The Effect of Dilution on HAZ Liquation Cracking in PTAW Ni-base Superalloys Overlay Deposit

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In this study, the effects of dilution on the HAZ liquation cracking susceptibility of PTAW (Plasma Transferred Arc Welding) Inconel 625 and Inconel 718 overlay on Nimonic 80A were observed. In order to evaluate the HAZ liquation cracking susceptibility, the Varestraint test was utilized. A possible mechanism of HAZ liquation cracking was suggested, on the basis of microstructure examination and thermal analysis.

The HAZ liquation cracking of the diluted Inconel 625 and Inconel 718 with Nimonic 80A was closely related with solidification temperature range and the amount and distribution of γ/NbC and γ/Laves eutectic phases formed along the solidification grain boundaries. As the dilution was increased, the C/Nb ratio increased, while the amount of eutectic phases decreased. The solidification temperature range was lowered with increases in the diluted in each overlay. Therefore susceptibility of HAZ liquation cracking diminished with increases in dilution.

KEY WORDS: PTAW (plasma transferred arc welding); dilution; Inconel 625; Inconel 718; Varestraint test; HAZ liquation cracking.

1. Introduction

Plasma transferred arc welding process (PTAW) is one of the overlay coating technologies, but various processing parameters have restricted its use in engineering and industrial applications. However, developments in microprocessors and apparatus now make the PTAW process more applicable and economical to perform. Moreover it becomes a much more reliable process due to the fundamental studies investigating the relationship between process parameters and coating properties. Currently, the PTAW process is primarily utilized for surface modification of structural materials in aerospace, steel-making, nuclear and chemical industries.1,2)

In order to improve the surface properties of valve spindles exposed to high temperature and high-pressure environments, a valve spindle made of Nimonic 80A was overlaid with a coating of PTAW Stellite 6. Though Stellite 6 exhibits an excellent oxidation resistance at high temperature, its initial cost is high and periodic repairs add significantly to the overall expense of this surface treatment. Inconel 625 and 718 are often substituted for Stellite 6 because of their good oxidation resistance and lower cost. However a main drawback of Inconel 625 and 718 is the hot cracking resulting from the formation of low temperature phases in the grain boundary during solidification. The liquation of the low melting phases causes a liquid film to form, with resultant hot cracking under the thermal stress of welding.3–6)

The major low melting phases resulting in hot cracking are different according to the chemical compositions of alloys. For example, it is known that M6C phase is for Hastelloy X, NbC and Laves phases are for Inconel 625, TiC is for Waspaloy, and MC and Laves phase are for Inconel 718. The local liquation of TiC or Si segregate is known to cause hot cracking in Alloy 800.7–9) In addition, the constitutional liquation results from sulfides, borides and intermetallic compounds such as NbC and TiC in stabilized stainless steel like Ti-bearing type 321 and Nb-bearing type 347.10)

The dilution between substrate and overlaying materials occurs during the plasma transferred arc welding process. This dilution results in a variation of chemical compositions in an overlay. The solidification behavior and microstructures of a PTAW overlay largely depend on these changes in chemical composition; therefore, the liquation cracking is dependent on the dilution rate of the PTAW overlays. In general, Laves phase increases with an increase in the content of Fe and Si alloying elements. This is due to an increase of the dilution rate during the plasma transferred arc welding of an Inconel 625 overlay on a steel substrate.11)

The content of Nb, Mo, Ti, and C alloying elements are the primary factor affecting the susceptibility of liquation cracking in the PTAW Inconel 625 and 718 overlays. This is because the solidification temperature range and the contents and morphology of the low melting temperature phases markedly depend on the chemical compositions.

In this study, the effects of the dilution between the alloy substrate and PTAW Inconel 625 and 718 on the solidifica-
tion behavior and susceptibility of liquation cracking were evaluated.

2. Experimental Procedure

2.1. Materials Preparation

The Inconel 625 and Inconel 718 powders were deposited on Nimonic 80A, which is used in the exhaust valve spindle using PTAW. The alloy compositions used in this study are given in Table 1. The degree of mixing is defined by the percentage dilution, $D$:

$$D(\%) = \frac{A_s}{A_s + A_{fm}} \times 100$$ ................................(1)

where $A_s$ is the melted cross-sectional area of the substrate and $A_{fm}$ is the cross-sectional area of the deposited filler metal. Figure 1 is a schematic illustration of dilution as measured by an image analyzer.

To observe the variation of composition in the layer and the behavior of HAZ liquation cracking with dilution, Inconel 625 and 718 PTAW overlays were formed with 10%, 20% and 30% dilution. Table 2 demonstrates the chemical composition of specimens after PTA overlay welding.

2.2. Varestraint Testing

The HAZ liquation cracking susceptibility of Inconel 625 and Inconel 718 layers was evaluated using Varestraint testing. The overlay samples were machined to standard size Varestraint specimens (165 x 25 x 3.2 mm). Schematic representation of the Varestraint test and specimen are displayed in Figs. 2 and 3, respectively. The welds were produced under the following parameters: 80 A, 2 mm arc distance, and 500 mm/min travel speed with argon shielding. In this test, straining occurs as a moving GTA weld is made with cracks forming in the nearly solidified weld fusion zone at the trailing edge of the molten weld pool. The augmented strain imparted to the outer fibers of the test specimen during the Varestraint tests is approximated by the relationship:

$$\varepsilon = t/2R$$

where $t$ is the thickness of the sample and $R$ is the radius of the die block. In this study, augmented strains of 1% and 4% were applied, with two specimens from each alloy at the individual dilution. Quantitative cracking data for both tests were obtained by measuring the length of each crack on the heat affected zone (HAZ) with 25 x magnification optical microscopy. Total crack length (TCL) and maximum crack length (MCL) were recorded for each sample.

Table 1. Chemical compositions of the materials used in this study.

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Ti</th>
<th>Nb</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
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<td>0.058</td>
<td>0.480</td>
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<td>Inconel 718</td>
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<td>17.71</td>
<td>17.37</td>
<td>1.01</td>
<td>4.97</td>
<td>9.36</td>
<td>0.045</td>
<td>0.200</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic illustration of dilution in single pass welds.

Table 2. Chemical compositions of Inconel 625 and Inconel 718 deposit layer with dilution after PTA welding.

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Ti</th>
<th>Nb</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
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<tr>
<td>Inconel 625 D10</td>
<td>64.60</td>
<td>19.91</td>
<td>2.70</td>
<td>0.13</td>
<td>3.59</td>
<td>8.53</td>
<td>0.059</td>
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<td>Inconel 625 D20</td>
<td>66.79</td>
<td>20.52</td>
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<td>2.82</td>
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<td>67.38</td>
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<td>2.75</td>
<td>6.34</td>
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<td>Inconel 718 D10</td>
<td>58.71</td>
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<td>16.38</td>
<td>1.09</td>
<td>4.47</td>
<td>2.61</td>
<td>0.049</td>
<td>0.203</td>
</tr>
<tr>
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<td>59.09</td>
<td>18.09</td>
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<td>3.99</td>
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<td>3.47</td>
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<td>0.130</td>
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</table>

Fig. 2. Schematic diagrams of Varestraint test and specimen preparation. (a) Schematic diagram of Varestraint test. (b) Varestraint test specimen.
2.3. Metallurgical Characterization and Thermal Analysis

The Varestraint test specimens were sectioned, mounted, and polished perpendicular to the coating surface using conventional polishing procedures. Etching for cross-sectional examinations was carried out using an electrolytic etching process in a solution containing 100 ml of distilled water and 10 g of CrO$_3$. The microstructure was studied by an optical microscope and a Scanning Electron Microscope (SEM) equipped with EDS.

In order to assess the solidification temperature range of each alloy, differential thermal analysis was conducted using a differential scanning calorimeter (DSC). Samples were melted and solidified under flowing argon in alumina crucibles using pure Ni as the reference material. The specimen was heated to 1400°C, and heating and cooling rates were 10°C/min. During cooling, a major peak of $\gamma$ matrix and 2 minor peaks, which are related with eutectic-type reactions, were observed. Reaction temperatures were taken as deviations from the local baseline.

3. Results

3.1. Macro Cracking Characterization

After the Varestraint test, liquation cracking is observed in PMZ (Partially Melted Zone) and HAZ around the fusion boundary. Figure 4 shows a typical morphology of the liquation cracking observed in the HAZ of an Inconel 718 overlay at 4% augmented strain. Intergranular cracks propagate in a normal fashion to the fusion boundary, and some of the cracks go through the fusion zone due to the epitaxial growth of grains between the HAZ and fusion zone.

3.2. Quantitative Cracking Analysis

Total crack length and maximum crack length are used as the criteria for the liquation crack susceptibility in the HAZ of overlays. The effects of the dilution and strain on the susceptibility of the liquation cracking can be shown in Fig. 5. The liquation cracking susceptibility decreases as the dilution increases, and increases as the strain increases. In addition, the HAZ of Inconel 718 overlay was more susceptible to the liquation cracking than that of Inconel 625. Thus, the susceptibility of the liquation cracking in the PTAW overlays is markedly dependent on the compositional changes, solidification behavior, and the resultant microstructure caused by the dilution between substrate and overlay.

3.3. Microstructure Characterization

Low melting temperature eutectic constituents ($\gamma$/NbC and $\gamma$/Laves) formed in the last-to-solidify region at the last stage of the solidification of the Inconel 625 and 718, Nb-bearing Ni base superalloys. Element distribution across the dendrite was analyzed by EDS and the chemical composition variations of $\gamma$ matrix and $\gamma$/Laves eutectic constituent according to dilution are shown in Table 3. The content of Nb and Mo alloying elements is much higher at $\gamma$/Laves eutectic constituent than in the dendrite core. The low partitioning coefficient of Nb and Mo alloying elements ($k<1$)
resulted in the partitioning of them to dendrite interstices during solidification. Thus, the enrichment of Nb and Mo occurred at solidification substructure boundaries and grain boundaries in overlays.

Figure 6 shows the morphologies of the $\gamma$/NbC and $\gamma$/Laves eutectic constituents formed at dendrite and grain boundaries in the HAZ of PTAW overlays. The formation of low temperature phases in HAZ occurs in the following processes. Firstly, the formation of these low-melting temperature eutectic constituents occurs due to the partition of the Nb, Mo, and Ti alloying elements to the substructure boundaries during solidification. Re-melting of these eutectic constituents then occurs due to the compositional liquation during a subsequent overlaying process. Finally, the enrichment of alloying elements resulted in the formation of the low temperature eutectic phases in HAZ during the re-solidification of the remnant liquid in HAZ.

Figure 7 shows $\gamma$/Laves phase formed by constitutional liquation between NbC and $\gamma$ matrix. It is supposed that NbC and the matrix were rapidly heated to the melting point, and then a liquid film formed at the surface of the NbC phase. Finally, the $\gamma$/Laves phase was formed by the re-solidification process. Figure 7(b) shows the composition change due to constitutional liquation around NbC phases.

As seen in Fig. 8, the liquation cracking occurs along the low temperature $\gamma$/Laves eutectic constituent, and the liquation crack surface has a dendritic appearance. It is supposed that the liquation cracking in the HAZ of the PTAW overlay resulted from the local liquation of the low temperature phases and thermal stress during PTAW heat cycles.

3.4. Thermal Analysis

The effects of the dilution between substrate and overlays on the solidification temperature range ($\Delta T$) and the solidification temperature of the low melting eutectic constituents are evaluated by thermal analysis. The results of the DSC analysis are presented in Table 4. $\Delta T$ is defined as a temperature difference between the solidification temperature of the $\gamma$ matrix and that of the $\gamma$/Laves eutectic constituent. In the solidification of the Inconel 625 and Inconel 718 alloys, the formation of low temperature eutectic constituent lowered the solidification temperature range. As the dilution is increased, the $\gamma$ matrix solidification temperature is slightly decreased, but the $\gamma$/Laves eutectic temperature is increased. Therefore, $\Delta T$ is decreased with an increase in dilution. Also, $\Delta T$ of the Inconel 625 overlay is smaller than that of the Inconel 718 overlay.

![Table 3. The compositions of dendrite core (DC), $\gamma$/Laves eutectic phase in Inconel 625 and Inconel 718 deposit layers.](image)

- **Table 3.** The compositions of dendrite core (DC), $\gamma$/Laves eutectic phase in Inconel 625 and Inconel 718 deposit layers. (unit: wt. %)

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Nb</th>
<th>Mo</th>
<th>Ti</th>
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<td>Inconel 625 D10</td>
<td>65.71</td>
<td>20.35</td>
<td>2.53</td>
<td>2.35</td>
<td>7.36</td>
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<tr>
<td>$\gamma$/Laves</td>
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<td>1.72</td>
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<td>0.22</td>
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<td>Inconel 625 D20</td>
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<td>2.21</td>
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<td>13.67</td>
<td>1.25</td>
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<td>Inconel 718 D10</td>
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<td>2.89</td>
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<td>15.21</td>
<td>2.68</td>
<td>2.14</td>
<td>1.15</td>
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<td>10.85</td>
<td>22.87</td>
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<td>2.35</td>
<td>1.60</td>
<td>1.30</td>
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<tr>
<td>$\gamma$/Laves</td>
<td>48.88</td>
<td>13.60</td>
<td>9.45</td>
<td>21.31</td>
<td>4.87</td>
<td>1.89</td>
</tr>
</tbody>
</table>

![Fig. 6. The eutectic constituents at HAZ of Inconel 625 and Inconel 718.](image)

(a) Inconel 625. (b) Inconel 718.
4. Discussion

4.1. Critical Phase Balance with Solidification Behavior

The C/Nb ratio and the contents of low melting point phases with the dilution in PTAW overlays are shown in Table 5. As dilution is increased, the total contents of the eutectic constituents are decreased. However, the γ/Laves eutectic phase content is decreased, but the γ/NbC eutectic phase content is increased with an increase in dilution, due to the changes of the chemical composition induced by the dilution. As seen in Table 2, Nb and Mo alloying element contents, Laves phase former, is decreased, whereas Ti content, carbide former, is increased in an overlay with an increase in dilution. It is considered that the decrease of the total low melting phases contents results from a decrease of Nb content, which affects the formation of the Laves phase and carbide. In reality, Inconel 718 overlay contains more Nb alloying element than Inconel 625 overlay. This is the reason why more eutectic constituent was present in Inconel 718 overlay than Inconel 625 overlay.11,15–17)

γ/NbC eutectic constituent content is decreased but the γ/Laves eutectic constituent is increased with a decrease in the C/Nb ratio. The important alloying elements concerned with the formation of the low melting point eutectic constituents are Ni, Nb, and C. The primary factor affecting the solidification behavior, especially the formation of the low melting phases, is the C/Nb ratio according to the dilution. The microstructure of the PTAW overlay and the hot cracking susceptibility of an overlay depend on the dilution. For instance, carbide/Laves phase content ratio is increased with an increase in the C/Nb ratio.

4.2. HAZ Liquation Cracking Tendency with Solidification Behavior

According to B. Radhakrishnan and R. G. Thompson et al., Inconel 718 alloy solidifies in the following sequence.18)

\[
\text{Inconel 625 has the same solidification process as Inconel 718.11)}
\]

When the C/Nb ratio becomes lower, the Nb content in liquid is still high after the \( L \rightarrow L + \gamma + NbC \) reaction and thus the subsequent \( L \rightarrow (\gamma + \text{Laves}) \) reaction occurs as the solidification proceeds. Therefore, the content of the \( \gamma/\text{Laves} \) eutectic constituent increases with a decrease in the C/Nb ratio.

Figure 9 shows the variation of liquation cracking susceptibility (TCL) with changes in the C/Nb ratio. The liquation cracking susceptibility is increased with a decrease in the C/Nb ratio. This is due to an increase in the low melting phase (\( \gamma/\text{Laves} \) eutectic constituent) content with the increase in Nb content.

In addition to the formation of the eutectic constituents, the liquation cracking susceptibility depends on the solidifi-
cation temperature range as shown in Fig. 10. Figure 10 also reveals the relationship between the \(\gamma/Laves\) eutectic temperature and maximum crack length (MCL). As the \(\gamma/Laves\) eutectic temperature increases, the resultant solidification temperature range is decreased. Therefore, the width of the region susceptible to the cracking is decreased. Also, the liquation cracking susceptibility is decreased due to an increase of the \(\gamma/Laves\) eutectic temperature by the increase of dilution. It seems that the higher liquation cracking susceptibility in the Inconel 718 overlay compared with that of the Inconel 625 overlay is due to the lower \(\gamma/Laves\) eutectic temperature in the Inconel 718 overlay.

5. Conclusions

The main objectives of this study were to assess the dilution effect of PTA overlay processes on their solidification behavior and liquation cracking susceptibility. The results of this study are as follows:

(1) The C/Nb ratio is the primary factor controlling the liquation cracking susceptibility of the Inconel 625 and 718 overlays. As the C/Nb ratio is decreased, the content of \(\gamma/NbC\) eutectic constituent is slightly decreased, but the content of \(\gamma/Laves\) eutectic constituent is markedly increased. Therefore, the total content of eutectic constituents is increased.

(2) As the dilution is increased, the C/Nb ratio is increased and the low melting phases content is decreased because of chemical mixing between overlay alloys and base metal. Thus, the HAZ liquation cracking susceptibility of Inconel 625 and Inconel 718 overlays is decreased with increased dilution.

(3) The solidification temperature range is decreased with increased dilution; and therefore, the liquation cracking susceptibility is decreased. Also, the liquation cracking susceptibility of Inconel 718 overlay is higher than that of Inconel 625 overlay due to the higher content of the low melting eutectic constituents and wider solidification temperature range.

Acknowledgments

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