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TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of Cast Tubular Specimens of Al–5Zn–1Mg While Processing at Room Temperature by Equal Channel Angular Pressing (ECAP)

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Abstract The ECAP process is a promising technique for imparting large plastic deformation and breaking down the ingot cast structure without a resultant decrease in cross-sectional area. In the present study, the suitability of this technique for processing cast Al–5Zn–1Mg tubular specimens at room temperature has been investigated. Tubular specimens were extruded through an ECAP die with an angle of 150° between the two intersecting channels without a back pressure. Sand was used as a mandrel during pressing. The tubular specimens failed miserably in the first pass itself. A failure analysis was carried out using SEM, and cause for failure was determined.

Keywords ECAP · Tube · Mandrel · Al–Zn–Mg · Plastic deformation

Introduction

Segal in 1980s introduced a manufacturing process to process billets with homogeneous simple shear deformation called as equal channel angular pressing (ECAP). It gained enough popularity around the world in 90s, and the processes were improved by several research groups like Iwahashi et al. [1]. Many researches on mechanical properties revealed high strength and good ductility for bulk ultrafine grains which was processed by severe plastic deformation (SPD) techniques [2]. ECAP can be employed even for a cast ingot, thus producing submicron grain structure without residual porosity. ECAP processing involves an intense plastic deformation of the material through two channels of equal cross section intersecting at an angle φ that varies between 60 and 150°. A schematic diagram of ECAP die with sharp and round corner intersections is shown in Fig. 1. Since the two sections of the channels within the die are equal in cross section, there is no change in the billet dimensions during processing. This facilitates repetitive pressing through the channels. According to Segal [3], an important characteristic of ECAP is its ability to fragment the bulk by simple shear into a very fine grain size of one order of magnitude less than that produced by any conventional processing method.

Among aluminum alloys, Al–Zn–Mg system is the hardest of all. Previous researches on the processing of Al and its alloys by ECAP were generally concentrated on the mechanism of grain refinement [4–6]. More recently, there has been a keen interest in controlling the precipitation microstructures of Al alloys and thereby achieving a combination of strengthening from both grain refinement and precipitation hardening [7].

A procedure that can be adopted for overcoming the difficulties in pressing hard and difficult-to-work materials like Al–5Zn–1Mg is by increasing the channel angle φ to a value higher than the conventional angle of 90°. This approach has been successful with several materials. For example, experiments on commercially pure tungsten revealed extensive cracking when pressed at 1273 K with a channel angle of $\varphi = 90°$, whereas appreciable results were achieved for the same temperature when the channel angle was increased to 110° [8]. Similarly, billets of a Mg–8% Li alloy were capable of sustaining only a single

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pass without cracking when pressed at room temperature using a channel angle of $\varphi = 90°$, but the alloy was easily pressed to ten passes at room temperature when the channel angle was increased to 135° [9].

A few works related to property enhancement of wrought tubular specimen were reported by Nagasekhar et al. [10] using ECAP with a channel of 150° without any back pressures, but no work on cast tubular specimen is reported yet. So an attempt to process Al–5Zn–1Mg in tubular form without back pressure is carried out.

In the present study, sand was used as a mandrel for maintaining tube concentricity and form. The use of sand as a mandrel transforms the pressing process into a friction-aided process and expects a reduction in the punch pressure. Therefore, ECAP was carried out at room temperature (which is much lower than the discontinuous recrystallization temperature of 200 °C [11] for commercially pure Al) with a die of 150° angle and MoS_2 lubricated Al–5Zn–1Mg tube to study the feasibility of the process. A good grain refinement effect was observed in most of the soft materials such as Cu [12], Al alloys [13, 14], Fe [15], and low-carbon steel [16, 17] when processed by ECAP at room temperature.

Experimental

Aluminum rods were melted and alloyed with 5 wt.% zinc and 1 wt.% magnesium to get an alloy of Al–5Zn–1Mg. Table 1 shows the bulk chemical analysis of the sample cast. Tubular specimens were machined out of Al–5Zn–1Mg rod with outer diameter of 20 mm, inner diameter of 13 mm, and length of 60 mm, which were used for the pressings (shown in Fig. 2). The end thickness (t) of 3 mm was provided to support the mandrel (sand in this study). The die used for ECA pressing consisted of two intersecting channels 20 mm in diameter intersecting at a die channel angle of 150° and the outer corner angle of 30° (as shown in Fig. 1). A 30° taper was made at one end of specimen to facilitate easy start of ECAP. Molybdenum disulfide was used as lubricant. To avoid buckling, the height to diameter ratio of the punch is kept less than 3. For pressing, the die was assembled, mounted on the press bed, and then secured to the bed with the help of connecting bolts. The experimental setup of the present study is shown in Fig. 3. All the specimens were annealed at 300 °C for 2 h. Specimens were extruded at room temperature in a 250T hydraulic press with a velocity of 13 mm/s. Schematic diagram showing direction of punch travel, mandrel, deformation zone, and exit direction of pressing, of the tubular specimen used for ECA pressing is shown in Fig. 4. It was intended to carryout multipasses using various routes to increase the strain. But the specimens cracked in spite of repeated trials and failed miserably in the first pass itself. A failure analysis of the tube was carried out using scanning electron microscope (SEM) and with the help of data available from the deformation behavior of Al–5Zn–1Mg.

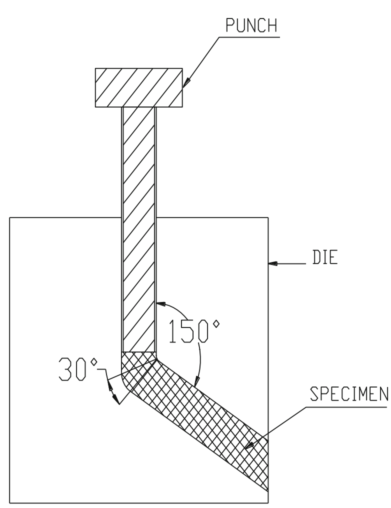

Fig. 1 Schematic diagram of equal channel angular pressing with round corner

Results and Discussion

After each pass, the Von Mises equivalent true strain (e) imparted to the billet by shear through the die in plain strain is dependent upon the channel or die angle ‘2φ’ and outer corner angle ‘χ,’ and it is given by Segal et al. [18] as,

$$\text{The equivalent plastic strain} = 2\cot[\varphi + (\chi/2)] + \chi\operatorname{cosec}[\varphi + (\chi/2)]/\sqrt{3}, \quad \text{(Eq 1)}$$

where $2\varphi = 150°$ and $\chi = 30°$ for the die configuration used in the present study. The equivalent true strain imparted would have been 0.3 if the sample survived a pass, but the sample showed multiple fractures after a pass as shown in Fig. 5. Theoretical work required for ECA pressing of tubular specimens was calculated according to work done principle. Figure 6 shows the stresses and forces acting during ECA pressing of tubular specimens.

Table 1 Chemical composition of the alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Sn	V	Al
wt.%	0.86	0.238	0.016	0.56	1.46	0.0069	5.72	0.0041	0.0031	91.13

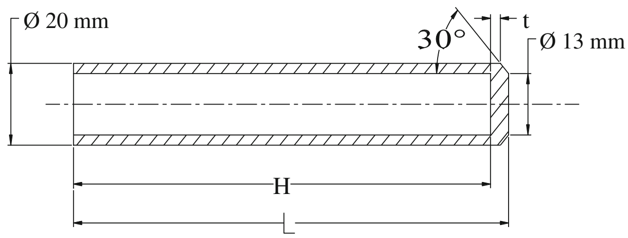

Fig. 2 Dimensions of Al–5Zn–1Mg alloy tube

Fig. 3 Experimental setup of ECAP

Theoretical force required for ECAP of tubes is the addition of the following forces (similar to work done principle in metal forming) [19].That is

$$F_{tot} = F_{Shear} + F_{FW} + F_{FS}\cos\psi - F\cos\psi - F_{FM} - F_{FSM}\cos\psi, \quad \text{(Eq 2)}$$

where F_{tot} is the total pressing force needed for the ECAP; F_{Shear}, the force required for shear deformation; F_{FW}, the force due to friction between the die wall and outer surface of the specimen (before entering deformation zone); F_{FS}, the force in the deformation zone due to friction between die wall and outer surface of the specimen; F_{FM}, the force due to friction between mandrel (sand) and inner surface of the specimen (in the deformation zone); F_{FSM}, the force due to friction between mandrel (sand) and inner surface of the specimen (after leaving the deformation zone); and ψ is the angular separation between the direction of application of load and the direction in which the pressed tube emerges.

The friction factor of Al–5Zn–1Mg at room temperature was determined by Rijesh M et al. [20] using ring compression test, and strength coefficient of Al–5Zn–1Mg was determined at room temperature by a compression test [21].The flow properties are given in Table 2.

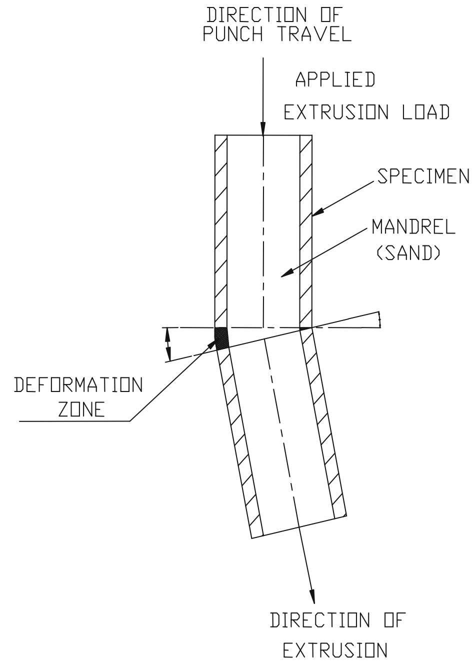

Fig. 4 Schematic diagram showing direction of punch travel, mandrel, deformation zone, exit direction of extrusion, of the tubular specimen used for ECA pressing

Microstructure

The initial microstructure before ECAP consisted of coarse grains in which η' precipitates were homogeneously distributed (Fig. 7). Similar precipitates (η') were identified by Zhang et al. [22] as $MgZn_2$ intermetallic particle, and matrix was semi-coherent. The local dislocation density is generally very high next to the precipitates. The high strength coefficient (K) and strain hardening exponent (n) values reveal the same.

Fracture Analysis

The process of brittle fracture consists of three stages: (1) plastic deformation which involves pileup of dislocations along the slip planes at an obstacle, (2) the buildup of shear stress at the pileup to nucleate a microcrack, and (3) the stored elastic strain energy drives the microcrack to complete fracture without further dislocation movement or a distinct growth stage is observed in which an increased stress is required to propagate the microcrack [23].

In the present study, ECAP, which is a SPD process, would have helped dislocations to pileup near $MgZn_2$ precipitates. ECAP is a material processing technology by simple shear stresses which would help to build up shear stresses at the head of the pileup to nucleate many microcracks in Al–5Zn–1Mg alloy. Shallow dimples intermingled with microscopic cracks suggesting localized

Fig. 5 Al–5Zn–1Mg tubular specimen before and after the first pass

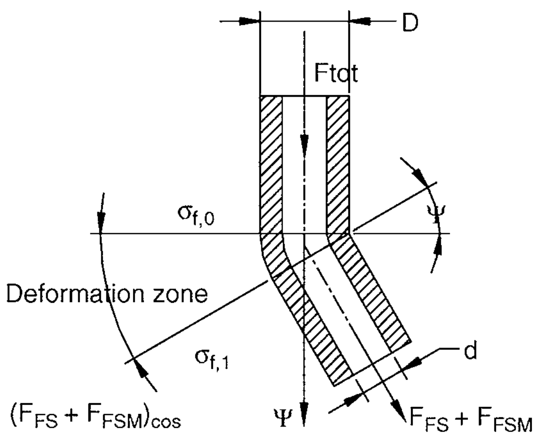

Fig. 6 Stresses and forces during ECAP of tubular specimen geometries [10]

Table 2 Flow properties of Al–5Zn–1Mg at room temperature

Strength coefficient [K(MPa)]	Strain hardening exponent (*n*)	Friction factor (*m*)
611	0.54	0.29

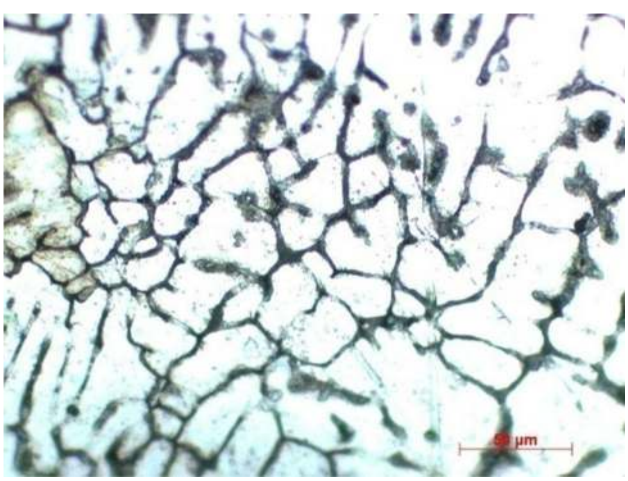

Fig. 7 The microstructure of Al–5Zn–1Mg tubular specimen before ECAP

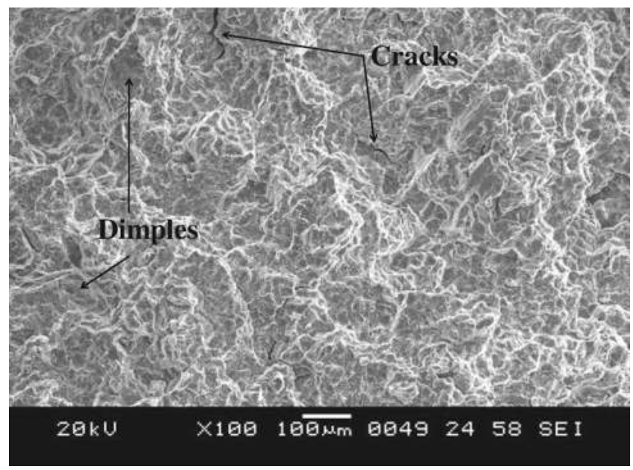

Fig. 8 Shallow dimples intermingled with microscopic cracks suggesting localized ductile and brittle deformation

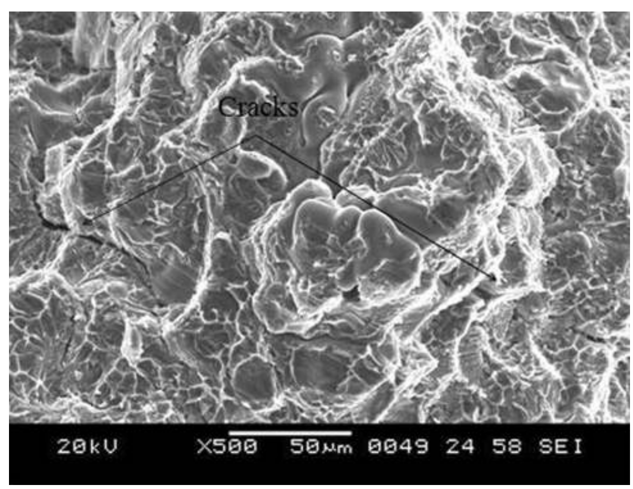

Fig. 9 Microscopic cracks of varying size and shape and dimples

ductile and brittle deformation of Al–5Zn–1Mg alloy are shown in Fig. 8. Since the cross section of tubular section is less than a rod section in area for the equal diameter, the stored elastic strain energy can easily drive the microcrack to complete fracture. Microcrack propagation into various sizes and shapes are shown in Fig. 9. Figure 10 exhibits flat

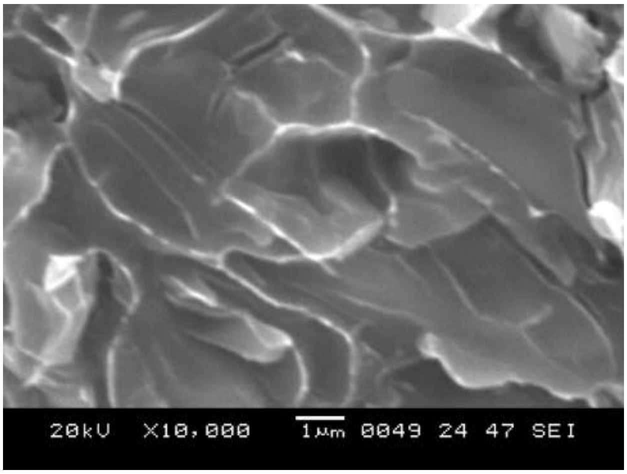

Fig. 10 Cleavage of Al–5Zn–1Mg caused by severe plastic deformation (ECAP) at room temperature

facets. The river markings are caused by the crack moving though the crystal along a number of parallel planes which form a series of plateaus and connecting ledges. These are indications of the absorption of energy by local deformation. The direction of the 'river pattern' represents the direction of crack propagation.

Conclusions

Al–5Zn–1Mg cast ternary alloy have uniform $MgZn_2$ precipitates. These precipitates help in piling-up of dislocations and thus increase the strength of the alloy. ECAP is a simple shear process which buildup shear stresses at the head of pileup, and these shear stresses are responsible for crack nucleation. The tube thickness being 3.5 mm can easily drive the microcracks while forming due to the elastic stored energy.

So it can be concluded that cast Al–5Zn–1Mg tube cannot be processed by ECAP at room temperature without a back pressure. A proper workability range, where precipitates are dissolved, and flow stresses are minimum, is to be determined to process cast Al–5Zn–1Mg tube. A suitable back pressure is also to be determined for a sound product. High heat retention capacity of sand and the movement of mandrel (sand) along with the specimen causing drag friction acting in the same direction as the main punch force are also to be considered while determining the working range.

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