Thermal and Flow Analysis of Friction Surface Cladding with Varying Clad Layer Thickness

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Abstract

Friction Surfacing Cladding (FSC) is a recently developed, solid-state process to deposit thin metallic clad layers on a substrate. The process employs a hollow rotating tool containing the clad material. The tool is moved along a predefined trajectory at a given distance above the substrate surface while the clad material is pressed out and deposited on the substrate surface beneath the tool.

In this study the deposition of a thin layer of AA1050 on an AA2024-T351 substrate was investigated. The study concentrated on the effect of the clad layer thickness on the clad layer profile, the thermal distributions in the FSC tool and the substrate and the generated pressure below the tool. Four cladding experiments were carried out with the nominal layer thickness increasing from 0.2 mm to 0.8 mm with an increment of 0.2 mm. In each experiment the associated supply rate of the clad material and the tool rotation rate were adjusted to obtain a relatively low process
temperature of approximately 330 °C that was high enough to manufacture defect free clad layers.

The experimental results showed that the manufacturing of thicker clad layers required higher tool rotation rates: from 300 rpm at 0.2 mm to 450 rpm at 0.6 mm and 0.8 mm, but the resulting process induced normal pressure on the substrate decreased from 16.4 MPa to 9.1 MPa. The substrate hardness after the cladding process was hardly affected for all cases.

The effect of the clad layer thickness and the tool rotation rate was studied numerically employing a 2D axisymmetric thermal and flow coupled finite element model. The simulation results confirmed the observed trends in the tool rotation rate and the process induced pressure as a function of the nominal layer thickness.

**Keywords:** friction stir welding, extrusion, thermal analysis, heat generation, precipitation

1. Introduction

Friction surfacing cladding (FSC) is a recently developed solid-state cladding process\(^1\). It can be used for modification of the mechanical and/or corrosive properties of structural materials at the surface. It uses a cylindrical, rotating cladding tool with a central opening containing a clad rod. The tool is held at a predefined distance above the substrate to control the layer thickness. Like friction surfacing\(^2\), the clad material is supplied downwards by a speed-controlled
hydraulic system and it is deposited on the substrate beneath the tool, as shown in Figure 1. The strong plastic deformation of the clad material and the occurring friction of the clad material with the FSC tool and the substrate contribute to the heat generation which softens the clad material and enables the deposition process.

The FSC process comprises two phases: a preheating phase and a cladding phase. In the preheating phase, the clad material is pressed outwards from the rotating tool and frictional heating occurs when it contacts the substrate. When the tool temperature is sufficiently high, the cladding phase starts where the rotating tool translates over the substrate surface while the clad layer is continuously being deposited. In this way clad layers with a fairly uniform thickness can be deposited on a substrate. The presence of the stiff tool enhances the lateral spreading of the clad material and supports the bonding of the clad layer to the substrate[1].

The heat generation plays a significant role in friction surface cladding. The heat origin in the cladding process is analogous to that in friction stir welding where this topic has been well studied[3]. For instance, an analytical model has been developed by Schmidt[4] and that has been employed widely. Based on an introduction of a contact state variable, the model describes that the frictional heat generation rate at the contact interface is proportional to the normal pressure and the coefficient of friction in the case of slipping condition. When sticking occurs, the heat generation rate is linearly related to the shear strength of the material being
welded. This analytical heat generation model can in principle also be applied to friction surface cladding.

In this study, the influence of the nominal layer thickness on the cladding process has been studied for the case of the deposition of relatively soft AA1050 onto an AA2024-T351 aerospace alloy. The deposition appearance, the temperature fields, the generated normal forces and the substrate hardness distributions have been analyzed. Assuming a full sticking contact condition, a 2D thermal and flow coupled finite element model provides further understanding of the influence of the deposition process variables.

2. Experimental procedure and materials

The experimental FSC configuration is depicted schematically in Figure 1. The FSC tool contains a central opening (Ø 10 mm, length 40 mm), a slightly profiled bottom (Ø 30 mm) and a speed-controlled hydraulic system that presses the clad rod outwards\cite{1}. It is fixed at a certain height above the substrate (300 mm × 141 mm × 4 mm) to control the clad layer thickness. A backing plate provides support to the substrate.

During the cladding process both the temperature in the substrate and the FSC tool were measured, along with the forces and material supply rates. Five K-type thermocouples (\(T\text{Ci}, i = 1, 2, 3, 4, 5\)) were placed in the middle thickness of the substrate exactly beneath the cladding center line, as shown in Figure 1(b). An additional thermocouple (\(T\text{Ct}\)) was placed in the tool 2 mm above the tool bottom.
and 7 \( \text{mm} \) from the tool center line. The normal force \( (F_n) \) generated during the FSC process was recorded by load cells. In addition, the supply rates of the cladding material \( (v_f) \) were collected in all experiments.

![Figure 1](image)

Figure 1 a) Principle of the FSC process, b) FSC experimental configuration with locations of substrate thermocouples.

Four experiments were carried out with the nominal clad layer thickness equal to 0.2, 0.4, 0.6 and 0.8 \( \text{mm} \). The process parameters are listed in Table 1. In all cases the tool translation speed \( v_{tr} \) was 60 \( \text{mm/min} \) in the cladding phase, and the tool tilt angle \( \theta \) was equal to \(-1^\circ\). In each experiment, the tool rotation rate and the supply rate of the clad material were adjusted to build up defect-free clad layers with similar widths, but different thicknesses. In experiment 1, 2 and 3, the supply rate remained constant during the cladding phase. In case of experiment 4, the supply rate was gradually increased to provide enough material and to obtain a sufficiently high tool temperature of approximately 330 \( ^\circ\text{C} \). Preliminary experiments
indicated that at this temperature the FSC process performs well with the current materials and setup. In addition, Table 1 provides the dimensions of the produced layers. The local width and thickness of the analyzed samples near TC3 are indicated by \( W_3 \) and \( H_3 \), respectively; \( F_{n3} \) is the local average normal force near this thermocouple, and \( P_3 \) the local average pressure, \( P_3 = \frac{4F_n}{\pi W_3^2} \); \( W_{avg} \) is the average layer width along the entire clad layer.

The substrates and the consumable clad rods used in these experiments were rolled aluminum alloy plates AA2024-T351 and commercially pure aluminum AA1050, respectively.

3. Numerical model description

3.1 Flow model

A 2D axisymmetric thermal and flow coupled finite element model was established in COMSOL employing the Eulerian framework. The clad material flows into the tool opening at the top surface with a speed \( v_f \) and flows out of the narrow space between the tool bottom and the substrate at a distance \( r = R_{disk} \), with \( R_{disk} \) the radius of the clad disk. Here, the pressure drops to zero. The thickness and width of the clad layer near TC3 determine the tool-substrate distance and the outlet position of the clad material in the 2D model. The clad rod length used in the model is equal to 10 mm, which is approximately the rod length at the location of TC3 during the experiment. A fixed wall condition (no slip) was applied at the interface.
between the clad material and the substrate. The same condition holds for the clad material in contact with the horizontal portion of the FSC tool. Within the axial (vertical) part frictionless movement of the clad material is assumed in the axial direction. The translation speed of the FSC tool was relatively small with respect to its rotation rate in the experiments and was neglected for this 2D model. Also the small tilt angle of the tool is not considered. The process parameters including the tool rotation rate and nominal layer thickness were studied in the numerical model.

Figure 2 Description of the 2D axisymmetric model geometry with definition of relevant parameters.

Under the assumption of full sticking contact, the strain rate is defined as

$$
\dot{\varepsilon} = \nabla \mathbf{u} + (\nabla \mathbf{u})^T = \frac{1}{2} \gamma
$$

(1)
and the equivalent strain rate is

$$\dot{\varphi}_{eqv} = \sqrt[3]{\varepsilon \dot{\varepsilon}}.$$  \hspace{1cm} (2)

Therefore, the relation between the equivalent strain rate and the shear rate equals

$$\dot{\varphi}_{eqv} = \frac{1}{\sqrt{3}} \dot{\gamma}.$$  \hspace{1cm} (3)

The clad material viscosity is defined as

$$\mu = \frac{\sigma_{eqv}}{3\dot{\varphi}_{eqv}}.$$  \hspace{1cm} (4)

According to the flow rule, plastic yielding occurs when the equivalent stress reaches the flow stress, $\sigma_{eqv} = \sigma_f$. Thus, the viscosity can also be described as

$$\mu = \frac{\sigma_f}{3\dot{\varphi}_{eqv}} = \frac{\sigma_{eqv}/\sqrt{3}}{\dot{\gamma}} = \frac{\tau_m}{\dot{\gamma}},$$  \hspace{1cm} (5)

where $\tau_m$ is the shear strength of the clad material.

The flow stress of the clad material used in this study is an equation developed based on the experimental results measured by Prasad\cite{5}:
\[ \sigma_f = \left( \sigma_0 + k \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \left[ \exp \left( \frac{T_m - T}{T_m - T_r} \right) \right]^n \sinh^{-1} \left( \frac{Z}{A} \right) \]  \hspace{1cm} (6)

with

\[ Z = \dot{\epsilon} \exp \left( \frac{Q}{RT} \right) \]  \hspace{1cm} (7)

where \( Q \) and \( R \) are the activation energy and the gas constant, respectively; \( \sigma_0 \) is the flow stress at \( \dot{\epsilon} = \dot{\epsilon}_0 \), and \( \dot{\epsilon}_0 = 1e - 3 \) \( s^{-1} \) is the initial strain rate. The melting temperature of the clad material is \( T_m \) and \( T_r \) is the ambient temperature. Here, \( A \), \( m \), \( n \) and \( k \) are constants. The values of the relevant variables are listed in Table 2.

With these flow boundary conditions and material properties, the flow model calculates the pressure in the clad material and the material flow velocity by solving the continuity equation and the momentum equation\cite{6,7}.

3.2 Thermal model

Under the full sticking condition, only the viscous heat, \( Q_{vh} \), dissipated in the strongly deforming clad material contributes to the heat generation, i.e., \( Q_{vh} = \tau : \dot{\epsilon} \).

Besides this heat source, both the heat conduction in the experimental setup and the convective heat transfer to the surroundings were considered. The heat conservation equation used was:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_{vh} \]  \hspace{1cm} (8)
where $C_p$, $k$ and $u$ were the specific heat capacity, the thermal conductivity and the material flow speed vector, respectively. Both $C_p$ and $k$ of the substrate material were temperature dependent and the values cited from Li[8] were used. The thermal conductivity and heat capacity of the clad material were assumed constant with values equal to $190 \, W/(m \cdot K)$ and $900 \, J/(kg \cdot K)$, respectively.

The thermal boundary of the thermal and flow coupled model consists of contacting interfaces between the cladding tool, the clad material, the substrate and the backing plate and all exposed surfaces to the ambient. Perfect thermal contact between the substrate and the backing plate was assumed to occur near the FSC tool where high compressive stresses are present. Further away from the tool the (less effective) heat transfer was described by an effective heat transfer coefficient of $200 \, W/(m^2 \cdot K)$, which was also applied to the upper surfaces of the tool, as shown in Figure 2. A value of $10 \, W/(m^2 \cdot K)$ was used at the top surface of the substrate in contact with air.

4. Results and discussion

4.1 The appearance of the FSC samples

Defect free clad layers were successfully deposited in all experiments. The top view of each clad specimen near TC3 is shown in Figure 3(a) – (d). The red vertical line in each image shows the positions where the specimens for hardness measurement and microstructural observation were extracted. A clad layer with a rather smooth top surface, a straight edge on the advancing side and a slightly
wavy edge on the retreating side was produced in experiment 1. The clad layer fabricated in experiment 2 turned out to be similar to that in experiment 1, except for two small notches on the advancing side. Compared with experiment 1 and 2, experiment 3 also produced a relatively smooth layer, but with notable notches and cladding burrs observed on the advancing and retreating side, respectively. The sample with the largest nominal layer thickness also showed these less desirable features and the surface roughness was also larger than for the other clad layers. These types of dimensional variations are probably related to stick/slip phenomena taking place during the lateral spreading of the clad material. This is a subject of future study.
Figure 3 The left column: top view of the clad layers from 0.2 $mm$ to 0.8 $mm$. The vertical lines indicating the location of thermocouple TC3. The right column: the corresponding transverse cross sections. (AS: advancing side; RS: retreating side).

The transverse cross sections of the extracted specimens along the red lines depict not only the local cladding performance, but also the local dimensions of the clad layers. Straight bonding interfaces between the clad layers and the substrates were observed in all the specimens as shown in Figure 3. Clearly, no substrate deformation or intermixing between both materials occurred. The average thickness along the width direction increased with the nominal layer thickness, from 285 $\mu m$ in experiment 1 to 783 $\mu m$ in experiment 4. The clad layer thickness deviated somewhat from the intended values due to the finite stiffness of the
experimental setup in the axial direction and a limited accuracy in the measurement system for the distance between the FSC tool and the substrate. The layer thickness near the advancing side was slightly larger than that near the retreating side. Along the cladding center lines, the clad layers tended to be thinner than those near the edges due to the slightly inclined orientation of the FSC tool axis with respect to the substrate normal.

4.2 Experimental temperature and force distributions

The evolution of the FSC tool temperature as recorded by $T_{Ct}$ for all experiments is shown in Figure 4. The tool temperature of experiments 1 – 3 was just below 300 °C for the first part of the cladding phase and then increased somewhat. This is related to the finite dimensions of the cladded substrate and the cooling conditions at the substrate-backing plate interface. In case of experiment 4 the supply rate was increased after about 125 s leading eventually to a similar tool temperature as for experiments 1 – 3 for the remaining part of the cladding phase.

Despite the variation occurring in the measured tool temperature of the four experiments, the local substrate temperatures recorded by $T_{C3}$ tended to be similar. The peak value from $T_{C3}$ was approximately 320 °C for all experiments, which was 30 – 40 °C higher than the measured tool temperature at the moment the tool passed this position.

The recorded normal force is also shown in Figure 4. At the start of the cladding phase the normal force had a peak value, but after some distance, it reduced and
remained fluctuating about an approximately constant or slightly increasing average value. The local average force $F_{n3}$, is shown in Figure 5(a). This force decreased with the nominal clad layer thickness, indicating that the clad material can be distributed over the substrate more easily at larger FSC tool-substrate distances. The local average pressure, $P_3 = \frac{4F_{n3}}{\pi W_3^2}$ reduced nearly linearly with the nominal thickness, as illustrated in Figure 5(b).

Figure 4 Temperature recorded from the FSC tool ($T'_C$), the third thermocouple ($TC_3$) and the normal forces ($F_n$) in all experiments.
The relatively low temperatures and normal forces measured during the FSC experiments help to explain the presence of a straight bonding interface between the clad layer and the substrate. The observed temperatures and forces were low enough for the yield strength of the substrate material (45-115 MPa at 340 °C) to remain substantially higher than that of the clad material (8-11 MPa)[9]. This strongly prevented large scale plastic deformation of the substrate and/or mixing of both materials.
Figure 5 Process induced normal force on the substrate and related pressure as a function of the nominal layer thickness.
4.3 Hardness distributions

Hardness measurements performed at the cross sections indicated a value of about 30-40 $HV$ in the deposited clad layers. Within the substrates beneath the clad layers a fairly uniform hardness distribution of about 130 $HV$ was observed. This value represented a small decrease with respect to the value of 140 $HV$ measured in the as-received substrate, which was in line with the temperature development in the substrate during the experiments\(^{[10,11]}\).

5. Numerical results

The temperature distribution and the normal force exerted on the substrate were computed in the 2D model by varying the clad layer thickness and the tool rotation rate. The supply rate and the clad layer width values used reflect the average values of the experiments: $v_{f,\text{sim}} = 3 \text{ mm/min}$ and $W_{\text{sim}} = 2R_{\text{disk}} = 16 \text{ mm}$, respectively.

In the first simulation series the tool rotation rate was varied between 250 $rpm$ and 500 $rpm$ at a constant nominal thickness of $h_0 = 0.2 \text{ mm}$. An example of the resulting thermal fields for $\Omega = 300 \text{ rpm}$ and $h_0 = 0.2 \text{ mm}$ after simulating 30 $s$ of cladding, corresponding approximately to the thermal conditions near $TC3$, is shown in Figure 6. As illustrated, the highest temperature occurred near the clad-material/tool interface due to the generated viscous heat; the temperature reached around 310 $^\circ$C in the mid-thickness substrate region, which is in agreement with the
experimental result. The calculations with other rotation rates provided similar thermal trends, but with different magnitudes as shown in Figure 7.

Figure 6 Simulated temperature distribution for $\Omega = 300$ rpm and $h_0 = 0.2$ mm after 30 s.

The effect of the varying tool rotation rates on the mid-thickness substrate temperature and the pressure near the clad disk bottom is clearly visible. At higher tool rotation rates the resulting temperatures are higher due to the higher heat generation rate, but at the same time the normal pressures at the clad layer-
substrate interface are lower. The temperature is highest just beneath the tool in the clad layer and decreases with increasing distance due to heat conduction and heat loss to the environment. The pressure distribution is rather uniform just below the clad rod opening ($R_{rod} = 5 \text{ mm}$) and decreases to zero towards the edge of the supplied clad material at $R_{disk} = 8 \text{ mm}$. The total viscous heat generated per unit of time as a function of the rotation rate, along with the total normal force exerted on the substrate is shown in Figure 8. Clearly, these figures reflect the same trends as observed in Figure 7.

In the second simulation series the influence of the layer thickness on the thermal distribution and the pressure was studied at $\Omega = 300 \text{ rpm}$. The results are collected in Figures 8. The viscous heating rate increases with the rotation rate in a nearly linear fashion and decreases also approximately linearly with the nominal layer thickness. In both cases the resulting normal force on the substrate decreases.

The simulation results explain the trends observed in the rotation rate as a function of the clad layer thickness in the experiments: the rotation rate was increased from $300 \text{ rpm}$ at $h_0 = 0.2 \text{ mm}$ to $450 \text{ rpm}$ at $h_0 = 0.8 \text{ mm}$ (see Table 1). Since the tool temperature remained similar for all layer thicknesses in the experiments (at least near $TC3$), suggesting a constant viscous heating term, the rotation rate needed to be increased accordingly. The experimentally measured normal forces decreased with the layer thickness and this behavior was in line with the simulation results. Although the conditions in the 2D model differ from the 3D experimental case, apparently the observed trends in the viscous heating rate and the normal forces
can be explained well. Further work will concentrate on a more accurate description of the stick/slip phenomena taking place at the various material interfaces to better understand the processes determining the clad layer deposition process and quality.
Figure 7 Temperature distribution in the middle thickness of the substrate and the pressure distribution at the clad layer-substrate interface for different rotation rates.

Figure 8 Total viscous heat dissipated per unit of time and the total normal force on the substrate as a function of the rotation rate at $h_0 = 0.2 \text{ mm}$ and the nominal layer thickness at $\Omega = 300 \text{ rpm}$.
6. Conclusions

The experimental results revealed the feasibility of depositing soft AA1050 layers with various layer thicknesses on a relatively hard AA2024-T351 substrate. In all cases homogeneous, void free clad layers were deposited. The clad layer-substrate interface remained straight and no significant plastic deformation of the substrate and/or mixing occurred. The substrate hardness was hardly affected. These results can be explained by the relatively low maximum temperatures and process induced forces occurring during the FSC process.

The tool rotation rate needed to be adjusted when the clad layer thickness was modified at constant clad layer width. For thicker clad layers the FSC tool rotation rate had to be increased to maintain the same process temperature; the process induced normal forces decreased. The observed behavior was confirmed by a 2D axisymmetric thermal and flow coupled model.

References


Table 1 The process parameters of the experiments, the produced layer dimensions and local forces

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$h_0$ [mm]</th>
<th>$\Omega$ [rpm]</th>
<th>$v_f$ [mm/min]</th>
<th>$W_3$ [mm]</th>
<th>$H_3$ [mm]</th>
<th>$F_{n3}$ [kN]</th>
<th>$P_3$ [MPa]</th>
<th>$W_{avg}$ [mm]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>300</td>
<td>3.13</td>
<td>16.7</td>
<td>0.29</td>
<td>3.7</td>
<td>16.4</td>
<td>16.8</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>400</td>
<td>4.31</td>
<td>17.2</td>
<td>0.39</td>
<td>3.1</td>
<td>13.3</td>
<td>17.6</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>450</td>
<td>5.85</td>
<td>16.1</td>
<td>0.53</td>
<td>2.4</td>
<td>11.8</td>
<td>16.5</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>450</td>
<td>9.83</td>
<td>19.1</td>
<td>0.78</td>
<td>2.6</td>
<td>9.1</td>
<td>16.0</td>
</tr>
</tbody>
</table>

$h_0$, $\Omega$ and $v_f$ are the nominal layer thickness, the tool rotation rate and the supply rate of the clad material, respectively; $W_3$ and $H_3$ are the width and the thickness of the clad layer near $T_{C3}$, $F_{n3}$ and $P_3$ the average local normal force and average local pressure; $W_{avg}$ is the average layer width along the entire clad track.

Table 2 Values for the variables in Eq.6 and Eq. 7

<table>
<thead>
<tr>
<th>AA1050</th>
<th>$\sigma_0$ [MPa]</th>
<th>$k$ [MPa]</th>
<th>$n$</th>
<th>$Q$ [kJ/(mol)]</th>
<th>$A$ [s$^{-1}$]</th>
<th>$m$</th>
<th>$T_m$ [°C]</th>
<th>$T_r$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17.0</td>
<td>0.11</td>
<td>2.1</td>
<td>156</td>
<td>$3.02 \times 10^{10}$</td>
<td>0.15</td>
<td>646</td>
<td>15</td>
</tr>
</tbody>
</table>

$Q$ is the activation energy, $\sigma_0$ is the flow stress at $\dot{\varepsilon} = \dot{\varepsilon}_0$, and $\dot{\varepsilon}_0 = 1 \cdot 10^{-3}$ s$^{-1}$ is the initial strain rate, $T_m$ and $T_r$ are the melting temperature of the clad material and the tool temperature and $A$, $m$, $n$ and $k$ are fitting constants.