CO₂ Laser Welding Characteristics of 800 MPa Class TRIP Steel

Tae-Kyo HAN, Sin Sang PARK, Ki-Heok KIM, Chung-Yun KANG, In-Su WOO and Jong-Bong LEE¹⁾

Department of Material Science and Engineering, Pusan National University, Pusan 609-735, Korea.

1) Pohang Iron & Steel Co. Ltd. Pohang 709-785, Korea.

(Received on June 9, 2004; accepted in final form on October 28, 2004)

Basic characteristics of CO₂ laser welded 800 MPa class TRIP steel such as defects, microstructure, mechanical properties and formability was investigated. Bead-on-plate welding was carried out under various power, welding speed and shield gas. Porosity fraction reduced with increasing the welding speed and using Ar–He mixed shield gas compared to Ar gas. The maximum hardness was obtained at the weld metal as well as HAZ near the weld metal. The value was the same regardless of welding speed and was nearly equal to that of water quenched raw metal. In the perpendicular tensile test to the weld axis, the joints produced at optimum condition were fractured at the base metal and the tensile property was nearly equal to the raw metal. In a parallel tensile test, the strength of the joints was higher than that of the base metal, but elongation was found to be lower than that of the raw metal because a crack was initiated in the bead at the strength levels corresponding to the tensile strength of the base metal and was propagated perpendicular to tensile direction. Elongation and formability were further improved using low power or Ar+He mixed gas compared to high power or Ar gas.

KEY WORDS: CO₂ laser welding; TRIP steel; mechanical property; porosity; formability.

1. Introduction

Recently, a weight of automobile has been increased in order to satisfy the consumer's desire such as comfort, convenience, safety as well as transfer, attaching the safe or convenient parts to car body. Reversely, energy or environment control has compelled the automotive industry to reduce the weight, resulting from increasing mileage and decreasing the amount of exhaust gas. For above reason the next important subject in automotive industry should be to satisfy the consumer's desire at the same time and to reduce the weight. So the material having high strength and high formability at once has been demanded. To meet the needs of the times a study of TRIP (Transformation induced plasticity) steel with relatively high elongation in comparison to high strength has been progressed.^{1–5)} Laser welding is the light application technique using high-density energy as a heat source. It has the advantages that high welding speed and low heat input as compared with other welding methods cause to decrease heat deformation, and the narrow width of bead and HAZ (heat affected zone) makes it possible to weld complex part won't weld with other methods.^{6,7)} So the importance of laser welding has spread widely. Presently, it has been known that Japan, America *etc.* in advanced rank of automotive industry have already tried to apply the laser welding technique to many parts in manufacture.⁸⁾ However, the research about laser welding technique is insufficient at home. Additionally a study of laser welding in TRIP steel expected to play an important role in structural or reinforced steel has been little reported. Therefore the basic characteristics of CO₂ laser welded 800 MPa class TRIP steel such as defect, microstructure,

mechanical property and formability with a shield gas or a welding speed was investigated.

2. Experimental

A cold rolled TRIP steel sheet with a tensile strength of 800 MPa was used and its chemical composition was Fe–0.2C–1.5Mn–1.5Si–0.01N by weight. The thickness of plate to be welded was 1.2 mm. The amount of retained austenite measured using XRD method^{9,10)} was 10 %. Bead-on-plate welding was performed at a welding speed of 4–12 m/min under 4.5–6 kW. Helium (He), Argon (Ar) and He+Ar were applied as a shield gas and its quantity and a focal distance were maintained at 20 L/min and 0 respectively. An image analysis technique was utilized to determine the porosity fraction and the microstructure was observed by optical microscopy or scanning electron microscopy (SEM). A micro Vickers hardness was measured near weld metal with the load holding time of 15 s and the load of 2.94 N. A tensile test was carried out under a perpendicular load or a parallel road to the weld axis with a crosshead speed of 5 mm/min. The formability of joints was evaluated by the Erichsen test with a punch rising speed of 7 m/min.

3. Results and Discussion

Figure 1 shows the effect of power on the maximum welding speed full penetration occurred in. The solid and open marks mean partial penetration and full penetration according to the welding condition, respectively. The maximum speed increased with increasing power in both shield

Fig. 1. Classification of penetration with welding condition.

Fig. 2. Cross-sections of the beads with different welding speeds or shield gas under 6 kW: (a) 5 m/min-Ar, (b) 7 m/min-Ar, (c) 10 m/min-Ar, (d) 5 m/min-He, (e) 7 m/min-He, (f) 11 m/min-He.

gases. But the maximum welding speed used He was higher than that used Ar. This may result from the difference of dissociation voltage between Ar and He. Ar having a low dissociation voltage is easily dissociated and promotes the growth of induced plasma to make laser beam unstable, lowering its energy and finally decreasing the penetration depth. However He has a high dissociation voltage and its dissociation is difficult, increasing penetration depth.

Figure 2 shows representative cross-sections of joints with He or Ar as a shield gas under 6 kW. Bead has wine-cup shape having the wide width of upper part and the narrow width of bottom part like 'Y' type in low welding speed. Average bead width decreased with increasing a welding speed in the range of the welding speeds in which full penetration occurred. But the bead shape changed to the 'V' type in the partial penetrated welding speeds.

Figure 3 shows the longitudinal sections of bead containing porosities. The porosity has a globular shape and the diameter of a big one is $250\text{ }\mu\text{m}$. It is character that the big bubbles are mainly located in the upper part. The porosity fraction of the bead produced with Ar is larger than that of the bead produced with He.

The effect of a shield gas (a) or power (b) on the porosity fraction is shown in Fig. 4. In (a), the maximum value ob-

Fig. 3. Longitudinal sections of the beads with different welding conditions: (a) 6 m/min-Ar, (b) 4 m/min-He.

Fig. 4. Effect of a shield gas on porosity fraction with a welding speed.

tained at a welding speed of 6 m/min with Ar was 14.5% and decreased with increasing a welding speed, but remained 1% at a welding speed of 10 m/min. Also in case of He the porosity fraction had a similar tendency. The porosity fraction reached maximum value at a welding speed of 4 m/min and decreased to 0% over a welding speed of 6 m/min. In real manufacturing process to reduce the cost of production, Ar is preferred as a shield gas rather than He. So as the second best policy, the mixed gas made by adding 50% He into Ar, Ar+He gas was tried as a shield gas. In case of Ar+He mixed gas, the similar tendency with He was obtained. While in Fig. 4(b), the porosity fraction suddenly decreased to below 2% with decreasing power. And this result is thought that the lower power induced to decrease the growth of induced plasma and to make key-hole stable, resulting in decreasing the porosity fraction.

What is the reason that the porosity exists in a low welding speed but its amount decreases with increasing a welding speed although there is a little difference among 3 types shield gas?

It has been reported that the flow of melted metal is different according to the welding speed.¹¹⁾ In a low welding speed melted metal moves a long distance along the solidi-

fied wall, at this time the porosity is formed at the bottom of keyhole moves with the flow of the melted metal. So the porosity is easy to be trapped during solidification, resulting in increasing porosity fraction. The other hand in a high welding speed the melted metal moves to a direct upside and the evaporated substances goes out to a direct upside. The evaporation pressure prevents outer gas from entering, causing to make porosity formation difficult and finally induce the decrease of porosity fraction.

Figure 5 shows the hardness distribution of joints with a welding speed of 7 m/min measured at 150 μm intervals along 300 μm virtual line under the top bead. The hardness reached maximum value at not only weld metal but also HAZ near weld metal and decreased approaching base metal along the virtual line.

The microstructures of each area in the weld zone taken by SEM are shown in **Fig. 6**. The martensite and ferrite

Fig. 5. Hardness distribution near weld zone with a welding speed of 7 m/min.

Fig. 6. Microstructures of each area near weld zone with a welding speed of 7 m/min with He: (a) weld metal, (b) weld metal/HAZ, (c) HAZ/base metal, (d) base metal.

Fig. 8. Microstructures of the weld metal with a welding speed of 4 m/min (a) and a water quenched raw metal (b).

phases are marked to 'M' and 'F', respectively. The weld metal and HAZ near the weld metal contained only martensite. With approaching base metal, the HAZ near base metal consisted of ferrite and martensite. This fact indicates that the full martensite structure allows the weld metal and HAZ near the weld metal to have the maximum hardness, and the decrease in the hardness of HAZ near the base metal results from relatively soft ferrite having a low hardness.

The hardness distributions of the other joints tended to be the same out of all welding speeds with all shield gas. So the hardness distributions of the other joints are omitted and the maximum hardness of all joints with a welding speed is shown in **Fig. 7**. The maximum hardness was nearly same out of all conditions. Also, the value was equal to that of a water-quenched specimen, indicating that the cooling rate of the laser welding with all used condition is equal to that of water quenching.

Figure 8 shows the microstructures of the weld metal with a welding speed of 4 m/min with He (a) and of a water-quenched raw metal (b). All of them were found to be full martensite.

Figure 9 shows the result of tensile test under a load of perpendicular direction to a weld axis. Yield strength (YS), tensile strength (TS) and elongation are nearly equal to those of the base metal out of all welding condition, which is thought to be resulted from the fracture, not in the weld zone but in the base metal that will be shown in **Fig. 11(a)**.

The tensile properties under a load of parallel direction to the weld axis are shown in **Fig. 10**. In case of Ar gas, elongation was lower than that of base metal and increased with increasing a welding speed. But YS and TS were nearly equal to those of raw metal and increased slightly with increasing a welding speed. In **Fig. 11(b)**, the appearances

Fig. 7. Change of maximum hardness with a welding speed.

Fig. 9. Tensile properties under a load perpendicular to the weld axis.

Fig. 10. Tensile property under a parallel load to weld axis.

Fig. 11. Specimen shapes with different loads after tensile test: (a) a perpendicular load, (b) a parallel load.

of the both of upper and lower pieces are of the cup type. This indicates that the elongation of the bead is different from that of the whole and, as a result, it is necessary to measure their elongations separately. The elongation of bead was lower than that of the whole. In case of He, TS and YS were larger than those of raw metal and decreased with increasing a welding speed. The elongation was the same tendency with Ar but the value was larger than that of joint produced with Ar. In case of Ar+He, the value was lower than that of the joints produced with He.

Figure 11 shows the specimen shapes after tensile test under different loads. The specimen of a perpendicular load

Fig. 12. Change of specimen shape during a tensile test and the corresponding strength-elongation curves according to the shield gas.

tensile test (a) was broken into 45 degrees that is along the maximum shear plane at base metal with a fracture strength of 520 MPa. However, the both of upper and the lower pieces of the specimen broken under a parallel load to weld axis were of cup type (b) with a fracture strength of 449 MPa.

Why does the difference in elongation between the bead and the whole exist in the parallel direction tensile test although there is a little gap according to the shield gas?

Figure 12 shows the change in the appearance of a specimen and the corresponding strength-elongation curve. A water-quenched raw metal is broken after few elongations but had high strength. However, the welded specimen produced with Ar is elongated uniformly, like the raw material at the initial stage and begins to neck at (a) point. At (b) point, the very first crack is initiated at the bead and then grows. The decrease in real area resulted in a reduction in the road and at the same time, the base metal part was necked continuously and the crack grows (c) until reaching the final fracture point (d). In summary, the base metal part was elongated continuously along with the crack growth after the initiation of crack in the bead and then broken, resulting in the difference in the elongation, ΔE . The same behaviour occurred in case of He although the value was not same.

Figure 13 shows the effect of power on the tensile property under a load parallel to the weld axis with shield gas of Ar. The specimens were selected with different welding speed such as 4.5 kW–5 m/min, 5 kW–6 m/min, 5.5 kW–6 m/min and 6 kW–7 m/min because the optimum condition was used under different power. Both tensile strength and

Fig. 13. Effect of power on the tensile properties under a load parallel to the weld axis.

Fig. 14. SEM microstructures of the fractured surfaces with different welding conditions: (a), (b) 5 m/min-Ar, (c), (d) 7 m/min-Ar+He.

yield strength showed little change with power and were nearly equal to those of raw metal. However the whole elongation decreased with increasing power resulting from mainly the increase of a porosity fraction. In spite of little difference in porosity fraction between 5 kW and 5.5 kW, the elongation with 5 kW is higher than that with 5.5 kW. This may result from the wider width with 5.5 kW than that with 5 kW caused by the different heat input.

In Fig. 14, the fractured surfaces of the specimen produced with Ar (a), (b) or Ar+He (c), (d) after a parallel tensile test are shown. A few porosities were observed at the upper part of the weld metal (a). In the magnified photograph (b), a lot of cells indicating a ductile fracture and a smooth surface indicating a relative brittle fracture coexisted. However in case of the joints with (Ar+He) mixed gas the joint had no porosity (c) and only consisted of a lot of dimples (d).

From this result, it can be concluded that the porosities that exist in the weld metal produced with Ar changed a fracture mode to a (ductile+brittle) mixed mode from the relative ductile mode in the joint produced with (Ar+He) gas, decreasing the elongation.

To evaluate formability Erichsen test was performed and

Fig. 15. Effect of shield gas on the forming height or the forming rate in Erichsen test.

the forming height and rate are shown in Fig. 15. As above results of porosity fraction with various welding condition, the forming height was further improved using a low power or mixed gas compared to a high power or Ar gas.

4. Conclusion

Basic characteristics of CO₂ laser welded 800MPa class TRIP steel such as defects, microstructure, mechanical properties and formability was investigated and the following results were obtained.

- (1) A lot of porosities were observed at a low welding speed under Ar gas but decreased with increasing welding speed. Porosity fraction can be decreased with the method of lowering power or using Ar+He mixed gas.
- (2) Hardness reached a maximum value at a weld metal as well as at HAZ near the weld metal, and decreased with approaching base metal regardless of the shield gas. The maximum hardness was not connected with a shield gas and a welding speed.
- (3) In a tensile test parallel to the weld axis, all specimens were broken at the base metal and the tensile property was the same as that of the raw metal without regard to the shield gas.
- (4) In a tensile test perpendicular to the weld axis, both yield strength and tensile strength in all shield gas were larger than those of raw metal. However the elongation was lower than that of raw metal and its value was highly affected by porosity fraction.
- (5) The forming height of the joint produced with He was 6.86 mm, bigger than those of the joint used Ar+He (6.3 mm) and Ar (4.8 mm). Also the forming height was further improved with the method of lowering porosity fraction.

Acknowledgments

This research work was financially supported by Korea Science and Engineering Foundation under the grant no. R05-2003-000-11698-0.

REFERENCES

- (1) K. Sugimoto, N. Usui, M. Kobayashi and S. Hashimoto: *ISIJ Int.*, **32** (1992), 1311.
- (2) H. C. Chen, H. Era and M. Shimizu: *Metall. Mater. Trans. A*, **20A** (1989), 437.
- (3) S. K. Kim, H. C. Chen, J. H. Chung and Y. W. Chang: *J. Kor. Inst. Met. Mater.*, **36** (1998), 151.

- 4) Y. Sakuma, O. Matsumura and H. Takechi: *Metall. Mater. Trans. A*, **22A** (1991), 489.
- 5) D. B. Im, C. G. Lee, S. J. Kim and I. M. Park: *J. Kor. Inst. Met. Mater.*, **38** (2000), 3.
- 6) J. K. Kristensen: *The Industrial Laser Hand Book, Potential and Challenges in Laser Welding Structural Steels*, Springer-Verlag, New York, (1993).
- 7) C. M. Banas: *The Industrial Laser Annual Handbook*, Pennwell Publications, Tulsa, (1986), 69.
- 8) J. Suh and Y. H. Han: *J. Kor. Weld. Soc.*, **12** (1994), 49.
- 9) R. L. Miller : *Trans. Am. Soc. Met.*, **57** (1964), 892.
- 10) R. L. Miller : *Trans. Am. Soc. Met.*, **61** (1968), 592.
- 11) Katayama : *J. Jpn. Weld. Soc.*, **19** (2001), No. 1, 213.