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Microstructure and mechanical properties of AZ91 tubes fabricated by Multi-pass Parallel Tubular Channel Angular Pressing

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ABSTRACT

Parallel Tubular Channel Angular Pressing (PTCAP) process is a novel recently developed severe plastic deformation (SPD) method for producing ultrafine grained (UFG) and nanograined (NG) tubular specimens with excellent mechanical and physical properties. This process has several advantageous compared to its TCAP counterparts. In this paper, a fine grained AZ91 tube was fabricated via multi pass parallel tubular channel angular pressing (PTCAP) process. Tubes were processed up to three passes PTCAP at 300 °C. Evolution of microstructure, mechanical properties and fracture behavior of the processed tubes after different passes were evaluated. Hardness, strength, and elongation were increased for processed tubes. Mean grain size was notably reduced to 3.8 µm for the tube which processed three passes from a 150 µm for the unprocessed tube. The maximum strength was found for second passes PTCAP processed tube which increased considerably about 108 %. The strength of the first pass processed tube increased about 62.5%. Increasing in elongation at room temperature was occurred, too. Mechanical properties of the third pass processed tube were deteriorated relatively because of appearing microcracks on the surface. Also, the hardness improved and it was increased about 77%. The result showed that the achieved mechanical properties consistent with microstructure.

Keywords: *PTCAP; Mechanical Behavior; AZ91; Tube; Grain Refinement.*

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1. Introduction

Magnesium alloys, as the lightest metallic structural material, owing to their low density and high specific strength and stiffness, have been broadly used for different kinds of industries. For instance, they broadly utilized automotive and aerospace industries in which high strength to weight ratio is crucial [1, 2]. However, utilizing them are still limited because they cannot used for applications which need robust mechanical properties. AZ91 alloy is one of the most common magnesium alloys which is cost-effective, has high strength, desirable castability and many potential application [3]. However, magnesium alloys have poor ductility because of the hexagonal close packed (HCP) crystal structure and abundant dendritic second phases which it causes limiting the broad application [4]. Investigation low ductility of magnesium alloys have been performed by some researchers recently [5-8].

Several researches have shown that grain refinement which can be achieved by severe plastic deformation (SPD) processes, leads to improve the mechanical properties, and it increases the yield strength at room temperature. [9]. Extensive research on SPD methods have been carried out to develop them to produce UFG material with enhanced properties. Various SPD processes such as equal channel angular pressing (ECAP) [9, 10], Cyclic extrusion compression (CEC) [11], accumulative roll bonding (ARB) [12] and high pressure torsion (HPT) [13], have been introduced for widespread applications. In all SPD methods, an UFG material are produced by applying severe plastic strain, and final dimensional of the specimen is not varied. Although there is a need of using high strength to weight ratio tubes in a broad range of industrial applications, most of the introduced SPD techniques were proposed for bulk and sheet materials and limited research have been proposed for tubular materials. Recently, Faraji etal. developed two novel and effective SPD methods for tubular materials include Parallel tubular channel angular pressing (PTCAP) [14] and tubular channel angular pressing (TCAP) [15]. PTCAP process has some advantages such as better strain homogeneity and needing lower process load in comparison to TCAP process[14]. In order to investigate the applicability of the process, Faraji et al. have performed several researches on various materials [16-18]. Dislocation densities of copper tubes processed by PTCAP process was investigated in [17]. Results showed that the dislocation densities were decreased by increasing the number of the PTCAP passes. Mesbah etal. [19] could produce nanostructured aluminum processed by TCAP process. In this process, increasing the strain leads to equiaxed grains which were elongated at first. Although several studies have been performed for producing fine grained tubes by PTCAP process, there is a lack of extended work on processing of AZ91 tubes that have widespread industrial application as mentioned earlier. In the current study, AZ91 magnesium tubes were processed up to three passes by PTCAP process and the effect of process on mechanical properties, microstructural evolution and micro-hardness variations were investigated.

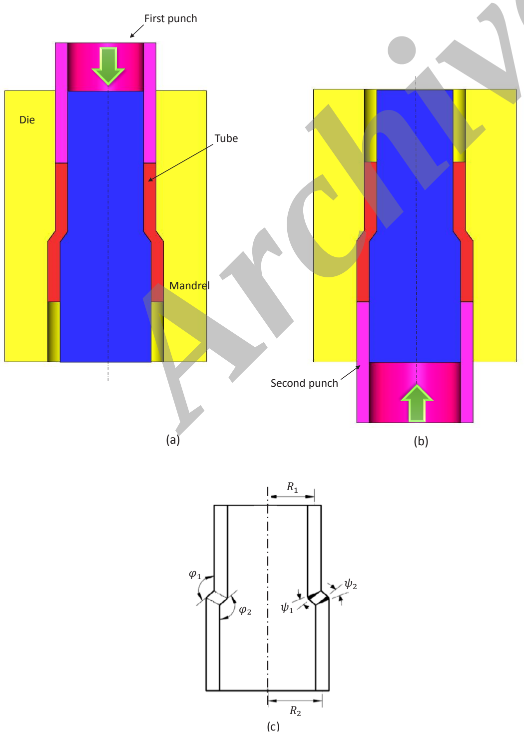


Fig. 1- Schematic of the (a) first and (b) second half passes of PTCAP process and (c) die parameters

Fig. 1 shows the PTCAP process schematically. It consists of two half cycles and each half cycle includes two shear zones. In the first half cycle, the diameter of the tube increased to a maximum value and it decreased to an initial value in the second half cycle. The total equivalent strain achieved from N cycles of the PTCAP process can be colculated from the following equation [16]:

$$\bar{\varepsilon}_{tot} = 2N\left\{\sum_{i=1}^{2}\left[\frac{2\cot(\phi_i/2+\psi_i/2)+\psi_i \operatorname{cosec}(\phi_i/2+\psi_i/2)}{\sqrt{3}}\right]+\frac{2}{\sqrt{3}}\ln\frac{R_2}{R_1}\right\}$$

(Eq.1)

2. Experimental Procedure

In the present study, the as-cast AZ91 magnesium alloy was used. Dimensions of the tube was as following, outer diameter of 20 mm, length of 40 mm and thickness of 2.5 mm were machined from as-received material. Die parameters of PTCAP die is shown in Fig.1 that the channel angle was $\varphi_1=\varphi_2=120^\circ$ and the curvature angle was $\psi_1=\psi_2=0^\circ$. With this parameters, after each cycle of PTCAP an equivalent strain about 1.6 was applied to the tube.

Die and its components were manufactured from hot-worked tool steel and hardened to 55 HRC. The tubes were processed by PTCAP up to three passes. The process was conducted at the ram speed of 10 mm/min at temperature of 573K. The die and tube was heated by the heater and the temperature was controlled by the termocouples which was inserted inside the die and in contact with the tube. Molybdenum disulfide (MoS_2) was utilized to decrease the friction between contact surfaces. Tensile test was performed at room temperature with the initial strain rate 0.001s^{-1}. Fig. 2 shows that samples were wire-cut in axial direction of tube. In order to investigate microstructure evolution, standard metallographic procedure was conducted on samples, then optical microscopy (OM) was used to observe and evaluate the microstructure. The Vickers microhardness testing was used with a load of 100 gr for 15 s. Fracture surfaces of tensile test samples were analayzed by scanning electron microscope (SEM).

3. Results and Discussion

3.1. Microstructure evolution

Initial and PTCAP processed tubes are shown in Fig. 3. Because of applying lubricant between conctact surfaces, the appearances of them were changed. Also as can be seen, there is some micro surface cracks on three passes tube which can influence on mechanical properties. Optical microstructures of AZ91 alloys can be observed

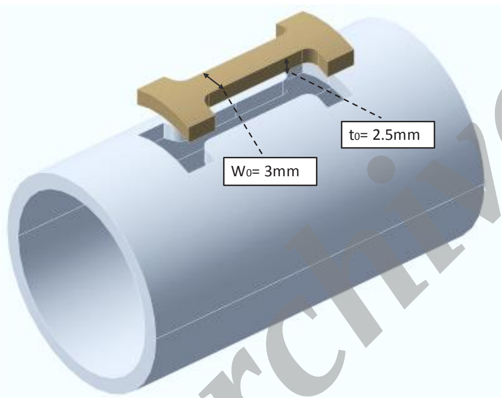
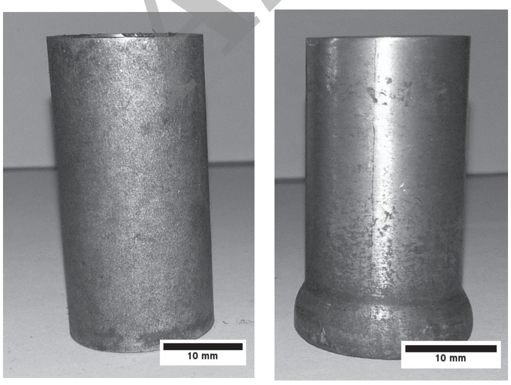


Fig. 2- Dimension of a tensile test specimen.



(a) (b)

Fig. 3- Pictures of the (a) unprocess and (b) third passes processed tube.

in Fig. 4. As shown in Fig. 4(a), the microstructure of unprocessed tube includes a dendritic structure with coarse grains, and average grain size is about ~150 μm. As obviously shown, networks of β phase ($Mg_{17}Al_{12}$) which is shown by arrows in figures, surrounded α-Mg phase. Existing β phase networks have adverse effect on mechanical properties, especially ductility. So ditribution of it in grains by percipitating and breaking, can improve mechanical properties. Because of limitated slip systems of magnesium alloys, deformation process should be performed at high temperature to considerably activate other slip systems. Therefore, PTCAP process was performed at 300°C. As shown in Fig. 4(b), for one pass processed tube, fine grained achieved through coarse grains due to occuring dynamic recrystallization (DRX). Also, many twins were existed in the original grain. As it is obvious, β phase networks was broken, and distribute through the grains which can be cause of the improving mechanical properties. However, the distribution is not completely homogeneous, and average grain size was reduced to 9 μm.

Studies on AZ91 showed that DRX occurs during deformation at 300 °C [20]. Due to the pivotal role of shear strain in grain refining, applying , more shear strain lead to more fine and recrystallized grains achieve instead of coarse grains [21]8 . The mean grain size notably reduced to 4.5 μm and relatively a homogeneous structure for two passes processed tube in comparison with one pas processed tube, was achieved. β phase precipitates can siginificantly affect on mechanical properties and homogeneous distribution can make better mechanical properties of magnesium alloys [22]. The β phase is broken heavily and spread randomly along the α-Mg phase. As clearly can be seen from Fig. 4(c) fine-grained increased and dominated over the coarse grains. Microstructure of the third passes processed sample is relatively similar to second passes processed sample (Fig. 4(d)). The average grain size reduced to about 3.8 μm and also, a homogenous microstructure was achieved. As a result, the PTCAP process can affect heavily on microstructure of AZ91 magnesium alloy. the grain refinement after PTCAP process. Grain refinement process occurred by deformation twins and dynamic recrystallization. During deformation by increasing the shear strain high angle grain boundaries formed and β phase networks were broken into small blocks and distributed at the newly formed DRX grain boundaries.

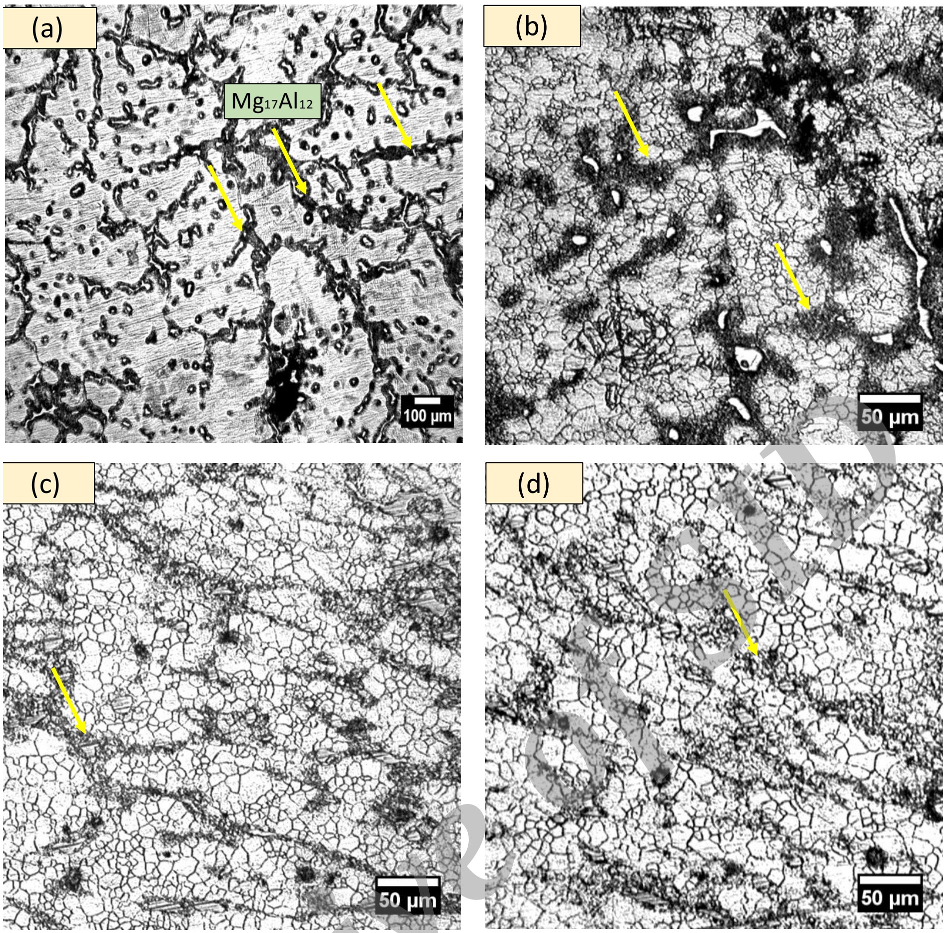


Fig. 4- Optical micrographs of (a) unprocess tube and (b) 1Pass, (c) 2Passes and (d) 3Passes PTCAPed tubes.

3.2. Mechanical properties

Mechanical properties of unprocessed and processed tubes were conducted by tensile tests at room temperature. Fig. 5 shows fractured tensile test specimens. Fig. 6 shows the true tensile stress-strain curves of the tubes at room temperature.

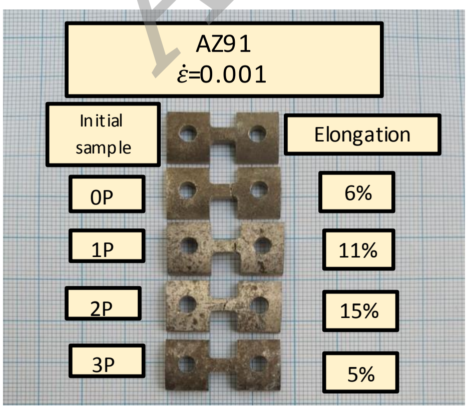


Fig. 5- Fractured specimens after the tensile test.

As clearly shown in Fig. 6(a), an increase in strength was occurred just after one pass process. The increase in ultimate strengths was about 62.5%. As mentioned, β phase networks at grain boundaries of as-cast sample lead to have poor mechanical properties [23]. For the two passes processed sample the ultimate strength was about 347 MPa (108%) . Also, the elongation increased. It was about 14% from an initial value of 6%. This results are consistent with well-known Hall-Petch equation. A considerable increase of the strength and homogeneous distribution of the β phase after the SPD process occurred because of a grain refinement [24]. Mechanical properties of AZ31 alloy processed by SPD technique was reported by Jin et al. [25]. Their results showed applying the more strain lead to increase the formability and decreasing strength as a result of grain refinement. However, the peresent study shows that the more strain causes both strength and elongation increased too. This difference can be explained by

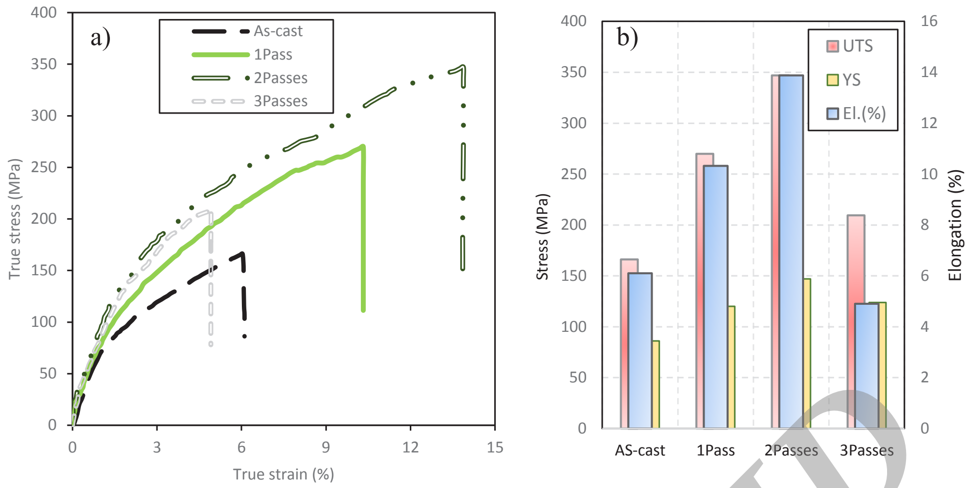


Fig. 6- (a) True stress strain curves of the unprocessed and PTCAP processed tubes. (b) UTS, YS and elongation of different specimens.

β phase distribution. Because of appearing cracks on the surface of the third passes processed tube, the strength and formability of the third passes processed tube was considerably decreased to 209 MPa and 5%, respectively.

The Vickers microhardness variation of the processed tubes is demonstrated in Fig. 7. As obvious, a notable increase in microhardness was obtained just after one pass process. The average microhardness was 56 Hv for initial specimen, and it was increased to 75 Hv for one pass processed sample. This improvement in microhardness was continued to 99Hv for three passes processed tube. This increasing trend of microhardness is completely consistent with the microstructure results. Despite of the increasing of the hardness of the three passes sample, the strength was decreased due to appearing micro cracks on the surface. Lack of slip systems in hcp metals causes that strength and hardness of these metals strongly dependent to

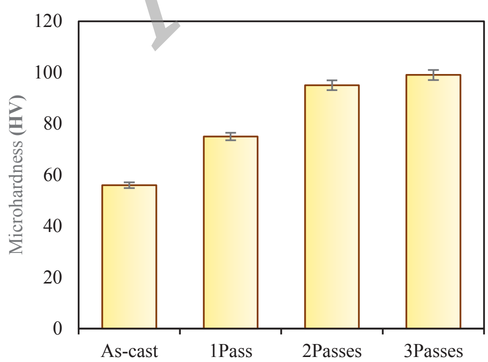


Fig. 7- Microhardness values of the sample processed via different passes.

grain size [26]. Also, the hardness of the β phase is notably more than α-Mg phase [27]. Hence, the trend of increasing the microhardness cand be attributed to distribution of β phase during the deformation procedure.

SEM microscopy was used to analyze fractured surfaces of tested tensile samples which was conducted at room temperature (Fig. 8). As shown, samples fracture by brittle rupture and without no tendency to neck. Small cleavage planes and tearing edges which reveal a characteristic of quasi-cleavage fracture, can be obviously seen in Fig. 8(a). Large grains and β phase networks at grain boundaries caused that the fracture of the unprocessed tube was mainly brittle. Previous studies have shown that cleavage or quasi-cleavage fracture are the main reasons of brittle fracture of magnesium alloys [28, 29]. After one pass PTCAP process, some dimples appeared on the fractured surface which occurred by the formation and coalescence of microvoid ahead of the crack. Refining the grain size, precipitate and uniform distribution of the β phase lead to change the rupture model and increase the formability. For two and three passes processed specimens, dimples increased. Low formabilty of the third passes processed sample is due to the existing microcracks on the fracture surface.

4. Conclusion

In the peresent study fine grained AZ91 tubes were produced by PTCAP process. The effects of number of passes on mechanical properties, microstructure evolution and fracture behavior

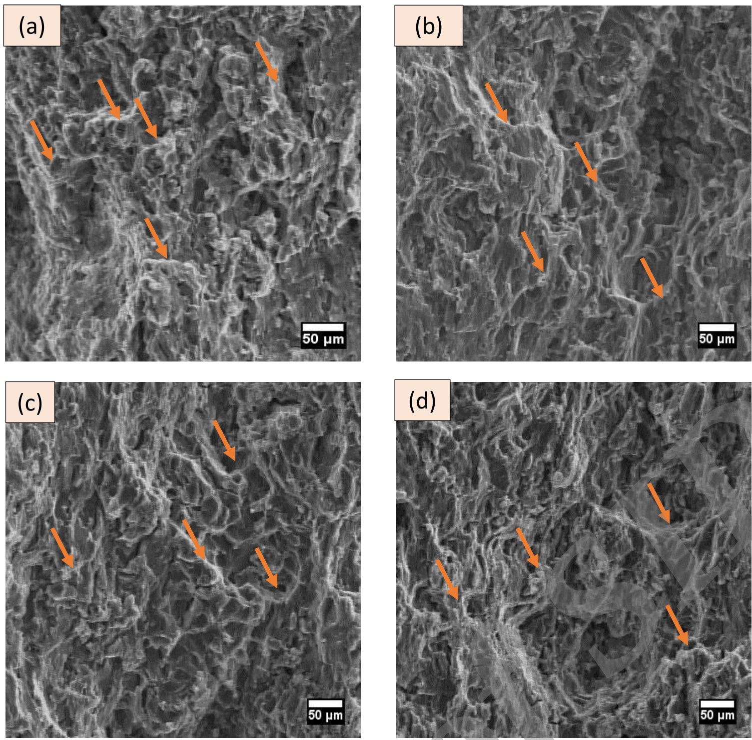


Fig. 8- SEM micrographs of the fractured surface of the tensile test specimens for (a) unprocessed, b) one Pass, c) two passes and d) three passes PTCAP processed specimens.

were studied. Several results were drawn as follows: Mean grain size was significantly reduced to 3.8 µm for third passes processed tube from 150 µm for unprocessed tube. Strength of the second passes processed tube were considerably increased about 108 % . Also, ductility relatively increased at room temperature, too. Hardness remarkably increased about 77 % after 3passes process.

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