Research Article

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Effect of Chromium Addition on ZA40 Alloy Fabricated by Powder Metallurgy Method

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ABSTRACT

Keywords: ZA40, composite, powder metallurgy, tensile

This study aims to develop chromium particle-reinforced ZA40 metal-metal composites via the powder metallurgy route and to investigate the influence of varying chromium content on their microstructural and mechanical properties. Composites containing 5 wt.%, 10 wt.%, and 15 wt.% Cr were fabricated to evaluate the effect of reinforcement content. The ZA40 matrix and chromium powders were homogenized by ball milling for five hours, followed by hot pressing at 500 °C under a pressure of 500 MPa in an argon atmosphere for two hours. The resulting composites were characterized in terms of microstructure, hardness, density, and tensile strength. The results revealed that increasing chromium content led to higher porosity and a corresponding decrease in relative density. Notably, the composite containing 10 wt.% Cr exhibited the highest hardness (182 HB) and tensile strength (240 MPa), indicating an optimal balance between reinforcement and structural integrity. In contrast, excessive Cr addition (15 wt.%) resulted in deteriorated properties due to increased porosity. Overall, the findings suggest that the incorporation of Cr particles into the ZA40 matrix significantly enhances mechanical performance, particularly at an optimal Cr content of 10 wt.%. These results highlight the potential of ZA40-Cr composites as cost-effective and high-performance materials for structural and engineering applications.

1. Introduction

In the development of engineering materials, the limitations of conventional monolithic materials have directed researchers and engineers toward alternative solutions. Achieving a balanced combination of mechanical properties such as toughness, hardness, strength, and elongation is often challenging with monolithic materials. Therefore, composite materials, which combine different constituents to provide enhanced properties, have become critical in modern material science. Due to their ability to optimize mechanical strength, lightweight characteristics, wear resistance, and thermal stability, composites offer significant advantages over traditional materials in various engineering applications [1,2]. Metal matrix composites (MMCs) have emerged as promising candidates for applications requiring high strength, wear resistance, and thermal stability. The development of MMCs has driven significant advancements, especially in the aerospace, automotive, electronics, and defense industries [3–5]. In this context, zinc-aluminum (ZA) alloys have attracted considerable attention for their excellent castability, low melting points, superior tribological performance, and cost-effectiveness [6]. These alloys serve as strong alternatives to conventional engineering materials such as aluminum casting alloys, cast iron, and brass. ZA alloys demonstrate exceptional performance under high mechanical loads and moderate sliding speeds. Their tribological advantages are primarily attributed to the formation of alumina (Al_2O_3) and zinc oxide (ZnO) phases during wear, which provide self-lubricating mechanisms [7–9]. Among ZA alloys, ZA40 holds a unique position[10–12]. Comprising approximately 60% zinc and 40% aluminum, this alloy offers an ideal balance of

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strength, ductility, and wear resistance. These characteristics make ZA40 a highly suitable choice for applications requiring low-speed and high-load conditions [13]. However, further improvements in the mechanical properties of ZA40 are necessary to enhance its potential in engineering applications. In recent years, incorporating reinforcement elements such as metal particles or ceramic phases into the ZA matrix has become a prevalent approach to enhancing the performance of these alloys [1]. Chromium (Cr) particles, with their high hardness, corrosion resistance, and mechanical strength, are an effective reinforcement material for MMCs. The addition of Cr particles to the ZA40 matrix can significantly improve both mechanical and tribological properties. Cr reinforcement may react with the matrix material to form intermetallic phases, which can have a pronounced impact on mechanical strength and wear resistance [14-16]. Furthermore, the uniform distribution of Cr particles within the ZA40 matrix contributes to controlling critical properties such as relative density and porosity.

The objective of this study is to investigate the mechanical and microstructural properties of ZA40-Cr metal-metal composites and evaluate the effects of Cr particle reinforcement on the ZA40 matrix. The study focuses on analyzing key properties such as relative density, porosity, hardness, and tensile strength of composites produced with varying Cr reinforcement ratios. Additionally, the influence of Cr-induced intermetallic phases and microstructural changes on mechanical performance is explored. By leveraging existing knowledge in literature, this work aims to design a novel and optimized composite material, contributing valuable insights to the field.

2. Experimental Study

ZA40-Cr metal-metal composites were produced using the advanced manufacturing technique of mechanical alloying, and the effect of Cr reinforcement content on the mechanical and corrosion properties of the composites was investigated. The chromium powder used in the study had an average particle size of 27 μm, a body-centered cubic (BCC) crystal structure, and an atomic radius of 0.130 nm. In this study, ZA40 alloy powders were used as the matrix phase, and the chemical composition of these powders is provided in Table 1 [17]. Additionally, the percentage contribution ratios of chromium are presented in Table 2.

Table 1. Chemical composition of ZA40 alloy

Material	Cu	Mg	Al	Zn
ZA40	2.0	0,015	40	Balance

Table 2. Sample codes and reinforcement ratios

Sample Code	ZA40 %	Cr %
ZA40	100	0
S1	95	5
S2	90	10
S3	85	15

First, ZA40-based composite powders with Cr weight ratios of 5%, 10%, and 15% were prepared. These powders were then subjected to mechanical alloying for five (5) hours using a high-energy ball mill. The composite samples were labeled as ZA (unreinforced), S1, S2, and S3. Following the mechanical alloying process, the powders were consolidated using the hot-pressing method for two hours. This process was carried out under a protective argon gas atmosphere at a pressure of 500 MPa and a temperature of 500°C. After the pressing process, metallographic procedures were applied to the samples to investigate their microstructure, density/porosity, hardness, and tensile strength. The microstructure and composition of the Cr-reinforced composites were characterized using a ZEISS EVO LS10 SEM equipped with EDS. Hardness measurements were conducted in Brinell units using an Innovatest-Nemesis 9000 hardness testing device in accordance with the ASTM E10-18 standard, with a load of 31,25 kg and a 2.5 mm diameter indenter. Tensile strength tests were performed using an MTS Criterion Universal Testing Machine at a tensile speed of 1 mm/min, following the ASTM E8 standard. The experimental density of the samples was determined using the Archimedes principle, in accordance with the ASTM B962–08 standard.

3. Results and Discussion

3.1. Microstructural Investigation

Figure 1 shows the micrographs of ZA40 and ZA40 matrix composites. These micrographs contain different ratios of chromium particles. In the micrographs, the light grey and dark areas represent the chromium and ZA40 alloy respectively. As can be seen from the images, the chromium particles are homogeneously distributed throughout the matrix (Figure 1 c-d). Previous research on metal matrix composites has shown that ceramic reinforcement components tend to separate from the matrix due to insufficient wetting and mechanical bonding between the ceramic particles and the metal matrix. As a result, the expected increase in strength was not achieved. In this study, however, no delamination was observed as shown in the micrographs. Due to the metallic nature of both the matrix and the reinforcement, good interfacial bonding was observed. Yalçın and Çanakçı [18], in their study, reported that multiwall carbon nanotubes (MWCNT) powders were effectively dispersed within the ZA40 matrix, achieving sufficient embedding and uniform distribution. However, they observed that the distribution was not entirely homogeneous, as increased MWCNT particle aggregation led to clustering, adversely affecting the composite's mechanical and tribological properties.

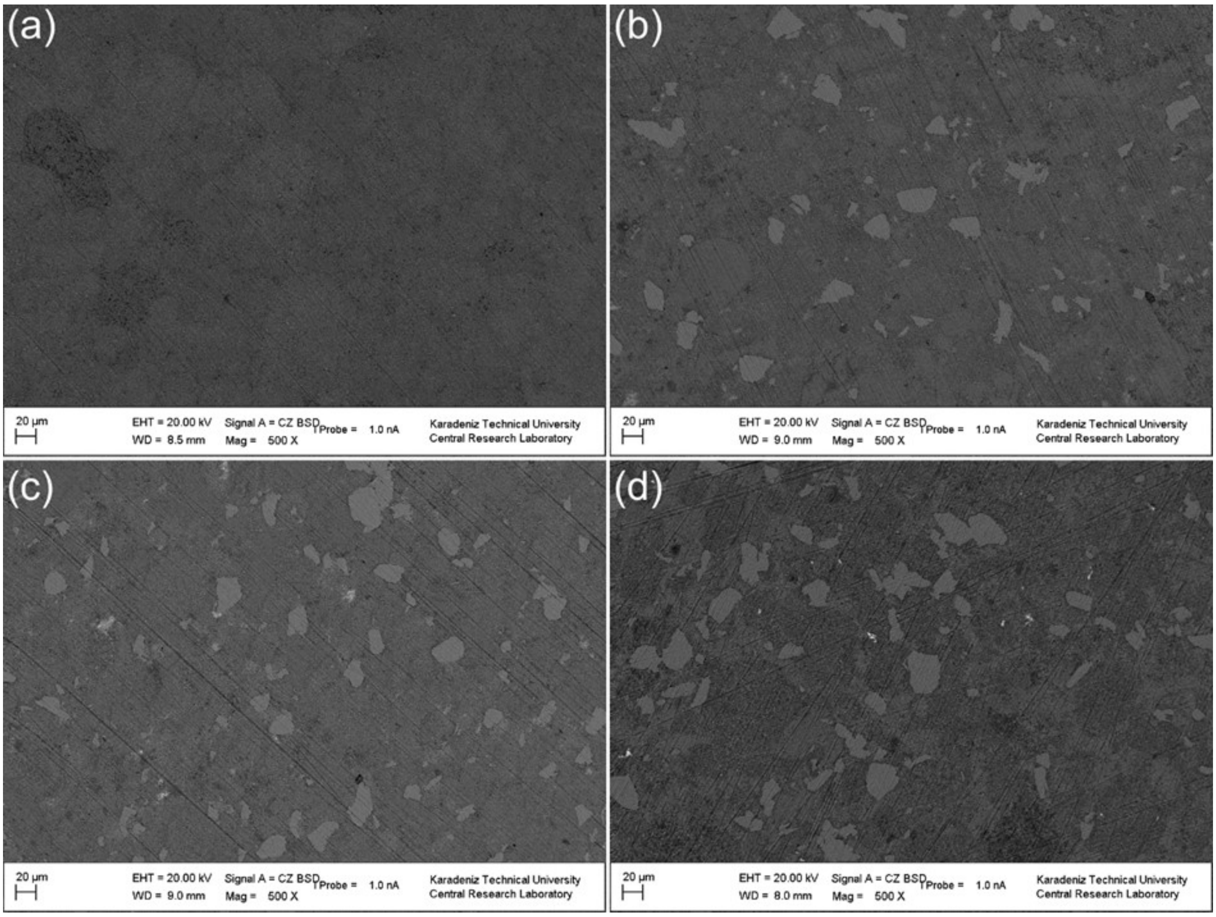

Figure 1. Microstructural images of a)ZA40, b)S1, c)S2 and d) S3 samples

Figure 2 presents the energy dispersive spectroscopy (EDS) mapping images of the ZA40 alloy, and the composites obtained with chromium reinforcement (b-d). A detailed examination of these mapping images provides significant insights into the microstructural properties of the composites. Upon analyzing the mapping results, the EDS map in Figure 2a shows a dense distribution of Zn (zinc) and Al (aluminum) elements. This confirms that zinc and aluminum, the primary components of the ZA40 alloy, exhibit a homogeneous distribution within the microstructure. In contrast, the images in Figures 2b-d clearly reveal the impact of chromium reinforcement on the microstructure. Particularly in the b-d images, a notable increase in the intensity of the zinc element, represented by red color, is observed. This increase indicates that the chromium reinforcement affects the distribution of zinc in the microstructure, leading to more concentrated regions. Moreover, changes in the homogeneity of zinc and the potential formation of segregation areas in the microstructure with chromium reinforcement were also observed. In conclusion, the EDS mapping analyses of ZA40 and Chromium-Reinforced composites provide a valuable method for quantitatively and qualitatively evaluating the effects of reinforcements on the microstructure. The results of the study highlight the necessity of investigating the impact of microstructural changes on mechanical properties in greater detail.

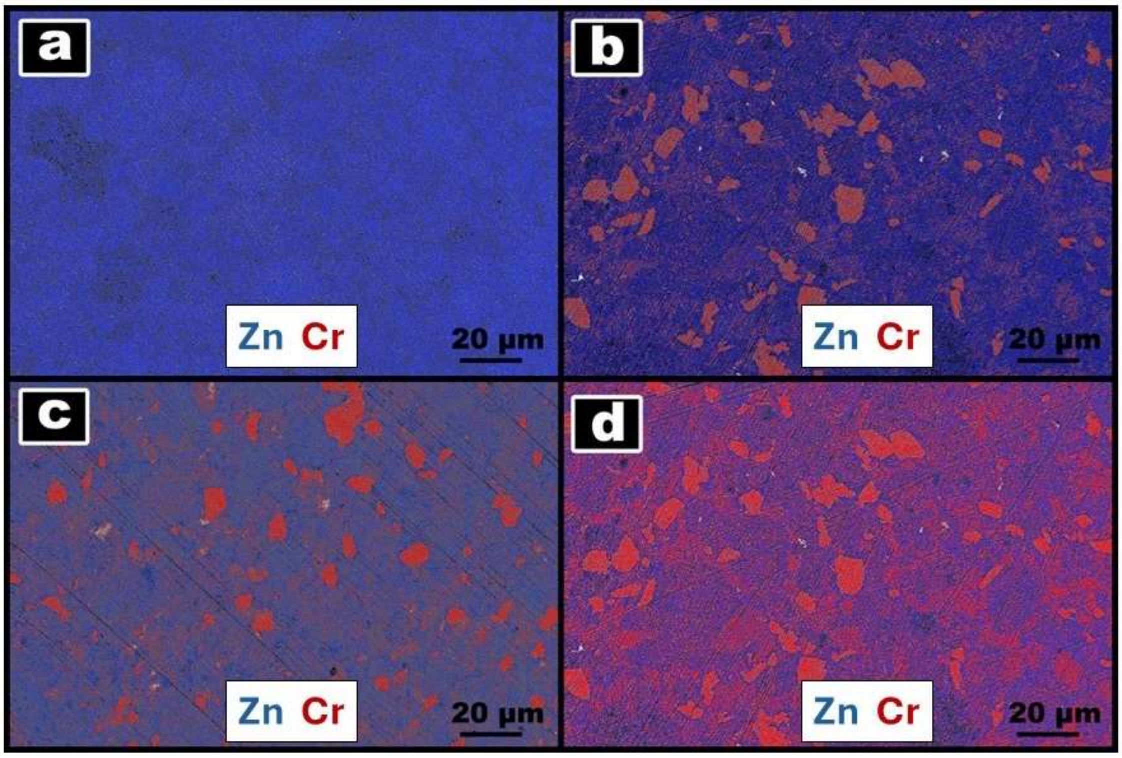

Figure 2. EDS mapping images of a)ZA40, b)S1, c)S2 and d) S3 samples

As demonstrated in Figure 3, the results of the EDS spectral analysis provide a comprehensive overview of the chemical compositions of the ZA40 alloy, and the composites produced with different chromium (Cr) additions. These results offer valuable data for evaluating the microstructural properties and elemental distributions of the alloy and composites. According to the EDS analysis depicted in Figure 3a, the ZA40 alloy contains aluminum (Al) at 46.95 wt.% and 68.08 at.%, while zinc (Zn) is detected at 48.96 wt.% and 29.29 at.%. These values represent the primary components of the ZA40 alloy. In Figure 3b, for the composite produced by adding 5% Cr to the ZA40 alloy, Al is found at 47.36 wt.% and 67.73 at.%, while Cr is present at 7.64 wt.% and 5.67 at.%, and Cu is detected at 2.62 wt.% and 1.59 at.%. The presence of Zinc (Zn) is determined to be 42.38 wt.% and 25.01 at.%. In Figure 3c, for the composite produced with 10% Cr addition, Al is found at 45.37 wt.% and 65.99 at.%. The presence of Cr is detected at 7.52 wt.% and 5.67 at.%, while Cu is present at 2.83 wt.% and 1.75 at.%, and Zn at 44.29 wt.% and 26.59 at.%. Finally, Figure 3d illustrates the composite produced with 15% Cr addition, where Al is detected at 42.91 wt.% and 63.22 at.%, and Cr at 12.97 wt. The presence of Cu is noted at 2.63 wt.% and 1.65 at.%, while Zn is detected at 41.48 wt.% and 25.22 at.%. It is evident from the EDS spectral analyses that the addition of varying Cr ratios to the ZA40 alloy significantly affects the chemical composition and microstructural homogeneity. The ZA40 alloy is distinguished by its balanced composition, with aluminum and zinc components in equal proportions. However, the introduction of Cr leads to alterations in the distribution of zinc within the microstructure, accompanied by the evident incorporation of Cr into the microstructure. Çanakçı and çelebi [19], in their study, reported that they identified the presence of an Al-rich α-phase in the microstructure through EDS mapping analysis.

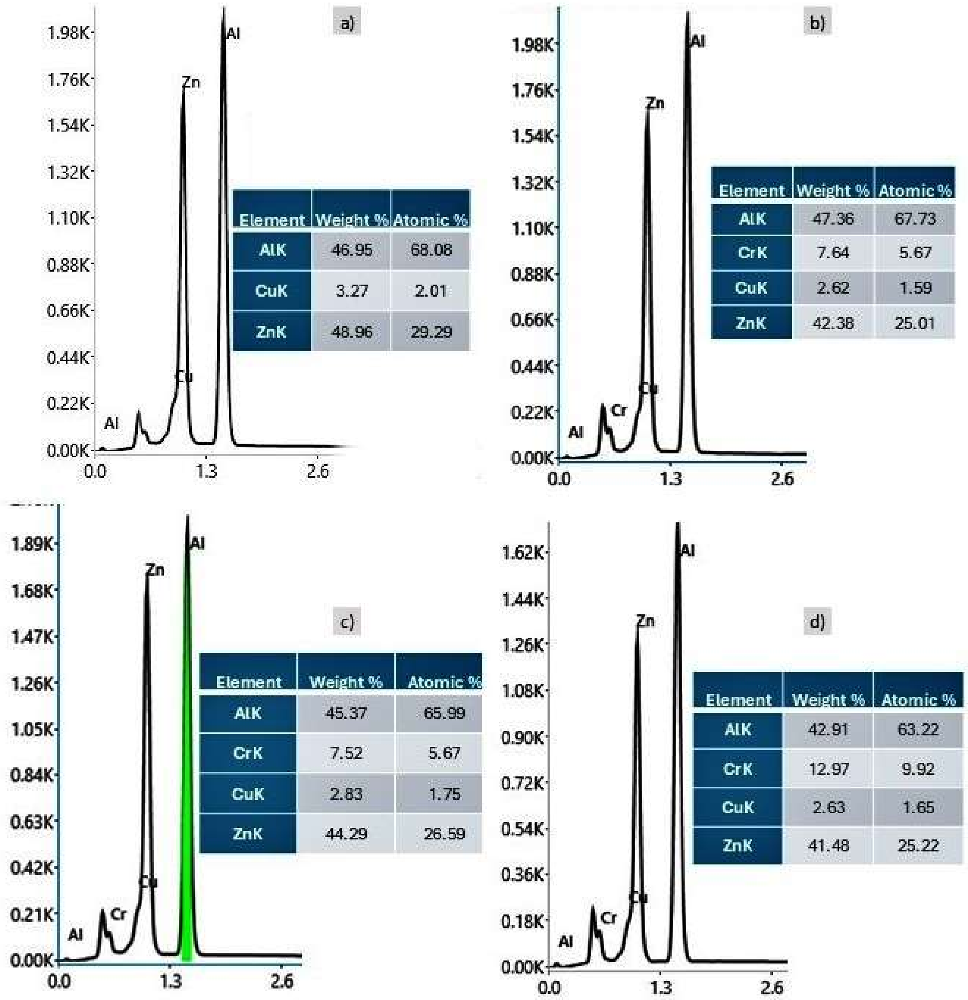

Figure 3. The results of the EDS spectral analysis of a)ZA40, b)S1, c)S2 and d) S3 samples

3.2. Examination Porosity and Hardness

The remaining solutions are assumed to be Omega (ω). In the GWO algorithm hunting (optimization) is guided by α, β and δ. Figure 4 illustrates the porosity and relative density graphs of the samples, which vary with increasing Cr content. Examining the relative density curve reveals that the highest relative density value, 97.93%, was obtained in the ZA40 sample, while this value decreased with increasing Cr content. The lowest relative density, 91.75%, was observed in the S3 sample containing 15% Cr. Relative density is inversely proportional to porosity, meaning that a decrease in relative density indicates an increase in the sample's porosity. Regarding the porosity values, the ZA40 sample exhibited a porosity of 2.07%, while the samples containing 5%, 10%, and 15% Cr had porosity values of 2.43%, 4.41%, and 8.25%, respectively. These results clearly demonstrate that increasing Cr content leads to higher porosity. In the study conducted by Çelebi et al., it was observed that increasing the milling duration of ZA40-based hybrid nanocomposites (HNCs) resulted in a decrease in relative density values and an increase in porosity. While the porosity of the unmilled sample was recorded as 1.95%, the maximum porosity value reached 2.8% after 8 hours of milling [17].

These changes in relative density and porosity can be attributed to the fact that Cr particles are harder than the ZA40 phase. In the ZA40 sample, only ZA40 powders were pressed, resulting in the highest relative density value. However, when Cr particles, which are harder than ZA40, were added to the structure, they resisted compression and packing during the pressing process. Consequently, micro-scale voids formed between the powders, adversely affecting their packing. This led to a decrease in relative density and an increase in porosity with higher Cr content. When examining the hardness values of the samples (Figure 5), the ZA40 sample showed a hardness of 150 Brinell. For the composites, the hardness increased to 167 Brinell with 5% Cr addition and 182 Brinell with 10% Cr addition but decreased to 128 Brinell with 15% Cr addition. These variations in hardness can be explained by the higher hardness of Cr particles compared to the ZA40 phase, in line with the rule of mixtures. The contribution of Cr particles to the ZA40 phase increased the hardness of the composite up to a certain threshold.

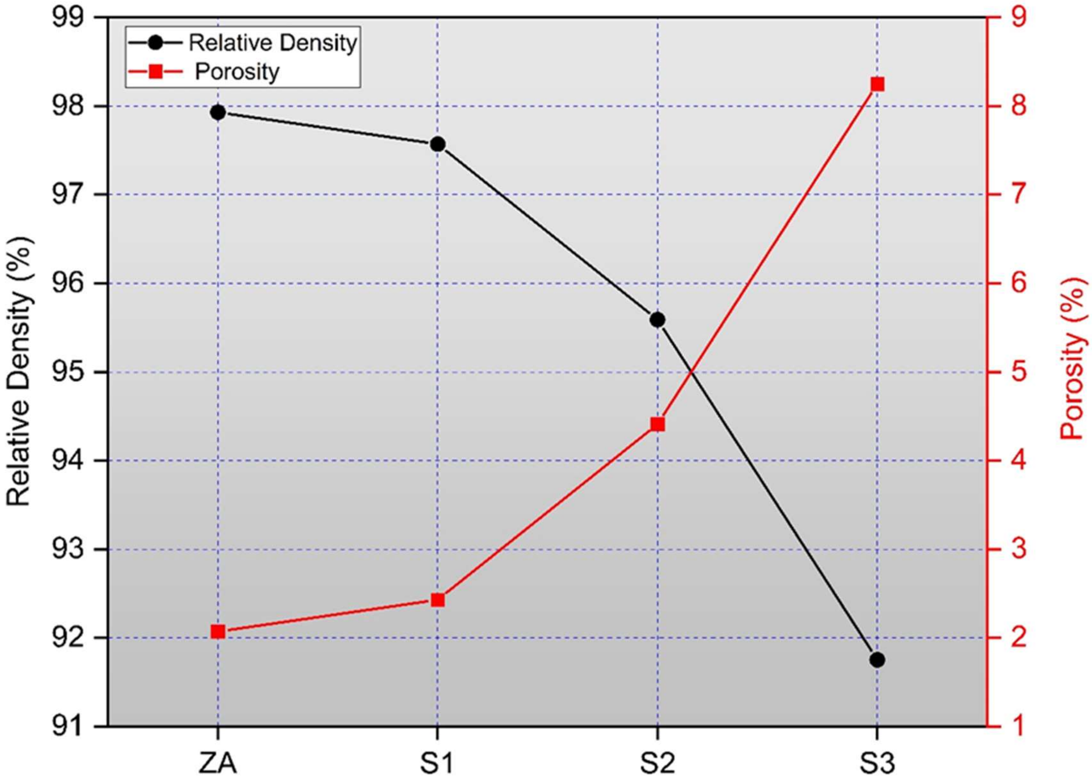

Figure 4. Porosity and relative density of samples

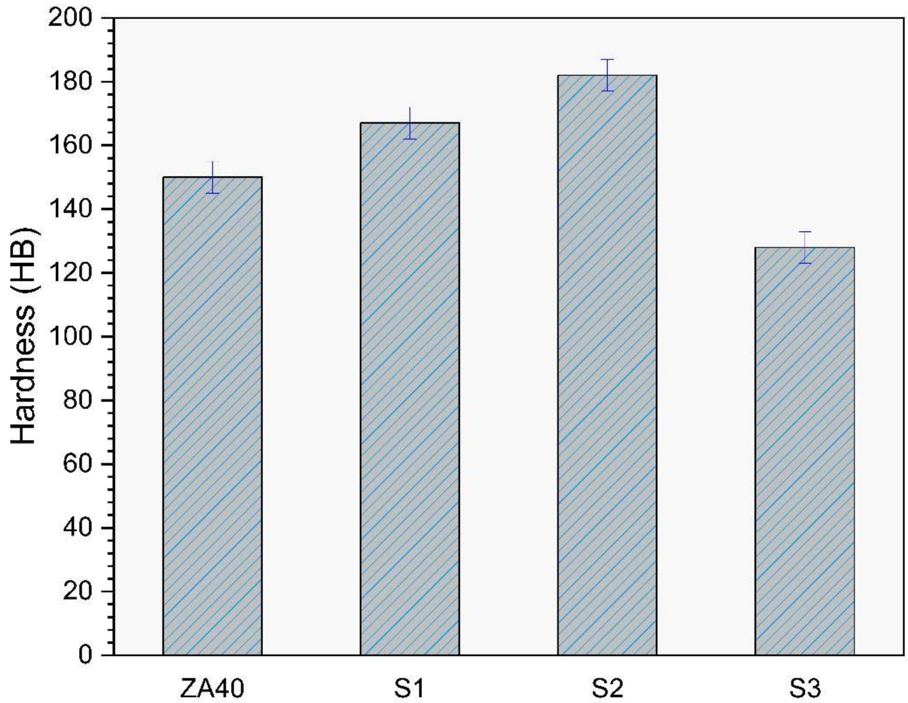

Figure 5. Hardness Graph of the Samples

However, the decline in hardness observed in the 15% Cr sample can be attributed to the detrimental effect of increased porosity on hardness. The elevated porosity present in the ZA40+15Cr sample is believed to mitigate the beneficial contribution of Cr reinforcement to the hardness of the composite. This suggests that while Cr can effectively enhance hardness up to a certain threshold, its impact on relative density and porosity may become negative beyond that point, outweighing its positive influence on hardness. These findings align with those reported by Çelebi et al. [20], who observed a significant increase in hardness when B4C metal powders were incorporated into the ZA40 matrix. Their study suggests that while reinforcement particles can enhance hardness, this effect may be influenced by the nature and distribution of the reinforcement, as well as the matrix properties. Yu et al [21], noted that among the studies conducted on ZA40, the addition of Cu-SiCp particles enhances hardness and inhibits α-dendrite growth. They stated that the dispersed distribution of Cu-SiCp significantly increases the hardness of the alloy while strengthening its mechanical durability by elevating internal stress.

3.3. Investigation of Tensile Strength

Figure 6 illustrates the tensile strength results for all the produced samples. Upon analyzing the data, it is evident that the tensile strength of the ZA40 sample was 160 MPa. With the addition of 5% Cr, the tensile strength increased to 228 MPa, and further increased to 240 MPa with 10% Cr, reaching the highest value observed. However, when the Cr content was raised to 15%, the tensile strength decreased significantly to 180 MPa. These results suggest that the effect of Cr on tensile strength is two-phased: at lower to moderate Cr levels, tensile strength improves, whereas at higher Cr concentrations, it begins to decrease.

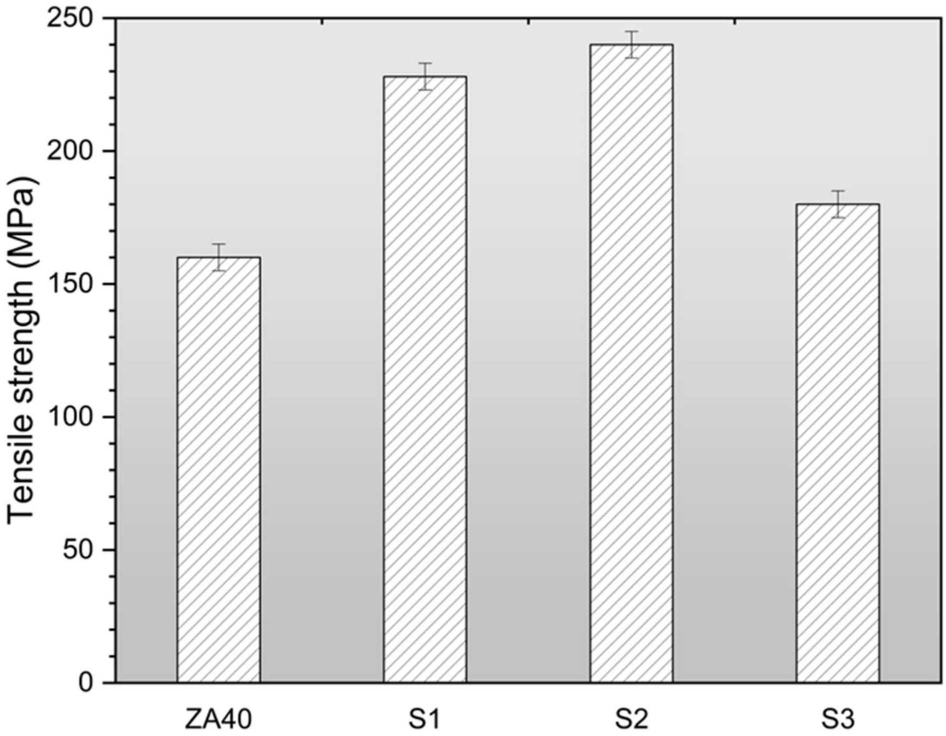

Figure 6. Tensile strength values of samples

The reinforcement of the ZA40 matrix with Cr particles has had a direct impact on tensile strength. Particularly, the observed increase in strength with 5% and 10% Cr additions can be attributed to the mechanical support provided by Cr particles, which possess high hardness and strength properties, thus enhancing the matrix structure. In line with the hardness data, the sample with 10% Cr exhibited the highest values in both hardness (182 Brinell) and tensile strength (240 MPa). However, the decrease in tensile strength observed in the 15% Cr sample is believed to be related to the increase in porosity caused by the higher Cr content. Porosity values revealed that the ZA40 sample exhibited 2.07% porosity, while the samples with 5%, 10%, and 15% Cr additions showed porosities of 2.43%, 4.41%, and 8.25%, respectively. The notable increase in porosity in the 15% Cr sample (8.25%) indicates that the microvoids formed in the material's internal structure negatively affected its strength. Relative density values also support this observation. The relative density of the ZA40 sample was 97.93%, while the 15% Cr sample exhibited a significant reduction to 91.75%. The decrease in relative density correlates with the increase in microvoids, helping to explain the reduction in tensile strength. This suggests that, at the 15% Cr content, the positive contribution of hardness could not offset the adverse effects of porosity, leading to an increase in brittleness. In conclusion, the optimum Cr content for tensile strength was determined to be 10%. The 10% Cr sample achieved the highest values in terms of hardness, relative density, and tensile strength, striking a balance between these mechanical properties. Conversely, the 15% Cr sample saw a reduction in relative density and mechanical properties due to increased porosity. This indicates that the effect of Cr addition depends not only on its quantity but also on its interaction with the matrix's mechanical and microstructural properties. Li et al [22]., reported that the addition of 0.4% Yttrium (Y) to the ZA40 alloy caused changes in its tensile properties, specifically leading to a 4.2% decrease in tensile strength with the incorporation of Y.

4. Conclusions

In this study, the effects of Cr (chromium) addition at different ratios on the microstructure, porosity, relative density, hardness, and tensile strength of ZA40 alloy-based composites were investigated. The results of the study show that Cr particles are homogeneously distributed within the ZA40 matrix, and the microstructure remains quite uniform up to 10% Cr addition. However, at higher Cr contents, heterogeneities in the microstructure and changes in zinc distribution were observed. In terms of porosity and relative density, an increase in Cr content resulted in a decrease in relative density and an increase in porosity. The ZA40 alloy exhibited the highest relative density value of 97.93% and the lowest porosity of 2.07%. In contrast, the composite with 15% Cr had a relative density of 91.75% and a porosity of 8.25%. This change can be explained by the fact that Cr particles, being harder than ZA40, made the pressing process more difficult, leading to the formation of micro-sized pores. Hardness values increased with Cr addition, reaching the highest hardness of 182 Brinell with 10% Cr. However, with 15% Cr, the hardness decreased to 128 Brinell due to the increased porosity. These results indicate that the optimal Cr content for hardness is 10%. Tensile strength results followed a similar trend to the hardness data. While the ZA40 alloy exhibited a tensile strength of 160 MPa, the composite with 10% Cr showed a significant increase to 240 MPa. However, with 15% Cr, the tensile strength decreased to 180 MPa due to the increased porosity. These findings suggest that the Cr content has both positive and negative effects on tensile strength. In conclusion, the optimal Cr addition for ZA40 composites was determined to be 10%. This composition provided the best balance in terms of hardness, tensile strength, and relative density. Higher Cr contents led to excessive porosity, which caused a reduction in mechanical properties. The findings emphasize the importance of carefully optimizing Cr addition and considering microstructural changes when designing ZA40 alloy-based composites. This study provides valuable insights for the design and development of metal matrix composites. This study is limited to specific Cr contents (5%, 10%, and 15%) and fixed processing parameters. Other key properties such as wear resistance and fracture behavior were not investigated. Future work should explore a wider reinforcement range, evaluate additional mechanical and tribological properties, and apply advanced characterization techniques (e.g., XRD, TEM) to better understand phase formation and interfacial behavior.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

References

[1] S. S. Owoeye, D. O. Folorunso, B. Oji, and S. G. Borisade, "Zinc-aluminum (ZA-27)-based metal matrix composites: a review article of synthesis, reinforcement, microstructural, mechanical, and corrosion characteristics," *The International Journal of Advanced Manufacturing Technology*, vol. 100,

no. 1–4, pp. 373–380, Jan. 2019. doi: 10.1007/s00170-018-2760-9

[2] M. Babic, S. Mitrovic, and B. Jeremic, "The influence of heat treatment on the sliding wear behavior of a ZA-27 alloy," *Tribol Int*, vol. 43, no. 1–2, pp. 16–21, Jan. 2010. doi: 10.1016/j.triboint.2009.04.016

[3] C. Testani and F. Ferraro, "Development of a Low-Cost Process for Manufacturing of Ti-Metal Matrix Composite by Roll-Diffusion Bonding," *J Mater Eng Perform*, vol. 19, no. 4, pp. 521–526, Jun. 2010. doi: 10.1007/s11665-010-9620-6

[4] G. M. Reddy, K. S. Prasad, K. S. Rao, and T. Mohandas, "Friction surfacing of titanium alloy with aluminium metal matrix composite," *Surface Engineering*, vol. 27, no. 2, pp. 92–98, Mar. 2011. doi: 10.1179/174329409X451128

[5] J. Hashim, "The Production of Cast Metal Matrix Composite by a Modified Stir Casting Method," *J Teknol*, vol. 35, no. A, pp. 9-20, Jan. 2012. doi: 10.11113/jt.v35.588

[6] P. Choudhury, S. Das, and B. K. Datta, "Effect of Ni on the wear behavior of a zinc-aluminum alloy," *J Mater Sci*, vol. 37, no. 10, pp. 2103–2107, 2002. doi: 10.1023/A:1015297904125

[7] S. C. Sharma, B. M. Girish, R. Kamath, and B. M. Satish, "Graphite particles reinforced ZA-27 alloy composite materials for journal bearing applications," *Wear*, vol. 219, no. 2, pp. 162–168, Sep. 1998. doi: 10.1016/S0043-1648(98)00188-4

[8] M. T. Abou El-khair, A. Daoud, and A. Ismail, "Effect of different Al contents on the microstructure, tensile and wear properties of Zn-based alloy," *Mater Lett*, vol. 58, no. 11, pp. 1754–1760, Apr. 2004. doi: 10.1016/j.matlet.2003.10.058

[9] E. Gervais, R. J. Barnhurst, and C. A. Loong, "An Analysis of Selected Properties of ZA Alloys," *JOM*, vol. 37, no. 11, pp. 43–47, Nov. 1985. doi: 10.1007/BF03258743

[10] M. T. Abou El-khair, A. Daoud, and A. Ismail, "Effect of different Al contents on the microstructure, tensile and wear properties of Zn-based alloy," *Mater Lett*, vol. 58, no. 11, pp. 1754–1760, Apr. 2004. doi: 10.1016/j.matlet.2003.10.058

[11] W. Zhang, X. Ma, and D. Ding, "Aging behavior and tensile response of a SiCw reinforced eutectoid zinc-aluminium-copper alloy matrix composite," *J Alloys Compd*, vol. 727, pp. 375–381, Dec. 2017. doi: 10.1016/j.jallcom.2017.08.130

[12] R. Michalik, A. Iwaniak, and J. Wieczorek, "Influence of heat treatment on the wear resistance of the ZnAl40Cu1.5Ti1.5 alloy," *Archives of Metallurgy and Materials*, vol. 62, no. 1, pp. 129–136, Mar. 2017. doi: 10.1515/amm-2017-0017

[13] P. P. Ritapure, R. G. Yadav, V. T. Rasal, A. V. Damale, and Y. R. Kharde, "Comparative review and experimental validation of Tribological and Mechanical Properties of Zinc Aluminium Alloy (ZA27) and Aluminium Zinc Alloy (Al-25Zn)," *Journal of Alloys and Metallurgical Systems*, vol. 7, p. 100099, Sep. 2024. doi: 10.1016/j.jalmes.2024.100099

[14] B. K. Prasad, "Dry sliding wear response of zinc-based alloy over a range of test speeds and loads: a comparative study with cast iron," *Tribol Lett*, vol. 25, no. 2, pp. 103–115, Jan. 2007. doi: 10.1007/s11249-006-9054-3

[15] S. Özkaya, "Microstructural, Mechanical, and Tribological Characteristics of ZA40 Alloy Reinforced with AlCrCuFeNi High Entropy Alloy: An Experimental Study," *JOM* , vol. 77, no. 7, pp. 5510–5525, 2025. doi: 10.1007/s11837-025-07401-3

[16] T Varol, O Güler, S. B. Akçay, H. Çolak, "The evolution of microstructure and properties of Cu-Cr alloys synthesized via flake powder metallurgy assisted by mechanical alloying and hot pressing," *Mater Today Commun*, vol. 33, p. 104452, 2022. doi: 10.1016/j.mtcomm.2022.104452

[17] M. Çelebi, A. Çanakçi, O. Güler, B. Akgül, and A. H. Karabacak, "Study on Effect of Milling Time on the Mechanical and Wear Properties of the ZA40-B4C-Graphene Hybrid Nanocomposites Fabricated by Vacuum Hot-Pressing," *JOM*, vol. 75, no. 9, pp. 3935–3950, Sep. 2023. doi: 10.1007/s11837-023-06007-x

[18] A. Çanakçı and E. Deniz Yalçın, "Investigation of Tribological Applications and Mechanical Properties of Zinc-Aluminium (ZA40)/Multi-Wall Carbon Nanotube (MWCNT) Composite Alloys," *Tehnički glasnik*, vol. 17, no. 4, pp. 620–627, Oct. 2023. doi: 10.31803/tg-20220831200112

[19] A. Çanakçı and M. Çelebi̇, "Determination of nano-graphene content for improved mechanical and tribological performance of Zn-based alloy matrix hybrid nanocomposites," *J Alloys Compd*, vol. 1001, p. 175152, Oct. 2024. doi: 10.1016/j.jallcom.2024.175152

[20] M. Çelebi, A. Çanakçı, O. Güler, H. Karabacak, B. Akgül, and S. Özkaya, "A study on the improvement of wear and corrosion properties of ZA40/Graphene/B4C hybrid nanocomposites," *J Alloys Compd*, vol. 966, p. 171628, Dec. 2023. doi: 10.1016/j.jallcom.2023.171628

[21] T. Yu, G. Geng, P. Xue, and L. Zhang, "The Research of Reinforced Cu-SiCp/ZA40 and Cu-SiCp/AZ91D Metal Matrix Composites' Mechanisms," *IOP Conf Ser Mater Sci Eng*, vol. 381, p. 012173, Aug. 2018. doi: 10.1088/1757-899X/381/1/012173

[22] M. Li, S. Lu, F. Long, M. Sheng, H. Geng, and W. Liu, “Effect of Y Addition on the Mechanical Properties and Microstructure of Zn-Al Alloys,” *JOM*, vol. 67, no. 5, pp. 922–928, May 2015. doi: 10.1007/s11837-014-1269-4