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Correlation between shear punch and tensile measurements for an AZ31 Mg alloy processed by equal-channel angular pressing

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Abstract

An AZ31 magnesium alloy was extruded and then processed by equal-channel angular pressing (ECAP) at 200 °C for 1, 2, and 4 passes. The grain structure was refined from 20.2 to 1.6 μm after 4 passes. The shear punch testing (SPT) technique and uniaxial tensile tests were employed to evaluate the mechanical properties of the extruded and ECAP samples. The 4 pass ECAP alloy showed lower yield stress and higher ductility compared to the as-extruded condition, indicating that texture softening overcame the strengthening effects of grain refinement. The same trends in strength and ductility were also observed in shear punch testing. Three different linear correlations between the shear data and tensile data were established for ductility, yield stress, and ultimate strength. It is shown that SPT is a useful method for evaluating the mechanical properties of small quantities of fine-grained materials processed by ECAP.

Key words: equal-channel angular pressing (ECAP), magnesium alloy, shear punch test, tensile testing, texture

1. Introduction

Magnesium alloys are promising candidate materials for extensive use in the automobile, aerospace and electronic industries because of their low density, excellent damping capacity, good recycling capacity and machinability. Their superior specific stiffness and strength offer a broad range of technical applications, particularly in the automotive industry where it is imperative to reduce vehicular weight and hence fuel consumption [1]. Despite these advantages, they have poor formability and limited ductility at room temperature due to their hexagonal close-packed (hcp) structure and limited slip systems. Accordingly, many attempts have been made to improve the formability of wrought Mg alloys [2].

It is well known that microstructural refinement is an effective way for increasing both the ductility and strength of these alloys. This goal can be achieved by a variety of techniques including by imposing significant severe plastic deformation [3] in processes such as equal-channel angular pressing (ECAP) [4] and high-pressure torsion (HPT) [5]. In processing by ECAP, the cast or extruded material is repetitively pressed through a die contained within an L-shaped channel so that a very high shear strain is introduced without any change in the cross-sectional area. It has been shown that the optimum microstructural homogeneity is produced by rotating the sample through 90° around the longitudinal axis after each pass where this is designated route B_c [6].

Because of their low ductility, magnesium alloys are generally processed by ECAP at temperatures at or above 473 K in order to avoid cracking. Typically, processing at these temperatures gives a grain size of the order of about 1 μm [7] and the ECAP microstructures usually have a high degree of homogeneity [8]. It has been suggested that ECAP is most effective in Mg-based alloys when using a two-step procedure in which the materials are prepared initially by extrusion

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*Corresponding author: tel.: +98 21 8208 4137; fax: +98 21 8800 6076; e-mail address: mahmudi@ut.ac.ir and then subsequently processed by ECAP in the procedure termed EX-ECAP [9]. The success of the intermediate extrusion step is attributed to the production of a texture in extrusion where a majority of the basal planes lie parallel to the extrusion direction [10] so that the basal planes are no longer oriented for easy slip in the subsequent processing by ECAP.

The mechanical properties of Mg alloys depend strongly on the crystallographic texture, mainly due to the limited slip systems of their hcp structure at room temperature [11]. In spite of the grain refinement produced in Mg alloys by ECAP, the yield strength often decreases while the ductility is improved. This behaviour has been attributed to an unusual texture in which the basal planes are highly inclined ($\sim 45°$) to the extrusion axis [12–14].

It is well documented for numerous materials that the tensile strength can be related to the effective shear strength obtained through the shear punch testing (SPT) method of thin specimens [15, 16]. The SPT method is attractive because it provides a means of evaluating the flow properties when only a small amount of material is available, and this becomes important in ECAP samples with only limited dimensions. The SPT procedure is similar to the blanking operation in which a flat cylindrical solid punch shears sheet material through a die at a constant speed. The load-displacement curve obtained from the punch shearing operation exhibits many similarities to that of tensile test curves, including an initial linear elastic region, a yield point, a plastic deformation region and an ultimate load. Guduru et al. [17] thoroughly studied the effect of sample thickness, die-punch clearance and the strength of materials on the variation of yield and ultimate strength measured by SPT and their results showed a good correlation between the shear punch and tensile data for yield and ultimate strengths.

Although this technique was initially employed for testing thin rolled materials, it was extended recently to magnesium alloys processed by ECAP [18, 19]. Thus, the SPT method seems to be suitable for the assessment of the mechanical properties of ECAP materials. In the present study, the AZ31 Mg alloy (Mg-3%Al-1%Zn) was extruded and processed to 4 passes of ECAP following route B_c and the room temperature mechanical properties were then evaluated using both tensile and shear punch tests. The results confirm there is a direct correlation between the shear and tensile test data.

2. Experimental material and procedures

2.1. Material and processing

High purity Mg (99.90 wt.%), Al (99.84 wt.%) and Zn (99.95 wt.%) were used to prepare the Mg-3Al-1Zn-0.3Mn (AZ31) alloy. Melting was carried out in an electrical furnace held at 750 ℃ under a covering flux to protect molten magnesium from oxidation. The melt was then poured into a preheated steel die by a tilt casting technique in order to minimize the casting defects and turbulences in the melt. The cast billets of 44 mm diameter were homogenized at 385 ℃ for 12 h and extruded to 11 mm × 11 mm bars at 370 ℃. The billets for ECAP, having dimensions of 10 mm × 10 mm × 80 mm, were machined from the extruded bars. The ECAP was performed at 200 ℃ using a die with a channel angle of $\Phi = 90°$ and an arc of curvature at the intersection of the channels of $\psi = 20°$. The samples subjected to repetitive pressings were rotated by 90° in the same sense between each pass in the procedure designated route B_c. These die angles lead to an imposed strain of ~ 1 on each passage through the die [20]. Samples were sprayed with MoS_2 lubricant prior to pressing and they were pressed at a speed of $1\ \mathrm{mm\,s^{-1}}$ for 1, 2 and 4 passes.

The microstructures of the side faces (perpendicular to the transverse direction) of the ECAP billets at the exit from the die were examined by optical metallography and scanning electron microscopy (SEM). The metallographic samples were polished using 0.3 μm α-Al_2O_3 and then etched in a solution of 4.2 g picric acid, 10 ml acetic acid, 10 ml distilled H_2O and 70 ml ethanol. Microanalysis was carried out using the X-ray energy dispersive spectroscopy (EDS) system of the SEM. The intensity distributions of the $\{0002\}$ and $\{10\bar{1}0\}$ pole figures were measured by the Schultz reflection method of the side face of the ECAP specimens. This measurement was performed using Co Kα radiation at 50 kV with the sample tilt angle ranging from 0° to 90°.

2.2. Mechanical property measurements

Miniature dog-bone tensile specimens, 12 mm long, 3 mm wide, and 2 mm thick, were cut using electro-discharge wire-cut machining along the longitudinal direction of the ECAP specimens. Tensile tests were carried out at room temperature with an initial strain rate of $1 \times 10^{-3}\ \mathrm{s^{-1}}$. The strength of the materials was also assessed using the SPT technique. Several 800 μm thick slices were cut from the ECAP bars parallel to the extrusion direction. These slices were carefully ground to a thickness of 500 μm and located in a specially designed fixture with a 3.175-mm diameter flat cylindrical punch and 3.225-mm diameter receiving hole: a schematic illustration is given in Fig. 1. Details of the testing arrangement are provided elsewhere [21], and therefore only a brief description is included here. All shear punch tests were performed at room temperature using a screw-driven MTS testing system. Tests were run with a load cell of 20 kN capacity and a constant cross-head speed of 0.1 mm min^{-1}. After application of the load, the applied load P was measured automatically as a function of punch displacement. The data were acquired by a computer so as to determine the shear stress of the tested materials using the relationship

$$\tau = \frac{P}{\pi d t}, \tag{1}$$

where P is the punch load, t is the specimen thickness, and d is the average of the punch and die diameters. Three different samples were tested for each condition and it was found that the variations in the measured values of the ultimate shear strength were very small.

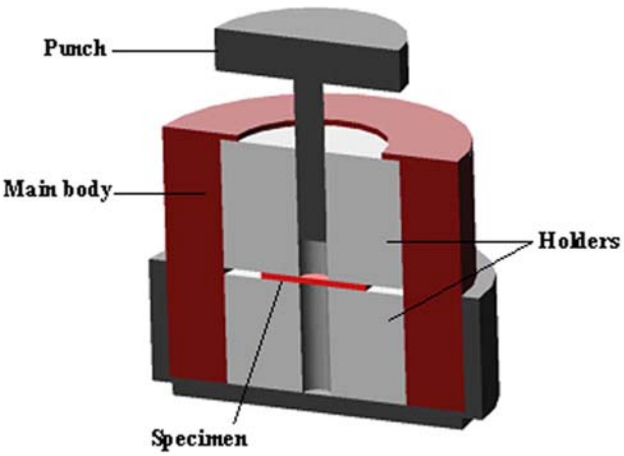

Fig. 1. Schematic representation of shear punch-die assembly.

3. Results and discussion

Figure 2 shows the microstructural evolution of the AZ31 alloy in the as-extruded condition and after processing by ECAP for 1, 2, and 4 passes. It is apparent that the extruded and ECAP microstructures consist of equiaxed grains, thereby implying that dynamic recrystallization has occurred during the hot extrusion and ECAP process. In the fine-grained materials, a uniform grain size distribution is important in achieving homogeneous mechanical properties. The grain size distribution data for the extruded and ECAP conditions, collected from a number of samples,

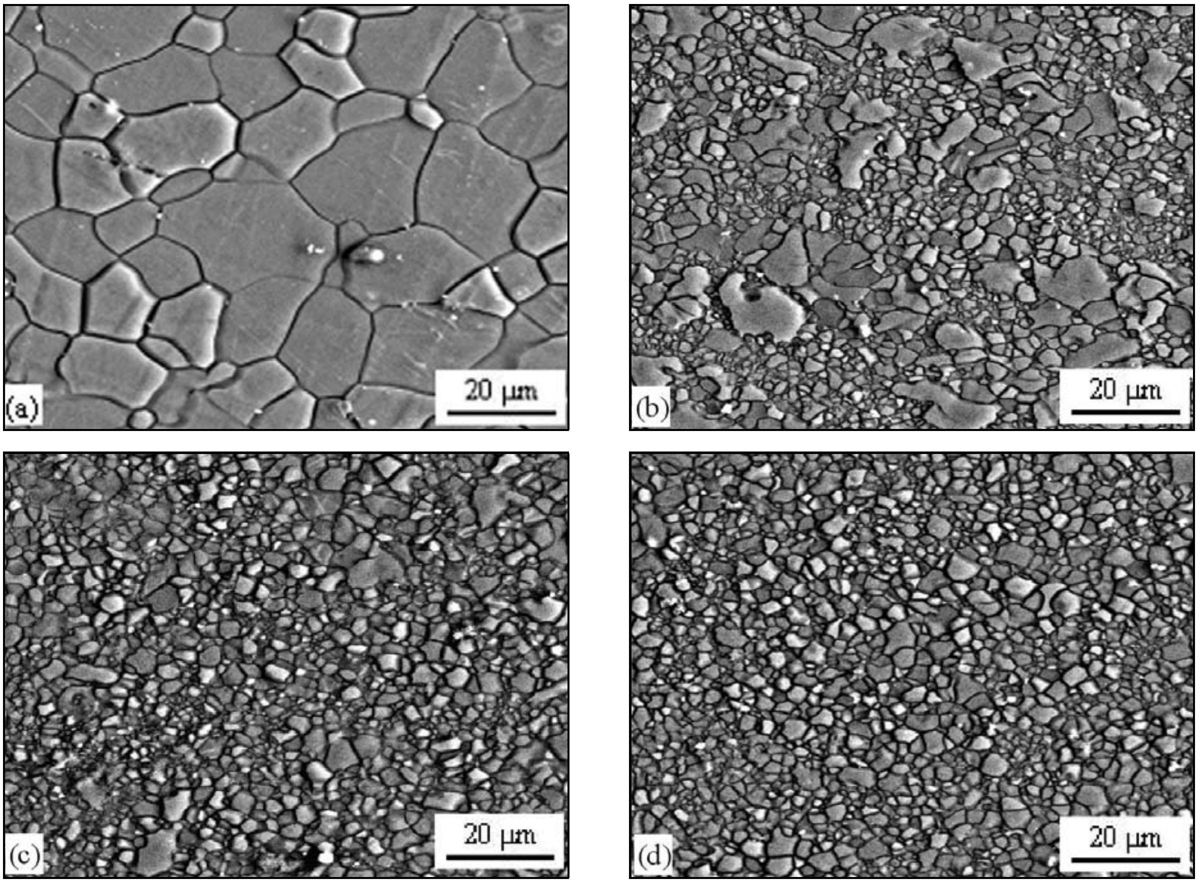

Fig. 2. SEM micrographs showing the microstructural evolution after: (a) extrusion, (b) 1 ECAP pass, (c) 2 ECAP passes, and (d) 4 ECAP passes.

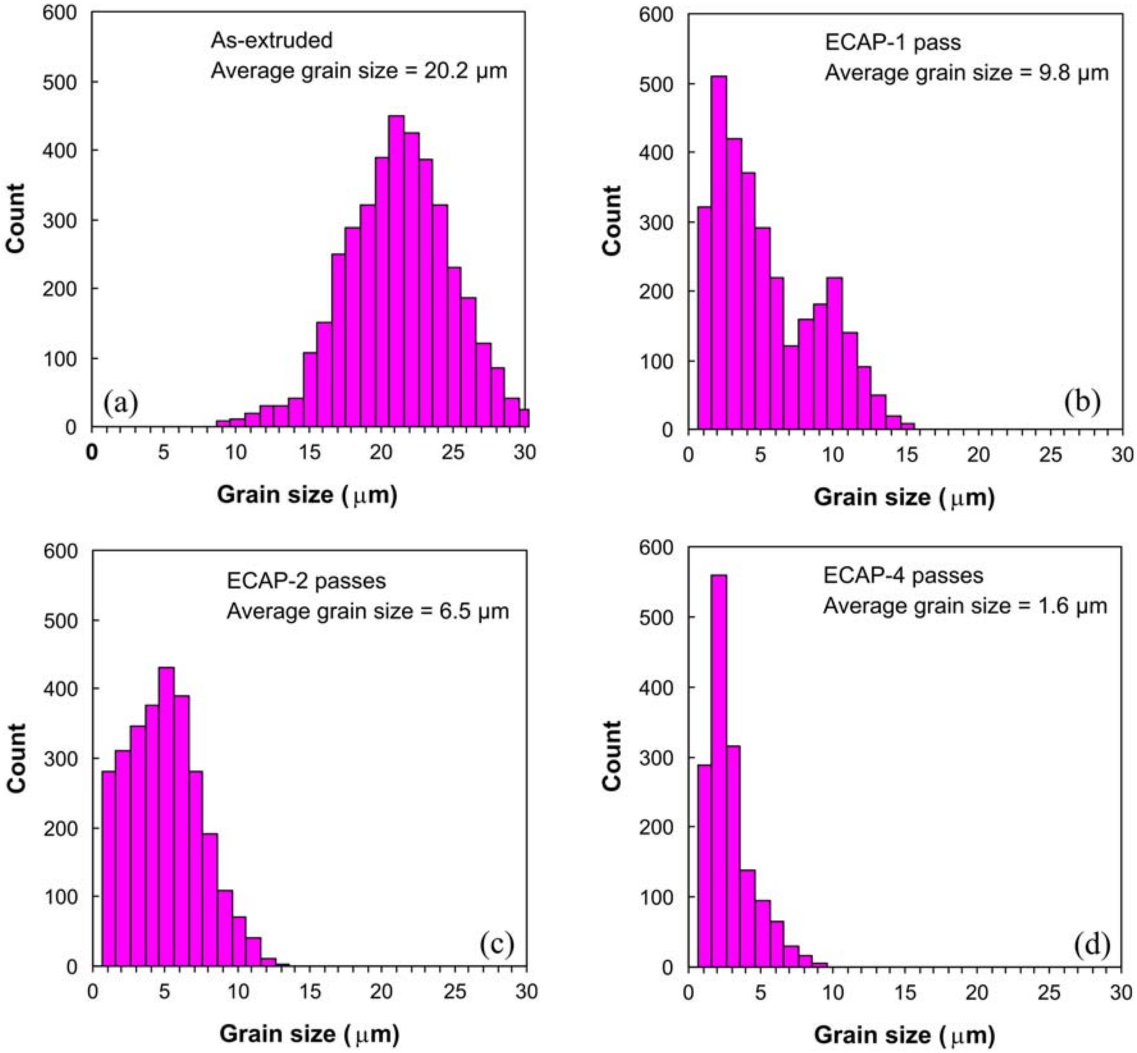

Fig. 3. Average grain size and grain-size distribution of: (a) as-extruded, (b) 1 ECAP pass, (c) 2 ECAP passes, and (d) 4 ECAP passes.

are shown in Fig. 3. It is clear from Figs. 2a and 3a that a near-normal distribution prevails for the extruded material with an average grain size of about 20.2 µm. According to Figs. 2b and 3b, after one pass of ECAP the grains of the initial microstructure are split into a bimodal distribution of fine grains (1.5–2 µm) and coarse grains (9–10 µm). A model for the development of bimodal grain structures in magnesium alloys processed by ECAP was developed recently [22]. However, as anticipated from the model, the bimodal structure is lost at higher strains and it is evident from Fig. 3c that it is no longer present after 2 passes. Finally, the microstructure becomes reasonably uniform with an average grain size of about 1.6 µm after 4 passes of ECAP (Figs. 2d and 3d).

The $\{0002\}$ and $\{10\bar{1}0\}$ pole figures of the AZ31 alloy in the extruded condition and after ECAP for 4 passes are shown in Fig. 4. In the as-extruded condition (Figs. 4a,b), it is evident that the $\{0002\}$ basal planes and the $\langle 10\bar{1}0\rangle$ directions in the basal plane are mostly oriented parallel to the extrusion direction. After 4 ECAP passes, however, the $\{0002\}$ basal planes and the $\langle 10\bar{1}0\rangle$ directions are inclined at about 45° to the extrusion axis, as shown in Figs. 4c,d. A similar orientation of basal planes with respect to the extrusion direction after direct extrusion and ECAP was observed in other investigations of Mg alloys [10, 12, 13]. The rotation of the basal planes during ECAP process appears to be related to shearing parallel to the basal planes [13]. Based on the X-ray diffraction analyses of ECAP AZ31, it was suggested that the distribution of basal plane is similar for the directions parallel and perpendicular to the extrusion direction [10]. The stronger texture achieved after ECAP may be attributed to the fact that route B_c in ECAP represents a highly redundant strain path [23, 24] that is in sharp contrast with the monotonic strain imposed in conventional extrusion. This may have a profound effect on the texture since there is a single textural fibre evident, where the basal

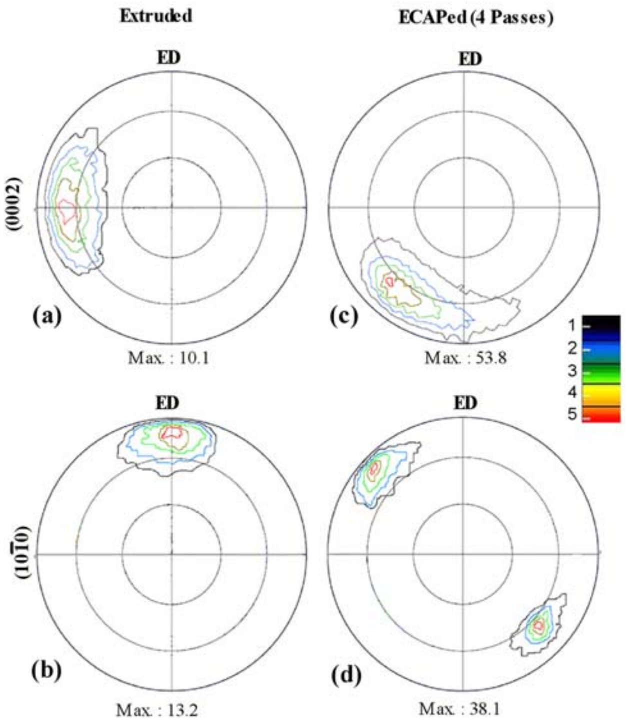

Fig. 4a–d. $\{0002\}$ and $\{10\bar{1}0\}$ pole figures for the extruded and 4-pass ECAP conditions.

planes are aligned with the shear plane of the ECAP die.

Figures 5a,b show, respectively, the tensile and shear punch test results of the material after ECAP for 1, 2, and 4 passes compared with those of the extruded alloy. There are two important findings in the tensile behaviour (Fig. 5a). First, the yield stress decreases after 4 ECAP passes although the grain size decreases considerably. Secondly, the ductility increases with increasing numbers of passes. Furthermore, after 4 passes of ECAP, the alloy has approximately the same ultimate tensile strength values as those of the extruded material although their yield stresses are lower. This may imply that the strain hardening capacity of the material has increased after 4 ECAP passes. The same type of trend is observed in the shear punch testing results (Fig. 5b) which plot the variation of shear stress with normalized displacement. These results are similar to the conventional tensile stress–strain curves such that, after a linear elastic behaviour, the curve deviates from linearity before it reaches a maximum point. The deviation point is taken as the shear yield stress (SYS) and the stress corresponding to the maximum point is referred to as the ultimate shear strength (USS). The decrease in yield stress, despite decreasing grain size, in the ECAP material is attributed to the texture modification occurring in the hcp crystal structure of Mg [11].

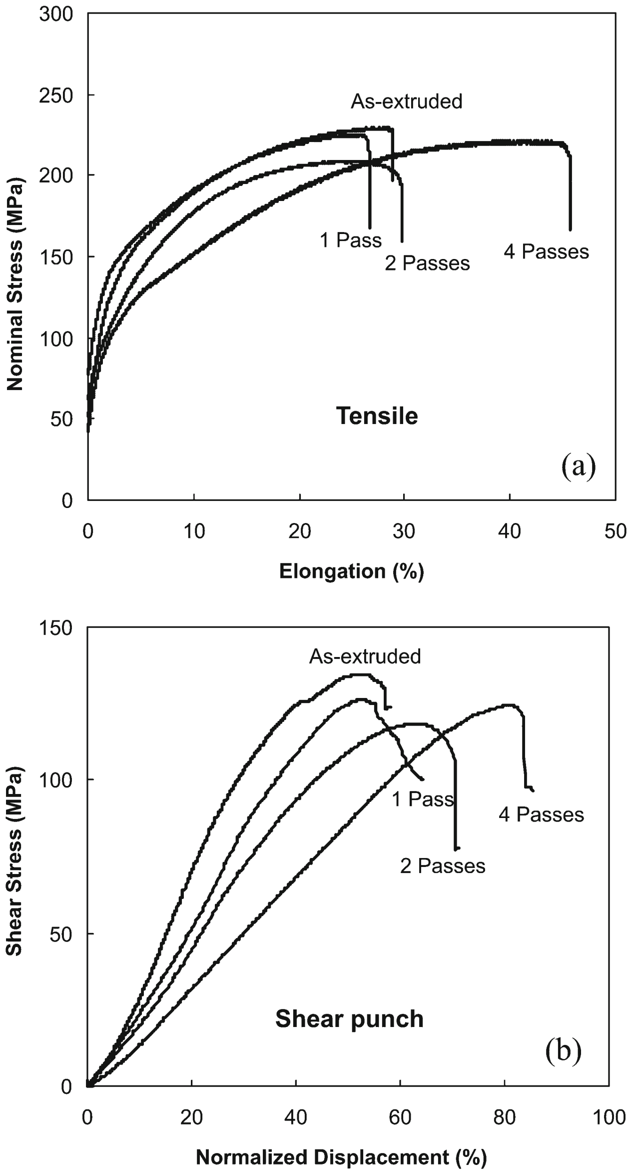

Fig. 5. (a) Engineering stress-strain and (b) shear stress plotted against punch displacement normalized initial thickness for extruded and ECAP conditions.

Metals with an hcp structure are known to develop a simple $\langle 10\bar{1}0\rangle$ fibre texture that is parallel to the axisymmetric direction after axisymmetric deformation in wire drawing or extrusion at low temperatures [25]. In Mg alloys, the basal plane rotates until it contains the wire axis (Figs. 4a,b), tending to coincide with the direction in the basal plane. Rolling tends to rotate the slip plane of hcp metals into the plane of the rolled sheet and the predominant textures are $\{0001\}$ $\langle\bar{1}\bar{1}20\rangle$ or $\{0001\}$ $\langle 10\bar{1}0\rangle$ [25]. Primary slip also occurs on the (0001) basal planes in Mg alloys at room temperature because of their low critical resolved shear stress by comparison with non-basal slip on the prismatic and pyramidal planes [26]. Therefore, for the rolled and extruded materials slip on the basal

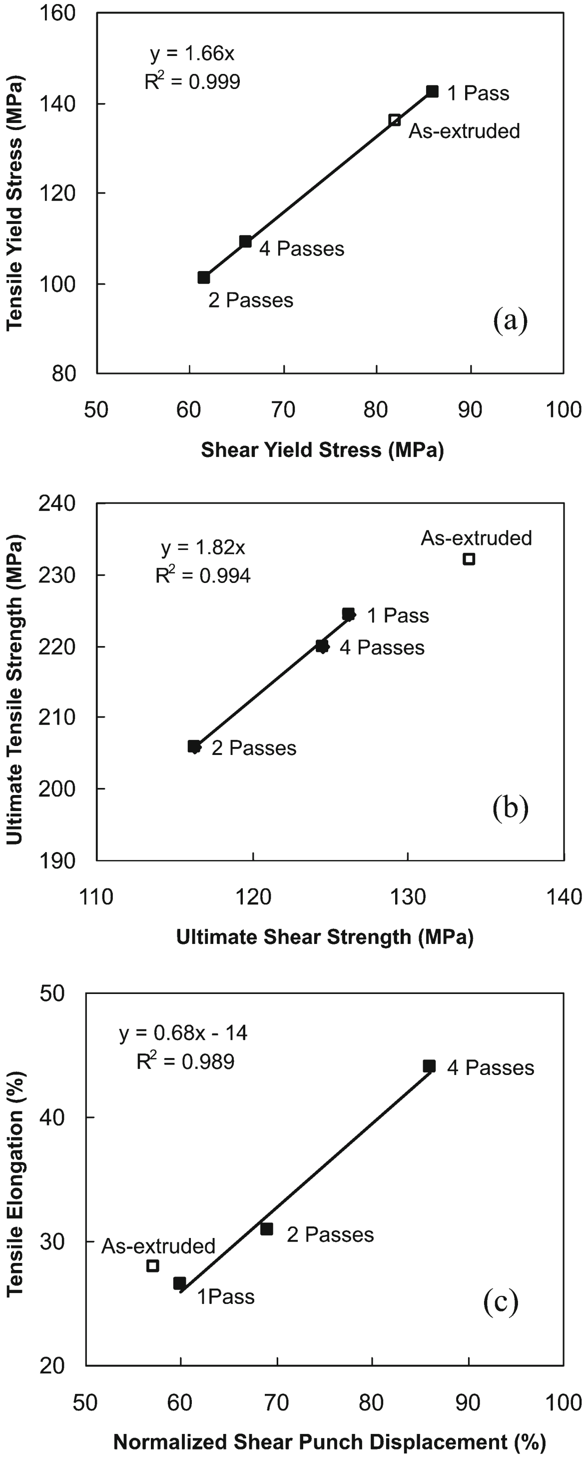

Fig. 6. The correlations between: (a) tensile yield stress and shear yield stress, (b) ultimate tensile strength and ultimate shear strength, and (c) tensile elongation and shear elongation.

plane is difficult and it is known that the strength increases for Mg alloys with limited non-basal slip activities. However, the Schmid factor on the (0001) basal planes increases by the rotation of the basal planes (~ 45°) during the ECAP process (Figs. 4c,d), and thus a lower stress is needed for yielding of the ECAP materials.

Another feature of materials processed by ECAP is their enhanced ductility with respect to the extruded conditions. Similar to the strength properties, grain refinement and texture modifications are the main reasons for the observed ductility enhancements. Koike et al. [27] investigated the contribution of grain boundary sliding (GBS) to the total tensile deformation of an AZ31 Mg alloy at room temperature and reported that this contribution is about 8 % when the strain rate and grain size are set at $10^{-3}\,\mathrm{s}^{-1}$ and 8 μm, respectively. However, the grain size dependence of tensile elongation is not sufficient to explain the large increase of the tensile ductility.

Mukai et al. [10] applied ECAP processing to the AZ31 alloy to reduce the grain size to 1 μm. After annealing, which was accompanied by substantial grain growth, the alloy retained its relatively high tensile elongations at room temperature. This was then attributed to the texture modification. However, this large increase in the tensile ductility cannot be achieved only by activation of the basal planes due to texture modifications because basal slip provides only two independent slip systems and this is less than the necessary five independent systems for homogeneous deformation defined by the von Mises criterion. Consequently, some prismatic and pyramidal slip planes were also activated easily because of a rotation of about 45° from the extrusion axis by ECAP [28]. The significant strain hardening observed in the tensile and shear curves of the ECAP materials (Fig. 4a) is in agreement with the proposal that two or more slip systems are active during tensile testing.

Due to the miniature dimensions of the ECAP materials, the preparation of tensile samples and the assessment of their properties is always a time-consuming and delicate task. Furthermore, the problem is enhanced because of the variations in strain that may be recorded when using miniature tensile specimens having different overall dimensions [29]. Therefore, it is desirable to devise other methods, for which the samples are made more easily, where the evaluation of the mechanical properties is readily achievable. The shear punch test is one of these techniques which has been shown as suitable for evaluating mechanical properties when the material availability is limited [17]. Although this method has been employed primarily for testing thin rolled sheets, it was used recently for evaluating anisotropic mechanical properties of an AZ31 magnesium alloy processed by ECAP at room temperature [18].

The correlations between the tensile and shear yield stresses, the ultimate strength and the ductility are plotted for the ECAP conditions in Figs. 6a,b,c, respectively. For comparison, the data corresponding to the extruded state are also included. Each datum point is the average of three different readings to avoid any inaccuracy. It is observed in Fig. 6a that a linear relationship with a high correlation factor of 0.999 exists between the tensile and shear yield stress of the ECAP conditions. Interestingly, the datum point for the extruded condition lies on the fitted line. The correlation line passes through the origin and satisfies the relationship TSS = 1.66 SYS. Figure 6b exhibits the correlation between the tensile and shear strength data which is represented by the linear relationship UTS = 1.82 USS. It is noted that the extruded datum point does not lie on the fitted line. Thus, the USS of the extruded condition is much higher than predicted by the extrapolation of the fitted line for the ECAP materials.

The correlations obtained in the present investigation between shear and tensile data are comparable to previous results obtained by other investigators using different materials [15–17]. It is well known that for pure shear the von Mises and the Tresca yield criteria give ratios of 1.73 and 2, respectively, for kinematically hardening materials [30]. The observed deviations from the theoretical values are attributed to factors such as compression, bending and stretching in the SPT specimens during testing [15]. The fact that the yield stress correlation of the ECAP conditions is in agreement with that of the extruded material, but differs for the ultimate tensile strength, may imply that the work hardening behaviour of the fine-grained structures produced by severe plastic deformation is different from those obtained in extrusion.

The correlation of tensile elongation with the normalized punch displacement, shown in Fig. 6c, is also indicative of a linear relationship with a slope of 0.68. In contrast to the strength data, this correlation does not pass through the origin and it exhibits an intercept of 14. This means that when there is no tensile elongation at the beginning of the shear test there would be some punch displacement due to the bending of the thin shear punch specimen.

4. Conclusions

1. The room temperature mechanical properties of the AZ31 magnesium alloy were examined after extrusion and ECAP using the shear punch and uniaxial tensile tests. The results show the ECAP alloy exhibits lower yield stress and higher tensile ductility by comparison with the extruded material because of a texture modification during ECAP.

2. A linear relationship was achieved between the uniaxial tensile and shear test data with slopes of 1.66 for yield strength and 1.82 for ultimate strength. A similar linear correlation was found between the tensile and shear elongations with a slope of 0.7.

3. It is demonstrated that the shear punch testing technique is a useful method for measuring the mechanical properties of miniature samples of magnesium alloys after processing by ECAP.

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