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The initiation of roll coating buildup during thermomechanical processing of aluminum-magnesium alloys

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ABSTRACT

The roll coating developed on an AISI 440C steel work roll during the laboratory hot rolling of an Al-Mg alloy was examined and its microstructure and composition were characterized. The AISI 440C steel work roll had a surface roughness (R_a) of 0.02 μm and the hot rolling schedule involved 20 passes under lubricated conditions. Initial examination of the roll coating generated on the work roll surface revealed it was patchy, discontinuous, streaked in the rolling direction and composed mainly of aluminum, magnesium, oxygen and carbon. Further analysis revealed that the roll coating possessed a complex layered microstructure. Under these rolling conditions, the roll coating microstructure comprised of an amorphous magnesium-rich oxide layer lying on an amorphous mixture of aluminum, magnesium, carbon and oxygen with amorphous iron and chromium-rich oxide particles embedded within it. Damage to the work roll surface and work roll debris observed within the roll coating highlighted that the work roll surface was involved in the roll coating formation. Analysis of the roll coating suggested that the initial roll coating composition and microstructure were influenced by the work roll and work piece material composition.

1. Introduction

The tribological interactions that occur during rolling between the steel work roll surface, the lubricant and the hot aluminum surface are characterized by the formation of an aluminum roll coating on the work roll surface. This roll coating is formed by the buildup of material transfer from the aluminum surface. Material transfer from the workpiece surface to the work roll surface is referred to as pickup, and for aluminum alloys occurs regardless of the roll topography and the applied load [1,2]. The buildup of material transfer, pickup, from the aluminum surface to the work roll increases with work roll roughness and highly influences the morphology of the work roll [1–5]. The buildup of the roll coating is therefore influenced by the surface morphology of the work roll, rolling force and the rate of cooling [1,6]. The thickness of the roll coating however, is thought to be dependent on the size of the oxide fragments covering the work piece surface, the rolling stage and emulsion [1,2,5,7–9]. While little relation has been found between roll coating development, rolling load and coefficient of friction, Budd et al. [10] have related the thickness and distribution of the roll coating on the work roll surface to the emulsion viscosity and additive type, concentration, pairing, and the hydrocarbon chain length [7]. Yoshida et al. [7,8,11,12] observed a relation between the roll coating thickness and surface appearance with the oil concentration, particle size, state, composition and preparation method of the emulsion, and the molar ratio of oleic acid to triethanol amine. Yoshida et al. [11] also observed the buildup of a uniform roll coating with the oleic acid additive. They proposed that the roll coating was caused by the accumulation of aluminum debris sticking to a polymerized lubricant layer formed on the work roll surface due to the oxidation of the hydrocarbon chain at elevated temperatures [11,12]. The thickness of the roll coating would therefore be dependent on the quantity of the lubricant oil adhered to the work roll surface, inferring the important role that emulsions play in roll coating formation and composition [2,3,6,8,11].

The appearance of the roll coating during lubricated rolling has been described as patchy, discontinuous and streaky, irrespective of the work roll surface structure, especially during the early stages of buildup with more continuous coverage observed with an increasing number of passes [8,9,13,14]. Smith et al. [9] have described the initial aluminum pickup to the work roll as appearing as isolated lumps streaked out on the work roll surface. Tripathi's [1] observations of roll coatings noted a difference in the color of the roll coatings at different stages of the rolling process. It was reported in the reversing mill as shiny grey, the tandem mill as dark black, and the cold rolling mills as bluish black. It has been suggested that the color of roll coatings is an indication of the thickness of the coating and its lubricant induced polymeric film. Based on his observations, Tripathi [1] proposed two mechanisms for the formation of roll coatings depending on the speed of rolling. The

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first mechanism was proposed to occur at low speeds by micromechanical entrapment, i.e. the micromechanical interlocking of plastically deformed metal on the rough profile of the work rolls. The second mechanism was proposed for higher rolling speeds, as the tribo-chemical generation of a polymeric film from the lubricant oxidation adhered to the work rolls, which entrapped wear debris particles from the rolled aluminum slab and work roll, similar to that proffered by Yoshida et al.'s [11]. Hui et al. [15] have reported that the chemical reaction between the lubricant and the surface of aluminum produces a soap, polymer and absorption film, depending on the lubricant composition. The formation of these films was related to aluminum dissolving in the lubricant during rolling and to the transfer of the rolled aluminum to the work roll surface [15]. Treverton et al. [16] reported the chemisorption of lubricant additives by aluminum surfaces during the hot rolling process. Smith et al. [9] reported the presence of carbon observed within the roll coating. Treverton et al. [4], however, suggested that areas of roll coating were possibly separated from the work roll surface by a relatively featureless film of aluminum metal, which would thus influence the interaction of the roll coating with the work piece during contact. Roll coating composition has been observed, using X-ray photoelectron spectroscopy (XPS), to include aluminum oxide (Al_2O_3) and metallic aluminum, the ratio of which appears to depend on lubrication and temperature [7,9,14].

Roll coatings are believed to be linked to the wear of the work rolls during the back transfer of the roll coating to the aluminum workpiece, which form pickup defects or grooves on the aluminum surface [1,9]. Back transfer of aluminum buildup from the work roll is believed to occur when the roll coating is unstable, which can manifest due to thermal and mechanical stress cycling [1,9,13]. Defects in the roll coating are also imprinted on the rolled aluminum alloys and were believed to force oxide particles into the aluminum alloy [4]. Thus, the properties of the roll coating influence the surface quality of the rolled aluminum sheets [8]. Yoshida et al. [7] reported a smooth and fine rolled aluminum sheet surface when the roll coating thickness and aluminum metal to oxide ratio of the roll coating were small.

In the aluminum rolling industry, however, roll coatings are thought to be beneficial, and the development of uniform, fine roll coatings on fresh work rolls is promoted as an industrial practice, as the refusals of slabs is thought to occur in their absence [1,17,18]. The roll coating is also understood to mitigate against further aluminum adhesion to the work roll surface by weakening the adhesion affinity of aluminum to the steel work roll surface during subsequent rolling passes [19]. However, the performance of the roll coating is dependent on its thickness and uniformity as back transfer from the coating to the rolled aluminum sheet (pickup defects) would occur when the coating is too thick, while a thin coating has been associated with unfavorable and unstable friction conditions [1,18].

Previous works have been based on the metallographic examination of the roll coating and pickup defects developed during the rolling of commercially pure aluminum alloys. Analysis used to determine the structure of the roll coating has been limited to XPS, optical microscopy and scanning electron microscopy (SEM). While preliminary transmission electron microscopy (TEM) of the aluminum pickup on a CrN-coated work roll revealed a nanocrystalline structure, the analysis was performed after only the first pass of hot rolling a commercially pure aluminum alloy and limited discussion was provided [20]. The present study intensively examines the initial buildup of a roll coating developed on a steel work roll during a 20 pass hot rolling schedule of an Al-Mg alloy. The microstructure of the roll coating has been investigated using focus ion beam (FIB) and transmission electron microscopy (TEM).

2. Experimental procedure

Hot rolling experiments were performed using a tribo-simulator with a roll-on-block configuration, the operational principles of which have been described in detail previously [19]. The tribo-simulator was designed to emulate the rolling processing conditions. The work roll was machined from an AISI 440C steel alloy to a diameter of 21 mm. The surface of the work roll was then polished to an average roughness (R_a) of 0.02 μm. Rolling tests were conducted with an Al-Mg alloy with a 4.5 wt% Mg content. The Al-Mg blocks were machined to dimensions of 10 mm width, 30 mm thickness and 95 mm length, and then polished with a 1 μm diamond paste. The work roll and the Al-Mg blocks were then ultrasonically cleaned in acetone before rolling to remove surface contaminants. A rolling schedule of 20 passes with a 7% forward slip and the rolling direction reversed after each pass was carried out. Rolling began at a temperature of 550 °C for the first two rolling passes, with a 10 °C temperature reduction after every two subsequent passes, so that the temperature at the final rolling pass was 460 °C. Lubrication was provided by an oil-in-water emulsion with a 4% (*v*/v) concentration.

The specimen surfaces were then examined using a FEI Quanta 200 FEG environmental scanning electron microscope (SEM) under high vacuum. The roll coating microstructure was also examined, using a ZEISS NVision 40 Cross Beam Workstation focused ion beam (FIB), with a gallium ion beam operated at low beam currents and an operating voltage of 30 kV. The surface was protected by the deposition of a thin layer of carbon. Cross-sectional trenches were ion milled using the FIB H-bar method. The samples prepared by using the lift-out method were examined using an FEI Titan 80–300 LB transmission electron microscope (TEM).

3. Experimental results

3.1. Surface analysis of roll coating

The roll coating buildup on the work roll surfaces was examined with a SEM after 20 rolling passes. The roll coating observed initiated on the work roll surface was patchy, discontinuous and randomly dispersed (Fig. 1a). The non-uniform patches, which represent the initial stages of the buildup of the roll coating, were streaked in the rolling direction, spread over the carbides and surface of the work roll. Examinations at higher magnification revealed isolated, smaller patches of material transfer on the work roll surface that appeared at lower magnification as blotches on the work roll surface. (Fig. 1b). In other areas, the roll coatings possessed a wavy surface appearance, while darker material at the edges of the roll coating could be observed lying on the surface of patches of roll coating, appearing in some areas as a network of dark blotches. There were dark expanses detected at the edges of these patches and the streaks of material transfer forming the roll coating. A closer examination of these dark areas at the side of the roll coatings revealed wear debris particles embedded within this dark region, which was suspected to be polymerized lubricant (Fig. 1c), as well as cracks within the thicker regions of the roll coating (Fig. 1d). The presence of these cracks suggested that the roll coating was unstable at these regions.

Another feature observed imprinted on the work roll surface at lower magnification, was a network of lines in the form of grain boundaries (Fig. 2a). The patches of material transfer that made up the roll coating could be seen to be located within these grain boundaries. A comparison of the rolled aluminum surface (Fig. 2b) with the steel work roll surface (Fig. 2a) revealed that these imprinted grain boundaries were corresponded with the elevated grain boundaries on the rolled aluminum surface. The grain boundaries distinctly observed on the rolled aluminum surface were rich in magnesium. These elevated grain boundaries on the rolled aluminum surface were possibly imprinted onto the steel work roll surface during the hot rolling schedule.

Energy dispersive spectrometry (EDS) analysis, in the form of mapping, of the work roll surfaces revealed that the roll coating buildup was primarily composed of aluminum, magnesium and oxygen (Fig. 3). The carbide particles were observed to be rich in chromium (Fig. 3e). The