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

Brady McBride (CSM)
Faculty: Kester Clarke (CSM)
Industrial Mentor: Ravi Verma (Boeing) and John Carpenter (LANL)

31.1 Project Overview and Industrial Relevance

Accumulative roll bonding (ARB) is a severe plastic deformation (SPD) technique used to develop an ultrafine grain structure in materials. The process involves stacking two sheets of material and roll bonding them with approximately 50% reduction such that the resultant material is twice the original length. The as-rolled material is then sectioned in half, degreased and stacked, constituting one roll bonding cycle. Subsequent cycles are repeated with a 50% reduction to maintain the original geometry of the sheet. Typical studies conduct 5 or 6 subsequent cycles of roll bonding such that intense strain accumulates within the material, leading to submicron grain refinement and Hall-Petch type strengthening behavior.

The potential advantages of accumulative roll bonding are numerous, especially compared to other SPD techniques such as high-pressure torsion (HPT), equal channel angular extrusion (ECAE) and friction stir processing (FSP). HPT is generally limited to thin disks of material a few millimeters thick, while ECAE is limited to small billets a few centimeters in cross section; both of these techniques require specialized equipment for processing material. ARB on the other hand, can be performed with a conventional laboratory or production rolling mill and is not limited to laboratory scale geometries. Instead of processing discontinuous pieces of material, it is theoretically possible to process coiled sheets of material with ARB for large scale continuous production.

The attraction to ARB lies in its ability to produce ultrafine grained material with conventional processing equipment. With the accumulation of intense strain, dislocation cells structures form within the material that further transform into refined grains. Significant grain size strengthening is noticed after one or two ARB cycles, which tends to reach a plateau up to five cycles. Aside from grain-size strengthening, the fine grain size of materials subjected to ARB can also enhance superplasticity where elongations in excess of a few hundred percent are achieved. Superplasticity is an important phenomenon for certain high-temperature sheet forming processes. Enhanced superplasticity has the potential to decrease forming temperature while increasing forming strain rates, thus reducing part forming time.

31.2 Previous Work – Literature Review

Typical superplastic forming of aluminum alloys is characterized by elongations in excess of 300 %. To achieve such elongations, temperatures in excess of 500°C and strain rates on the order of 10^{-3} s^{-1} are required [31.1]. Grain refinement as achieved by accumulative roll bonding has been shown to significantly reduce superplastic formation temperature. Superplastic elongations of about 220 % have been exhibited at temperatures as low as 200 °C in Al 5083 subject to five ARB cycles — about 300 °C lower than the aforementioned parameters [31.2]. This phenomenon was concurrent with a grain size reduction from 10 μm to 280 nm [31.2]. Similar studies of ARBed Al 5083 have noted a 1.7x increase in room temperature yield stress, showing the significant grain size strengthening potential of ARB. Similar superplastic properties have been noted in Al 2024 subject to HPT and FSP where elongations as high as 525 % have been achieved for temperatures and strain rates around 400 °C and 10^{-2} s^{-1}, respectively [31.3-31.4]. Due to the discontinuous nature HPT and FSP, the samples from these studies are limited to laboratory-scale sizes. ARB studies on Al 2024, which has the potential for continuous bulk production, have been very limited to date.

A major obstacle for the evolution of the ARB process is the occurrence of edge cracking. Edge cracks develop due to tensile stresses on the edges of the sheet, where material exhibits tensile stresses due to both longitudinal and lateral elongation. Extreme edge cracking has been noted in Al 5083 after only two cycles of ARB, which has prohibited further processing of the material [31.5]. A common practice is to remove cracked regions before subsequent ARB cycles, which drastically reduces the process yield. Typical ARB studies use samples that are about 30 mm wide. It is possible the narrow widths of these samples encourage edge cracking due to high stress gradients, but ARB studies with samples as wide as 60 mm have noted similar cracking behavior [31.5]. It has been 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 [31.6]. Canning or other techniques aimed at reducing lateral spread may be potential solutions to mitigate edge cracking and would require additional investigation.

Other issues of roll bonding include relative motion between sheets during rolling. If unconstrained, the sheets may move laterally with respect to each other and cause lateral spreading, resulting in a ‘Y’-shape, as seen in **Fig 31.1a**. To mitigate lateral spreading, the two sheets are often bound together at the corners with wire or with the use of spot welds [31.5]. While this method resolves the issue of spreading, the bounded region of the sample must be removed prior to subsequent cycles, resulting in yield loss. Other mitigation strategies include the use of guides on the feeding side of the rolling mill to prevent lateral movement of the sheets during rolling [31.5]. Although it hasn’t been experimentally confirmed, it is unlikely this problem would be present in a continuous process with coiled sheet; the back tension of the sheets entering the mill should prevent lateral spreading.

31.3 Recent Progress

31.3.1 Preliminary Rolling Tests

Preliminary rolling tests were conducted using 6061 aluminum sheets on a Fenn rolling mill at Colorado School of Mines (CSM) in the 2-high hot rolling configuration to develop a better understanding of the mill’s capabilities and performance. Strips were rolled down to 0.050” (1.25 mm), degreased with acetone and brushed with a stainless steel wire brush rotating at about 1,000 RPM. Two sheets were then stacked on top of each other, without binding, and rolled with a targeted 50% reduction at room temperature. The single-speed Fenn rolling mill operates at about 50 fpm. The desired reduction in thickness was obtained but there was no bonding between the two sheets, likely due to the rough surface finish imparted from the hot rolling setup. The sheets also exhibited excessive damage due to relative motion between each other during rolling. It was evident that surface roughness and preparation are two pertinent factors in achieving successful roll bonding.

31.3.2 CSM Rolling Mill Conversion

The Fenn rolling mill at CSM was previously arranged in a 2-high hot rolling configuration with 5.25” rolls. This configuration was converted to a 4-high cold rolling configuration with 1.625” work rolls in order to produce better surface finish and thickness control. The 4-high setup proved to be very difficult to feed material into, even when making minimal rolling reductions. With this limitation, the 50% single-pass reductions for accumulative roll bonding would be exceedingly difficult to achieve. The mill was finally converted into a 2-high cold rolling configuration with 5.25” working rolls. Spare strips of Al 6061 were used to make necessary adjustments to the rolling mill until material consistently rolled straight with uniform thickness.

31.3.3 First Successful Accumulative Roll Bonding Cycle

Additional roll bonding tests were conducted in the 2-high cold rolling configuration. Two strips of Al 6061 were rolled to 0.063” and subject to a solutionizing heat treatment followed by a water quench. The strips were vigorously wiped with acetone and wire brushed with a 0.008” stainless steel wire wheel rotating at about 3,000 RPM. The strips were then stacked on top of each other, without binding, and rolled at a 50% reduction. The resultant sheet showed successful bonding with a thickness of 0.068” (46% reduction). The material exhibited a significant ‘Y’-shape near the trailing edge, where it is likely the two sheets slid laterally past each other and separated (**Fig 31.1a**). Virtually no reduction occurred in this region as the fins of the ‘Y’-shape were composed of a single sheet of the starting material. A longitudinal cross section of the leading edge was examined with optical microscopy (**Fig 31.1b**). The resultant interface appeared to have adequate bonding without large voids or inclusions. The formation of edge cracks was immediately noticeable.

31.3.4 Second Accumulative Roll Bonding Cycle

The sample obtained after one successful roll bonding cycle was sectioned to remove the defective trailing edge and machined into a rectangular shape. Edge cracks present after the first rolling bonding cycle were not specifically removed unless they were located outside of the machined rectangular shape. The sample was then sectioned into two equal portions that were vigorously wiped with acetone, brushed with the aforementioned parameters and rolled, unbound, with the same desired 50% reduction. A reduction of 49% was achieved and a similar ‘Y’-shape had developed at the trailing edge of the sample (**Fig 31.2a**). The consistent location and magnitude of the ‘Y’-shape suggests a recurring issue with the sheets sliding relative to each other during rolling as the trailing edge of material enters the rolls. The bonding appeared to be well developed in the leading edge of the sample, but distinct layers of material were observable by naked eye towards the trailing edge. Optical microscopy of the longitudinal cross section showed adequate bonding of all four layers up to the trailing edge of the sample. Lack of bonding near the trailing edge was visible in the interface that developed after the first ARB cycle (**Fig 31.2b**), likely due to the lateral spreading of the sheets. New cracks developed along the edges of the material, and existing cracks grew substantially.

31.4 Plans for Next Reporting Period

Preliminary experiments in roll-bonding provided valuable information about technical difficulties associated with achieving adequate bonding. The majority of work to follow in the next reporting period will be focused on the following:

- Develop processing techniques for successive accumulative roll bonding cycles
    - Further explore surface preparation processes that provide adequate bonding
    - Investigate strategies to mitigate lateral spreading of the trailing edge of samples
    - Characterize resultant bonding interfaces with optical microscopy
- Develop test matrix for future roll bonding of Al 2024
    - Consider enough samples for successive roll bonding cycles with destructive tensile tests and interface evaluation after each subsequent processing cycle

31.5 References

[31.1] N. Ridley, "Metals for Superplastic Forming," in *Superplastic Forming of Advanced Metallic Materials: Methods and Applications*, Woodhead Publishing, 2011, pp. 3-33.

[31.2] N. Tsuji, K. Shiotsuki and Y. Saito, "Superplasticity of Ultra-Fine Grained Al-Mg Alloy by ARB," *Materials Transactions,* vol. 40, no. 8, pp. 765-771, 1999.

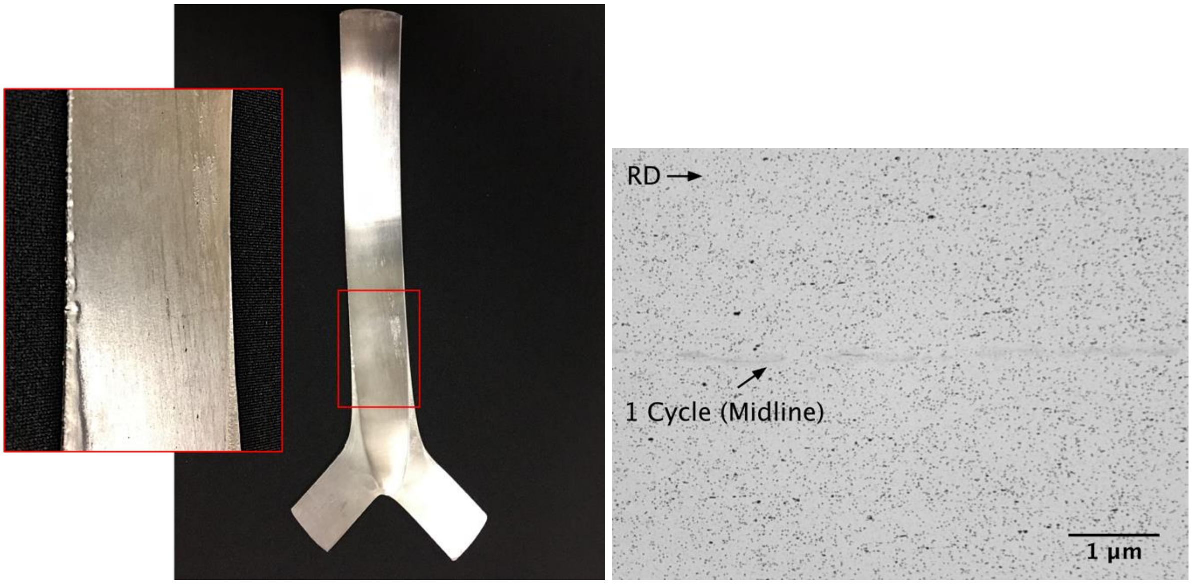
[31.3] I. Charit &. R. S. Mishra, "High strain rate superplasticity in a commercial 2024 Al alloy via friction stir processing," *Materials and Engineering A,* vol. 359, pp. 290-296, 2003.

[31.4] A. Alhamidi &. Z. Horita, "Grain refinement and high strain rate superplasticity in alumunium 2024 alloy processed by high-pressure torsion," *Materials Science & Engineering A,* vol. 622, pp. 139-145, 2015.

[31.5] N. Tsuji, "Production of Bulk Nanostructured Metals by Accumulative Roll Bonding (ARB) Process," *Severe Plastic Deformation: Toward Bulk Production of Nanostructure Materials,* pp. 545-565, 2006.

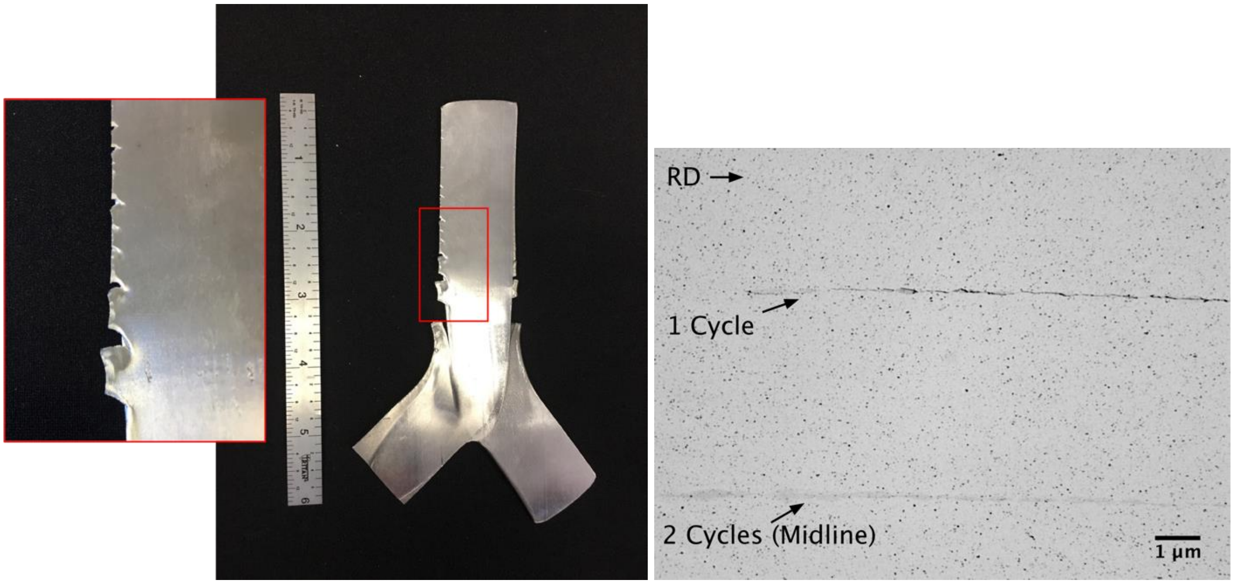
[31.6] H. Sheikh & E. Paimozd, "Effect of Hot Accumulative Roll Bonding Process on the Mechanical Properties of AA5083 Abstract," *Open Journal of Metal,* vol. 1, pp. 12-15, 2011.

31.6 Figures and Tables



(a) (b)

Figure 31.1: Sample after one cycle of roll bonding. (a) shows lateral spreading at the trailing edge of the sample and the development of edge cracks. (b) shows the result bonding interface observe at the leading edge of the sample after one ARB cycle. Width of sheet is about 1.0 in (25.4 mm).



(a) (b)

Figure 31.2: Sample after two cycles of roll bonding. (a) shows the propagation of edge cracks and the redevelopment of lateral spreading at the trailing edge. (b) shows the development of interfaces at the trailing edge of the sample, near the centerline. Lack of bonding is evident in the interface created after one cycle due to lateral motion of the sheets. Width of sheet is about 1.0 in (25.4 mm).