Mechanical Anisotropy of Aluminium AA1050 and Aluminium Alloy AA6016 produced by Accumulative Roll Bonding

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Abstract- The present work investigates the plastic flow anisotropy of pure aluminium AA 1050 and aluminium alloy AA6016 followed by eight cycles of Accumulative Roll Bonding (ARB) at room temperature. Samples were oriented with their strong basal pole texture aligned with rolling direction, perpendicular (900) to the rolling direction and 450 to the rolling direction. The plastic anisotropy has been investigated by tensile deformation via the Lankford parameter. The average normal and planar anisotropies slight increase from 0.62 to 0.91 and decrease from 0.60 to −0.70 as a function of ARB cycles, respectively. Results are compared with those from experiment and discussed with regard to strain rate sensitivity.

Keywords – Accumulative Roll Bonding, Mechanical Anisotropy, Nano- Structured Materials, Lankford parameter, Aluminium

I. INTRODUCTION

Severe plastic deformation involves very large strain at a comparatively low temperature and develops nano-structured material with a significant grain size up to a few hundred nm, as a result its physical properties are enhanced extensively. In conventional methods, such as in rolling, forging, drawing or extrusion processes these requirements cannot be achieved without any defects. Primary attempts to produce nano-structured material followed a number of methods like; inert gas condensation, high-energy ball milling with subsequent consolidation, electro-deposition, and crystallization from an amorphous state. However, all these mentioned methods recognized as 'Bottom-up Approach' are not capable to achieve the correct dimensions of the sample. Besides this, a number of complexities such as residual porosity, impurities, and exposure to dangerous nano powder, have prohibited these techniques from reaching realistic applications, in addition to the reality that they are not matched for manufacture on an industrial scale. In the last few years, an adaptive alternative approach called as 'Top-down Approach' has been innovated, which works on the principle of Severe Plastic Deformation (SPD), This approach has achieved significance due to direct conversion of metals and alloys with conventional grain sizes of nano-scaled materials with exceptional new properties [1]. Other SPD techniques, such as, Equal Channel Angular Pressing (ECAP) [2], High Pressure Torsion (HTP) [3], Cyclic Extrusion Compression (CEC) [4], Repetitive corrugation and straightening of sheet metals [5] Continuous Confined Strip Shearing and Mechanical Milling processes [6] are have some drawbacks. Firstly, the above pointed out processes are found to be improper to produce bulk materials. Secondly, they required forming dies, which are quite expensive and also the required very high forces. As compared to the above processes, ARB has no such inadequacies. In order to produce ultrafine grained and /or nano-structured bulk aluminium sheets, the ARB process was at first suggested by Saito et al. [7] then it was modified successfully by Tsuji et al. [8] by producing UFG bulk sheet of interstitial free (IF) steel. The present work aims at studying the development of texture thoroughly in AA1050 and AA6016 as a function of ARB cycles. This metal is often used in the automotive industry and aerospace industries for body panels. Therefore, based on the Taylor factor and the calculated Lankford parameter, the mechanical anisotropy of the advanced metal sheets is discussed.

II. MATERIALS SELECTION AND EXPERIMENTAL PROCEDURE

Pure aluminium AA1050 and aluminium alloys AA6016 are characterized by low density, high strength and good formability. Commercial purity aluminium AA1050 was used as a model material and the first ARB results concerning processing and mechanical properties were then compared to technically relevant aluminium alloy AA6016. In the automotive industry, there is a special interest regarding this alloy, due to its strength and good formability. Aluminium alloy AA6016 derives its strength primarily from the precipitation strengthening mechanism of the second phase particles Mg2Si. Another advantage of this allow is that it does not build any strain marks upon sheet metal forming and it is for this reason usually used for the outer body automobile panels. The chemical composition [10] to two aluminium alloys can be seen in table 1.

Table 1 chemical composition of aluminium AA1050 (highest allowable values) and AA6016

Wt.%	**Si**	**Cu**	**Fe**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Other**	**Al**
AA1050	**0.25**	**0.05**	**0.4**	**0.05**	**0.05**	**-**	**0.07**	**0.05**	**0.03**	**Balance**
AA6016	**1.0-1.5**	**0.52**	**0.5**	**0.2**	**0.25-0.6**	**0.1**	**0.2**	**0.15**	**0.15**	**Balance**

All test samples were prepared by Accumulative Roll Bonding (ARB) Process belongs to a group of severe plastic deformation (SPD) techniques used to develop ultrafine-grained and/or nano-structured sheets by applying repeated rolling, which leads to high levels of shear strain throughout the sheet thickness as shown in Fig. 1.

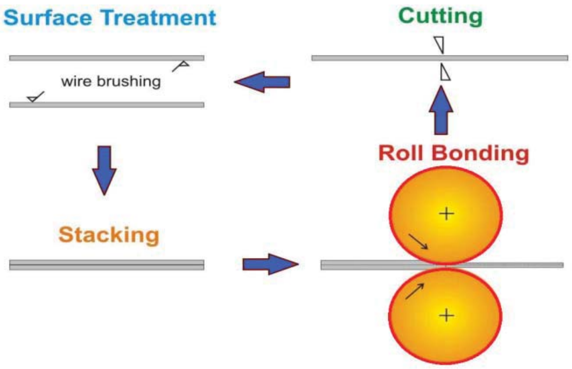


Figure 1 Schematic illustration showing the principle of Accumulative Roll Bonding [9] process.

The surface of one millimeter thick and 30x100 mm metal strips were preliminary wire brushed in order to remove oxide layer for better interlamellar bonding of sheets, and subsequently folded or stacked on top of each other and rolled together without lubrication using a two-high rolling mill (Vaid Engineering Industries, New Delhi, roller diameter: Ø = 135 mm) or a four-high rolling mill (Vaid Engineering Industries, New Delhi; roller diameter: Ø = 30 mm). The process was then repeated a number of times. The roll diameter and the peripheral roll speed of the four-high rolling mill average 30 mm and 80 revs. /min., respectively. The initial state of the material and the ARB parameters are listed in table 2.

Table 2: Initial states of material prior to rolling and the corresponding ARB process parameters

Materials	**Thickness Reduction**	**Initial State**	**ARB cycles**	**Thickness**	**Temp.**
AA6016, AA1050	**50%**	**Solutionised 520^0 C,1 h water quenched**	**8**	**1mm**	**RT, 230^{0}C**

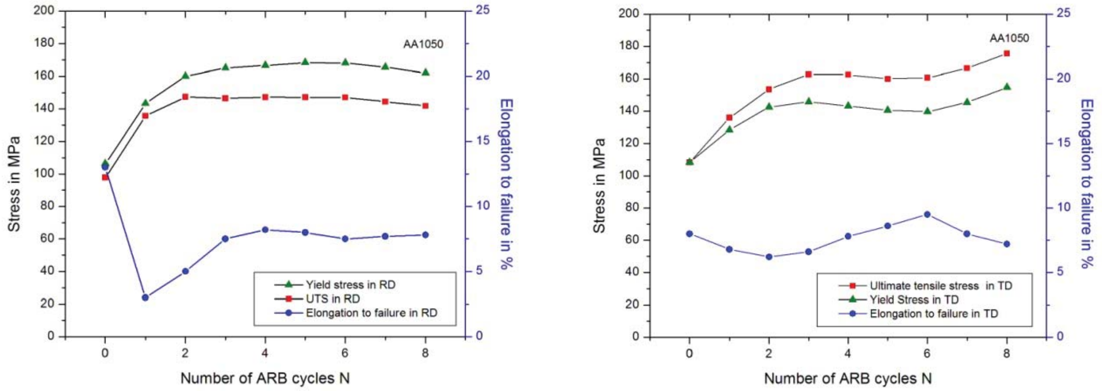
In this work The Lankford parameter is measured at three angles = (0^0, 45^0, 90^0), and in the following will be referred to as r_{RD}, r_{45° and r_{TD} (RD= Rolling Direction, TD = transverse direction). From this orientation dependent Lankford parameter the mean Lankford parameter (r) and its variation Δr can be obtained characterizing the average normal and planar anisotropy of the whole sheet, respectively:

$$(r) = 1/4(r_{RD} + 2r_{45^\circ} + r_{TD}),$$
$$\Delta r = 1/2(r_{RD} - 2r_{45^\circ} + r_{TD})$$

With the help of these two parameters the mechanical anisotropy of the sheets can be quantified. The Lankford parameter after a critical axial strain becomes constant. The ARB material used was ductile enough to reach the plateau value. In order to minimize the influence of local inhomogeneities at least three samples were taken from the same sheet and measured for each direction.

III. RESULT AND DISCUSSION

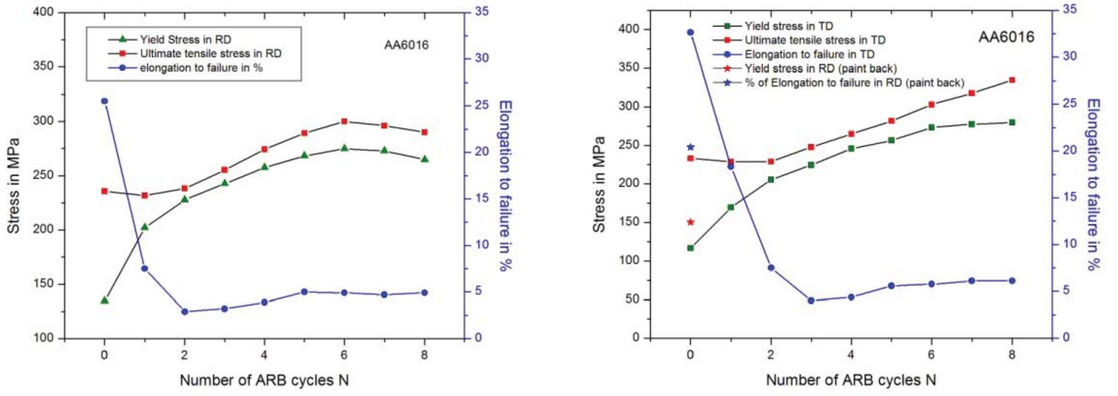
The development of mechanical properties on the rolling direction (RD) and the transverse direction (TD) with an increasing number of ARB cycles can be seen in figures 2 a) and b).



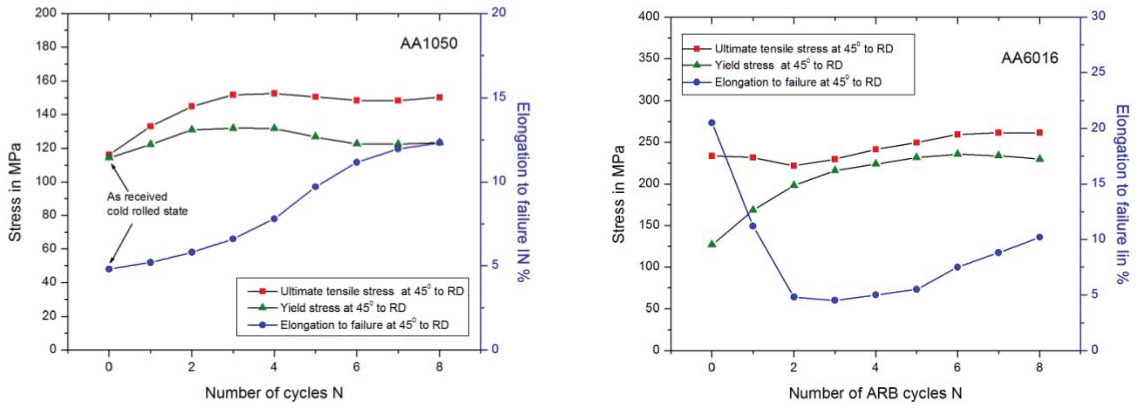
a) *b)*

Figure 2 a), b) Yield strength, ultimate tensile strength and elongation to failure, in the rolling direction, transverse direction vs. the number of ARB cycles N for commercial purity aluminium AA1050

As discussed earlier, yield and tensile strength, as well as elongation to failure gradually increase with the growing number of ARB cycles. An increasing variance of yield and tensile strength curves after the first ARB cycles of AA1050 suggests an increasing strain hardening potential. The saturation level is achieved after 2 ARB cycles and is attributed to a relatively rapid dynamic recovery process through rolling.



a) *b)*



c) *d)*

Figure 3 a), b), c), d) Yield strength, ultimate tensile strength and elongation to failure, in the rolling direction, transverse direction and at 45° to the rolling direction vs. number of ARB cycles N for commercial purity aluminium AA1050 and aluminium alloy AA6016 processed at 230 º C.

Similar development and values of yield and tensile strength as well as elongation to failure in the rolling and transverse direction of AA1050 were also reported by Kim et al. [11]. On the other hand it should be noted that the authors investigated the enhancement of ductility by cross rolling is performed at higher temperatures and carried out tensile teats at a strain rate of 10^{-3} s^{-1}. From figure 2 b) and figure 3 a) it is obvious that the samples in the transverse direction (TD) show no substantial drop of strength or elongation to failure in evaluation to the samples in the rolling direction (RD) however a strongly elongated microstructure was observed for both materials AA1050 and AA6016. Conversely, the tensile tests of samples taken at 45° to the rolling direction established surprising results. From figures 2 c) and d), it can clearly be seen that there is no substantial variation in the yield and tensile strength between the samples taken in the rolling direction and at 45° to the rolling direction, but the samples taken at 45° to the rolling direction show much elevated elongation to failure, by greater than 50 %, in the evaluation of the samples taken in the rolling and transverse direction. As well, the elongation to failure enhance continuously with a rise in number of ARB cycles and it does not achieve a typical saturation level after about 4 to 6 cycles, as in general the case for the samples obtained in the rolling direction. Higher elongation to failure of samples obtained at 45° to the rolling direction might be associated with the crystallographic texture. By an increase in number of ARB cycles, the texture build up into a typical rolling texture, which typically occurs in face centered cubic (FCC) metals with high stacking fault energy. The AA6016 samples confirm a characteristic ß-fiber texture [12] with a Cu constituent after 8 ARB cycles. It was revealed that the anisotropy values of the as- received state in the rolling direction and transverse direction are higher than those at 45° to the rolling direction. But after the ARB process, this correlation was inverted. The anisotropy standards in terms of the Lankford parameter r, of samples taken at 45° to the rolling direction increased with increasing number of ARB cycles and reached a maximum at 8 ARB cycles as shown in Fig. 4. This specifies a possible transform in the strain state during tensile testing and after those different values of the elongation to failure. Another possible justification is that previously mentioned process of thermally stimulated recovery of dislocations at grain boundaries [13] is generated by the ß-fiber texture.

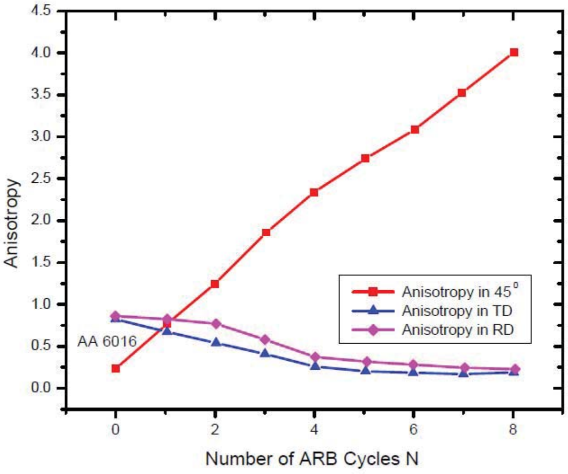
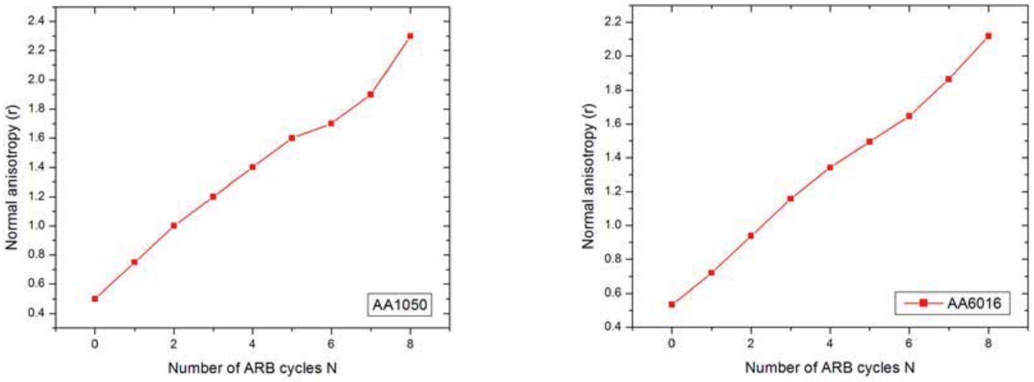
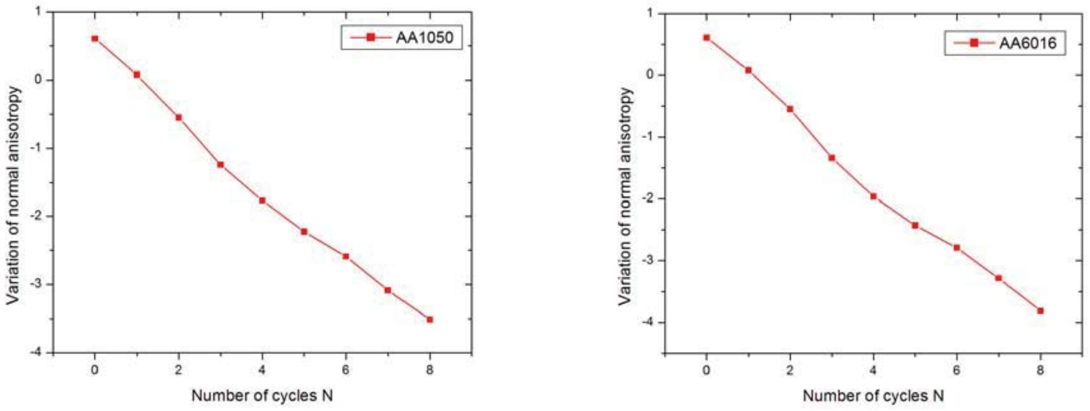


Figure 4 Lankford parameter <r> calculated for tensile deformation of AA6016 in different directions as a function of the number of cycles

The authors also investigated the normal anisotropy <r> and the variation of anisotropy Δr [12, 14] for the as-received and ARB processed AA6016 aluminium alloy. The deep drawing conditions of the sheets can be estimated from the magnitudes of <r> and Δr. Larger <r> values result in reduced thinning during deep drawing, while smaller Δr values result in reduced earing. As can be seen in figure 5 a), b) <r> increases steadily with an increasing number of ARB cycles, while Δr changes its sign. Therefore, the initial and high-cycle ARB state are best suited in order to avoid sheet thinning. In contrast, the low-cycle ARB state should not result in any earing. From figures 5 c) and d), it can clearly be seen that the best compromise between these two parameters can be achieved for samples rolled up to 4 ARB cycles. The results obtained here tells that low cycle ARB materials may be optimized for deep drawing, at the same time they also show good strength and ductility. While more ARB cycles direct to higher strength and ductility [15], advantageous drawing properties are not projected due to earing. It is pointed out that the considerations made above are based on typical room temperature deformation mechanisms. As pointed out in literature, high temperature deformation mechanisms like coble creep, thermally activated annihilation and grain boundary sliding of dislocations should be considered for UFG aluminium materials even at low homologous temperatures [12, 16]. Therefore, it is recommended that for obtaining a good compromise between strength and



a) b)



c) d)

Figure 5 a), b) Coefficient of normal anisotropy <r> and c), d) its variation Δr of AA1050 and AA6016 as a function of the number of ARB cycles calculated using two different models

deep drawing capability, the sheets should be rolled between 3 to 5 numbers of ARB cycles. In this reference, it should be also pointed out that current results on ARB processed AA1050 andAA6016 alloy up to 8 cycles show extremely promising formability under the complex loading conditions. The observed formability of UFG AA6016 is as well as to the conventional grain-sized counterpart's aluminium AA1050.

IV. CONCLUSION

The mechanical properties of ARB processed aluminium and aluminium alloys have proven to be anisotropic as shown in Figs. 2 and 3. Tensile testing performed on AA1050 and AA6016 in three different directions showed pronounced differences between the samples oriented at 0° and 90° to the rolling direction and the ones oriented at 45° to the rolling direction. A considerable increase of strain to failure was observed for samples oriented at 45° to the rolling direction, while the maximum stress was comparable to that of samples at 0° and 90° to the rolling direction. Surprisingly, yield strength, tensile strength and elongation to failure were found to be similar for samples tested in the rolling direction and the transverse direction. One possible reason for the higher elongation to failure of samples oriented at 45° to the rolling direction might be related to the crystallographic texture

V. ACKNOWLEDGEMENT

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