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Influence of process parameters in the friction surfacing of AA 6082-T6 over AA 2024-T3

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Abstract

Friction Surfacing is a solid state coating technique with applications in hardfacing, corrosion protection and repair. Since it doesn’t require the fusion of the materials involved, it is suitable to join aluminium alloys while avoiding several of their processing difficulties. The present study addresses the deposition of AA 6082-T6 coatings on AA 2024-T3 substrates, while focusing on the effect of process parameters, such as, axial force, rotation and travel speed. Sound aluminium coatings were produced with limited intermetallic formation at bonding interface. It was observed that low travel and rotation speeds contribute to an increase of coating thickness and width. Bonding at coating edges deteriorates for faster travel speeds. The axial force is determinant in achieving a fully bonded interface.

1. Introduction

Research in welding and joining has been marked recently by significant breakthroughs in the development of friction based solid state processes. These processes often provide superior results, while avoiding some of the difficulties inherent to fusion based processes. The temperatures achieved during processing are below fusion temperature, allowing to join materials which would be difficult to join otherwise due to their intrinsic thermo-physical properties, such as, aluminium alloys [1-2].

In the field of coating techniques, Friction Surfacing (FS) is best known for enabling dissimilar material combinations, while reducing substrate distortion and the loss of material properties [3]. Similar to other solid-state friction based technologies, the coatings produced by FS comprise a series of advantages, being more environmentally friendly and avoiding metallurgical defects inherent to fusion based processes.

As depicted in Fig. 1a, a rotating rod is pressed against a substrate with an applied axial force. Heat is triggered by friction at the interface, thereby enabling plastic deformation at the rod contact surface (Fig. 1b). The pressure and temperature conditions lead the bonding between the plasticized material and the substrate [4]. By applying a relative movement between the consumable rod and the substrate, a continuous coating is produced (Fig. 1c-d). The coating material is provided by the consumable rod with no external heat source.

In FS, as in all friction based manufacturing technologies, a viscoplasticized solid state region is generated and processed into a new shape and metallurgical condition. Although this region remains in solid state, it presents a three-dimensional material flow pattern that enables the blending between different materials. This phenomenon is generally referred to as the “third-body region” concept [5]. This “third-body region” is characterized by a relatively low flow stress and temperatures above the recrystallization temperature but below the melting temperature of the material. Being driven exclusively by the introduction of mechanical energy, the heat is generated by friction dissipation during deformation at contacting interfaces and internally by material flow.

One relevant property of the “third-body region” is to produce strong bonds at the interface between the...
coating material (undergoing viscoplastic flow) and the substrate surface, which may be undergoing less severe deformation, like elasto-plastic deformation.

The solid state joining mechanism is mostly controlled by diffusion, and approximation to interatomic equilibrium distances can also be found for lower temperature and higher pressure conditions at the joining interface. Some mechanical bonding was also observed for dissimilar material combinations [6].

In FS, the “third-body region” is not fully constrained. The highly plasticized material at the tip of the consumable rod is pressed against the substrate without lateral restraint. This promotes the development of a flash, as well as, the lack of bonding at the coating edges on both the advancing (AS) and retreating sides (RS) [7].

Process parameters, such as: axial force, rotation and travel speed, control the characteristics of the coating produced [8] and there are some studies reported in literature that allow predicting some effects on thickness, width and bonding strength [9-11].

Industrial applications for friction surfacing have been reported, mainly in the manufacturing of long-life cutting tools with a strong resistance to delamination. Several studies also suggest promising uses in hardfacing, corrosion protection or damage repair [12]. A wide range of materials has been deposited by friction surfacing, mainly tool steels, stainless steels, mild steel, copper and nickel-based alloys [13-15].

Regarding aluminium alloys, Sakihama et al. [16] used friction surfacing to deposit an AA 5052 alloy over plates of the same material. Tokisue et al. [17] addressed the single and multilayer deposition of AA 2017 alloy on AA 5052 substrates. More recently, Suhuddin et al. [18] studied the grain refinement process in the FS of an AA6082-T6 over AA2024-T3. The authors found that simple-shear deformation is the predominant cause of grain deformation and recrystallization.

The present investigation addresses the influence of the main process parameters, namely force, rotation and travel speed on coating shape and bonding in the deposition of AA 6082-T6 over AA 2024-T3.

2. Materials and methods

The materials used in this study were: AA 2024-T3 aluminium plates with 4 mm thickness and AA 6082-T6 rods with 20 mm diameter. Table 1 presents the chemical composition of both materials.

Friction surfacing was performed using an ESAB LEGIOTM 3UL friction stir welding machine, equipped with position and force control modes. Consumable rod and substrates were degreased prior to deposition. Table
2 presents the process parameters used, chosen based on previous experience.

Coated samples were cross sectioned, polished and etched with Keller reagent for metallographic analysis.

Table 1. Chemical composition of AA2024-T3 and AA6082-T6

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA2024</td>
<td>&lt;0.1</td>
<td>3.8</td>
<td>&lt;0.5</td>
<td>1.2</td>
<td>0.3</td>
<td>&lt;0.5</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>AA6082</td>
<td>&lt;0.25</td>
<td>&lt;0.1</td>
<td>&lt;0.5</td>
<td>0.6</td>
<td>0.40</td>
<td>0.7-1.3</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

Table 2. Process parameters

<table>
<thead>
<tr>
<th>Axial Force [kN]</th>
<th>Rotation speed [rpm]</th>
<th>Travel speed [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 9</td>
<td>3000</td>
<td>4.2 - 14.2</td>
</tr>
</tbody>
</table>

Optical microscopy (OM) was performed using a Leica DMI 5000 M inverted optical microscope, while SEM analysis was performed using a ZEISS DSM 962, equipped with energy dispersive spectroscopy (EDS). Micro-hardness indentations were performed under a load of 1.96 N in a Mitutoyo HM-112 Micro-Vickers hardness testing machine.

3. Results and discussion

3.1. Metallographic analysis

Fig. 2 presents a macrograph of a coating cross section. Dynamic recrystallization enabled the nucleation of a new grain structure. The relatively fast cooling rate prevents grain growth and a fine microstructure is produced (Fig. 2a).

Grain size measurements reveal an average size of 4 ± 2 μm, which accounts for a 33% grain refinement compared to the rod in as-received condition. The diffusion bonding interface between the coating and the substrate can be seen in Fig. 2b.

Coating hardness is slightly higher near the surface reaching a maximum of 91 HV0.2. Although the coating presents a refined microstructure, the loss of the T6 artificial ageing heat treatment due to heat exposure results in a 15% hardness decrease compared to the rod in as-received condition.

Heat conducted to the AA2024-T3 substrate resulted in a slight over ageing, evidenced by a 6% hardness decrease along a 2.2 mm depth at the heat affected zone. Fig. 2c depicts the edge on the retreating side. As-received consumable rod microstructure is depicted in Fig. 2d, presenting an anisotropic grain structure aligned along the rod extrusion direction.

Fig. 3 depicts a fully bonded interface, free of porosity and intermetallics. The heat affected zone in the substrate presents some precipitates, although their concentration and size appear to be reduced just below the interface.

With the tested processing parameters, the coating produced has a width of about 20 mm and a minimum thickness of approximately 2 mm. The ratio between the effectively joined width and the coating width is of about 77%. Approximately 30% of the rod material consumed was deposited onto the substrate. The remaining material was consumed as flash.

3.2. Influence of process parameters

Fig. 4 depicts the effect of travel speed on the coating thickness, width and bonded width. Travel speed presents a similar effect for different axial forces. Since travel speed influences the rate at which the material is deposited, higher travel speeds result in thinner deposits.

Fig. 2. Coating cross section macrograph; (a) coating; (b) bonding interface; (c) unbonded edge; (d) as-received consumable rod

Fig. 3. Interface analysis by BE scan electron microscopy
The substrate heat affected zone and bonded width decreased for higher travel speeds, due to shorter exposure periods to force and heat.

Axial force improves bonding width and results in wider and thinner deposits, as shown in Fig. 5a. Insufficient forging forces result in poor consolidated interfaces, with a decrease on bonded width (Fig. 6a). The decrease in thickness for higher axial forces was also followed by concave shaped cross sections and enhanced substrate heat affected zones (Fig. 6b). Excessive forces can also result in the depression of the substrate surface as evidenced in Fig. 6b.

Rotation speed influences the bonding quality and coating width (Fig. 5b). While lower to intermediate rotation speeds enhance bonding quality, higher rotation speeds produce a more flat and regular deposit.

Friction surfacing is best suited for applications requiring thin deposits, strongly bonded with no dilution. Since no melting of the bulk takes place during the coating process, it is possible to produce dissimilar joining of materials that would be otherwise incompatible or difficult to deposit by fusion based methods.

The absence of melting also results in low residual stress levels since solidification shrinkage does not occur.

FS coatings are inherently homogeneous, thereby presenting attractive mechanical or corrosion properties compared to other fusion based coating processes, as was demonstrated by Rao et al. [19] and Puli et al. [20] for arc welding processes. The absence of spatter, radiation emissions or fumes makes friction surfacing a cleaner and more environmental friendly technology [12]. Considering other solid state cladding processes, such as, explosive cladding or roll bonding, friction surfacing can be seen as a more versatile alternative for specific coating treatments.

However, there are some relevant drawbacks that contribute to a limited range of engineering applications. One of the main process disadvantages is the poor bonding at the coating edges, as post-processing operations are often required to remove them. The usable bond width is less than the width of the coating produced, as described by Voutchkov et al. [21].
Moreover, the generation of a revolving flash at the consumable rod tip contributes to a decrease in mass transfer efficiency, as it represents a fraction of material that does not bond to the substrate. Friction surfacing enables a limited control over the deposited thickness and width, as coating geometry is determined by a relatively narrow range of process parameters [21-22]. The length of consumable that can be used is also limited to prevent bucking. Some rod guiding/support systems allow to increase the length of rod used and the coating length. However, other coating processes based on wire or powder feed present more competitive approaches, since they allow continuous feeding.

Nonetheless, the search for superior coating solutions has drawn increasing focus on FS, considering its advantages related to solid state processing.

![Image](image_url)

Fig. 6. Influence of axial force and rotation speed on coating cross section and substrate HAZ; (a) 3kN, 1500 rpm, 4.2 mm/s; (b) 9 kN, 3000 rpm, 4.2 mm/s

4. Conclusions

From the present work, the following can be concluded:

- AA 6082 was successfully deposited on AA 2024 by friction surfacing.
- The interface was free of porosity and no significant evidence of intermetallic formation was found.
- High travel speeds contribute to a decrease of coating thickness, width and bonded width.
- Axial force improves bonding width and results in wider and thinner deposits. Excessive forces will result in concave shaped cross sections.
- Lower rotation speeds were beneficial for joining.

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