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Influence of Processing Temperature on Mechanical Properties of Al 6061 Alloy During Accumulative Roll Bonding

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ABSTRACT: Accumulative Roll Bonding (ARB) is a severe plastic deformation technique used to enhance the mechanical properties of metallic materials through repeated rolling and bonding cycles. In this study, the influence of processing temperature on the mechanical properties of Al 6061 alloy during ARB was investigated. ARB processing was performed at varied temperature (100 °C and 200 °C) and the processed sheets were characterized for tensile properties and Hardness evolution. Results showed that 200 °C processing temperatures facilitate dynamic recovery leading to coarser grain structures but enhanced ductility. However, 100 °C temperature promote greater strain hardening and finer grains resulting in higher ultimate tensile strength. These findings provide insights into optimizing ARB processing parameters for Al 6061 alloy to achieve desired combinations of strength and ductility.

KEYWORDS: Accumulative Roll Bonding (ARB), Al 6061 Alloy, Processing Temperature, Grain Refinement, Dislocation Strengthening, Mechanical Properties, Severe Plastic Deformation

I. INTRODUCTION

Aluminium and its alloys have been widely used as a material of choice in various industries due to their desirable properties (Yang et al., 2014). This stems from its reputation as a light weight structural material. Aluminum alloys possess high-strength-to-weight ratio, they are resilient and ductile at low temperatures, corrosion resistant and non-toxic, therefore making them preferred metal in most industries (Raj et al.,2021). Among the aluminum alloys, Al 6061 is a popular choice for applications in the automotive, aerospace, and construction industries due to its superior mechanical properties and favorable cost-benefit ratio (Kumar et al., 2021). It is ideal for marine and chemical environments as well as good for welds in complex assemblies. However, there has been continuous effort to enhance the mechanical properties of Al 6061 alloy to meet the increasing demands of modern engineering applications (Frank, 2020). For instance, increasing the strength and reducing the cost of processing increases the usability of Al 6061 alloy for a broader range of applications.

Rolling, the second most-used metal forming process after casting is essential in shaping metals. Hot rolling enables grain refinement but poses thermal and oxidation challenges (Singh et al., 2025). Cold rolling improves surface and strength via strain hardening but needs more force (Mishra et al., 2018). Warm rolling merges benefits from both processes, offering balanced strength and finish with fewer issues (Samuel et al., 2021). Over the years, rolling technology has evolved from manual methods to complex systems like two-high, four-high, and tandem mills. Tandem mills allow for high-speed continuous rolling with precise dimensional control but are costly and complex. Advanced mills prioritize accurate thermal regulation, roll-gap settings, and lubrication to maintain product quality (Olaogun, 2018).

Severe plastic deformation (SPD) techniques have emerged as powerful methods to overcome these limitations by imposing very large strains on metallic materials without significant changes in overall dimensions (Kumar et al., 2023). Among SPD techniques, Accumulative Roll Bonding (ARB) has gained considerable attention due to its simplicity, scalability, and effectiveness in producing bulk ultrafine-grained (UFG) metals (Rao et al., 2022). ARB involves repeated rolling, cutting, and stacking of metal sheets. This leads to grain refinement, dislocation accumulation, and sub-grain formation which collectively contribute to enhanced strength and hardness (Hasanabadi et al., 2024). The processing temperature during ARB is a key factor that influences the balance between strain hardening, dynamic recovery, and recrystallization. Low temperatures generally promote high dislocation density and finer grains, enhancing strength, whereas elevated temperatures facilitate dynamic recovery, which can improve ductility but may reduce the ultimate tensile strength. Several studies have explored ARB of aluminum alloys, demonstrating the role of strain accumulation and microstructural evolution in property enhancement (Singh et al., 2025, Sajjadi et al., 2023, Naresh et al., 2025, Roghani et al., 2023).

While Accumulative Roll Bonding (ARB) has been widely studied for aluminum alloys, most investigations focus on general mechanical improvements without systematically correlating processing temperature with microstructural evolution and underlying strengthening mechanisms. There is a lack of detailed understanding of how temperature variations during ARB influence grain refinement, dislocation behavior, and property optimization in Al 6061 alloy. This study addresses this gap by providing a comprehensive analysis linking precise temperature control to microstructural dynamics and mechanical performance, offering a pathway for tailored property enhancement in lightweight engineering applications. Therefore, this study investigates the influence of processing temperature (100 °C and 200 °C) on the mechanical properties of Al 6061 alloy during ARB. The findings aim to provide practical insights into temperature-dependent optimization of ARB, enabling the production of materials with superior combinations of strength and ductility.

II. MATERIALS AND METHODS

A. Material

Al 6061 Alloy sheets of thickness 1mm were obtained and its chemical composition determined using optical emission spectroscopy (OES) (see Table 1). The Al 6061 alloy sheet was cut to dimensions of length 100mm and width 50mm respectively. To removed dust of grease on the sheet surfaces, samples was cleaned in ethanol for 5 mins, flushed with acetone and dried in hot air. This was done to ensure proper bonding during the ARB process (Duan, 2016).

Table 1: Chemical Composition of AL 6061 alloy.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.60	0.50	0.28	0.02	1.02	0.24	<0.01	0.035	Bal.

B. Accumulative Roll Bonding (ARB) Procedure

The ARB process was carried out using a laboratory-scale rolling mill. Sheets were processed at two different temperatures, 100 °C and 200 °C, to investigate the effect of thermal conditions on microstructural evolution and mechanical properties. The Sheets were cut to uniform dimensions and stacked in pairs. Each stack was preheated to the target temperature (100 °C and 200 °C) in the furnace for 30 minutes to ensure uniform temperature distribution. Sheets were rolled to 50% thickness reduction per pass using rollers with 100 mm diameter and 150 mm length at a controlled speed of 2 m/min. After each rolling pass, the sheets were sectioned, cleaned, and stacked for the next cycle. The process was repeated for four ARB cycles to achieve significant plastic strain accumulation. Friction between the sheet and rollers was minimized using a lubricated rolling setup, with the friction coefficient maintained at 0.3 (Coulomb model) to reduce surface defects.

C. Mechanical Property

Tensile Test: This was performed in accordance to ASTM E8/E8M-16a (Afifi et al., 2018). Values of the tensile strength was obtained and % elongation determined.

Hardness Test: Vickers hardness test was performed on ARB processed samples in accordance to ASTM E-834 standard (Khelfa et al., 2021). The test was performed at three random points for each sample omitting the outliers and averaging the remaining measurements.

III. RESULTS AND DISCUSSION

A. Tensile Properties

Figures 1, 2 and 3 shows the results of the tensile properties of the ARB processed al 6061 alloy.

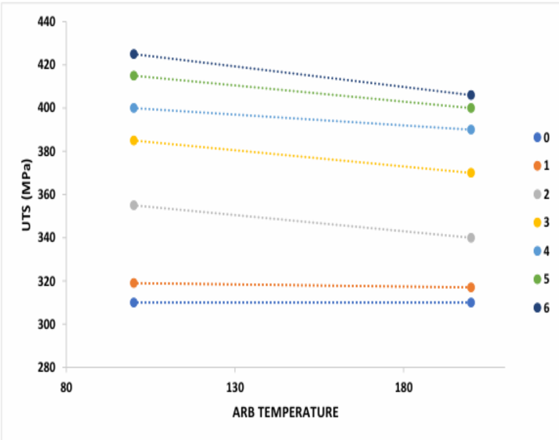

Figure 1: Plot of Ultimate Tensile Strength (UTS) against ARB processing temperature

At both temperatures explored, UTS increased with increase in ARB cycles. At 100 ºC, a 37.1% increase was seen from as-cast value to six rolled cycle (310 to 425 MPa). Similarly, same trend was seen at 200 ºC temperature where a 31% increase occurred from as-cast value to six rolled cycle (310 to 410 MPa). The yield strength also increased with increase in the number of rolled cycles. A 37.1% increase was seen at 100 ºC temperature and a 31% increase was seen at 200 ºC temperature from the as-cast to six rolled cycle. However, a decrease in % elongation (ductility) was seen as number of rolled cycles increased. Particularly, a 62% decrease was seen at 100 ºC temperature from the as-cast value to six rolled cycle. Similarly, a 67.0% decrease was seen at 200 ºC temperature. For each cycle, the ARB process imposed large plastic strains thereby increasing dislocation density and producing UFGs. This is in agreement with Alvand et al, (2021).

The rise in UTS and YS with increase in ARB cycle can be attributed to the cumulative plastic strain which produces increased dislocation density grain refinement and progressive layer bonding (Nan and Xueping, 2020). Generally, samples processed at 100 ºC showed slightly higher UTS and YS than those processed at 200 °C. this is consistent with partial recrystallization which occurs at higher temperatures thereby reducing the dislocation accumulation of the processed material. A negatively linearly related trend characterized by the equation Y = - m(x)+b for plot of UTS, YS and %Elongation against temperature.

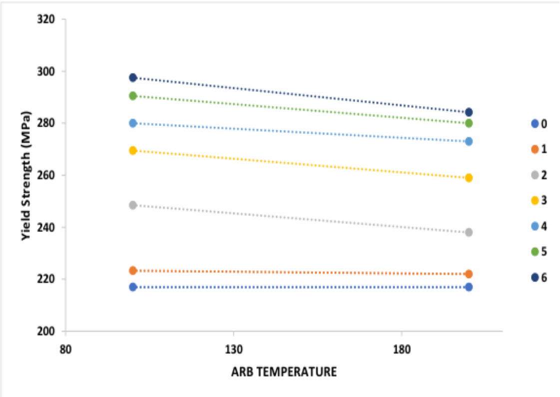

Figure 2: Plot of Yield Strength against ARB processing Temperature

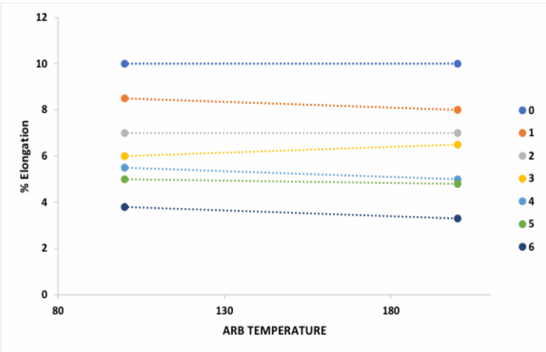

Figure 3: Plot of % elongation against ARB processing Temperature

B. Hardness Test

The variations of Vickers microhardness of al 6061 alloy at different temperatures (see Figure 4). In the "before ARB" scenario, regardless of the temperature variations, the microhardness values remained consistent. However, the introduction of the ARB process with six (6) cycles produced a distinct effect leading to an increase in microhardness values as the number of rolling cycles increased. For sheets rolled at 100 ^{O}C, there was a consistent increase in hardness after the first roll cycle from the as-cast value of 96.3HV to 105HV followed by a rise at same rate for the second to the sixth roll cycles. Same trend was observed at 200 ^{O}C.

The optimum microhardness value 130HV was obtained after the sixth roll cycle at 100 ^{O}C temperature suggesting that lower ARB temperature and 6 roll cycles can lead to high microhardness of the material. This is in agreement with Wang et al., (2018) who noted that ARB processing leads to increase in material hardness at lower processing temperature. At 200 ^{O}C, just a slight increase in microhardness (98.5HV) was observed. This suggests that at higher ARB temperatures, the microhardness of processed alloy could significantly be affected since higher deformation temperature and lower strain rate are known to form coarser grains throughout the deformation stage (Lui et al., 2014).

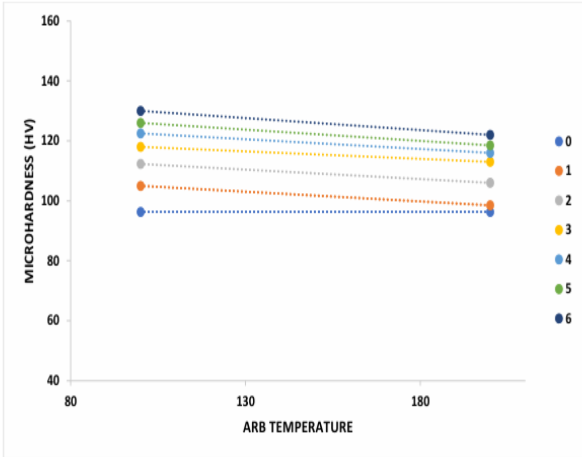

Figure 4: Plot of Microhardness against ARB processing temperature

A negatively linearly related trend characterized by the equation Y = - m(x)+b is seen. Y represents the independent variable (hardness), x represents the independent variable (number of cycles) and b is the intercept. This trend can be used to predict the hardness of the material as the number of cycles or ARB temperature changes.

IV. CONCLUSION

In this study, the influence of processing temperature on the strengthening mechanisms of Al 6061 alloy during Accumulative Roll Bonding (ARB) was examined. The processing temperature significantly affects the mechanical performance of processed alloy. At 100 °C ARB processing produced higher tensile strength and hardness which is attributed to enhanced grain refinement, dislocation accumulation and sub-grain formation. At 200 °C, improved ductility due to dynamic recovery and partial recrystallization was seen. However, a slight reduction in strength and hardness is observed. Furthermore, low processing temperatures are suitable for applications requiring enhanced strength and hardness. Higher temperatures on the other hand are favourable for applications prioritizing ductility and formability. Thus, demonstrating that controlling ARB processing temperature allows for balance strength.

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