

# Microstructure and Mechanical Properties of AZ91 Magnesium Cup Processed by a Combined Backward Extrusion and Constrained Ironing Method

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**Abstract:** A combined metal forming process consisted of backward extrusion (BE) and constrained ironing (CI) is used to produce thin walled ultrafine grained (UFG) magnesium cups. In this new method, the initial thick-walled cup is formed from the bulk material using the BE process and then the CI process is used to produce a UFG thin-walled cups. The advantage of the CI process is applying compressive stresses that are suitable to form hard to deform materials like magnesium alloys without fracture while achieving higher thickness reduction ratio (TRR). The results showed that after this new combined method, the tensile strength raised to 233 MPa, from the initial values of 123 MPa. Simultaneous improvement in strength and ductility attributes to very high hydrostatic compressive stresses and also breakage of  $Mg_{17}Al_{12}$  precipitates in to smaller parts that facilitate the movement of dislocation. Also, the hardness increased to about 233 MPa from the initial values of 58 HV. Significant grain refinement was also taken place and the grain size in the BE+CI sample reduced to  $\sim 1 \mu m$  from the initial value of  $\sim 150 \mu m$  due to imposing high value of strain. This combined method is very promising for processing of UFG thin-walled cup-shaped samples from hard to deform materials. SEM images illustrated the brittle fracture at unprocessed and BE samples with existence of wide crack and shallow-elongated dimples but BE+CI sample revealed brittle fracture with fewer cracks due to hydrostatic pressure.

**Keywords:** AZ91, Backward extrusion, Constrained ironing, Thickness reduction ratio, Thin-walled cup

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## 1 INTRODUCTION

Backward extrusion (BE) is a bulk deformation process for producing close-ended cylinder shape components and hollow parts [1], [2]. Higher surface finish and dimensional accuracy, lower production cost, suitable mechanical properties and elimination of additional processing are several advantages of the BE process in comparison with other conventional metal forming process [3], [4]. Primary study of back extrusion on the axisymmetric extruded parts was investigated by Kudo [5] in 1961. Avitzur et al., [6] developed the upper bound approach to analyse the early stage of back extrusion process of a thin or thick-walled cup. Then, Luo and Avitzur [7] presented the limitations of BE process. They used the upper-bound approach to update the study of the back extrusion process. In previous years, several studies have been carried out to develop the BE process for different advanced applications. To investigate the capabilities of the backward extrusion to produce the ultra-fine grained materials, Faraji et al., [8], [9] studied a new deformation process entitled accumulative back extrusion (ABE).

This process is suitable for producing the nanostructured and UFG cup-shaped parts with the high strength and hardness. Abdolvand et al., [10] proposed a novel combined parallel tubular channel angular pressing (PTCAP) [11], [12] and tube backward extrusion (TBE) method for producing UFG thin-walled cylindrical tubes. The main purpose of their method is facilitating severe plastic deformation (SPD) processes for producing thin-walled tubes. Despite the production of thin-walled tubes, no effort to produce thin-walled cup-shaped components was made. Recently, Khodsetan et al., [13] developed the constrained ironing (CI) method as a novel technique for producing thin-walled hollow components with an extra high TRR during the one stage ironing. The advantages of this method in comparison to conventional ironing process is the extraordinary higher ironing thickness reduction ratio (TRR) of about more than 80% through only one stage ironing [13].

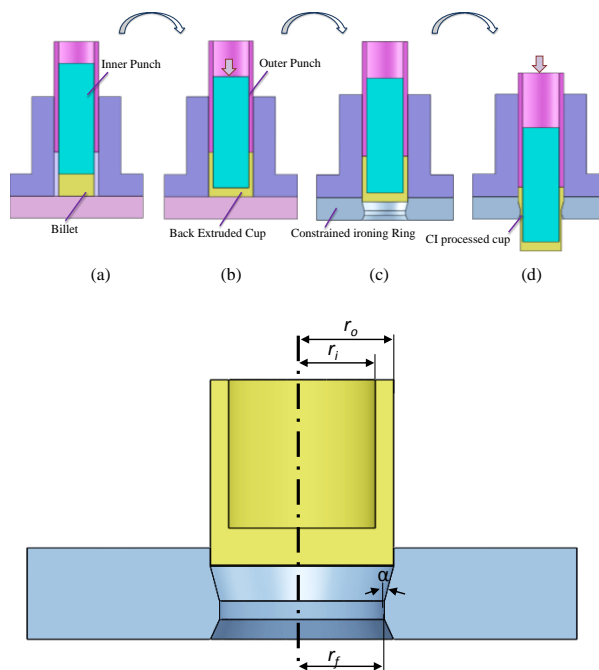
Constrained ironing is based on compressive stresses that help to produce thin-walled cylindrical components. Processing thin-walled cup-shaped samples from Mg, and its alloys may be very hard because of two reasons. First, the existence of tensile stresses in conventional ironing and second, very limited ductility of Mg alloys. To overcome this limitation, compressive deformation processes could be very useful. The aim of the current study is the development of a combined compressive process for producing aforementioned parts. In this paper, a combined method consisted of BE and CI processes is presented for producing UFG thin walled magnesium components. To investigate the applicability of the new

combined approach, a magnesium alloy AZ91 is processed at 300 °C.

## 2 EXPERIMENTAL PROCEDURE

### 2.1. Principles of the process

In conventional ironing processes for producing cylindrical components, first the initial cup produced by deep drawing process from the sheet material and then ironing process is applied to reach thin-walled cylindrical cups. The schematic of new combined method consisted of two stages of BE and CI processes was shown in Fig. 1. In the first stage, the billet is put into the BE die cavity (Fig. 1(a)). The billet is pressed back using the inner punch for producing the extruded cup (Fig. 1(b)). In the second stage, as shown in Fig. 1(c) the extruded cup is put into the gap between punch and die. Then, outer punch moves down and presses the back extruded cup to reduce its wall thickness through ironing the cup wall (Fig. 1(b)).



**Fig. 1** Schematic illustration of the combined process (a) at the starting and, (b) during the back extrusion and (c) at the starting and (d) during the constrained ironing process and (e) CI die parameters.

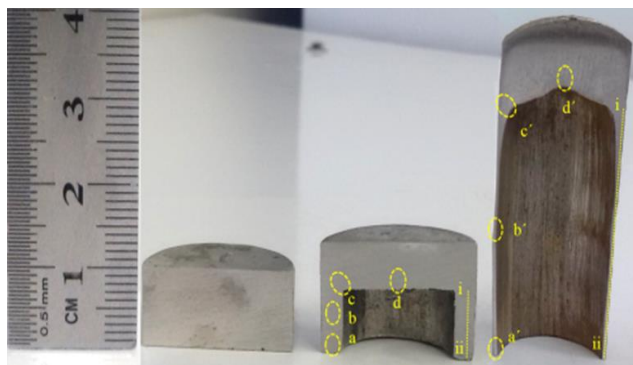
### 2.2. Experimental procedures

The samples of AZ91 magnesium alloy were prepared with diameter of 20 mm and 10 mm in length from as-cast ingots. The BE and CI dies were manufactured from hot-worked tool steel. All the die parts were hardened to 55 HRC. Value of die parameters as shown

in Fig. 1(e), is ironing die angle  $\alpha=15^\circ$ ,  $r_o=10$  mm,  $r_i=7.5$  mm,  $r_f=8$  mm. The thickness of the BE processed cup wall is 2.5 mm which is reduced to  $\sim 0.5$  mm (TRR ratio is 80%) after constrained ironing process. The BE and CI processes were carried out at the ram speed of 10 mm/min at 300 °C. Die and ingot were checked during the test to have the same temperature. To reduce the friction on the specimens and dies surfaces, the MoS<sub>2</sub> lubricant was used. Samples for microstructural and microhardness studies were cut in axial direction. Microstructural investigations were done using optical microscopy (OM) on the samples prepared through common metallographic methods. The Vickers microhardness (HV) testing was performed using with a load of 200 gr applied for 15 sec. Sub size tensile test samples were prepared using wire electro discharge machine. The samples were tested using Instron tensile test machine at a strain rate of about  $0.5 \times 10^{-3}$  at room temperature. The fracture morphology of the fractured samples was observed by Hitachi scanning electron microscope (SEM) with voltage of 30Kv.

### 3 RESULTS AND DISCUSSION

Fig. 2 shows the cross-sections of unprocessed, BE processed and BE+CI processed samples. The higher reduction of cup wall initial thickness after constrained ironing is lead to a large height of ironed cup in comparison with the back extruded cup.



**Fig. 2** Cross-sections of unprocessed, BE processed and BE+CI processed samples.

Fig. 3 (a)-(d) show the microstructure of the cross section of the back extruded cup at the different zones. Moreover, Fig. 3 (a')-(d') show the microstructures of the cross section of BE + CI processed cup at the different regions. To investigate the microstructure evolution during the deformation, the cross-section of the cup was divided into four zones denoted as “a” to “d” for backward extruded cup and “a'” to “d'” for BE+CI processed cup. In the “a” and “b” region, no

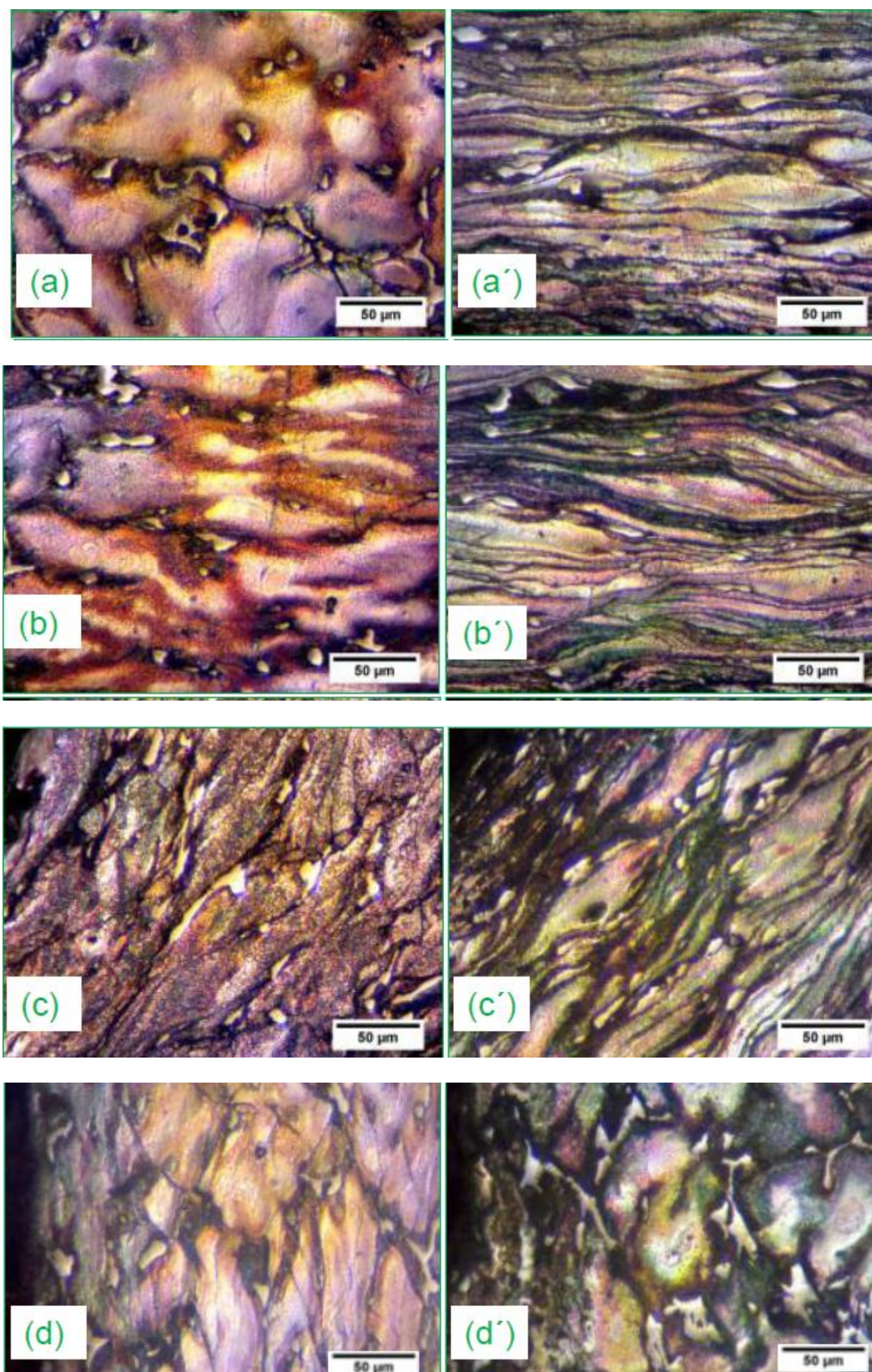
shear stress is applied to the material, and the material is affected by normal strain [15].

Consequently, there is not any grain refinement in these zones (Fig 3 (a) and (b)). In the “c” region, shear stress is applied when the inner punch moves down, and grain refinement occurs (Fig 3 (c)) [16]. A normal strain occurs at the bottom region labelled by “d”, as shown in (Fig 3 (d)) [15]. In this region, the flow of material along the deformation channel is seen in the form of shear bands [16]. In the “a'”, “b'” and “c'” regions, the severe shear strain occurs, and it leads to achieving high TRR. Therefore, the significant grain refinement could be seen in these regions. In Fig. 3 (d') the microstructure of “d'” zone can be observed which is similar to the “d” zone because the normal strain is applied in these regions.

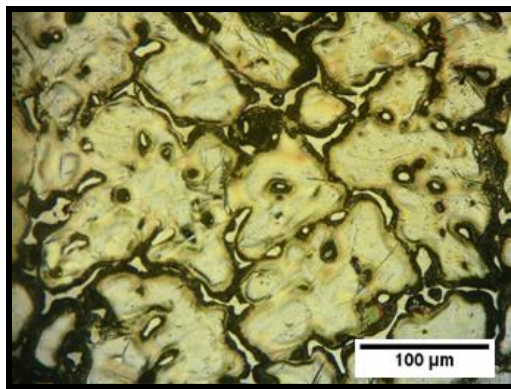
Fig. 4 (a) illustrates the microstructure of the initial sample of AZ91 magnesium alloy. As shown in the figure, the as-cast AZ91 alloy consists of large grains of  $\alpha$ -Mg phase with the mean grain size of 150  $\mu$ m and eutectic  $\beta$ -phase (Mg<sub>17</sub>Al<sub>12</sub>) which was located on inter-dendritic network [8], [14]. Fig. 4 (b) and (c) show optical micrographs of the back extruded and BE+CI processed samples. The average grain size was reduced to  $\sim 5.6$   $\mu$ m after back extrusion. As shown in Fig. 4 (b), there are some undissolved eutectic  $\beta$ -phase in the microstructure of back extruded cup. After constrained ironing process (BE+CI) (Fig. 4(c)), the average grain size is refined to  $\sim 1$   $\mu$ m. Feeding the cup material into the deformation zone with a higher thickness reduction plays the fundamental role in grain refinement of ironed cup material.

Thus, the accumulative strain after BE+CI process causes to achieve the UFG material. According to the Taylor criteria, magnesium alloys requires five independent, easy slip systems for better formability that these slip systems were enabled at high temperatures [17]. The temperature plays the main role in a variation of the grain size [18], [19] in Mg alloys because it is affected by the rapid grain growth at higher temperatures [20].

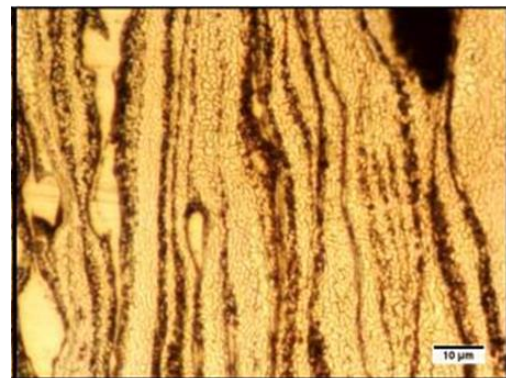
During the hot working, dynamic recrystallization (DRX) performed under the condition of high accumulative strain and processing temperature [21] and the grain refinement is achieved through DRX mechanism [2], [22]. The dynamic recrystallization process was incomplete, and some unrecrystallized regions and some undissolved eutectic  $\beta$ -phase can be found in the microstructure of back extruded cup while these regions were limited in the BE+CI processed sample. Also, the grain size distribution of the back extruded sample is no uniform while the dynamic recrystallization process was complete and uniform grain size distribution with almost fully recrystallized regions can be seen in the microstructure of BE+CI processed cup.



**Fig. 3** OM photographs showing the microstructural change during the BE+CI process at positions of a-d and a'-d' shown in Fig. 2

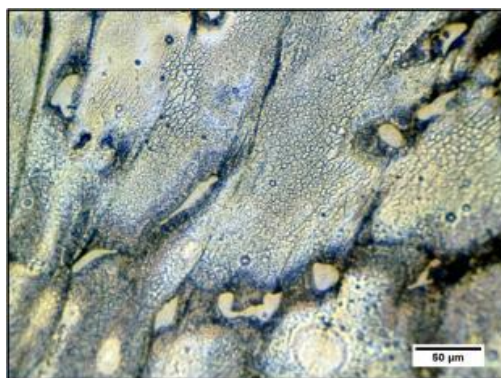


(a)

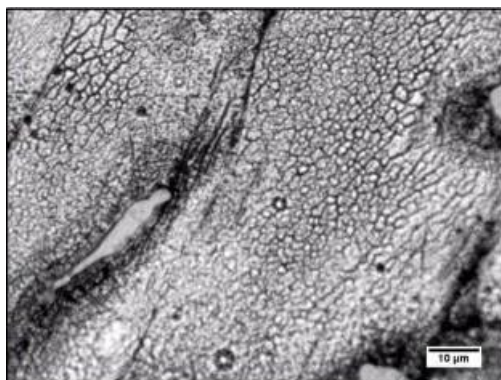


(b)

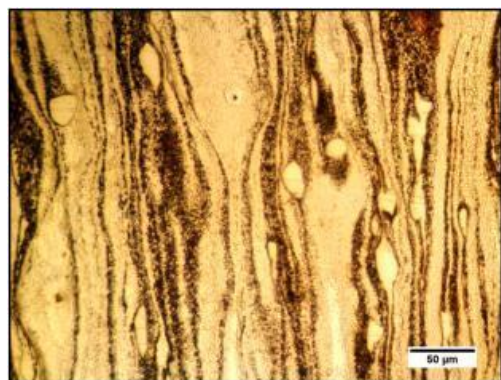
**Fig. 4** OM photographs showing the microstructure of (a) as received unprocessed AZ91 alloy (b) backward extruded, and (c) BE+CI processed cup.



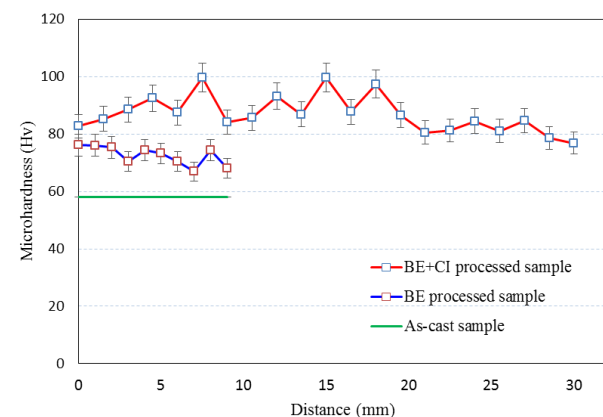
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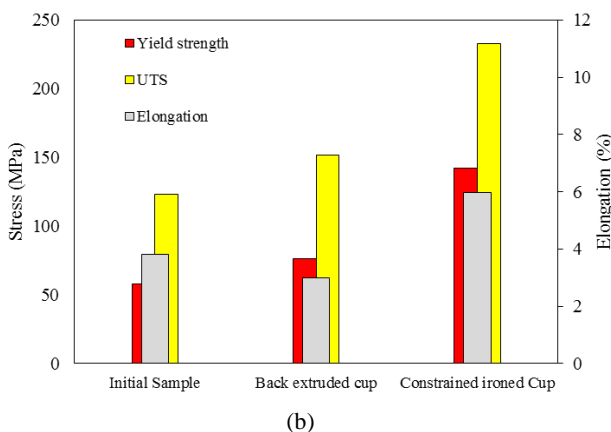
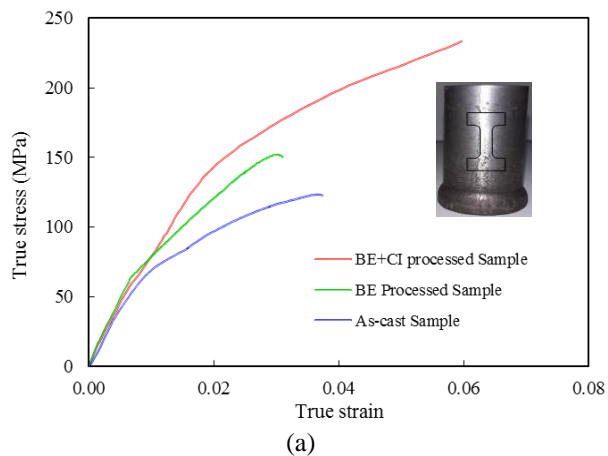
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**Fig. 5** Microhardness distribution at the cross-section of various samples

Fig. 6 represents true stress-strain curves obtained for the initial, BE and BE+CI processed samples with illustrating the place of tensile sample. According to

the curves, after the BE and BE+CI process, different curve appeared compared with initial one. Apparently, after BE process, yield and ultimate strength were increased while elongation to failure was decreased similarly to SPD methods [23]. The tensile strength increases from 123MPa to ~152 MPa. However, the elongation was slightly decreased in BE specimen. Surprisingly, After CI+BE process, the ductility and the strength were significantly increased. The tensile strength of 123 MPa with 4% elongation was seen at the as-cast unprocessed specimen. After CI+BE process, the elongation and the tensile strength increase to the values of ~6% and 233 MPa, respectively. Increase in the elongation despite grain refinement is a fabulous result of this investigation. In CI process two phenomena took place: (1) The breakage of Mg17Al12 precipitates into smaller parts and scattered over the grains which make the dislocation motion easier and (2) immense hydrostatic pressure is applied to the material during CI process which leads to eliminating the probable cracks and defect initiation and propagation.



**Fig. 6** (a) True stress-strain and (b) UTS, YS and elongation of unprocessed, BE and BE+CI processed samples

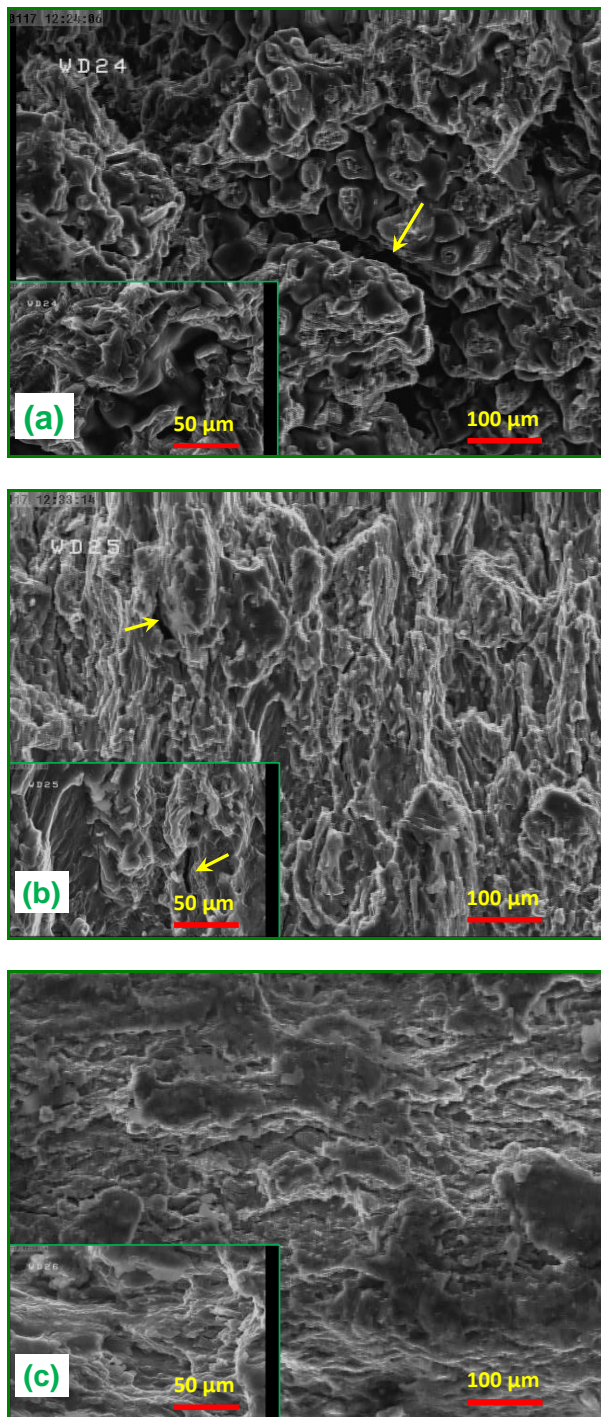
Besides, the significant improved of mechanical properties of the magnesium alloy may be caused from higher TRR [24], leading to higher plastic strains in constrained ironing process. Higher hydrostatic compressive stresses lead to the high workability of the material. After BE+CI process, a severe plastic deformation is applied to the cup wall in the deformation zone. The simultaneous increase of the ductility and strength may attribute to the higher compressive stresses during the deformation. Higher compressive stresses may limit the crack initiation and propagation.

Consequently, a significant grain refinement is achievable after BE+CI process. According to the Hall-Petch equation, an increase in strength and hardness is due to a decrease in grain size [2]. Thus, reduction of the grain size impedes the movement of dislocations in (UFG) material, and it results in increasing the hardness and strength. So, simultaneously increase in the strength and elongation was achieved using the combined process. From the engineering point of view, simultaneous higher strength and elongation is the best property for a load bearing material.

Fig. 7 shows SEM observation of the fractured surface of the tensile samples. The fractography images of as-cast, BE and BE+CI processed AZ91 alloys after tensile test are respectively illustrated in Figs. 7(a)-(c). It is evident from Fig. 7(a) that the as-cast AZ91 sample exhibits a trans-crystalline fracture surface, in which several wide cracks shown by the yellow arrows could be observed. These kinds of cracks in fracture surface are related to brittle fracture in which the specimen experiences a little plastic deformation before fracture.

As indicated in the previous study [25], the fracture shape and mechanism of fracture is affected by experiencing plastic deformation. Fig. 7(b) represents the morphology of fracture surface of BE sample. It also reveals brittle fracture mood by shallow and elongated dimples. In addition, more cracks appear in the BE processed sample because of significant plastic deformation. This kind of fracture has been attributed to fine grain size and also in-homogeneously intermetallic particle that existed in AZ91 alloys. Fig. 7(c) shows that the BE+CI processed AZ91 alloy sample exhibited brittle fracture with observing some cleavage and tiny dimples. Remarkable noting is that the less crack was observed in the sample in comparison with as-cast and BE samples.

This may be related to higher compressive hydrostatic stresses in CI process in comparison to BE stage. In CI process, huge hydrostatic compressive stress leads to rejoining the cracks surfaces, limiting crack initiation and propagation leads to more elongation and strength.



**Fig. 7** The tensile fracture surface of AZ91 alloy samples: (a) as-cast. (b) BE and (c) BE+CI.

#### 4 CONCLUSION

A new combined backward extrusion and constrained ironing method was introduced for producing thin-walled UFG magnesium cups. This combined

technique was successfully applied to a magnesium alloy AZ91, and the main results of this research are as follows:

- The high thickness reduction ratio about 80% was achieved on the brittle material after only single stage constrained ironing.
- The microstructure of the back extruded sample followed by constrained ironing process was significantly refined.
- UFG thin-walled cup with the thickness of 0.5 mm was produced.
- After combined BE and constrained ironing process, the average grain size was refined to  $\sim 1 \mu\text{m}$  from  $\sim 150 \mu\text{m}$  for the as-cast initial sample.
- The higher microhardness of the processed cup was obtained from the initial value 58 HV to 87 HV.
- After BE stage, the ductility of the AZ91 was slightly reduced while after BE+CI process, simultaneous improvement of strength and ductility was observed as a result of high hydrostatic compressive stress during CI process.
- The cracks in the BE+CI samples almost disappeared due to high hydrostatic compressive stress during CI process.

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