Influence of ECAP temperature on the formability of a particle reinforced 2017 aluminum alloy

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Abstract. Severe plastic deformation methods are commonly used to increase the strength of materials by generating ultrafine-grained microstructures. The application of these methods to Al-Cu alloys is, however, difficult because of their poor formability at room temperature. An additional reduction of formability of such alloys occurs when ceramic particles are added as reinforcement: this often triggers shear localization and crack initiation during ECAP. This is the main reason why equal-channel angular pressing (ECAP) of aluminum matrix composites (AMCs) can generally only be performed at elevated temperatures and using ECAP dies with a channel angle larger than 90° (e.g. 120°). In this study we present a brief first report on an alternative approach for the improvement of the formability of an AMC (AA2017, 10 % SiC): ECAP at low temperatures. We show that, using a temperature of -60 °C and a channel angle of 90° (corresponding to an equivalent strain of 1.1), ECAP of the AMC can be successfully performed without material failure. The mechanical properties of the strongly deformed AMC are analyzed by tensile testing. Our results indicate that the increased formability of the AMC at low temperatures can be attributed to the suppression of unstable plastic flow that affects formability at room temperature.

1. Introduction

Compared to conventional aluminum alloys, aluminum matrix composites (AMCs) combine advanced mechanical properties, such as high specific strength or high wear resistance, with enhanced creep resistance and thermal stability [1, 2]. Equal-channel angular pressing (ECAP) of AMCs also in principle offers the possibility of strain-hardening and induces an ultrafine-grained microstructure [3, 4]. Most relevant publications on ECAP, however, report on pure metals or their alloys [5-8]. Only a limited number of studies have been focused on ECAP of AMCs [3, 9-11], mainly because AMCs are prone to shear localization or the formation of cracks during processing. Most of these earlier investigations have considered AMCs produced by melting routes [4]. There are almost no publications about ECAP of powder metallurgical, SiC-reinforced AA2017, because such difficult-to-work materials are hard to deform at lower temperatures [11-13]. A homogeneous, crack-free deformation is typically only possible at significantly elevated temperatures, larger channel angles of the ECAP die (> 90°) and using a sufficiently large amount of back pressure.

In the present study, we demonstrate that an AMC can be successfully performed by ECAP at a low temperature (-60 °C), even using an ECAP die with a channel angle of 90°, and without any surface cracks. The purpose of this brief report is to document that low temperatures can improve the formability of the AMC, and reduce its tendency for unstable plastic deformation, which enables
processing in a 90°-ECAP die and thus to introduce sufficient amounts of severe plastic deformation to considerably increase the material’s strength.

2. Experimental

The chemical composition (wt.-%) of the 2017 alloy matrix material was 4.1 % Cu, 0.7 % Mg, 0.8 % Mn, 0.1 % Si, 0.2 % Fe, and balance Al. It was obtained as commercial, gas-atomized, spherical powder with a particle size below 100 µm. The base material and 10 vol.-% of SiC particle powders (particle sizes less than 2 µm) were milled for about 4 h in a high energy ball mill (Simoloyer1 CM08 by Zoz). Hot isostatic pressing (HIP) and extrusion of the mixed powders was performed at Powder Light Metals GmbH in Gladbeck (Germany) to produce semi-finished AMC products. Further details on the fabrication procedures are given in [11].

Figure 1. Schematic illustration of (a) the thermo-mechanical route associated with low temperature ECAP processing: solution annealing at 505 °C for 60 min and water quenching, short time under-aging heat treatment at 140 °C for 30 min, and one pass of ECAP at -60 °C; in an ECAP die (b) with a channel angle of Φ = 90°. The shear deformation is introduced in the shear zone (characterized by the corner angle Ψ, which is quite small when an appropriate back pressure is applied).

Table 1. Material conditions of AA2017 + 10 vol.-% SiC and the corresponding thermo-mechanical processing parameters.

| Condition | Processing |
|-----------|------------|
| ua        | solution annealing at 505 °C, 60 min; water quenching to RT; short time aging at 140 °C, 30 min |
| E1(-60 °C) | ECAP (N=1) of the ua condition at -60 °C; ECAP tool with a channel angle of Φ = 90° and an outer corner angle of Ψ ≈ 0°; effective strain of φ = 1.1 [15]; pressing speed 5 mm/min; back pressure 110 MPa |
For the characterization of strength and ductility, cylindrical tensile samples (with a length of 10.5 mm and a diameter of 3.5 mm) were machined from the billets in extrusion direction after ua, and after one pass of ECAP, respectively. Quasi-static tensile tests were performed in a conventional testing machine (Zwick-Roell) with a constant cross-head speed corresponding to an initial strain rate of $10^{-3}$ s$^{-1}$. While the E1 condition was only tested at RT to document the increase of strength after ECAP, the ua condition was tested at different temperatures (RT, -60 °C, -196 °C). Three samples for each temperature were tested. Low temperature testing was realized using two different experimental methods: For testing at -196 °C, liquid nitrogen was filled in a special double-ring cooling device placed around the specimen. For tensile testing at -60 °C, a climate chamber was used.

3. Results and Discussion
As reported in our earlier publications [11-13], ECAP of powder metallurgically produced AA2017 + 10 % SiC was only possible using an ECAP tool with a channel angle of 120°. The equivalent plastic strain per ECAP pass was 0.67. Our first results presented below demonstrate that ECAP of this material can indeed be performed with a tool with a channel angle of 90° when the temperature is decreased to -60°C.

Prior to the single pass of low temperature ECAP considered in this study, the AMC was ua in order to increase the workability of the material. Figure 2a shows (true) stress-strain curves of the initial (prior to ECAP) ua material condition at different testing temperatures. The ua condition exhibits serrated flow at room temperature, which is directly related to unstable plastic flow and the formation of deformation bands. It is generally well known that such unstable deformation processes often depend on temperature and/ or strain rate, e.g. when they result from a Portevin-Le-Châtelier effect, but further work is required to analyze the microstructural origins in the AMC considered here. Tensile tests were also performed at much lower temperatures (-60 °C and -196 °C) in order to observe the effect of temperature on the unstable plastic flow. There is still some serrated flow at -60 °C (but less than at RT), whereas the stress-strain curve measured at -196 °C shows no traces of unstable plastic flow. This indicates that a reduction of temperature can be beneficial in suppressing localized plastic deformation in this AMC.

![Figure 2](image)

**Figure 2.** a) True stress-strain curves and b) smoothed data of strain hardening rate curves as a function of true stress of AA2017 + 10 % SiC in the ua condition, measured at RT, -60 °C and -196 °C.

In our previous work on low temperature ECAP of an AA7075 alloy, we observed an increase of ductility with decreasing testing temperatures [18]. Moreover, tensile strength of this alloy monotonously increases from RT to -196 °C. At low temperatures, thermally activated cross slip of screw dislocations is strongly suppressed, which leads to an increase of strain hardening and therefore decreases the alloy’s tendency for localization of plastic strain. The material behavior of the AMC...
considered in the present study is different: first, strength hardly increases when the testing temperature is reduced from RT to -60°C, and a somewhat higher initial yield stress is only observed at -196 °C. Second, ductility is not increased at lower temperatures. It is likely that this effect is related to the presence of the SiC particles, which may place a limit on the maximum admissible total strain before cracks are initiated in the AMC and fracture occurs; an analysis of fracture surfaces to determine microstructural fracture mechanisms is currently under way.

Figure 2b shows the strain hardening rate \( \Theta \) (which in this study we simply define as the first derivative of true stress with respect to true strain), obtained from the true stress-strain data shown in figure 2a, plotted against true stress for the three investigated temperatures. Prior to numerically determining \( \Theta \) values, the data was numerically smoothed in order to reduce fluctuations in the \( \Theta-\sigma \) plots. The strain hardening rate at -60 °C does not differ from the one measured at RT. At -196 °C, the strain hardening rate is significantly higher. A separation of the data into strain hardening stages III (dynamic recovery processes) and IV (interaction of the increasing number of dislocations with grain boundaries) cannot be performed. This indicates that the microstructural processes related to hardening stages III and IV take place simultaneously [18]; the presence of the SiC particles may further obscure the individual contributions of the different microstructural processes to the macroscopic stress-strain behavior. We finally note that all tensile samples failed prior to the onset of necking, which may again be explained by brittle failure caused by the ceramic particles under tensile loading. It is important to note that this failure mechanism cannot directly be transferred to the compressive/shear loading conditions during ECAP.

Figure 3 shows billets of the investigated AMC after ECAP processing at two different pressing temperatures: As expected, processing at RT in the 90°-tool leads to a pronounced formation of cracks in regular intervals (figure 3a). Despite of the fact that at -60 °C no improvement of ductility was observed during tensile testing, the AMC could be deformed almost homogeneously at -60 °C in the ECAP die with a channel angle of \( \Phi = 90° \) (figure 3b). This first result shows for the first time that homogeneous severe plastic deformation of AMCs via ECAP is indeed possible at low temperatures. This positive effect of decreased processing temperatures on formability can be related to an increase of work hardening. Moreover, lower temperatures seem to reduce the material’s tendency for serrated flow, which may also be beneficial in suppressing early cracking. Furthermore it should be pointed out that, especially in the case of particle reinforced materials, their mechanical behavior under tensile loading is not suitable to fully describe the deformation behavior under compressive loading; compression or shear testing is likely to provide more relevant data on ductility that can be more readily used to predict formability in severe plastic deformation processes like ECAP.

We finally provide some information on the effect of low temperature ECAP on the mechanical behavior of the ECAP-processed AMC. Figure 4 shows an overview of engineering stress strain curves of the investigated conditions, comparing the pre-ECAP (ua) and the post-ECAP behavior. Obviously, low temperature ECAP of the ua condition results in an increase of yield strength by about 19 %, but it simultaneously decreases ductility. This loss of ductility is typical for SPD-processed materials that are not yet ultrafine-grained or nanocrystalline [3, 11, 19], and may be partly reversed by subsequent heat treatments.

Figure 3. ECAP billets: a) heterogeneously deformed and cracked sample after RT deformation in an ECAP die with an internal angle of \( \Phi = 90° \); b) homogeneously deformed and crack-free sample after deformation at -60 °C in the same ECAP die.
4. Summary and conclusions
ECAP of an aluminum matrix composite (AA2017 + 10 % SiC) at a low temperature (-60 °C) was successfully performed in a die with a channel angle of 90°, resulting in a homogeneous deformation and no cracking. Our results can be summarized as follows:

1. The under-aged condition of the AMC (AA2017 + 10 % SiC) exhibits serrations in the stress-strain curve at room temperature. Testing at lower temperatures indicates a reduction of unstable plastic flow. At -60 °C, some serrations occur, while at -196 °C this effect is completely suppressed.
2. Reducing the temperature from RT to -60 °C does not result in an increase of ductility under tensile loading. This can be explained by the presence of SiC particles, which generally lead to a more brittle deformation behavior in tension. All samples failed prior to the onset of necking. The strain hardening rates determined from tensile testing are almost equal at RT and at -60 °C. Only at -196 °C the strain hardening rate is significantly higher.
3. Despite of the only minor changes observed when changing the testing temperature from RT to -60 °C in tensile testing, ECAP of the AMC can be successfully performed at a pressing temperature of -60 °C. Severe plastic deformation by low temperature ECAP results in an increase of the tensile strength of about 25 % compared to the initial under-aged condition, but simultaneously decreases ductility.

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