# Mechanical properties and dilatation performance of magnesium alloy (WE43) for vascular stents application after room temperature ECAP processing

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## INTRODUCTION

Stents are a kind of elastic metal frame with cylindrical spatial structure and millimeter sizes implanted into a critically stenosed section of the coronary vessel to support its walls and dilate its lumen. Permanent vascular stents are going to be replaced by the implementation of biodegradable magnesium-based stents in the medical treatment of vascular diseases because of many concerns associated with conventional implants [1]. However, the low mechanical properties of biodegradable magnesium-based biomaterials are the main challenge. It is well known that the use of severe plastic deformation (SPD) techniques is one of the most effective ways to refine the grain size and microstructure of polycrystalline metals. According to the Hall-Petch equation, this grain refinement can improve mechanical properties such as hardness and strength [2]. Previous studies conducted the Equal channel angular pressing (ECAP) process on rare earth containing WE43 biodegradable magnesium alloy at elevated temperatures [3-6]. Using the core-sheath method, imposing a back pressure on the billet could reduce the working temperature during the ECAP technique [7]. This research aims to investigate the performance of the WE43 alloy after room temperature core-sheath ECAP used as a vascular stent.

## OBJECTIVES

- Reducing the working temperature of the ECAP technique
- Increasing strength of the WE43 alloy by grain refining
- Simulation of stent's behavior in contraction and expansion modes during implantation

## MATERIALS & METHODS

The investigated magnesium alloy WE43 was supplied in the as-extruded condition. The chemical composition of the used alloy is given in Table 1. The billet was solution-treated at 525 °C for 8 hours and then quenched in a solution containing 80 °C water and 10wt% salts. Cylinder-shaped specimens with a diameter of 5 mm and a length of 40 mm were machined from this material and prepared as core billet. Cylindrical Bars of AISI 1015 steel with a diameter of 20 mm and a length of 125 mm were machined and used as sheath material. ECAP of this core-sheath billet was conducted using a die with an angle of 90 ° between two intersecting channels (Φ) and an angle of 20 ° as the corner angle (Ψ) at room temperature.

The alloy's microstructure in the initial state, solution treated, and ECAP-processed was examined using a ZEISS optical microscope and field emission electron microscope (FESEM). Samples were etched first with a solution containing ethanol and 3v% nitric acid and second with a solution containing 4.2 g picric acid, 10 ml acetic acid, 70 ml ethanol, and 10 ml distilled water called Picral.

The mechanical properties were evaluated through a uniaxial tensile test carried out at room temperature in a SANTAM UNIVERSAL testing machine equipped with a 200 kN load cell. A constant cross head-displacement rate was maintained, corresponding to the nominal initial strain rate of 0.0001 $s^{-1}$.

Table 1. Chemical Composition of WE43 alloy

| Mg (wt%) | Y (wt%) | Nd (wt%) | Other RE (wt%) |
|---|---|---|---|
| Bal. | 4.47 | 2.42 | 0.29 |

The pattern of the stent was designed using commercial AutoCAD software based on mathematical calculations of imposed stresses in implantation conditions. Furthermore, a prototype stent with an outer diameter of 3mm, a thickness of 0.25 mm, and a length of 13 mm was fabricated by laser cut with a laser beam frequency of 4 kHz.

In order to evaluate the performance of stents in contraction and expansion modes, a 3D geometrical model was designed and imported to commercial ABAQUS software.

## RESULTS & DISCUSSION

1 .Microstructure analysis

The microstructure of as-extruded alloy consists of solid solution α-Mg matrix with three types of intermetallic precipitates (Fig.1. (a)). Globular and cuboid precipitates are enriched with Nd and Y, respectively. These two type phases with the chemical composition of $Mg_{41}Nd_5$ and $Mg_{24}Y_5$ most likely originate from the primary solidification of the alloy during casting [8]. Needle-like precipitates with the composition of $Mg_3$(Y, Nd) and grain boundary segregation were usually arising from thermo-mechanical processes on the alloy.

The microstructure of the solution-treated alloy is shown in Fig.1. (b). All needle-like precipitates dissolved into the Mg matrix, and grain boundary segregation disappeared. Also, most globular and cuboid phases dissolved, and the volume phase fraction of secondary phases reached the lowest point.

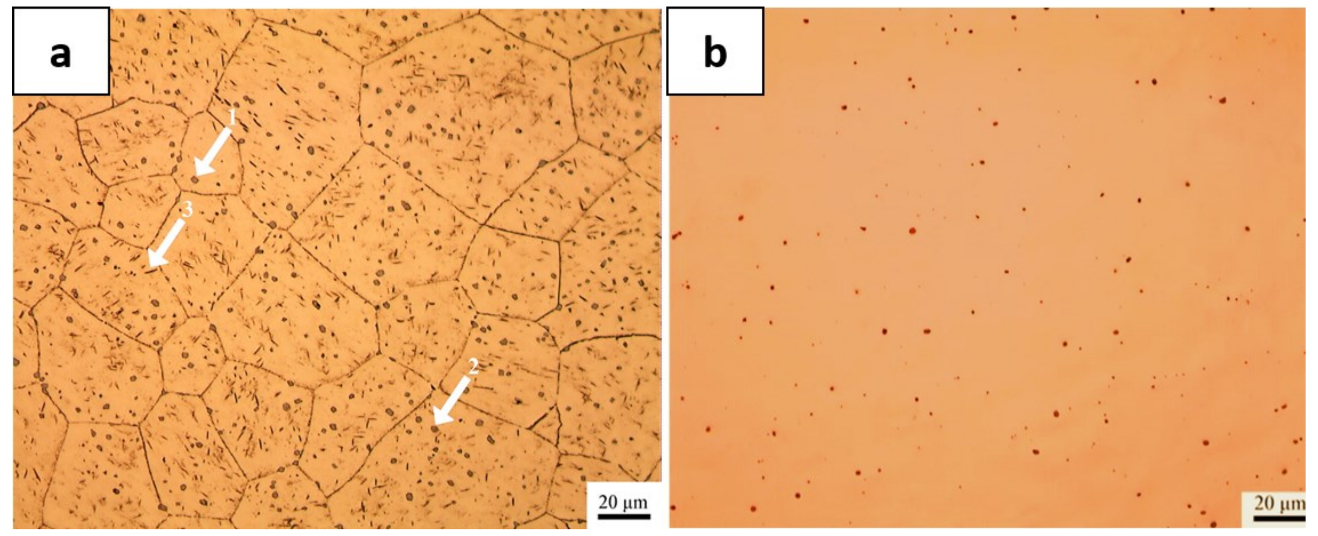


Fig. 1. Optical Microstructure of a) as-extruded alloy and b) solution treated alloy.

FESEM images of the alloy after one pass room temperature ECAP are shown in Fig 2. Coarsed precipitates along the deformation direction formed during ECAP. Shahmir et al. [9] reported that billet temperature rise during core-sheath ECAP at room temperature was 6°C. Since the ECAP process was conducted at room temperature in this research, strain-induced precipitation occurred in the alloy during ECAP.

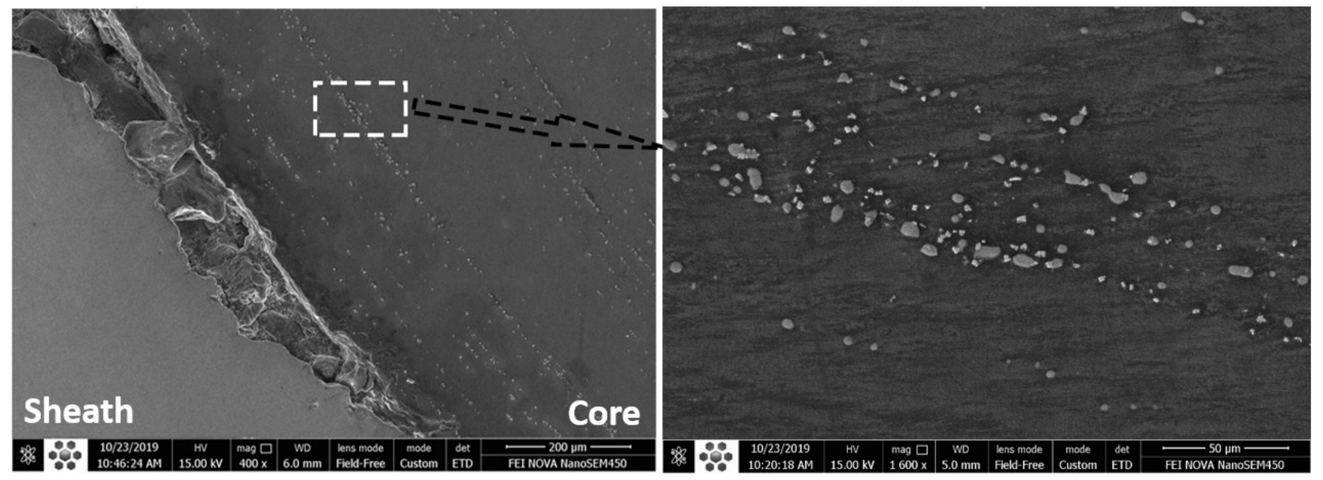


Fig. 2. FESEM of coarsed precipitates in ECAP-processed alloy.

2. Mechanical properties

2.1 Hardness measurement

Table 2 shows the results of the hardness and volume fraction of precipitates (VFP) measurement of the alloy in as-extruded, solution treated, and ECAP-processed conditions. Microhardness and VFP of the as-extruded alloy were 86.1 HV and 7.6 v%, respectively. After solution treatment, the minimum value of microhardness and VFP was obtained. ECAP processing at room temperature increased microhardness to 113.4 HV significantly, and a noticeable increase in VFP was observed.

Table 2. Micro hardness and volume fraction of precipitates

| Alloy Condition | Micro Hardness (HV) | Volume Fraction of Precipitates (v%) |
|---|---|---|
| As-Extruded | 86.1 ± 2.2 | 7.6 ± 0.34 |
| Solution Treated | 69.9 ± 1.5 | 0.76 ± 0.22 |
| ECAP-Processed | 113.4 ± 3.3 | 2.73 ± 0.29 |

2.2 Tensile properties

Figure 3 demonstrates a comparison of tensile properties between solution treated and ECAP-processed alloy. Due to the larger grain and minimum VFP, lower yield strength (YS) and ultimate tensile strength (UTS), and higher strain to fracture were observed in the solution-treated alloy. It can be seen that the alloy strengthened with ECAP and represent excellent UTS and YS. The combination of precipitation hardening together with a significant strain hardening resulted in a remarkable increase of strength. YS and UTS were obtained 276 and 374, respectively, which has not been reported so far. However, strain to fracture severely decreased.

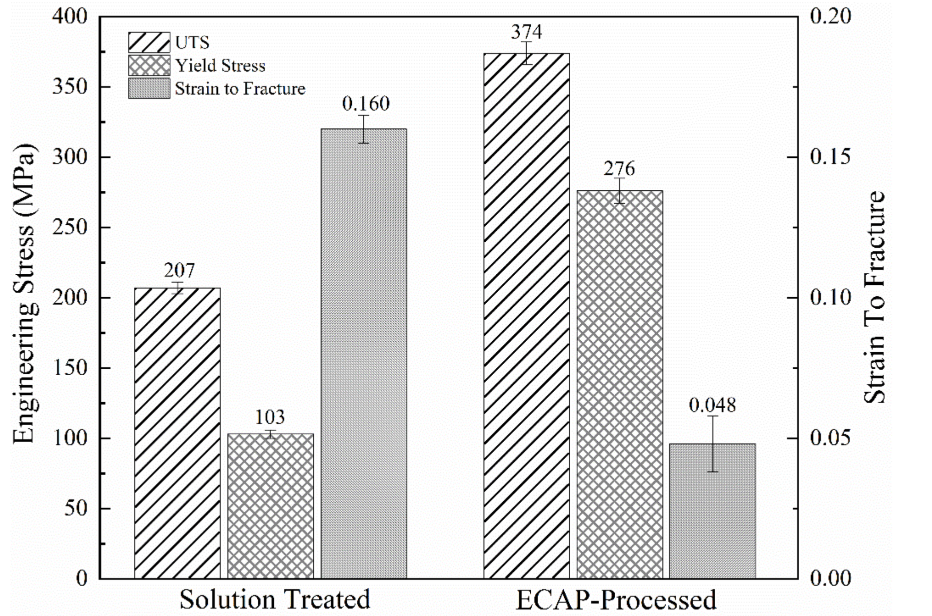


Fig . 3. Tensile properties of solution treated and ECAP-processed WE43 alloy.

3. Simulation of Stent's behavior

Figure 5. (a) shows the prototype stent fabricated by laser-cut, and the 3D geometrical model of the stent is shown in Fig.5 (b). Absolute values of diameter change of stent in contraction and expansion modes which were obtained from simulations are shown in Fig. 5. (c) and (d), respectively. Diameter change with respect to initial diameter determines the performance of stent in implantation conditions. Table 3 shows a comparison of diagonal shrinkage and dilatation of the stent in the solution treated and ECAP-processed condition of the alloy. Diagonal shrinkage and dilatation in solution treated were obtained 14 and 17%, respectively. For as much as ECAP processing increased the YS and UTS of the alloy, maximum shrinkage and dilatation were reached to 16 and 22%, respectively.

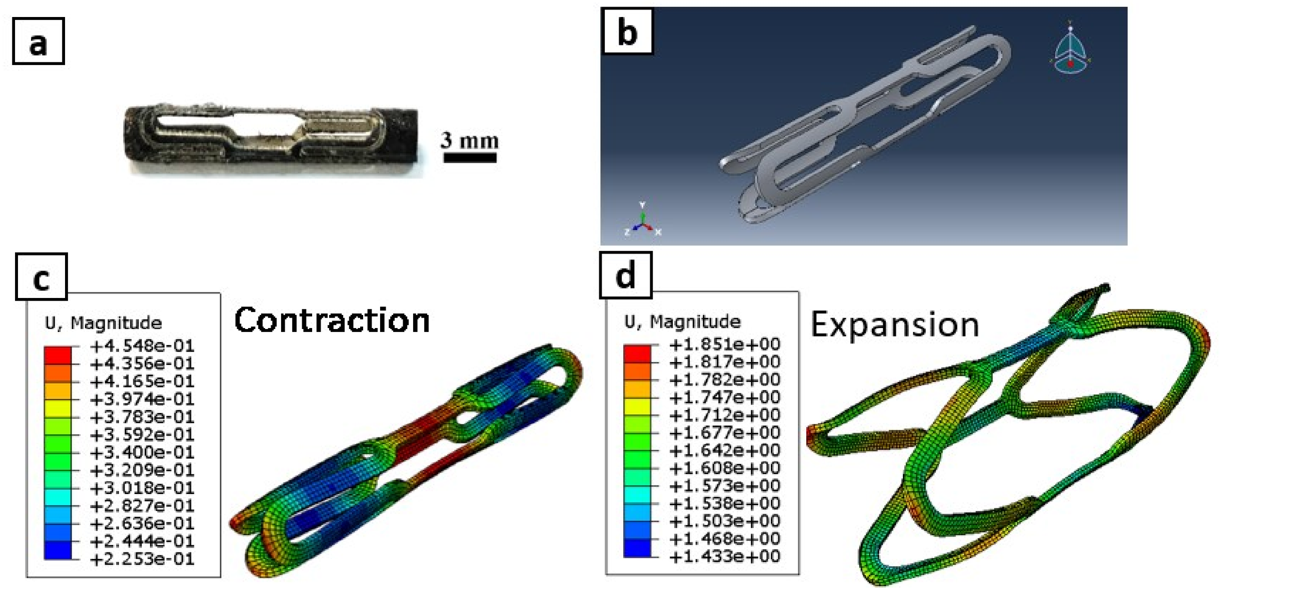


Fig 4. a) Prototype fabricated stent, b) 3D model of stent, c) contraction mode and d) expansion mode in implantation condition.

Table 3. Diagonal shrinkage and dilatation of stent

| Alloy Condition | Diagonal Shrinkage (%) | Diagonal Dilatation (%) |
|---|---|---|
| Solution Treated | 14 | 17 |
| ECAP-Processed | 16 | 22 |

## CONCLUSION

1. Solution annealing treatment resulted in minimum hardness and volume fraction of precipitates with respect to as-extruded alloy.
2. Room temperature ECAP processing and strain induce precipitation increased strength of the alloy significantly.
3. Shrinkage and dilatation performance improved after ECAP.

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