Material Flow Visualization during Friction Surfacing

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Metal flow behavior within friction surfaced coating was studied using tungsten powder as a marker. The results show that the top and bottom layers within the coating exhibit distinct flow patterns. The transport of material takes an involute path, and the material transfer starts from the advancing side of the coating to the retreating side and terminates at the center. The recirculation of material occurs at the retreating side of the coating.

DOI: 10.1007/s11661-011-0614-2

Friction surfacing is an emerging technique for producing thick solid-state coatings to combat wear and corrosion. In this process, localized heating is produced by the friction generated between the rotating consumable rod and the substrate. The rubbing surface of the consumable rod undergoes intense plastic deformation at elevated temperatures, resulting in the formation of hot plasticized material, which is transferred into the substrate to form the coating. The material is transferred in successive discrete layers, which constitute the coating.[1] A typical stainless steel friction surfaced coating is shown in Figure 1. Many studies have been carried out on the feasibility of depositing a variety of materials on different substrates.[2–4] However, studies on fundamental aspects of friction surfacing are very limited, particularly on metal flow behavior during friction surfacing.[5,6]

Friction surfacing involves a combination of stirring, extrusion, and forging. Hence, a simple analytical description of metal flow behavior is difficult. In this study, a marker technique is adopted to visualize the metal flow patterns in the coating during friction surfacing. The transverse cross sections of the coated regions were studied with X-ray radiography and scanning electron microscopy (SEM).

The consumable material used for this study was stainless steel AISI 304, and the marker material used was tungsten powder. Two rods, 18-mm diameter and 100-mm long, were used for producing the coating. Eight holes, 1.5-mm diameter, were drilled along the periphery of the rubbing surface of one consumable rod, and a 3-mm hole was drilled at the center of the second consumable rod (Figure 2). These holes were filled with tungsten powder prior to friction surfacing. X-ray radiography was conducted from the top surface of the as-deposited coatings, while the transverse cross section of the coatings was examined in the unetched condition with scanning electron microscopy in the backscattered electron (SEM-BSE) mode.

Figures 3(a) and (b) show the X-ray radiograph of the coating produced with marker at the center and periphery, respectively. The distribution of tungsten powder at the starting and the middle regions of the coating is to be noted carefully. At the starting region, the location of markers corresponds to the same position as originally placed in the consumable rod. However, when the coating proceeds, there is a difference in the location of markers, which can be accounted with two stages of the coating process: (1) dwell period at the start, where the consumable rod is allowed to rotate until it attains the plastic state; and (2) coating stage, where the material transfer occurs while the substrate is in motion. In the former, the metal flow sticks to the circular path as the substrate is stationary, while in the latter, the metal flow is disturbed when the substrate moves due to the interaction between the velocity components. In addition to these, the axial load also plays a role in deciding the nature of the metal flow. The involvement of these three components makes the metal flow regime quite complex.

A sectional view of the friction surfacing system comprising the consumable rod, the coating, and the substrate is presented schematically in Figure 4. The extreme bottom layer of the coating, which is very close to the coating/substrate interface, shows flow patterns that can be compared with the velocity of the substrate. Similarly, the top layer of the coating, which is closer to the rubbing interface of the consumable rod, moves in the direction defined by the rotating consumable rod. The distribution of marker powders in the coating at the retreating side is shown in Figure 5. A separation in the direction of the flow pattern can be observed at the middle. The top layers tend to flow upward and the bottom layers show a tendency to move toward the substrate. These observations show that, within the coating, the metal flow pattern differs between the top and bottom layers.

The flow of plasticized material confined between the rubbing interface and the substrate interface is analogous to fluid flow between two parallel plates, where one

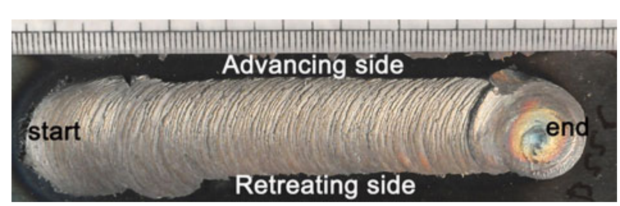

Fig. 1—Typical stainless steel coating formed with friction surfacing.

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Manuscript submitted November 25, 2010.
Article published online January 27, 2011

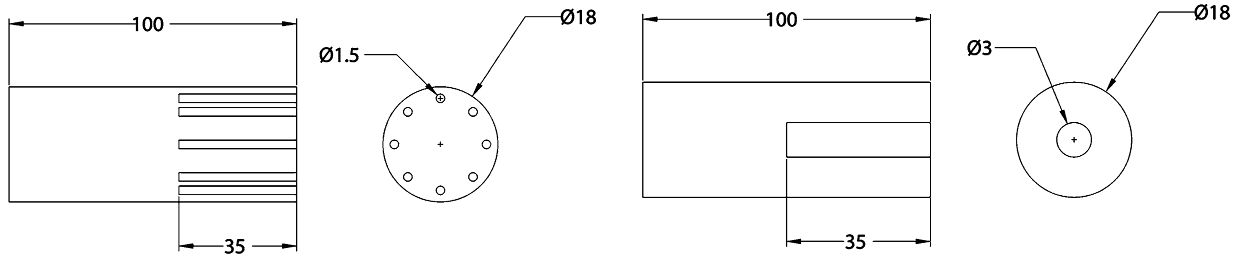

Fig. 2—Holes for filling markers drilled at the periphery and center of the consumable rods (all dimensions in millimeters).

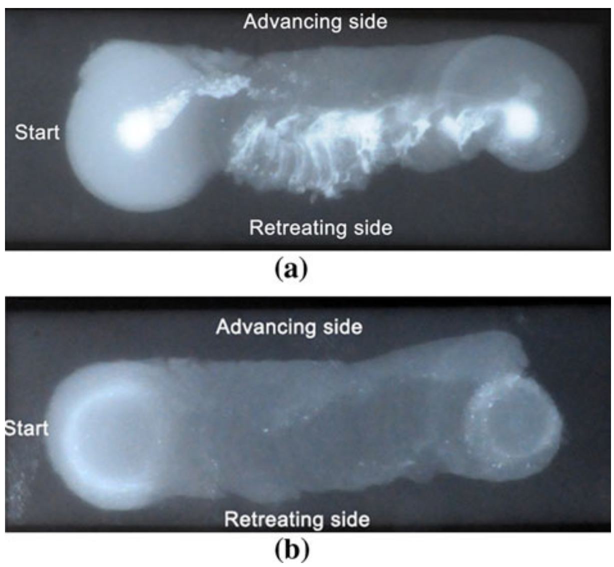

Fig. 3—X-ray radiographs: (*a*) marker at center and (*b*) marker at periphery.

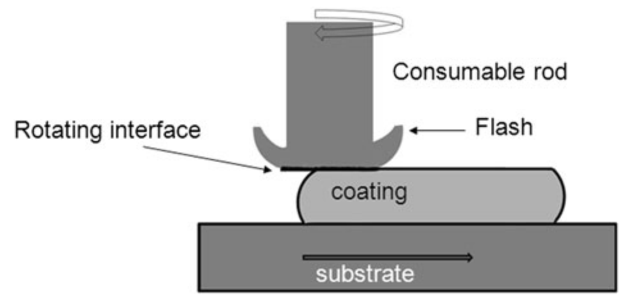

Fig. 4—Schematic of the friction surfacing system.

plate is moving under an axial load (Couette–Poiseuille flow).[7] However, in friction surfacing, the additional influence of the rotational motion of the consumable rod makes the flow pattern more chaotic. The formation of localized vortices (shown with arrows in Figure 5) at the retreating side indicates recirculation and the transition from radial to unsteady flow. The vortex formation in the center represents an updraft of plasticized material toward the center line where the radial and axial components of velocity are zero (Figure 6).

Though the translational velocity is much smaller than the linear velocity of the consumable rod at its periphery, there is a significant difference in the coating at either end due to the flow of material.

To summarize, the marker method used in this study provides a qualitative view of the movement of hot plasticized material during the friction surfacing of steel. The material flow occurs from the advancing side to the retreating side and terminates at the center. Within the coating, the flow in the top layers is influenced by the rotation of the consumable rod and the flow at the bottom layers is influenced by the translational motion of the substrate.

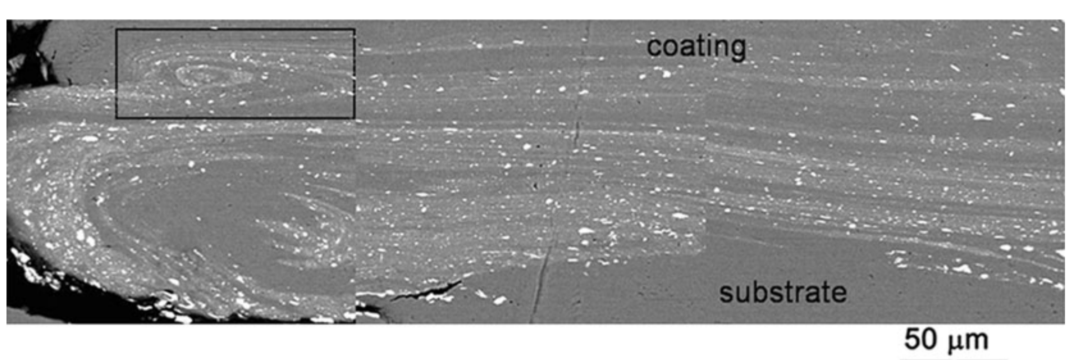

Fig. 5—Montage of SEM-BSE images taken from the retreating side of the coating cross section. The area enclosed in the rectangle shows the formation of the vortices.

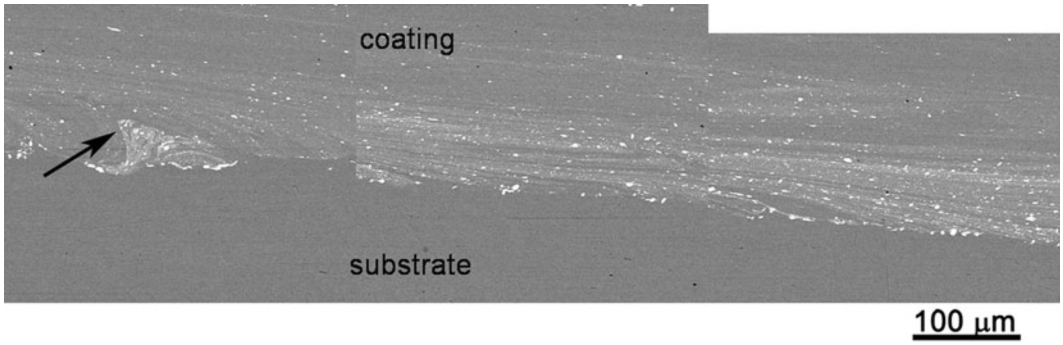

Fig. 6—Montage of SEM-BSE images taken from the center of the coating cross section. Arrow shows formation of the vortex.

REFERENCES

1. A.W. Batchelor, S. Jana, C.P. Koh, and C.S. Tan: *J. Mater. Process. Technol.*, 1996, vol. 57, pp. 172–81.
2. G.M. Bedford, V.I. Vitanov, and I.I. Voutchkov: *Surf. Coat. Technol.*, 2001, vol. 14, pp. 134–39.
3. M. Chandrasekaran, A.W. Batchelor, and S. Jana: *J. Mater. Process. Technol.*, 1997, vol. 72, pp. 446–52.
4. G. Madhusudhan Reddy, K. Srinivasa Rao, and T. Mohandas: *Surf. Eng.*, 2009, vol. 25 (1), pp. 25–30.
5. G.J. Bendzsak, T.H. North, and Z. Li: *Acta Mater.*, 1997, vol. 45, pp. 1735–45.
6. H.N.B. Schmidt, T.L Dickerson, and J.H. Hattel: *Acta Mater.*, 2006, vol. 54, pp. 1199–1209.
7. F. Marques, J. Sanchez, and P.D. Weidman: *J. Fluid Mech.*, 1998, vol. 374, pp. 221–49.