606 KSME International Journal, Vol. 12, No. 4, pp. 606~614, 1998

CO_2 Laser Welding of Zinc-Coated Steel Sheets

Jae-Do Kim*, Il Na* and Chan-Cheol Park*

(Received August 28, 1997)

Welding of zinc-coated steel sheets for the automotive industry has been investigated experimentally and theoretically, using a continuous wave 2 kW CO_2 laser. The specimens of 0.8, 1.0 and 1.2 mm thickness were welded as butt joint and lap joint. Argon gas was shielded co-axially to reduce the plasma and to protect the molten pool from atmosphere. The mechanical tests of specimens were carried out to investigate the ductility of welds in butt joint and lap joint, using the Erichsen test, ball punch test and tensile shear test. The value of transverse weld pattern is higher than others. The fatigue life of longitudinal weld is superior, but that of circular weld pattern is inferior due to the high tensile residual stresses in the weld. The maximum Erichsen value was obtained as 96% and the deformability of zinc-coated steel butt-welded was found to be 80% in the ball punch test. The high pressure formed by vaporization of zinc with the low boiling temperature during laser lap-joint welding splattered the molten pool and created porosities in the weld. The optimum gap was calculated to be 0.1 mm in the lap joint welding of zinc-coated steel sheet which was a good agreement with the experimental result.

Key Words: Laser Welding, Zn-Coated Steel, Lap Joint, Gap Size, Tensile Shear Test, Fatigue Test, Erichsen Test, Ball Punch Test, Porosity

1. Introduction

Since the development of laser in 1960 high power lasers have been advanced to apply to materials processing such as welding, cutting, drilling, heat-treatment and cladding in industries. Laser beam welding is becoming increasingly popular in sheet-metal manufacturing processing such as auto-body assembly. Laser beam welding is very flexible since welds can be made in continuous and complex shapes, can be performed at relatively high travel welding speeds, and can achieve the deep penetrated welds. Laser beam welds are generally narrow and deep, comparing to the technique of the conventional welds. (Roessler, 1991 ; Willians, 1988)

Zn-coated steel sheets is an important material. It is durable, cheap and very useful for corrosion resistance. It has been used mainly in the automotive industry, but it is also employed in all sheet metal industries such as appliances, doors and ventilating systems. Automotive industries have used the uncoated sheet for a long time with the addition of a paint coating. However, the demand for rust proof is so strong that automotive industries are aiming to guarantee cars for 10 years against perforation corrosion. Since the corrosion resistance of the car body has been requested, the automotive industries have dramatically increased the usage of zinc-coated steels. In 1975, consumer pressure in United States forced the automobile manufacturer to use coated steel for a longer cosmetic life of cars as an alternative to the traditional cold rolled steel. Some countries have also introduced a legislation that forces the car manufacturer to give extended corrosion warranties. (Anderau and Opprecht, 1984 ; Heyden et al., 1990 ; Bagger, 1992 ; Baxter, 1996 ; Meuleman et al., 1985; Stevenson, 1986; Kim and Subromanian, 1988; Hull and Stewart, 1985; Roessler, 1990)

Zinc-coated steel has an outstanding performance to resistance of corrosion. However, weld-

* Department of Mechanical Engineering, Inha University

ing of zinc-coated steel has many problems due to the marked differences in physical and mechani cal properties of the two metals. Welding of zinc-coated steel poses the difficulty in the high surface resistance of coating, which causes overheating and splash during the conventional welding such as shielded metal arc welding, gas metal arc welding, submerged arc welding and oxyacetylene welding. The zinc coating increases electrode wear in spot welding and this means that weld size can deteriorate rapidly. There is an urgent requirement for a system which can inspect welds as they are made and indicate when welds are unsatisfactory. Arc welding is particularly difficult due to the interference of the zinc vapors with the arc stability, which also decreases the life of electrode. (Sayegh, 1992 ; Suh et al., 1995 ; Min et al.. 1996 ; Krawczyk and Sluzalec. 1975 ; Gregay, 1968)

Laser beam welding of zinc-coated steel, especially lap joints, has a problem of zinc vapor produced during welding which has a low vaporization temperature of 906℃. It is lower than the melting temperature of steel (1500℃). The high pressure formed by vaporization of zinc during laser welding splatters the molten pool and creates porosities in weld. One of the research objectives of this paper is to investigate the optimum gap size of lap joint in zinc-coated steel sheet.

Welding of zinc-coated steel sheet has been investigated experimentally and theoretically, using a continuous wave 2 kW CO_2 laser. The specimens of 0.8, 1.0 and 1.2 mm thickness were welded as butt joint and lap joint. The mechanical tests of specimens were carried out to investigate the ductility of welds in butt joint and lap joint, using the Erichsen test, ball punch test and tensile shear test. The results can be used as the data in the body welding of automobile, especially the tailored blank welds.

2. Experiment

2.1 Materials

The materials used in lap and butt joint welds were the same as those used in the automotive industry, 0.8, 1.0 and 1.2 mm thickness, which has the coated zinc with thickness of 5μm. The chemical compositions of specimens are shown in Table 1. The specimens for laser welding were machined as 80×100 mm.

Table 1 Chemical compositions of specimens (wt. %).

Composition / Thickness	C	Mn	P	S	Fe
0.8 mm	0.0024	0.13	0.011	0.006	base
1.0 mm	0.0030	0.09	0.012	0.005	base
1.2 mm	0.0030	0.08	0.008	0.008	base

Table 2 The conditions of laser lap welding for zinc-coated steel sheet.

Gap size (mm)	No gap	0.05	1.0	1.5
Laser power (kW)	1.7	1.7	1.7	1.7
Travel speed (m/min)	1.8	1.8	1.8	1.8

2.2 Laser beam welding

The experimental specimens were welded by using a continuous wave 2 kW CO_2 laser which is of fast axial flow type and is linked to a NC table. The laser beam is reflected down and focused by a ZnSe lens with a focal length of 127 mm. The welding area was protected by argon gas, of which the flow rate was 8 l/min. The laser power was between 0.8 and 1.8 kW and the travel speed was between 1.2 and 2.2 m/min. A focal point was on the surface of specimen. The gap was adopted as 4 kinds, no gap, 0.05, 0.1, 0.15 to investigate the optimum gap in lap laser welding. Table 2 shows the laser lap welding conditions.

2.3 Mechanical tests

Figure 1 shows the three kinds of welded specimens for tensile shear and fatigue tests. The tensile test was performed on a Universal Material Testing Machine with the capacity of 10 ton and the tensile speed was 2 mm/min. For the fatigue test the Hydraulic Fatigue Machine was used under the constant sine wave dynamic loading which has a frequency of 25 Hz. The load was between 1960 N and 784 N.

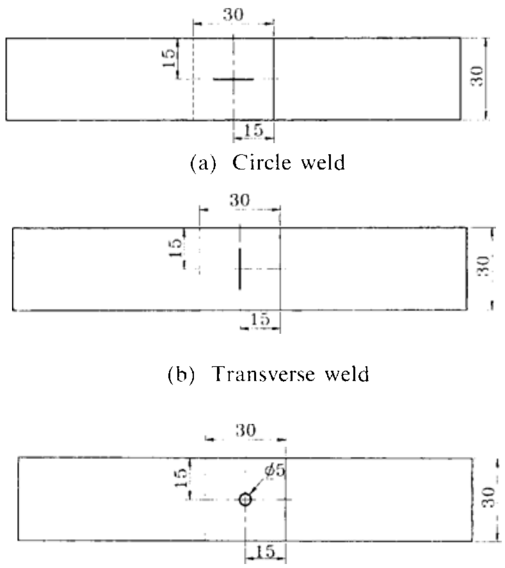
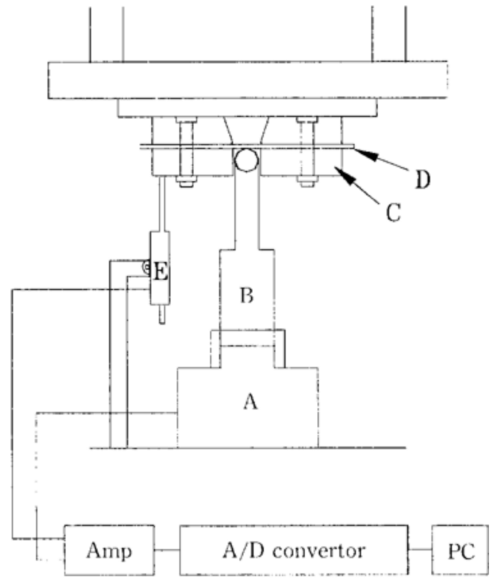


Fig. 1 Dimension of 3 lap-welded specimens (mm).

2.4 Deformability tests of welds

To measure the deformability of laser welds the Erichsen test was performed on the butt joint welds using the hydraulic press (50 ton) with a deformation test tools (ball punch) prepared under the rule of ASTM. The punch speed was 5 mm/s, the displacement of punch was 25 mm and the pressure of press was constant 200kN. It was important to decide the proper end point that just starts the fracture of specimen. The drop-in-load method (Brazier and Thompson, 1986) has been used to obtain an accurate data instead of inspection methods such as necking or fracture. As the punch presses the specimen, the pressure of the loading increases gradually. However, it drops down suddenly when the fracture of specimen just starts. This is the end point at which the pressure and the displacement have been recorded in the Erichsen test. The start point is decided the point at which the specimen just deforms considering the time delay.

Figure 2 shows the schematic diagram of the measurement system of the deformation. The data of displacement and pressure were measured by a transducer and a load cell, respectively until the start of fracture. Their data were stored at PC after they were amplified and converted.



A : Load cell
B : Punch
C : Die
D : Test piece
E : Transducer

Fig. 2 Schematic diagram of ball punch test system.

3. Theoretical Analysis for Gap Size

The laser beam welding of zinc-coated steel has a problem which the porosity occurs in the weld, particularly in the lap joint. The source of the problem is reported as the vaporization temperature of zinc is lower than the melting point.

Akhter et al. (1991) has reported that the volume escaped through the gap is the same as the volume of zinc generated in the laser welding as shown in Fig. 3. The velocity of the zinc vapor calculated using Bernoulli's equation and assuming ideal flow is as follows. (Akhter et al., 1991 ; Suh et al, 1996)

$$V_2 = \sqrt{\frac{2\Delta P_{12}}{\rho_v}} \tag{1}$$

where ΔP_{12} is the difference of the vapor pressure at points 1 and 2.

The volume per second exhausted through the gap is

$$Q_1 = \frac{V_2 \pi (w + 2b) g}{2} \tag{2}$$

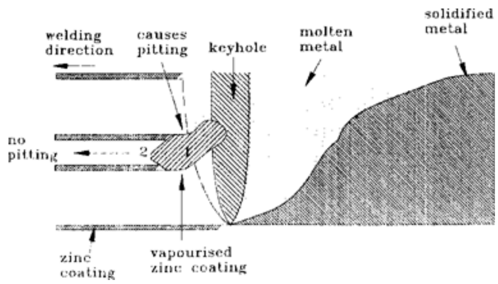
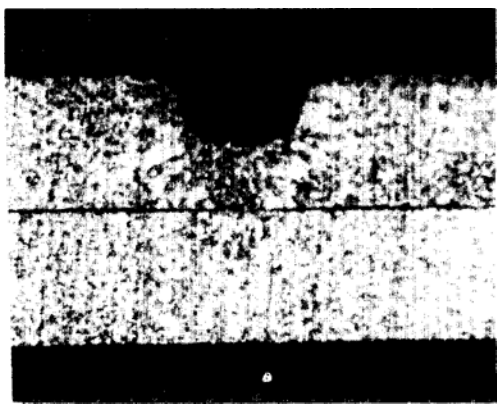


Fig. 3 Diagram representing the welding of zinc coated steel sheets with a small gap.



(a) No gap

(b) Gap size 0.1 mm

Fig. 4 Macrosections of laser lap welds (x25).

where g is the gap between two sheets.

The volume of zinc vapor generated is given by

$$Q_2 = \frac{2 t_{zn} V (2b + w) \rho_s}{\rho_v} \tag{3}$$

From $Q_1 = Q_2$,

$$V_2 = \frac{4 t_{zn} V \rho_s}{\pi g \rho_v} \tag{4}$$

where w is the weld width, b is the heat-affected zone, V is a travel speed (m/sec), t_{zn} is the thickness of zinc coating and t_p is the thickness of bare steel.

From Eqs. (1) and (4), and collecting the material constant as A, we have the optimum gap size, g_{op} as follows.

$$g_{op} = \frac{A V t_{zn}}{\sqrt{t_p}} \tag{5}$$

where A is a material constant (16.1 s/m$^{1/2}$ for zinc-coated steel). This indicates that the gap size increases linearly as welding speed increases. It is assumed that the thickness of sheet and zinc are constant and the materials of sheet is homogeneous.

It has been found that a smaller gap or zero gap leads to pitting, while a larger gap leads to a fall in the weld bead due to the molten metal flowing down the lower sheet material. The pitting phenomenon is shown in Fig. 4(a) as the hole on the surface of welds.

4. Results and Discussion

4.1 Lap weld

In case of no gap welding, the good welds were not achieved and it was found that the undercut and crater were created in the bead due to spatter. The porosities were also created because the gas of vaporized zinc was trapped in the bead during solidification. It happened due to the boiling point of zinc (906℃) is lower than that of steel (1500℃).

It was found that the bead had a good appearance in case of 0.1 mm gap size and the full penetration was achieved with the bead width of 1.17 mm. In cases of 0.05 and 0.15 mm gap, the beads were not good. It was found that the optimum gap size obtained experimentally is about 0.1 mm in the lap joint of zinc-coated steel welded with the laser power of 1.7 kW and the travel speed of 1.8 m/min. For 0.8 mm thick steel coated with the zinc (5μm) the optimum gap size is calculated to be 0.095 mm from Eq. (5). The theoretical value is in a good agreement with the experimental result. The experimental result for

Table 3 Welding result of butt joint for zinc-coated steel.

Travel speed (m/min)	Thickness of base metal (mm)	Power (kW)	Remark
1.2	0.8	0.8	△
		1.0	◎
		1.2	●
		1.4	
1.4	1.0	1.0	◎
		1.2	◎
		1.4	●
		1.6	
1.6	1.0	1.0	△
		1.2	◎
		1.4	●
		1.6	
1.8	1.2	1.0	×
		1.2	△
		1.4	◎
		1.6	●

◎ : full penetration △ : cup-shaped penetration
● : full penetration with undercut × : no welding

the lap joint is shown in Fig. 4.

4.2 Butt weld

The result of butt weld shows the Table 3 where ◎ is full penetration, ● full penetration with undercut, △ cup-shaped penetration and × no welding. Figure 5 shows the macrosection of butt joint for zinc-coated steel. The optimum welding condition obtained as the ratio of laser power to travel speed is between 0.75 and 1.0. The aspect ratio (depth/width) is 0.91 for 0.8 mm steel, 0.93 for 1.0 mm steel and 0.93 for 1.2 mm steel. The Vickers microhardness of weld was found to be 208 Hv whereas that of base metal was 110 Hv.

4.3 Tensile shear test

The value of tensile shear test is between 3720 N and 4610 N for the specimens of good weld bead. Figure 6 shows the data for tensile shear test for various weld shape. Figure 7 shows the example of test result. The value of transverse

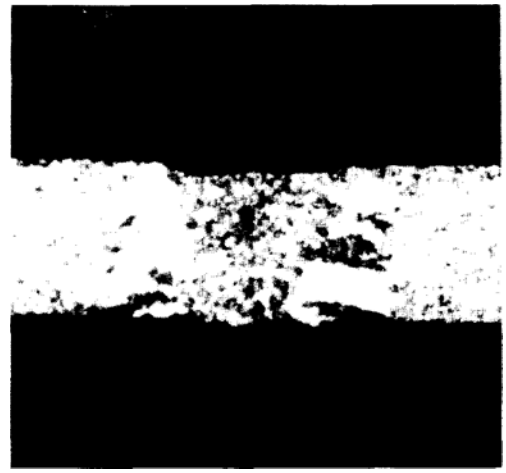


Fig. 5 Macrosection of butt joint for zinc-coated steel (x25)
P=1.2 kW, V=1.6 m/min.

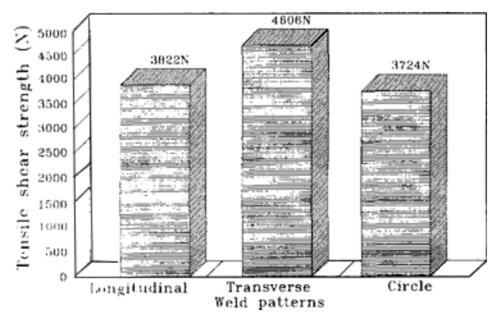


Fig. 6 Tensile shear test results for various weld patterns.

weld pattern is higher than others. The fracture starts from the heat-affected zone and deviates towards the base metal. This fracture deviation has a similar phenomenon with the result of Charpy V-notch impact test when it has applied to narrow welds such as laser beam welds or electron beam welds. If the yield strength of the base metal is much lower than that of the weld metal, the yielding can occur in the weaker base metal before it occurs in the weld metal. Fracture will then propagate through the base material even if the weld metal has lower strength. If the deviation occurs on a small testing specimen, the same trend would happen on the actual laser welded structure. (Kim, 1990, 1992 ; Goldak et al., 1977)

4.4 Fatigue test

Figure 8 shows the result of fatigue test for 3 kinds of specimens. This test result has generally the same trend. The fatigue life of longitudinal weld is superior, but that of circular weld pattern is inferior due to the high tensile residual stresses in the weld. It was found that the limit of fatigue loading is around 780 N. The fracture trend is the same as that of the tensile shear test. It starts from the heat-affected zone and deviates towards the base metal.(Kim et al., 1992)

(a) Top view

(b) Front view

Fig. 7 Photograph of tensile shear test results for laser lap welds.

4.5 Deformation test

Figure 9 shows the photograph of Erichsen test at which the specimens were welded by a laser power of 1.3 kW. The fracture was found to start at the maximum strain point of welded area in the test. There existed the loading tensile stresses with the tensile residual stresses. The Erichsen value was evaluated to be 5.5 mm at the specimen welded with the laser power of 1.3 kW and travel speed of 1.6 m/min whereas it was 11.1 mm at the specimens welded with the laser power of 1.3 kW and travel speed of 2.2 m/min. The latter value was 96% of Erichsen value of base metal. Figure 10 shows the Erichsen value of tested specimens. As the travel speed increases at the same laser power, the Erichsen value increases in the test range. As the heat input increases, the heat-affected zone and bead which affect the weakening of plastic deformation increase in the weld area. To easily deform the zinc-coated steel

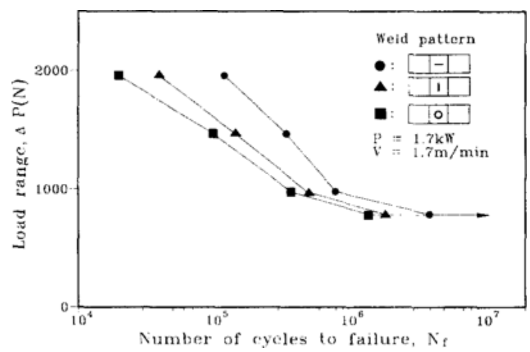


Fig. 8 Comparison of fatigue test for weld patterns.

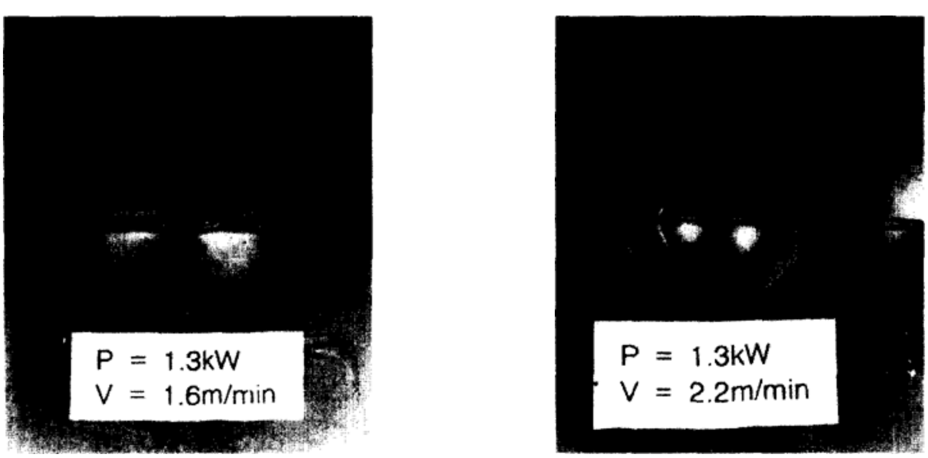


Fig. 9 Photograph of Erichsen test.

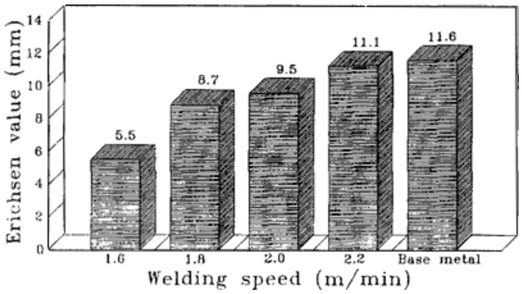


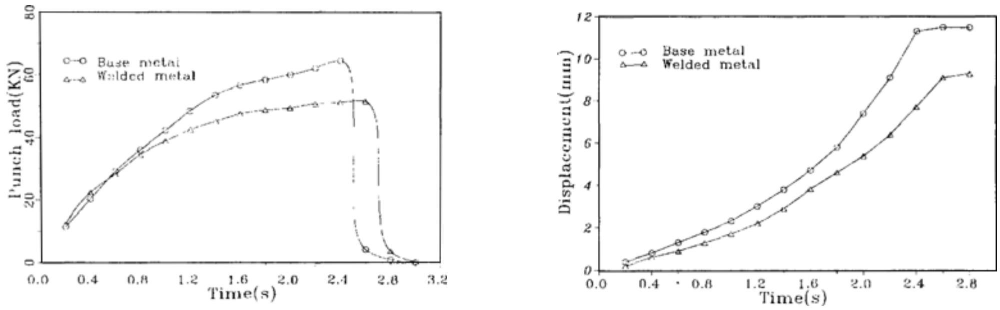
Fig. 10 Erichsen value of tested specimens.

welded with the laser it is necessary to weld with low heat input.

The specimens of ball punch test were butt-welded with the best welding conditions obtained

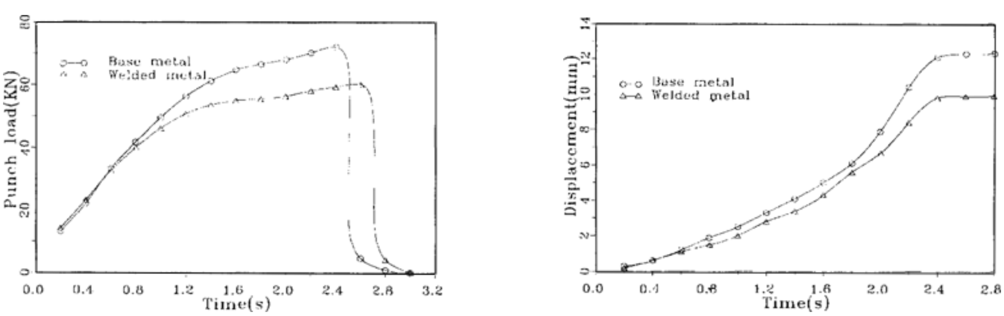
Table 4 Best conditions of laser butt welding.

Thickness (mm)	Power (kW)	Velocity (m/min)
0.8	1.0	1.2
1.0	1.2	1.6
1.2	1.4	1.8



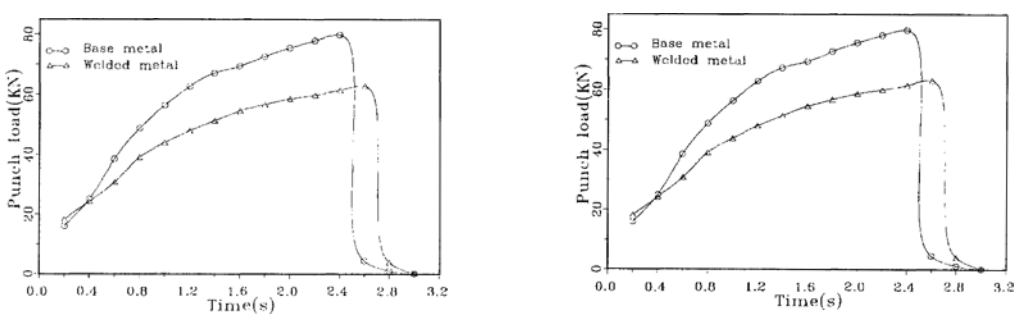
(a) Punch load (b) Displacement

Fig. 11 Diagram of punch and displacement according to pressing time (t=0.8 mm).



(a) Punch load (b) Displacement

Fig. 12 Diagram of punch and displacement according to pressing time (t=1.0 mm).



(a) Punch load (b) Displacement

Fig. 13 Diagram of punch and displacement according to pressing time (t=1.2 mm).

from the Erichsen test, shown in Table 4.

Figures 11, 12 and 13 show the pressure and displacement measured during the start of the fracture in the ball punch deformation test. The time delay of 0.2 sec when the pressure remains zero is observed during the test. The pressure increases up to 50 kN, then it decreases sharply. This is a point when the fracture start to grow. The displacement of deformation was found to be 9.1 mm as 80% of base metal.

5. Conclusion

(1) The optimum gap size was found to be around 0.1 mm for the lap joint of zinc-coated steel sheets in laser beam welding.

(2) The values of tensile shear is between 3720 N and 4610 N for the specimens of good weld bead. The value of transverse weld pattern is higher than others.

(3) The fatigue life of longitudinal weld is superior, but that of circular weld pattern is inferior due to the high tensile residual stresses in the weld. It was found that the limit of fatigue loading is around 780 N.

(4) The aspect ratio (depth/width) is 0.91 for 0.8 mm steel, 0.93 for 1.0 mm steel and 0.93 for 1.2 mm steel.

(5) The maximum Erichsen value was about 96% and the deformability of zinc-coated steel butt-welded was found to be 80% in the ball punch test.

Acknowledgments

This paper was financed by the Korea Science & Engineering Foundation (KOSEF 941-1000-060-2). The authors wish to thank the authority of KOSEF.

References

Anderau, E. A. and Opprecht, J., 1984, "Resistance Seam Welding of Coated Steel Sheets," *American Welding Society* 2501, pp. 1~20.

Akhter, R. Steen, W. M. and Watkins, K. G. 1991, "Welding of Zinc-Coated Steel with a Laser and Properties of the Weldment," *J. of Laser Applications*, pp. 9~20.

Bagger, C., Miyamoto, I., Olsen, F. and Maruo, H., 1992, "Process Behaviour during High Power CO_2 Laser Welding of Zinc-Coated Steel," *Proc. LAMP'92*, pp. 553~558.

Baxter, D. F., 1996, "Developments in Coated Steels," *Metal Progress*, pp. 31~35.

Brazier, W. G. and Thompson, R. W., 1986, "The Effect of Die Materials and Lubrication on Punch Stretching and Drawing Forces of Cold-Rolled and Zinc-Coated Steels," *Proc. of SAE*, pp. 2592~2604.

Gregory, E. N., 1968, "Arc Welding of Galvanized Steel," *Sheet Metal Industries*, Vol. 45, No. 12, pp. 501~507.

Goldak, J. A., et al., 1977, "A Fundamental Difficulty in Charpy V Notch Testing Narrow Zones in Welds," *Welding J.*, Vol. 56, No. 4, pp. 119s~125s.

Heyden, J., Nisson, K. and Magnusson, C., 1990, "Laser Welding of Zinc Coated Steel," *Industrial Laser Annual Handbook*, pp. 161~167.

Hull, D. M. and Stewart, A., 1985, "Laser Beam Profiles Principles and Definitions," *Laser and Applications*, pp. 75~80.

Kim, J. D., et al., 1992, "The Behaviour of Fracture Deviation in the Impact Test of Narrow Laser Welds," *Proc. of the Int'l Symposium on Impact Engineering*, Sendai, Japan, pp. 455~460.

Kim, J. D. and Subramanian, R. V., 1988, "Heat Flow in Laser Beam Welding," *4th Int' l Conf. on Welding by Electron and Laser Beams*, Cannes France, pp. 175~182.

Krawczyk, J and Sluzalec, A., 1975, "Strength and Corrosion Resistance of Galvanized Steel Spot Welds," *Welding Research International*, Vol. 5, No. 4, pp. 20~35.

Meuleman, D. J., Denner, S. G. and Cheng, F. L., 1985, "The Effect Zinc Coatings on the Formability of Automotive Sheet Steels," *SAE* 840370, pp. 2910~2915.

Min, J. K. et al., 1996, "A Study on the Spot Weldability of Automotive Steel Sheets," *J. of KWS*, Vol. 14, No. 3, pp. 140~146.

Roessler, D. M., 1991, "Update on Laser Processing in the Automotive Industry," *Int'l. Conf. on Lasers' 91*, San Diego.

Roessler, D. M., 1990, "New Laser Processing Developments in the Automotive Industry," *Industrial Laser Handbook*, pp. 109～127.

Stevenson, R: 1986, "Formability of Galvanized Steels," *SAE* 850276, pp. 2611～2613.

Sayegh, G., 1992, "Technical and Economical Analysis of Multispot Laser Welding in Carbody Assembly," *Proc. of 25th ISATA Symposium, Florence*, No. 921003.

Suh, J., et al., 1995, "CW CO2 Laser Beam Welding and Formability of Zn-coated Steel Plates," *J. of KWS*. Vol. 13, No. 1, pp. 577～587.

Suh, J., et al., 1996, "CO_2 Laser Beam Welding and Formability of Steel Plates with Different Thicknesses," *J. of KWS*, Vol. 14, No. 1, pp. 45～54.

Williams, N. T., 1988, "High Speed Resistance Seam Welding of Uncoated and Coated Steels," *Technical Steel Research Commission of the European Communications*, Report No. EUR 1150 EN.