Parameter Study for Friction Surface Cladding of AA1050 on AA2024-T351

S. Liu, University of Twente, Faculty of Engineering Technology, Department of Mechanics of Solids, Surfaces & Systems, Drienerlolaan 5, 7522 NB Enschede, The Netherlands

T.C. Bor, H.J.M. Geijselaers, R.Akkerman. University of Twente, Faculty of Engineering Technology, Department of Mechanics of Solids, Surfaces & Systems, Drienerlolaan 5, 7522 NB Enschede, The Netherlands.

Synopsis

Friction Surfacing Cladding (FSC) is a relatively new solid state process to deposit thin metallic clad layers on substrates. It employs a hollow rotating tool that supplies the clad material. Frictional and viscous heating take place that soften the clad material and enhance the bonding of the clad material to the substrate. Thin layers of commercially pure aluminium can be deposited well on an AA2024 aerospace aluminium alloy. Homogeneous and defect free layers with a fine grained microstructure can be manufactured. The relatively low heat input and normal forces exerted on the substrate during the FSC process assure a minimal influence of the process on the mechanical properties of the substrate.

A 3D thermal flow model is employed to study the influence of important process parameters, such as the tool rotation and translation rate and the width of the deposited layers on the generated heat and normal forces. Full sticking between the FSC tool, the clad material and the substrate is assumed. The thermal flow model shows that higher tool rotation rates lead to more heat input and higher process temperatures. However, the normal force level decreases significantly due to the shear thinning behavior of the clad material at elevated temperatures and high strain rates. At higher translation speeds the normal force strongly increases. The layer width also has a strong influence: it increases both the heat generation and the normal force.

The observed trends in the heat generation and normal force may be vital for further optimization of the FSC process. A direct comparison between the simulated and experimental values shows some discrepancy. A possible explanation is the presence of slip at the FSC tool, clad material and substrate interfaces.

Keywords: Friction surface cladding, friction surfacing, friction stir welding, Heat transfer, material flow.

1 Introduction

Friction surface cladding (FSC) is a new solid state process to deposit thin metallic layers on substrates. It is developed based on frictional heating at contact interfaces and plastic deformation dissipation within the clad material that is provided through the center of a hollow rotating
tool. The clad material at elevated temperatures becomes sufficiently soft to be distributed over the substrate surface beneath the FSC tool, see Fig. 1. In this way thin metallic layers can be manufactured with sound bond to the substrate over the entire cross section and a fine grained microstructure.

The FSC process has been developed to mitigate some of the problems confronting friction surfacing (FS) where a rotating rod of clad material is being pressed on top of the substrate, but then in absence of a supporting tool (Gandra et al. 2014). Typically, (i) lack of bonding between the clad material and the substrate at the edges of the deposited layers and (ii) excessive flash formation of the clad material may be observed. Furthermore, the dimensions of the deposited layer cannot be controlled easily.

The presence of the FSC tool provides an effective way to support the lateral distribution of the clad material in the space between the tool bottom and the substrate and to more easily control the layer dimensions (Van der Stelt 2014). Exploratory research has shown that homogeneous and defect free layers of commercially pure aluminium can be deposited well on top of an AA2024 substrate within a range of process settings (Liu et al. 2016).

The generation of heat is strongly related to the rotation motion of the tool relative to the substrate. Friction process occurs at the interfaces between the tool, the clad material and the substrate and and plastic deformation within the clad material. The process parameters such as the rotation rate (Ω), the translation rate (v_t) and the tool inclination angle (θ) which are also typical for friction stir welding are included in FSC. However, for FSC the layer width (W) and height (h_0) are also important parameters. The layer width and layer height of the product and translation speed define the volumetric supply speed (V_f) of the clad material. In this work the heat generation as a function of process parameters is studied with the help of a 3D thermal flow finite element model. In this way process windows can be developed that allow optimization of the manufacturing process for future applications.

![process steps of FSC](image)

Fig. 1 Schematic process steps of Friction Surface Cladding (FSC): (a) the cladding tool positioned at required height; start of tool rotation at a rotation rate of Ω, (b) the clad rod is pressed out with a volumetric flow rate of V_f, [mm³/s], (c) frictional preheating of substrate, clad rod and tool material and (d) cladding phase: the rotating tool translates with respect to the substrate at translation rate v_t. Note: the tilt angle θ of the tool is increased for clarification.

2 Experimental procedure and FE model distribution

The FSC experiments are performed on a modified planer machine equipped with an in-house developed FSC tool and a 13 kW electrical engine rotating between 250–1500 rpm. The substrate
is clamped on a large backing table made of steel, see Fig. 2(a). Five thermocouples, $TC_i$ ($i = 1$ to 5), glued in the mid plane of the substrate along the cladding center line and one thermocouple, $T_t$, in the tool are employed to measure the substrate and the tool temperatures, respectively. The mounting and positioning of the thermocouples are described in detail in Liu et al. (2016). The cladding process starts at approximately the $TC_1$ position. The normal force exerted by the cladding system to the substrate is measured by three load cells. The supply rate is registered.

The nominal layer thickness is determined by the minimum distance between the inclined tool and the substrate as measured by a feeler gauge. The clad rod (original length $\approx 20\text{ mm}$ and $\Phi 10\text{ mm}$) made of commercially pure aluminum (AA1050) is deposited on an AA2024-T351 substrate ($300\text{ mm} \times 141\text{ mm} \times 4\text{ mm}$). Samples are picked from the clad specimen for hardness testing after at least two weeks of ageing. Some samples are etched with 50% NaOH at a temperature of around $70^\circ\text{C}$ for 20 to 30 s for microstructural investigation.

A 3D thermal flow coupled finite element model is developed to analyze the influence of the process variables on the heat generation and the normal force. The physical geometry and thermal boundary conditions of a 3D thermal model described in Liu et al. (2016) is used for the thermal flow model here. The heat generation is caused by viscous dissipation within the clad material (see the blue region in Fig. 2(c)) and as such it replaces the user-defined surface heat source employed in Liu et al. (2016). The clad material is assumed to be axisymmetric due to the high ratio of the tool rotation rate to the translation rate. The diameters of the clad rod ($D_0$) and disk equal the tool opening diameter and the layer width, respectively. The rod length in the model is equal to 10 mm which is half of the original length in the experiment. The clad material flows into the rod at the inlet with a volumetric supply rate of $V_f$ and flows out at the outlet where the pressure is set to zero, see Fig. 2(c). Full sticking conditions are assumed for all the contacting interfaces: the clad material is bonded to the substrate (fixed wall) and it rotates with the tool at the tool rotation rate (moving wall). The vertical velocity of the clad material at the opening wall-clad rod interface equals $4V_f/(\pi D_0^2)$. Viscous heat is generated within the clad material which also exerts pressure on the substrate. The total normal force on the substrate can be calculated by integrating the pressure at the clad layer-substrate interface beneath the tool.

The constitutive law of the clad material used in the FEM is developed by fitting the experimental data from Prasad and Sasidhara (1997). The temperature and shear rate dependent flow stress of the clad material is

$$
\sigma_f = (\sigma_0 + k_0 \ln \frac{\dot{\epsilon}_s}{\dot{\epsilon}_0}) \cdot \exp\left(\frac{T_m - T}{T_m - T_r}\right)^{k_1} \cdot \sinh^{-1}\left(\frac{T - T_m}{T_m - T_r}\right)^{k_2},
$$

(1)
with

\[ Z = \dot{\varepsilon} \exp \left( \frac{Q_0}{R T} \right), \]  

(2)

where \( Q_0 \) and \( R \) are the activation energy and the gas constant, respectively; \( \sigma_0 \) is the flow stress at the initial strain rate of the clad material \( \dot{\varepsilon}_0 \) which is set as \( \dot{\varepsilon}_0 = 0.1 \, \text{s}^{-1} \). The melting temperature of the clad material is \( T_m \) and \( T_r \) the ambient temperature. Here, \( A_1, k_0, k_1 \) and \( k_2 \) are fitting constants. The values of the relevant variables are listed in Table 1. This material law is also described in Liu et al. (2015).

Table 1 The values of the constants in Eq.1 and Eq.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \sigma_0 ) [MPa]</th>
<th>( k_0 ) [MPa]</th>
<th>( k_1 ) [kJ/mol]</th>
<th>( Q_0 ) [J/(mol * K)]</th>
<th>( R ) [J/(mol * K)]</th>
<th>( A_1 ) [s(^{-1})]</th>
<th>( k_2 )</th>
<th>( T_m ) [°C]</th>
<th>( T_r ) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1050</td>
<td>17.0</td>
<td>0.11</td>
<td>2.1</td>
<td>156</td>
<td>8.314</td>
<td>3.02 \times 10^{10}</td>
<td>0.15</td>
<td>646</td>
<td>15</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Experiments

A representative sample produced with \( \Omega = 300 \, \text{rpm}, v_t = 60 \, \text{mm/min}, h_0 = 0.2 \, \text{mm} \) and \( v_f = 3.13 \, \text{mm/min} \) is shown in Fig.3. The defect free and continuous clad layer is characterized with a relatively smooth top surface and uniform layer width. The layer edge at the advancing side (AS) is rather straight whereas a slightly wavy edge is visible at the retreating side (RS). The cross sections in Fig.3(b and A) picked along the black solid line in Fig.3(a) show a uniform layer thickness and a sound bonding interface. No mixing between substrate and clad layer occurred.

The temperature and the normal force distributions during the cladding process and the post-cladding hardness distribution are shown in Fig.4. The tool temperature remains approximately 300 °C, which is around 20 - 50 °C lower than the mid-plane substrate temperature, \( T_{C_i} \). An exception occurs at \( T_{C_2} \) where the thermocouple may not have been connected properly to the substrate. The hardness of the substrate is hardly changed due to the relatively low process temperature: it resembles 90% of the original hardness value. The hardness of the clad layer is substantially lower in accordance with the different composition.

The generated normal force is fairly constant during the cladding phase with a value of 3 kN - 4 kN. A peak value of the normal force, around 10 kN, is observed near the start of the cladding phase (at \( t = 0 \)). During the preheating phase the clad material is continuously supplied while the tool is rotating but not translating. Accumulation of clad material under the tool takes place, which partly blocks the path of the translating tool at the start of the cladding phase. More space becomes available once the tool has translated some distance as observed from the drop of the normal force.

3.2 Thermal flow modeling

Dissipative heat generation

The thermal field, the generated heat and normal forces are computed employing the thermal flow FEM with the process variables from the experiment shown in Fig.3 under full sticking conditions. The calculated temperature at the mid plane of the substrate near \( T_{C_3} \) is nearly 80 °C higher than the experimental value as indicated by the red solid line in Fig.4(a). This is in line with the larger
Fig. 3 The cladding performance of the representative experiment: (a) top surface of the clad path; (b) Cross section of the clad sample picked along the vertical black line in (a); A: the magnified cross section near cladding center line in the position marked by A in (b).

Fig. 4 (a) The measured temperature and normal force distributions shown in black lines for the representative experiment, along with the FEM temperature in red solid line ($\delta = 1$) and red dashed line ($\delta = 0.53$); (b) the hardness in the clad layer and the mid-plane substrate; (c) the hardness contour at the cross section shown in Fig.3(b).
heat generation (1.81 kW) calculated by the thermal flow model (1.81 kW), which is also larger than the required heat flux to explain the measured temperature profiles (1.3 kW) as determined in [Liu et al.] (2016). The overestimated heat generation and temperatures can be explained from the full sticking assumption at the respective interfaces with the tool, the clad material and the substrate. The heating and cooling rates are comparable with the registered values during the FSC experiment. The temperature distribution in the entire FSC setup along the cladding center line is shown in Fig. 5. The heat is predominantly generated at the tool bottom-clad layer interface where high temperatures over 400 °C occur. The highest temperature of approximately 430 °C is observed in a region between the end of the clad rod and the top of deposited layer.

The simulated normal force is around 1.3 kN, which is smaller than the experimental value. The deviation between the simulation and the experiment is again attributed to the assumption of the full sticking condition. The flow stress of the clad material becomes smaller at higher temperatures, leading to relatively low normal forces.

The calculated temperatures and normal forces by the 3D thermal flow model under full sticking conditions are not comparable with the experimental values. It is hypothesized that the contact status at the interfaces between the tool, the clad material and the substrate may affect the heat generation and the normal force. Non full-sticking conditions are also common with other friction based processes such as friction stir welding as observed by [Doude et al. (2014)] and [Schneider et al. (2006)]. An average sticking factor $\delta$ is applied in the current thermal flow model as an exploratory study of the contact status. The clad material effectively rotates at $\delta\Omega$ at the tool-clad material interface, see Fig. 2(c), with $0 < \delta < 1$ and $\delta = 1$ indicating full sticking conditions. The other boundary conditions remain unchanged.

If the temperature distribution, heat generation and normal forces are recalculated for various values of $\delta$, the heat generation and temperatures decrease for smaller values of $\delta\Omega$ and the normal force strongly increases, as visible in Fig. 6. It is found that with $\delta = 0.52$, the temperature profile at $TC_3$ closely matches that of the experiment. The simulation results indicate that partial sticking ($0 < \delta < 1$) may occur in FSC. This will be part of a future study.

![Fig. 5 The temperature distribution in the entire cladding setup along the cladding center line for the representative experiment.](image-url)
Parameter study $\Omega$, $v_t$ and $W$

The 3D thermal flow model also provides a way to study the influence of the process parameters involved in FSC. At this stage full sticking conditions are used in the following parameter study, since the real contact status among the tool, the clad layer and the substrate remains unclear. Three series of parameter cases are investigated with variable tool rotation rate, translation rate and layer width, respectively, see Fig. 7.

The influence of the tool rotation rate is shown in Fig. 7(a). If the tool rotation rate is increased, the generated heat increases almost linearly. This seems comparable with the analytical thermal model derived by Schmidt et al. (2004) for friction stir welding without considering the temperature influence on the material properties. The peak temperature at the mid plane of the substrate is also raised by the higher tool rotation rate but, it does so at a smaller slope than the heat generation. This is mainly attributed to the decreasing thermal conductivity of the substrate at higher temperatures. The peak substrate temperature ($T_{Cm} > 450 \, ^{\circ}C$) is generally higher than the experimental values due to the full sticking assumption as discussed before.

The higher tool rotation rate also reduces the normal force. The clad material shows shear thinning behavior, which leads to a lower effective viscosity at higher shear rates. Hence, the lateral flow of the clad material requires a smaller pressure build up as reflected by smaller normal force values. The influence of the tool rotation rate on the heat generation and the normal force analyzed by the thermal flow model is in line with the experimental observations of Liu et al. (2016).

At higher tool translation rates the viscous heat generated is only slightly modified, but the normal force is strongly increased as more material needs to be supplied per unit of time, see Fig. 7(b). As temperature gradients are generally steeper at higher FSC tool translation speeds, heat conduction is improved, leading to lower maximum temperatures in the center of the substrate.

The effect of the layer width is shown in Fig. 7(c). At larger layer widths a strong increase in the normal force is observed which is caused by the fact that more material needs to be distributed laterally per unit of time. The amount of viscous heat generated is also increased due to the larger contact area and so is the temperature at the mid plane of the substrate. This is largely in line with the straightforward heat generation model of Schmidt et al. (2004) which also predicts an increase with the (tool) radius.
The 3D thermal flow model is introduced to investigate and optimize the FSC process. Important trends can be observed from the model results as discussed above. It can be learned that higher production speeds at constant layer dimensions (height and width) are possible, but will lead to larger normal forces (Fig. 7(b)). Increasing the rotation rate is an effective means to decrease the normal force (Fig. 7(a)), while maintaining to a large extent a constant process temperature.

Increasing the layer widths is associated with an increase of the heat generation and the normal force (Fig. 7(c)). If the normal force should not be increased too much to prevent plastic deformation at the clad layer-substrate interface, the simulation results indicate that a possible solution is not to change the rotation speed. Rather one should consider increasing the size of the clad rod relative to the layer width. This limits the lateral trajectory under the FSC tool and may serve as a better way to limit the normal force. Further study is necessary to experimentally verify the suggested trends that may be helpful to facilitate future FSC applications.

Fig. 7 The influence of various process parameters on the heat generation rate $Q$, the maximum temperature in the middle of the substrate $TC_m$ and the normal force $F_n$ during FSC at constant clad layer thickness.

4 Conclusion and discussion

Layers of commercially pure aluminum can be successfully deposited on AA2024 by friction surface cladding (FSC). Homogeneous and void free clad layers with dimensions of approximately 0.2 mm mm 20 mm mm can be manufactured best at 300 rpm. The mechanical properties of the underlying substrate are well maintained due to the relatively low process temperature and normal force.

The 3D thermal flow model results show that the generated viscous heat increases nearly linearly with the tool rotation rate, the translation rate and the layer width for the current materials. The normal force increases strongly with the tool translation rate and the layer width, but decreases with the tool rotation rate. Worthwhile guidelines are provided to minimize the effect of the processing temperature and the normal force on the mechanical properties of the substrate while maintaining the required conditions at the clad layer-substrate interface for proper bonding.

The thermal flow model results overestimate the generated heat and underestimate the exerted normal force. It suggests that the contact status at the interfaces with the FSC tool, the clad material and the substrate deviates from full sticking as assumed in the current study. The simulated temperature fields compared better to the experimental ones if some degree of slip was assumed. Further study is required to thoroughly explain the observed differences in heat generation and normal force on this point.
Acknowledgment

This research was supported by the Materials innovation institute M2i (http://www.m2i.nl) under project number MC8.07290. The Chinese Scholarship Council is sincerely acknowledged for the financial support.

References


