Materials Science & Engineering A 597 (2014) 122–127

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Influence of cross-rolling on the mechanical properties of an accumulative roll bonded aluminum alloy AA6014

Mathis Ruppert*, Heinz Werner Höppel, Mathias Göken

Institute I: General Materials Properties, Department of Materials Science and Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form
29 November 2013
Accepted 21 December 2013
Available online 1 January 2014

Keywords:
Ultrafine-grained materials
Accumulative roll bonding
Cross-rolling
Aluminum alloy

ABSTRACT

Sheets of aluminum AA6014 (AlMgSi) were successfully accumulative roll bonded from T4 condition up to eight cycles. Using the conventional ARB route, processing was on the one hand performed at room temperature. On the other hand, sheets were pre-heated in a furnace for 2.5 min at 210 °C prior to each rolling step. Besides the conventional ARB route an ARB cross-rolling route, where the rolling direction is rotated around 90° after each cycle, was used at room temperature. For all three processing conditions an ultrafine-grained microstructure was obtained. Due to a change in strain path, the ultimate tensile strength and the yield strength of the cross-rolled AA6014 exceed those of the samples processed by conventional ARB. However, a strong decrease in terms of elongation to failure is visible after 6–8 cycles of ARB compared to the pre-heated ARB sheets. Fracture analysis reveals necking of individual layers for the samples processed at room temperature. Therefore, after 7 cycles of cross-rolling at RT, one last cross-rolling step at elevated temperature was performed in order to improve bonding quality. This leads to a high strength of about 475 MPa and a satisfactory elongation to failure of about 10%.

1. Introduction

Up to date, several methods of severe plastic deformation (SDP), like high pressure torsion (HPT) [1,2], equal channel angular pressing (ECAP) [3] and accumulative roll bonding (ARB) [4,5] have been developed. The common principal of all of these SPD processing techniques is to impose a high amount of strain to a conventionally grained (CG) bulk material, leading to strong grain refinement and to grain sizes between 100 nm and 1 μm (see [6] for details). Those ultrafine-grained (UFG) materials exhibit superior mechanical properties, like high strength e.g. [7–10] and enhanced strain rate sensitivity compared to their conventionally grained counterpart [11–13]. However, especially the ARB process offers many possibilities to combine different materials and tune the mechanical properties [14]. Moreover, it has been reported that a change in strain path during deformation can promote grain refinement and further enhance the mechanical properties. Therefore Dupuy et al. [15] conducted 8 passes of equal channel angular extrusion using an aluminum magnesium alloy AA5083 following routes A, B_A, B_C and C (see also Furukawa et al. [16] for more details). As a result, routes A and C lead to a lower strength compared to route B. This showed, that for a given strain, the mechanical behavior of UFG AA5083 is strain path dependent. The reason for this behavior was attributed to an activation of previously latent slip systems for route B, which leads to latent hardening, while routes A and C correspond to a reversion of strain. Furthermore, Sakai et al. [17] investigated the influence of different strain paths, i.e. simple shear, compression and a combination of both, on the recrystallization behavior of AA1100. It was found, that the combined strain path led to a finer recrystallized grain size, due to the introduction of a higher fraction of high-angle grain boundaries compared to the monotonic strain paths. Likewise, Kaneko et al. [18] reported an enhancement of strength as well as a further grain refinement of AA1100 after ARB with cross-rolling, compared to conventional ARB. In ARB with cross-rolling, the rolling-direction is rotated 90 ° around the sheet plane normal after each cycle in order to change the strain path. Alizadeh et al. [19,20] also investigated the influence of cross-rolling on the mechanical properties of AA1100. However, they introduced ceramic particles into the bond plane during the first cycles of the ARB process and afterwards used cross-rolling to disperse the particles. As a result, the mechanical properties of the cross-rolled material were enhanced, compared to the conventional ARB process. On the one hand the improvement was attributed to the deagglomeration of particle clusters, which act as sites for crack initiation. On the other hand, it was attributed to the decrease in aspect ratio of lamellar and interconnecting boundary spacing. Similar results were obtained by Yaghtin et al. [21] for cross-rolling of boron carbide reinforced AA1050A.

* Corresponding author. Tel.: +49 9131 85 27478; fax: +49 9131 85 27504.
E-mail address: mathis.ruppert@fau.de (M. Ruppert).
URL: http://www.gmp.ww.uni-erlangen.de (M. Ruppert).

0921-5093/$ - see front matter
http://dx.doi.org/10.1016/j.msea.2013.12.075

The results for cross-rolling as reported in literature also seem very promising for technically relevant alloy systems, like 6xxx-series alloys. Due to its good mechanical properties and excellent surface quality, the alloy system shows great potential for the automotive industry. Additionally, cross-rolling appears to be beneficial compared to conventional ARB as superior mechanical properties can be achieved after a smaller number of ARB cycles. Therefore, in this work, an AlMgSi-alloy (AA6014) was accumulative roll bonded up to 8 cycles using the conventional route and by using cross-rolling, respectively. The different samples were microstructurally characterized and the mechanical properties were investigated with tensile tests.

2. Experimental

The material used in this work was an AlMgSi-alloy AA6014, provided by Novelis Switzerland SA (for composition see Table 1). The ARB process was carried out using sheets with an initial size of 300 mm × 100 mm × 1 mm for conventional ARB and 100 mm × 100 mm × 1 mm for ARB with cross-rolling. The samples were recrystallized at 520 °C for 1 h, quenched in water and naturally aged at room temperature (T4 condition). As a surface treatment, acetone cleaning followed by wire brushing was applied. The nominal thickness reduction in each cycle was 50%. In case of conventional ARB, the sheets were either pre-heated for 2.5 min at 210 °C prior to rolling (ARB pre-heated) or processed at room-temperature (ARB at RT). ARB with cross-rolling was only conducted at room-temperature (ARB cross-rolled). For ARB with cross-rolling, the rolling direction was rotated around 90° normal to the sheet plane after each cycle, while for conventional ARB the rolling direction was kept the same for all cycles. In each case a four high rolling mill (BW 200, Carl Wezel, Germany) was used and samples with 2, 4, 6 and 8 ARB cycles (N2–N8) were produced.

Mechanical properties were determined using an Instron 4505 universal testing machine for uniaxial tensile testing at room temperature at a strain rate of $10^{-3}\,s^{-1}$. The tensile specimens had a gauge length of 10 mm and were taken in rolling direction of the last cycle in each case. Microstructural characterization was done in a Zeiss Cross Beam 1540 EsB (Carl Zeiss AG, Oberkochen, Germany) using secondary electron and backscattered electron contrast techniques, respectively.

3. Results and discussion

Fig. 1 exemplarily illustrates the results from tensile testing for the CG-reference, N2 and N8. Compared to the CG state, the UFG curves show reduced strain hardening and reach the uniform elongation very soon. However, the UFG samples reach a much higher strength compared to their conventionally grained counterpart. To study the evolution of strength and ductility with the number of ARB cycles in more detail, mechanical properties from tensile testing are separately presented in Fig. 2. The pre-heated samples reveal the typical behavior for accumulative roll bonded samples. That is to say, the ultimate tensile strength and yield strength are increasing with the number of ARB cycles, however are saturating after 6 cycles. On the one hand this is a consequence of dynamic recrystallization and recovery processes taking place during the deformation of the sheet material. Although these dynamic processes were not directly observed in this study, it is a well-known behavior in pertinent literature (see for example [6,22]). On the other hand, precipitates are overageing due to the high amount of strain and the introduction of heat during every rolling and pre-heating sequence. Hence, a maximum ultimate tensile strength (UTS) of 399 ± 6 MPa and a maximum yield strength (YS) of 383 ± 8 MPa are reached after 8 cycles. This means, that the UTS is by a factor of 1.6 and the YS by a factor of 2.8 higher compared to the T4 condition. ARB processing at RT leads to an additional increase of the UTS by 32 MPa and 39 MPa for the YS. Moreover the UTS is not running into saturation after 8 cycles, but is still increasing. Thus, an UTS of 477 ± 7 MPa is reached for ARB at RT after 8 cycles. Regarding the mechanical properties of the cross-rolled specimens it is generally found that the UTS as well as the YS lie at a level which is about 20 MPa above the values for the samples processed at RT and about 60 MPa above the values of the pre-heated material. Therefore, slow dynamic recrystallization and suppressed overaging at RT lead to a final ultimate tensile strength of 495 ± 7 MPa after 8 cycles of ARB.

The general behavior of the uniform elongation (A_g) with the number of ARB cycles appears to be comparable for all three conditions. That is to say, after the first cycle, a strong decrease from 19.3 ± 1.0% to about 2.0 ± 0.4% can be observed. However, after 8 cycles, A_g has increased again to a final value of about 2.5 ± 0.3% for the pre-heated condition and about 2.8 ± 0.1% for ARB at RT and 3.0 ± 0.8% for cross-rolled condition, respectively. In contrast to that, elongation to failure (A) is developing differently for the three conditions. On the one hand, for the pre-heated samples, A is steadily increasing with the number of ARB cycles, reaching a final value of 9.5 ± 1.2%. On the other hand, ARB at RT and ARB cross-rolled show a decreasing elongation to failure after 6 cycles of ARB. Finally, ARB at RT reaches a value of 4.9 ± 0.6, while ARB cross-rolled end at 2.9 ± 1.6% after 8 cycles.

The results of the microstructural investigations are shown in Fig. 3 for the T4 condition (CG-reference) and also for the different UFG states after 8 cycles of ARB. All UFG samples exhibit a quite homogeneous ultrafine-grained microstructure. As during cross-rolling the rolling direction is changed after each cycle, the usual terms used in ARB microstructural analysis "rolling direction" and "transverse direction" are exchanged by "short direction" d_s and "long direction" d_l. It is clearly visible that grain sizes are below

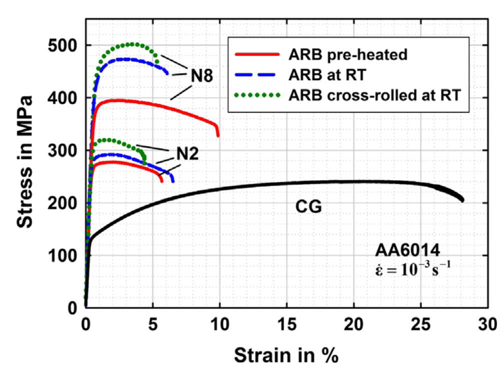

Fig. 1. Stress–strain curves of AA6014 after pre-heated ARB (2.5 min/210 °C), ARB at RT and cross-rolling. Curves are shown exemplarily for CG-reference, N2 and N8 at a strain rate of $10^{-3}\,s^{-1}$.

Table 1
Composition of the applied sheet material AA6014.

wt%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Others
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