CO2 Laser Cladding and Plasma Cladding of Ni-Based Alloy Powder on the SUS316LN Stainless Steel∗

Guojian XU∗∗, Munaharu KUTSUNA∗∗ and Zhongjie LIU∗∗

Clad layers of Ni-based alloy were deposited on the power plant machinery parts made of SUS316LN stainless steel by CO2 laser cladding and plasma cladding. A smooth clad bead was obtained by CO2 laser cladding. The phases of the clad layers were investigated by laser microscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis, electron probe microanalysis (EPMA), and energy-dispersive spectroscopy (EDS). The microstructures of clad layers belonged to a hypereutectic structure. Primary phases consisted of boride CrB and carbide Cr7C3. The eutectic structure consisted of Ni + CrB or Ni + Cr7C3. Compared with plasma cladding, excellent wear resistance, fine microstructures, low dilutions and high Vickers hardness were obtained by CO2 laser cladding. All these results show that laser cladding realizes higher efficiency and good cladding quality.

Key Words: Laser Cladding, Plasma Cladding, Hypereutectic Structure, Vickers Hardness, Wear Resistance

1. Introduction

SUS316LN stainless steel is widely used in power plants and chemical plants due to its characteristics such as excellent ductility, toughness and corrosion resistance. However, SUS316LN lacks wear resistance(1). To improve the wear resistance and oxidation resistance of this kind of steel, a cladding layer was deposited on the surface of SUS316LN stainless steel. Although plasma cladding and TIG cladding are usually used, liquation cracks occur easily in the heat-affected zone because of large heat input and high thermal stress(1). Furthermore, ductility-dip cracks occur easily due to the brittleness and hardness of the cladding layer. It is difficult to prevent the two kinds of crack at the same time.

To prevent the mergency of the cracks mentioned above, a low heat input low distortion cladding process was investigated. As a result, laser cladding process was adopted for depositing clad layers on power plant machinery parts made of SUS316LN stainless steel. In this study, SUS316L steel plates were used as the substrates for determining the appropriate processing parameters of laser cladding. After that, the clad layers were deposited on the surface of practical power plant parts made of SUS316LN using the optimized parameters. The wear resistance, microstructure, cladding efficiency and hardness of the laser cladding layer were compared with that of the plasma cladding layer.

2. Experimental Procedure

2.1 Materials used

The chemical compositions of SUS316L, SUS316LN stainless steel and Ni-based alloy powder (WELPC-6) are shown in Table 1. The dimensions of the SUS316L stainless plate are 80 mm × 30 mm × 10 mm. The dimensions of the power plant machinery part made of SUS316LN stainless steel was shown in Fig. 1. The particle size of Ni-based alloy powder was in the range of 47 – 165 µm in diameter.

2.2 Experimental setup

A schematic drawing of the laser cladding setup for the SUS316L stainless-steel plate is shown in Fig. 2 (a). A 2.4 kW CW CO2 laser was used in the experiments. The power distribution within the beam approximated the quasi-Gaussian distribution known as the TEM01* beam. The beam was focused using a ZnSe lens of 200 mm focal length. A TWIN10-SPG powder feeding system made by Sulzer Metco (Japan) Ltd. was used for supplying powder to the nozzle using carrying gas, Ar(2). The powder feeding rate was controlled by the rotation speed of the feeder.
The specimen was preheated in a resistance furnace at a temperature above the proper preheating temperature 323 K for 10 minutes making the temperature well distributed. Before cladding, the preheating temperature was measured using an S-423K-01-1-TPC-1-ASP temperature sensor to make sure its value was correct. During cladding of the power plant machinery part (Fig. 2 (b)), the machinery part was installed on a rotation device, which was positioned on a CNC-controlled XY-table. A smooth spiral clad bead was obtained by rotating the specimen on the rotation device and simultaneously line-moving it on the XY-table.

Specimens for optical metallography were obtained from the transverse direction of the clad bead, followed by mechanical polishing based on the standard technique and etching with aqua regia (nitric acid: hydrochloric acid = 1:3). The samples were observed using laser microscopy (Keyence VK8510).

After cladding, the surface of the clad layer was ground and cut into 5 mm × 5 mm × 1 mm specimen for XRD analysis. The Vickers hardness was measured using
an AKASHI AAV-500 automotive hardness tester.

The wear tests were performed using an MM200-type wear tester under dry and room permanent hyphen temperature conditions. The working principle of the wear testing machine is shown in Fig. 3. The counterpart was made of bearing steel GCr15 with a size of $\Phi 50 \times 10$ mm and a hardness of HRC60 $\sim$ 65. After laser cladding, the specimens were ground and cut into $14 \times 10 \times 10$ mm's for wear tests. The normal load was 98 N, The sliding speed was 62.8 m/min, and the test time was 30 min. The friction coefficient, $\mu$, was calculated using the following equation;

$$\mu = \frac{M}{RP},$$

where, $M$ is the friction moment, $R$ is the radius of the counterpart, and $P$ is the normal load on the specimen. The wear mass loss of the specimens was weighed using a TG328B-type electron balance with an accuracy of 0.1 mg.

2.3 Cladding conditions

SUS316L stainless plates were used for investigating the optimal cladding conditions\(^{(3)}\). The power plant machinery part was deposited with a single-pass layer using the obtained optimal laser cladding conditions shown in Table 2. A 10-pass spiral clad layer was achieved at a 30% overlapping rate of each bead. Plasma cladding conditions are shown in Table 3.

3. Experimental Results and Discussion

3.1 Crack susceptibility in laser cladding

Trails were formed for obtaining optimal process conditions. The bead lengths of single-pass and multipass beads were all $50 \mathrm{~mm}^{(2),(3)}$.

Cracks appeared at room temperature and low preheating temperatures. The surface cracks of single-pass and multipass layers by laser cladding are shown in Fig. 4. The most cracks occurred perpendicular to the direction of the single-pass and multipass, Namely, transverse cracks appeared. The cracks were prevented from emerging at preheating temperatures of no less than 673 K for single-pass cladding and 693 K for multipass cladding.

It is thought that the residual stress had become small\(^{(4)}\) because the residual plastic strain is reduced in the clad layer by preheating; thus, crack susceptibility becomes small. Compared with the single-pass bead, the crack susceptibility becomes as large as that of the multipass bead, because of the large residual stress due to the repeated heating process, and a high preheating temperature.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Conditions of plasma cladding for power plant part</th>
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</thead>
<tbody>
<tr>
<td>Current</td>
<td>58—68 A</td>
</tr>
<tr>
<td>Voltage</td>
<td>26 V</td>
</tr>
<tr>
<td>Turning table rotation speed</td>
<td>0.35 rpm</td>
</tr>
<tr>
<td>Powder</td>
<td>WELPC-6</td>
</tr>
<tr>
<td>Powder feeding rate</td>
<td>1.5 g/min $\sim$ 4.5 g/min</td>
</tr>
<tr>
<td>Carrier gas</td>
<td>Argon: 2.5 L/min</td>
</tr>
<tr>
<td>Substrate material</td>
<td>SUS316L stainless steel</td>
</tr>
<tr>
<td>Plasma gas</td>
<td>Argon: 0.8 L/min</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>Argon: 15 L/min</td>
</tr>
<tr>
<td>Electrode diameter</td>
<td>3.2 mm</td>
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<tr>
<td>Conditions after welding</td>
<td>Air cooling</td>
</tr>
<tr>
<td>Preheating temperature</td>
<td>643 $\sim$ 698 K</td>
</tr>
</tbody>
</table>

![Fig. 3 Schematic of wear test setup](image)

![Fig. 4 Surface crack in single pass and multipass by laser cladding layers](image)
ture is demanded in laser cladding.

3.1.1 Cross section of clad layer  The vertical section of the single-pass bead formed by laser cladding is shown in Fig. 5. The direction of the crack almost becomes vertical with the fusion line, as shown in Fig. 5 (a). This crack stops neatly at the fusion line, and is not seen in the heat-affected zone. The progress of the crack took place in primary phase or interprimary phase, as determined by observation using a microscopy (Fig. 5 (b)).

3.1.2 Fractography of clad layer  The fractography of the single-pass bead formed by laser cladding is shown in Fig. 6. Chevron and river patterns were observed by SEM observation. This is a typical brittle fracture due to ductility dip. It is thought that ductility dip was induced by precipitation of compound phases at high temperatures and that the quasi-cleavage-type brittle fracture was obtained in the laser clad bead (2), (5), (6).

3.2 Wear test  
The friction coefficients of specimens with laser and plasma clad layers are shown in Fig. 7 (a), and are in the range of 0.42 – 0.48 and 0.51 – 0.58, respectively. The mass loss of the specimens is shown in Fig. 7 (b). The mean mass losses brought about by laser cladding and plasma cladding are 7 mg and 380 mg, respectively. Compared with plasma cladding, laser cladding showed a low friction coefficient and a small wear mass loss.

Images of specimens on the worn surface formed by laser cladding and plasma cladding are shown in Fig. 8. Signs of slipping are seen, and compounds (borides or carbides), which are mentioned in section 3.3, were observed using a laser microscopy. The volume fraction of compound phases in the laser coating layer was 46%, whereas the volume fraction in the plasma coating layer was lower.
was 34%, as obtained using point counting measurement. Compared with the worn surface of plasma cladding, that of laser cladding showed a high volume fraction of compounds and a small size. The compounds of hard projection become a frame, protect the matrix, and improve the wear resistance of the clad layer. It seems that the matrix protection effect increased with the volume fraction of the compounds.

3.3 Microstructure of clad layer

X-ray diffraction analysis results of laser and plasma clad layer are shown in Fig. 9. The existence of Ni-rich $\gamma$ solid solution ($\gamma$-Ni), and borides and carbides such as CrB and Cr$_7$C$_3$ was confirmed in both clad layer.

3.3.1 Microstructure of plasma clad layer

The microstructures of the plasma clad layer are shown in Fig. 10. The microstructures belong to the hypereutectic structure. The planar growth, eutectic structure and hypereutectic structure were observed in the area of the fusion line to the clad surface, as Fig. 10(a).

The primary phases of strip form (Fig. 10(a)), starfish form (Fig. 10(b)), needle form (Fig. 10(c)), block form (Fig. 10(c)), and cornuted form (Fig. 10(d)), the eutectic structure of blower form (Fig. 10(e)), and the normal eutectic structure (Fig. 10(f)) were observed in the plasma clad layer. The maximum width of the primary phase was about 20 $\mu$m. As regard heat input, the heat input in the plasma cladding process is higher and the $G/R$ ($G$: temperature gradient. $R$: solidification speed) ratio is lower than those in the laser cladding process. As a result of the
Higher heat input, the primary phase was the main phase in the microstructure\(^9\).

Figure 11 shows the EPMA line analysis results of the plasma clad layer for Cr, Ni, B and C. It can be found that the contents of the different elements were changed in the different forms of primary phase (Fig. 11(a) – (d)). The contents of B and Cr were high in the strip-form primary phase (Fig. 11(a)) and the contents of C and Cr were high in the needle and cornuted forms (Fig. 11(b) and (c)). It can be concluded that CrB and Cr\(_7\)C\(_3\) had been exited in Fig. 11(a) – (c), respectively, on the basis of the contents of C, B and Cr and the X-ray analysis result mentioned above. The contents of B and Cr were higher in the black area than in the white area in the blower-form eutectic, as shown in Fig. 11(d).

EDS mapping analysis results of Cr, C and Ni on the plasma cladding of the practical power plant parts are shown in Fig. 12. In the normal eutectic structure (Figs. 10(f) and 12), the contents of Cr and C in the white area are higher than in other areas, and the same as that of Ni in the black area.

3.3.2 Microstructure of laser clad layer

The bead appearance and cross section of the laser cladding of the machinery part are shown in Fig. 13 without defects. The spiral-clad layer was as smooth as the original surface.

The microstructures of the clad layer formed by laser cladding are shown in Fig. 14. In this case, the microstructures also belong to the hypereutectic structure. From the fusion line to the clad surface, the planar growth, hypoeutectic structure, eutectic structure and hypereutectic structure were observed, as shown in Fig. 14(a).
primary phases of the needle form (Fig. 14(b)), granular form (Fig. 14(c)) and block form (Fig. 14(d)) were observed in the hypereutectic structure. The size of the primary phase is below 5µm due to the fast cooling in the laser cladding process.

The EPMA line analysis results of the laser clad layer for Ni, Cr, B and C are shown in Fig. 15. It can be noted that the contents of B and Cr were high in the primary phase such as in the needle form (Fig. 15(a)), block form (Fig. 15(a)) and granular form (Fig. 15(b)), compared with those in the interprimary phase. Thus, the boride, CrB, can be considered as the main compound in the primary phase(5), (6). As shown in Fig. 15(b), the contents of Cr and C were higher at the same position, and the white region in this figure were consisted of Cr7C3(5), (6).

The results of EDS mapping for analyzing the eutectic structure in the laser clad layer for Ni and Cr are shown in Fig. 16. In the pine needle eutectic structure, a Ni-rich or Cr-rich mixture phase was observed. The eutectic struc-
Fig. 16  EDS mapping results of Ni and Cr for eutectic structure of clad layer formed by laser cladding of power plant machinery part

Fig. 17  Vickers hardness of clad layer formed by laser cladding and plasma cladding for power plant machinery part

The microstructures of the laser clad layer and plasma clad layer were shown as Figs. 10 and 14. The main reason why the microstructure is different is that the heat input differed depending on the cladding process. The heat input in the plasma cladding process was six times more than that in the laser cladding process. As a result, the primary phase in the plasma-coated layer had enough time for growth.

3.4 Hardness of clad layer

The Vickers hardness distributions of laser clad and plasma clad layers for power plant machinery parts are shown in Fig. 17. The Vickers hardness value of the laser clad layer was about 730, as in the matrix. However, that of the plasma clad layer was only about 500. The different hardnesses of the laser and plasma clad layers were due to the different cooling speeds in the cladding process\textsuperscript{(10)}. The primary phase in the laser-coated layer has a higher percentage than that in the plasma-coated layer. There were more eutectic microstructural units in the laser-coated layer due to the higher cooling speed, with eutectic point moving. The peak points of hardness curves were the points of carbide or boride. From the fusion line to the clad layer, the hardness distribution is also different. The dilution in the laser clad layer is only 0.1 mm; however, it is 0.45 mm in the plasma clad layer.

4. Conclusions

(1) A smooth, crack-free and porosity-less spiral clad layer was achieved by laser cladding at three times the speed of plasma cladding.

(2) The wear resistance realized by laser cladding was improved greatly compared with that by plasma cladding.

(3) The crack fractography of a laser clad layer belongs to quasi-cleavage-type brittle fracture. Preheating can prevent crack formation when the preheating temperature is above 420°C.

(4) The microstructures of the clad layer achieved by laser cladding and plasma cladding belong to the hypoeutectic structure. The primary phases contain boride CrB and carbide Cr\textsubscript{7}C\textsubscript{3}. The eutectic structures consist of γ-Ni + CrB in the laser clad layer, and γ-Ni + CrB and γ-Ni + Cr\textsubscript{7}C\textsubscript{3} in the plasma clad layer. The size of primary phase structure in the laser clad layer was less than 5 µm, and that in plasma clad layer was about 20 µm.

(5) The Vickers hardness of the laser clad layer was higher than that in the plasma clad layer.

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