Tensile properties of UFG aluminium alloy AA6016 at low temperatures

J Scharnweber, L Hollang, K Reuther, SR Dey, C-G Oertel and W Skrotzki
Institut für Strukturphysik, Technische Universität Dresden, D-01062 Dresden, Germany
werner.skrotzki@physik.tu-dresden.de

Abstract. The ultrafine grained aluminium alloy AA6016 produced by accumulative roll bonding (ARB) up to eight cycles was deformed in tension at 25K, 77K, 180K and 296K at a constant strain rate. The stress-strain curves were analyzed with regard to the evolution of yield stress $\sigma_p$, ultimate stress $\sigma_m$ and fracture strain $\varepsilon_f$ as a function of temperature for zero, four and eight ARB cycles processed aluminium plates. For all materials $\sigma_p$, $\sigma_m$, $\sigma_m-\sigma_p$ and $\varepsilon_f$ decrease with increasing temperature. With increasing number of ARB cycles, $\sigma_p$ and $\sigma_m$ increase, while $\sigma_m-\sigma_p$ and $\varepsilon_f$ were found to decrease. Based on the experimental results the influence of temperature and number of ARB cycles is discussed.

1. Introduction
Since its introduction by Saito et al. [1] accumulative roll bonding (ARB) has become a successful severe plastic deformation (SPD) method to produce ultrafine grained (UFG) metals and alloys with grain sizes ranging from 1 µm to about 100 nm [2 - 4]. Compared to their conventional large grained counterparts, UFG materials show an enhanced strength [e.g. 5] with only a slightly decreasing and in some aluminium alloys even increasing ductility [6 - 8].

The influence of ARB processing on the tensile behaviour at ambient temperatures has been described for various UFG materials, e.g. for the technically relevant age-hardening aluminium alloy AA6016 [9]. Investigations at other temperatures are less frequent. Therefore, in this study AA6016 plates of different degree of ARB deformation were subjected to tensile tests below room temperature in order to investigate the influence of temperature on the strength and ductility.

2. Experimental
In this investigation samples of the initial state and after four and eight ARB cycles were tested. Prior to ARB the plates with a thickness of 1 mm were solution heat treated in a furnace for 1h at 520°C and subsequently quenched in water. The grain sizes of the completely recrystallized initial material in rolling and normal direction (RD and ND) are about $d_{RD} = (18.2 \pm 2.2) \mu m$ and $d_{ND} = (16.2 \pm 3.0) \mu m$. The ARB-process with a thickness reduction of 50% per rolling pass was applied to aluminium plates with a width of 100 mm and a length of approximately 300 mm using a four high rolling mill (Carl Wezel, Mühlacker). Prior to rolling the plates were pre-warmed at 230°C for four minutes. After each cycle the surfaces of the air-cooled bonded plates were wire brushed to remove the oxide layer. The ARB process was done up to a maximum of eight cycles, which corresponds to a von Mises strain of 6.4 and leads to a plates with $2^8 = 256$ bonded layers each having a thickness of 3.9 µm. The conditions of the ARB processing are described in more detail in [10]. The grain sizes after four and
eight ARB cycles are $d_{RD} = (0.7 \pm 0.4) \, \mu m$ and $d_{ND} = (0.6 \pm 0.2) \, \mu m$ and $d_{RD} = (0.5 \pm 0.1) \, \mu m$ and $d_{ND} = (0.2 \pm 0.1) \, \mu m$, respectively [9]. Only high angle grain boundaries with a misorientation angle higher than $15^\circ$ were considered for the grain size determination. The chemical composition of the aluminium alloy AA6016 is listed in Table 1.

**Table 1. Chemical composition of AA6016 (mean values).**

| wt.%  | Si     | Cu  | Fe  | Mn   | Mg  | Cr  | Zn  | Ti  | other | Al   |
|-------|--------|-----|-----|------|-----|-----|-----|-----|-------|------|
| AA6016| 1.0-1.5| 0.52| 0.5 | 0.2  | 0.25-0.6 | 0.1 | 0.2 | 0.15| 0.15  | balance |

The tensile tests were performed at 25K, 77K, 180K and 296K using an Instron 4500 deformation machine at a constant strain rate of $9.2 \times 10^{-4} \, s^{-1}$ until necking occurred. The low temperature deformation is described in detail in [11, 12]. The tensile direction was parallel to the rolling direction. To calculate the true stress and true strain the diminution of the cross section of the specimen was taken into account.

3. Results and Discussion

Figure 1 reveals the strong influence of both deformation temperature and numbers of ARB cycles on the stress-strain curves. All curves show work hardening which increases with decreasing temperature. At 25K the specimens of the ARB processed material fractured directly after onset of necking.

**Figure 1.** Stress-strain curves for samples deformed at different temperatures: (a) initial material, (b) four and (c) eight ARB cycles.
As can be seen in figure 2, yield stress $\sigma_p$ and ultimate stress $\sigma_m$ are similarly affected by the ARB process. For the initial as well as the ARB processed material there is an almost linear decrease of $\sigma_p$ with temperature (figure 2a). A higher deformation degree shifts the yield stress to higher values and leads to a stronger temperature dependence. Compared to the initial state eight ARB cycles increase the yield stress by about 600% at all temperatures applied. It is widely accepted that this increase with the deformation degree is due to dislocation and grain boundary hardening. In [9] it was shown that the main grain size reduction of AA6016 has taken place until the fourth cycle. Accordingly, about 83% of $\sigma_p$ is already reached after four cycles.

The decrease with temperature is stronger for $\sigma_m$ than for $\sigma_p$ (figure 2b). Compared to the initial material, eight ARB cycles increase $\sigma_m$ at 25K only by 22%, while at 296K it is 130%.

![Graphs showing the decrease of $\sigma_p$ and $\sigma_m$ with temperature for different ARB cycles.](image)

**Figure 2.** (a) $\sigma_p$ and (b) $\sigma_m$ for different numbers of ARB cycles versus deformation temperature.

The difference $\sigma_m - \sigma_p$ shown in figure 3b characterizes the strain hardening capacity of the material. If during tensile deformation certain regions of the specimen deform stronger than others, more dislocations are generated there in order to achieve the higher deformation. The enhanced dislocation hardening in these regions stabilizes and hence homogenizes the deformation process of the specimen. Thus, the strain hardening capacity of the material governs its ductility (figure 3b). Accordingly, both $\sigma_m - \sigma_p$ and the fracture strain $\varepsilon_f$ are influenced similarly by deformation degree and deformation temperature: At lower temperatures both strain hardening capacity and ductility non-linearly decrease with temperature. The strain hardening capacity is limited by the saturation dislocation density $\rho_s$. If during tensile deformation $\rho_s$ is reached, no more dislocations can be produced to stabilize the deformation of the specimen leading to its inhomogeneous deformation and hence to necking. Due to faster recovery caused by enhanced climb and cross slip of edge and screw dislocations, respectively, the saturation dislocation density and accordingly strain hardening capacity and ductility decrease with increasing deformation temperature. The reason that strain hardening is observed even at 296K is that ARB processing and tensile testing was done at elevated and ambient temperatures, respectively.

ARB processing strongly reduces the high strain hardening capacity and ductility of the annealed initial state. This reduction correlates with the degree of deformation: after eight cycles $\sigma_m - \sigma_p$ at 25K and 296K is only 35% and 23% of that of the initial material, respectively. As mentioned above, the strain hardening capacity during tensile testing is related to the difference between the dislocation density before testing and at saturation. Accordingly, the highly deformed ARB specimens show lower strain hardening than the annealed initial material.

For the two highest temperatures, 180K and 296K, $\sigma_m - \sigma_p$ is constant from the fourth to the eighth cycle. Assuming that at temperatures of 180K and higher, $\rho_s$ is already reached during the first four ARB cycles, the specimens after four and eight cycles would have the same dislocation density before the tensile testing and hence the same strain hardening capacity.
The maximum fracture strain of 46% is reached in the initial material at 25K. ε_f reduces to 28% at 296K. After eight cycles ε_f at 25K and 296K is reduced by a factor of 3 and 4, respectively. Again, the main decrease has occurred during the first four ARB cycles. The slight increase of ε_f at 296K after four cycles may be related to the increase of the strain rate sensitivity [9].

Figure 3. (a) σ_m-σ_p and (b) ε_f for different numbers of ARB cycles versus deformation temperature.

During the tensile tests additional relaxation experiments were performed (stress drops in figure 1). They yield information about the deformation mechanisms controlling the plastic behaviour at the particular deformation temperatures. They are analysed in detail in [13].

4. Conclusions
Between 25K and 296K the yield stress and ultimate stress decrease with increasing temperature, while there is an increase with the number of ARB cycles due to dislocation and grain boundary hardening. Moreover, the ductility decreases with increasing temperature and increasing number of ARB cycles (except at 296K) due to decreasing strain hardening capacity.

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