Flow Properties of Cast Al-Zn-Mg Alloys Subjected to Equal Channel Angular Pressing

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Abstract. Flow stress can be described as the stress necessary to continue deformation at any stage of plastic strain. The strength coefficient (K) and strain-hardening exponent (n) are the two important flow properties of the material. In the present work, flow properties of three different cast Al-Zn-Mg alloys processed by equal channel angular pressing (ECAP) were investigated. ECAP processing was carried out in a die having $\Phi = 120°$ and $\Psi = 30°$. After ECAP processing, significant grain refinement and increase in the hardness was observed. Compression test was used to determine the flow properties of ECAP processed samples. Force-stroke data was recorded from the compression test. Flow curves were drawn by using force-stroke data. Strength coefficient and strain-hardening exponent were determined from the log-log plot of true stress-strain curves. Significant increase in the strength coefficient was observed after ECAP processing. Also, the strength coefficient is increased when the zinc content is increased in the alloy. Strain-hardening exponent was decreased with increase in the number of ECAP passes.

Keywords: ECAP, Al-Zn-Mg alloy, Flow curves, Flow properties

1. Introduction

Equal channel angular pressing (ECAP) is one of the effective severe plastic deformation (SPD) methods to develop materials with ultrafine grained (UFG) structure by the application of large strain during deformation [1]. The major advantage of the ECAP processing is that the cross-sectional area of the specimen remains unchanged during processing so that the same specimen can be processed a number of times to accomplish huge plastic strain [2]. Compared to other SPD techniques, ECAP process results in high degree of grain refinement along with the development of high-angle grain boundaries [3]. Also, the technique can be scaled up for processing the large size samples [4]. Aluminium and its alloys are known for its distinctive properties like low density and high strength to weight ratio. Aluminium and its alloys have great potentials for applications towards automotive and aerospace industries [5]. The Al-Zn-Mg alloys fulfil the foremost request of industries in the production of lightweight materials having high toughness and high strength characteristics [5].

Strain-hardening or work-hardening are the terms interchangeably used to define the increase of the stress level essential to continue plastic deformation. The term flow stress is used to define the stress essential to continue deformation at any stage of plastic strain. The engineering stress-strain

curves will not provide proper information of the deformation characteristics of the material in the plastic region because it is based on the original dimensions of the material. To obtain proper information of the deformation characteristics of the material true stress-strain curves are used. True stress-strain curves are normally spoken as flow curves since it provides the stress essential to cause the metal to flow plastically to any given strain. Mathematical explanations of true stress–strain curves are required in engineering investigations that contain plastic deformation. The most commonly used expression is the simple power law equation given by $\sigma = K\varepsilon^n$, where K is the strength coefficient and n is the strain-hardening exponent. This equation is valid after the starting of plastic deformation [6]. The strain-hardening exponent plays a very significant role in stretch forming since it shows the capability of a metal to distribute the strain over a wide region.

Experimental difficulty in measuring the flow curves under metalworking conditions is more severe than in the standard stress-strain test. Generally metalworking process involve large plastic strains, it is desirable to measure the flow curve in strain range from 2.0 to 4.0. Also, many of the metalworking processes involves higher strain rates which is difficult to measure with standard stress-strain test. The true stress-strain curve obtained from the standard tension test is of minimum usefulness since necking restricts the uniform deformation to true strains less than 0.5. The compression test of a cylindrical sample is a much better option for measuring the flow stress in metalworking applications. Since there is no problem of necking formation and the material can be strained to larger extent [7].

To the author's knowledge, there have been only few studies reported on the flow properties of ECAP processed materials. Sivaraman & Chakkingal studied the flow properties after ECAP processing of commercial purity aluminium by compression test. It was reported that, flow stress of commercial pure aluminium was improved after ECAP processing in route A and route C [8]. Preetham Kumar & Chakkingal investigated the flow properties after ECAP processing of commercial pure titanium by compression test. It was reported that, flow stress of commercial pure titanium was improved after ECAP processing in route B_C [9]. The present study is motivated by the realization that, no efforts have been attempted in previous studies to report the flow properties of Al-Zn-Mg alloys subjected ECAP processing. In this work, three different cast Al-Zn-Mg alloys were processed by ECAP and flow properties were evaluated by compression test.
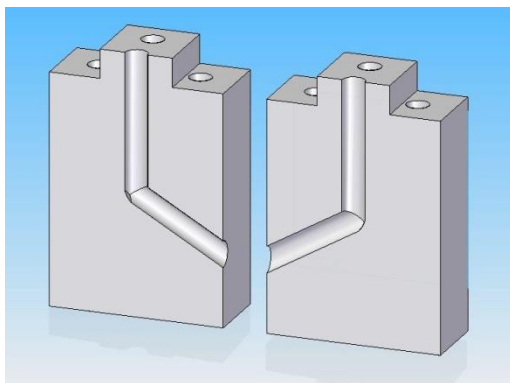
2. Experiments

Figure 1. 3D Model of the ECAP die.

Figure 2. Images of the compression test samples

The materials studied in the present investigation are Al-5Zn-2Mg, Al-10Zn-2Mg and Al-15Zn-2Mg alloys. These alloys were designated as X1, X2 and X3 alloys, respectively. These alloys were prepared by gravity die casting method and the detail procedure of the samples preparation through gravity die casting method was briefly discussed in our earlier work [10]. After casting and before ECAP processing, homogenization treatment of the materials was taken place at 480 ºC upto 20 hours. For ECAP processing, homogenized materials were machined to Ø 15.8 mm and 80 mm length. Figure 1 displays the 3D view of the ECAP die employed in the present work having internal angle

(Φ) of 120º, outer arc of curvature (Ψ) of 30º and channel diameter of 16 mm. ECAP processing was conducted at a speed of 0.5 mm/sec. To avoid friction amid the sample and the die during processing molybdenum disulphide was used as the lubricant. Temperature of the ECAP die was maintained to the required temperature while processing with the help of heating coils. X1 alloy was fruitfully processed upto four number of passes in route B_C at both 150 ºC and 200 ºC. X2 and X3 alloys were successfully processed upto one pass at 150 ºC and samples were failed during second pass in route B_C at 150 ºC. X2 and X3 alloys were fruitfully processed upto four number of passes in route B_C at 200 ºC.

Microhardness measurements were carried out according to ASTM E384 standard by imposing a load of 50 gm up to 15 seconds. To examine the repeatability of the outcomes, 10 microhardness measurements were measured at different locations of the sample and average values were considered. Compression tests were conducted to estimate the flow curves, strength coefficient and strain-hardening exponent of the unprocessed and processed samples. Compression tests were conducted according to ASTM E9-09 standards in room temperature and at a constant cross head speed of 0.5 mm/min. For compression test, cylinder-shaped samples of Ø 8 mm and 10 mm length (h/d ratio 1.25) were machined from the unprocessed and processed samples as shown in figure 2. Cast and homogenized samples were machined parallel to the ingot axis and ECAP processed samples were machined parallel to the processed direction. To control the friction amid the compression test sample and the anvil of the universal testing machine molybdenum disulphide was applied on the mating surfaces. Testing was carried out up to a compressive strain of 0.8. Force-stroke data was recorded from the compression test using a data acquisition system. Flow curves were drawn by using force-stroke data. Strength coefficient and strain-hardening exponent were determined from the log-log plot of true stress-strain curves. The flow stress data from compression test was fitted to the standard strain-hardening Hollomon equation, $\sigma = K\varepsilon^n$. To examine the repeatability of the results three specimens were tested in each condition and average values were considered.

3. Results and discussion

3.1. Microstructure

In cast condition, dendritic morphology was observed in all three alloys and precipitates were located along the inter-dendritic regions. In cast condition, large dendrites of size 200 μm, 280 μm and 200 μm was observed in X1, X2 and X3 alloys, respectively. After homogenization, precipitates in the inter-dendritic regions were uniformly distributed in the aluminium matrix and grain boundaries were observed. After ECAP processing in route B_C, significant decrease in the grain size was perceived. After four passes at 150 ºC the grain size of the X1 alloy was decreased to 3 μm and after four passes at 200 ºC the grain size of the X1 alloy was decreased to 5 μm. After one pass at 150 ºC the grain size of the X2 alloy was decreased to 60 μm and after four passes at 200 ºC the grain size of the X2 alloy was decreased to 8 μm. After one pass at 150 ºC the grain size of the X3 alloy was decreased to 40 μm and after ECAP passes at 200 ºC the grain size of the X3 alloy was decreased to 10 μm. Detailed investigations of the microstructure evolution after ECAP processing of these alloys were presented in our earlier work [11].

3.2. Hardness

Table 1 represents the microhardness of the alloys in different conditions. After ECAP, noticeable increase in the microhardness was observed. After four passes at 150 ºC the hardness of the X1 alloy was increased by 122%. After four passes at 200 ºC the hardness of the X1 alloy was increased by 94%. After one pass at 150 ºC the hardness of the X2 alloy was increased by 50%. After four passes at 200 ºC the hardness of the X2 alloy was increased by 67%. After one pass at 150 ºC the hardness of the X3 alloy was increased by 46%. After four passes at 200 ºC the hardness of the X3 alloy was increased by 58%. It was observed that, processing the material at lower temperature leads to more reduced grain size and better enhancement in the hardness. The increase in the hardness of the alloys

after ECAP processing is credited to the reduction in the grain size of the alloys. Also, hardness of the alloy also increased when the zinc content is increased in the alloy. A detailed discussion on the mechanical properties of these alloys after ECAP processing were presented in our earlier work [11].

Table 1. Microhardness (Hv) of the alloys in different conditions

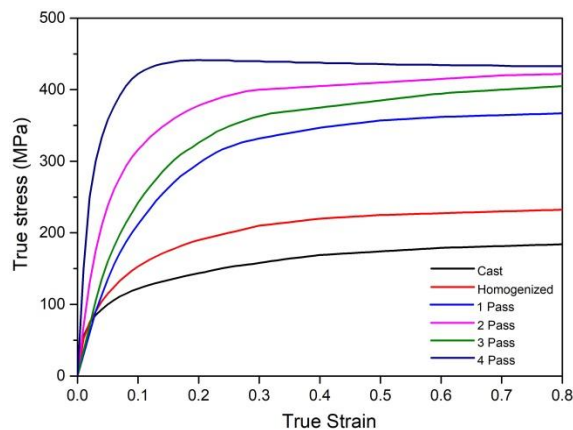| Processing temperature	X1 alloy		X2 alloy		X3 alloy	
	150 ºC	200 ºC	150 ºC	200 ºC	150 ºC	200 ºC
Cast	90	90	144	144	173	173
Homogenized	105	105	155	155	189	189
1 pass	168	158	216	204	252	239
2 pass	192	175	-	223	-	261
3 pass	188	184	-	232	-	274
4 pass	200	188	-	240	-	274

3.3. Flow properties

Figure 3. Flow curves of the X1 alloy ECAP processed at 150 ºC.
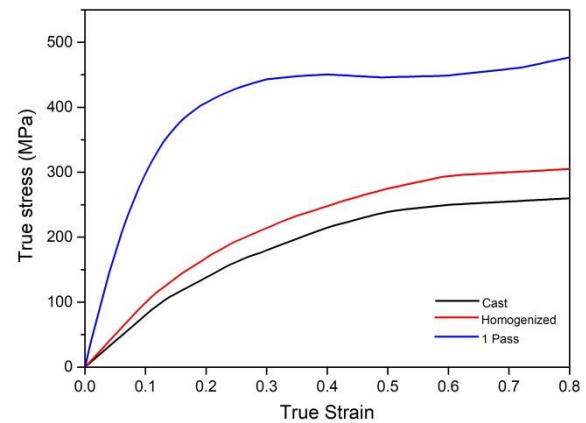

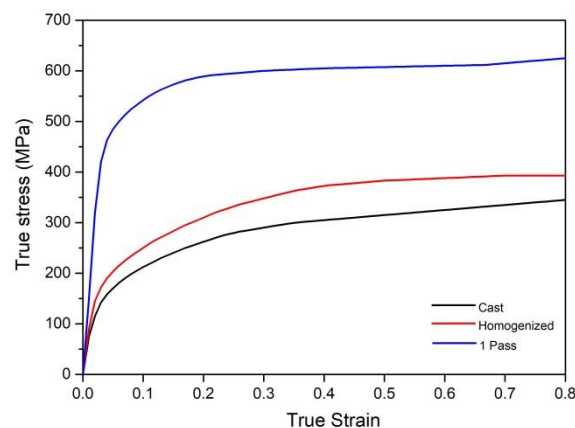**Figure 4.** Flow curves of the X2 alloy ECAP processed at 150 ºC.

Figure 5. Flow curves of the X3 alloy ECAP processed at 150 ºC.

Figure 3 shows the flow curves of the X1 alloy ECAP processed at 150 ºC. The strain-hardening rate is initially less in cast and homogenized samples and it increases with increasing the strain. The strain-hardening rate is initially high in the ECAP processed samples and it decreases with increasing the strain. It was observed that ECAP processed samples exhibits better strength compared to cast and

homogenized samples. After first pass, noticeable increase in the strength of the material was perceived compared to later passes. Figure 4 shows the flow curves of the X2 alloy ECAP processed at 150 ºC. Similar to X1 alloy, the strain-hardening rate is initially less in cast and homogenized samples and it increases with increasing the strain. Also, the strain-hardening rate is initially high in the ECAP processed sample and it decreases with increasing the strain. X2 alloy exhibits better strength compared to X1 alloy in cast and homogenized conditions. This is due to the increase in the zinc quantity in X2 alloy compared to X1 alloy. Figure 5 shows the flow curves of the X3 alloy ECAP processed at 150 ºC. The strain-hardening behaviour is similar to those observed in X1 and X2 alloys. X3 alloy exhibits better strength compared to X1 and X2 alloy in cast and homogenized conditions. This is due to the increase in the zinc quantity in X3 alloy compared to X1 and X2 alloys.
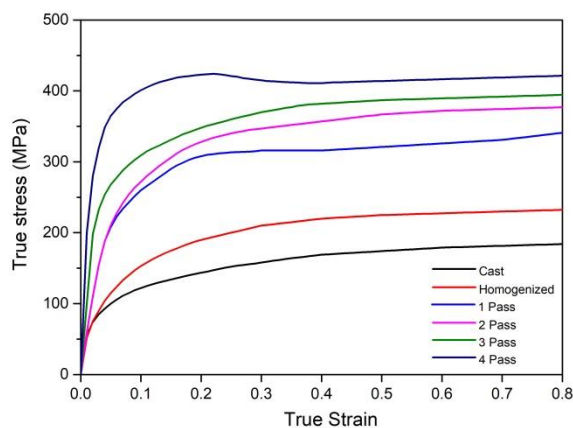

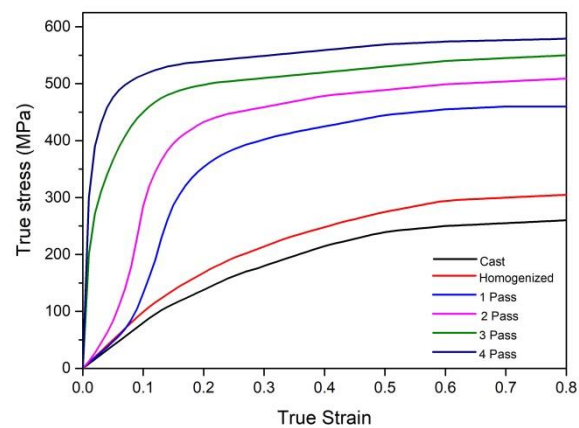**Figure 6.** Flow curves of the X1 ECAP processed at 200 ºC.

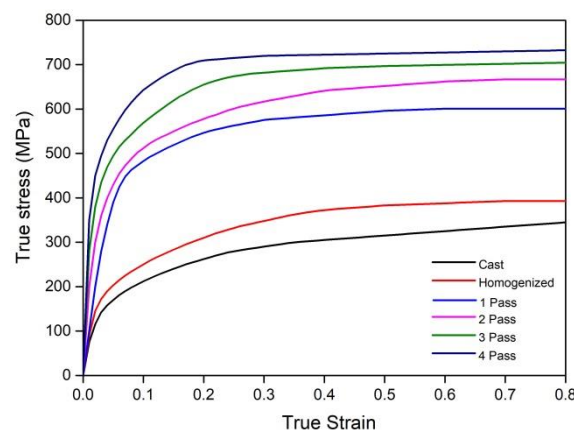**Figure 7.** Flow curves of the X2 alloy ECAP processed at 200 ºC.

Figure 8. Flow curves of the X3 alloy ECAP processed at 200 ºC.

Figure 6 shows the flow curves of the X1 alloy ECAP processed at 200 ºC. Similar trend was observed in strain-hardening behaviour of X1 alloy while ECAP processing at 200 ºC compared to ECAP processing at 150 ºC. However, the strength of the alloy is slightly reduced with increase in the processing temperature from 150 ºC to 200 ºC. Figure 7 shows the flow curves of the X2 alloy ECAP processed at 200 ºC. Figure 8 shows the flow curves of the X3 alloy ECAP processed at 200 ºC. Similar trend was observed in the strain-hardening behaviour of the X2 and X3 alloys compared to X1 alloy ECAP processed at 200 ºC. X2 alloy exhibits better strength compared to X1 alloy; this is credited to the increase in the zinc quantity in X2 alloy compared to X1 alloy. Similarly, X3 alloy exhibits better strength compared to X1 and X2 alloy; this is attributed to the increase in the zinc quantity in X3 alloy compared to X1 and X2 alloys. In all three alloys, strength increased with

increase in the ECAP passes. But, after first pass significant increase in the strength was perceived compared to later passes.

Generally, true stress-strain curves attained from the compression test of UFG materials will have initial small region of strain-hardening immediately followed by a long region of minor strain-hardening and even sometimes work-softening. The strain-hardening area is moderately small and in the strain range of 1–3%. While coarse grained (CG) materials exhibits strong strain-hardening behaviour to large strains. UFG materials obtained from SPD methods are usually composed of high density of dislocations and show flat true stress-strain curves. The strain-hardening behaviour in UFG materials is very small since the density of dislocations attained to a saturation level in the occurrence of dynamic recovery. Strain-hardening is possible only when large additional strain is imposed. Therefore, over a range of plastic strains the flow stress would seem to have attained a steady state.

Strain hardening exponent is a measure of persistence of hardening. Generally, the strain hardening exponent of the materials varies from 0.1 to 0.6 for different materials. If the strain hardening exponent is low, strain-hardening rate is initially high, but it decreases with increasing the strain. In contrast, if the strain hardening exponent is high, the initial work hardening is less and it increases with increasing the strain. The strain hardening exponent shows how the material behaves when it is being formed. Materials with high strain hardening exponent have better formability than those with low strain hardening exponent. If the strain hardening exponent is high, the flow stress increases with the strain results in distribution of strain uniformly throughout the material. Owing to this uniform distribution, forming limit or formability increases. Consequently, more material can be elongated before necking.

Table 2. Strength coefficient (*K*) and strain hardening exponent (*n*) of the alloy ECAP processed at 150 ºC.

	X1 alloy		X2 alloy		X3 alloy	
	K (MPa)	*n*	*K* (MPa)	*n*	*K* (MPa)	*n*
Cast	180	0.38	260	0.32	340	0.28
Homogenized	215	0.36	295	0.3	390	0.25
1 pass	366	0.28	482	0.22	620	0.16
2 pass	418	0.24	-	-	-	-
3 pass	406	0.22	-	-	-	-
4 pass	432	0.21	-	-	-	-

Table 3. Strength coefficient (*K*) and strain hardening exponent (*n*) of the alloy ECAP processed at 200 ºC.

	X1 alloy		X2 alloy		X3 alloy	
	K (MPa)	*n*	*K* (MPa)	*n*	*K* (MPa)	*n*
Cast	180	0.38	260	0.32	340	0.28
Homogenized	215	0.36	295	0.3	390	0.25
1 pass	334	0.3	446	0.24	600	0.18
2 pass	374	0.26	509	0.21	665	0.15
3 pass	393	0.23	552	0.19	696	0.13
4 pass	408	0.22	574	0.18	720	0.12

Table 2 presents the strength coefficient and strain-hardening exponent extracted from the flow stress data of the X1, X2 and X3 alloys ECAP processed at 150 ºC. Considerable improvement in the strength coefficient of the alloys was perceived after ECAP processing. After four passes, the strength coefficient of the X1 alloy was increased by 140%. After one pass, the strength coefficient of the X2 alloy was increased by 86%. After one pass, the strength coefficient of the X3 alloy was increased by 82%. But, the strain-hardening exponent was decreased with increase in the ECAP passes. It may be noted that, after ECAP processing substantial increase in the hardness and strength of the alloys were

perceived [11]. It was deduced that, high strength materials have lower strain-hardening exponent than the low strength materials [6]. Accordingly, ECAP processed samples have high strength and possess lower strain-hardening exponent, while the cast and homogenized samples have low strength and possess higher strain-hardening exponent. It was also perceived that, the strain-hardening exponent decreased when the zinc content is increased in the alloy. Since the high zinc content alloys have high strength possess lower strain-hardening exponent than the low zinc content alloys.

Table 3 presents the strength coefficient and strain-hardening exponent obtained from the flow stress data of the X1, X2 and X3 alloys ECAP processed at 200 ºC. Similar type of observations were seen in the strength coefficient and strain-hardening exponent of the X1 alloy ECAP processed at 200 ºC compared to ECAP processing at 150 ºC. The strength coefficient was increased with the increase in the ECAP passes. But, after first pass significant increase in the strength coefficient of the material was perceived compared to later passes. After four passes, the strength coefficient of the X1 alloy was increased by 127%. It was observed that, increase in the processing temperature from 150 ºC to 200 ºC leads to slight decrease in the strength coefficient. But, the strain-hardening exponent was slightly increased with increase in the processing temperature. The strength coefficient of the X2 and X3 alloys also increased after ECAP processing at 200 ºC. After four passes, the strength coefficient of the X2 and X3 alloy was increased by 121% and 112%, respectively. It was perceived that, the strength coefficient of the X2 alloy is higher than the X1 alloy; this is due to the increase in the zinc quantity in X2 alloy compared to X1 alloy. Also, the strength coefficient of the X3 alloy is higher than the X1 and X2 alloy, this is due to the increase in the zinc quantity in X3 alloy compared to X1 and X2 alloy.

4. Conclusions

The main conclusions of the present work are as follows-
- After ECAP, significant grain refinement and noticeable improvement in the hardness was observed. In all three alloy, ECAP processed samples possess better strength compared to cast and homogenized samples.
- In cast condition, strength coefficient of 180 MPa, 260 MPa and 340 MPa was observed in X1, X2 and X3 alloys, respectively. After four passes at 150 ºC, strength coefficient of the X1 alloy was improved to 432 MPa. After one pass at 150 ºC, strength coefficient of the X2 and X3 alloys was improved to 482 MPa and 620 MPa, respectively.
- After four passes at 200 ºC, strength coefficient of the X1, X2 and X3 alloy was improved to 408 MPa, 574 MPa and 720 MPa, respectively. Strain-hardening exponent was decreased with increase in the ECAP passes. Also, it decreased when the zinc content is increased in the alloy.

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