Microstructure and mechanical properties of accumulative roll bonded aluminium alloy AA5754

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Abstract. The aluminium alloy AA5754 is used for many technical applications. In this work, the accumulative roll bonding process is applied to this alloy in order to investigate the potential of an ultrafine-grained structure on the mechanical properties of this Al-Mg alloy. Sheets from AA5754 (AlMg3) were successfully processed by accumulative roll bonding in order to obtain an ultrafine-grained microstructure. The ARB process was performed at 230 °C or 250 °C up to 7 or 8 cycles respectively. Thus the grain size decreased from 10 µm (initial state) to approximately 80 nm (ultrafine-grained state, normal direction). The microstructural evolution and the mechanical properties have been investigated by means of scanning electron microscopy, hardness measurements and tensile testing. After one ARB cycle the samples showed an increase in hardness by a factor of almost 2 in comparison to the as-received material. Further processing causes a linear increase of hardness with each additional cycle. Yield strength and tensile strength of the roll bonded specimens are highly increased in comparison to the as-received samples whereas the ductility declined. A considerable increase in ductility is obtained by heat treatment of the ARB specimens at 250 °C, but on the expense of a moderate decreased strength. The deformation behaviour is also influenced by the ultrafine-grained structure. The occurrence of the Portevin-Le Chatelier effect is manifested by serrated stress-strain curves. The amplitude of serrations increases with increasing number of ARB cycles but can be reduced by the appliance of a higher strain rate. Lüders strain only occurs at the as-received, i.e. not strained, samples.

1. Introduction
For reason of weight reduction aluminium and its alloys become more and more important in the automotive industry. While aluminium alloys of the 6xxx series are mostly used for outer panels for which besides strength, a good formability and a high surface quality are required, 5xxx alloys are mostly used for structural panels where strength, good deep drawing and stretch behaviour are important issues [1]. The enhancement of strength and stiffness provides the possibility of scaling down the dimensions and consequently an improvement in light-weight design. For this purpose an ultrafine-grained microstructure which is coincided with extraordinary mechanical properties affords high potential. In this context, accumulative roll bonding (ARB) is a well known process for the production of ultrafine-grained sheet materials [2]. Aluminium of commercial purity and numerous aluminium alloys have already been subjected to the ARB process and show promising properties for prospective engineering application, see for example [3-6]. In this work, the accumulative roll bonding
process is applied to the aluminium alloy AA5754 in order to investigate the potential of an ultrafine-grained structure on the mechanical properties of this Al-Mg alloy.

2. Experimental
The material investigated was the aluminium alloy AA5754 often used in the automotive industry for structural panels [1]. The chemical composition is listed in Table 1.

Table 1. Chemical composition of aluminium alloy AA5754.

| Wt.% | Si | Fe | Cu | Mn | Mg     | Cr | Zn | Ti | other | Al   |
|------|----|----|----|----|--------|----|----|----|-------|------|
| AA5754 | 0.4 | 0.4 | 0.1 | 0.5 | 2.6-3.6 | 0.3 | 0.2 | 0.15 | 0.15 | balance |

The as-received sheets were in the recrystallized (soft) state. The ARB-process was applied to sheets with 1 mm x 100 mm x 300 mm in size. Prior to roll bonding the surfaces were wire brushed in order to remove the oxide layer, stacked on top of each other and pre-warmed to 230 and 250 °C respectively for 210 s in a furnace. The sheets were immediately after pre-warming roll bonded in a four high rolling mill (Carl Wezel, Mülhacker) with a nominal thickness reduction of 50 % per cycle. The bonded aluminium sheets were air cooled, halved, wire brushed and stacked again before rolling the next cycle. For more details concerning ARB see [2, 3]. The sheets were roll bonded up to 7 or 8 cycles respectively.

The microstructure was observed using the electron channeling contrast (ECC) in a scanning electron microscope (SEM, Crossbeam 1540 EsB, Zeiss) in order to characterise microstructural changes during ARB. The specimens were mechanically grinded and polished and electropolished using the standard Struers electrolyte A3 at 25 V for 20 s at room temperature.

The hardness depending on the number of ARB cycles was determined using a Vickers hardness tester (V-100 A, Leco) at a load of 49.05 N. Flat tensile specimens with a gauge length of 33.5 mm were machined in rolling direction from the as-received and the roll bonded sheets after 2, 4, 6 and 7 or 8 cycles respectively. For monotonic testing a universal testing machine Instron 4505 with a clip-on extensometer was used. All tensile tests were performed at room temperature using three strain rates of \(10^{-2} \text{s}^{-1}, 10^{-3} \text{s}^{-1}, 10^{-4} \text{s}^{-1}\).

Furthermore ARB specimens after 4 cycles were investigated after an annealing heat treatment at 250 °C for 10 minutes and 60 minutes and a heat treatment at 450 °C for 10 minutes to achieve a recrystallized state.

3. Results and discussion

3.1. Microstructure
The development of the microstructure during the ARB process is shown in Figure 1. The mean grain-size in the as-received soft condition of the aluminium alloy AA5754 is 10 µm.

Figure 1. SEM electron channelling contrast micrographs of AA5754 a) in the as-received state (AR) and after b) two, c) four and d) eight ARB cycles processed at 250 °C (RD: rolling direction).
After 2 cycles the grains show an irregular morphology due to deformation (figure 1b). Further rolling leads to an ultrafine-grained microstructure after 3-4 ARB cycles with elongated grains in rolling direction (figure 1c-d). After 8 ARB cycles the median grain size perpendicular to the rolling direction is 80 nm whereas there is no distinction between small and high angle grain boundaries.

3.2. Mechanical Properties

The evolution of the hardness with regard to the number of ARB cycles is shown in figure 2. There is no influence of the process temperature on the hardness of the sheets. However processing of ARB sheets by 8 ARB cycles has only been possible at 250 °C. After the first ARB cycle the hardness is nearly twice as high as in the initial state. Further processing leads to a linear increase in hardness up to 7 or 8 cycles respectively for both processing temperatures. Compared to the results on AA6016 [4] it becomes obvious that for the non-precipitation hardened alloy AA5754 the introduction of an ultrafine-grained microstructure by ARB is more effective in terms of strengthening the material by fine grains. In combination with the findings for the AA1050 alloy [3] the high degree of solute atoms in AA5754 appears to be the key-issue for the continuous increase in strength with increasing ARB cycles.

![Figure 2](image2.png)

**Figure 2.** Hardness evolution at different process temperatures of the aluminium alloy AA5754 with an increasing number of ARB cycles.

![Figure 3](image3.png)

**Figure 3.** Stress-strain curves of as-received, cold rolled and ARB processed AA5754 performed at room temperature and a strain rate of $10^{-3} \text{s}^{-1}$.

Representative tensile stress-strain curves of the as-received, the cold rolled (30 %) and the ARB samples can be seen in figure 3. With increasing number of ARB cycles the yield and the ultimate tensile strength (UTS) progressively increase. After 4 ARB cycles, a remarkable increase in yield strength of 330 % and in UTS of 170 % in comparison to the soft condition can be achieved. The elongation to failure is compromised by 75 % in comparison to the as-received condition but is increased slightly in comparison to the cold rolled CG condition. The gain in strength by further processing is on the expense of the ductility.

In order to improve the ductility, ARB specimens rolled-up to 4 cycles were heat treated at 250 °C for 10 minutes and 60 minutes and at 450 °C for 10 minutes to get a fully recrystallised condition. The mechanical properties received by tensile testing are shown in figure 4. Even though the heat treatment of 10 minutes at 250 °C causes a drop of 83 MPa in yield strength and UTS the values are still above the ones of the hard conventional grain-sized (CG) condition. Furthermore the elongation to failure is doubled in comparison to the not annealed ARB sample. In the case of the specimens heat treated for one hour at 250 °C the strength of the hard CG state and additionally almost the ductility of the recrystallized state are reached.

A Lüders strain behaviour is only observed in the case of the soft as-received condition (figure 3, black curve) which fulfills the precondition of the absence of mobile dislocations. The serrated yielding
due to the Portevin-Le Châtelier (PLC) effect is observed for all conditions. The magnitude of serrations increases with increasing strain and as well with increasing number of ARB cycles. The decreasing grain size of the ARB processed samples is simultaneously attended by an increasing number of grain boundaries which act as obstacles for mobile dislocations [7].

![Figure 4. Mechanical properties of AA5754 with 4 ARB cycles after different annealing treatments in comparison to CG AA5754 sheets. Data for CG materials from [8].](image)

The results of tensile testing at different strain rates of the as-received samples and ARB specimens roll bonded up to 4 cycles show that the serrations form with different intensity and morphology. More detailed, serrations of type B are found for the strain rates $10^{-3}$ s$^{-1}$ and $10^{-4}$ s$^{-1}$ and serrations of type A for $10^{-2}$ s$^{-1}$, compare [9]. For the ARB specimens, an inverse strain rate sensitivity is qualitatively observed, as for higher strain rates lower strength levels are revealed. Due to the occurrence of the serrations a quantitative analysis of the strain rate sensitivity exponent $m$ does not make sense.

4. Conclusions

Aluminium alloy AA5754 has been processed up to 7 or 8 cycles respectively by using accumulative roll bonding producing an ultrafine-grained microstructure down to 80 nm. This favourably influences the mechanical properties like highly increased hardness, yield and ultimate tensile strength. Ductility is lost in comparison to the as-received state but is, up to 4 ARB cycles, increased in comparison to the cold rolled CG condition. A considerable increase in ductility can be reached by a short heat treatment at 250 °C, but on the expense of a moderately decreased strength. The deformation behaviour is also influenced by the ultrafine-grained structure. The occurrence of the Portevin-Le Châtelier effect is manifested by serrated stress-strain curves. The amplitude of serrations increases with increasing number of ARB cycles but can be reduced by the appliance of a higher strain rate. Lüders strain only occurs in the as-received, i.e. not strained, samples. The ultrafine-grained condition of AA5754 shows a high potential for lightweight constructions in automotive applications.

References

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