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A study of the development of micro-cracks in surface/near surface of aluminum–manganese alloys during hot rolling

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ABSTRACT

The tribological aspect of the hot rolling of aluminum alloys is of particular interest, as the complex interactions between the roll and alloy surface influence the defects that are induced on the surface of aluminum alloys. These induced surface defects tend to reduce the quality of the final product. A hot rolling tribometer designed to simulate the rolling process was used to study the evolution of defects that occur on alloy surfaces during high temperature deformation. Scanning electron microscopy, energy dispersive spectroscopy, and focused ion beam microscopy were used to examine the effect of sequential rolling passes on the evolution of surface defects on an aluminum–manganese alloy. Cracks on the alloy surface were initiated mainly at grain boundaries due to rolling stresses and grain boundary sliding, causing an overlapping of grains. Cracks, which propagated along grain boundaries into the alloy subsurface, were observed on subsequent passes, with the immediate areas surrounding the cracks appearing rich in MgO in the subsurface regions. The orientation of cracks in relation to the rolling direction also influenced crack propagation.

1. Introduction

Enhanced shear deformation experienced during metal forming processes, such as rolling, is known to influence the surface quality of the final product [1–3]. Hot rolling, in particular, has been reported to induce a thin, heavily deformed tribolayer on aluminum alloys. This tribolayer has been characterized as having a microstructure comprised of ultrafine grains with oxide-decorated boundaries [2–10]. The surface appearance of aluminum alloys has been described as being etched with the surface morphology of the mating surface (the work roll), shingled, and having surface cracks transverse to the rolling direction [2–5,7].

The shingling and surface cracks have been attributed to the interaction between the aluminum alloy and the roll surface, and result in the surface roughening of the alloy [2–6]. The appearance of shingles has been recognized as an indication of the presence of a near-surface layer [4,5]. Though transverse cracks have been identified as a surface feature observed along with shingles, research into their manifestation is limited. Fishkis et al. [2] first reported that these cracks were initiated during the first few rolling passes and then covered by thin layers of aluminum on successive passes, leading to a shingled surface appearance. The lower ductility of the surface layer, shear stress reversals in the roll bite, and metal transfer/back-transfer to the roll were reported as being responsible for the crack formation [2]. Liu et al. [4] observed cracks that showed delamination of the near surface to different degrees. Shingles have also been reported to enhance the possibility of the appearance of holes and cracks in the alloy subsurface, with holes having the potential to evolve into subsurface cracks [6,11]. The areas around these cracks were noted to possess fine grains with diameters of about 100 nm [6]. The evolution of cracks on the alloy surface during rolling is acknowledged to affect the final surface quality of rolled products, with the depth of their propagation determining if the final product is acceptable [12,13].

The transverse cracks in the flat rolling of steel have been extensively analyzed, and the closure and growth of cracks in relation to crack shape, contact pressure, and crack tip stress have been examined [12,13]. It has been observed that with higher temperatures around the perimeter of cracks, compressive stresses can cause crack healing to occur [12]. The behavior of cracks during hot rolling is not well understood. Most researchers assume that crack defects exist on the strips before the rolling process and investigate their evolution during rolling using field emission microscopy (FEM), while in the rolling industry, these cracks are believed to occur only during cold rolling [12,13]. Similar research

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of micro-cracks on aluminum alloy surfaces has noted that cracks initiate in the brittle oxide film at locations of maximum stress, and act as sites through which aluminum is extruded [1]. These cracks are modeled as being within the oxide layer, forming near the entry of the bite, and leaving the alloy surface with porous oxide fragments [1].

Magnesium's diffusion to the surface of aluminum alloys is well documented [2–4,14–17]. MgO has been observed consistently as the topmost oxide layer on magnesium containing aluminum alloys after hot rolling, due to its high diffusion rate and affinity for oxygen [2–6,14–18]. The thickness of MgO on the aluminum alloy has been reported to be affected by the magnesium concentration in the alloy [17,18]. This oxide has also been observed to reduce aluminum adhesion to steel surfaces, especially at high temperatures [17,18].

This paper presents results of a study on the evolution of surface damage in the form of transverse cracks occurring on aluminum alloy surfaces during hot rolling. High resolution surface and cross-sectional images are presented to show the evolution of the crack morphology during sequential passes, and a mechanism for crack formation is proposed.

2. Experimental procedure

A hot rolling tribo-simulator designed at the University of Windsor, the working principle of which has been previously described by Riahi et al. [3], was used to study the tribological aspect of the hot rolling process. It possesses a roll-on-block configuration and allows for the variation of several rolling parameters, enabling the examination of their individual effects on the rolled alloy surfaces.

The roll and workpiece can be set to run at various speeds, while a lubrication system sprays lubricant on the roll. Rolling was simulated by allowing the revolving roll to run across the face of the test specimen. A thermocouple was placed in a hole drilled into the test specimen, so as to monitor the exact surface temperature of the alloy. The lubricant used was an oil-in-water emulsion with a 4% (v/v) concentration.

An AISI 52100 steel roll with a diameter of 21 mm was used. The test specimens used were machined from an Al–Mn alloy piece (containing 0.8–1.4% Mg, 0.8–1.3% Mn, 0.8% Fe, 0.6% Si, 0.25% Zn, 0.05–0.25% Cu) cut to dimensions of 10.5 mm width, 30 mm height, and a length of 95 mm. The roll surface and the aluminum test specimens' 10.5 mm by 95 mm faces were polished using a 1 μm diamond suspension and then cleaned ultrasonically in acetone for five minutes to remove surface contaminants. The roll was polished to eliminate the effect of roll roughness and to effectively study the effect of rolling stresses on the surface defects. It was cleaned with a 15% (wt/wt) sodium hydroxide solution to remove any aluminum transfer, and then polished to maintain the surface roughness after each pass.

The rolling conditions observed for these tests are listed in Table 1. A total of four passes in the forward and reverse directions were carried out, simulating industrial breakdown rolling. The roll and stage speeds were kept constant for a constant forward speed of 7%. The temperature of each subsequent pass was reduced by 10 °C from a starting temperature of 550 °C.

Table 1
Pass schedules in the hot rolling experiments.

Pass	Temperature (°C)	Direction of pass
1	550	Forward (F)
2	540	Reverse (R)
3	530	Forward
4	520	Reverse

The specimen surfaces were examined with an FEI Quanta 200 FEG environmental scanning electron microscope (SEM) under high vacuum. Surface roughness measurements were then made using a WYKO NT1100 optical surface profilometer in the vertical scanning interferometry (VSI) mode. The average surface roughness (R_a) was determined from several areas, and the mean values of these measurements were recorded for each pass. The near-surface microstructures of the specimens were examined with a ZEISS NVision 40 Cross Beam focused ion beam (FIB) microscope after each rolling pass, using gallium ions operated at low-beam currents and an operating voltage of 30 kV. The area of interest was protected by depositing a thin layer of tungsten or carbon. Cross-sectional trenches were ion-milled using the FIB H-bar method. The samples, which were prepared with the lift-out method, were examined using an FEI Titan 80-300 LB transmission electron microscope (TEM).

3. Experimental results

3.1. Surface morphology developed during deformation

3.1.1. Surface roughness

To better understand the effect of the deformation stresses on the alloy surface, the surface topography was examined after each pass and is represented in Fig. 1. A significant increase in surface roughness (R_a) was observed after the first pass, from 0.020 μm (after polishing) to 0.365 μm. The surface topography taken after the second pass displayed a decrease in surface roughness, dropping to 0.167 μm. A continual reduction with each subsequent pass occurred, dropping to 0.130 μm after the third pass and 0.095 μm after the fourth pass. The surface profiles in Fig. 1 display the surface roughness reduction after each pass, with distinct grain boundaries appearing from the second pass in Fig. 1(c) through the fourth in Fig. 1(e). Deep depressions were observed after the first pass (shown in Fig. 1(b)) that can be compared to the smooth polished surface displayed in Fig. 1(a).

The SEM images in Fig. 2 display the evolution of surface features that form after each pass, and are responsible for the initial increase and subsequent decrease of surface roughness in the same area. These SEM images parallel the optical profiles displayed in Fig. 1 only in that they are from the same surfaces. Fig. 2(a) hints at a misalignment of grains at their boundaries after the first rolling pass. An overlapping of grains at their boundaries, which have likely been deformed during sliding, is observed to produce a step in this figure. The significant increase in surface roughness after the first pass is due therefore to grain boundary sliding (GBS). Fig. 2(b) displays the surface after the second pass in the reverse direction. The surface appears slightly darker with surface features, such as transverse cracks and grain overlaps, observed after the first pass, and visually appears compressed or flattened. An examination of the grains' step heights from the surface topography data confirmed a reduction, from an average of 0.47 ± 0.25 μm after the first pass to 0.37 ± 0.17 μm after the second pass, thus reducing the initially higher surface roughness. The surface of the sample after the third pass is shown in Fig. 2(c). It displays less distinct grain boundaries, while the surface profile data indicates further grain step height reduction to 0.27 ± 0.13 μm. After the fourth pass, as seen in Fig. 2(d), the grain steps and overlapping visually appear to have been mostly eliminated; this is supported by the reduced surface roughness evident in Fig. 1(e). As observed in Fig. 2, no shingles appear on the alloy surface at any stage during the rolling process. The surface