Friction Surface Cladding of AA1050 on AA2024-T351; influence of clad layer thickness and tool rotation rate

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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 rotating tool with a central opening to supply clad material and support the distribution and bonding of the clad material to the substrate. The tool is held at a given distance above the substrate and translates relative to the substrate while the clad material is pressed out and deposited. This work studies the effect of the tool rotation speed and the clad layer thickness on the deposition quality of AA1050 clad layers on top of AA2024-T351 substrates at constant process temperatures. Well bonded, defect free clad layers with uniform thickness and width are produced. A 2D axisymmetric thermal-flow model predicts the influence of the process parameters and confirmed the experimental observations.

Keywords: Friction surface cladding, friction surfacing, heat generation, material flow.

Introduction
Friction surface cladding (FSC) is a recently developed solid state process to deposit thin metallic layers on substrates [1]. This approach requires a rotating tool for heat generation, see Fig.1. The clad material is supplied through the center of the tool. Before the cladding process the tool is fixed at a certain distance above the substrate, which controls the clad layer thickness. The clad material is pressed out of the tool and when it comes into contact with the substrate, heat is generated through plastic deformation of the clad material and friction with the tool and the substrate. When the FSC tool is heated up sufficiently, it starts to translate and a clad layer track is deposited. The presence of the FSC tool allows for improved control over the amount of heat generated and the clad layer dimensions (width and thickness). In this way the problem of flash formation, as often observed in friction surfacing [2], can be avoided and all the supplied clad material is deposited on the substrate without losses.

Figure 1 Schematic process steps of Friction Surface Cladding (FSC): a) tool positioned at required tool-substrate distance and start of tool rotation at a rotation speed of $\Omega$, b) clad rod is pressed out with speed of $v_f$, c) frictional preheating of substrate, clad rod and tool and d) cladding phase: tool moves relative to the substrate with translation speed $v_t$; $\theta$ and $F_n$ are the tool tilt angle and the normal force applied on the tool, respectively.

The process parameters of the FSC process are the tool rotation rate $\Omega$, the clad material supply speed $v_f$, the nominal tool-substrate distance $h_0$, the translation speed $v_t$ and the tool tilt angle $\theta$. Previous work on FSC of AA1050 on 2024-T351 substrates has indicated that the process
temperature slowly increases during the cladding phase [1, 3], even though the process parameters are kept constant. Apparently, the amount of heat generated per unit of time in the FSC process is larger than the amount of heat transferred away. Future applications of the clad substrates require uniform material properties and hence the FSC process temperature needs to be controlled well. This study focuses on the influence of the tool rotation rate and the tool-substrate distance on the process temperature and normal force by performing both experimental and modelling work.

**Experimental setup and materials**

The FSC experiments are carried out at a modified planar machine equipped with a 13 kW electrical engine using an in-house developed FSC setup. The FSC tool is produced with a $\phi 10 \text{mm}$ central opening and a slightly profiled $\phi 30 \text{mm}$ tool bottom [1, 3, 4]. Experiments were performed with $h_0 = 0.2$ and $0.4 \text{mm}$. The tool rotation rate was adjusted continuously during each cladding process to maintain a constant cladding temperature, as measured in the FSC tool ($T_t$). The tool translation speed was $v_t = 1 \text{mm/s}$ and the tool tilting angle $\theta = -1^\circ$. In each experiment commercially pure aluminium AA1050 was deposited on top of an A2024-T351 substrate ($300 \text{ mm} \times 141 \text{ mm} \times 4 \text{mm}$). Samples were extracted from the clad substrates after natural ageing for 14 days and were prepared for OM observation and hardness measurement. The samples were etched with 50 % NaOH at 70 $^\circ$C for 20-30 (s).

**Results and discussion**

The FSC experiments produce homogeneous, defect and void free layers that are well bonded to the substrates even at the edges at the advancing (AS) and retreating side (RS). Typical results are shown in Fig.2. The clad-layer/substrate interfaces remain straight and no mixing of the clad layers and the substrates occurs [1]. The average layer widths are 17.6 mm ($h_0 = 0.2 \text{mm}$) and 18.1 mm ($h_0 = 0.4 \text{mm}$). The layer thicknesses determined from the cross section differ from the nominal values: $H = 0.24$ and $0.34 \text{mm}$, respectively.

![Figure 2](image-url)

**Figure 2** Cladding appearance of experiment $h_0 = 0.2$ and $0.4 \text{mm}$: (a) and (c) are the top surfaces of the clad layers; (b) and (d) are the cross sections of the clad layer and the substrate picked along the black line marked in (a) and (c); AS='advancing side', RS='retreating side'.

![Figure 3](image-url)

**Figure 3** The applied tool rotation rates and the measured tool temperatures (a); the normal forces and the layer widths (b) for experiment $h_0 = 0.2$ and $0.4 \text{mm}$; The tool started to translate at time = 0, marked by vertical black lines and indicated by $v_t$ \text{Start}. 

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The development of the tool rotation rates and the tool temperatures during the FSC experiments are shown in Fig. 3a. The tool rotation rates were initially relatively high to start up the FSC process efficiently. During the cladding phase they were adjusted to smaller values to keep the tool temperature constant at $T_t \approx 300 \, ^\circ\text{C}$ for both cases. The concomitant development of the normal forces and the layer widths are shown in Fig. 3b. The normal forces increases during the cladding phase. The clad layer widths show some variation between 16 mm and 20 mm in accordance with Fig. 2a and 2c.

A 2D axisymmetric thermal flow model has been employed to explain the above observed trends in the tool temperature, the normal force and the tool rotation rate during the cladding phase. The model geometry consists of the FSC tool with $\varnothing 10$ opening, rotating at $\Omega$ rpm, an AA2024-T351 substrate located at a distance $H$ below the tool bottom and a steel supporting table. The clad material is forced to flow through the central opening with a pre-set speed of $v_f$. This speed is related to the central opening radius $R_0$, the layer width $W$, the real layer thickness $H$, and $v_f$ according to $v_f = (WHv_t) / (\pi R_0^2)$ assuming conservation of clad material volume. The radius of the clad layer in the 2D model equals $W/2$. The heat generated within the strongly plastically deforming clad material is calculated assuming full sticking conditions at the respective interfaces with the tool bottom and the substrate. The temperature and strain rate sensitive flow stress of the clad material is based on experimental results of Prasad [5] and modelled accordingly. The calculations include the conduction of heat into all parts of the modelled setup and surroundings employing appropriate thermal material properties and boundary conditions.

The values of the viscous heat generation rate $\dot{Q}$ and the normal force $F_n$ after 30 (s) of simulation are selected as being representative for the FSC process with the process parameters selected. This is the time it takes for the FSC tool to travel across a point on the substrate from the leading to the trailing edge at $v_t = 1 \, \text{mm/s}$. For further details, see [4].

The influence of the tool rotation rate $\Omega$, the clad layer thickness $H$ and the clad layer width $W$ on the viscous heat generation rate $\dot{Q}$ and the normal force $F_n$ have been studied. The results are shown in Fig.4. The first simulation series (Fig.4a) employed a clad layer with $H = 0.2 \, \text{mm}$, $W = 16 \, \text{mm}$ and $v_f = 4 \, \text{mm/min}$. Here, $\dot{Q}$ increases nearly linearly with $\Omega$ from 200 rpm to 500 rpm. However, $F_n$, as calculated by integrating the pressure distribution over a plane at 0.01 mm above the substrate/clad-layer interface, decreases strongly with $\Omega$. Detailed analysis has shown that there are two reasons. (i) $F_n$ is inversely related to $\Omega$ at constant process/tool temperatures. Under full sticking conditions a higher $\Omega$ results in higher shear stresses in the circumferential direction, effectively reducing the required pressure to distribute the clad material in the radial direction, lowering $F_n$ [1]. This complies with the experimental results shown in Fig.3: an increase of $F_n$ is observed for both cases upon lowering $\Omega$. (ii) At higher $\Omega$ the average process/tool temperature increases, reducing both the yield stress of the clad material and the pressure levels required for clad material distribution.

The second simulation series (Fig.4b) with $W = 16 \, \text{mm}$ and $\Omega = 300 \, \text{rpm}$ shows that $\dot{Q}$ is hardly influenced by $H$. This is also observed in the experiments: the rotation rates of both cases do not differ much, see Fig. 3a. The simulations also indicate that $F_n$ decreases with $H$, despite the fact that more material has to be supplied to build up a thicker clad layer. In the experiments no large difference in the normal force is observed. However, the actual difference in layer thickness is smaller (0.24 mm as compared to 0.34 mm) and the clad layer width of the thicker layer is slightly larger. The last simulation series (Fig.4c) shows the effect of the layer width with $H = 0.2 \, \text{mm}$ and $\Omega = 300 \, \text{rpm}$. The normal force increases with the layer width. In this way the effects of layer thickness and width on $F_n$ partly level out.
The combined effects of all process parameters are also studied by modeling both experimental cases. The layer dimensions and the supply rates applied in the model are the same as the experimental values. The tool rotation rate (Fig.3a) is considered constant first (0~5s) and then it decreases linearly until the end of the simulation time (5~30s). The temperature in the middle of the substrate is plotted after 30 (s) of simulation in Fig.5 for both cases. The temperature distributions are very similar, confirming the experimentally observed thermal behavior.

**Conclusions**

FSC enables the deposition of thin pure aluminium clad layers on an AA2024-T351 substrate in the solid state. Homogeneous, void and defect free layers can be manufactured with uniform properties. The process temperature can effectively be controlled by adjusting the tool rotation rates. The experimentally observed changes in the tool rotation rate and the tool normal force at constant process temperature could be explained and confirmed from a dedicated 2D thermal flow model utilizing the actual dimensions of the clad layers manufactured.

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**References**


