31.0 ACCUMULATIVE ROLL BONDING OF AL AND TI SHEETS TOWARD LOW TEMPERATURE SUPERPLASTICITY

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31.1 Project Overview and Industrial Relevance

Accumulative roll bonding (ARB) is a severe plastic deformation technique used to produce ultra-fine grained material by introducing intense plastic strains within a material [31.1]. The surfaces of two sheets are prepared in a particular manner before being stacked and roll bonded together in a conventional rolling mill [31.1]. After rolling, the material is sectioned in half and the process is repeated. A single-pass, 50% rolling reduction is commonly employed to ensure adequate bonding and to retain the sample's original dimensions after each roll bonding cycle [31.1]. The ARB process is largely different from conventional rolling processes in that heavy single-pass reductions are conducted without lubrication. This introduces redundant shear into the surface of the rolled material, which is introduced through the material's thickness with subsequent roll bonding cycles [31.2]. The interfaces that form between layers, which can include oxides and inclusions, are thought to strengthen the material by inhibiting grain growth [31.3].

The attraction to ARB lies in the ability to produce ultra-fine grained material with conventional processing equipment. With the accumulation of intense strain, dislocation cell structures form within the material that further transform into refined grains [31.4-5]. Significant grain size strengthening is observed after one or two ARB cycles, which tends to reach a plateau after around 6 cycles [31.4]. Grain sizes as small as 670 nm have been obtained in Al 1100 after 8 cycles [31.4], and as small as 280 nm in Al 5083 after 5 cycles [31.6]. Ultrafine grains produced by ARB can also lead to superplastic responses at lower temperatures. Superplastic elongations above 200% have been exhibited by ARBed Al 5083 at strain rates of 10^{-3} s^{-1} and temperatures as low as 473 K [31.6]. Enhanced superplasticity would be beneficial to superplastic sheet forming operations, where reduced temperatures and increased strain rates could lead to cost savings and reduced die wear.

31.2 Previous Work – Literature Review

Previous work was focused on a literature review of roll bonding mechanisms and defects. Two theories are generally adopted to describe the bonding process during ARB: the film theory and the diffusion theory. The film theory states bonding is prohibited by thin films of oxides or contaminants on the mating surfaces; as a result, bonding can only occur when virgin material beneath the thin film is exposed [31.3]. Wire brushing prior to rolling creates a very brittle surface layer of oxides on the material, which fractures upon rolling to expose the material beneath it, thus allowing bonds to form [31.3]. The diffusion bonding theory complements the film theory, stating that once virgin material from two mating surfaces comes within atomic distance, diffusion of atoms across the newly created interface enhances the strength of the bond [31.3]. Thus, post-process heat treatments have the potential to increase bond strength, due to the enhancement in diffusion between mating surfaces.

A combination of acetone degreasing followed by wire brushing is commonly used to prepare mating surfaces prior to roll bonding. It has been observed that the bond strength of wire-brushed samples starts to decrease in as little as 10 minutes after being exposed to ambient atmospheres prior to rolling [31.7-8], necessitating the need for prompt rolling after wire brushing. It is believed adsorption of moisture onto the wire-brushed surface inhibits bonding, which can be avoided by minimizing the time between wire-brushing and rolling [31.3], storing prepared samples in desiccators prior to roll bonding [31.3], and "baking out" adsorbed surface layers [31.9].

Aside from achieving sufficient bonding, obtaining defect-free material is of vital importance to the ARB process. The most common defect to occur is edge cracking, which develops due to tensile stresses on the edges of the sheet, where material exhibits tensile stresses due to both longitudinal and lateral elongation. Although wider specimens reduce the tendency for edge cracking by minimizing stress gradients, severe edge cracking has been noted in samples as wide as 60 mm after only two ARB cycles [31.10]. If edge cracks are present in a material, the sample must either be sheared to remove edge cracks, or discarded if the edge cracks are too severe. Some studies have found that warm rolling of Al 5083 at 300 °C limits edge cracking while still producing enhanced mechanical properties, even after 6 cycles of ARB [31.11].

31.3 Recent Progress

31.3.1 Development of tooling and fixtures

Multiple tools and fixtures had to be designed and fabricated to successfully replicate the ARB process at CSM. Examples of such tooling include a clamp-down setup for wire brushing, adjustable edge guides for the rolling mill, a digital data acquisition system to measure roll separating force, and a CNC fixture to rapidly machine tensile samples. Most critical to ARB processing are the edge guides and data acquisition system.

Adjustable edge guides are necessary to laterally constrain sheets as they enter the rolling mill. Guides with two degrees of freedom were designed and machined to accommodate stacked sheets up to 3 in. wide and 0.25 in. thick. Adjusting the constraint in the width dimension ensures the sheets do not inadvertently move relative to each other during rolling. The use of edge guides removes the need to fix the sheets together by means of wire binding or spot welding, and thus allows for material to be promptly rolled after wire brushing.

The digital data acquisition system records and outputs roll separating force in real time by means of two load cells on each end of the rolls. The single-pass 50% reductions conducted in ARB are associated with high roll separating forces, which increase with subsequent ARB cycles. Wider samples, which are attractive as a means of reducing edge cracking, also significantly increase roll separating force. It is therefore imperative to accurately measure rolling loads to ensure that rolling is conducted within the capacity of the rolling mill, and understand the loads necessary for bonding as a function of ARB cycle count.

31.3.2 8 Successful ARB Cycles of Al 1100

With use of aforementioned tooling and fixtures, eight successful roll bonding cycles of Al 1100 were conducted. A macroscopic image showing strips of Al 1100 processed from one to eight subsequent ARB cycles is shown in **Fig. 31.1**. Despite efforts to remove initiated edge cracks between cycles by shearing, edge cracking became noticeable after the third bonding cycle. Edge cracking was severe if the edges of the two sheets were not sheared perfectly parallel, or if lateral movement between the two sheets was not constrained, as exhibited in the inset figure of the fifth bonding cycle in **Fig. 31.1**. Severe edge cracking was observed after the eighth roll bonding cycle, which prohibited further processing of the material.

The ARB processed samples become noticeably narrower and shorter with increased roll bonding cycles due to shearing, thus reducing sample yield. Although shearing is necessary to reduce the severity of edge cracking and ensure the samples are straight, a significant yield loss of about 6.6% on average occurs between each pass. A 75% yield remained after five cycles and only a 50% yield remained after eight cycles. Note these losses should remain constant in magnitude as a function of strip width, so the ability to process wider strips would greatly increase yield.

31.3.3 Preliminary Mechanical Properties

The stress-strain curves for the as-processed material are presented in **Fig. 31.2**. A significant increase in ultimate tensile strength is apparent for all samples relative to fully-annealed starting material, which had a strength of 89 MPa and uniform elongation of 30%. The strength after one roll bonding cycle alone was 185 MPa, an increase by a factor of two. A trend of increased strength with additional ARB cycles is evident. The maximum strength achieved was around 300 MPa, which stayed approximately constant from the sixth cycle onwards.

The room-temperature uniform elongation of all samples decreased significantly compared to the fully-annealed value of about 30%. Samples subject to one ARB cycle exhibited about 3% uniform elongation. This value increased to about 5% uniform strain for additional cycles and remained relatively constant. Post-uniform elongation values also remained very low, generally on the order of 1 to 2% strain.

Samples subjected to post-process heat treatments of either 100°C or 200°C for 1 hour were also tensile tested. These strength and uniform elongation values are summarized in **Fig. 31.3**. Very little difference is noted between the as-processed and the 100°C heat treated condition in terms of either strength or uniform elongation; the properties remain relatively constant. The 200°C heat treatment, however, displayed a significant decrease in tensile strength. The tensile strength decreased slightly after one ARB cycle to around 150 MPa and stayed around this value for all subsequent ARB cycles. A strength decrease of about one half is noted for samples subjected to six or more roll bonding cycles. Microstructural characterization is needed to fully explain the changes observed in mechanical properties.

31.3.4 Fractography

Fracture surfaces of the tensile specimens were examined to develop a better understanding of the failure mode. Secondary electron micrographs of the fracture surfaces for samples subjected to 5 ARB cycles are shown in **Fig. 31.4**. In the as-processed condition, the fracture seems to be an equal mix of ductile and brittle fracture. Obvious delamination has occurred at the centerline bond and local delamination of other bonds is also visible. In the sample heat treated at 100°C for 1 hour, the fracture surface appears to be more uniformly ductile. Although delamination of the centerline bond is obvious, delamination in other regions of the sample is restricted to only the most two recent bonds at quarter-thickness and semi-quarter thickness intervals of the sample. In the sample heat treated at 200°C for 1 hour the fracture appears to be mostly brittle; the only noticable bond is the centerline which has minimal delamination. Evidently, post-deformation heat treatments change the fracture characteristics of ARBed material. These different failure mechanisms are likely to alter post-uniform elongation of samples, and it is worth understanding the mechanisms by which post-deformation heat treatments can alter mechanical properties.

31.4 Plans for Next Reporting Period

Successful accumulative roll bonding of Al 1100 has provided opportunity for process and tooling development. Work to follow in the next reporting period includes the following:

- Develop proficiency in microstructural characterization techniques for aluminum alloys including anodizing for grain contrast, transmission electron microscopy and electron backscatter diffraction.
- Conduct high temperature tensile testing of ARBed Al 1100 with Gleeble to better understand effects of temperature and strain rate on mechanical properties.
- Explore ARB processing of other aluminum alloys including 5083, 5182 and 5754.
- Quantitatively measure bond strength in roll bonded aluminum alloys subjected to preheating before rolling and post-deformation heat treatments.

31.5 References

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31.6 Figures and Tables

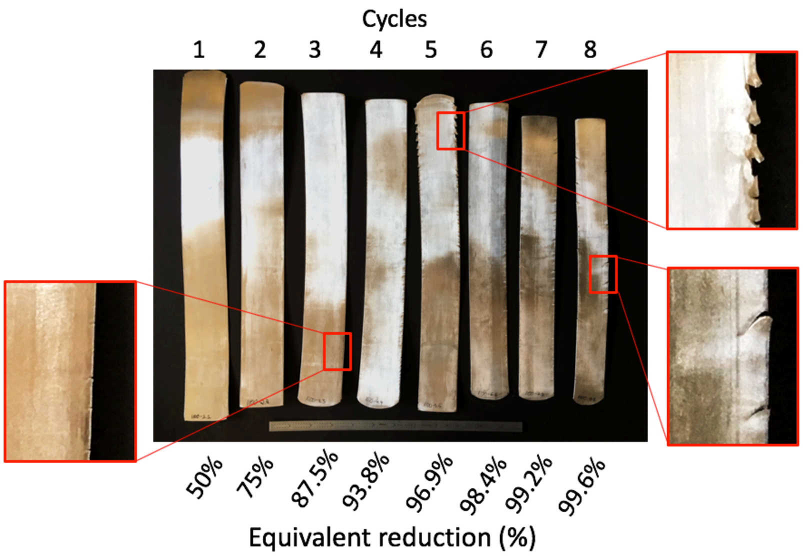


Figure 31.1: Samples of Al 1100 processed between one and eight successive roll bonding cycles. Equivalent rolling reductions are noted. Inset figures highlight edge cracks that form despite shearing between roll bonding cycles. Starting samples were about 50 mm wide.

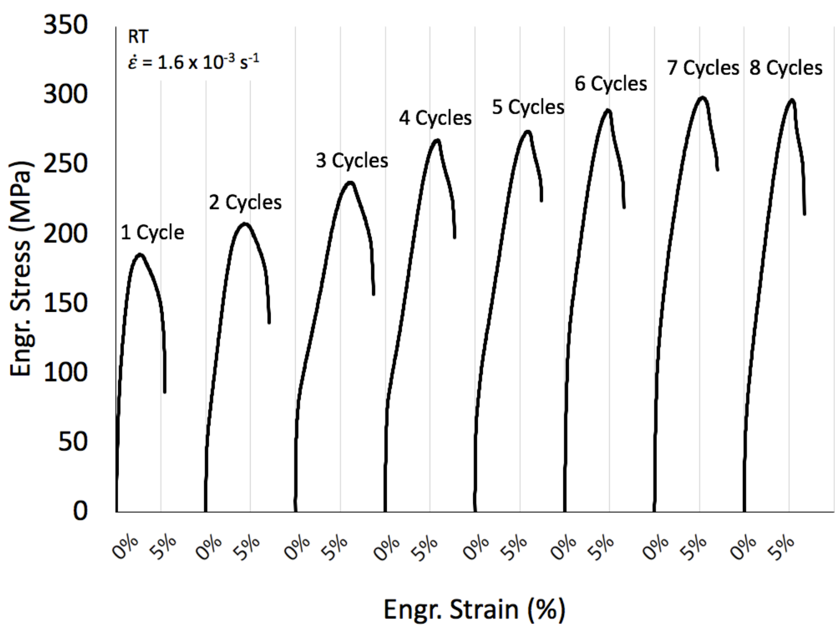


Figure 31.2: Stress-strain curves for as-processed samples subjected to one to eight ARB cycles.

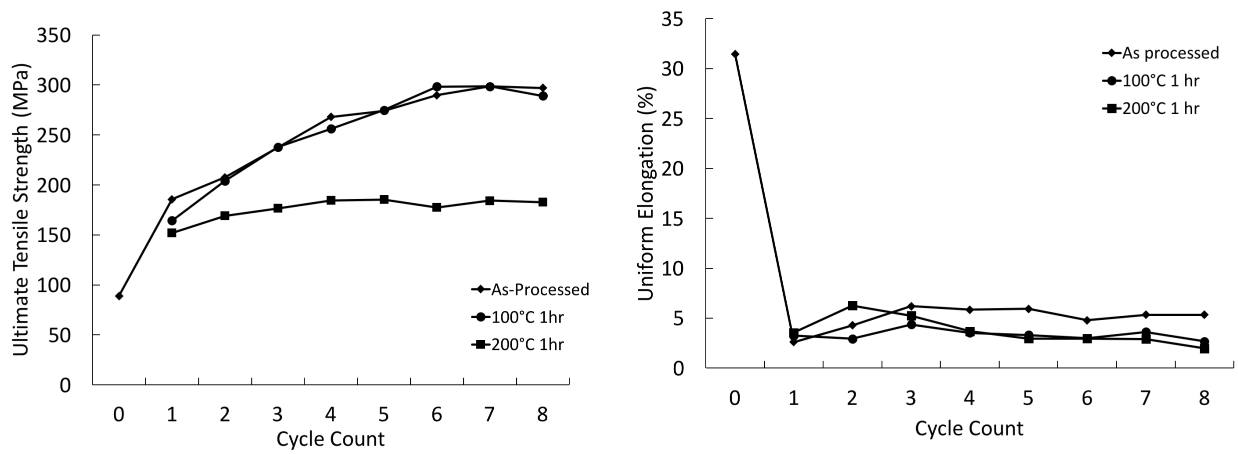
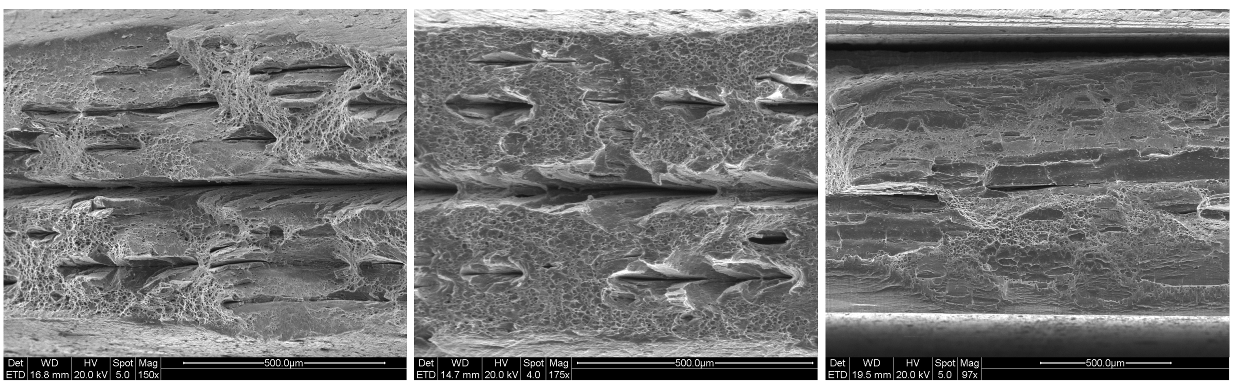


Figure 31.3: Strength (left) and elongation values (right) of roll-bonded material subject to heat treatments at either 100°C or 200°C for one hour.



(a) (b) (c)

Figure 31.4: Tensile test fracture surfaces of Al 1100 subject to 5 cycles in the (a) as-processed (b) 100°C for 1 hour and (c) 200°C for 1 hour conditions. All samples were tensile tested at room temperature with a strain rate of 1.6 x 10^{-3} s^{-1}.