1. Introduction

AISI 304 stainless steel is a variation of the 18% chromium - 8% nickel austenitic alloy, the most familiar and most frequently used alloy in the stainless steel family. This stainless steel alloy may be considered for a wide variety of applications and exhibits good corrosion resistance, ease of fabrication, excellent formability, and high strength with low weight. Owing to the superior properties of stainless steel, it is pertinent to make use of it in various automotive, aerospace, nuclear, chemical and cryogenic applications.

AISI 304 can be welded by several welding processes including arc welding, resistance welding, electron and laser beam welding. The new generation of high power fiber lasers presents several benefits for industrial purposes, namely high power with low beam divergence, flexible beam delivery and high efficiency.

Although extensive researches relevant to laser welding have been conducted, including laser beam delivery systems and mechanical behavior of laser welded stainless steels\(^1\)\(^-\)\(^4\), few papers have dealt with metallurgical and mechanical properties of the fusion zone of fiber laser beam welds in relation to laser parameters\(^5\)\(^-\)\(^7\).

Compared with conventional lasers, fiber laser welding is characterized by high melting efficiency, different keyhole modes and power density characteristics, which could affect the heat and melt flow of the molten pool during welding. The objective of the present work was to study the fiber laser weldability of 5 mm thick AISI 304 austenitic stainless steel plates; therefore, bead-on-plate welding was exploited on AISI 304 stainless steel plates with different laser powers, welding speeds, defocused distances with different types of shielding gas and their effects on the weld zone geometry and properties and final solidification microstructure at room temperature. Laser power, welding speed and defocused distance have a great effect on the bead appearance and weld zone shape while almost no significant effect on both the type of microstructure and mechanical properties of welds. The microstructure of all laser welds was always austenitic including about 3~5% ferrite. However, the lower the laser power and/or the higher the welding speed, the finer solidification structure, primary ferrite or mixed-mode solidification resulted in crack-free welds.

**Key Words:** fiber laser, austenitic stainless steel, power density, solidification structure

2. Experimental Procedure

AISI 304 stainless steel plates of 5 mm in thickness with chemical compositions and mechanical properties given in Tables 1 and 2, respectively, were used in this study.

A continuous wave (CW) fiber laser (IPG YLR-10000) was used for bead-on-plate welding. The maximum laser power is 10 kW and the beam parameter product (BPP) is 4.5 mm*mrad. The experimental set-up of the laser welding system is shown in Fig. 1. A new laser welding system, used by Katayama, et al.\(^5\), was...
employed for this experiment. In this system a fiber laser beam was transmitted through two kinds of optical fibers and focused on the specimen surface by lenses of two different focusing lengths. Laser beam focusing situations and power density distributions at the focused position are shown in Fig. 2.

The effect of laser power density on the formation of sound welds was investigated by varying the laser power, welding speed and defocusing distance. The laser welding parameters investigated are summarized in Table 3.

Welded joints were visually inspected and samples were sectioned transverse to the welding direction, mechanically polished and etched. Oxalic acid's reagent was used for revealing weld microstructure. Optical and electron scanning microscopes were used to study the microstructures in the fusion and heat affected zones of the welds. Vickers hardness measurements were made on the transverse section of the welds under a load of 1.96 N.

### 3. Results and Discussion

#### 3.1 Weld bead appearances

In order to investigate the effect of laser power density on weld performance of AISI 304 stainless steel, bead-on-plate welding was performed at 4 to 6 kW under the other constant conditions.

The laser power has a direct effect on the heat input during welding as shown in the following equation,

\[ H.I = \frac{\text{Power density}}{\text{Speed}}, \]

While Power density = Power/Spot area.

At constant laser beam parameters, the laser power has no significant effect on the spot diameter. The fiber laser beam of feeding fiber (0.1 mm) at the focus point is \( \approx 200 \mu \text{m} \) spot diameter as shown in Fig. 2. The effects of laser power and defocused distance are shown in Fig. 3. The weld bead width was almost controlled by welding speed and defocused distance at all laser power levels.

The results show that at high speed (10 m/min) the weld beads were unstable meandering ones with spatters at all laser powers range. Because at higher welding speed the molten pool became shorter and the keyhole was unstable, so, the spattering became more severe, while at low speed (6 m/min) full penetration welds and stable beads were obtained.

![Fig. 2 Fiber laser beam power density and profile](image)

**Table 3** summary of welding parameters

<table>
<thead>
<tr>
<th>Laser welding conditions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>3–6 kW</td>
</tr>
<tr>
<td>Weld speed</td>
<td>1–8 m/min</td>
</tr>
<tr>
<td>Focus Position</td>
<td>( \pm 20 \text{ m} )</td>
</tr>
<tr>
<td>Gas</td>
<td>Ar, Ar+N(_2), N(_2)</td>
</tr>
<tr>
<td>Gas flow rate</td>
<td>30–50 L/min</td>
</tr>
</tbody>
</table>

### 3.2 Macrostructure and weld penetration

The shape and soundness of the welds produced were critically affected by laser power, welding speed and focus position. In various cases the weld beads were wide or narrow; some joints had also an excessive weld profile (weld convexity), undercut around the bead, or weld concavity. The macrostructure of the fiber laser welds obtained at laser focal point with different laser power presented in Fig. 4 shows a narrow and deep weld penetration with narrow heat affected zone. On the other hand welding at defocused positions produce different shapes of molten pools varying between wide and shallow penetrate welds which are consistent with conduction mode and narrow and deep penetrate welds which are consistent with the keyhole mode of welding, as shown in Fig. 5.

The weld depth to width ratio (D/W) is an important quality

![Fig. 3 Weld bead appearances under different welding conditions](image)

![Fig. 4 Cross section of weld beads produced with various laser powers](image)
criterion in welding, which is determined by the heat transport
mode in the molten pool. This ratio is obtained for changing of
molten pool from conduction mode to keyhole mode. Based on
the weld cross-section, the weld depth/width ratios of the fusion
zones were calculated for all the samples. The weld D/W ratios
are plotted as a function of laser power and defocused distance in
Figs. 6 and 7. The results show that at a high speed welding of 10
m/min the penetration depth was varying with the laser power,
and D/W ratio increased with the increase in laser power from 3.9
at 4 kW laser power up to 8.3 at 6 kW. On the other hand at 6
m/min, while full penetration of 5 mm plate was obtained, the
D/W ratio decreased from 7.1 at 4 kW up to 4.6 at 6 kW. This is
because the penetration depth is limited by the plate thickness,
and thus the increase in laser power reflected on the heat input
effected only on the width of the weld pool

3.3 Microstructure and porosity

Microstructure of the as-received material is presented on
Fig. 8, showing an equiaxed, twinned microstructure; the
alignment of ferrite precipitates indicates the rolling direction.
A general view of the transverse section of the material after laser
welding shows, that the extension of the heat affected zone is
negligible. This is the typical positive effect associated to a
highly focused welding heat source10.

Metallographic examination of the weldments did not reveal
any cracks in any of the specimens examined, although some
isolated pores were found in some of the welds. No noticeable
inclusions were noticed in fusion zones. The noticeable feature is
the highly directional nature of the microstructure around the axis
of the laser beam. This is due to solidification of the weld metal
at high cooling rate compared to that of conventional welding9.

The solidification sequence of AISI 304 stainless steel
weldments is given by L → L + δ → L + δ + γ → δ + γ → γ. In
other words, the solidification of this steel begins with the
formation of δ-phase as the primary production of
solidification (Fig. 9)4, 9.

Investigation of the microstructure of the laser welds shows
that the solidified structure is dendritic and contains austenite and

Fig. 5 Cross sections of weld beads produced at various defocusing
distances

Fig. 6 Effect of welding speed and laser power on depth/width ratio of
AISI 304 stainless steel welds

Fig. 7 Effect of defocused distances on depth/width of AISI 304
stainless steel laser weld

Fig. 8 Microstructure of base metal of AISI 304 stainless steel plate

Fig. 9 Show the 70 pct constant Fe vertical section of the Fe-Ni-Cr
System
a few percents of delta ferrite as shown in Fig. 10 and 11. Energy
dispersive spectroscopic (EDS) analysis performed with scanning
electron microscopy (SEM) showed that chemical analysis of FZ
remained largely unchanged by welding conditions; however EDS
spot analysis showed the delta ferrite was enriched with
chromium content (Fig. 12).

The results show that neither laser power nor welding speed
has noticeable change on the microstructure of the solidified zone.
However, the type of a shielding gas could decrease the ferrite
number form 4.25 in 100% Ar to 3.13 in 100% N₂ (Fig. 13). On
the other hand, it can be noticed that the higher the welding speed
is, the finer the dendrite structure is, and higher laser power
renders the dendrite structure coarser due to a decease in the
cooling rate (Fig. 14).

3.4 Hardness

Macrohardness profiles were recorded across the width of the
FZs of laser welded specimens with a load of 1.96 N (Fig. 15).
The results show that no significant increase in hardness on the
melted region was observed. Although the structure refinement at
the surface could lead to an increase on the yield stress, the flow
stress measured by the hardness test is not expected to change
much particularly in a high strain hardening rate material like the
AISI 304 stainless steel.

The measurements revealed that in comparison to the largely
uniform hardness profile across the laser weld, however in the
case of using N₂ as a shielding gas instead of argon, the hardness
slightly decreased, it could be due to the decrease of the ferrite
content in the fusion zone (Fig. 16).
4. Conclusions

(1) The amount of spatters and instability of weld bead increased at high welding speeds.

(2) D/W ratio changed with the change in laser power, welding speed and defocused distance, depending on the heat input.

(3) The microstructure of all laser welds was always austenitic with a small amount of delta ferrite.

(4) Except welding with nitrogen as shielding gas, the welding conditions have no significant effect on the hardness distribution

References


