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Mechanical and Microstructural Properties of Ultra-fine Grained AZ91 Magnesium Alloy Tubes Processed via Multi Pass Tubular Channel Angular Pressing (TCAP)

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Ultra-fine grained (UFG) cylindrical tubes were produced via recently developed tubular channel angular pressing (TCAP) process through different passes from as-cast AZ91 magnesium alloy. The microstructure and mechanical properties of processed tube through one to four passes of TCAP process at 200 °C were investigated. Microhardness of the processed tube was increased to 98.5 HV after one pass from an initial value of 67 HV. An increase in the number of passes from one to higher number of passes has no more effect on the microhardness. Yield and ultimate strengths were increased by 4.3 and 1.4 times compared to those in as-cast condition. Notable increase in the strength was achieved after one pass of TCAP while higher number of passes has no more effect. Microstructural investigation shows notable decrease in the grain size to around 500 nm from the primary value of ~150 μm. Dissolution and distribution of hard Mg₁₇Al₁₂ phase in the grain boundaries of dynamically recrystallized UFG AZ91 with a mean grain size of ~500 nm was an interesting issue of TCAP processing at 200 °C compared to other severe plastic deformation processes.

KEY WORDS: Severe plastic deformation; Tubular channel angular pressing; AZ91; Grain refinement; Mechanical behaviour

1. Introduction

In recent years, improvement of material properties by grain refinements using severe plastic deformation (SPD) has been much attractive whereas ultra-fine grained (UFG) and nano-structured materials exhibit outstanding properties^[1]. There are different SPD methods such as equal channel angular pressing (ECAP)^[2], high-pressure torsion (HPT)^[3], and accumulative roll bonding (ARB)^[4]. Most of SPD methods are suitable for bar and rod form parts^[5,6], along with application to plate and sheet parts^[7–10]. Despite the need for high strength tubes in a wide range of industrial applications, few efforts have been undertaken to produce UFG tubular parts using SPD methods. An especially attractive method named as tubular channel angular pressing (TCAP) method was recently developed by Faraji et al.^[11] as an effective and novel SPD process suitable for

processing tubes to very large strains. They processed AZ91 magnesium alloy using TCAP method at 300 °C and reported more grain refinement and significant improvement in the mechanical properties after only single pass^[11]. They also investigated the effects of process parameters such as channel geometry^[12] and channel angles^[13] on plastic deformation behaviour and process load using finite element modelling. In this study, AZ91 magnesium alloy is processed via multi pass TCAP process at 200 °C and the effects of the number of passes on grain refinement, microhardness and compression behaviour were investigated.

Fig. 1(a) shows the principle of TCAP process. The tube material is pressed by a hollow cylindrical punch into a gap between die and mandrel, which forms a tubular angular channel with three shear zones I, II and III (Fig. 1(b)). The cross-section of the TCAP processed tube remains unchanged at the end of process. In multi pass TCAP, the process is repeated as many times as necessary to achieve distinct strains without any reduction in the cross-section of workpiece.

As mentioned in literature^[12], the strain–stress state during TCAP is different from that during the ECAP. In the ECAP process, the strain state could be considered as simple shear, while in the TCAP process, there are some additional radial and circumferential tensile and compressive strains. The exact value

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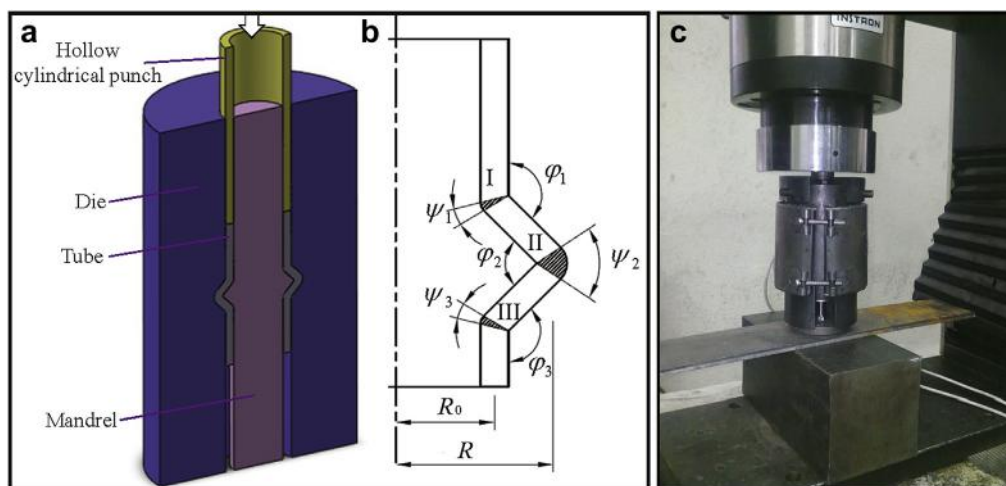


Fig. 1 Schematic of TCAP (a), processing parameters (b) and experimental setup (c).

of total accumulated strain ($\bar{\epsilon}_T$) after N passes of TCAP processing can be calculated by the following relationship, which results from common engineering plasticity formulae and the geometry of Fig. 1(b)^[11]:

$$\bar{\epsilon}_{TN} = N \left\{ \sum_{i=1}^3 \left[\frac{2 \cot(\phi_i/2 + \psi_i/2) + \psi_i \operatorname{cosec}(\phi_i/2 + \psi_i/2)}{\sqrt{3}} \right] + \frac{4}{\sqrt{3}} \ln \frac{R}{R_0} \right\} \quad (1)$$

From Eq. (1), the total equivalent plastic strain in TCAP with the parameters used in this work after one, two, three and four passes are ~ 2.2 , 4.4, 6.6 and 8.8, respectively.

2. Experimental

An as-cast AZ91 magnesium alloy with a composition Al 9.1 wt%; Zn 0.68 wt%, Mn 0.21 wt%, S 0.085 wt%, Cu 0.0097 wt%, Ni 0.001 wt%, Fe 0.0029 wt%, and Mg balance was used as starting material. Cylindrical tubes of 20 mm in outer diameter and 50 mm in length were machined from as-cast ingots. A TCAP die was manufactured from hot worked tool steel and hardened to 55 HRC. Die parameters and their values are listed in Table 1. The TCAP experiments were carried out with an INSTRON press with a pressing speed of 20 mm/min at 200 °C. Experimental setup is shown in Fig. 1(c). Friction between the specimen and dies was reduced by applying MoS₂ as lubricant^[14]. The sample was cut in two directions, parallel and perpendicular to the tube axis. Microstructural investigations were performed by general metallographic methods. Microhardness of the specimens was measured with a Vickers microhardness test machine in a load of 100 g. Stress-strain curve was extracted from compression test^[15] on the rings cut from the processed tubes at room temperature at a strain rate of

10^{-3} . Compression test sample and its dimensions are shown in Fig. 2(c). To minimize the effect of friction, a thin Teflon layer together with silicon lubricant was used between the ring ends and plates.

3. Results and Discussion

Fig. 2(a) and (b) shows the AZ91 workpiece before and after TCAP. During the process, the tube diameter increases and

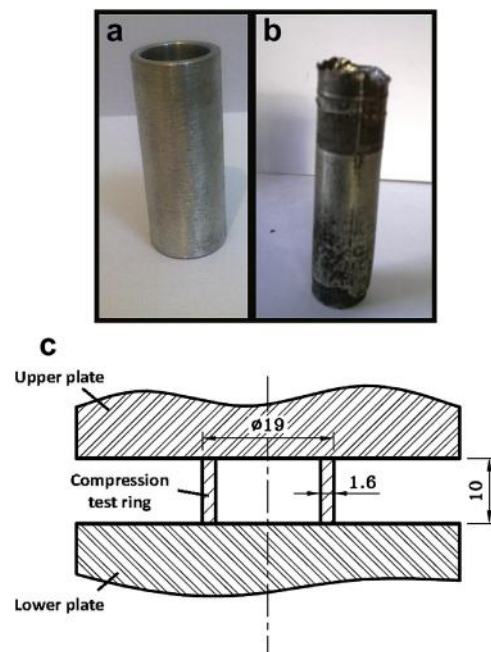


Fig. 2 AZ91 workpiece before (a) and after (b) one pass of the TCAP process; (c) compression test sample and dimensions.

Table 1 Die parameters and their values

ϕ_1, ϕ_3	ϕ_2	ψ_2	ψ_1, ψ_3	R/R_0	R_0	Thickness
135°	90°	90°	0°	1.2	8.75 mm	2.5 mm

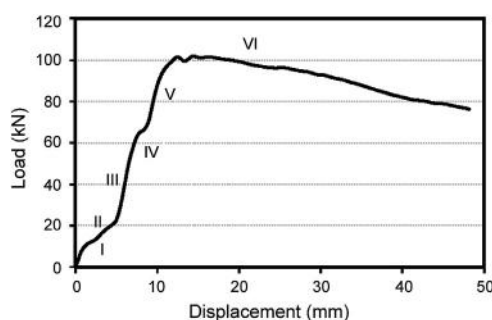


Fig. 3 Experimental punch load vs displacement curve during TCAP processing through single pass.

returns to the initial size at the end of TCAP. As shown in this figure, the cross-section area of the tube before and after TCAP remains constant though the tail part has some inconsistency. Fig. 3 shows hollow cylindrical punch load vs its displacement during the process. Maximum required load is about 100 kN. It is clearly seen that the force diagram could be divided to six parts. In the first part I the tube material is pressed to fill the first corner. Load curve in the tube material passage between the first and second corners and the second and third corners are noted by parts II and IV, respectively. In these parts, the load is increased very slowly compared to the parts I and III. In the parts I, III and V, the required load increases sharply. In these parts the tube materials fills the corresponding corners. In the part VI, where the tube end passed the last corner, punch load is slowly decreased. It is reported that there are two reasons for this phenomenon. The first reason is elastic recovery^[16] and the second one is related to the friction force, which is decreased with punch displacement^[12,13].

3.1. Microstructure

Fig. 4(a) shows the microstructure of the initial as-cast material. It shows a typical dendritic structure with primary Mg phase (α) embedded in an $Mg_{17}Al_{12}$ network with a mean grain

size of 150 μm . Fig. 4(b–e) shows the effect of the number of TCAP passes on the cross-sectional microstructure of the processed tube along perpendicular to axis direction. These microstructures correspond to the TCAP processed tube after imposing the strain levels of ~ 2.2 , 4.4, 6.6 and 8.8. As can be seen, all microstructures of the TCAP processed tubes are totally different from the unprocessed one (Fig. 4(a)). The microstructures are significantly refined and the grain size is hard to be measured. There are some unrecrystallized regions in the microstructure of TCAP processed tube after one pass (Fig. 4(b)). This type of regions is formed in SPD processing of AZ91 alloy at elevated temperatures and medium strain levels (~ 2)^[14]. Increase in the number of passes causes to decrease the unrecrystallized regions in the microstructure so that in the microstructures corresponding to the second, third and fourth passes unrecrystallized regions can be seen hardly. However there are some undissolved $Mg_{17}Al_{12}$ phases in all the processed microstructures, shown in Fig. 4. The hardness of $Mg_{17}Al_{12}$ phase is very higher than that of primary α phase. During the SPD processing, this hard phase can be divided into two parts. Some minor parts of this phase are dissolved and distributed into the grains and the residue plays pinning effect as rigid particles. Dissolution and distribution of $Mg_{17}Al_{12}$ phase are affected by the process temperature and the level of strain. After TCAP, the intermetallic $Mg_{17}Al_{12}$ became partially dissolved due to the processing temperature^[17]. However, the time is too short to allow complete homogenization during processing, i.e. segregation is only reduced but not eliminated^[18]. The grain size of the AZ91 alloys was strongly affected by the accumulated strain values. As is well recognized, the deformation shear component plays main role in grain refinement, grain shapes, and texture during SPD^[14]. Dynamically recrystallized (DRXed) grains are formed as a result of shear strain and processing temperature. From Fig. 4, it is clear that the higher accumulated strain gave the finer recrystallized grains of the Mg alloy.

Fig. 5(a) and (b) shows FESEM (field emission scanning electron microscopy) micrographs of the as-cast and TCAP processed tube, respectively. As shown in Fig. 5(a) a primary Mg phase (α) embedded in an $Mg_{17}Al_{12}$ network with a mean grain

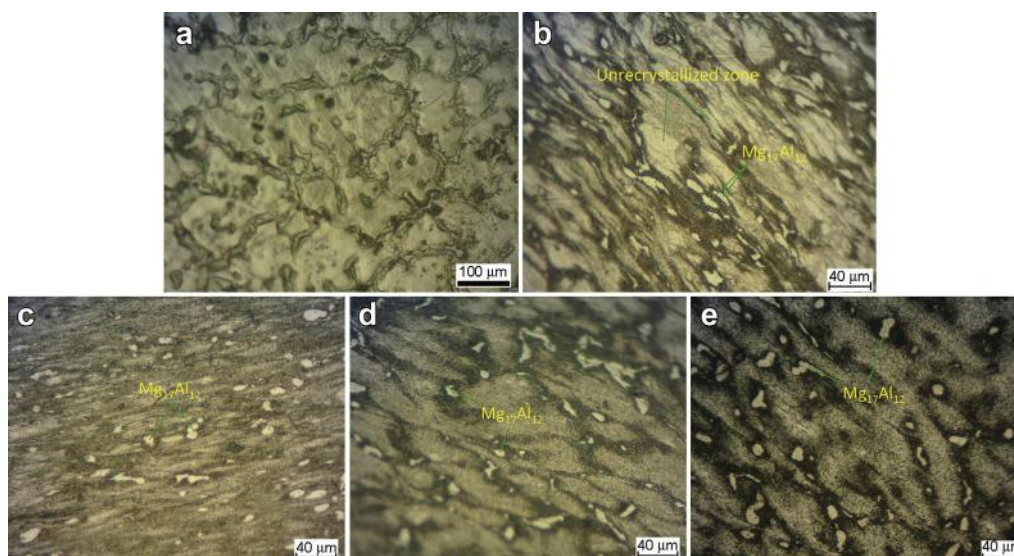


Fig. 4 Optical micrographs of the microstructure of the initial as-cast material (a) and the processed tube along perpendicular to axis direction after first pass (b), second pass (c), third pass (d) and fourth pass (e) of TCAP.

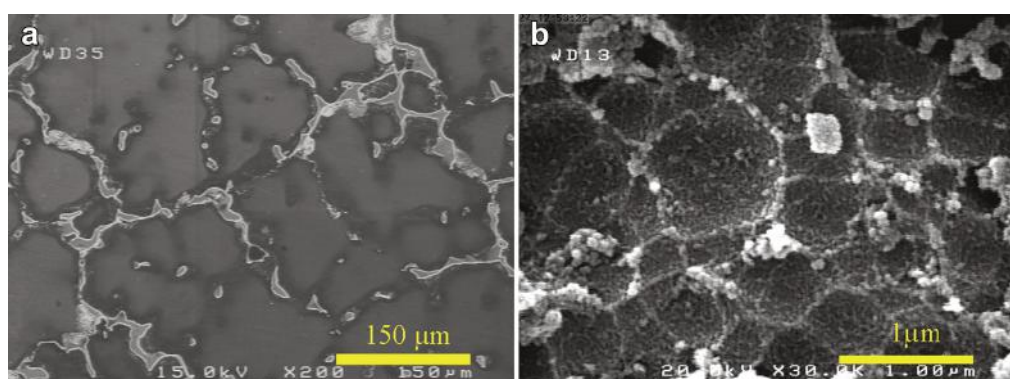


Fig. 5 FESEM micrograph of the microstructure of (a) the initial as-cast material and (b) the processed tube along perpendicular to axis direction after first pass TCAP.

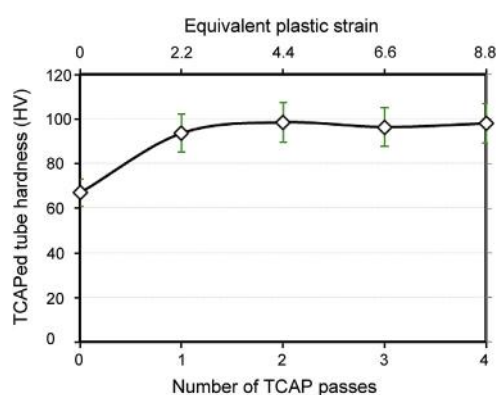


Fig. 6 Microhardness of the TCAP processed tube vs number of TCAP passes.

size of 150 μm . Dissolution and distribution of hard $\text{Mg}_{17}\text{Al}_{12}$ phase in grain boundaries of UFG AZ91 with a mean grain size of ~ 500 nm are clear in Fig. 5(b). $\text{Mg}_{17}\text{Al}_{12}$ phase are distributed in grain boundaries not only in as-cast microstructure but also in grain boundaries of UFG structure^[14,16] produced via TCAP at 200 $^{\circ}\text{C}$ like other methods. ECAP processing of AZ91^[17], leads to a solution of $\text{Mg}_{17}\text{Al}_{12}$ phase in interior of DRXed grains. Also, accumulative back extrusion processing of this alloy at 300 $^{\circ}\text{C}$ ^[19,20] causes a distribution of $\text{Mg}_{17}\text{Al}_{12}$ phase in interior of DRXed grains.

3.2. Microhardness

Fig. 6 shows the microhardness of the processed tube vs number of TCAP passes. Hardness increased notably after first pass. TCAP leads to an increase in microhardness to 98.5 HV from the initial value of 67 HV. This means that the microhardness increases about 47% after first pass of TCAP process. It is accepted that hexagonal closed pack metals such as magnesium exhibit a strong dependency of strength and hardness on grain size due to the lack of slip systems^[21]. The increase in the hardness of the AZ91 alloy could be due to the grain refinement, as well as the dissolution and distribution of the $\text{Mg}_{17}\text{Al}_{12}$ phase. It should be noted that the $\text{Mg}_{17}\text{Al}_{12}$ phase is a hard and brittle phase that is distributed over the grain boundaries^[22]. Increase in the number of TCAP passes after one pass to higher number of passes has no more effect on the microhardness. This saturation could also be seen in ECAP processing of copper^[23] and aluminium^[24].

3.3. Stress–strain curves

Fig. 7(a) shows the stress–strain curve of the processed tube vs number of TCAP passes, which was resulted from the compression test. Engineering stress–strain curves of the as-cast coarse-grained AZ91 material and the TCAP processed alloy with different number of passes were compared. As shown in this figure, curves corresponding to the processed tubes are totally different from that corresponding to unprocessed one.

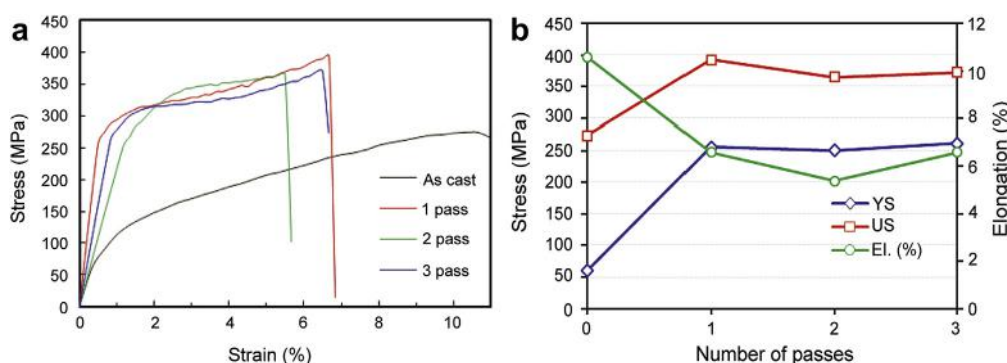


Fig. 7 (a) Engineering stress–strain curve of as-cast and processed AZ91 tube after one to three passes of TCAP resulted from ring compression tests, (b) effects of the number of TCAP passes on yield and ultimate strengths and elongation to failure of processed tube.

After first pass yield and ultimate strength (YS and US) were notably increased while elongation to failure was decreased. In all cases the yield and ultimate strengths corresponding to the TCAP processed samples are about 4 and 1.5 times, higher than those in the as-cast state, respectively. As expected the elongation was decreased about 40%–50% in all TCAP processed samples. As illustrated in Fig. 7, the highest strength increase takes place after the first TCAP pass. Consequently successive TCAP passes almost has no more strengthening effect. This takes place in the large strain rolling of AZ91 alloy^[20]. The notable improvement in the mechanical properties of the as-cast AZ91 alloy at room temperature can be attributed to the simultaneous achievement of a very small grain size (~ 500 nm) and distribution of $Mg_{17}Al_{12}$ phase in the grain interiors, which limits dislocation movement^[14]. It is well known that the Hall–Petch slope in Mg alloys is very pronounced compared to Al alloys and thus, grain refinement has a significant effect in the mechanical behaviour^[25].

4. Conclusion

Ultra-fine grained (UFG) cylindrical tubes were produced via multi pass tubular channel angular pressing (TCAP) process from as-cast AZ91 magnesium alloy. The microstructure and mechanical properties of processed tube through one to four passes of TCAP process at 200 °C were investigated. Microhardness of the processed tube was increased to 98.5 HV after one pass from an initial value of 67 HV. An increase in the number of passes from 1 to higher number of passes has no more effect on the microhardness. Yield and ultimate strengths were increased 4.3 and 1.4 times compared to those in as-cast condition. Notable increase in the strength was achieved after one pass TCAP while higher number of passes has no more effect. Microstructural investigation shows notable decrease in the grain size to around 500 nm from the primary value of ~ 150 μm . Dissolution and distribution of hard $Mg_{17}Al_{12}$ phase in grain boundaries of UFG AZ91 with a mean grain size of ~ 500 nm, similar to initial microstructure, was an interesting issue of TCAP processing at 200 °C.

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