WEAR PROTECTION OF HIGHLY LOADED COMPONENTS: ADVANTAGES OF PLASMA TRANSFERRED ARC WELDING AS HARDFACING TECHNOLOGY
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Abstract: Hardfacing is one of the most economical surface treatment technologies to improve service life and durability of metal parts subjected to wear. The application of hardfacings is technically feasible with different welding technologies. In this work, the plasma transferred arc (PTA) process was used for deposition of different hardfacings. For a better understanding of the correlation of PTA processing and wear behaviour, two different alloys were investigated under various deposition parameters. The influence of cooling conditions was studied by temperature controlling of the substrate. Key words: tribology, hardfacing, plasma transferred arc, wear protection

1. INTRODUCTION
Plasma transferred arc (PTA) welding is an increasingly used technology to protect highly stressed components with a wear resistant thick coating. In different industrial applications e.g. mining, recycling industry and agricultural machinery, hardfacings are used for wear protection to increase lifespan and support component efficiency [1,2].
The hardfacing process normally uses materials consisting of a metallic matrix material and hard particles as reinforcement. The metallic matrix acts as a binder for the hard particles where iron, nickel and cobalt are used. An essential condition for embedding the hard particles is their ability of wetting [3]. Furthermore, the wear mechanism has a significant role in the selection of material composition. Investigations showed under abrasive conditions that an increase of hard phase content in the metallic matrix is beneficial. Furthermore, the metallic matrix can be modified too. A softer and more ductile matrix is more insensitive to impact wear than a brittle matrix with high hardness. For reducing material loss due to wear, it is necessary to find a compound of material properties related to the major wear regime [4]. Applying PTA technology, a coating with excellent wear resistance can be deposited on a cheap bulk material. The wear behaviour of this hardfacing is mainly influenced by many different factors and process parameters. The challenge is to find the optimised adjustment of hardfacing parameters to reach the claimed wear behaviour. For this goal, a fundamental knowledge of each parameter effect on the properties of the compound is necessary [5,6]. It is possible to homogenise the microstructure and resulting wear behaviour of hardfacing by modulating the welding parameters [7]. Within this work, a NiCrBSi based hardfacing reinforced with coarse tungsten carbides is investigated and show clearly the effect of working parameters during the hardfacing process on the microstructure and wear behaviour, respectively. Furthermore, a FeCrVC based material with homogenous dispersed hard phase precipitations is deposited under various cooling conditions. Optimised wear behaviour under abrasion conditions and at the same time low wear rates under combined impact/abrasion should be achieved by selection of adjusted processing parameters.
2. EXPERIMENTAL

2.1 Testing material and hardfacing

A Ni-based matrix alloy with enhanced B, Si and Cr content was used to manufacture testing samples to investigate the effect of welding current modulation. This matrix was reinforced by coarse tungsten carbide (WC/W₂C, fused & crushed) with particle diameter distribution between 75 µm and 150 µm at a fraction of 40 % and 60 % mass, respectively (samples N1 to N3). Mild steel 1.0037 with 8 mm thickness was used.

To investigation the influence of cooling conditions, an iron based alloy with Cr, V and C content was used. The hard particle content is formed by precipitations of vanadium and carbon. Mild steel 1.0037 substrate (samples FM) and austenite substrate 1.4301 (samples FA) with 5 mm thickness were used. The chemical compositions of alloys are given in Table 1.

PTA welding was done with a EuTronic® Gap 3001 DC at AC²T research GmbH (see Fig. 1). Hardfacing parameters including welding current, oscillation and welding speed, substrate, powder feed rate, nozzle distance to substrate, carrier, shielding and plasma gas flow rates are optimised based on practical welding procedures. Hardfacing parameters are given in Table 2.

<table>
<thead>
<tr>
<th>[mass-%]</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>B</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiCrBSi</td>
<td>0.2</td>
<td>2.5</td>
<td>-</td>
<td>4.0</td>
<td>base</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Fe-VC</td>
<td>2.8</td>
<td>0.7</td>
<td>1.1</td>
<td>5.7</td>
<td>-</td>
<td>1.7</td>
<td>12.5</td>
<td>base</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of alloys

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>FM</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>current [A]</td>
<td>85</td>
<td>110</td>
<td>80</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>pulsing time [ms]</td>
<td>8-4</td>
<td>8-4</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>velocity [mm/s]</td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td>0.9</td>
<td>1.15</td>
</tr>
<tr>
<td>osc. velocity [mm/s]</td>
<td>20</td>
<td>25</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>osc. width [mm]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>WC/W₂C content [%]</td>
<td>60</td>
<td>60</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>substrate thickness [mm]</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>(mild steel)</td>
<td>(austenite)</td>
</tr>
</tbody>
</table>

Table 2. Hardfacing parameters

To describe the pulsing cycle, the modulation of welding current was given as pulsing time “8-4”. This means that after 8 ms of nominal current, a pause of 4 ms followed. This schematic is given in Fig. 2a. As result of the “on-off” switching of the current a sawtooth-shaped current profile can be measured (Fig. 2b). It was not possible to reach a deactivation of current due to upkeeping of the welding plasma by the pilot current (15 A).

Testing specimens were prepared by waterjet cutting to avoid heating up of substrate and hardfacing.

For measuring the cooling time during the hardfacing process, thermocouple type K was used by sticking in the liquid melt pool and the temperature/time values was recorded with a thermocouple measuring board National Instruments NI 9213.
2.2 Wear investigation
Abrasion tests on a dry-sand rubber-wheel tester according to ASTM G65 Procedure A were performed simulating conditions of 3-body abrasion under low stress. Testing parameters were conducted at a rotational speed of 200 rpm, a normal load of 130 N, a sliding distance of 4309 m, and with Ottawa silica sand grain size of 212–300 μm. Each test was repeated three times for statistical calculation. Wear characterisation was done by mass loss of specimens during wear testing.

Wear tests under combined impact/abrasion were performed on a specially designed impeller-tumbler apparatus (CIAT). The device consists of a slowly rotating outer tumbler and a fast rotating inner impeller, where the testing specimens were mounted and spun at rotation speeds of 60 and 650 rpm respectively. The tumbler was filled with a defined amount of abrasive, and controlled the flow of abrasive particles hitting the fast moving testing specimens (see Fig. 3a and b). Due to the kinematical motion, the particles contact the specimen (surface exposed to abrasive particles, 25×10 mm) at an impact velocity of approximately 10 m/s. The abrasive material was 1 kg of corundum particles (5–10 mm). Each run lasted 20 min, and each test was repeated 3 times for statistic calculation. Wear characterisation has been done by gravimetric mass loss of the testing specimen during wear testing.

Fig. 3. Combined impact/abrasion test device - Principle of particle flow.

3. RESULTS AND DISCUSSION
3.1 Modulation of current by pulsing
As result of the pulse modulation of the welding current (see Table 2) the effect on the carbide reinforced Ni-matrix is clearly shown in Fig. 4. Note that the dilution process of the hard particles is significantly reduced (N2) in comparison to the standard welding (N1). The decrease of heat input reduces the formation of the matrix-carbide interphase zone and helps to maintain the volume fraction of the origin hard particles which is required for abrasion resistance. In the pulsed sample, the amount of secondary precipitations is also reduced due to less solved WC/W2C (Fig. 4c, d).

The difference in dissolution can be observed in hardness level of the compound too. The comparison of investigated hardfacing conditions (see Tab. 2) shows no difference in hardness of the metallic matrix. This means that the Ni-alloy is not significantly modified in the chemical composition by the dissolution process. On the other side, the macro hardness of the pulsed sample N2 is increased in comparison with the standard sample N1 and is a result of the increased area content of origin hard particles. The reduction of hard particle content from 60 to 40 weight-% leads to a decrease in macro hardness as expected.

Fig. 4. Optical image of surface microstructure a) sample N1 (without pulsing) b) sample N2 (with pulsing) c) detail sample N1 d) detail sample N2
The wear behaviour under 3-body conditions is given in Fig. 6. Standard sample N1 shows a relatively good abrasion resistance with a wear rate of 0.0026 mm³/m in comparison to industrial deposited hardfacings with similar composition (~ 0.0038 mm³/m). The gap in the wear rate is a consequence of the different focus of the welding process, whereas the industrial parameters are dominated by increased heat input for high deposition rates.

With pulse modulation of the welding current, the wear rate of sample N2 decreases by nearly 20 % down to 0.002 mm³/m despite the fact the current is increased to 110 A. This increase is necessary to ensure the dissolution of the metallic matrix and keeps it liquid for homogenous distribution of hard particles to form a connection between the hardfacing and the substrate material.

A reduction of the hard particle content in pulsed sample N3 comes to a reduction of wear resistance and the wear rate increases up to 0.004 mm³/m. This doubling of wear rate illustrates a significant loss of wear resistance; however, the wear rate is still on a low level for this type of hardfacing. It shows clearly the effect of reduced hard particle content and distance between the particles, respectively. However, the amount of expensive carbide content and the density of the hardfacing can be reduced.

3.2 Effect of cooling conditions

To substitute expensive hardfacing compounds, like WC/W₂C reinforced NiCrBSi alloys, iron based hardfacing alloys has become very popular in the last few years. In this work, a common iron based hardfacing powder with high content of vanadium and carbon (Table 1) is used for investigations of cooling effects during the deposition process.

The microstructure of the Fe-VC type consists of primary precipitated hard phases, which are homogenously distributed in the matrix (Fig. 7).
Table 3. Dilution, cooling time and hardness of Fe-VC samples

<table>
<thead>
<tr>
<th></th>
<th>FM1</th>
<th>FM2</th>
<th>FM3</th>
<th>FA1</th>
<th>FA2</th>
<th>FA3</th>
</tr>
</thead>
<tbody>
<tr>
<td>dilution</td>
<td>0.058</td>
<td>0.061</td>
<td>0.107</td>
<td>0.151</td>
<td>0.136</td>
<td>0.163</td>
</tr>
<tr>
<td>cooling</td>
<td>47.4</td>
<td>44.8</td>
<td>45.2</td>
<td>35.2</td>
<td>42.1</td>
<td>66.4</td>
</tr>
<tr>
<td>time t8/5</td>
<td>655±3</td>
<td>730±4</td>
<td>680±16</td>
<td>590±38</td>
<td>645±13</td>
<td>611±3</td>
</tr>
</tbody>
</table>

The spherical shaped carbides (black phase A) are small with diameters between 2 and 5 µm in comparison with the WC/W2C reinforcements above. The precipitations consists not only of vanadium and carbon, but iron can be also found in the carbide phase (A) that comes to a vanadium rich mono carbide type of (Fe,V)C. The metallic matrix is martensitic (Phase B in Fig. 7).

For the realisation of different cooling conditions, the substrate is passively cooled with a water cooled copper plate down to 10 °C (attachment “1” in sample name), is set in with room temperature (attachment “2”) and is pre-heated to 100 °C (attachment “3”). The different welding parameters for mild steel and austenite substrate are necessary to receive a usable hardfacing bead and can be explained by the different thermal conductivity of these alloys.

After hardfacing process microstructural properties (dilution and hardness) are determined and compared with the cooling time between 800 °C and 500 °C (t8/5); data is given in Table 3. For the mild steel substrate, low dilution can be achieved, increasing with the substrate temperature (TM1-3). Remarkably, the cooling time t8/5 does not change significantly at a moderate level of 45 s. However, an effect on the hardness can be observed, where FM2 shows the highest hardness level, which is not expected. A change in substrate composition to austenite material diversifies the values for dilution and hardness. The welding current has to be regulated down to 75 A as consequence of the decreased thermal conductivity and comes to an increase of cooling time from 35 s (FA1) up to 66 s (FA3). The hardness level of FM series cannot be reached due to the higher dilution with the substrate. This leads to a modified composition with enhanced content of Cr and Ni from the austenitic substrate.

To correlate the abrasion resistance with the impact/abrasion behaviour of the different cooled samples, a wear map can be compiled and is given in Fig. 8. This figure helps to identify the fields of application for materials in mineral wear regime.

The passively cooled sample deposited on the mild steel shows the best wear resistance under both conditions. With increasing, the substrate temperature abrasion wear rate is increased and maintains a constant level, whereas the impact/abrasion wear resistance decreases significantly. The loss of alloying elements in the hardfacing due to higher dilution with the mild steel substrate and the fast cooling time leads to a more brittle matrix on a high hardness level.

Hardfacing samples on the austenitic substrate (FA) show less abrasion resistance than sample series FM with a maximum factor of 2. This can be explained by the higher dilution with the substrate, which leads to an enrichment of Cr and Ni in the hardfacing composition. Due to decreasing carbon content in the hardfacing, the formation of carbide precipitations is reduced, leading to lower hard particle content. However, the combined impact/abrasion resistance is still excellent, independent of cooling performance. Again, the same mechanism in microstructure is responsible for this effect. The reduced hard phase content helps to dissipate the impact energy and reduces the wear rate. The moderate cooling rate of sample FA2 with relatively low dilution shows the best performance considering 3-body abrasion resistance.
4. CONCLUSION

Based on the study within this work, the following conclusions can be drawn:

1. Reduced energy input by current modulation shows a reduced dissolution of origin hard particle and reduced content of secondary precipitations in the Ni-matrix.
2. Pulsing current successfully optimises micro-structure of WC/W2C reinforced Ni-matrix under 3-body abrasion conditions.
3. WC/W2C content can be reduced to 40 weight-% for low level abrasion wear rates.
4. Fe-VC alloy system can act as all-round hardfacing under abrasive and impact/abrasive wear conditions.
5. Cooling and substrate conditions have a significant influence on wear behaviour at Fe-VC system.
6. Hardness is not the major parameter for wear behaviour evaluation.
7. Dilution, thermal conductivity and substrate composition have to be considered for practical application of Fe-VC hardfacing systems.

5. ACKNOWLEDGEMENT

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6. REFERENCES


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