Minimization of Edge Delamination During Cold Rolling of Aluminum Sheet

PURDUE UNIVERSITY

School of Materials Engineering

Student Names: Megh Kansara, Jeremy MacPherson, Austin McKibben, Lucas Witte
Faculty Advisors: Dr. David Gildemeister
Industrial Sponsors: Paige Breymeyer, Matthew Volle, Ginny Hammersmith

Edge cracking and edge delamination are phenomena that occur during rolling of 5182 aluminum and cause significant losses for Logan Aluminum. This study investigated the causes of these phenomena as well as ways to minimize or eliminate their occurrence and severity. Simulated rolling experiments, metallography, and material property testing on material at different stages throughout the rolling process showed that edge cracking can be reduced by reducing the reduction speed while rolling.

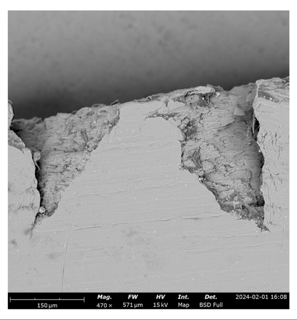
This work is sponsored by
Logan Aluminum, Russellville, KY

LOGAN ALUMINUM

Background

Logan Aluminum primarily produces two alloys, 3104 (can body) and 5182 (can end stock). Edge cracking and delamination contribute to the second largest yield loss source at Logan. Edge delamination is a condition where layers within the sheet begin to separate along the edges. The delamination phenomenon tends to affect the 5182 alloy specifically, likely due to the higher magnesium content, so the focus was understanding the 5182 alloy. However, due to the strict monitoring of magnesium levels that are maintained by Logan, the focus of the team was on the processing and rolling of the 5182 alloy rather than a compositional difference between delaminated and non-delaminated sheets.


Macrograph of Sample B1 at 90% reduction with edge cracking present


SEM micrograph of edge cracks on Logan sample 12

The conditions under which rolling is conducted play a crucial role; excessive tension, high rolling speeds, and improper temperature regulation during the process can all contribute to the initiation and growth of edge cracks in delaminated sheets. The microstructural characteristics of the aluminum sheet, particularly the grain structure, significantly affect the likelihood of crack formation, with a coarse grain structure facilitating the initiation and propagation of cracks. Additionally, the initial condition of the sheet edges, if not adequately prepared, can act as stress concentrators and thereby induce cracking. Non-uniform cooling rates may introduce thermal stresses, further exacerbating the tendency for crack development. The occurrence of this edge cracking is intricately linked to edge delamination. Due to inadequate equipment and constraints for temperature, tension, and roll pressure, our focus will be on how the reduction rate in thousandths of inches per pass affected the initiation and propagation of edge cracking and delamination.

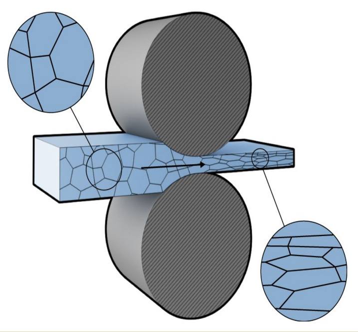


Diagram of rolling process showing reduction in thickness and elongation of grains through cold working

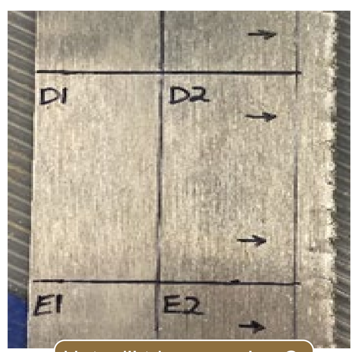
Experimental Methods

Tests were performed on hot rolled trim from right after the finishing mill as well as partially or fully cold rolled samples, some of which were already showing signs of edge cracking and delamination.

Rolling Experiments:

- Three iterations of cold rolling experiments were performed on samples sent from Logan Aluminum. Samples of the Hot rolled trim from coil 943778 (about .115 in. thick) were cut to remove any edge cracks from the hot mill and rolled in two iterations. The first of which had two samples, (A and B) sectioned and rolled to 30%, 60%, and 90% reductions, with final thicknesses of about .065, .042, and .014 inches respectively. A second iteration was performed with three samples (C, D, and E). Each sample was rolled and sectioned at the same three reduction percentages. However, the samples were reduced by 3 thousandths, 2 thousandths, and 1 thousandth of an inch per pass respectively. A third cold rolling experiment was performed on a partially cold rolled sample from coil 959033 sent from Logan that was just starting to crack to get imaging of how the crack would grow and progress after another rolling pass.

Hot mill trim: samples A and B



Hot mill trim: samples C, D, and E

Hardness Measurements:

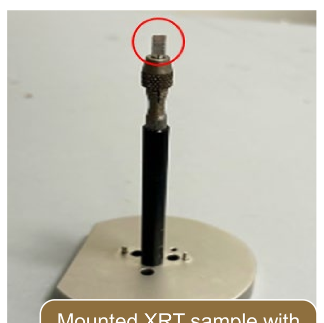
- Vickers Hardness testing was conducted on sections from samples A and B at each stage of rolling from 0-90% reductions, and on a sample from the same 943778 coil partially cold rolled by Logan at approximately 30% reduction. Before Testing, samples were mounted in Bakelite and polished to 1200 grit polishing paper.

Optical Microscopy:

- Optical imaging was performed on rolled samples C, D, and E at their 60% and 90% reductions at 1.5x magnification to view edge crack depth and frequency. Cold rolled samples from coil #943778 were imaged at 2x magnification for comparison to those rolled in house. Images were also capture of the cold rolled samples from Logan used in rolling experiment 3 both before and after rolling at 2x magnification. Cracked edges were imaged from the side as well as with the edge facing the lens.

X- Ray Tomography:

- XRT was performed on three 2mmx10mm samples, two of which were from cracked samples sent by Logan Aluminum, and one of which was from our rolling experiments. The scan settings were 80 kV, a 1 µm/voxel resolution, the detector at 4X, a 3-second exposure time, and 4 hours per scan.

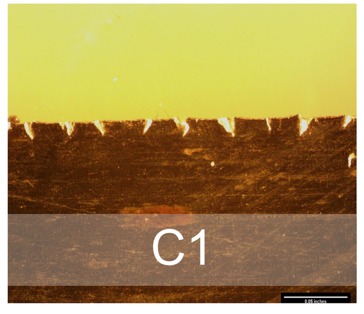

Mounted XRT sample with scan location indicated in the red circle.

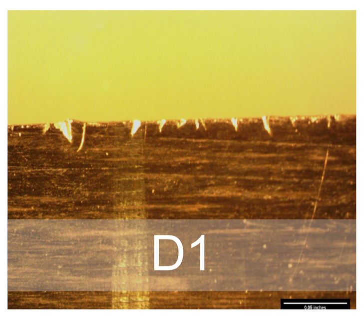
Electron microscopy and Electron Dispersive Spectroscopy:

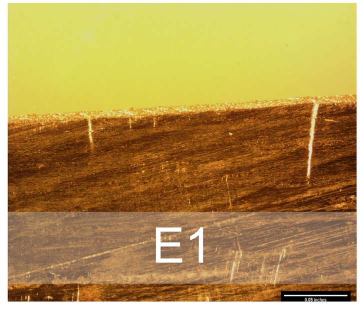
- Samples from rolling experiment 2 as well as Logan's cold rolled samples were mounted in Bakelite and polished to 1 µm diamond paste before being etched for 20 seconds using Keller's Etchant. SEM images and compositional analysis were then recorded using a Phenom Desktop SEM in BSD mode at 15kV. Point detector mode was used for compositional analysis at several points near the edge cracks and within the bulk material.

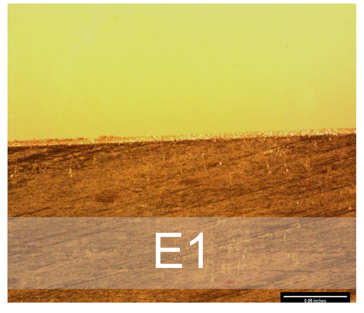
Rolling Experiments

As discussed in Experimental Methods, section C was rolled under the most aggressive rolling schedule, with section D being less aggressive and section E the most passive. Seen below are optical images taken of the edge condition after a 90% reduction. Samples C and D show prominent edge cracking, with varying depth and distance between cracks. Sample E did not show widespread cracking, with only one set of cracks on the sample. This can be seen in the two images above, labeled E1 The team reasoned that the cracking in the E1 sample was not due to shear banding, but rather a stress concentration created during sectioning. These samples were then compared to cracked/delaminated samples sent from Logan Aluminum.



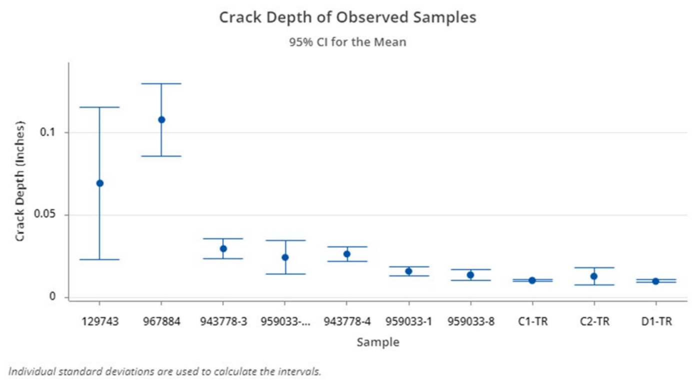


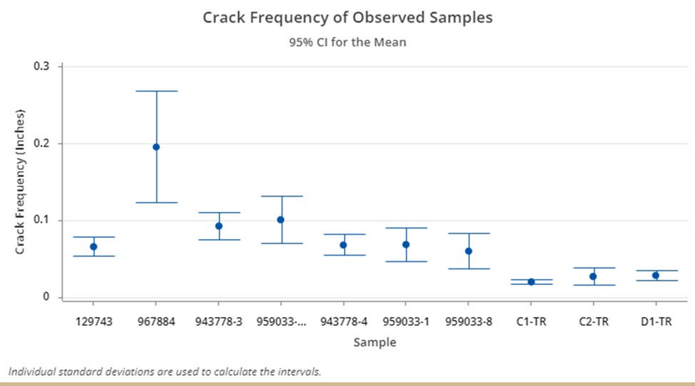




The optical images shown above were taken from samples 943778-3 and 943778-4 received from Logan Aluminum. The crack character in these samples is comparable to that seen in samples C and D above. The likeness of these to samples C and D also further implies that the cracking seen in E1 is not due to edge cracking/delamination but rather an outside influence.

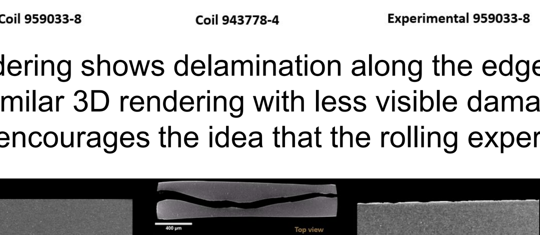
To quantify the cracking observed in optical microscopy, ImageJ was used to take measurements of the crack depth and frequency. The distance from the edge of the sample to the end of the crack (crack depth) and the distance between cracks (crack frequency) were measured. This data was then input into Minitab for statistical analysis. Seen above are 95% confidence intervals for the crack depth and frequency of each sample observed in optical microscopy. Except for samples 129743 and 967884 received from Logan Aluminum, the crack depth was relatively similar in both types of samples. The distance between cracks was lower on average in the team-rolled samples when compared to those received from Logan Aluminum. This data, along with later metallography, will determine how well the team's experiment modeled the phenomena seen at Logan Aluminum.





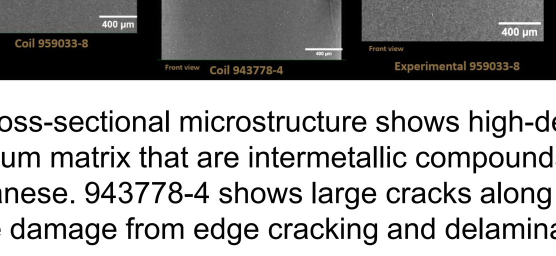
X-Ray Tomography

X-ray computed tomography (XCT) was utilized as a non-destructive technique for observing the microstructure and internal features of samples. This was performed on two different 5182 coil samples from Logan (959033-8 and 943778-4) as well as one sample from experimental rolling which initially was the 959033-8 coil. The objective in XCT was to compare the Logan samples with the experimentally rolled samples and confirm similar characteristics and microstructure.



3D Rendering of Samples

3D rendering shows delamination along the edge of 943778-4. 959033-8 samples show similar 3D rendering with less visible damage and delamination. These results further encourages the idea that the rolling experiment conducted emulates Logan's.

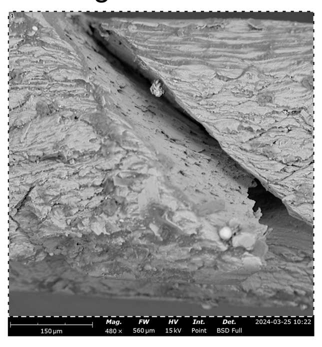


Cross-sectional Microstructure of Samples

The cross-sectional microstructure shows high-density white regions within the grey aluminum matrix that are intermetallic compounds containing magnesium and manganese. 943778-4 shows large cracks along the length of the sample indicating severe damage from edge cracking and delamination.

Metallography

SEM and Optical mages were taken to examine the occurrence of shear banding. Following, EDS analysis was performed to assess the material's composition at various sites. The compositional data obtained aligned well with expectations and supports the known specifications of Al 5182. This data suggests that the occurrence of banding and delamination may not be a compositional defect.

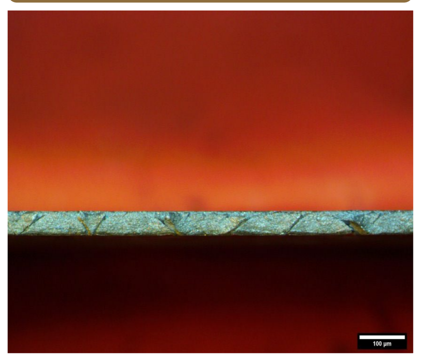

SEM micrograph of Shear Banding region

EDS Analysis of Sample

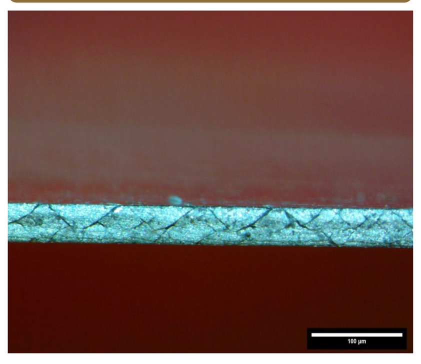
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	50.75	63.26
8	O	Oxygen	29.45	21.76
6	C	Carbon	15.11	8.39
12	Mg	Magnesium	4.48	5.04

Given our understanding of shear banding, we can expect to see microstructural instability because of the strain path change. Literature suggests that Aluminum alloys are susceptible to adiabatic shear banding (ASB) during high-strain-rate deformation rather than typical dislocation-based plasticity seen in static deformation. An ASB reflects a thermomechanical deformation instability developed under high strain and strain rates, finally leading to dynamic fracture (creating a branch-like fracture extending from the original sites). An ASB first occurs under severe shear localization, followed by a significant rise in temperature due to high strain rate adiabatic conditions as mentioned. As the term adiabatic suggests, no heat is transferred into or out of the system and the changes in internal energy are only influenced by work. This activates thermal softening and mechanical degradation mechanisms, and as they react to strain instability, they propagate micro voids, leading to material failure.

943778 DR 0.02 in thickness

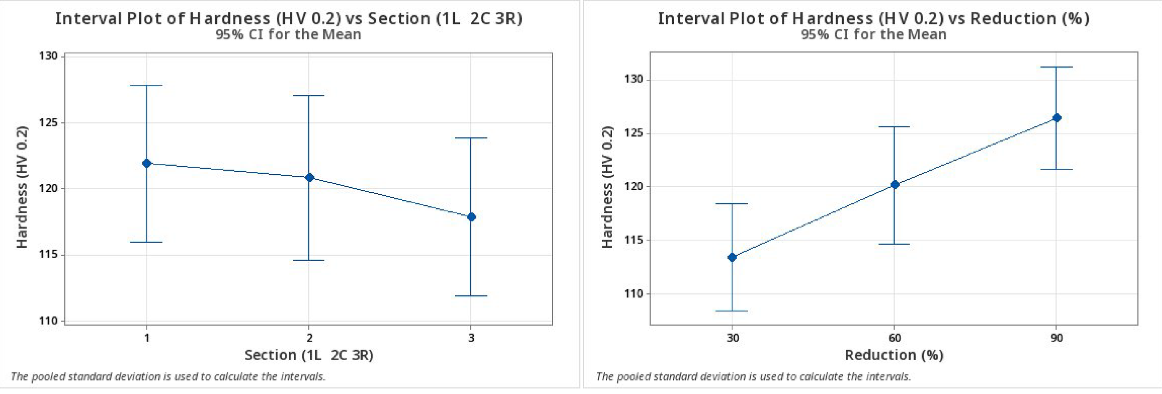


Team sample B1 with 90% reduction



Hardness

The analysis of hardness across different sections reveals a consistent pattern: there is no significant difference in hardness values between the sections themselves. However, there is a notable trend when examining the relationship between hardness and the percentage of reduction. The data visualized in the graphs below indicates that as the percentage of reduction increases, so does the hardness of the material, irrespective of the specific section considered.



For a reduction of 30%, the average hardness measured was 113.44 HV, with a standard deviation of 8.33 HV, and the 95% confidence interval ranged from 108.44 HV to 118.44 HV. When the reduction percentage doubled to 60%, the mean hardness increased to 120.19 HV, accompanied by a slightly tighter standard deviation of 7.25 HV, and a 95% confidence interval stretching from 114.71 HV to 125.67 HV. The most substantial increase was observed at a 90% reduction, where the average hardness further escalated to 126.45 HV, despite a slightly larger standard deviation of 9.47 HV, with the confidence interval lying between 121.64 HV and 131.25 HV.

This pattern is observed in the graphs above, clearly illustrating the direct relationship between the degree of reduction and the resultant hardness of the material across all sections. The graph underscores the consistent increase in hardness with higher percentages of reduction, confirming the observed trend in the numerical data.

Process Recommendations

Based on our analysis of our rolling experiments and metallography, slower reductions can reduce crack propagation in delaminated or delaminating samples. We recommend that Logan Aluminum slows down their reductions in their rolling mills if and only if doing so enough to eliminate edge cracking and delamination is more profitable than simply continuing to roll at the current rate and scrap coils when needed.

While the direct cause of these phenomena is still unknown and requires further investigation, our rolling experiments showed that slowing reduction speed will prevent the edge cracking phenomena. Lowering the reduction slightly will not reduce the cracking experienced. Lowering the reduction speed to a threshold will prevent the phenomena, but marginal reductions will have little gain. Further investigation is needed to determine the location of this threshold and to assess whether reducing speed to meet it is economically viable.

Acknowledgments

Prof. Kevin Trumble, Prof. Nikhilesh Chawla, Eshan Ganju