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ULTRAFINE GRAINED MATERIALS

Tailoring materials properties of UFG aluminium alloys by accumulative roll bonded sandwich-like sheets

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Abstract Accumulative roll bonding (ARB) as a method of severe plastic deformation is a well-established process to produce ultrafine-grained (UFG) sheet materials with extraordinary mechanical properties. In this work ARB is applied to combine different sheet materials in order to tailor the materials properties by producing sandwich-like structures. The high strength aluminium alloy AA5754, after 4 ARB cycles (N4), is used as a core material. To achieve high corrosion resistance and good visual properties, it is cladded with commercially pure aluminium AA1050A (N4) at room temperature and alternatively with AA6014 (N4) at 230 °C. All materials are UFG and satisfactory bonding between the different layers of aluminium alloys is achieved. Nanoindentation measurements reveal that there is a sharp transition in hardness at the interface. The yield and tensile strength of the core material are fully retained in the case of the AA6014/AA5754 sandwich. The strength of the AA1050A/AA5754 sandwich is slightly lower compared to the core material but still twice as high as the clad material. The serrated yielding effect which is strongly visible in tensile tests on the pure AA5754 alloy completely disappears in the sandwich sheets, which means the surface quality is strongly enhanced.

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Introduction

Aluminium and its alloys become more and more important in the automotive industry for light-weight constructions. The enhancement of strength and stiffness consequently offers an improvement in light-weight design. For this purpose an ultrafine-grained (UFG) microstructure which coincides with extraordinary mechanical properties offers high potential. In this context, accumulative roll bonding (ARB) as a method of severe plastic deformation (SPD) is a well-known process for the production of UFG sheet materials [1]. Various materials, especially aluminium and its alloys, have already been subjected to the ARB process and show promising properties for prospective engineering application, see for example [2–5]. Relating to automotive applications this work focuses on aluminium and its alloys. With regard to car body sheets aluminium alloys of the 6xxx series are mostly used for outer panels. Besides strength, good formability and high surface quality are required. On the other hand, 5xxx alloys, tending to the formation of stretcher strain marks, are mostly used for structural panels where strength and good deep drawing behaviour are important issues [6]. Applying ARB to commercially pure aluminium AA1050, it was shown that the strength as well as the ductility increase with cumulative deformation [4, 5]. This increase in ductility is related to the enhanced strain rate sensitivity which is strongly influenced by the UFG microstructure introduced during the ARB process [4, 5, 7–10].

Tsuji et al. [11] showed that a tensile strength of 480 MPa and an elongation to failure of 7% can be achieved by performing 5 ARB cycles on the aluminium alloy AA5083. Additionally superplasticity and pronounced strain rate sensitivity was found at 200 °C. ARB of AA5754 sheets has been performed by Slámová et al. [12] showing steadily increasing hardness up to the 5th

ARB cycle, although coincided by severe edge and notch cracking. Recent investigation on this alloy by Hausöl et al. [13] has shown excellent mechanical properties after ARB processing although serrated yielding due to the Portevin-Le Châtelier (PLC) effect was found.

Joining different sheet materials by roll bonding and thereby producing multicomponent materials permits to tailor materials properties. For more than 50 years, metallic composite materials have been produced by pressure welding [e.g. 14] and cold roll bonding (CRB), also called cold pressure welding by rolling or cladding [15–18]. Thereby special combinations of properties such as corrosion resistance, electrical resistivity or antifriction wear resistance can be achieved [17]. A topical review on CRB of metals was given by Li et al. [19].

The invention of the ARB process [1] is related to the repeated roll bonding of similar materials in order to achieve an UFG microstructure by SPD. Combining different sheet materials by the ARB process offers manifold possibilities for intelligent material design. Beside the advantage to introduce an UFG microstructure the repeated rolling cycles open a broad variety of alternative stacking architectures. A feasible combination of the beneficial properties of the base materials creates new possibilities concerning potential applications. The aim of this work was to investigate the potential of the ARB process for the production of UFG graded sheet materials.

Experimental

Materials and processing of stacked sheets

In this work, multicomponent materials composed of different ARB processed aluminium alloys were produced. Commercially pure aluminium AA1050A and the technically relevant aluminium alloys AA5754 and AA6014 were used as base materials, all provided by Novelis Switzerland SA. The chemical compositions of these alloys are listed in Table 1.

In order to obtain an UFG microstructure the aluminium sheets were individually roll bonded up to 3 and 4 ARB cycles, respectively. The sample states and sizes before ARB are given in Table 2. Prior to roll bonding the surfaces were wire brushed in order to remove thick oxide layers, stacked on top of each other and rolled together without lubrication using a four high rolling mill (BW 200, Carl Wezel, Germany) at a 50% thickness reduction. (The roll diameter and the peripheral roll speed averaged 32 mm and 80 rev/min, respectively.) Commercially pure aluminium AA1050A was roll bonded at room temperature. With the exception of AA5754 N4 the sheets of AA6014 and AA5754 were pre-heated at 230 °C for 210 s prior to roll bonding, see Table 3. For AA5754 processed with 4 ARB cycles a pre-heating temperature of 250 °C was used (Table 3). The bonded sheets were air cooled, halved, wire brushed and stacked again before rolling further cycles. For more details concerning the ARB process, see [1, 4, 5]. In the following the number of ARB cycles is denoted as *Nx*, where x reflects the number of ARB cycles. After ARB the AA1050A sheets were rolled to a thickness of 0.5 mm, denoted as one ARB cycle, and the AA6014 sheets, having a thickness of 1.5 mm, were rolled to a thickness of 1.0 mm, denoted as 2/3 ARB cycles.

In order to produce sandwich-like structures the high strength aluminium alloy AA5754 in UFG condition was used as core material. The AA5754 N4 core was cladded with UFG AA1050A N5 from both sides, according to the scheme in Fig. 1a. Therefore, both surfaces of the core material and one surface of the cladding sheets were wire brushed and stacked together. The three sheets were roll bonded at room temperature down to a thickness of 1 mm (50% thickness reduction).

In a second process UFG AA5754 was cladded with UFG AA6014. In this case cladding was performed in two ARB cycles, see Fig. 1b. An AA5754 N3 sheet was roll bonded with an AA6014 N3 $+ 2/3$ sheet at 230 °C in a first step. Then the received duplex sheet was halved, wire brushed and rolled together as shown in Fig. 1b.

Microstructural investigations

Microstructural examinations were performed using electron channelling contrast (ECC) in a scanning electron microscope (SEM/FIB, Crossbeam 1540 EsB, Zeiss, Germany). The samples were prepared by standard metallographic procedures, mechanical grinding, polishing and fine polishing in order to achieve sufficiently smooth surfaces for the microstructural characterisation.

Table 1 Chemical composition (highest allowable values) of aluminium alloys investigated (data from Novelis Switzerland SA)

wt%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Other	Al
AA1050A	0.25	0.4	0.05	0.05	0.05	–	0.07	0.05	–	0.03	Balance
AA5754	0.4	0.4	0.1	0.5	2.6–3.6	0.3	0.2	0.15	–	0.15	Balance
AA6014	0.3–0.6	0.35	0.25	0.05–0.2	0.4–0.8	0.2	0.1	0.1	0.05–0.12	0.15	Balance

Table 2 Sample states and sizes before ARB

Alloy	Pre-ARB condition	Size
AA1050A	As fabricated	1.0 mm × 100 mm × 300 mm
AA5754	Recrystallised (as-received)	1.0 mm × 100 mm × 300 mm
AA6014	Solutionised: 520 °C, 1 h + water quenched	1.5 mm × 100 mm × 300 mm

Table 3 Parameters of accumulative roll bonded sheet materials as initial materials for producing multicomponent materials

Alloy	Component used as	Process temperature T_{ARB}	Number of ARB cycles N	Final thickness t	Final number of ARB cycles N
AA1050A	Clad	25 °C	4	0.5 mm	5
AA5754	Core	250 °C	4	1.0 mm	4
AA6014	Clad	230 °C	3	1.0 mm	$3 + 2/3$
AA5754	Core	230 °C	3	1.3 mm	3

Note: 2/3 indicates a rolling cycle leading to 33% thickness reduction

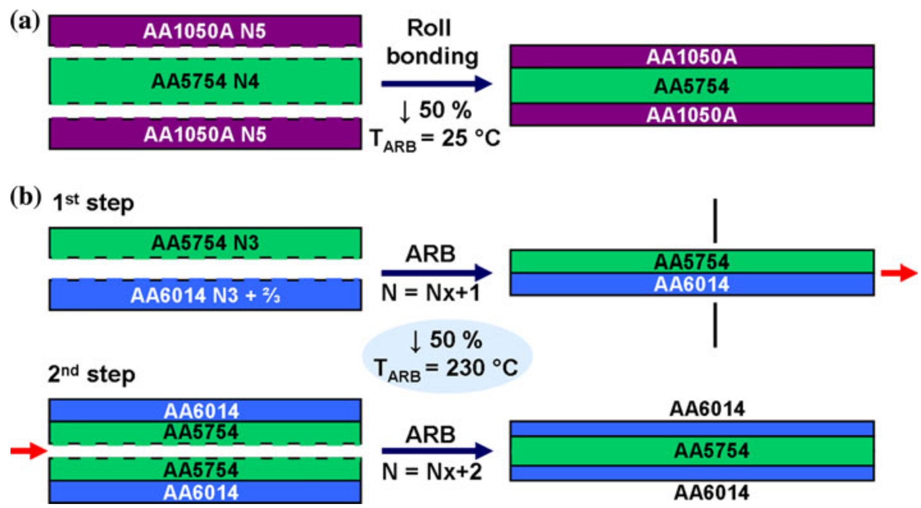

Fig. 1 Schematic drawings showing the production of sandwich-like structures. The *dashed lines* represent the wire brushed surfaces. **a** Roll bonding of AA1050A/AA5754 sandwich at room temperature with a thickness reduction of 50%, **b** Roll bonding of AA6014/AA5754 sandwich at 230 °C using two ARB cycles with a thickness reduction of 50% per cycle

Mechanical characterisation

Nanoindentation experiments were performed on a Nanoindenter G200 (Agilent Technologies, Santa Clara, USA), using a three-sided Berkovich pyramid and a load controlled method. Tip shape calibration was performed according to the Oliver–Pharr method [20] taking machine compliance into account. The mechanical properties were analysed on the basis of load–displacement curves recorded during loading and unloading. Load values ranged from 15 to 30 mN with 5 loading/unloading cycles in order to check for depth dependence of the microhardness. Depending on the material indentation depths varied from 600 to 1100 nm. Neighbouring indentations have a minimum distance of 15–20 times the maximum indentation depth to avoid an influence of the plastic zone around an indent [21].

Flat tensile specimens with a gauge length of 33.5 mm were machined in rolling direction. The tensile tests were performed on an universal testing machine Instron 4505 with a clip-on extensometer. All tensile tests were performed at room temperature with engineering strain rates of $\dot{e} = 10^{-3}\ s^{-1}$, $10^{-4}\ s^{-1}$ and $10^{-5}\ s^{-1}$, respectively.

Results and discussion

Microstructure

Sandwich-like structures were produced by the ARB process using ARB processed AA5754 as core material and AA1050A or AA6014, respectively, as clad materials. In the case of AA1050A/AA5754 sandwich the thickness ratio of the layers AA1050A–AA5754–AA1050A changed from 1:2:1 before roll bonding to 1:3:1 after roll bonding. This can simply be explained by the strongly differing strength of these two materials for which reason the softer AA1050A material is more deformed than the stronger

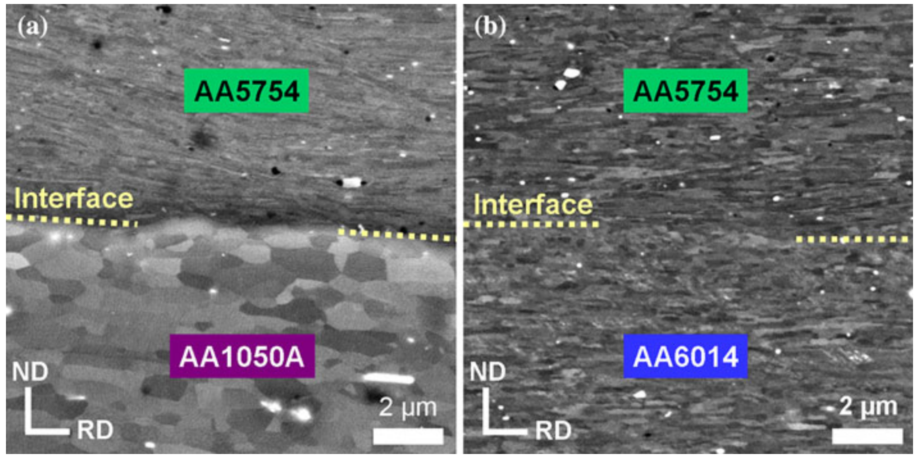

Fig. 2 SEM micrographs (electron channelling contrast) of sandwich-like laminates at the material interface: **a** AA1050A/AA5754 sandwich, **b** AA6014/AA5754 sandwich; *RD* rolling direction, *ND* normal direction

AA5754 alloy. For the AA6014/AA5754 sandwich, however, the thickness ratio before and after rolling is almost constant as both materials are of similar strength. Figure 2 shows the microstructure of these sandwich-like laminates at the material interfaces. All materials are UFG with strongly elongated grains in rolling direction, even though the grain size of AA1050A is significantly coarser than the one of AA5754 and AA6014, respectively.

Bonding between the different aluminium alloy layers is achieved in both cases as can be seen in Fig. 2. The AA1050A/AA5754 interface (Fig. 2a, indicated by the dotted line) is clearly identified as the grain size significantly differs. However, the interface of the AA6014/AA5754 sandwich (Fig. 2b, indicated by the dotted line) can only be identified by a slight difference in brightness: the AA5754 region appears slightly darker and sharper than the AA6014 region.

Mechanical properties

The mechanical properties across the interface have been investigated by means of nanoindentation experiments. The hardness profiles of the two multicomponent systems are shown in Fig. 3.

For the AA1050A/AA5754 sandwich the hardness of the core material is almost three times higher than the AA1050A clad (Fig. 3a). The difference in hardness is not that pronounced in the AA6014/AA5754 sandwich although a clear jump at the interface is also observed (Fig. 3b). For both sandwich materials only one indent was located at the interface of the different Al alloy layers indicating that the two materials are directly bonded and that there is no transition region with locally different mechanical properties in between which is also approved by the micrographs in Fig. 2.

In both cases there is a quite pronounced scattering of hardness values in the AA5754 alloy. Nevertheless, a slight increase in hardness at the interface was observed in all

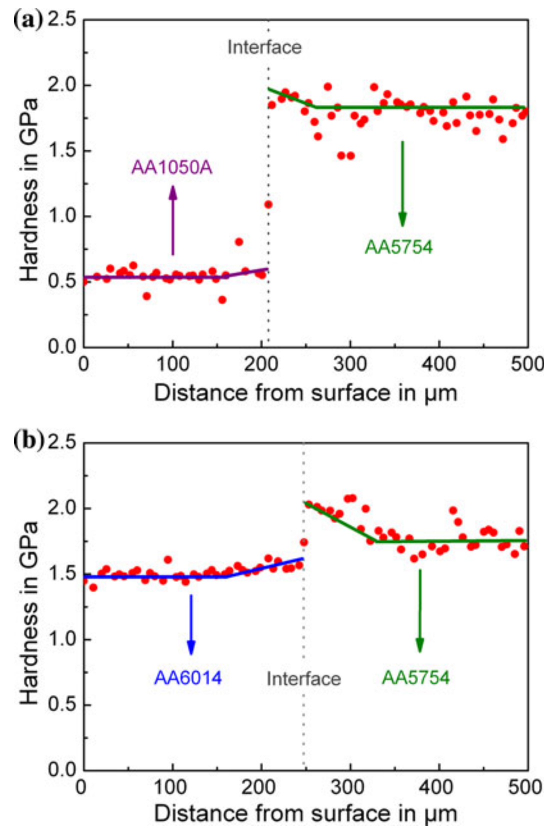

Fig. 3 Hardness profile across the interface core/clad material of **a** AA1050A/AA5754 sandwich and **b** AA6014/AA5754 sandwich

materials. This behaviour was previously observed for conventionally ARB processed AA6061 by Lee et al. [2, 22] which was attributed to wire brushing and, as rolling surfaces from previous cycles get inside bulk material, also to work hardening by the redundant shear strain near the surface.

The differences in hardness of core/clad material correspond to the results from tensile tests of the accumulative roll bonded single component materials, as can be seen in

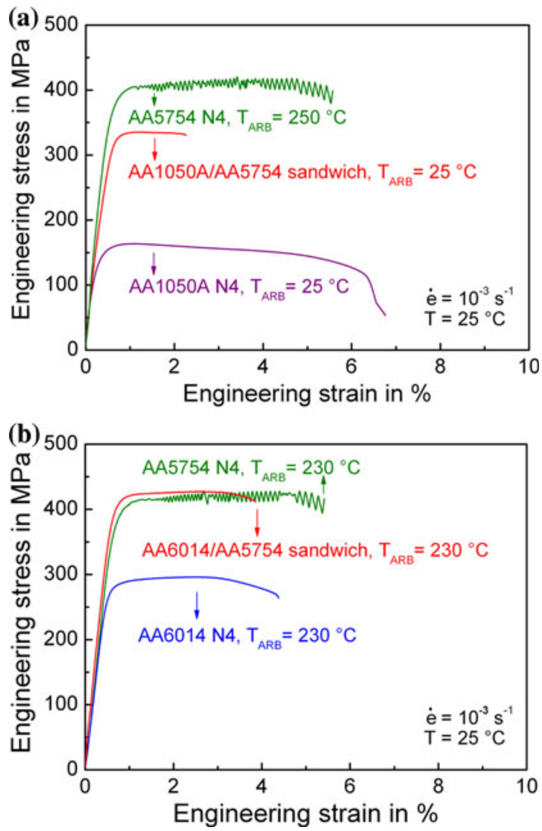

Fig. 4 Stress/strain curves of **a** AA1050A/AA5754 sandwich and **b** AA6014/AA5754 sandwich in comparison to the ARB processed single component materials. The tensile tests were performed at room temperature and a strain rate $\dot{e} = 10^{-3}\ \mathrm{s}^{-1}$

Fig. 4. The yield and the ultimate tensile strength of AA5754 N4 are nearly 3 times higher than the ones of AA1050A N4 (Fig. 4a) and about 25% above the values of AA6014 N4 (Fig. 4b). For the AA1050A/AA5754 sandwich material the strength is mainly provided by the core material as AA1050A starts to deform plastically at an engineering stress of about 150 MPa while the core material is still deforming elastically, compare Fig. 4a. The ultimate tensile strength (UTS) of this sandwich is slightly smaller than the UTS of the single component material AA5754 after 4 ARB cycles. This is related to the reduced volume of the AA5754 alloy in the sandwich. As shown above the thickness ratio after roll bonding is 1:3:1, which means that the volume fraction of AA1050A is 2/3 that of AA5754. However, in the case of the AA6014/AA5754 sandwich the yield and tensile strength of the sandwich are as high as those of the core material (Fig. 4b). While the ductility in the AA6014/AA5754 sandwich is similar to AA5754 N4, it is strongly decreased for the AA1050A/AA5754 laminate.

Interestingly, the serrated yielding due to the Portevin-Le Châtelier (PLC) effect clearly visible in AA5754 almost fully disappears in both multicomponent materials (Fig. 4). Although not fully understood, this might be explained by the dependence of the PLC effect on the surface quality which was shown by Abbadi et al. [23]. By comparing polished and unpolished specimens in tensile tests, Abbadi et al. observed that geometrical defects on the specimen surface act as stress raisers corresponding to fluctuations. Cladding of AA5754 with a material not showing such discontinuities compensates geometrical defects on the AA5754 surface and therefore shows the same effect like polishing. Thus, cladding of AA5754 with either AA1050A or AA6014 results in aluminium sheets with a combination of the beneficial properties of its individual materials: high strength of the AA5754 core material and good surface quality properties of the cladding materials.

By tensile testing at lower strain rates, the ductility (elongation to failure) of AA1050A/AA5754 sandwich considerably increases as shown in Fig. 5a. Concerning the strength, there is no change in the stress/strain curves recorded at engineering strain rates $\dot{e} = 10^{-3}\ \mathrm{s}^{-1}$ down to $\dot{e} = 10^{-5}\ \mathrm{s}^{-1}$. This is related to the AA5754 core material not showing strain rate sensitive behaviour at room temperature. The enhanced ductility with decreasing strain rate

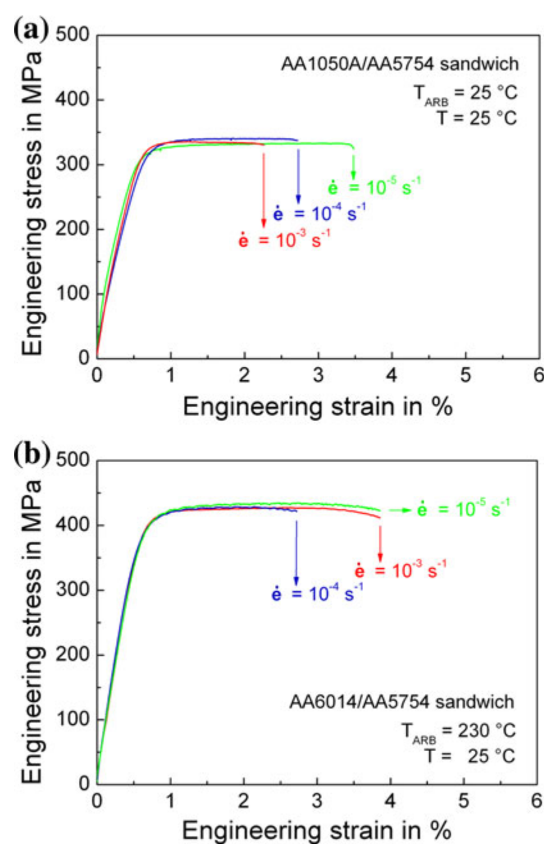

Fig. 5 Stress/strain curves of **a** AA1050A/AA5754 sandwich and **b** AA6014/AA5754 sandwich performed at room temperature and different strain rates

originates from the AA1050A clad which already shows a pronounced strain rate sensitive behaviour at five ARB cycles [4]. Therefore, necking is retarded. The AA6014/AA5754 sandwich does not show a strain rate sensitive behaviour at all, see Fig. 5b. This is meeting our expectations as AA6014 does not show strain rate sensitivity at less than 6 ARB cycles. The reason for the reduced elongation to failure found for the test performed at $\dot{e} = 10^{-4}\ \mathrm{s}^{-1}$ is not completely clear at the moment and might be due to statistical scatter.

Furthermore, Fig. 5a and b reveals that there is a plateau in the stress/strain curves where a dynamic equilibrium of strain hardening and strain softening has been established. For the AA6014/AA5754 sandwich it is found that very faint serrations reappear by decreasing the strain rate. This is according to the observations of Wen and Morris [24] showing an increasing magnitude of serrations by decreasing the strain rate for aluminium alloys of the 5xxx series.

Conclusions

The ARB process is well suited to produce multicomponent materials with tailored properties. Joining of UFG AA5754 and AA1050A or AA6014 alloys, respectively, results in well-bonded sandwich laminates which exhibit a combination of the positive properties of the single component materials: high strength of the core material and good surface quality of the clad materials. In particular for the AA6014/AA5754 sandwich, the strength of AA5754 with 4 ARB cycles is fully conserved while serrated yielding disappeared. Therefore, the application area of ARB processed materials is extended. A great variety of possibilities for grading and tailoring materials properties is given by the ARB process by intelligent material design.

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