CO₂ laser welding of AISI 321 stainless steel

A Hussain, A H Hamdani and R Akhter
1Pakistan Institute of Lasers & Optics, P.O. Box 505, Rawalpindi, Pakistan
E-mail: pilo786@yahoo.com

Abstract. CO₂ laser welding of AISI 321 austenitic stainless steel has been carried out. Bead on plate welds on 2mm thick steel were performed with 450W CO₂ laser at speeds ranging from 200 to 900 mm/min. It was observed that weld depth and width was decreased with increasing the speed at constant laser power. Butt welds on different sheet thickness of 1, 2 and 2.5 mm were performed with laser power of 450 W and at speed 750, 275 and 175 mm/min, respectively. The microstructures of the welded joints and the heat affected zones (HAZ) were examined by optical microscopy and SEM. The austenite/delta ferrite microstructure was reported in the welded zone. The microhardness and tensile strength of the welded joints were measured and found almost similar to base metal due to austenitic nature of steel.

1. Introduction
Laser welding of austenitic stainless steel has established a significant attention in industry due to its wide applications in high pressure tanks for transportation of liquids and compressed gases, in power plants, petroleum refinement stations, pharmaceutical industry, households etc. Laser welding produces good metallurgical properties, high production rate and ease of automation [1]. Low contents of carbon in austenitic stainless steels prevent the intergranular corrosion at welds. Extensive work on weldability of stainless steel has been reported [2-4], which gives the essential conditions for ensuring good quality welds.

Laser welding is a high energy density and low heat input process resulting in a small heat-affected zone (HAZ), very little distortion, and a high depth-to-width ratio for the fusion zone. The flow of heat and molten metal (in the weld pool) can significantly influence the temperature gradients, the cooling rates and the solidification rates of the weld zone which ultimately controls the penetration and shape of the fusion zone [5].

Laser welding involves a number of variables such as laser power, welding speed, focused spot size, type of shielding gas, etc. These parameters considerably influence the microstructure of the fusion zone [6-8].

High power lasers are normally used, in kilowatt range, for welding of steels [9-11]. In this paper bead-on-plate and butt welding of 1, 2 and 2.5mm thick austenitic stainless steel (AISI 321) was carried out using a 450W CO₂ laser at different speeds. Microstructure, microhardness and tensile strength of the welds were analyzed and discussed.

2. Experimental setup
Figure 1 shows the experimental set up for laser welding of steel. A 500W CO₂ laser operated at 450W was used to carry out the welding experiments for bead-on-plate and butt joints on AISI 321 steels. Laser beam was focused on steel plates using a 100mm focal length ZnSe lens.
The sample was fixed in a jig on the CNC table, which moved beneath the focused laser at different speeds. Argon was used as shielding gas to protect the laser treated zone from oxidation. Beads-on-plate welds were formed on 2 mm thick plate. Weld samples with thickness of 1, 2, 2.5-mm were prepared for butt joints with dimensions of 30×70 mm and were held firmly using fixture to prevent distortion. After welding, the samples were visually inspected and sectioned transversely. Samples were mounted for grinding and polishing and then etched in 2% ferric chloride to observe the microstructure. The shape and microstructure of the fusion zone and base metal were examined using optical microscope. SEM studies of microstructure of the weld zones were also carried out. Mechanical tests including tensile strength and hardness measurements of butt welds were performed.

3. Results and discussion

3.1. Effect of traverse speed on weld depth and width

The welding of the samples was performed with focused laser beam having a spot size ~ 0.3 mm, which produced a continuous blue flash during the welding process. Figure 2 shows a graph for depth and width of the laser treated zone versus working speed for bead-on-plate weld. It can be seen that the depth and width of the welds decreases with increase of speed for fixed laser power. The interaction time of laser beam is decreased with increase of speed which ultimately reduces the heat input in the sample.

3.2. Microhardness and Microstructures

Figure 3 shows the microhardness of the laser weld samples along the depth at various speeds. It is clear from the figure that the microhardness of fusion zone remains almost the same as that of the base metal which is about 170±20Hv. It was observed that the hardness of weldment was almost same with increasing the speed of laser beam due to austenitic behavior of welded zone.
Figure 2. Variation of weld depth/width at different working speeds at laser power of 450W.

Figure 3. Microhardness Vs depth of weld zone at different speeds at constant laser power of 450W.

Figure 4 shows a micrograph of the bead-on-plate (a) blind weld treated at 400mm/min using laser power of 450W. The micrograph shows three zones at higher magnification i.e., (b) heat affected zone (HAZ) (c) laser melted zone and (d) base metal. It can be seen that the fine dendritic structure is observed in fully laser melted zone which is attributed to high solidification rate. In this case the white region represents the austenite phase whereas the black lines show the δ-ferrite with vermicular morphology. In heat affected zone, the heat is transferred to base metal at very high cooling rate. Therefore heat energy finds insufficient time to melt the material which results in the partially melted zone as shown in Figure 4-b. HAZ is very small as compared to welded zone and is about 60-70 µm in width. Figure 4-d represents the microstructure of the base metal. It was also observed that the shape of the fusion zone was transformed from an elliptical shape to almost vertical and parallel sided for full penetration at low speed. Increase of laser power and decrease of working speed leads to increase in the heat affected zone (HAZ).

3.3. Butt welding

Three thicknesses 1, 2, 2.5mm of the austenite stainless steel AISI-321 sheets were welded with CO₂ laser at different speeds of 750, 275 and 175mm/min respectively at constant laser power of 450W. Complete penetrations of welded zones were obtained at parameters given in Table-1. The welded zones were symmetrical about the axis of the laser beam which shows that the welding was carried out at optimum laser parameters. No welding cracks or porosities were found in any of the welds by virtue of good crack resistance of the base metal and provision of suitable welding conditions.

Visual examinations of all butt joints showed that the surface of the joint’s faces and roots were flat, smooth and with no undercuts. The weld heights were minimum and thermal distortions were negligible. It was found that the average width of butt welds of austenitic steels having sheet thickness 1, 2 and 2.5mm were 1.6, 1.8 and 2.2 mm, respectively which were less than the weld width reported elsewhere [8].

Table-1: Optimum welding parameters for various sheet thicknesses

| S.No | Sheet thickness (mm) | Laser power (Watts) | Speed (mm/min) | Shielding gas |
|------|----------------------|---------------------|----------------|---------------|
| 1.   | 1                    | 450                 | 750            | Argon         |
| 2.   | 2.0                  | 450                 | 275            | Argon         |
| 3.   | 2.5                  | 450                 | 175            | Argon         |
3.4. Microhardness and Microstructure

Measurements of microhardness profiles on the cross-section of the weld for each thickness showed that the fusion zone hardness was similar to base metal as shown in Figure 5. The steels of three thicknesses were welded at different speeds which were responsible for different solidification rates. However, it was observed that the hardness of weld metal, HAZ and base metal remained in the range of $185 \pm 15\text{Hv}$ due to austenitic nature of stainless steel.

![Figure 4](image)

Figure 4. The microstructure of the laser treated sample (a) full bead, (b) heat affected zone, (c) melted zone and (d) base metal.

![Figure 5](image)

Figure 5. Microhardness across the welds width for three thicknesses
The analysis of macro and microstructure of butt welded steels at optimum laser parameters showed that the shape of the fusion zone was regular and symmetric and also the width of the HAZ is very narrow and is about 60-70µm.

In this paper, the microstructure of 2mm thick steel is being discussed because the similar behaviour of structural changes in the welding zones of 1 and 2.5mm steels was observed. Figure 6 represents the optical microstructures of base metal and fusion zone of 2mm austenitic steels which was carried out at speeds 275 mm/min with constant laser power. Figure 6-a shows the base metal, HAZ and fusion zone at low magnification. The microstructure of Figure 6-b represents the microstructure of annealed austenitic stainless steel of base metal. It is clear from the Figure 6-c that the laser melted zone has dark δ-Fe dendritic structure with vermicular morphology in austenite matrix which is attributed to high solidification and cooling rates due to low heat input. The width of heat effected zone is about 60-80 µm. The primary and secondary dendrite arm length in the structure is about 12-20 µm and 4-8µm, respectively. The average dendrite arm spacing of δ-Fe in laser welded zone is about 10-20µm.

Figure 7 shows the microstructure of welded zone using SEM; a) near the welding edge; b) center of the welding zone and, c) enlarge view of microstructure of “b”. It can be seen that δ-ferrite exists as vermicular morphology near the edge of welding zone whereas skeletal morphology of delta ferrite in austenite structure near the center of the welding zone. This is due to the non-equilibrium rapid solidification condition in welding process. In laser welding, the peak temperature in fusion zone is much higher than the upper limit of phase balance between δ-Fe and γ-Fe phase. The austenite begins to precipitate at the ferrite grain boundaries during the cooling of welds in the temperature range 1573-1073K. Since the δ→γ transformation is a diffusion controlled process, the fast cooling in the welding process does not offer sufficient time to complete the phase transformation, which results in a large portion of δ-Fe is retained in weld. Further more, the incomplete transformation results in the retention of skeletal δ-Fe dendrite within the austenite matrix [9].

![Figure 6. Optical microstructure of; a) weld zone b) base metal and c) fusion zone of 2mm thick AISI 321 steel.](image)
3.5. Tensile test

Tensile test of four samples for each thickness was carried out. The average value of yield strength, ultimate tensile strength and percentage elongation of these samples are shown in Table-2. The results of all welds showed that failure had taken place near the heat affected zone of the welds. The tensile strength of these welds is close to the base metal which was about 650MPa [9]. The percentage elongation of 2mm steel is lower than 1 and 2.5mm thick austenitic stainless steel as given in the Table-II. The percentage elongation depends on grain size and grain boundary area. In smaller grains there exists large grain boundary area per unit volume which lowers percentage elongation. Low percentage elongation of 2mm steel is attributed to smaller grain size of the base metal as compared to other two steels. However the results show that the yield strength, UTS and % age elongation are close to the reported data [12].

Table 2. Tensile test result of the samples

| Sheet thickness (mm) | Yield strength (MPa) | UTS (MPa) | % Elong (GL 25mm) |
|----------------------|----------------------|-----------|-------------------|
| 1                    | 300                  | 640       | 51.6              |
| 2                    | 312                  | 632       | 35.5              |
| 2.5                  | 283                  | 646       | 56.2              |

Figure 7. SEM microstructure “a, b and c” of laser welded zone for 2 mm thick AISI 321 steel.
4. Conclusions
Bead-on-plate and butt welding of austenitic steel with varying thickness have been carried out at low power using a 450W CO₂ laser.

- The depth and width of weld zone decreases with increase in speed for constant laser power due to relatively lower thermal input at higher speeds.
- The δ-ferrite was found as vermicular morphology near the edge of welding zone whereas skeletal morphology of delta ferrite in austenite structure was found near the center of the weld zone.
- The mechanical properties of laser welded butt joints of austenitic steel sheets are almost similar to the base metal.

5. References
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