NARROW GAP LASER WELDING OF THICK SECTION STAINLESS STEEL

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Abstract
Laser welding of metals typically has a weld penetration of 1-2 mm/kW laser power. Therefore laser welding of thick section materials would require very high power lasers. In this paper we report an investigation into multi-pass laser welding of 316L stainless steel sheets of 5-10 mm thickness, based on narrow gap (1.5 mm) approach using a 1 kW single mode fibre laser. A filler wire of 316L with a 0.8 mm diameter was used in the welding process. The integrity of the weld, microstructure and heat affected zones, as well as weld bead geometry, and mechanical properties were examined. The effect of laser welding parameters on these properties is discussed.

Introduction
Thick-section austenitic stainless steels have wide industrial applications especially in the oil/gas industry and nuclear power plants[1]. Multi-pass arc welding and electron beam welding are the most common and traditional techniques used for joining thick section stainless steels[1-2]. Production efficiency for arc welding is low due to low welding speed and too many weld passes. Arc welding also leads to high distortion due to high heat input and mass deposition. Electron beam has the highest-production efficiency and maximum penetration depth by deep keyhole single pass welding in vacuum [3]. It is, however, limited to smaller components due to the requirement of a vacuum environment. Laser welding can be carried out in atmospheric conditions and the beam can be delivered over an optical fibre and integrated with an industrial robot. However, for thick section welding, it requires very high laser powers, thus high costs. Narrow gap laser welding can achieve thick section welds using a relatively lower power laser [4-5]. It provides economical and metallurgical advantages for the welding of thick materials [6]. Generally, the optimum welding processes aim to achieve defect-free welds, with minimum distortion [7]. Despite the advantages of narrow gap welding, it is considered as a more complex process. It has more interacting variables, which affect the welding bead quality. It has also strict requirements for the wire material and feeding, laser/wire alignment, process shrouding inside the gap. The wire feed should have a good accuracy (less than ± 0.5%) to have homogeneous distribution of the layers inside the gap [6, 8]. Some of previous investigations concentrated on the effect of filler material on the metallurgy and properties of the weld metal in laser narrow gap welding [9]. The influence of autogenous laser welding parameters on weld-bead profile and mechanical properties of stainless steels were also studied [10-12]. The present work investigates further quality aspects of narrow gap laser welding process including microstructures, weld bead geometry characteristics, hardness, and welding parameter interactions.

Experiment procedures
Figure 1 shows the experiment setup. The laser system used in the experiments is an IPG single-mode continuous wave (CW) fiber laser, with a maximum power of 1 kW, and a beam quality factor of $M^2 < 1.07$. The laser beam was optically delivered (fiber core diameter – 14 µm) to a welding head consisting of a lens unit and a gas nozzle.

Figure 1. Experiment set up.
(H=5mm, W=1.5mm parallel side gap, $\alpha=45^\circ$)
The minimum spot size measured was 70 µm using a 7.5" focal length lens. A 316L stainless steel wire with a 0.8 mm diameter was delivered through a nozzle at 45° to the laser beam. The weld zone was shrouded with argon gas delivered via a coaxial nozzle, and a shielding gas shower tube to avoid surface oxidation with the gas flow rate at 10 L/min. A linear motor CNC traverse table was used to move the workpiece relative to the laser beam. The narrow gap width was 1.5 mm with parallel sides.

**Results and Discussion**

**Homogeneity of the bead shape inside the gap**

The weld bead shape homogeneity is one of the most important quality factors for the multi pass narrow gap. The weld bead shape factor is defined by:

\[
D = \frac{d_{outer} - d_{inner}}{2}
\]

(a)                (b)

![Figure 3 Experimental results for weld bead shape factor.](image)

Where \(D\) is shape factor, \(d_{outer}\) is maximum bead width, \(d_{inner}\) is minimum bead width as shown in Figure 2.

A good weld should have a minimum value of \(D\) so that a straight sidewall of weld beads can be achieved. This affects the homogeneity of the material properties across the weld cross-section, and the probability of voids formation between beads. The weld bead cross-sections of welds at two welding speeds are shown in Figure 3. The welding parameters are: power = 802 W, wire feed rate = 25 mm/s for both cases. In experiment one: speed = 7 mm/s and 4 passes, \(D_1 = 175\mu m\) as shown in Figure 3a, and for experiment 2, speed = 11 mm/s, with 6 passes, and \(D_2 = 80\mu m\) as shown in Figure 3b.

The experiment was repeated for different laser power and wire feed rates. The results show that increasing the welding speed decreased the interaction time between consequence beads, thus decreased the shape factor. Six passes will be needed to fill the gap as shown in Figure 3b. On the other hand decreasing the speed led to an increase in the beads interaction consequently the number of passes decreased to 4, and shape factor increased to 175µm.

**Influence of the welding parameters on the weld bead integrity**

Weld bead integrity relates to the amount of porosity and voids in the weld beads. It is evaluated as following:

\[
\text{Integrity of weld bead} \% = 100 - \text{the percentage of the voids area with respect to total weld bead area.}
\]

The objective of this section is to understand the influence of the welding parameters on the quality of the weld bead inside the gap. The experimental conditions are shown in Table 1.

**Table 1. Laser welding parameters used in weld bead integrity evaluation.**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Power [W]</th>
<th>wire feed rate [mm/s]</th>
<th>Speed [mm/s]</th>
<th>number of passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>857</td>
<td>21</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>b</td>
<td>857</td>
<td>21</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>c</td>
<td>857</td>
<td>27</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>

The weld integrity for experiment a = 98%, experiment b = 78 %, and experiment number c = 83%.
Influence of the welding parameters on the weld bead integrity

Experiment (a) represents near optimum parameters, where the weld beads had minimum voids. Weld integrity evaluation is 98% as shown in Figure 4a. Decreasing the traverse speed led to a decrease in the number of filling passes. On the other hand, increasing the wire delivery rate per unit length consequently decreased the ability of the wire to penetrate the narrow gap and an increase in the voids in the welding beads as shown in Figure 4b. Increasing the wire feed rate led to a decrease in the delivered power per unit length of the wire, and increasing the reflectivity of laser beam[9]. Both factors will decrease the wire melting efficiency, and deteriorate the welding bead integrity as shown in Figure 4c.

Influence of welding speed on micro-hardness

Two welding experiments with different welding speeds were carried out in order to understand the influence of the welding speed on the hardness distribution across the welding bead. The hardness was measured at four vertical positions. At each position, hardness was measured horizontally at five points (-2,-1, 0, 1, 2) as shown in Figure 5. The zero position was at welding center. Points 1,-1 were on the both sides of the welding beads, and points 2,-2 were just outside of the welding bead from both sides. This was repeated for the two experimental conditions a, b. Experiment (a) welding parameters are; power 912 W, speed 11 mm/s, wire feed rate 17mm/s, 7 passes as shown in Figure 5. Experiment (b) welding parameters are; power 912 W, speed 7 mm/s, wire feed rate 17mm/s 5 passes as shown in Figure 5 b.

The hardness of the base material is 170 HV. For experiment (a) the average hardness of the upper bead was 222 HV, and increase gradually to 600 HV at the lower bead. For experiment (b) the hardness was 175 HV and increased gradually to 284 HV for the lower bead as shown in Figure 6. Hardness values for experiment (a) generally increased more than in experiment (b) due to higher welding speed.
consequently the cooling rate is higher and grain size is finer as will be discussed in next section. The number of passes required for filling the gap of experiment (a) was 7 passes, and for experiment (b) was 5 passes.

**Microstructure of the welding zone**

![Microstructure Image]

*Figure 7 Micro-structure a) welding speed of 11 mm/s b) welding speed of 7 mm/s*

The influence of the welding parameters on the microstructure of the bead across the weld depth was investigated. Figure 7 shows the typical weld bead microstructures under two welding speeds. The grain size increases for the upper weld tracks for both welding conditions. This is mainly due to the higher cooling rate for the lower cross section passes (as it is close to the substrate) with respect to higher cross section passes. The average grain size in the weld zone for the welding speed of 12 mm/s is generally finer than grain size in the weld zone under a welding speed of 7 mm/s. An increase in welding speed leaves less time for laser irradiation on each material point resulting in higher solidification rates, consequently finer grain size and increased hardness[12-13].

**Composition analysis for welding experiments**

Two EDX analysis done for two sets of experiments, power 912 W, wire feed rate 17 mm/s and two welding speeds as shown in Figure 8. The results are shown in Table 2. Cr<sub>eq</sub> is calculated and Ni<sub>eq</sub> are calculated according to equations 2,3[14]

\[
\text{Cr}_{eq} = \text{Cr} + \text{Mo} + 0.7\text{Nb} \\
\text{Ni}_{eq} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu}
\]

*Table 2 Composition analysis of welds*

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Mo</th>
<th>C</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>17.6</td>
<td>1.8</td>
<td>69.4</td>
<td>9.87</td>
<td>2.54</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>Spec 5 (S= 7mm/s)</td>
<td>17.3</td>
<td>1.8</td>
<td>66.3</td>
<td>10.3</td>
<td>3.20</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Spec2(S= 11mm/s)</td>
<td>19.1</td>
<td>1.7</td>
<td>67.2</td>
<td>10.5</td>
<td>3.36</td>
<td>0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Both Cr<sub>eq</sub>, Ni<sub>eq</sub> are used to calculate the ferrite number for two welding conditions according the, (Kotecki and Siwert diagram) [14]. It was found that ferrite number for welding speed=11 mm/s is higher than the welding speed = 7 mm/s. Increasing the delta ferrite percent, and grain refinement are considered the main reasons for increased hardness at high welding speed[15].

**Influence of wire feed on bead shape quality, number of filling passes and hardness profile**

Two different wire feed rates were used for the next set of experiments. The first welding parameters were Power = 912 W, Wire feed = 17 mm/s Speed = 11 mm/s. The second welding parameters were: Power = 912 W, Wire feed = 25mm/s, Speed = 11 mm/s.
Figure 9. Effect of wire feeding on weld bead harness. a) position of hardness, b) hardness profile across welding

Figure 9 shows weld hardness profiles. Increasing the wire feed rate leads to a decrease in the number of filling passes from 7 to 5, and increases in the shape factor to 120 μm with respect to 70 μm at the lower wire feed rate. Increasing the wire feed rate leads to an increase in the amount of reflected power and an increase in the feed material per unit length, thus less power for penetration[6]. Hardness is ascending in the downward direction for both conditions. As the wire feed rate increases, the hardness reduces. At wire feed rate of 25 mm/s the hardness value increases to 290 HV at the root, while at a feed rate of 17 mm/s the hardness reaches 650 HV.

Influence of laser power on weld quality, number of filling passes and hardness

Two sets of welding experiments with different powers were carried out. The welding parameters were: wire feed rate = 17 mm/s, and welding speed =11 mm/s for both experiments, and power = 912 W for the first experiment, power = 802 W for the second experiment. Figure 10 shows the positions of hardness testing and the bead shape for the two sets of welding parameters respectively. Increasing the laser power led to a decrease in the amount of the laser beam losses by reflection [6] consequently penetration between beads will improved and outer shape factor will be decreased, on the other hand the number of filling passes will be increased.

Figure 10. Effect of laser power on hardness. a) position of hardness test. b) hardness profile across welding

The number of filling passes = 5 passes when power = 802 W. The number of passes increased to 7 by increase the power to 912W. An increase of laser power improves the shape quality factor by decreasing the outer shape factor from 125 μm to be 70 μm. The hardness increase is found higher with increasing the used power. The hardness increasing value = 690HV with power = 912W, while at 802W the hardness value = 250 HV at the root pass as shown in Figure 10b.

Hardness profile across 10 mm section

A 10 mm thick stainless steel block was welded using the narrow gap approach and the hardness profile was found to have the same behaviour as shown above. The value of hardness reduces towards to upper end of the weld. At each level the hardness profile is increased at the bead edge with respect to the centre due to the change of the cooling rate. The outer layer of each bead has increasing in delta ferrite due to high cooling rate. This layer tends to increase the hardness at the weld bead sides with respect to the centre position. Welding parameters used were: power 912 W, speed 7 mm/s, wire feed rate 17 mm/s 9 passes. Figure 11 shows the hardness profile at six vertical cross sections. The value at the upper region is around 218 HV increasing to a value of 355 HV at the lower region. The grain size is found to be coarser at the upper region of the welding cross section.
Conclusion

This investigation has shown specific welding parameter effects on the weld bead microstructure and geometry quality in multi-pass narrow gap laser welding of thick 316L steel sheets. The hardness in the weld zone decreases as the number of passes increases and the top section of weld always has lower hardness values. The weld zone hardness increases with the welding speed, and laser power, and decreases with increasing wire feed rate. The number of filling passes is affected by the welding parameters. Increasing the speed, and decreasing the wire feed rate, and the laser power will lead to an increase in the number of filling passes for the gap. The quality of the bead shape through the weld shape factor is improved by increasing the welding speed and decreasing the wire feed rate, and also increasing the laser power inside the windows of weld acceptance.

REFERENCES

[1] E. A. Xudong Zhang (2010), welding of thick stainless steel plates up to 50 mm with high brightness lasers, presented at the International Congress on Applications of lasers and Electro-Optics, USA.


