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The influence of work roll roughness on the surface/near-surface microstructure evolution of hot rolled aluminum–magnesium alloys

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ABSTRACT

The effect of work roll roughness on the surface/near-surface evolution of aluminum alloys during hot rolling was examined with the use of a rolling tribo-simulator. Work rolls made of steel alloy AISI 52100 with two different surface roughness (R_a) values, 0.1 μm and 1.1 μm, were used to hot roll Al-Mg alloy samples under similar laboratory conditions for one and ten passes. Surface features on both rolled samples included cracks, grooves, and rolling ridges, but shingles were only observed on the samples rolled with the rougher work roll. Near-surface damage was observed to increase with work roll roughness. Cross-sectional examinations revealed that transverse micro-cracks on the sample rolled with the smoother work roll extended to depths of 2.8 μm, while cracks were 3.2 μm in depth for the rougher work roll. In addition, the oxide-rich near-surface layers formed on the samples were thicker and more discontinuous for the rougher work roll. The oxide distribution in the transverse direction could be correlated to the size of the rolling ridges, which were larger for the samples rolled with the rougher work roll. A critical work roll surface roughness was proposed to influence the initiation of shingles on the aluminum alloy surfaces. The extent of the near-surface damage and the surface features formed on the rolled aluminum alloys were shown to be dependent on, but not limited to, the work roll surface topography.

1. Introduction

The surface appearance of wrought aluminum sheets is one of the major criteria used to evaluate their commercial value. The surface quality of these sheets however, is critically influenced by hot rolling conditions. The surface and near-surface features of rolled aluminum sheets are a result of the tribological conditions at the work roll/work piece interface, which are influenced by such rolling parameters as forward slip, pressure, speed, temperature, lubrication conditions, and the surface topography of the work rolls. However, the morphology of the rolled aluminum surface is a reflection of the work roll surface morphology. Dick and Lenard (2005) observed an increase in the surface roughness of rolled aluminum sheets with increased work roll roughness, while showing that the aluminum sheet roughness would also depend on the reduction chosen. Frolish et al. (2005) proposed that the combination of the sticking conditions and forward/backward slip conditions, which cause ploughing and machining by the work roll asperities, would imprint the work roll surface on the rolled aluminum. Frolish et al. (2006) suggested that the work roll roughness should be one of the major factors that determines the surface/near-surface features of the aluminum alloy at each stage of rolling.

Rolled aluminum sheets' surfaces have been observed to be covered with shingles, transverse cracks, grooves and rolling ridges, all features that are a function of the surface morphology of the work roll. However, the work roll surface morphology is actually essential for drawing the work piece into the roll bite. Dick and Lenard (2005) established the work roll surface morphologys' influence on the rolling lubrication conditions as well as the roll separating force. Tan et al. (1996) calculated the oil film thickness using an average flow model, and showed that the work roll surface morphology also influences the oil film formation in the deformation zone during aluminum rolling. They reported the close relation of the oil film thickness with the directionality of the work roll roughness lay. According to Sutcliffe and Le (2000), while the work roll roughness generates the necessary surface finish on the rolled product, the cold rolled aluminum surface roughness is also affected by the thickness of the lubricant film. Chen et al. (2013) observed that the rate of occurrence of micro-defects on stainless steel surfaces was

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decreased by using a lower work roll roughness. Chen et al. (2013) also noted a direct relation between the work roll roughness and the lubricant distribution and entrapment on steel alloy surfaces.

Frolish et al. (2005) associated the presence of shingles and transverse cracks on rolled aluminum surfaces with the development of highly deformed near-surface layers that differ in composition and microstructure from the bulk alloy. Fishkis and Lin (1997) identified these deformed near-surface layers as consisting of ultra-fine grains with grain boundaries decorated with oxide particles. Frolish et al. (2005) also proposed that the deformed near-surface layers were a result of the high shear stresses induced during the hot rolling process due to the tribological conditions at the work roll/work piece interface. Scamans et al. (2010) observed that these near-surface layers were not limited to rolled aluminum but were also observed on mechanincally ground and machined alumiunum. While Li et al. (2013) identified two types of near-surface deformed layers present on rolled aluminum, noting the difference between them as the presence of oxide particles at the grain boundaries and the temperature at which they were formed. Frolish et al. (2005) related the thickness of the near-surface layer to the height of the asperities on the work roll surface. Frolish et al. (2005) also, while referring to the shingles on the aluminum surface as asperities, identified using surface contour analysis, noted that the asperities appeared to correlate with the depths of the subsurface layers. Zhou et al. (2010) established that the aluminum surface roughness corresponded to its shingled appearance. Liu et al. (2010) though, directly related the thickness of the deformed near-surface layers with the shingles and intermetallic particle distribution. Liu et al. (2010) also suggested that the occurrence of shingles and other near-surface features indicated the significant interaction between the work roll and aluminum surface.

Fishkis and Lin (1997) suggested that shingle formation was related to material transfer to the aluminum surface during the rolling process, little though is known of the aluminum alloy or the rolling conditions. Gjonnes (1996) proposed that shingle formation was due to the deformation or smearing of large steps, peaks, or protruding features formed on the aluminum surface from previous passes and that point in a direction opposite to the rolling direction. Gjonnes (1996) and later Gjonnes and Andersson (1998) suggested that this deformation was governed by forward slip and that shingle size and presence were related to the surface structure of the work rolls. Noting that his research was focused on the cold rolling of cast aluminum, it should be stated that in hot rolling of aluminum alloys, shingles have been observed on the alloy surface from the first rolling pass. Liu et al. (2010) cross-sectional examination of a shingle's head separated from the bulk alloy led them to conclude that shingle formation was due to the metal at the surface being pushed backward and smeared across the surface. Liu et al. (2010) reported that the combination of high aspect ratios, high rolling speeds and worn (but still rough) roll surfaces induced high populations of shingles and thick near-surface deformed layers, whereas low shingle populations could be attained from freshly ground roll surfaces, low aspect ratios and low rolling speeds. Riahi et al. (2012) proposed that shingle formation was due to the plastic deformation of micro-wedges formed by the grooves on the work roll surface. Riahi et al. (2012) work also involved exploring the effect of forward slip on shingle occurrence, noting that an increase in forward slip resulted in higher frequency of shingle occurrence. Preliminary studies by Gali et al. (2015), who evaluated the effect of the work roll roughness, indicated that shingles were formed on rolled Al-Mg alloy samples when a WC-coated work roll with a surface roughness (R_a) exceeding 5 μm was used, but none were observed with a polished work roll with a roughness of 0.01 μm. Gali et al. (2015) showed that the introduction of a ground work roll in the rolling process influenced the depth of near-surface damage induced on the aluminum alloy during hot rolling.

While a relation between the occurrence of shingles and the work roll roughness has been suggested, the prospect of mitigating the manifestation of shingles with a ground work roll is still in question. This is due to the inability of previous works to examine the effect of rolling parameters individually. Consequently, the underlying mechanism of shingle formation is still in dispute. The objective of this study is to further investigate the influence of the work roll surface morphology on the development of the near-surface microstructure on Al-Mg alloys. It continues to explore the effect of work rolls with different surface roughness values on the evolution of surface damage features and the near-surface microstructure. This study seeks to correlate the relationship between work roll roughness, shingle manifestation and the depth of near-surface damage.

2. Experimental procedure

Hot rolling tests were carried out using a rolling tribo-simulator with a roll-on-block configuration, with operational principles previously described by Riahi et al. (2012) and displayed in Fig. 1. The block, representing the aluminum slab, was fixed on a stage which allowed motion on both the X- and Y-axes. Load cells were used to measure the normal force and cartridge heaters to heat the sample. The temperature was monitored by means of a thermocouple inserted into the aluminum block. The block was heated to the desired rolling temperature while the roll was set to revolve at a desired speed, in lubricated condition. The stage was then set to move in the desired direction, allowing the roll to run across the face of the sample, at a contact pressure of 128 MPa. The operational principles of the configuration allow for the simulation of the tribological reactions occurring during rolling and sliding.

Work rolls were machined from a steel alloy AISI 52100 to a diameter of 21 mm. The work rolls' surfaces were ground to surface roughness (R_a) values of 1.1 μm and 0.1 μm. The surface morphologies of the work rolls, which were examined with optical interferometry using a WYKO NT1100 in the vertical scanning interferometry (VSI) mode, both consisted of discontinuous grinding grooves (Fig. 2). The grooves on the 1.1 μm R_a work roll (Fig. 2a) were deeper and wider in comparison with those observed on the 0.1 μm R_a work roll (Fig. 2b). The work rolls were cleaned after each test with a 15% (wt/wt) sodium hydroxide solution to remove aluminum transfer.

The Al-Mg blocks, which contained about 4.5 wt.% of Mg, were machined to dimensions of 10 mm width, 30 mm thickness and 95 mm length. The blocks were polished with a 1 μm diamond paste before being ultrasonically cleaned in acetone to remove surface contaminants. The microstructure of the polished Al-Mg blocks is displayed in Fig. 3. The rolling schedule of the Al-Mg blocks involved ten passes at a 7% forward slip, with the rolling direction reversed with each pass. Hot rolling temperatures started at 550 °C for the first rolling pass with a 10 °C temperature reduction at each subsequent pass such that the temperature at the final (tenth) rolling pass was 460 °C. Lubrication was provided by an oil-in-water emulsion with a 4% (v/v) concentration.

The specimen contact surfaces were then examined using an FEI Quanta 200 FEG environmental scanning electron microscope (SEM) under high vacuum. The near-surface microstructure of the samples was examined using a ZEISS NVision 40 Cross Beam workstation focused ion beam (FIB), with a gallium ion beam operated at low beam currents and a voltage of 30 kV. The surfaces of the samples were protected by the deposition of a thin carbon layer.