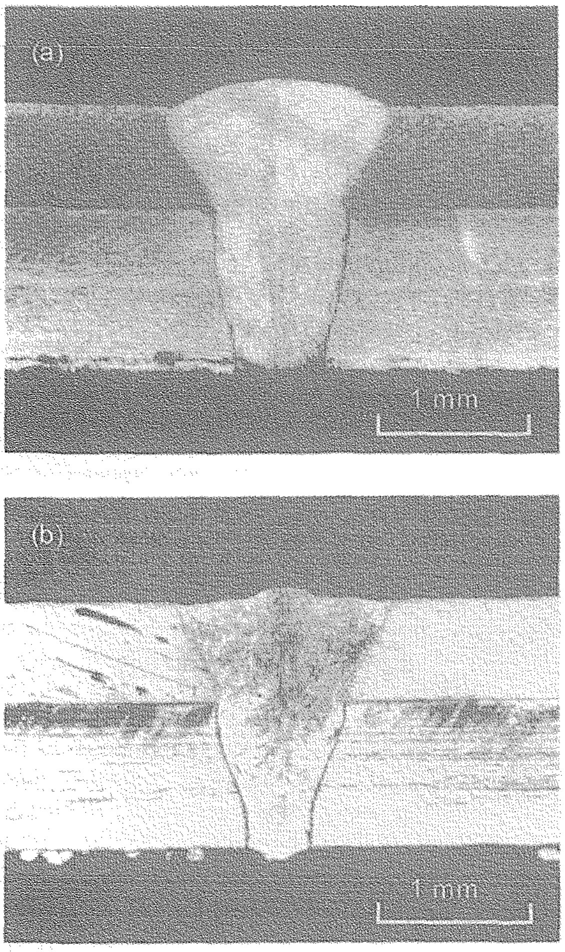

Fig. 4 Low magnification stereoscopic photograghs of cross sections taken from laser welds of Fig. 3

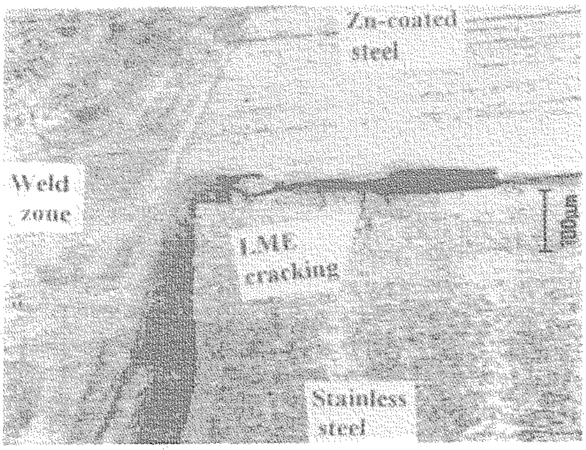

Fig. 5 Typical example of optical micrograph of a cross section taken from laser welds produced using Helium as a shielding gas with its optimum flow rate; 30 *l*/min

3.2 Effect of Gap between the Sheets

In the above section, lap welds were made with a good contact, i.e. without a gap between the sheets. In order to clarify its effect on weld joint quality, a gap was introduced between the sheets with shielding using either Argon or Helium with its lower flow rate (15 *l*/min) which resulted in weld porosity in the previous experiments.

Typical examples of cross section taken from laser lap welds produced using 0 and 0.025 mm gap between the sheets in case of Helium shielding are shown in Fig 6(a) and (b) respectively. As has been explained in the previous section, no-gap welds with such low shielding gas flow rate showed unacceptable levels of porosity with varying amounts of top surface undercutting and center-line humping of the weld bead (Fig. 6(a)). The Zinc vapourization from the underside of the joint in the case of complete weld penetration is not sufficient to prevent porosity formation. Introducing a small gap distance between the sheets with same welding conditions resulted in a sound weld where porosity was not observed (Fig. 6(b)). Also, weld profile was remarkably improved where a smooth curved and symmetrical fusion zone was

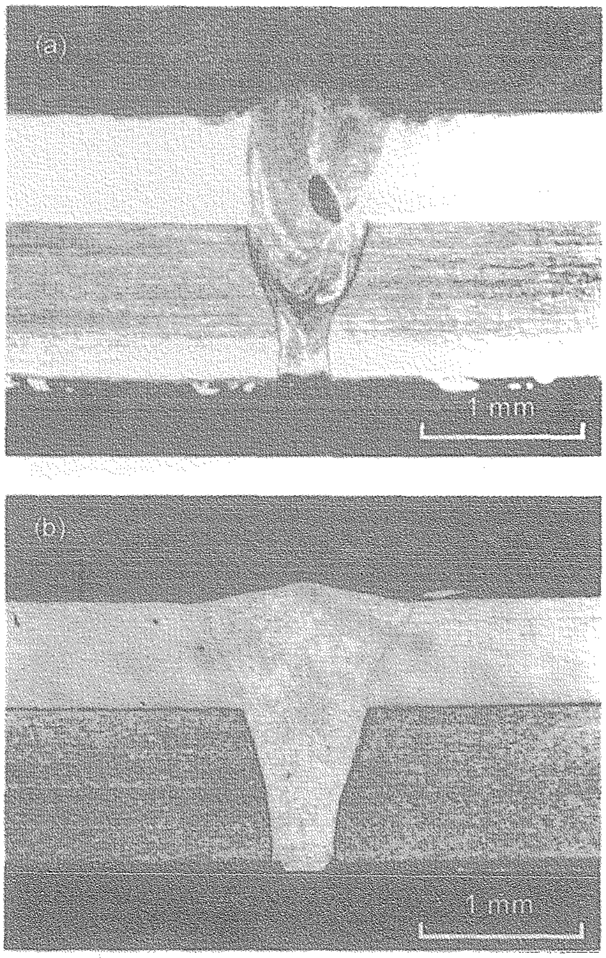

Fig. 6 Typical examples of cross sections taken from laser lap welds produced using 15 1/min Helium and different gap distances ((a) Gap: 0 mm, (b) Gap: 0.025 mm)

obtained.

In other words, acceptable quality for laser lap welds concerning soundness and profile could not be obtained with low shielding gas flow rate and no gap between the sheets. Once the heat input was sufficient to permit melting through the top sheet, there was explosive ejection of molten weld metal due to vapourization of the Zinc layers at the Zn-coated steel sheet-to-stainless steel sheet interface. This resulted in extensive weld metal porosity or complete expulsion of the weld metal in the case of no-gap weld leading to undercutting the top steel sheet, as shown in Fig. 6(a). This is in a good agreement with results previous investigations[12].

Generally, no porosity was found in any of the welds made with introduced gap between the sheets. However, welds made using gaps larger than 0.05 mm showed unacceptable weld profiles where weld depth /width ratio decreased sharply and the weld geometry began to deteriorate. Photographs of laser weld cross sections produced using 0.1 and 0.3 mm gaps are shown in **Fig.** 7(a) and (b) respectively. A gap distance of 0.1 mm gave a concave top surface, with a relatively low depth/ width ratio (Fig. 7(a)). The tendency of the molten pool to collapse increased significantly when increasing the gap to higher values. This resulted in remarkable undercut in the welds and excessive drop-through of the weld metal into the gap (Fig. 7(b)).

Generally, there are two mechanisms in laser welding, one is heat conduction under low energy density and the other is deep penetration (keyhole effect) under high energy density. In these experiments, the laser power density when laser beam touched the surface of the top sheet was high enough to melt the metal rapidly and formed the deep penetration. The power density greatly decreased when approaching the bottom plate, particularly in case of large air gaps between both plates that obstructed heat transfer. At this time, the heat transfer was mainly by means of conduction, which was illustrated by the weld shape and penetration depth. Based on the weld shape, the fusion lines at both sides of welds were approximately parallel under deep penetration welding conditions, while the fusion line was half circle under heat conduction welding. Consequently, under such experimental conditions, the welding mechanism of lap joints was a combination of deep penetration and heat conduction.

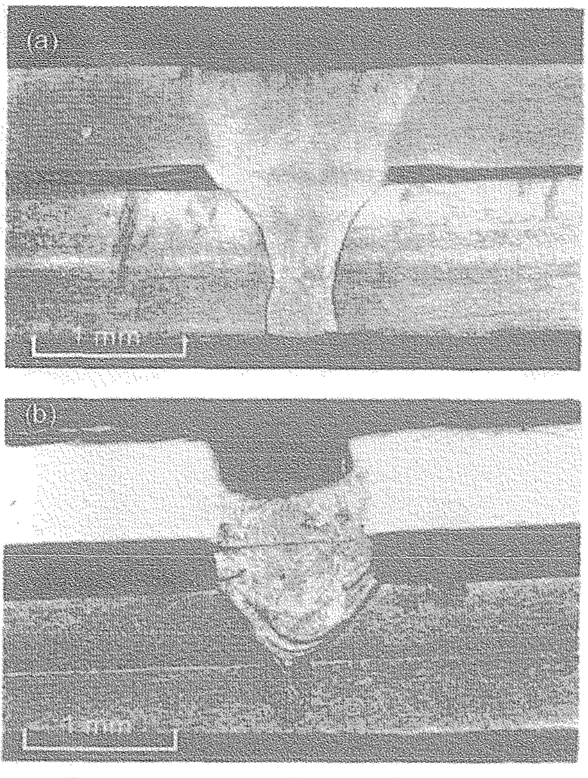

Fig. 7 Photographs of laser weld cross sections produced using (a) 0.1 mm and (b) 0.3 mm gap between the sheets

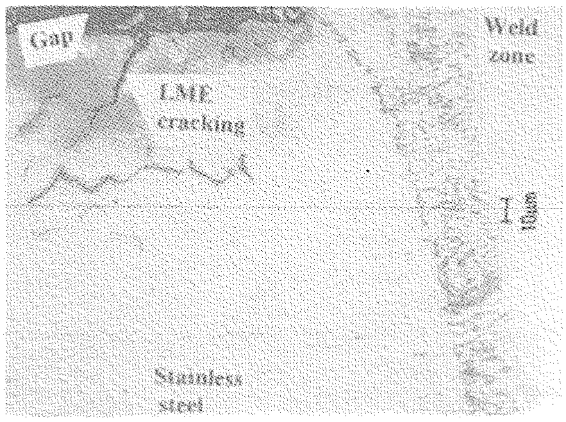

Fig. 8 Typical example of optical micrograph of a cross section of lap weld joint produced using 0.05 mm gap and 15 *l*/min Helium

Although introducing a small gap between these dissimilar material sheets has avoided porosity in the weld zone, it has no effect on Zinc induced LME cracking in austenitic stainless steel base metal. **Figure 8** shows a typical example of an optical micrograph of a cross section taken from lap weld joint produced using Helium with 15 *l*/min flow rate and 0.05 mm gap. It is noticed that a sound and uniform weld seam was obtained. However, the most important feature is the formation of LME cracking on grain boundaries of the stainless steel base metal as has been explained in the previous section. Cracking extended for a distance of about 0.5 mm around both sides of lap weld joints. These results of laser welding conform to other research work concerned with arc welding processes[2].

Generally, the influence of a gap between the sheets on weld geometry and quality can be explained using schematic illustrations shown in **Fig. 9**. Since the Zinc vapour has no escape route with zero gap, pores, welds with unacceptable profiles and LME cracking in stainless steel will be obtained (Fig 9(a)). Introducing a small gap between the sheets give the Zinc vapour an alternative escape route during welding and then, sound and acceptable weld joints will be produced. It should be mentioned that this gap should be limited to an

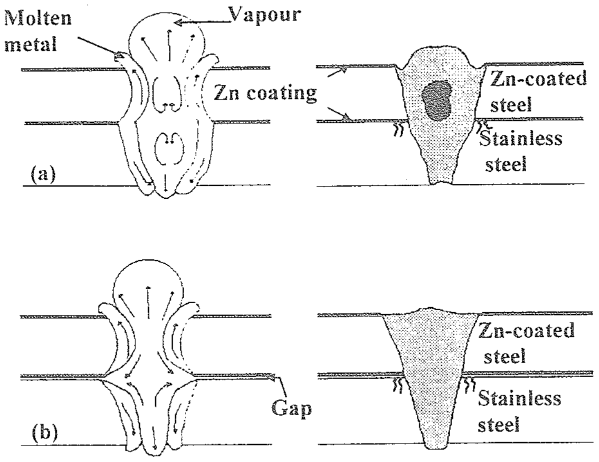

Fig. 9 Schematic illustrations showing the effect of introducing a gap between the sheets being welded on weld zone profile, porosity, and LME cracking

optimum value as has been reported by other researchers$^{7)}$. However, a problem still occurs with LME cracking in austenitic stainless steel base metal around both sides of the joint since it can not be prevented by these measures (Fig. 9(b)).

3.3 Effect of Zinc Removal Prior to Welding

The results of the previous two sections confirmed that LME cracking of austenitic stainless steel in laser lap joint with Zn-coated steel is attributed mainly to molten Zinc resulting from welding heat. Consequently, this section is concerned with studying this type of cracking as a function of Zinc removal prior to welding. In this respect, the effect of both one and two sides grinding of the weld area of Zn-coated sheets was investigated using the welding parameters which previously resulted in weld zone porosity.

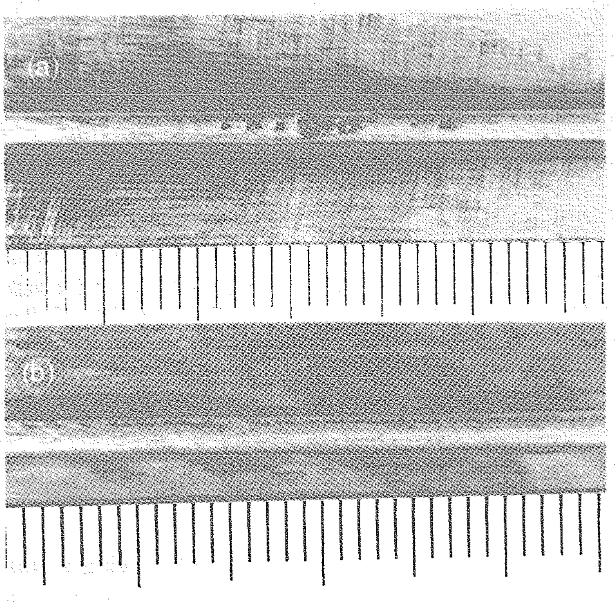

Fig. 10 Photographs of laser welds produced using 15 *l*/min Helium as a shielding gas and zero gap between the sheets after Zinc removal from (a) one side and (b) two sides of the weld area of Zn-coated sheet

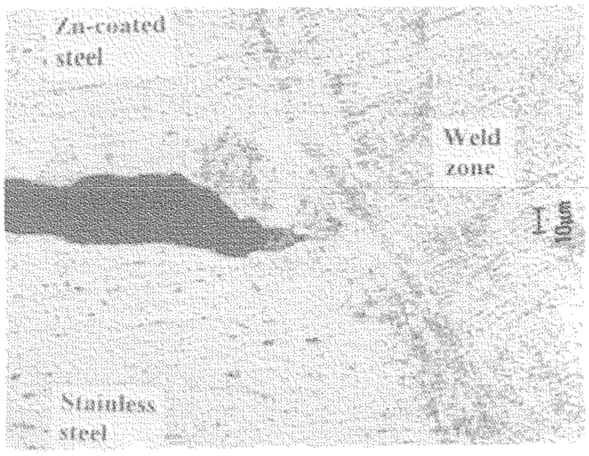

Fig. 11 Effect of two sides grinding of weld area of Zn-coated sheet on LME cracking susceptibility

Photographs of laser welds produced without a gap between the sheets and with 15 *l*/min of Helium shielding after Zinc removal by grinding of the weld area from one and two sides are shown in **Fig.10(a)** and **(b)** respectively. It can be noticed that removing of Zinc coating from only one side of Zn-coated sheet was not effective in producing sound welds since porosity was observed in the weld zone (Fig.10(a)). In the case of two sides grinding before welding, molten Zinc was avoided due to removing of Zinc coating then, molten metal was not ejected and this in turn resulted in a sound and uniform weld seam (Fig. 10(b)).

In addition, the most important finding in the case of two sides grinding is the disappearance of LME cracking in austenitic stainless steel as shown in **Fig.11** that could not be attained in the above two sections. This is due to the complete removal of Zinc coatings from the weld area prior to welding.

Results of tensile shear tests of laser lap joints as a

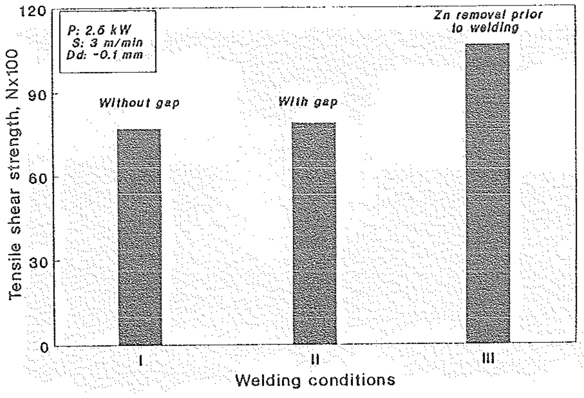

Fig. 12 Tensile shear strength of laser lap welded joints as a function of welding conditions used. Welding conditions I, II, and III are the optimum conditions used in sections 3.1, 3.2, and 3.3, respectively

function of welding conditions used are shown in **Fig. 12**. Tensile shear strength of joints produced after Zn removal from both sides prior to welding was considerably higher than that of all other joints produced with and without gap regardless of shielding gas type and flow rate. This is attributed to the absence of LME cracking in case of two sides grinding.

Recently, serious industrial incidents of Zinc-induced LME cracking in austenitic stainless steel have been reported[13-14]. The potential for cracking during field welding is certainly greater than the cracking potential in these test specimens. This is due to higher tensile stresses in the case of field welding. Therefore, the removal of galvanized Zinc coating prior to welding should be done properly to avoid contamination of austenitic stainless steel with any molten Zinc during welding.

4. Conclusions

From the above results, the following conclusions can be drawn:

(1) One way to produce sound and uniform laser lap welds of Zn-coated steel with austenitic stainless steel without a gap between the sheets is to optimize shielding conditions. This is of considerable importance to prevent plasma, prevent porosity and obtain full penetration without damaging the surface quality of the weld. Helium shielding produced noticeably deeper welds while Argon exhibited the smoothest top surface. A flow rate of 22 *l*/min was found to be satisfactory in the case of Helium in comparison with 30 *l*/min for Argon.

(2) The other way to produce sound and homogeneous laser lap welds with these dissimilar materials is the introducing of a small gap (0.025~0.05 mm) between the sheets. Maintaining such a gap between the sheets give the Zinc vapour an alternative escape route. Smaller gaps resulted in weld pores and random instabilities in the weld bead surface while larger gaps showed unacceptable levels of drop-through of the weld metal between the sheets.

(3) To preclude both weld porosity and cracking of the stainless steel by molten Zinc which in turn will improve tensile shear strength, the choice seems to be very clear that the Zinc coating must be scrupulously removed from the joint area prior to welding.

References

1) E. A. Metzbower: "Laser Welding", Naval Engineers Journal, 1991, Vol. 8, p. 41-49.
2) R. M. Bruscato: "Liquid Metal Embrittlement of Austenitic Stainless Steel When Welded to Galvanized Steel", Welding Journal, 1992, 71(12), p.455-s - 459-s.
3) D. A. Belforte: "Annual technology, Industry, and Market Review and Outlook", The Industrial Laser Annual Handbook, Pennwell Books Laser Focus, Tulsa, Oklahoma USA, 1990, SPIE 1241, p. xvi-xxxi.
4) D. M. Roessler: "Laser Processing; Global Overview and Future Trends", Proceedings of the 21st International Symposium on Automotive Technology and Automation, Vol. 1, Wiesbaden, Germany, November 1989, p. 494-516.
5) G. Marinono et al.: "Technical and Economic Comparison of Laser Technology With The Conventional Technologies For Welding", Proceedings of the 6th Int. Conf. on Laser in Manufacturing, IFS, May 1989, ISBN 1-85423-047-6, p.105-120.
6) E. Beyer and E. Gasser: "Plasma Fluctuations in Laser Welding With CW CO2-Lasers", Proc. of The 6th Int. Cong. on Appl. Lasers and Electro-Optics, ICALEO '87, San Diego, California, November 1987, p. 17-23.
7) C. Bagger, I.Miyamoto, F. Olsen and H. Maruo: "Process Behaviour During High Power CO2 Laser Welding of Zinc Coated Steel", Proceedings of LAMP, Nagaoka, Japan, June 1992.
8) R. Akhter, W. M. Steen and D. Cruciani: "Laser Welding of Zinc Coated Steel"', Proc. of The 5th Int, Cong. on Lasers in Manufacturing, LIM 5, Stuttgart, West Germany, September 1988, p. 195-206.
9) J. Heyden, K. Nilsson and C. Magnusson: "Laser Welding of Zinc Coated Steel", Proc. of The 6th Int, Conf. on Lasers in Manufacturing, LIM 6, May 1989, p. 93-104.
10) M. P. Graham, D. M. Hirak, H. W. Kerr and D. C. Weckman: "Nd-YAG Laser Welding of Coated Sheet Steel", Journal of Laser Applications, 1994, Vol. 6, p. 212-222.
11) N. S. Stoloff: "Recent Development in Liquid Metal Embrittlement", Proceedings Conference on Environment Sensitive Mechanical Behavior, AIME, Chicago, 1977.
12) M. G. Nicholas and C. F. Old: "Review of Liquid Metal Embrittlement", Journal of Material Science, 1979, Vol. 14, p. 1-18.
13) J. M. Johnson, M. R. Berry, and J. Gutzeit: "Zinc Embrittlement of Stainless Steel welds", Proceedings of AIME Meeting on Embrittlement by Liquid and Solid Metals, St. Louis, MO, 1982.
14) T. Shinohara and K. Matsumoto: "Welding Cracks of Zn-contaminated Stainless Steel Pipe", Corrosion Science, 1982, 22(8), p.723-737