

Sc/Zr and Zn/Zr modification of Al–7Mg alloys fabricated by laser- directed energy deposition: Grain refinement, tensile properties, and corrosion behavior

Umar Daraz

University of Science and Technology (UST)

Hyunkyu Lim

hklim@kitech.re.kr

Korea Institute of Industrial Technology (KITECH)

Bong-Hwan Kim

Korea Institute of Industrial Technology (KITECH)

Abdul Wahid Shah

Harbin institute of technology

Shae K. Kim

Korea Institute of Industrial Technology (KITECH)

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Abstract

This study investigates the development of high-strength and corrosion-resistant Al–7Mg-based alloys fabricated by laser-directed energy deposition (L-DED) using Sc/Zr and Zn/Zr modifications. Process optimization enabled the fabrication of crack-free deposits with low porosity. Sc/Zr addition produced substantial grain refinement, reducing the average grain size from $108.06 \pm 56.32 \mu\text{m}$ in the base alloy to $11.70 \pm 7.97 \mu\text{m}$ and $9.93 \pm 6.61 \mu\text{m}$ in the 0.2Sc–0.5Zr and 0.4Sc–0.5Zr alloys, respectively. Zn/Zr modification also markedly refined the microstructure, resulting in average grain sizes of $15.12 \pm 10.31 \mu\text{m}$ and $16.56 \pm 13.26 \mu\text{m}$ in the 2Zn–0.5Zr and 4Zn–0.5Zr alloys, respectively. After heat treatment, Al–7Mg–0.4Sc–0.5Zr exhibited the best mechanical performance, achieving a yield strength of $304.8 \pm 6.0 \text{ MPa}$, an ultimate tensile strength of $424.1 \pm 6.7 \text{ MPa}$, and an elongation of $11.1 \pm 0.8\%$. Al–7Mg–0.2Sc–0.5Zr demonstrated the highest corrosion resistance, with the lowest weight loss and corrosion rate after neutral salt-spray exposure. The Al–7Mg–4Zn–0.5Zr alloy achieved an ultimate tensile strength of $393.1 \pm 2.0 \text{ MPa}$ and an elongation of $10.1 \pm 1.0\%$. These findings demonstrate that low-Sc alloying provides an effective strength–corrosion balance, while Zn/Zr modification offers a promising lower-cost strategy for reducing Sc dependence in high-performance L-DED Al–Mg alloys.

1. Introduction

Aluminum alloys find extensive application in fields such as aerospace, automotive, marine, and biomedical due to their low density, high specific strength, resistance to corrosion, and excellent processability¹. Traditional manufacturing techniques, however, face challenges in creating intricate and lightweight parts^{2–4}. Laser directed energy deposition (L-DED) presents a versatile additive manufacturing approach that enables the production of near-net-shape components, repairs existing parts, and allows for direct material deposition onto substrates^{5–7}. In contrast to L-PBF, L-DED offers advantages like higher deposition rates, larger build volumes, and the ability to adjust compositions via powder or wire feeding^{8–11}. This makes it ideal for developing advanced aluminum alloys with customized microstructures, superior mechanical properties, and better corrosion resistance.

Previous studies on additively manufactured Al alloys have mainly focused on Al–Si eutectic systems, such as AlSi12 and AlSi10Mg, because of their good printability and resistance to hot cracking^{12–15}. However, their mechanical performance remains limited, with reported tensile strengths of about 330–355 MPa and low elongations of 5–6% for AlSi12^{16,17}, and approximately 360 MPa with 5.3% elongation for AlSi10Mg¹⁸. Higher-strength wrought alloys such as Al2024¹⁹, Al7075^{20,21}, Al6061²², and Al2618²³ offer greater strengthening potential, but they are difficult to print because of severe hot cracking and often fail to achieve desirable microstructures and mechanical properties after additive manufacturing²⁴. In addition to these widely investigated alloy systems, other L-DED Al-based materials have exhibited limited strength–ductility combinations. An AlSi7Mg/graphene²⁵ composite produced by laser metal deposition showed a UTS of only 150.06 MPa and an elongation of 2.9%, while an L-DED Al–5Si–1Cu–Mg alloy achieved a UTS of 304 MPa with an elongation of 9.8%²⁶. Similarly, a directed-energy-deposited Al–5Zn–1.9Mg–1.47Cu–2.9Si–1Zr alloy exhibited a UTS of 333 MPa and an elongation of only 2.9%^{27,28}. Although wire-oscillation^{29,30} laser-deposited 2319 Al achieved a comparatively high UTS of 421 MPa, its elongation remained limited to 8.3% while TiB₂/Al2024 composites produced by directed energy deposition showed an ultimate tensile strength (UTS) of 354.27 MPa and an elongation of only 4.44%^{31,32}. These results highlight the persistent challenge of increasing the tensile strength of L-DED Al alloys without substantially sacrificing ductility. To overcome this limitation, grain-refinement strategies have been increasingly investigated. Zr-modified Al7075^{33,34} and Sc/Zr-modified Al–Mg alloys such as Scalmaalloy and Al–Mn–Sc alloys^{24,35}, have shown improved printability and superior strength, with tensile strength values reaching nearly

560 MPa and elongation of about 18%^{3,36}. However, these alloys generally require relatively high Sc contents, and the high cost and limited availability of Sc restrict their large-scale industrial application.

Zn represents a potentially lower-cost alternative alloying element for strengthening Al–Mg alloys. Zn can contribute through solid-solution strengthening and, following appropriate heat treatment, may facilitate Mg–Zn-related precipitation^{37,38}. However, Zn does not provide the same heterogeneous nucleation capability as Sc, and its segregation during solidification may affect microstructural uniformity and corrosion behavior. Furthermore, both Mg and Zn are susceptible to evaporation during laser processing because of their relatively high vapor pressures^{39,40}. Therefore, the effectiveness of Zn/Zr modification must be assessed not only through mechanical testing but also through elemental retention, porosity, grain refinement, heat-treatment response, and corrosion performance. A direct comparison between low-Sc/Zr and Sc-free Zn/Zr alloys fabricated under identical L-DED conditions is necessary to determine whether Zn can reduce dependence on Sc without substantially compromising overall alloy performance. Understanding these relationships is essential for developing economically viable, high-performance Al alloys suitable for large-scale additive manufacturing.

Reducing Sc content in SLM-processed Al–Mg–Sc–Zr alloys often causes grain coarsening, hot cracking, and reduced mechanical properties, highlighting the need for printable, affordable, and high-strength Al alloys⁴¹. Although several Al–Mg-based alloys have been developed for L-PBF, only limited studies have explored their fabrication using the L-DED technique. Therefore, this study focuses on the development of cost-effective Al–Mg alloys with high strength and corrosion resistance through L-DED processing. In particular, Al–7Mg alloys^{42,43} were modified by the addition of Zr and Sc, with the Sc content kept lower than that typically used in Scalmalloy or Al–Mn–Sc alloys. Furthermore, Zn was introduced as a substitute for Sc to reduce alloying cost while preserving alloy printability, microstructural stability, mechanical strength, and corrosion resistance.

2. Methodology

A series of Al–7Mg based alloy powders modified with Sc, Zn, and Zr were fabricated via a gas atomization process. Prior to deposition, the alloy powders were sieved into < 53 μm , 53–100 μm , and > 100 μm fractions, and each fraction was weighed to determine the particle-size distribution; the 53–100 μm fraction was selected for stable powder feeding. The L-DED processing parameters, including laser power, scan speed, and powder feed rate, were first optimized using the Al–7Mg alloy based on mechanical performance, and the optimized parameters were then applied to the Sc- and Zn-modified alloys. The chemical compositions of the powders and deposited samples were determined by spark-generated plasma optical emission spectroscopy (OES; Bruker Q2 ION, Bruker, Billerica, MA, USA). Tensile tests were performed in accordance with ASTM E8 using a universal testing machine (DTU-900MHN, Daekyung Tech, South Korea). Sub-size specimens (25 mm gauge length) were tested at a crosshead speed of 1.5 mm/min, and elongation was measured with a clip-on extensometer (Epsilon Technology, USA). Rockwell hardness tests were performed using a Rockwell hardness tester (HR-210MR, Mitutoyo Corporation, Kawasaki, Japan). Artificial aging treatments were performed in a box furnace at different temperatures depending on the alloy composition. Density was measured by the Archimedes method, while porosity was evaluated using optical microscopy (Nikon, Tokyo, Japan). The microstructures were characterized by field-emission scanning electron microscopy (FE-SEM; FEI Quanta 200F, FEI, Hillsboro, OR, USA) equipped with energy-dispersive spectroscopy (EDS; EDAX, Pleasanton, CA, USA), together with electron backscatter diffraction (EBSD; Crystalin 200). The corrosion behavior was evaluated using a Neutral Salt Spray Tester (Model 606, ERICHSEN, Germany) through neutral salt spray (NSS) testing for 2 and 3 days in accordance with the ASTM B117 standard. The experimental conditions were strictly controlled using a 5 wt% NaCl aqueous solution, an internal chamber temperature of $35.0 \pm 0.1^\circ\text{C}$, a pH of 6.62, and a spraying pressure of 100 kPa. After the designated exposure

periods, the corrosion products were chemically removed, and the corrosion rate was subsequently determined based on the weight loss of the specimens.

3. Results and discussion

3.1. Chemical Composition and Elemental Retention:

Table 1 presents the chemical composition of the starting powders and the produced Al–7Mg based alloys. The highest Mg loss was observed in the Al–7Mg–0.2Sc–0.5Zr alloy, with a decrease rate of 27.7%, while the Al–7Mg–0.4Sc–0.5Zr alloy showed a slightly lower Mg decrease rate of 24.5%. This suggests that Mg evaporation occurred during processing³³, most likely due to the high vapor pressure of Mg and the localized high temperature generated during laser melting. Despite this loss, the produced alloys still retained Mg contents above 4.8 wt.%, confirming that the Al–Mg alloy system was successfully maintained after processing. Similarly, in the Al–7Mg–4Zn–0.5Zr alloy, the Zn content decreased from 4.22 wt.% to 2.50 wt.%, giving a decrease rate of 40.8%. These results show that Zn loss was more severe than Mg loss during processing. This can be attributed to the relatively high volatility of Zn under laser-induced melting conditions. In contrast, the Sc and Zr contents remained comparatively stable after processing.

Table 1
Chemical composition of the powders and all produced alloys measured by OES, and the corresponding decrease rates of Mg and Zn after laser processing.

Alloys	Powder composition analysis (wt. %)						Composition of the produced (wt. %)						Decrease rate (%)	
	Al	Mg	Sc	Zn	Zr	Ca	Al	Mg	Sc	Zn	Zr	Ca	Mg	Zn
Al-7Mg	Bal.	6.63				0.049	Bal.	5.17				0.050	22.0	
Al-7Mg-0.2Sc-0.5Zr	Bal.	6.69	0.18		0.56	0.050	Bal.	4.84	0.18		0.60	0.048	27.7	
Al-7Mg-0.4Sc-0.5Zr	Bal.	6.78	0.37		0.41	0.054	Bal.	5.12	0.36		0.36	0.051	24.5	
Al-7Mg-2Zn-0.5Zr	Bal.	6.78		2.13	0.47	0.051	Bal.	5.21		1.28	0.47	0.053	23.2	39.9
Al-7Mg-4Zn-0.5Zr	Bal.	6.74		4.22	0.38	0.048	Bal.	5.07		2.50	0.41	0.052	24.8	40.8

3.2. L-DED Process Optimization Using the Base Al–7Mg Alloy:

Figure 1 summarizes the powder morphology, solidification behavior, and L-DED process optimization of the Al–7Mg based alloys. The powders were sieved to 53–100 μm to ensure stable powder feeding, as finer particles caused nozzle clogging. SEM images (Fig. 1a) show mainly near-spherical to irregular powder particles with some attached fines, indicating suitable morphology for L-DED feeding. The calculated solid-fraction curves (Fig. 1d) reveal that Sc, Zr, and Zn additions slightly modify the solidification path of the base Al–7Mg alloy, which may help control melt-pool stability, microsegregation, and defect formation during L-DED.

Process optimization was first performed using the base Al–7Mg alloy. At a fixed powder feed rate of 2.5 g/min, laser powers of 300–500 W were insufficient for stable deposition, whereas 700 W caused severe oxidation. A laser power of 600 W provided suitable melting, and increasing scan speed reduced excessive heat accumulation. At 600 W, stable printing required a balance between powder feed rate and scan speed: stable deposition could not be achieved at 1.5 g/min, while stable deposits were obtained at 2.0–2.5 g/min from 0.9 m/min, at 3.0 g/min from 1.1 m/min, and at 3.5 g/min from 1.3 m/min. The optimized L-DED samples were fabricated at 600 W with dimensions of 6 mm × 100 mm × 10 mm.

SEM observations (Fig. 1c) confirmed that the selected L-DED conditions produced generally stable deposits, with only limited unmelted or partially melted particles. At 2.5 g/min and 0.9 m/min, more unmelted particles were observed, indicating insufficient powder incorporation into the melt pool. Increasing the scan speed to 1.1 m/min reduced these defects, while the condition of 3.5 g/min and 1.3 m/min also showed stable deposition with few unmelted particles. These observations indicate that powder feed rate and scan speed strongly influence melt-pool stability and sample quality. The tensile results in Table 2 further show that the condition of 600 W, 2.5 g/min, and 1.3 m/min provided the best combination of stable deposition and mechanical performance. Therefore, these parameters were selected for fabricating the Sc/Zr- and Zn/Zr-modified Al–7Mg alloys. Subsequently, the printed samples were examined for porosity, density, and defects using optical microscopy and the Archimedes method.

Table 2
L-DED processing conditions used for the fabrication of Al–7Mg alloy samples under different powder feeding rates and scan speeds, and the selected optimized parameters for producing the Sc and Zn modified Al–7Mg–0.5Zr alloys

3D printing conditions			Mechanical properties of as-built specimens		
Laser power (W)	Feeding rate (g/min)	Scan speed (m/min)	TYS (MPa)	UTS (MPa)	El. (%)
600	2.5	0.9	128.9	220.9	5.7
		1.1	135.7	249.4	10.5
		1.3	142.5	286.2	14.3
		1.5	136.7	278.5	12.9
	3.0	1.3	142.7	281.1	13.8
	3.5	1.3	139.6	256.9	9.6
Laser Power	Feeding rate	Scan speed	Layer thickness	Hatch spacing	Energy density
600 W	2.5 g/min	1.3 m/min	250 μm	500 μm	221.5 J/mm ³

3.3. Microstructural Characterization of Printed Alloys:

The OM images (Fig. 2a) show that all alloys were successfully fabricated without visible hot cracking, indicating that the selected processing parameters were suitable for stable deposition. The base Al–7Mg alloy exhibited the highest porosity of 0.221 ± 0.05%, and its measured/theoretical density ratio was about 0.98, which is attributed to pores remaining inside the printed sample. In contrast, the modified alloys showed a strong reduction in porosity, with values of only 0.024–0.028% (Fig. 2b), confirming improved densification after Sc/Zr and Zn/Zr additions. When Sc was replaced by Zn, the porosity did not increase significantly, suggesting that Zn-containing alloys also maintained good printability and defect resistance under the optimized L-DED condition. The base Al–7Mg alloy showed a

measured/theoretical density ratio of 0.98, mainly due to residual pores inside the printed sample. In contrast, the Sc/Zr- and Zn/Zr-modified alloys exhibited ratios close to or slightly above 1.0, which may be related to their very low porosity (Table S1) and the possible formation of dense MgAl_2O_4 spinel particles due to oxidation during L-DED process. Since MgAl_2O_4 has a higher density ($\sim 3.58 \text{ g/cm}^3$) than the Al matrix, it may contribute to the increased measured density; however, further phase analysis is required to confirm its presence⁴⁴. The reduced porosity of the Sc/Zr- and Zn/Zr-containing alloys is likely associated with improved melt-pool stability and grain refinement during solidification. Fine equiaxed grains reduce the susceptibility to solidification cracking while promoting more uniform liquid feeding during the final stages of solidification, thereby suppressing pore formation.

The SEM images (Fig. 3) show the cross-sectional morphologies of the Sc/Zr- and Zn/Zr-modified L-DED Al–7Mg alloys where Sc/Zr-containing alloys display relatively weak contrast variation within the deposited tracks, suggesting a more uniform elemental distribution after solidification. In contrast, the Zn/Zr-containing alloys exhibit more pronounced fine contrast features, particularly in Al–7Mg–4Zn–0.5Zr, indicating increased solute segregation and/or Zn-rich second-phase formation with increasing Zn content. This difference suggests that Sc/Zr mainly promotes microstructural stabilization, whereas Zn/Zr contributes to stronger local chemical heterogeneity during L-DED solidification. Figure 4a shows the EBSD grain orientation maps and grain size distributions of the L-DED printed Al–7Mg based alloys. The base Al–7Mg alloy exhibited a coarse and non-uniform grain structure with an average grain size of $108.06 \pm 56.32 \text{ }\mu\text{m}$. The broad grain size distribution indicates significant grain coarsening during solidification, which is commonly associated with the high thermal gradient and directional growth during L-DED. After adding Sc and Zr, the grain structure was strongly refined (Fig. 4b-c). The average grain size decreased to $11.70 \pm 7.97 \text{ }\mu\text{m}$ for Al–7Mg–0.2Sc–0.5Zr and further decreased to $9.93 \pm 6.61 \text{ }\mu\text{m}$ for Al–7Mg–0.4Sc–0.5Zr. This strong refinement is attributed to the formation of $\text{Al}_3(\text{Sc}, \text{Zr})$ particles, which act as effective heterogeneous nucleation sites and restrict grain growth during rapid solidification. The Zn-containing alloys also showed much finer grains than the base alloy (Fig. 4d-e), with average grain sizes of $15.12 \pm 10.31 \text{ }\mu\text{m}$ for Al–7Mg–2Zn–0.5Zr and $16.56 \pm 13.26 \text{ }\mu\text{m}$ for Al–7Mg–4Zn–0.5Zr. Although Zn addition refined the grain structure compared with Al–7Mg, its refinement effect was slightly weaker than that of Sc. The small increase in grain size with higher Zn content suggests that replacing Sc with Zn maintains a refined microstructure, but does not provide the same strong nucleation effect as Sc-containing alloys. The superior strength of the Sc-containing alloys is associated with their finer grain structure, whereas the Zn-containing alloys achieved comparable strength despite relatively coarser grains, suggesting that Zn alloying provides additional strengthening beyond grain refinement.

3.4. Mechanical and Corrosion Properties:

Figure 5(a–c) shows the tensile properties of the L-DED printed Al–7Mg based alloys. The base Al–7Mg alloy showed the lowest yield strength and ultimate tensile strength, mainly due to its coarse grain structure observed by EBSD. After Sc/Zr addition, both yield strength and tensile strength increased significantly. The Al–7Mg–0.4Sc–0.5Zr alloy showed the highest strength after heat treatment, with a yield strength of $304.8 \pm 6.0 \text{ MPa}$ and UTS of $424.1 \pm 6.7 \text{ MPa}$. This improvement is attributed to strong grain refinement and possible $\text{Al}_3(\text{Sc}, \text{Zr})$ precipitation strengthening⁴⁵. The Zn-containing alloys also showed higher strength than the base alloy, but their strengthening effect was slightly lower than that of Sc-containing alloys, consistent with their relatively larger grain size compared with Sc-modified alloys. The elongation values remained acceptable for all alloys, although some reduction occurred after heat treatment due to increased strengthening. The Al–7Mg–2Zn–0.5Zr alloy showed the highest as-built elongation of $17.4 \pm 1.8\%$, suggesting that Zn addition maintained good ductility while improving strength. Overall, the tensile results agree well with the EBSD grain size distribution: finer grains in Sc- and Zn-modified alloys enhanced strength, while the coarser grains in the base Al–7Mg alloy resulted in lower mechanical performance. Figure 6 presents the hardness evolution during heat treatment where Sc-containing alloys showed a clear hardness increase during aging at 325°C , indicating precipitation hardening from Sc/Zr-containing phases. The Al–7Mg–4Zn–0.5Zr alloy also showed increased hardness,

especially at 190°C for longer aging time, suggesting Zn-related precipitation/solute strengthening. These hardness trends are consistent with the tensile results, where refined grains and precipitation strengthening jointly improved the mechanical response. Figure 5(d) shows the corrosion rate after 2 and 3 days of exposure time. The Sc-containing alloy, especially Al–7Mg–0.2Sc–0.5Zr, showed the lowest corrosion rate, indicating improved corrosion resistance. In contrast, the Zn-containing alloys exhibited higher corrosion rates, particularly Al–7Mg–4Zn–0.5Zr. This may be related to increased solute segregation or second-phase formation in Zn-added alloys, which can promote local galvanic corrosion. Therefore, although Zn addition improves strength, excessive Zn may reduce corrosion resistance.

4. Conclusion

High-strength and corrosion-resistant Al–7Mg based alloys were successfully developed by L-DED through Sc/Zr and Zn/Zr alloy modification. The Al–7Mg–0.4Sc–0.5Zr alloy showed the best mechanical performance among the investigated alloys, despite its relatively low Sc content, due to strong grain refinement and precipitation strengthening. The Al–7Mg–4Zn–0.5Zr alloy showed properties approaching those of the 0.4Sc alloy, indicating that Zn can replace Sc as a lower-cost alloying strategy. Overall, low-Sc alloying and Sc replacement by Zn offer practical routes for developing cost-effective, high-performance L-DED-processed Al–Mg alloys.

Declarations

Conflict of Interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

U.D: Writing-original draft, Investigation, methodology. H.k: Funding acquisition, Investigation and Supervision. B.H: Conceptualization and Supervision. A.W: Data curation. S.K: Writing—review & editing and Investigation.

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Data Availability

The data that support the findings and research of this study are available from the corresponding author upon reasonable request.

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Figures

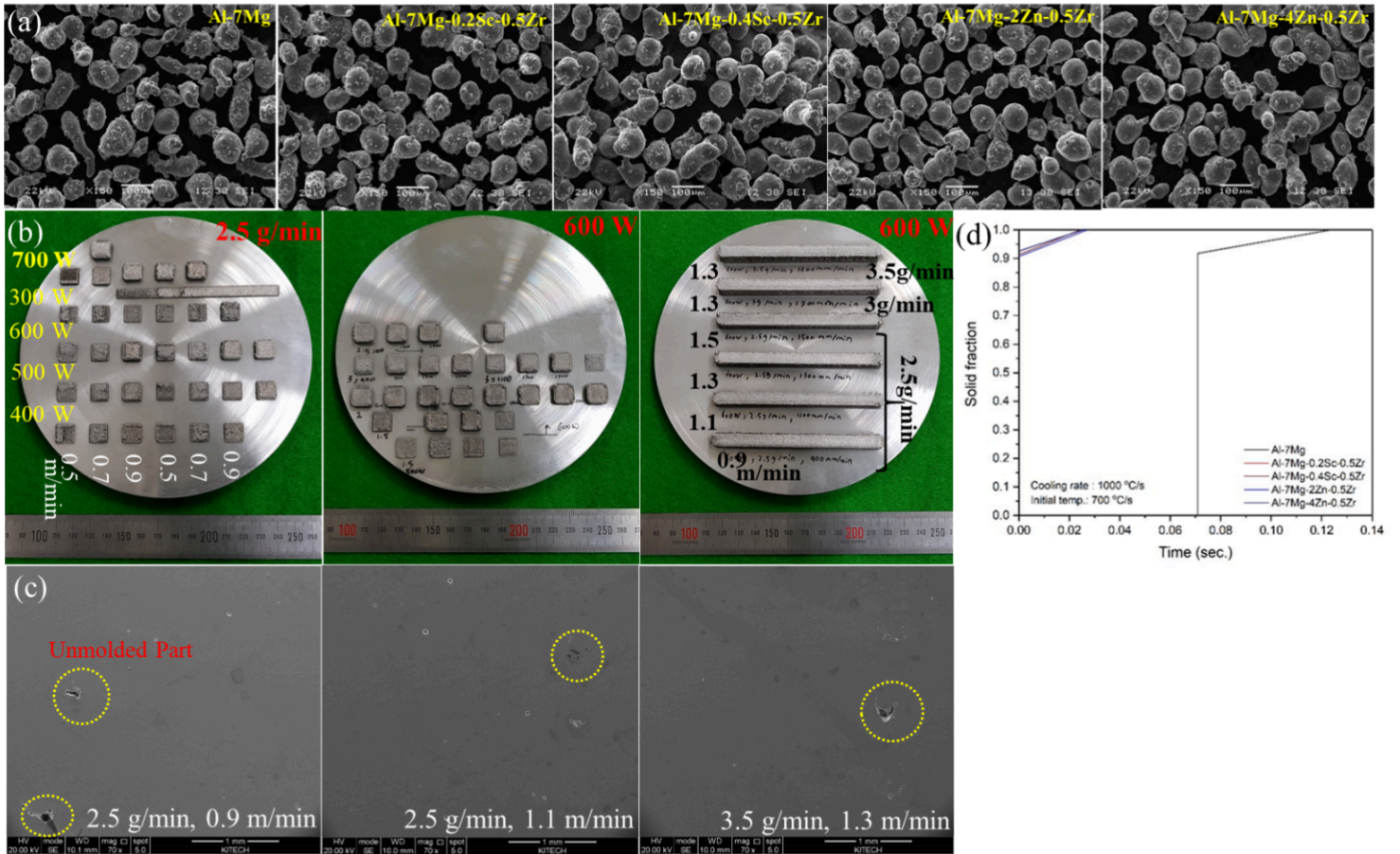


Figure 1

Powder morphology, L-DED process optimization, and solidification behavior of Al-7Mg-based alloys (a) SEM images of 53–100 μm powders, (b) effects of laser power, powder feeding rate, and scan speed on printability, (c) SEM observation of unmelted particles under selected conditions, and (d) calculated solid-fraction curves.

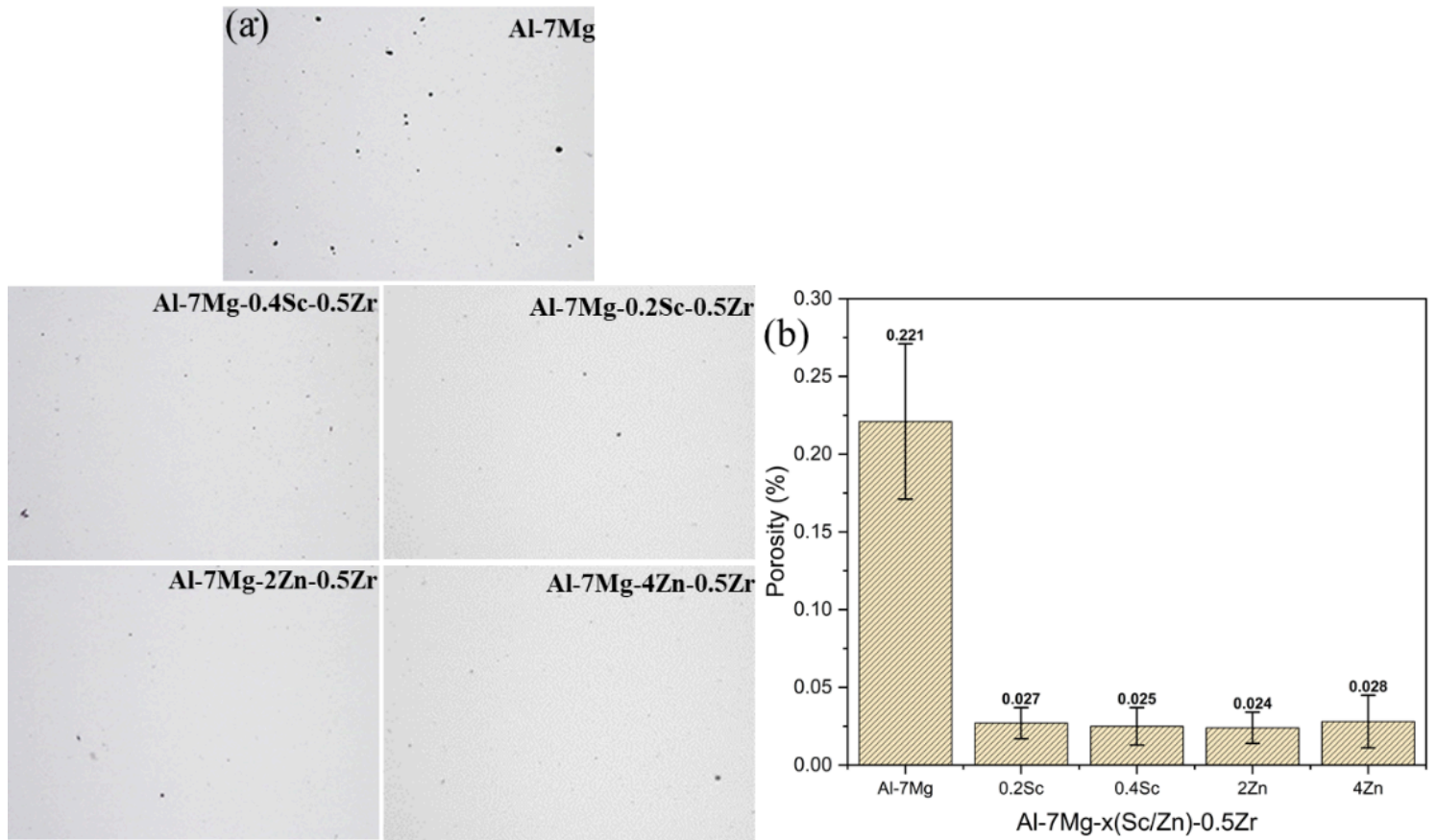


Figure 2

Porosity and density evaluation of L-DED-printed Al-7Mg-based alloys (a) optical micrographs showing pores/defects, (b) Average porosity of the printed alloys.

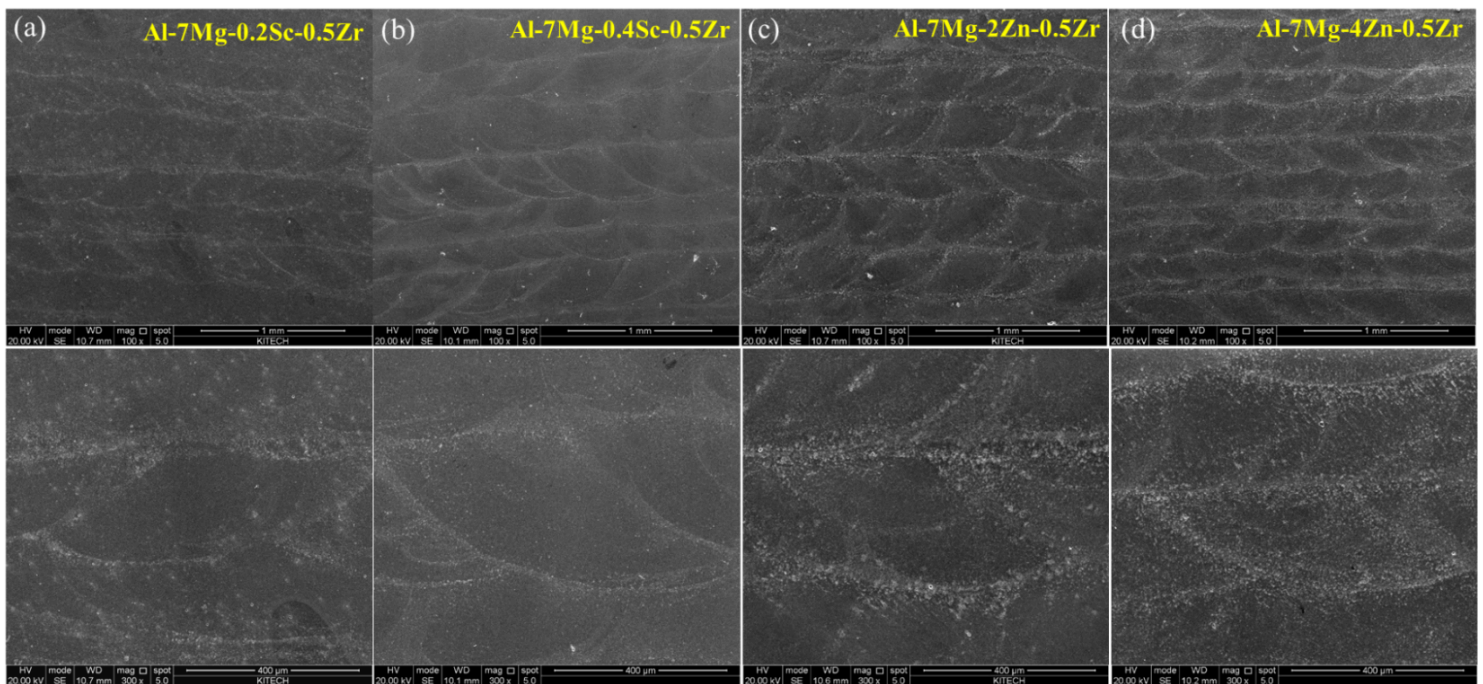


Figure 3

SEM images of L-DED-printed alloys (a) Al-7Mg-0.2Sc-0.5Zr, (b) Al-7Mg-0.4Sc-0.5Zr, (c) Al-7Mg-2Zn-0.5Zr, and (d) Al-7Mg-4Zn-0.5Zr.

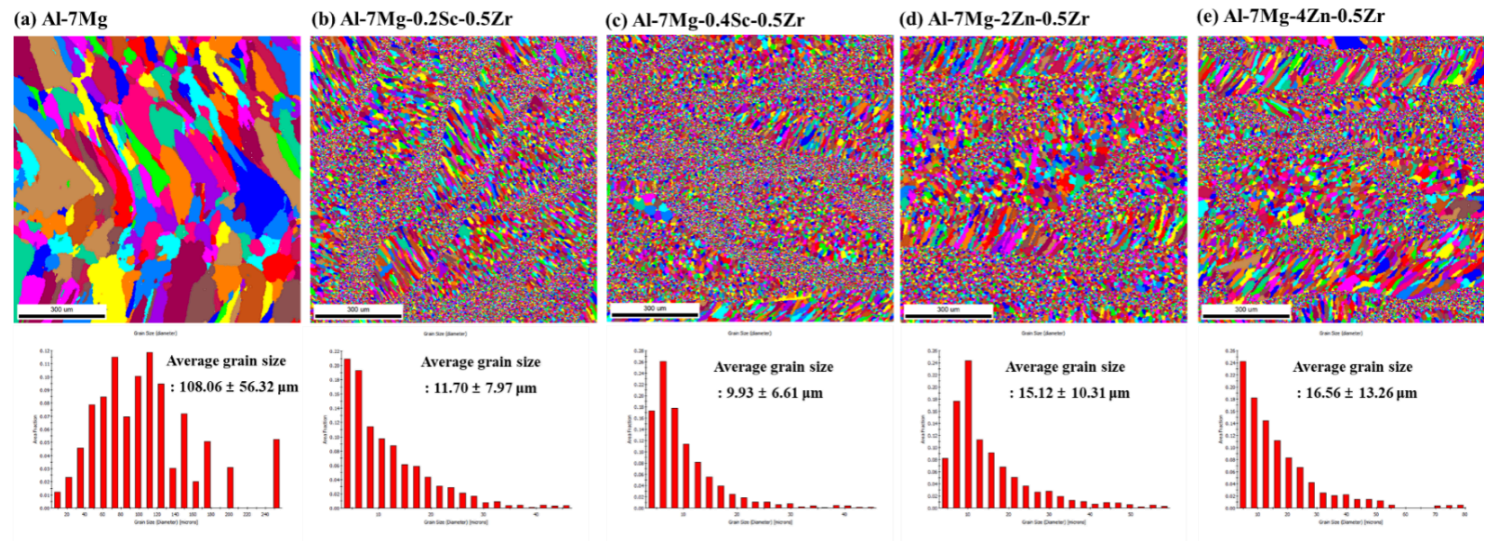


Figure 4

EBSD maps and grain size distributions of L-DED-printed alloys (a) Al-7Mg, (b) Al-7Mg-0.2Sc-0.5Zr, (c) Al-7Mg-0.4Sc-0.5Zr, (d) Al-7Mg-2Zn-0.5Zr, and (e) Al-7Mg-4Zn-0.5Zr.

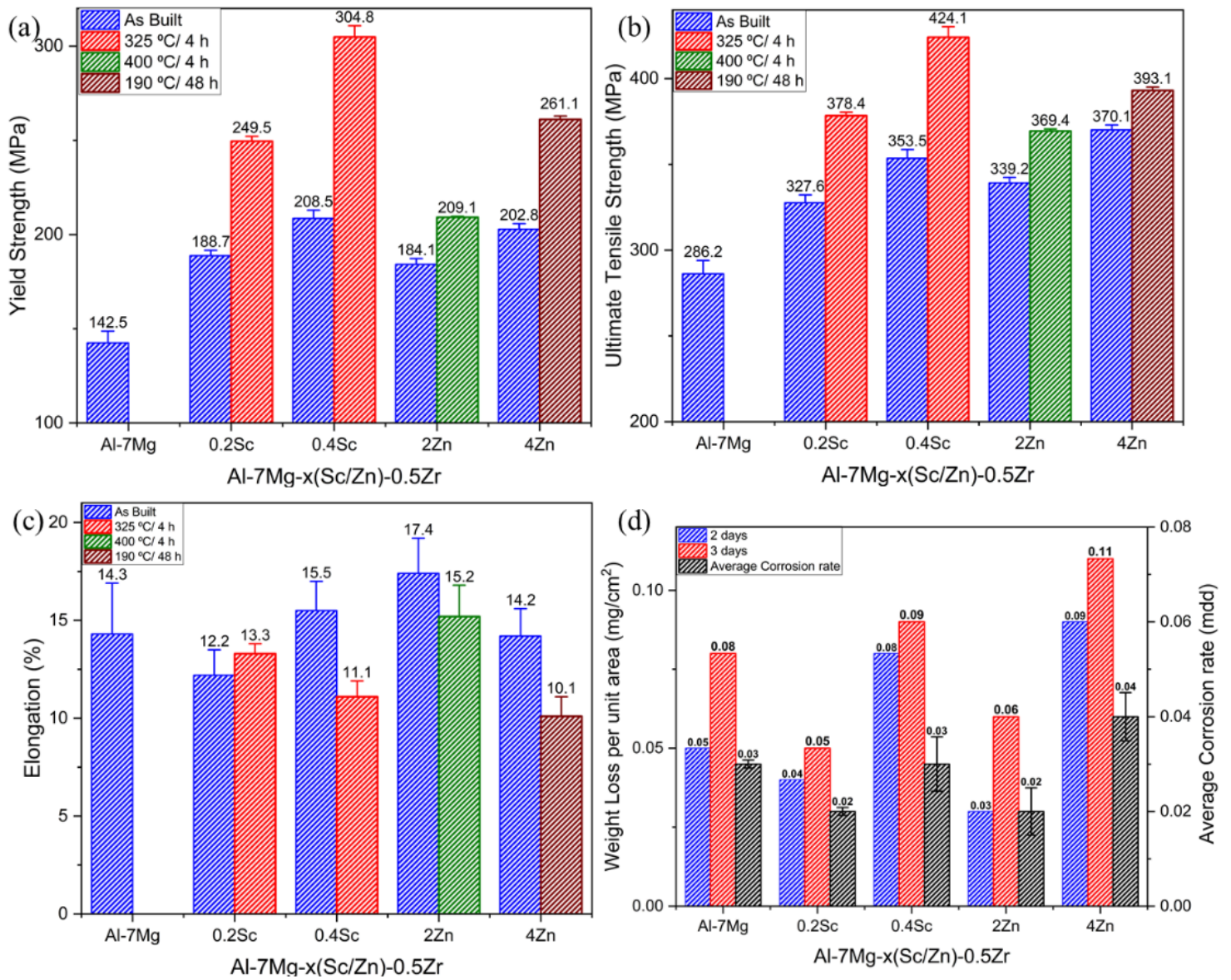


Figure 5

Mechanical and corrosion properties of L-DED-printed Al-7Mg-based alloys (a) yield strength, (b) ultimate tensile strength, (c) elongation, and (d) corrosion rate after 2 and 3 days exposure period.

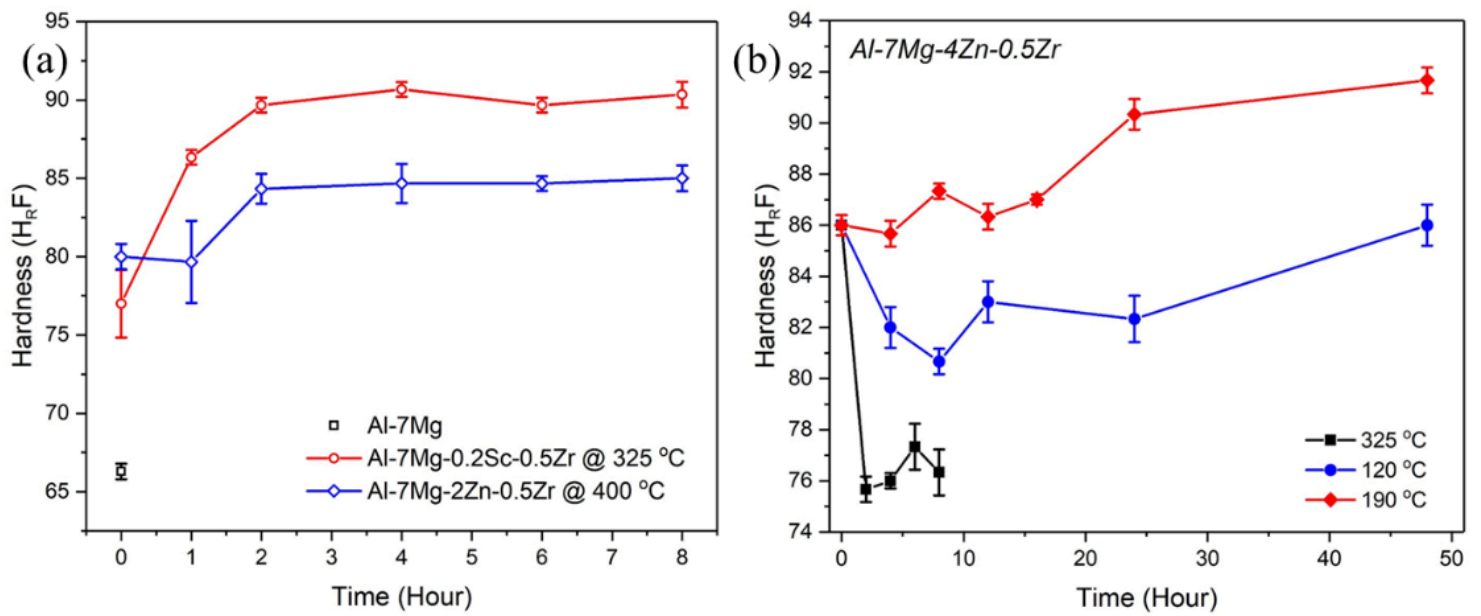


Figure 6

Hardness evolution during artificial aging of the L-DED Al-7Mg-based alloys (a) comparison of the base alloy, Al-7Mg-0.2Sc-0.5Zr aged at 325 °C, and Al-7Mg-2Zn-0.5Zr aged at 400 °C; (b) hardness evolution of Al-7Mg-4Zn-0.5Zr aged at 120, 190, and 325 °C.

Supplementary Files

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