Influence of processing conditions on EN AW 2014 material properties and fracture behaviour

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Abstract

The paper deals with the influence of processing conditions on material properties and fracture behaviour of the aluminium alloy EN AW 2014, depending on various processing conditions (as-rolling, quenching, severe plastic deformation – SPD by equal channel angular pressing – ECAP and ageing). (Tensile tests were carried out at strain rate of 2.5×10^{-4} s^{-1}.) The evaluated mechanical properties show that ECAP has the highest effect on formability and mechanical properties of the aluminium alloy EN AW 2014. Severe plastic deformation by means of ECAP causes rapid increase of strength and only partial decrease of ductility was achieved. Strengthening of material is caused by grains refinement, strain hardening of solid solution. Fractographical examinations revealed that there were two categories of dimples of transcrystalline ductile fracture, large dimples, formed by the intermetallic particles and small dimples, formed by submicroscopic and dispersive particles.

K e y w o r d s: aluminium alloy, severe plastic deformation-ECAP, mechanical properties

1. Introduction

In general, aluminium alloys find a wide variety of use due to their remarkable combination of characteristics such as the low density, the high corrosion resistance, high strength, easy workability and high electrical and heat conductivity [1].

The traditional process is to obtain the improvement in the mechanical properties of aluminium alloys through the precipitation of a finely dispersed second phase in the matrix. This is accomplished by a solution treatment of the material at a high temperature, followed by quenching. The second phase is then precipitated at room or elevated temperatures. For aluminium alloys this procedure is usually referred to as age hardening and it is also known as precipitation hardening [2–6]. In the past decade, the research focused on to strengthen Al alloys without any ageing treatment, via severe plastic deformation (SPD) [7–11]. Representing one of severe plastic deformation methods, the ECAP is intensively concentrated on the development of ultrafined and nanosized grains of metallic and non-metallic materials. To achieve such grain parameters, it is essential to resolve not only research problems related to physical metallurgy, construction of equipment for SPD, tribology etc., but also dealing with the synthesis of knowledge leading to industrial realization of materials with high physical and mechanical properties [12–15].

In this study, the properties of processing conditions of aluminium alloy EN AW 2014 subject to strengthening were investigated in terms of the fractographic features. Furthermore, from the detailed examination of the fracture surfaces using a scanning electron microscope (SEM), the difference in the dimples according to applied conditions was also investigated.

2. Material and experimental procedure

The material used in this experiment was alu-

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minium alloy EN AW 2014. The aluminium alloy EN AW 2014 had following chemical compositions: Cu – 4.32 %, Mn – 0.77 %, Si – 0.68 %, Mg – 0.49 %, Fe – 0.29 %, Zr – 0.12 %, Ti – 0.03 % and Al – balance.

Hot rolling was carried out by rolling-mill DUO 210 at temperature of 460 ℃ (as-rolled state). Solution annealing after rolling was performed at temperature of 520 ℃ (holding time 2.5 h) and cooled to the ambient temperature by water quenching (quenched state). The quenched specimens (d_0 = 10 mm, l_0 = 70 mm) were subjected to deformation in an ECAP die with channels angle $\Phi = 90°$ at rate of 1 mm s^{-1} (ECAPed state). The ECAP was realized by hydraulic equipment at ambient temperature, which makes it possible to produce the maximal force of the value of 1 MN. Hence, after one ECAP pass, the specimens were subjected to natural or artificial ageing at 100 ℃ for 200 hours (ECAPed + aged state).

Tensile specimens were taken after each processing treatment. The tensile testing was done on a FP 100/1 machine with 0.15 mm min^{-1} cross-head speed (strain rate of 2.5 × 10^{-4} s^{-1}). Tensile test on the short specimens $d_0 \times l_0 = 5 \times 10$ mm was performed. Subsequently, characteristics of the strength (yield strength: YS; ultimate tensile strength: UTS), elongation (El.) and reduction in area (Re.) were determined.

For optical microscopy, samples were individually mounted, mechanically polished and finally etched at room temperature using a mixture of 2 % HF, 3 % HCl, 5 % HNO_3 and 90 % H_2O (Keller's Reagent).

Transmission electron microscopy (TEM) analysis was performed on thin foils. The foils for TEM were prepared using a solution of 25 % HNO_3 and 75 % CH_3OH at a temperature −30 ℃. TEM was conducted at an accelerating voltage of 200 kV.

Finally, a fractographic study of the fracture surface of the materials after a conventional tensile strength test was carried out using SEM JEOL 7000F.

3. Experimental results and discussion

3.1. Tensile properties

The stress-strain curves under various processing conditions are plotted in Fig. 1. The implementation of severe plastic deformation via ECAP method caused an increase in materials strength if compared to both systems without application of severe plastic deformation (as-rolling and quenching). Marked strengthening of materials after first pass was observed by authors [8, 9, 11]. Strengthening of material is caused by grains refinement and strain hardening of solid solution.

The tensile results under various processing conditions are summarized in Table 1.

The difference in the strength values is basically due to the various materials modification. The reason for the increasing of strength and ductility in case of the as-rolled state in comparison to the quenched state was the reduction of strain hardening. The reason for the strength increasing in ECAP was severe plastic deformation of analysed alloy, which caused also a sensible decrease of ductility. ECAP increased the strength value approximately by 35 % if compared

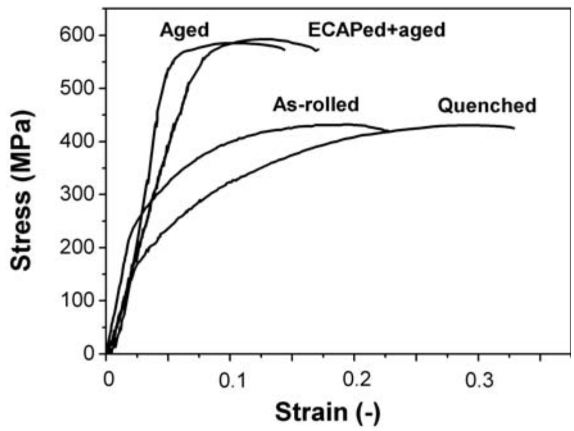

Fig. 1. Stress-strain curves of materials.

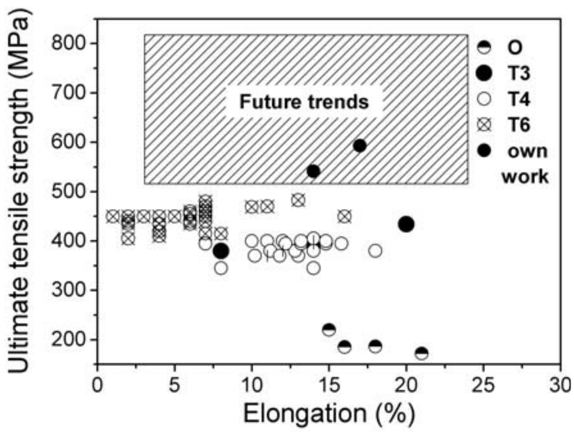

Fig. 2. Influence of processing conditions on mechanical properties of EN AW 2014.

Table 1. Mechanical properties of investigated EN AW 2014

	YS (MPa)	UTS (MPa)	El. (%)	Re. (%)
As-rolled	235	381	22.3	27.8
Quenched	157	394	32.8	34.4
ECAPed	511	593	17.1	18
ECAPed + aged	515	541	14.4	14

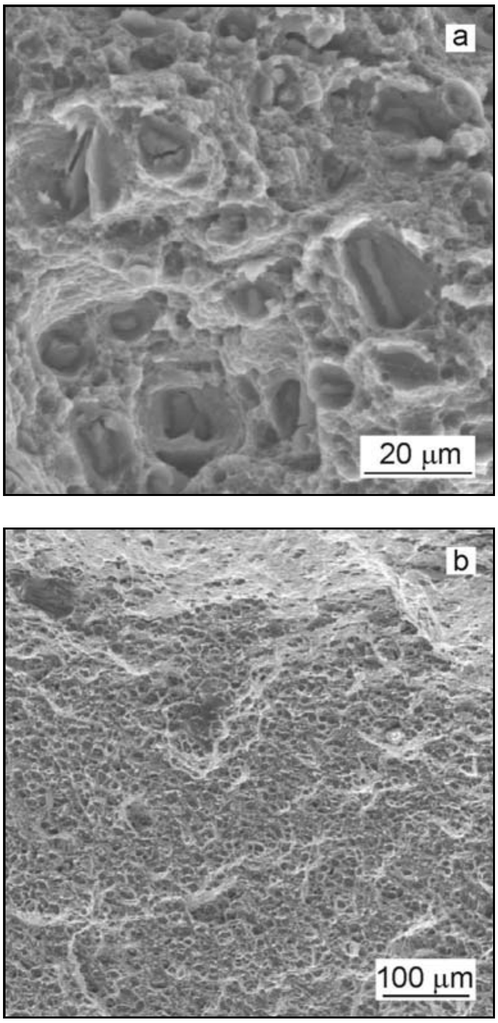

Fig. 3a,b. Transcrystalline ductile fracture – as-rolled state.

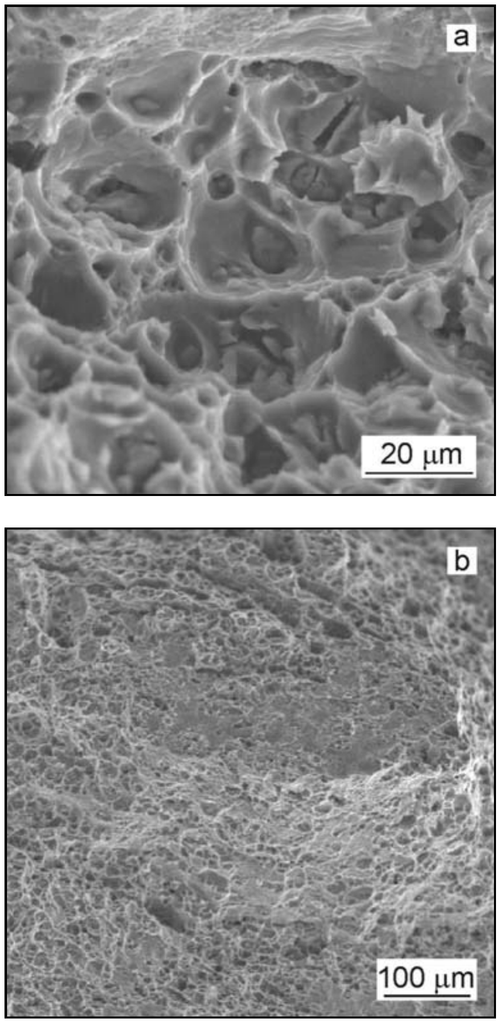

Fig. 4a,b. Transcrystalline ductile fracture – quenched state.

to the as-rolled and quenched alloy. Values of yield strength of approximately 55 % and 70 %, of the as-rolled and quenched material respectively, were obtained.

Overall very good complex mechanical and plastic properties were obtained after ECAP: yield strength of 511 MPa, ultimate tensile strength of 593 MPa, tensile elongation of 17.1 % and area reduction of 20 %.

Figure 2 reports the influence of processing conditions on the UTS of aluminium alloy EN AW 2014. In this figure values for aluminium alloys EN AW 2014 according to [16–18] are also included. It is clear that conventional forming methods and heat treatment can determine a limit in the level of strength-plastic characteristics adequate to structural properties. A combination of high strength and ductility of ultra-fine polycrystalline metals prepared by severe plastic deformation is unique and it indeed represents interesting case from the point of view of mechanical properties, as it is confirmed in [19, 20]. In the future, after the resolution of partial problems with microstructure heterogeneity [21], SPD materials with microstructures "tailored to the measure" can be expected. They will guarantee the suitable combination of high strength and plastic properties.

3.2 Structural analysis

The fracture surfaces analysis of investigated materials showed dominance of transcrystalline ductile fracture [22–25]. The effect of plastic deformation was revealed in particles cracking for the relevant materials. During plastic deformation, particles were cracked and/or particles were divided from interphase surface by means of cavity failure systems, which after that exhibited in the former dimples, Figs. 3a,b–6a,b.

Detailed fractographical examinations revealed that there were two categories of dimples of trans-

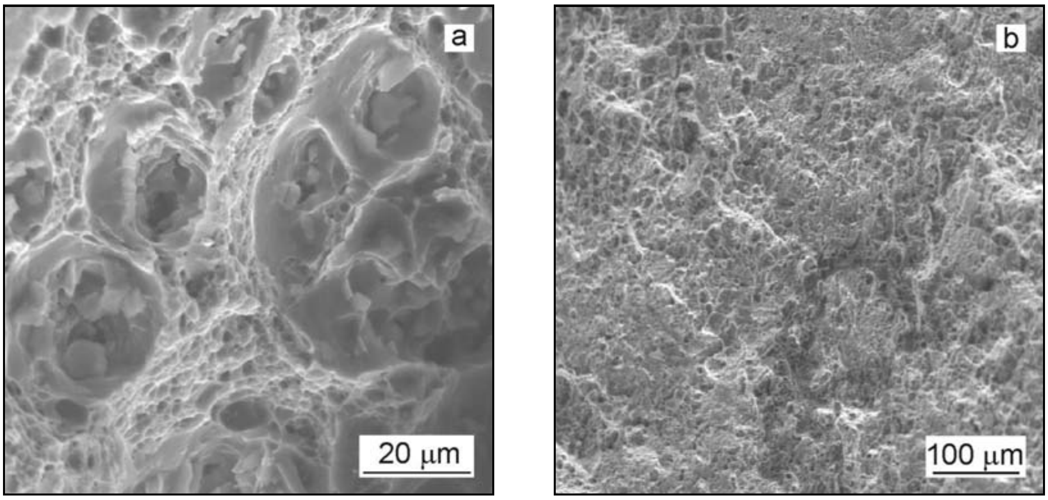

Fig. 5a,b. Transcrystalline ductile fracture – ECAPed state.

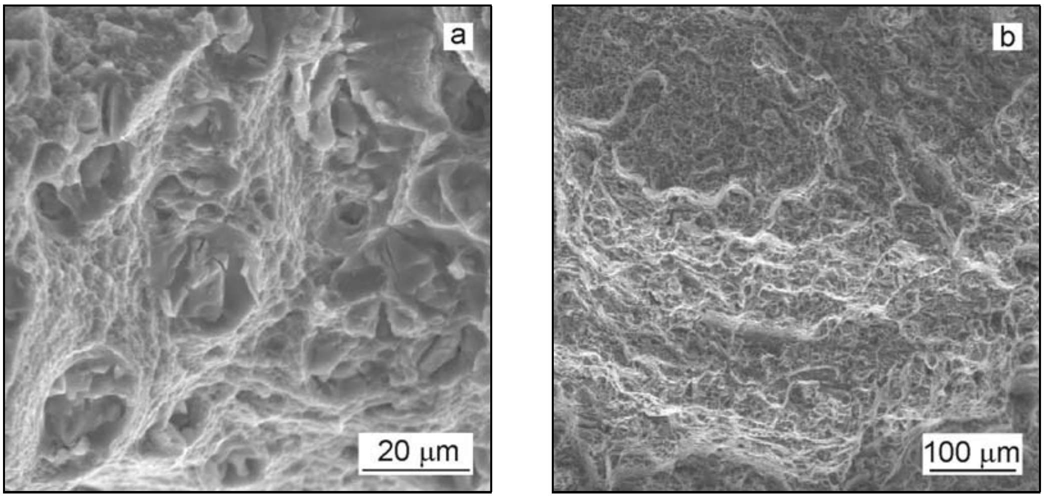

Fig. 6a,b. Transcrystalline ductile fracture – ECAPed + aged state.

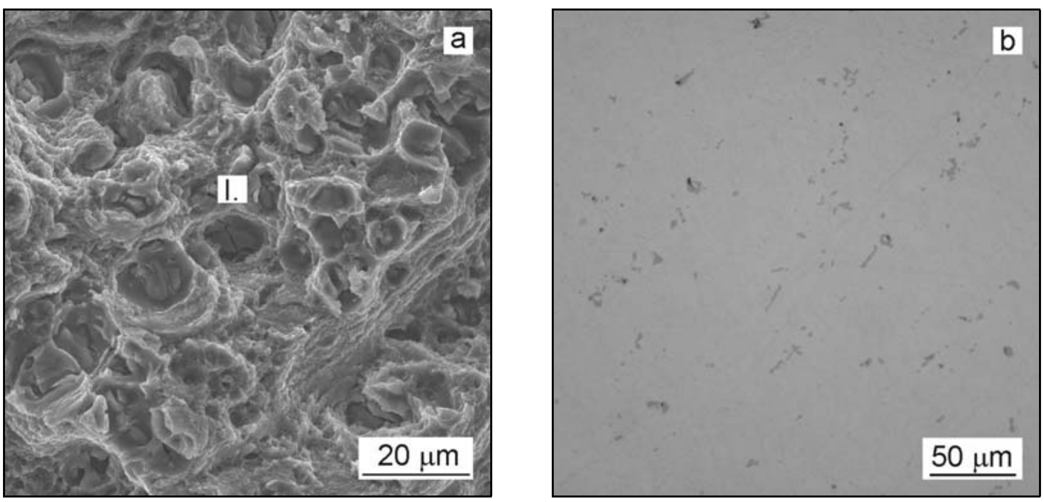

Fig. 7a,b. Intermetallic particles on the base of Fe and Si as initiators of large dimples.

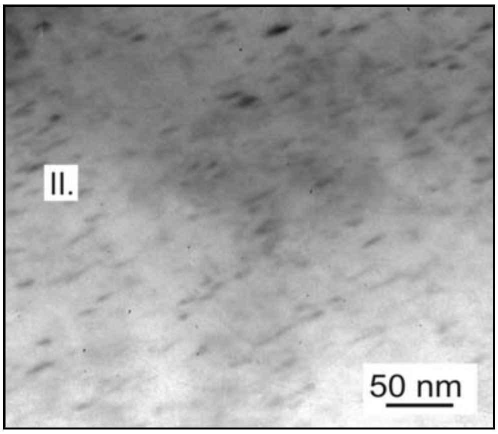

Fig. 8. TEM analysis revealed submicroscopic and dispersive particles as initiators of small dimples.

crystalline ductile fracture: large dimples with average diameter in the range from 5 to 25 μm, formed by the intermetallic particles on the bases of Fe and Si, which can be visible by metallographical examination (Fig. 7a,b) and small dimples with average diameter in the range from 0.5 to 2.5 μm, formed by submicroscopic and dispersive particles, which were observed by TEM investigation, Fig. 8.

Different average diameters of dimples were obtained for the investigated materials, according to the treatment: as-rolled approximately 10 μm, quenched approximately 9.5 μm, ECAPed approximately 8.5 μm and ECAPed + aged approximately 7.8 μm. The difference between dimples was affected by various processing conditions. For the as-rolled state, the initiator can be identified in the $CuAl_2$ particles, while for the quenched one, the role of initiators take intermetallic particles based on Fe and Si. Severe plastic deformation via ECAP method caused grains refinement, strain hardening of solid solution and intermetallic deformed particles.

4. Conclusions

Tensile test results show that, in the stress-strain curves, the stress increased with increasing strain conditions due to severe plastic deformation via ECAP. However, it was observed also that the ECAP exhibited decrease in ductility.

Severe plastic deformation via ECAP may be a very useful process on increasing mechanical properties with only partial and acceptable decrease of ductility. Strengthening of material is caused by grains refinement and strain hardening of solid solution.

Fractographical examinations revealed that there were two categories of dimples of transcrystalline ductile fracture: large dimples, formed by the intermetallic particles and small dimples, formed by submicroscopic and dispersive particles.

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