

Effect of Al or Cu Content on Microstructure and Mechanical Properties of Zn Alloys Fabricated Using Continuous Casting and Extrusion

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Abstract: The effect of Al or Cu content on the microstructure and mechanical properties of continuous casting and extrusion Zn alloys has been studied by a room temperature tensile test, X-ray diffraction, and scanning electron microscope. With the increase in Al content, the microstructure of continuous casting and extrusion Zn alloys slightly coarsens, and the lamellar eutectic structure increases. The changes in the above structural factors result in a slight decrease in strength and a significant increase in the elongation of Zn-Al alloys. The strength of Zn alloys increases as the Cu content increases due to the increased content and size of the second phase in the Zn alloys. This means that the mechanical properties of Zn alloys can be adjusted by a continuous casting and extrusion process, and the improvement of equipment capacity can improve the structure and morphology of the alloys.

Keywords: Zn alloy; continuous casting and extrusion; elongation; mechanical property; eutectic structure



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1. Introduction

Zinc and its alloys have a low melting point, fine fluidity, easy brazing, plastic processing, and other excellent properties, so they are widely used in thermal spraying, capacitor parts, gold accessory spraying, hardware, electronics, industrial equipment, and the automotive industry [1–3]. The current method of manufacturing rods or wires for the preparation of zinc and its alloys is mainly casting followed by extrusion. Harmful impurities, such as cadmium and tin, can accumulate at the grain boundaries of cast zinc alloys, leading to a significant reduction in mechanical properties. The low elongation of cast zinc alloy rods or wires makes them more difficult to machine, and multiple heating passes bring increased costs, which greatly limits their application [4–7]. However, the conventional hot extrusion process for the production of zinc alloy rods or wires is long, mainly because most zinc alloys have a hexagonal crystal structure that makes plastic deformation at room temperature quite difficult. However, through the mechanism of twin deformation, it is possible to maintain a good degree of plasticity. The process commonly used worldwide for zinc alloy rods or wires is a continuous or semi-continuous casting process, followed by the heating of the extrusion cylinder and extrusion die [8–10]. The strength and plasticity of zinc alloy can be greatly improved after deformation, but the process is long, and the production cost is high. Therefore, the ultimate goal of manufacturers is to shorten the manufacturing process as much as possible, reduce the negative impact of the production process on the environment, save energy, and increase the utilization of Zn alloys, while achieving economic efficiency [11]. It has become one of the hot spots for research to reduce the production cost and efficiency of zinc alloys, while ensuring the performance of the products.

The continuous casting and extrusion process has been successfully applied to the industrial production of Al alloy and Mg alloy bars and wires. This has successfully demonstrated the feasibility of continuous casting and extrusion in the production of alloys and has achieved great economic benefits [12–14]. Recently, it has been found that the continuous casting and extrusion process has been successfully applied to the preparation of zinc alloys. However, the current study focuses on the microstructure and room temperature mechanical properties of the Zn-15Al alloys by continuous casting and extrusion [15,16]. The Al and Cu are common alloying elements in zinc alloys [17–20]. However, little has been reported on the effect of trace amounts of Al and Cu on the continuous casting of extruded Zn alloys. Therefore, the effect of different Al or Cu contents on the microstructure and room temperature mechanical properties of Zn alloy by continuous casting and extrusion was discussed. This can provide a new idea for processing Zn alloys with low cost and high efficiency.

2. Materials and Methods

Small amounts of Al and Cu can significantly improve the properties of zinc alloys. The Zn-2Al and Zn-4Al alloys were conducted using pure Zn and Al with a purity of over 99.9 wt.% (mass fraction). Similarly, the Zn-2Cu and Zn-4Cu alloys were made using pure Zn and Cu with purities exceeding 99.9 wt.%. The chemical composition of the Zn alloy is listed in Table 1. As shown in Figure 1, the pure zinc was first heated to 600 °C for melting, and then pure aluminum or pure copper was added. After all the metal had been melted, a graphite bell was pressed into the alloy with 2 wt.% C₂Cl₆ for degassing. The temperature was lowered to 550 °C and then left to stand for 20 min to obtain the Zn alloy melt. The alloy melt was poured into the CASTEX-300 continuous casting and extrusion machine (Northeastern University, Shenyang, China). Before continuous casting and extrusion, clean the surface of the extrusion wheel, extrusion shoe, and die, and then install the extrusion die and groove block of the continuous casting extrusion machine into the extrusion shoe of the continuous casting and extrusion machine. Adjust the gap between the extrusion wheel and extrusion shoe to 0.5 mm, and preheat the crucible to 400 °C. Start the continuous casting and extrusion machine and adjust the rotation speed of the extrusion wheel to 8 r/min. Then, pour the above-mentioned Zn alloy melt into the cavity formed by the extrusion wheel and the groove sealing block with the preheat crucible. When the bar is to be formed, water cooling is to be started and should flow into the extrusion wheel. When the melt is finished and the pouring is stopped, adjust the rotation speed of the casting extrusion wheel to 3 r/min, and, under the rotating condition of the extrusion wheel, separate the extrusion shoe from the extrusion wheel, and then turn off the power supply to stop the extrusion wheel [21]. The rotational speed of the casting and extrusion wheel was 8 r/min, and the cooling water flow rate was 15 L/min.

Table 1. The chemical composition of the Zn alloy [wt.%].

Name	Al	Cu	Zn
Zn-2Al	2	0	Bal.
Zn-4Al	4	0	Bal.
Zn-2Cu	0	2	Bal.
Zn-4Cu	0	4	Bal.

After sanding with 200 # to 2000 # sandpaper, the Zn alloy was mechanically polished to a mirror shape. The corrosion solution was a 9% HNO₃+91% H₂O solution. The metallographic observation of the alloy was examined by the GX71 inverted optical microscope (OLYMPUS, Tokyo, Japan). The microstructure and fracture morphology of the alloy were observed under a JSM-6510 scanning electron microscope (JEOL, Tokyo, Japan). The phase composition of the alloy was carried out with the energy dispersive spectrometer (EDS, Oxford Instruments, London, Britain) analysis. The X-ray diffraction (XRD, Empyrean,

PANalytical, Eindhoven, The Netherlands) was conducted on the PW3040/60 X-ray analyzer with Cu target K_{α} line and a scanning speed of $3^{\circ}/\text{min}$. The tensile tests were carried out according to the ASTM E8-04 [22] standard at room temperature. The room temperature tensile specimen was machined from the Zn alloy with a gauge length of 25 mm and a diameter of 5 mm. The tensile tests at room temperature were enforced at a strain rate of 10^{-3} s^{-1} on a microcomputer-controlled AG-X electronic universal experimental machine (SHIMADZU, Tokyo, Japan). Five specimens were carried out to check the repeatability of the results.

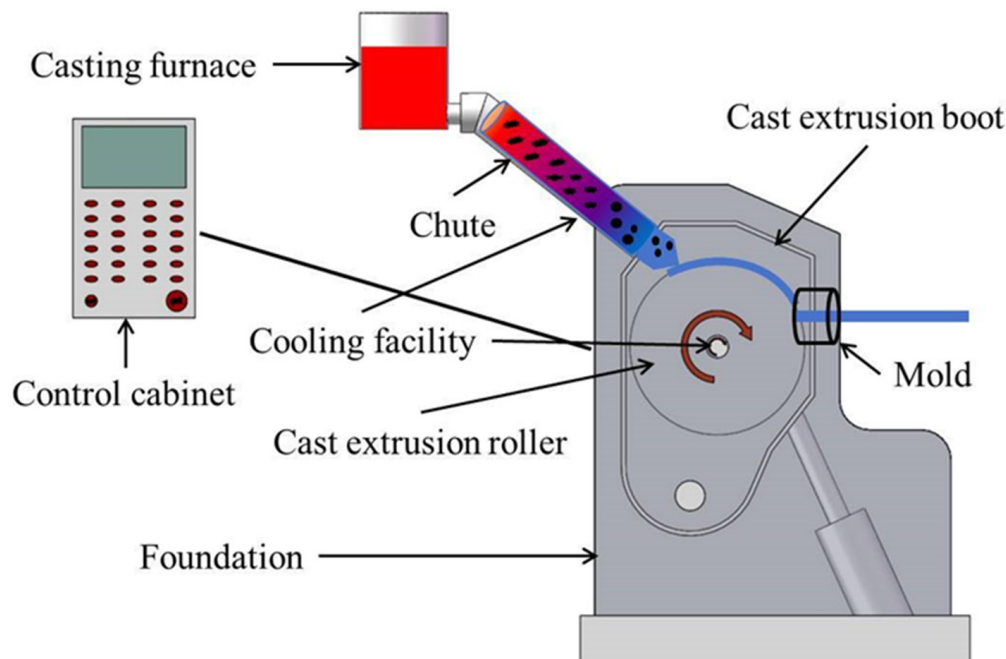


Figure 1. Schematic of continuous casting and extrusion Zn alloys.

3. Results and Discussion

3.1. X-ray Diffraction

According to the Zn-Al phase diagram, during the solidification process of the Zn-Al alloy with a mass fraction of 1–5%, rich Zn phases first precipitate. As the temperature decreases to 381°C (eutectic point), a eutectic structure composed of rich Al and rich Zn phases begins to precipitate (Figure 2a). The temperature continues to decrease, and the eutectic structure undergoes a dissolution process. Secondary rich Al and rich Zn phases precipitate in the rich Zn and Al phases [23]. Many researchers have carried out a number of studies on the effects of Al content (5–25 wt.%) on the microstructure and mechanical properties of the Zn alloys [24]. Therefore, the possibility of using the continuous casting and extrusion process to prepare Zn alloys with low Al content to replace Zn alloys with high Al content or Al alloys is a hot topic. From the Zn-Cu phase diagram (Figure 2b), it can be seen that the maximum solubility of copper in Zn is 2.75 wt.% at 425°C . The first intermetallic phase formed by Cu addition in Zn is the CuZn_4 phase [25]. The CuZn_4 phase plays an important role in improving the properties of the Zn-Cu alloy with low Cu content, which can act as nucleation sites for zinc grains during the dynamic recrystallization and ensure the compatibility of the phases during the plastic deformation [26].

Figure 3 shows the XRD patterns of continuous casting and extrusion Zn alloys. It can be seen that the Zn-Al alloys with different Al contents are mainly composed of rich Zn phase and rich Al phase. When the Al content increases, there is no significant change in the phase composition of the alloy, but the diffraction peak intensity of the Al-rich phase slightly increases, which agrees with the observation of the Zn-Al alloys [27]. The Zn-Cu alloys have similar phenomena as Zn-Al alloys.

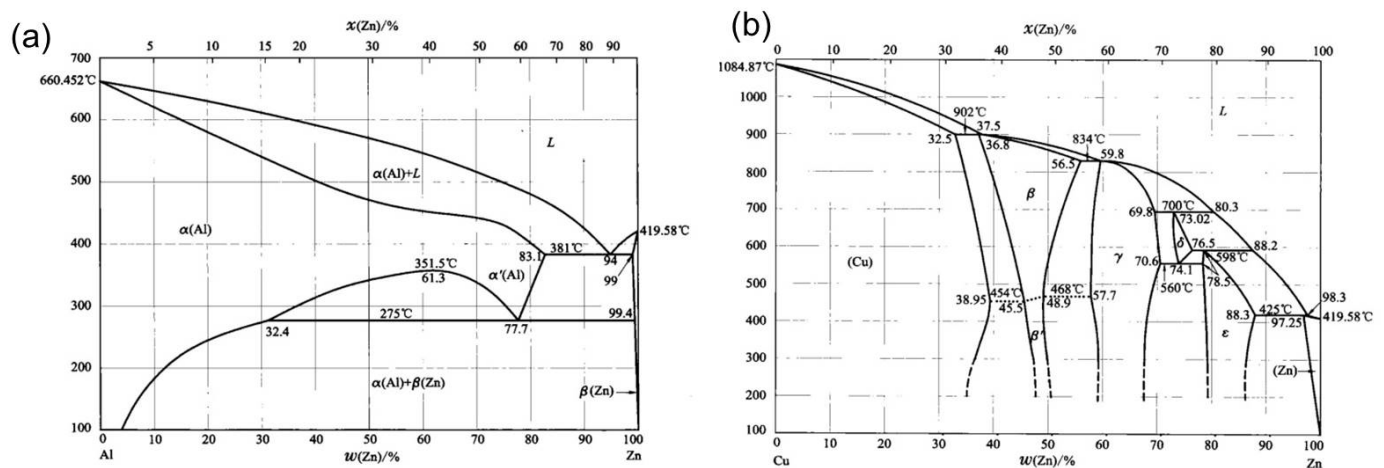


Figure 2. Zn alloy phase diagrams: (a) Zn-Al; (b) Zn-4Cu.

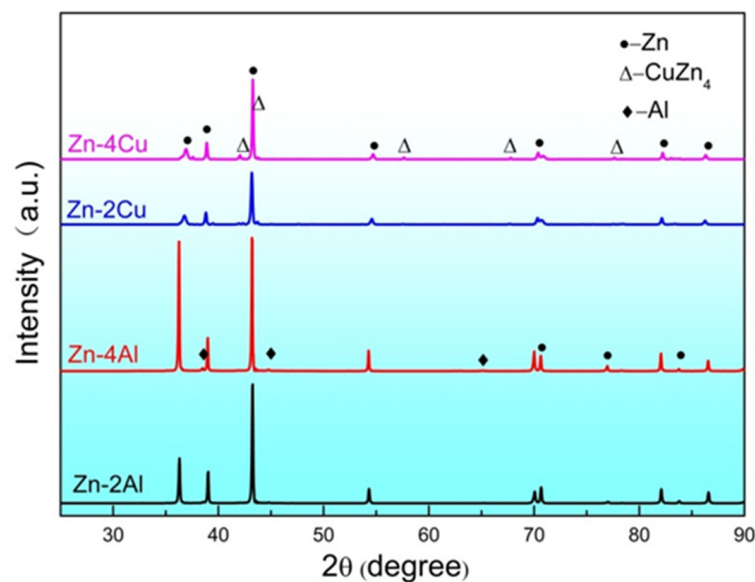


Figure 3. XRD patterns of continuous casting and extrusion Zn alloys.

3.2. Microstructure

The metallographic images of Zn alloys with different Al or Cu contents after continuous casting and extrusion are shown in Figure 4. It is clear from the figure and the Zn-Al phase diagram (Figure 2a) that the Zn-2Al alloy uses Zn-based solid solutions as the matrix, with a certain amount of Al-based solid solutions distributed. Among them, white is the Al-rich phase, and black is the Zn-rich phase. At the same time, it has deformation characteristics and presents fibrous characteristics along the extrusion direction (Figure 4a). The Zn-4Al alloy is composed of Zn-based solid solution and eutectic structure (Figure 2a). After continuous casting and extrusion, it undergoes complete recrystallization, and its grain size is relatively uniform (Figure 4b). Compare to the microstructure of the Zn-15Al alloys fabricated using continuous casting and extrusion. The Zn alloys with a low Al content have an absent dendrite structure and a low degree of phase deformation. The Zn-2Cu alloy and Zn-4Cu alloy are composed of a Zn-based solid solution and CuZn₄ second phase (Figure 2b). As the Al or Cu content increases, the deformation degree of the Zn alloy weakens, and the fibrous structure decreases (Figure 4).

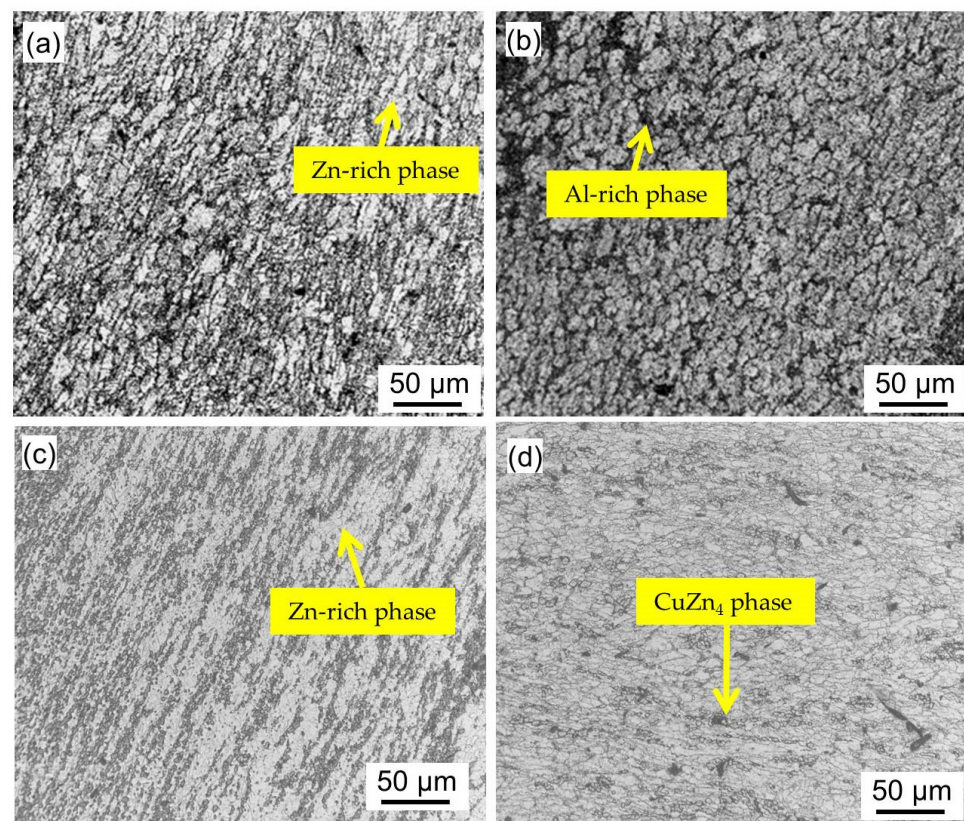


Figure 4. Metallographic microstructure of continuous casting and extrusion Zn alloys with different Al or Cu contents: (a) Zn-2Al; (b) Zn-4Al; (c) Zn-2Cu; (d) Zn-4Cu.

The SEM microstructure of continuous casting and extrusion Zn alloys with different Al or Cu contents is shown in Figure 5. The bright ones are rich Zn phase, while the dark ones are rich Al phase (Table 2). The microstructure of the Zn-2Al alloy by continuous casting and extrusion is composed of Zn-based solid solutions as the matrix, with a certain amount of Al-based solid solutions distributed. At the same time, there is a certain degree of deformation along the extrusion direction (Figure 5a). From Figure 5b, it can be seen that the continuous casting and extrusion Zn-4Al alloy is composed of a Zn-based solid solution and lamellar eutectic structure, which also produces a certain degree of deformation along the extrusion direction (Table 2). This microstructure is similar to other preparation methods of the Zn-Al alloy [28–30]. With the increase in Al content, the lamellar eutectic structure in the Zn-Al alloys increases, and the microstructure appears slightly coarse, but the degree of structural deformation weakens. The SEM microstructure of the Zn-Cu alloy is presented in Figure 5c,d. The micrometer-sized second phase (bright phases) gradually increases with the increasing Cu content in the Zn-Cu alloys [31]. This is presumed to be the CuZn_4 phase based on the results of existing studies and Table 2 using energy spectroscopy analysis.

Table 2. The phase composition of the Zn alloy [wt.%].

Name	Al	Cu	Zn
1	0.35	0	Bal.
2	22.46	0	Bal.
3	18.95	0	Bal.
4	0	1.72	Bal.
5	0	4.04	Bal.

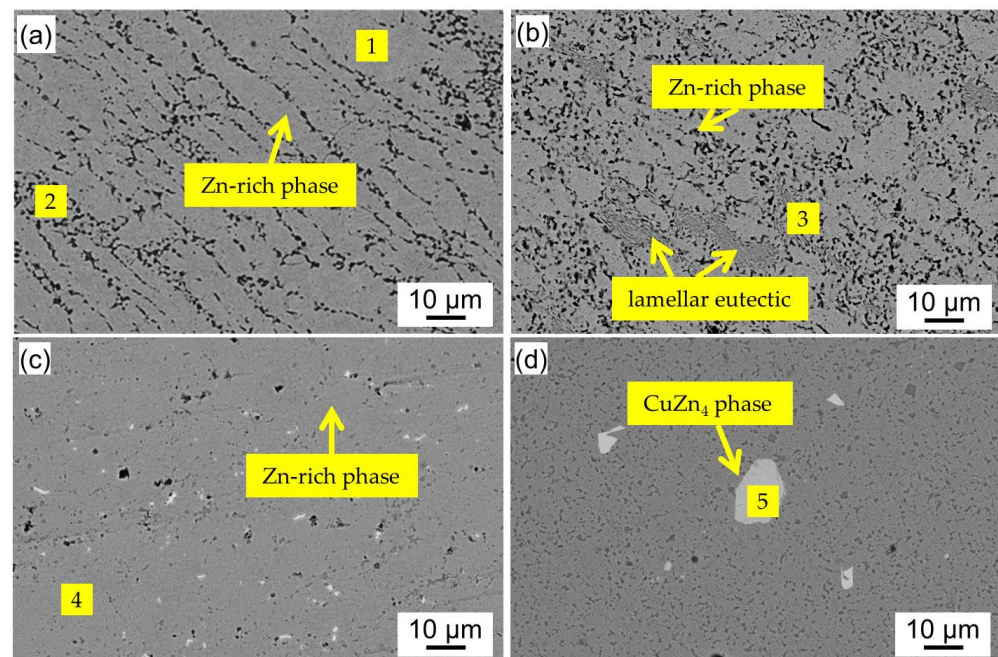


Figure 5. Microstructure of continuous casting and extrusion Zn alloys with different Al or Cu contents: (a) Zn-2Al; (b) Zn-4Al; (c) Zn-2Cu; (d) Zn-4Cu.

3.3. Mechanical Properties

Figure 6 shows the tensile engineering stress–strain curves at the room temperature of continuous casting and extrusion Zn alloys with different Al or Cu contents. The strength of the Zn alloy increases significantly with the addition of Cu compared to the addition of Al. With the increase in Cu content, the strength of the alloy gradually increases, but the elongation does not change much, basically around 2%. The tensile strength of the continuous casting and extrusion Zn-Al alloy slightly decreases with the increase in Al content, from 199 MPa to 197 MPa. The yield strength decreases with the increase in Al content, from 164 MPa to 148 MPa. The room elongation increases from 1.2% to 20% with the increase in Al content. The previously reported tensile strength and elongation of as-extruded pure Zn are 117 MPa and 14 %, respectively [32]. This predicts that the continuous casting of extruded Zn-4Al alloys can replace the extrusion of pure Zn in terms of mechanical properties. Generally speaking, with the increase in Al content, zinc alloys show a slight decrease in strength and a significant increase in plasticity. This is due to the effect of the Al refinement of the matrix and lamellar eutectic. With the increase in Cu content, the strength and plasticity of the Zn alloy increase simultaneously because the increase in Cu content refines the microstructure of the Zn alloy [33,34]. In this experiment, continuous casting and extrusion comprise a process that integrates casting and extrusion, so the Zn alloy has both casting and extrusion microstructures [35]. This microstructure results in a slight decrease in strength and a significant increase in Zn alloys prepared by continuous casting and extrusion. However, the strength and plasticity of the alloy are slightly enhanced as the Cu content is increased from 2 wt.% to 4 wt.%.

The room temperature tensile fracture morphology of continuous casting and extrusion Zn alloys with different Al or Cu contents is shown in Figure 7. Figure 7a,c,d shows the tensile fracture morphology of the Zn-2Al alloy, Zn-2Cu alloy, and Zn-4Cu alloy with some dimples and a certain amount of cleavage planes. Due to the different deformation abilities of the Zn-rich and second phases, the strength of the Zn-rich phase is lower, and tensile fracture is prone to develop at the interface between the Zn-rich and second phases. Therefore, the fracture modes of the Zn-2Al alloy, Zn-2Cu alloy, and Zn-4Cu alloy are ductile fracture and quasi-cleavage fracture. Phase boundary cracks are prone to initiation and propagation, which result in the Zn alloy having a very low elongation [36]. The tensile fracture surface

of the continuous casting and extrusion Zn-4Al alloy exhibits many deep dimples, which is a typical ductile fracture with plastic deformation characteristics (Figure 7b) [37]. This is because, under tensile stress, the second phase in the alloy increases, and the Al-rich phase becomes fine and dispersed, which significantly improves the plasticity of the Zn-4Al alloy.

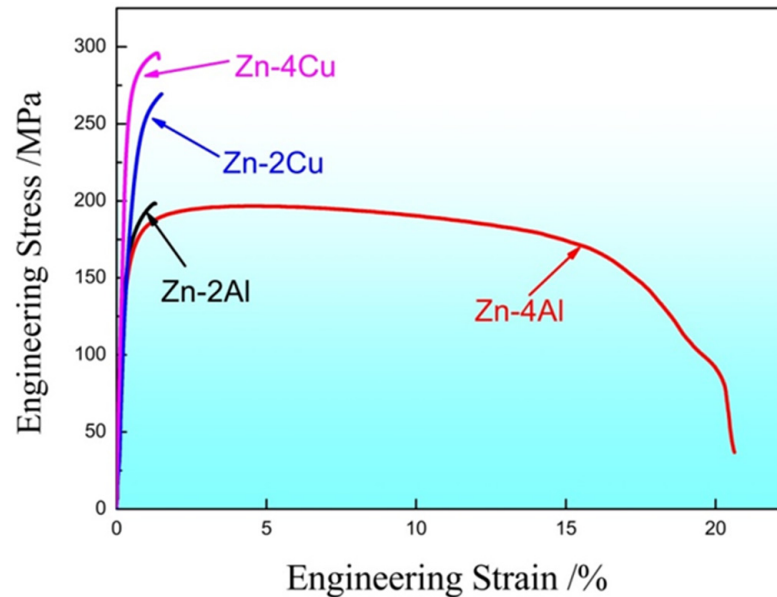


Figure 6. The room temperature tensile engineering stress–strain curves of continuous casting and extrusion Zn alloys with different Al or Cu contents.

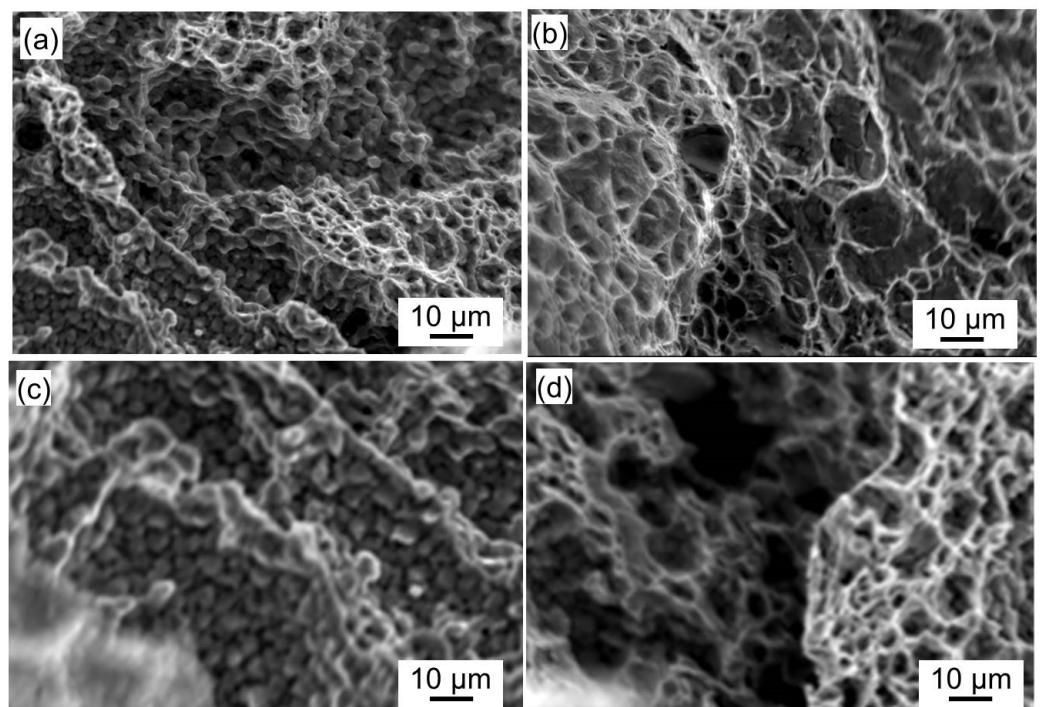


Figure 7. The fracture surfaces of continuous casting and extrusion Zn alloys with different Al or Cu contents: (a) Zn-2Al; (b) Zn-4Al; (c) Zn-2Cu; (d) Zn-4Cu.

In the present experiments, the mechanical properties of continuous casting and extrusion Zn alloys were altered due to grain refinement and the combined effect of the second phase content and morphology. With the increase in Al content, the size of the Zn-rich phase in the matrix of the Zn-Al alloys increases slightly, and there is an increase in

lamellar eutectic. The combined effect of the above microstructural factors leads to a slight decrease in the strength of the Zn-Al alloys with the increase in Al content and a substantial increase in the elongation. For the Zn-Cu alloys, the second phase plays a decisive role in increasing its strength and plasticity. The increase in Cu content refines the microstructure of the Zn alloy.

4. Conclusions

The continuous casting and extrusion process is a forming method that combines casting and extrusion. It is a short process and low-cost processing method, which can greatly improve the performance of alloys. Therefore, this article conducted the effect of Al or Cu contents on the microstructure and room temperature tensile properties of continuous casting and extrusion Zn alloys. The following conclusions were obtained:

- (1) The Zn alloy with a lower Al or Cu contents can be prepared by continuous casting and extrusion.
- (2) With the increase in Al content, the strength of the Zn-Al alloy slightly decreases, and the elongation of the Zn-Al alloy significantly increases from 1.2% to 20%, which is due to matrix refinement and the presence of lamellar eutectic.
- (3) Cu has a weak effect on enhancing the mechanical properties of Zn alloys compared to Al. This is attributed to the size and content of the second phase and refines the microstructure of the Zn alloy.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sun, S.N.; Ren, Y.P.; Wang, L.Q.; Yang, B.; Qin, G.W. Room temperature quasi-superplasticity behavior of backward extruded Zn-15Al alloys. *Mater. Sci. Eng. A* **2016**, *676*, 336–341. [[CrossRef](#)]
2. Kustra, P.; Wróbel, M.; Byrska-Wójcik, D.; Paćko, M.; Płonka, B.; Wróbel, M.; Sulej-Chojnacka, J.; Milenin, A. Manufacture technology, mechanical and biocorrosion properties of the Zn and ZnMg0.008 alloy wires designed for biodegradable surgical threads. *J. Manuf. Process.* **2021**, *67*, 513–520. [[CrossRef](#)]
3. Zhang, J.J.; Wang, Q.Z.; Jiao, Z.X.; Cui, C.X.; Yin, F.X.; Yao, C. Effects of combined use of inoculation and modification heat treatment on microstructure, damping and mechanical properties of Zn–Al eutectoid alloy. *Mater. Sci. Eng. A* **2020**, *790*, 139740. [[CrossRef](#)]
4. Sun, S.N.; Wang, H.L.; Yang, B.; Qin, G.W. Effect of extrusion temperature on mechanical properties of as-extruded Zn–22Al alloys. *Mater. Sci. Tech.* **2020**, *36*, 805–810. [[CrossRef](#)]
5. Ling, C.; Zhang, J.C. Strain rate and anisotropic effects on incipient plastic deformation of Zn–Cu–Ti alloy sheets. *Mater. Sci. Eng. A* **2024**, *890*, 145909.
6. Azad, B.; Eivani, A.R.; Salehi, M.T. An investigation of microstructure and mechanical properties of as-cast Zn–22Al alloy during homogenizing and equal channel angular pressing. *J. Mater. Res. Technol.* **2023**, *22*, 3255–3269. [[CrossRef](#)]
7. Zhang, J.D.; Zhu, X.L.; Guo, P.S.; Zhang, Y.D.; Xu, Y.; Pang, Y.; Song, Z.L.; Yang, L.J. Effects of Li addition on the properties of biodegradable Zn–Fe–Li alloy: Microstructure, mechanical properties, corrosion behavior, and cytocompatibility. *Mater. Today Commun.* **2024**, *39*, 108661. [[CrossRef](#)]

8. Li, L.; Liang, W.L.; Ban, C.Y.; Suo, Y.S.; Lv, G.C.; Liu, T.; Wang, X.J.; Zhang, H.; Cui, J.Z. Effects of a high-voltage pulsed magnetic field on the solidification structures of biodegradable Zn-Ag alloys. *Mater. Char.* **2020**, *163*, 110274. [[CrossRef](#)]
9. Shi, Z.Z.; Li, H.Y.; Xu, J.Y.; Gao, X.X.; Liu, X.F. Microstructure evolution of a high-strength low-alloy Zn-Mn-Ca alloy through casting, hot extrusion and warm caliber rolling. *Mater. Sci. Eng. A* **2020**, *771*, 138626. [[CrossRef](#)]
10. Jin, H.L.; Yang, L.; Lai, Y.L.; Liu, Y. The effects of Zr content and hot rolling on the microstructure and mechanical properties of Zn-1.5Cu-1.0Ag-xZr alloys. *J. Alloys Compd.* **2022**, *912*, 165116. [[CrossRef](#)]
11. Yang, Z.; Tang, J.; Mo, X.D.; Chen, W.T.; Fu, D.F.; Zhang, H.; Teng, J.; Jiang, F.L. Microstructure, mechanical properties, and strengthening mechanisms of ultra-high strength Al-Zn-Mg-Cu alloy prepared by continuous extrusion forming process. *Mater. Des.* **2024**, *242*, 112985. [[CrossRef](#)]
12. Yang, B.W.; Gao, M.Q.; Liu, Y.; Pan, S.; Meng, S.C.; Fu, Y.; Guan, R.G. Formation mechanism of refined Al₆(Mn, Fe) phase particles during continuous rheo-extrusion and its contribution to tensile properties in Al-Mg-Mn-Fe alloys. *Mater. Sci. Eng. A* **2023**, *872*, 144952. [[CrossRef](#)]
13. Cao, F.R.; Yin, B.; Liu, S.Y.; Shi, L.; Wang, S.C.; Wen, J.L. Microstructural evolution, flow stress and constitutive modeling of Al-1.88Mg-0.18Sc-0.084Er alloy during hot compression. *Trans. Nonferrous Met. Soc. China* **2021**, *31*, 53–73. [[CrossRef](#)]
14. Zhao, D.J.; Qin, J.; Lü, S.L.; Li, J.Y.; Guo, W.; Wu, S.S.; Zhang, Y.H. Mechanisms of extrusion-ratio dependent ultrafine-grain fabrication in AZ31 magnesium alloy by continuous squeeze casting-extrusion. *J. Mater. Process Tech.* **2022**, *310*, 117755. [[CrossRef](#)]
15. Sun, S.N.; Li, D.Y.; Liu, D.Y.; Yang, B.; Ren, Y.P.; Qin, G.W. Microstructure and mechanical properties of continuous casting and extrusion Zn-15 wt% Al alloys. *Mater. Lett.* **2020**, *261*, 127090. [[CrossRef](#)]
16. Sun, S.N.; Li, D.Y.; Liu, D.Y.; Yang, B.; Ren, Y.P.; Liu, J.T.; Xie, H.B. Effects of Bi and Ce addition on tensile properties and corrosion resistance of Zn-15Al alloys by continuous casting and extrusion. *Mater. Lett.* **2020**, *275*, 128027. [[CrossRef](#)]
17. Ye, L.F.; Sun, C.; Zhuo, X.R.; Liu, H.; Ju, J.; Xue, F.; Bai, J.; Jiang, J.H.; Xin, Y.C. Evolution of grain size and texture of Zn-0.5Cu ECAP alloy during annealing at 200 °C and its impact on mechanical properties. *J. Alloys Compd.* **2022**, *919*, 165871. [[CrossRef](#)]
18. Liu, C.; Li, Y.K.; Ge, Q.Q.; Liu, Z.X.; Qiao, A.K.; Mu, Y.L. Mechanical characteristics and in vitro degradation of biodegradable Zn-Al alloy. *Mater. Lett.* **2021**, *300*, 130181. [[CrossRef](#)]
19. Yang, H.T.; Jia, B.; Zhang, Z.C.; Qu, X.H.; Li, G.N.; Lin, W.J.; Zhu, D.H.; Dai, K.R.; Zheng, Y.F. Alloying design of biodegradable zinc as promising bone implants for load-bearing applications. *Nat. Commun.* **2020**, *11*, 401. [[CrossRef](#)]
20. Lu, X.K.; Xiao, S.J.; He, W.Q.; Wang, J.J.; Ma, Y.M.; Zhang, H.H. Effect of melt overheating treatment on the microstructure and mechanical properties of Zn–Al alloy. *Vacuum* **2022**, *201*, 111071. [[CrossRef](#)]
21. Cao, F.R.; Wen, J.L.; Ding, H.; Wang, Z.D.; Yu, C.P.; Xia, F. Extrusion force analysis of aluminum pipe fabricated by CASTEX using expansion combination die. *Trans. Nonferrous Met. Soc. China* **2014**, *24*, 3621–3631. [[CrossRef](#)]
22. ASTM E8-04; Test Methods for Tension Testing of Metallic Materials. American Society for Testing and Materials: West Conshohocken, PA, USA, 2004.
23. Song, Z.Z.; Niu, R.M.; Cui, X.Y.; Bobruk, E.V.; Murashkin, M.Y.; Enikeev, N.A.; Gu, J.; Song, M.; Bhatia, V.; Ringer, S.P.; et al. Mechanism of room-temperature superplasticity in ultrafine-grained Al-Zn alloys. *Acta Mater.* **2023**, *246*, 118671. [[CrossRef](#)]
24. Zhai, Y.L.; Wang, T.G.; Liu, M.Y.; Zhou, N.; Li, X.T. Effect of Al Content on the microstructure and Properties of Zn-Al Solder Alloys. *Metals* **2024**, *14*, 689. [[CrossRef](#)]
25. Jiang, J.M.; Huang, H.; Niu, J.L.; Jin, Z.H.; Dargusch, M.; Yuan, G.Y. Characterization of nano precipitate phase in an as-extruded Zn-Cu alloy. *Scr. Mater.* **2021**, *200*, 113907. [[CrossRef](#)]
26. Jara-Chaves, G.; Amaro-Villeda, A.; Campillo-Illanes, B.; Ramírez-Argáez, M.; González-Rivera, C. Effect of Ag and Cu Content on the Properties of Zn-Ag-Cu-0.05Mg Alloys. *Metals* **2024**, *14*, 740. [[CrossRef](#)]
27. Gutierrez-Menchaca, J.; Torres-Torres, D.; Garay-Tapia, A.M. Microstructural, mechanical and thermodynamic study of the as-cast Zn-Al-Sr alloys at high Sr content. *J. Alloys Compd.* **2020**, *829*, 154511. [[CrossRef](#)]
28. Sun, S.N.; Liu, J.T.; Li, X.L.; Ye, G.; Weng, Y.M.; Lu, Z.T.; Lou, D.F. High ductility Zn-6Al alloys with fine-grained microstructure processed by low temperature backward extrusion. *Rare Metal. Mat. Eng.* **2021**, *50*, 2263–2267.
29. Farabi, E.; Sharp, J.A.; Valid, A.; Fabijanic, D.M.; Barnett, M.R.; Gallo, S.C. Development of high strength and ductile Zn-Al-Li alloys for potential use in bioresorbable medical devices. *Mater. Sci. Eng. C* **2021**, *122*, 111897. [[CrossRef](#)] [[PubMed](#)]
30. Wu, Z.C.; Sandlobes, S.; Wu, L.; Hu, W.P.; Gottstein, G.; Korte-kerzel, S. Mechanical behaviour of Zn-Al-Cu-Mg alloys: Deformation mechanisms of as-cast microstructures. *Mater. Sci. Eng. A* **2016**, *651*, 675–687. [[CrossRef](#)]
31. Demirtas, M.; Kawasaki, M.; Yanar, H.; Purcek, G. High temperature superplasticity and deformation behavior of naturally aged Zn-Al alloys with different phase compositions. *Mater. Sci. Eng. A* **2018**, *730*, 73–83. [[CrossRef](#)]
32. Sun, S.N.; Ren, Y.P.; Wang, L.Q.; Yang, B.; Li, H.X.; Qin, G.W. Abnormal effect of Mn addition on the mechanical properties of as-extruded Zn alloys. *Mater. Sci. Eng. A* **2017**, *701*, 129–133. [[CrossRef](#)]
33. Tang, Z.B.; Niu, J.L.; Huang, H.; Zhang, H.; Pei, J.; Ou, J.M.; Yuan, G.Y. Potential biodegradable Zn-Cu binary alloys developed for cardiovascular implant applications. *J. Mech. Behav. Biomed.* **2017**, *72*, 182–191. [[CrossRef](#)]
34. Li, L.; Liang, W.L.; Yang, L.; Cao, F.L.; Sun, K.; Ban, C.Y.; Cui, J.Z. Structure refinement and homogenization of Zn-Cu alloys induced by a high-voltage pulsed magnetic field during the solidification process. *Int. J. Metal. Cast.* **2023**, *17*, 399–413. [[CrossRef](#)]
35. Shi, Z.Z.; Gao, X.X.; Zhang, H.J.; Liu, X.F.; Li, H.Y.; Zhou, C.; Yin, Y.X.; Wang, L.N. Design biodegradable Zn alloys: Second phases and their significant influences on alloy properties. *Bioact. Mater.* **2020**, *5*, 210–218. [[CrossRef](#)] [[PubMed](#)]

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36. Bolibruchová, D.; Bruna, M.; Matejka, M. Impact of Remelting on ZnAl4Cu3 Alloy with Addition of Cd on Selected Technological and Mechanical Properties. *Metals* **2022**, *12*, 1180. [[CrossRef](#)]
 37. Yang, H.; Huang, J.; Chen, S.; Zhao, X.; Wang, Q.; Li, D. Influence of the composition of Zn-Al filler metal on the interfacial structure and property of Cu/Zn-Al/Al brazed joint. *J. Acta Metall. Sin.* **2015**, *51*, 364–370.

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