



A microstructural analysis of aluminum buildup during thermomechanical processing

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ABSTRACT

The microstructure and composition of a roll coating built-up on an AISI M2 steel work roll during a 20 pass hot rolling schedule using a laboratory rolling tribo-simulator with a roll-on-block configuration was examined. The AISI M2 steel work roll was characterized by grinding grooves and possessed a surface roughness (R_a) of 0.17 μm . The roll coating developed under these lubricated conditions was discontinuous, patchy and streaked out in the rolling direction. The microstructure and chemical composition of the material transfer that made up the roll coating was analysed and revealed to possess a complex composite microstructure consisting of nanocrystalline aluminum, nanocrystalline/amorphous MgO and amorphous carbon layers. The nanocrystalline MgO layers were porous structures lying between the solid metallic aluminum layers. Debris particles from the wear of the work roll were detected embedded within the carbon layer and at the base of the roll coating. The microstructure of the roll coating appear to be determined by the deformation conditions experienced during the rolling process, while its composition is dependent on the composition of the rolled alloy, the work roll and the lubrication conditions employed.

1. Introduction

The tribological contact between an aluminum alloy and tool surfaces during thermomechanical processing induces material transfer to the tool surface, which in the case of rolling can lead to the buildup of a roll coating on the work roll surface [1–3]. This roll coating has been described as appearing non-continuous or continuous depending on the number of rolling passes [4–8]. The roll coating significantly influences the surface morphology of the work roll [1,2].

The chemical composition of the roll coating has been reported as, aluminum, oxygen and carbon, based on X-ray photoelectron spectroscopy (XPS) analysis which was used to identify the aluminum oxide (Al_2O_3), metallic aluminum and organometallic compounds components of the roll coating [5,9–11]. It is believed that while the small particles that make up the roll coating are oxidized, larger particles are coated with oxides but remain unoxidized [8,9]. The organometallic compounds, referred to as soaps, are generated from the reaction between the lubricant additives and the fresh unoxidized aluminum debris produced during rolling [1,10,11].

The formation and thickness of the roll coating is dependent on the roughness and topography of the work roll surface, as microstructural features like protruding carbides can hasten the formation of the roll coating [5,12]. The work roll material has also been linked to the

thickness of the roll coating through the aluminum wetting characteristics and thermal conductivity of the work roll material [4,5]. The rolling temperature is another parameter known to influence the thickness of the roll coating developed as higher temperatures lead to increased aluminum transfer to the work roll surface [7]. The occurrence and type of transfer layers formed on the work roll surface would also depend on the rolling or deformation conditions and the alloy being rolled [1,12].

The mechanisms of roll coating formation have been reported to include: the accumulation of aluminum wear debris stuck in the polymerized lubricant that adheres to the work roll surface (tribochemical), and the pickup of plastically deformed aluminum caused by entrapment in the rough profile of the rolls (micromechanical interlocking) as the hard work roll asperities plow the soft aluminum surface [7,13,14]. In addition, the transfer of aluminum to the work roll surface has also been attributed to adhesion, delamination, abrasion, and micro-cutting [3,11,15–17]. The aluminum transfer that makes up the roll coating can also be transferred back and re-welded to the aluminum surface during rolling [3,16–19]. The back transfer to the aluminum surface produces distinct macroscopic scale surface disturbances, referred to as a ‘pickup defects’ [3,7,8]. The transfer and back-transfer of aluminum between the roll coating and aluminum slab surfaces during rolling has been considered a “continuous two-way transfer” [8]. The buildup of the roll

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coating is thus described as a dynamic process, as the coating film is constantly being changed or removed during the rolling process [20].

In the aluminum rolling industry, roll coatings are typical and thought to be beneficial, even essential as their absence could result in refusals of aluminum slabs; however, they are also feared as they could eventually lead to galling [7,12]. Thus, roll coatings are developed as rolling progresses over several hundred passes, though their value is limited by an unascertained critical thickness [6,7]. However, studies into the roll coating have been limited to commercial purity aluminum alloys and its analysis to scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). In addition, the surface composition of aluminum alloys, which is transferred to the work roll surface, vary with the alloying composition, temperature and processing conditions [21]. Previous studies on roll coatings developed on CrN-coated [22] and polished AISI 52100 [23] work rolls revealed differing microstructures of those roll coatings, which could be related to the difference in the composition of the rolled aluminum alloy and deformation conditions. Therefore, it is necessary to characterize the effect of the rolling conditions on the structure and composition of the roll coating. The present study explores the microstructure of a roll coating developed from the transfer from an Al-Mg alloy to a ground AISI M2 steel work roll surface, which is more reflective of the work roll surfaces used in the rolling industry.

2. Experimental Procedure

Thermomechanical processing experiments were performed using a roll-on-block tribo-simulator which was designed to emulate the rolling processing conditions. The operational principles of tribo-simulator have been described in detail in [19]. The work roll was machined from AISI M2 steel to a diameter of 25.5 mm and its surface ground to an average roughness (R_a) of 0.17 μm . The surface topography of the work rolls was determined to consist of discontinuous grinding grooves using a WYKO NT1100 optical interferometer in the vertical scanning interferometry, VSI, mode. Rolling tests were conducted with an Al-Mg alloy that had a 4.5 wt% Mg content. The Al-Mg blocks were machined to a width of 10 mm, a thickness of 30 mm and a 95 mm length. It was then polished to an average surface roughness (R_a) of 0.02 μm . The work roll and the Al-Mg blocks were then ultrasonically cleaned in acetone before rolling.

The rolling schedule consisted of 20 passes at a forward slip of 9%, with the reversal of the rolling direction after each pass. Rolling began at a temperature of 550 °C for the first pass, and a 10 °C temperature reduction after each two-pass sequence, resulting in a final rolling pass temperature of 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 at 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. Analysis of Roll Coating

The roll coating initiated on the AISI M2 roll surface after the 20 pass hot roll schedule, examined with a scanning electron microscope (SEM), was patchy, discontinuous, and randomly dispersed. The non-uniform patches were streaked in the rolling direction, occurring predominantly within the work roll grooves and covering the carbides on

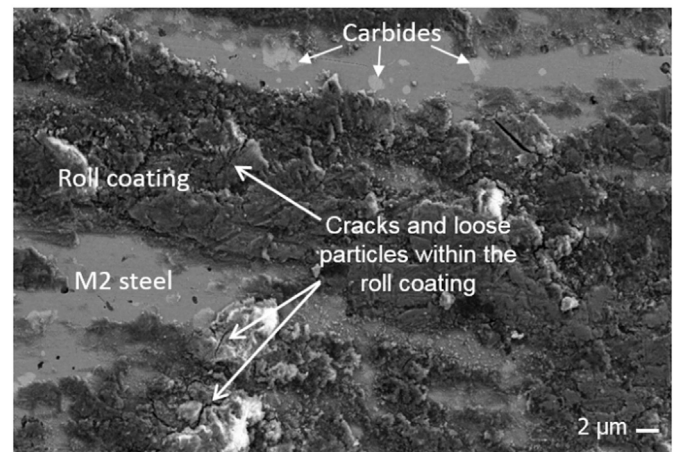


Fig. 1. SEM image of the roll coating initiated on the surface of the AISI M2 steel work roll displaying the material transfer distribution after 20 hot rolling passes against the Al-Mg sample.

the steel surface (Fig. 1). The carbides, possibly M_2C and M_6C , were identified to be rich in tungsten, molybdenum, chromium, and carbon [24]. There were also cracks and loose particles observed within the thicker regions of the roll coating surface. This could suggest that the roll coating built-up at this stage was unstable at these areas (Fig. 1).

Subsurface examinations of the roll coating from FIB-milled cross-sections along the rolling direction, displayed in Fig. 2a, revealed that the coating was comprised of a combination of bright, light and dark regions (Fig. 2b). The examination also revealed the lighter layers were richer in aluminum within the aluminum-magnesium transfer that made up the roll coating. The roll coating possessed a non-uniform thickness of $0.91 \pm 0.26 \mu\text{m}$ with several areas that appeared to be delaminating from the work roll surface, while other areas were adhered firmly. Higher magnification of the regions of the roll coating that were fully adhered to the work roll surface highlighted the layered structure of the roll coating (Fig. 2c). The thick, light, solid layers of the roll coating were identified to be separated by the dark, porous layers. A bright particle embedded within the darker regions was identified as being rich in aluminum. An examination of the work roll surface revealed no surface or subsurface damage to the work roll nor the carbide particles, neither were cavities nor holes observed.

3.2. Microstructural Characterization of the Roll Coating

The microstructure of the roll coating was examined using transmission electron microscopy (TEM) of the cross-sections from the material transfer built-up on the work roll surface. The roll coating was comprised of a complex layered structure of solid and porous phases stacked up on one another (Fig. 3). The solid layers of the roll coating were observed to be rich in aluminum, while the porous regions were rich in magnesium. The thickness of each of the phases varied along the aluminum-magnesium transfer. In particular, various aluminum layers were observed adhering to each other at several regions through a number of thin magnesium layers, while at other areas the thicker porous magnesium layers fully separated the solid aluminum layers. Fig. 3b displays another region of the roll coating with fewer aluminum and magnesium layers. The porosity of the thicker magnesium layers was evident from the large cavities that were randomly distributed. There was also a complex mixture of aluminum and magnesium beneath the lower porous magnesium layer, and the aluminum particles within this region were much smaller. The aluminum layers closer to the work roll surface were much smaller in comparison to other aluminum layers and were completely enclosed by the porous magnesium regions.

Energy dispersive spectroscopy (EDS) analysis exposed an

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