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ULTRAFINE-GRAINED MATERIALS

Influence of rolling direction on strength and ductility of aluminium and aluminium alloys produced by accumulative roll bonding

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Abstract Sheets from commercial purity aluminium AA1050 and aluminium alloy AA6016 were processed by accumulative roll bonding to obtain an ultrafine-grained microstructure. The accumulative roll bonded samples showed a significant increase in specific strength paired with high ductility. Despite a strongly elongated grain structure, tensile testing of samples oriented 45° to the rolling direction revealed considerable improvement in elongation to failure compared to the samples oriented parallel to the rolling direction. From hydraulic bulge tests, it was observed that the accumulative roll bonded samples reached higher burst pressures and slightly lower equivalent strains in comparison to the as-received conventionally grain-sized samples. This behaviour reflects the extraordinary mechanical properties of the ultrafine-grained materials and indicates promising metal sheet formability.

Introduction

Nanocrystalline or ultrafine-grained (UFG) materials with an average grain size below 1 μm, have shown superior mechanical properties in terms of strength and/or elongation to failure in comparison to the conventionally grained (CG) materials, see for example [1]. The ultrafine-grained aluminium sheets produced by accumulative roll bonding (ARB) have especially raised interest for potential engineering applications as structural, high durability components in the automotive, aerospace and medical industry due to their high specific strength [2]. The advantage of the accumulative roll bonding process in comparison to other severe plastic deformation (SPD) techniques, such as equal channel angular pressing (ECAP) and high pressure torsion (HPT), is that it can be scaled up and adapted to a conventional, industrial rolling process for large scale sheet metal manufacturing much more easily [3]. To meet the requirements placed upon today's modern materials, regarding strength, ductility, joinability, durability and cost, the UFG metal sheets have often been characterised with regard to their microstructure and mechanical properties [4, 5]. However, there is still very little information available on the deformation behaviour or formability of UFG sheets under multiaxial stress state conditions [6], which usually occur during sheet metal forming such as bending, deep drawing or stretching. Therefore, the aim of this work was to investigate the deformation behaviour of the accumulative roll bonded aluminium sheets in an uniaxial tensile test (in the rolling direction, transverse direction and at 45° to the rolling direction) and compare the results with those obtained from hydraulic bulge tests where the samples are subjected to a biaxial stress state. The focus of the work was placed on the commercial purity aluminium AA1050 and the age hardenable aluminium alloy AA6016. The materials were investigated in two different conditions: the as-received and the accumulative roll bonded condition.

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Experimental

Materials

The accumulative roll bonding process was performed on commercial purity aluminium AA1050 and technically

Table 1 Chemical composition of 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

Table 2 Parameters for hydraulic bulge testing

Size of the aluminium blank	Diameter of the die	Transition radius of the die	Clamping force	Forming medium	Temperature
0.5 mm × 120 mm × 100 mm	58 mm	5 mm	900 kN	Oil: Marlotherm®	20 °C

relevant aluminium alloy AA6016. The as-received AA1050 sheets were cold rolled and the AA6016-T4 sheets were solution heat treated and only naturally aged. The chemical compositions are listed in Table 1. Prior to roll bonding the aluminium sheets of 100 mm × 300 mm width and length, and 1 mm thickness were solution treated for 1 h at 500 °C (AA1050) and 520 °C (AA6016) and quenched in water. The surfaces were wire brushed to remove the oxide layer, stacked and rolled together without lubrication using a four high rolling mill (Carl Wezel, Mühlacker) to a 50% thickness reduction. The roll diameter and the peripheral roll speed averaged 32 mm and 80 revs/min, respectively. The commercial purity aluminium AA1050 was roll bonded at room temperature while the aluminium alloy AA6016 was heated in a furnace at 230 °C for 4 min prior to rolling. The bonded metal sheets were air cooled, halved and once again wire brushed before the next cycle. The accumulative roll bonding process was repeated up to eight times.

Microstructure

The microstructure was investigated using a light microscope (Leica DMRM) and a transmission electron microscope (TEM CM200, Philips). The light microscopy samples were prepared by mechanical grinding and polishing to 1 μm. They were subsequently electropolished using a standard electrolyte from Struers, A2 at 22 V and room temperature. The TEM samples were thinned using the same electrolyte and the same parameters.

Tensile tests

Tensile test samples were cut out after the ARB process on samples oriented in the rolling direction and at 45° to the rolling direction. All tensile tests were performed at room temperature and a strain rate of 1×10^{-4} s^{-1}.

Hydraulic bulge tests

Sheet metal forming was investigated using a hydraulic bulge test (Lasco TSP 100 S0, max. force 100 tons) in cooperation with the Institute of Manufacturing Technology at the University of Erlangen-Nürnberg. To obtain wider blanks necessary for bulge testing the original 1 mm thick sheets were rolled perpendicular to the original rolling direction after the ARB process. Cross rolling was performed at room temperature using a two-high rolling mill (Carl Wezel, Mühlacker). The sheets were reduced to 0.5 mm thickness and then cut to 120 mm width and 100 mm length. The blank was fixed from above using a circular die and deformed into a dome shape by pressurised oil (Marlotherm®) until fracture. The relevant parameters used for the bulge tests are listed in Table 2.

During deformation the strain distribution is measured optically using two CCD cameras situated directly above the blank and ARAMIS software based on the principle of photogrammetry. For the purpose of measuring the strain distribution, a pattern was sprayed onto the sample's surface. The X and Y coordinates of a point within a facet (small quadratic areas) and a grey scale distribution of the facet in a non-deformed state, are defined before the test starts. The grey scale gradient describes a local contrast and can be found within every single facet. Since the grey scale gradient of a non-deformed sample equals that of the deformed sample, while the original facet changes its coordinates during deformation, it is always possible to assign the amount of deformation of a facet at any point in time and thus measure the strain once the test is completed.

Microstructure

The microstructural characterisation was performed on the commercial purity aluminium AA1050 and aluminium alloy AA6016. The typical microstructure of the accumulative roll bonded state is shown in Fig. 1a. During rolling, the grains become strongly elongated in the rolling direction, with a relatively large aspect ratio and dislocation substructure inside the grains. The median grain size perpendicular to the rolling direction was determined from the line intercept method. The grain size decreases from 10 to 50 μm in the as-received state to approximately 200 nm after 8 ARB cycles

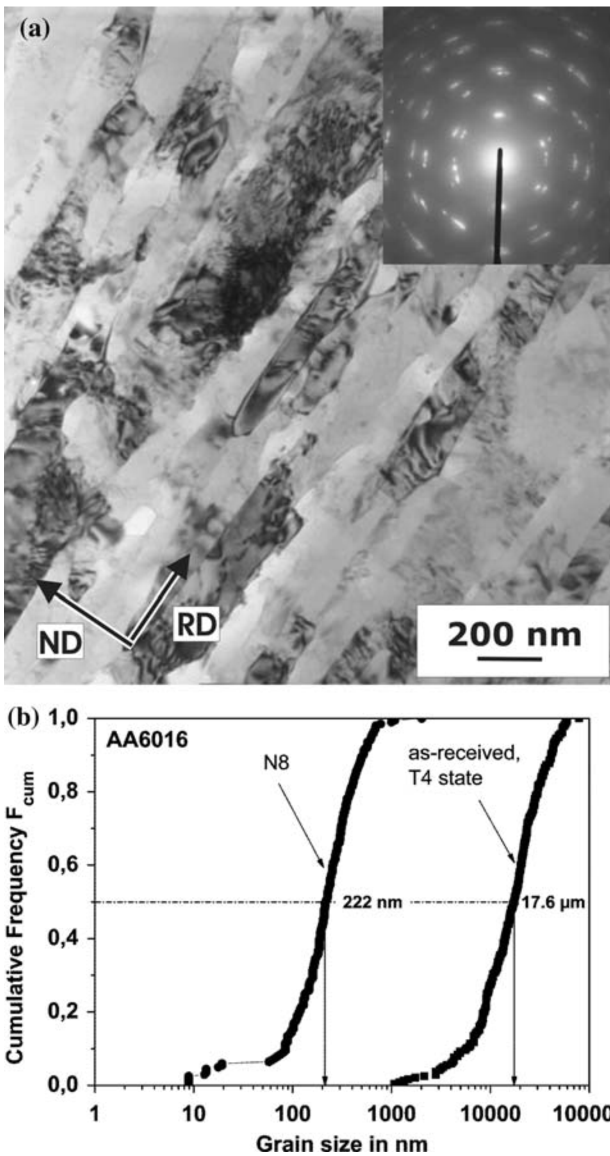

Fig. 1 (**a**) TEM micrograph taken in the rolling plane of accumulative roll bonded AA6016 aluminium after eight ARB cycles with the corresponding selected area diffraction pattern using an area of 25.3 μm^2 and (**b**) cumulative frequency grain size distribution of CG and UFG samples both measured perpendicular to the rolling direction

(Fig. 1b). The ultrafine-grained microstructure was confirmed from a diffraction pattern showing nearly closed-off circular patterns rather than discrete points.

The microstructure of the commercial purity aluminium AA1050 appears to be rather similar to that of the AA6016. The median grain size perpendicular to the rolling direction of AA1050 (N8) and AA6016 (N8) reached 324 nm [7] and 222 nm, respectively. The final grain size of the ARB processed AA6016 was smaller compared to the commercial purity aluminium AA1050 and the grains appeared more elongated, even though the alloy was roll bonded at an elevated temperature, see for details [8]. In this case, the alloying elements and the second phase particles Mg_2Si in the aluminium alloy AA6016 might have a significant pinning effect on the grain boundaries and retard recovery during rolling.

Mechanical properties

Tensile tests

Tensile testing was performed on both materials on samples taken in the rolling direction and transverse direction, and on samples taken at 45° to the rolling direction. As shown earlier no significant differences in the yield strength, tensile strength and elongation to failure between the samples oriented in the rolling direction and those in the transverse direction were obtained, although the strongly elongated microstructure suggested some extent of mechanical anisotropy [9]. Due to the fact that the tensile test results in the two aforementioned directions are similar, Figs. 2 and 3 are restricted to the tensile test results of samples in the rolling direction and at 45° to the rolling direction.

The tensile tests of samples taken at 45° to the rolling direction showed surprising results. From Fig. 2a and b, it can clearly be seen that there is no considerable difference in the yield and tensile strength between the samples taken in the rolling direction and at 45° to the rolling direction. However, the samples taken at 45° to the rolling direction (dashed lines) show much higher elongation to failure, of more than 50%, in comparison to the samples taken in the rolling and transverse direction (Fig. 3a, b). In addition, the elongation to failure increases continuously with an increase in number of ARB cycles and it does not reach a typical saturation level after approximately 4–6 cycles, as is usually the case for the samples oriented in the rolling direction.

The elongation to failure of AA1050 seems to increase continuously with increasing number of ARB cycles, while the elongation to failure of AA6016 significantly decreases after the first few cycles. To understand this behaviour, different initial states of AA1050 and AA6016 have to be considered. As already mentioned, the as-received state of commercial purity aluminium AA1050 is a cold rolled state. The initial, as-received state of aluminium alloy AA6016 is a solutionised state. Therefore, considerable decrease of elongation to failure of AA6016 is correlated with high plastic deformation of the material after a single ARB cycle. Upon further roll bonding, elongation to failure increases and the difference between the elongation to failure of samples taken in the rolling direction and those taken at 45° to rolling direction becomes particularly distinct after 8 ARB cycles.

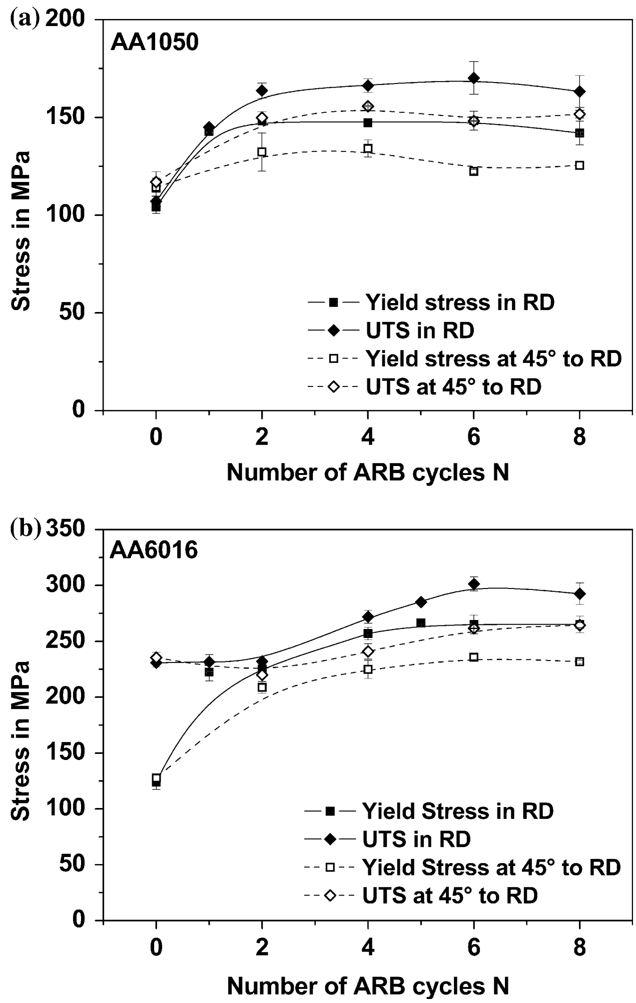

Fig. 2 Yield strength and ultimate tensile strength (UTS) for samples oriented in the rolling direction (full symbols) and for samples oriented at 45° to the rolling direction (half full symbols) versus the number of ARB cycles N for (**a**) commercial purity aluminium AA1050 rolled at room temperature and (**b**) aluminium alloy AA6016 rolled at 230 °C. All tensile tests were performed at room temperature and at a strain rate of 10^{-4} s^{-1}

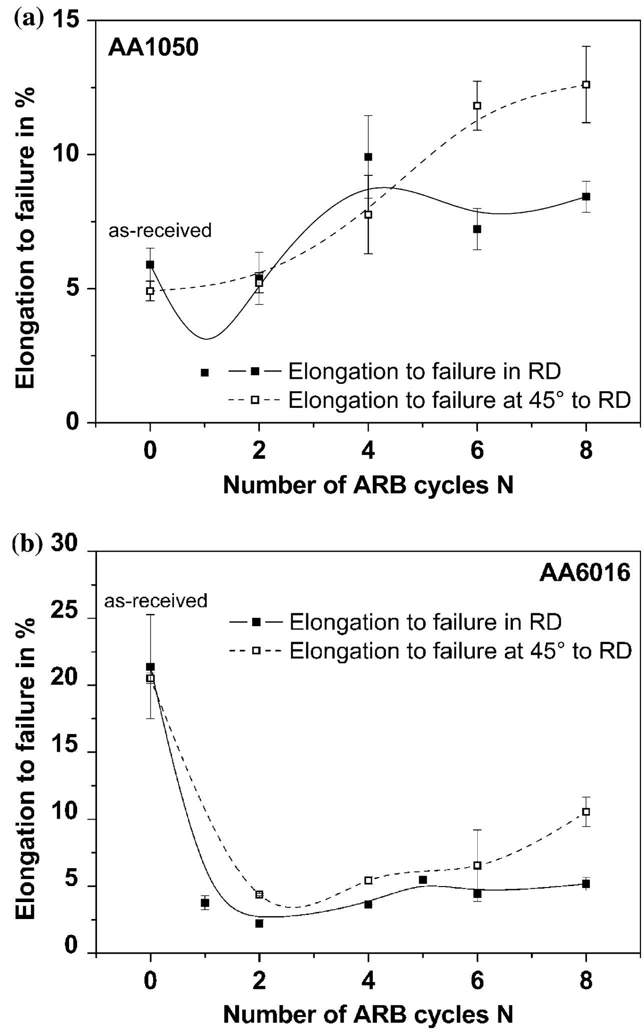

Fig. 3 Elongation to failure for samples oriented in the rolling direction (full symbols) and for samples oriented at 45° to the rolling direction (half full symbols) versus the number of ARB cycles N for (**a**) commercial purity aluminium AA1050 rolled at room temperature and (**b**) aluminium alloy AA6016 rolled at 230 °C. All tensile tests were performed at room temperature and at a strain rate of 10^{-4} s^{-1}

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. With an increase in number of ARB cycles, the texture develops into a typical rolling texture, which usually occurs in face-centred cubic (fcc) metals with high stacking fault energy. The AA6016 samples show a characteristic ß-fibre texture with a Cu component after 8 ARB cycles, see [10] for details. It was shown that the anisotropy values of the as-received state in the rolling direction (r_{RD}) and transverse direction (r_{TD}) are higher than those at 45° to the rolling direction. However, after the ARB process, this relationship was reversed. The anisotropy values (in terms of the Lankford parameter r) of samples taken at 45° to the rolling direction increased with an increase in the number of ARB cycles and reached a maximum at 8 ARB cycles (Table 3). This indicates a possible change in the strain state during tensile testing and therefore different values of the elongation to failure. Another possible explanation is that the earlier mentioned process of thermally activated recovery of dislocations at grain boundaries [7] is triggered by the ß-fibre texture.

Table 3 Anisotropy values of as-received and accumulative roll bonded AA6016 obtained from [10]

	N0	N2	N4	N6	N8
RD	0.82	0.82	0.43	0.33	0.25
45°	0.25	1.22	2.33	3.00	4.00
TD	0.82	0.54	0.25	0.18	0.18

At this point it should be mentioned that the additional transverse rolling of ARB samples, which was performed to obtain wider specimen geometry for bulge testing, may change the texture and the mechanical properties in all three directions. During rolling from six to eight ARB cycles, a total thickness reduction averages 100 %. The change in anisotropy values of samples in the RD and at 45° to the rolling direction reach approximately 25%, while the anisotropy values in the transverse direction remains the same. Therefore, the change of anisotropy values from N8 to cross rolling is supposed to be negligible or rather small, because the total thickness reduction by cross rolling averages only 50%. It is therefore believed that the thickness reduction during cross rolling of ARB samples is too small to have a marked affect upon texture and significantly the bulge test values.

Bulge tests on ARB processed samples

Hydraulic bulge tests were performed to investigate the biaxial deformation behaviour of the ARB sheets. Figure 4a shows the maximum burst pressure and the maximum von Mises equivalent strain versus the number of ARB cycles for the aluminium alloy AA6016. Earlier work showed that the geometry of bulge tests must be optimised for every material. The ratio between the sample thickness and the die diameter must be such as to obtain the deformation through the thickness of the sheet and to avoid premature failure of samples. The premature failure may arise as a consequence of higher bending stresses at the transition radius of the die [9]. Thus, aluminium sheets which have subsequently been rolled down to 0.5 mm were used for this investigation. It can clearly be seen that the maximum burst pressure increases by a factor of 3 in comparison to the as-received state with an increase in the number of ARB cycles, which is also reflected in the significant increase of the ultimate

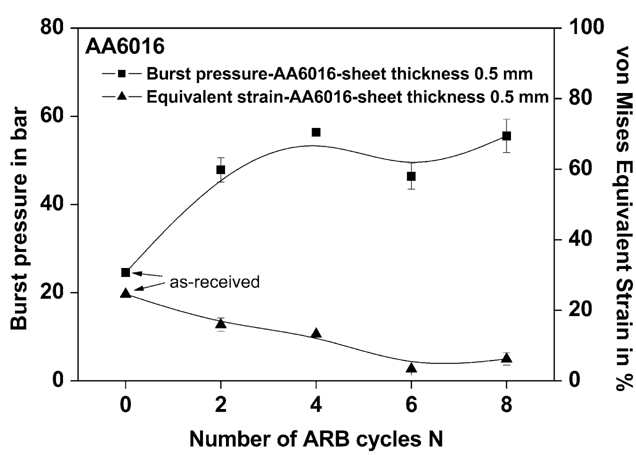

Fig. 4 Maximum burst pressure and von Mises equivalent strain versus the number of ARB cycles for the aluminium alloy AA6016

tensile strength observed during tensile testing. The maximum burst pressure reaches a saturation level after four ARB cycles.

Localised necking does not take place under biaxial stress state conditions and samples generally show higher uniform strain than under the uniaxial stress state conditions [11]. Therefore, higher strains were expected from the bulge tests than from the tensile tests for the as-received as well as the ARB samples. However, the maximum von Mises equivalent strain obtained from bulge tests decreases from approximately 20% in the as-received T4 state to 10% after eight ARB cycles, whereas the elongation to failure of samples after the same number of ARB cycles measured in an uniaxial tensile test reaches 5% (in the RD) to 11% (at 45° to the RD). The relatively low values of the maximum von Mises equivalent strain reached under a biaxial stress state can be attributed to higher deformation rates during bulge testing than those during tensile testing. Even though it was not possible to measure the strain rate during bulge testing, the deformation rate was definitely higher than that during tensile testing. Therefore, the deformation capability of UFG sheets can be improved by reducing the deformation rate or by increasing the testing temperature since the UFG aluminium sheets have pronounced strain rate sensitivity even at room temperature.

Although the maximum von Mises values and elongation to failure lie within the same range, they can only be qualitatively compared to each other. It is important to note that the two methods of testing cannot be quantitatively compared with one another due to different stress states, deformation rates, different sample thicknesses used in the experiments as well as possible, but unlikely differences in texture due to cross rolling.

Similar results have been observed for the AA1050 with regard to the maximum burst pressure. The burst pressure increased by 30% and reached a saturation level after 2–4 ARB cycles. On the other hand, the maximum von Mises equivalent strain increased by a factor of 2 after 4 ARB cycles, where it averaged approximately 75% (increase of pole height from 12 mm to 17.5 mm, from the as-received to 4 ARB cycles, respectively) [9].

In addition, it is possible to estimate the formability potential of metal sheets for, e.g. a deep drawing process from the coefficient of normal anisotropy $\langle r \rangle$ and the anisotropy variation Δr. Higher $\langle r \rangle$ values generally reduce the tendency towards sheet thinning and smaller Δr values reduce earing. Skrotzki et al. measured the anisotropy values of the ARB AA6016 and concluded that a good compromise between strength, ductility, small reductions in sheet thickness during deformation and reduced earing, can be reached from samples rolled up to 4 ARB cycles [10]. The results obtained from bulge tests support the conclusions made by Skrotzki et al.

Conclusions

Commercial purity aluminium AA1050 and aluminium alloy AA6016 were successfully accumulative roll bonded. The mechanical properties were investigated by tensile and hydraulic bulge tests. The samples taken at 45° to the rolling direction showed a remarkable enhancement of elongation to failure in comparison to the samples in the rolling direction for both materials, while the strength was not significantly compromised. The possible reason for the improved elongation to failure might be due to the development of a typical ARB texture or enhanced thermally activated recovery process of dislocations triggered by the fibre texture. The biaxial bulge tests indicated that the ARB AA6016 samples can reach higher burst pressures in comparison to the as-received samples, although the maximum von Mises strain was somewhat reduced.

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