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ENHANCING THE MECHANICAL PROPERTIES OF BIODEGRADABLE ZINC ALLOYS THROUGH SEVERE PLASTIC DEFORMATION TECHNIQUES

BY

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Abstract. Zinc-magnesium (Zn-Mg) alloys have emerged as promising candidates for biodegradable implants due to their excellent biocompatibility and controlled degradation rates. However, their limited mechanical properties often hinder their practical applications. In this study, hydrostatic extrusion (HE) and equal channel angular pressing (ECAP) were employed to enhance the microstructure and mechanical properties of a Zn-1%Mg alloy. The effects of these severe plastic deformation techniques on grain size, dislocation density, and tensile properties were investigated. The results demonstrated that both HE and ECAP significantly refined the microstructure, leading to substantial increases in strength and ductility. The enhanced mechanical properties were attributed to the synergistic effects of grain boundary strengthening and dislocation strengthening mechanisms. Furthermore, the study suggests that HE-processed and ECAP-processed Zn-Mg alloys have the potential to be used in various biomedical applications, such as biodegradable stents and orthopedic implants.

Keywords: Zn-Mg alloys, Biodegradable implants, Severe Plastic Deformation (SPD), Microstructure refinement.

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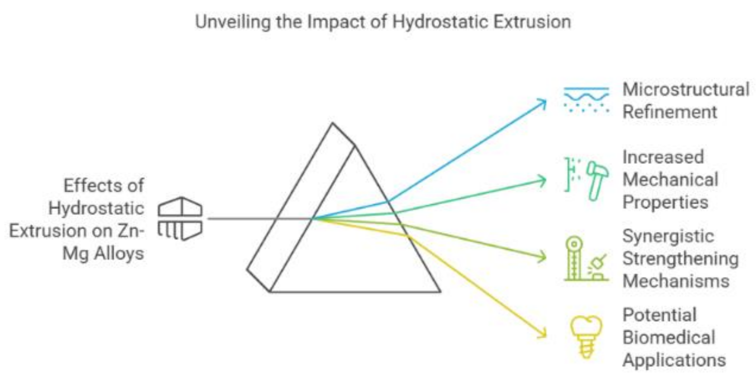
1. Introduction

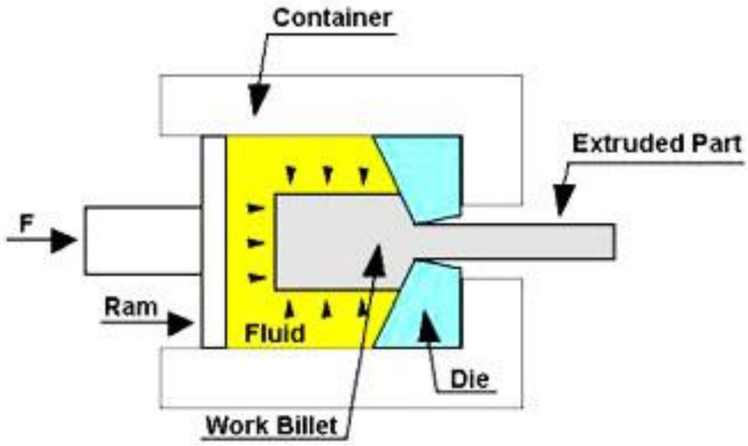
Biodegradable metallic implants have gained significant attention in recent years due to their ability to degrade and be absorbed by the body over time, eliminating the need for a second surgery to remove the implant (Panaghie, 2021; Istrate, 2022). Among various biodegradable metals, zinc-based alloys have emerged as promising candidates due to their excellent biocompatibility and controlled degradation rates (Panaghie, 2022; Istrate, 2020). However, the mechanical properties of zinc-based alloys, particularly their low strength and ductility, limit their application in load-bearing implants (Huang, 2021). Severe plastic deformation (SPD) techniques have been widely used to enhance the mechanical properties of metals and alloys (Comăneci, 2024). Hydrostatic extrusion (HE) and equal channel angular pressing (ECAP) are specific SPD techniques that can induce significant plastic deformation, leading to grain refinement and dislocation accumulation (Jarzębska, 2018; Khafizova, 2023). This study aims to investigate the effects of HE and ECAP on the microstructure and mechanical properties of Zn-1%Mg alloys, optimizing processing parameters to achieve desired mechanical properties for specific biomedical applications.

2. Hydrostatic Extrusion

Hydrostatic extrusion was performed at room temperature using a hydraulic press. The extrusion ratio was 4.33, and the total true strain was 3.33. The extruded rods were then subjected to various characterization techniques, including scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The impact of hydrostatic extrusion on the structure and properties of alloys and the schematic representation of Hydrostatic Extrusion are given in Fig. 1.



(a)



(b)

Fig. 1 – Effects of hydrostatic extrusion on Zn-Mg alloys in (a) and schematic representation of Hydrostatic Extrusion in (b) (http://www.industrialextrusionmachinery.com/extrusion_process_hydrostatic_extrusion.html, accessed 10 sept.2025) .

3. Equal Channel Angular Pressing (ECAP)

ECAP involved extruding a sample through a die with two identical channels intersecting at a specific angle (typically 90°), Fig. 2. The processing routes included route A (without rotation) and routes BA, BC, and C (with various degrees of rotation). The ECAP process was conducted at room temperature, and the samples were subjected to multiple passes to increase strain and refine the microstructure.

Tensile tests can be conducted at room temperature using a universal testing machine. Tensile specimens were machined from the extruded and ECAP-processed rods. Both HE and ECAP processes significantly refined the microstructure of the Zn-Mg alloy, leading to a reduction in grain size. After HE, the average grain size was approximately 700 nm in the transverse section and 1 mm in the longitudinal section. ECAP further contributed to the formation of ultrafine-grained or nanostructured materials. The deformation induced by both HE and ECAP resulted in a high density of dislocations, contributing to the strengthening of the material. The accumulation of dislocations acts as barriers to further dislocation motion, enhancing the overall strength.

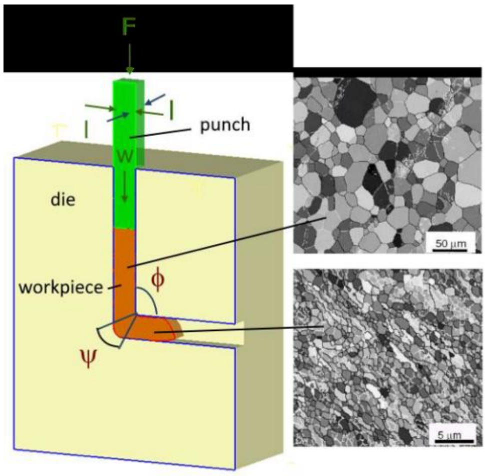


Fig. 2 – Schematic representation of ECAP and typical structural changes (Comăneci, 2024).

The HE-processed and ECAP-processed Zn-Mg alloys exhibited significantly improved yield strength (YS) and ultimate tensile strength (UTS) compared to the as-cast material. The YS reached 316 MPa, and the UTS reached 435 MPa, with elongation values of 35%. These improvements are attributed to the combined effects of grain refinement and dislocation strengthening. The enhanced work hardening behavior of the HE-processed and ECAP-processed alloys is attributed to the high density of dislocations and the fine-grained microstructure, which can accommodate plastic deformation more easily, leading to improved ductility.

The refined microstructure also contributes to improved corrosion resistance, forming protective oxide layers that enhance the biocompatibility of the alloys. These features make HE-processed and ECAP-processed Zn-Mg alloys suitable for various biomedical applications.

4. Future Work

Future research should focus on:

- Investigating the effect of different processing parameters (e.g., extrusion ratio, temperature, strain rate) on the microstructure and mechanical properties of Zn-Mg alloys (Peng, 2019).
- Studying the long-term stability of the microstructure and mechanical properties.
- Exploring the potential of combining ECAP with other processing techniques, such as heat treatment, to further enhance the properties of Zn-Mg alloys.

• Conducting in vivo studies to evaluate the biocompatibility and degradation behavior of ECAP-processed Zn-Mg implants.

By addressing these areas, future research can contribute to the development of advanced biodegradable materials for biomedical applications. Insights on hydrostatic extrusion (HE) has been shown to significantly enhance the mechanical properties of zinc-magnesium (Zn-Mg) alloys, which are promising materials for biodegradable implants. The study by Jarzebska et al. highlighted several key effects of HE on the Zn-1%Mg alloy (Jarzebska, 2018):

1. Microstructural Refinement: HE leads to a substantial reduction in grain size, achieving an average of about 700 nm in the transverse section. This fine microstructure is crucial as it contributes to the material's strength through mechanisms such as grain boundary strengthening.

2. Increased Mechanical Properties: The HE-processed Zn-Mg alloy exhibited a remarkable yield strength of 316 MPa, ultimate tensile strength of 435 MPa, and elongation of 35%. These values represent a significant improvement over the as-cast state, making the alloy more suitable for load-bearing applications like bioresorbable stents (Lu, 2024).

3. Synergistic Strengthening Mechanisms: The enhanced mechanical properties can be attributed to a combination of grain boundary strengthening and dislocation strengthening. The high density of dislocations introduced during HE contributes to the overall strength, while the fine-grained structure allows for improved ductility.

4. Potential Biomedical Applications: The findings suggest that HE-processed Zn-Mg alloys can meet the performance requirements for various biomedical applications, indicating their potential as effective materials for biodegradable implants (Panaghie, 2022).

Principles and Applications of Equal Channel Angular Pressing (ECAP)

Equal Channel Angular Pressing (ECAP) is another severe plastic deformation (SPD) technique that has gained traction for its ability to refine the microstructure of metals and alloys:

1. Principle of Operation: ECAP involves extruding a material through a die with two intersecting channels at a specific angle, typically between 90° and 120°. This process introduces high levels of shear strain without altering the material's overall cross-section, allowing for significant plastic deformation (Wang, 2021).

2. Microstructural Effects: ECAP is effective in generating ultrafine-grained or nanostructured materials. The process induces a high density of dislocations, which enhances mechanical properties such as strength and ductility (Panaghie, 2023). The repeated passes through the die allow for cumulative strain, further refining the microstructure (Vinogradov, 2019).

3. Deformation Mechanisms: The mechanisms responsible for microstructural refinement during ECAP include dislocation accumulation, grain

boundary sliding, and dynamic recrystallization. Each of these mechanisms contributes to the overall improvement in mechanical properties.

4. Applications: ECAP-processed materials have a diverse range of applications, including in aerospace, automotive, biomedical engineering, and electronics. The ability to tailor mechanical properties through microstructural refinement makes ECAP a valuable technique for developing advanced materials.

Mechanisms of Deformation and Dynamic Recrystallization in Hexagonal Close-Packed Metals

Hexagonal close-packed (HCP) metals, such as zinc and its alloys, exhibit unique deformation behaviors due to their crystal structure:

1. Deformation Mechanisms: HCP metals primarily deform through dislocation slip and twinning. The limited slip systems in HCP metals can restrict plastic flow, making twinning an essential mechanism for accommodating deformation, especially under conditions of high strain (Liu, 2019).

2. Dynamic Recrystallization (DRX): DRX is critical for the recovery of ductility and strength during deformation. It can occur through several mechanisms, including continuous DRX (gradual nucleation and growth of new grains), discontinuous DRX (nucleation at grain boundaries), and twinning-induced DRX (nucleation within twin boundaries) (Wu, 2025).

3. Influence of Alloying Elements: The addition of alloying elements such as magnesium can significantly influence the deformation behavior and DRX mechanisms in HCP metals. For instance, Mg additions to Zn can affect the distribution of phases and the activation of different slip systems, enhancing mechanical properties (Shi, 2020; Shi, 2022).

4. Processing Techniques: SPD techniques, including ECAP and HE, are effective for refining the microstructure of HCP metals, leading to improvements in mechanical properties. These techniques introduce significant plastic strain, promoting mechanisms that enhance strength and ductility.

5. Conclusions

This study presents that both hydrostatic extrusion and equal channel angular pressing are effective techniques for enhancing the mechanical properties of Zn-Mg alloys. The significant improvements in strength and ductility are attributed to the combined effects of grain refinement and dislocation strengthening. The findings suggest that HE-processed and ECAP-processed Zn-Mg alloys have the potential to be used in various biomedical applications, such as biodegradable stents and orthopedic implants. The integration of HE and ECAP techniques offers a promising avenue for enhancing the properties of Zn-Mg alloys and other HCP metals. Both methods effectively refine microstructures, leading to significant improvements in mechanical properties that are crucial for biomedical applications. Understanding the underlying mechanisms of deformation and DRX in HCP metals can further optimize processing parameters and alloy compositions, paving the way for the development of advanced materials with superior performance characteristics. Future research should continue to explore these techniques and their applications in various industrial and biomedical fields.

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ÎMBUNĂTĂȚIREA PROPRIETĂȚILOR MECANICE ALE ALIAJELOR DE ZINC BIODEGRADABILE PRIN TEHNICI DE DEFORMARE PLASTICĂ SEVERĂ

(Rezumat)

Aliajele zinc-magneziu (Zn-Mg) s-au impus drept un candidat promițător pentru implanturi biodegradabile datorită biocompatibilității lor excelente și a vitezelor de degradare controlate. Cu toate acestea, proprietățile lor mecanice limitate împiedică adesea aplicațiile practice. În acest studiu, extrudarea hidrostatică (HE) și presarea în canal unghiular egal (ECAP) au fost utilizate pentru a îmbunătăți microstructura și proprietățile mecanice ale unui aliaj Zn-1%Mg. Au fost investigate efectele acestor tehnici de deformare plastică severă asupra dimensiunii grăunților, densității dislocațiilor și proprietăților de tracțiune. Rezultatele au demonstrat că atât HE, cât și ECAP au rafinat semnificativ microstructura, conducând la creșteri substanțiale ale rezistenței și ductilității. Îmbunătățirea proprietăților mecanice a fost atribuită efectelor sinergice ale mecanismelor de durificare prin limite de grăunte și prin dislocații. În plus, studiul sugerează că aliajele Zn-Mg procesate prin HE și ECAP au potențialul de a fi utilizate în diverse aplicații biomedicale, cum ar fi stenturile biodegradabile și implanturile ortopedice.