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Research Article

Effect of MGZN$_2$ addition on the sintering density, microstructure and hardness of aluminum alloys prepared by powder metallurgy method

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ABSTRACT

In this study, the aluminum alloys with different $MgZn_2$ contents were prepared using the powder metallurgy method. The effect of the $MgZn_2$ contents on the sintering density, porosity, microstructure and microhardness was investigated using optical microscopy, scanning electron microscopy (SEM), X-ray diffraction, and Vickers microhardness. The function mechanism of the intermetallic compounds formed as a result of $MgZn_2$ addition was analyzed. The results revealed that the highest sintering relative density (95.1%), lowest porosity volume fraction (4.81%), and highest hardness (112.4 HV) were observed with the 5% addition of $MgZn_2$ contents. The XRD results show that the microstructure of the bare sample (Al) is mainly composed α-Al phase, while, with the addition of $MgZn_2$, the microstructure turned to have α-Al phase and some intermetallic compounds of $Al_5Mg_{11}Zn_4$ and $AlMg_4Zn_{11}$. These intermetallic compounds were formed with higher density at the grain boundaries as white precipitates.

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INTRODUCTION

Due to the high corrosion resistance, electrical drive capability, machinability, and relatively low cost, Aluminum (Al) and its alloys are significantly used in the aerospace industry [1-3]. Recently, Al alloys have been employed mainly in the automotive, maritime, aviation, and defense industries with improved resistance and impact properties. The Organization for Economic Cooperation (OECD) and Development International Energy Association (IEA) reported [4] that aluminum alloys are classified as good candidates that led to increased usage in transportation systems, including light vehicles, railcars, and aircraft as efforts to reduce fuel consumption. However, these alloys have drawbacks to notably used [5], due to their low strength. Thus, adding different alloying elements, such as Zn, Mg, and Cu [6, 7], is essential to improve hardness and strength [6, 7]. Furthermore, the higher solid solubility of Mg and Zn into the Al matrix may be considered to produce the strengthened hardening and thus improve the mechanical properties [8, 9]. Numerous experimental and theoretical

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studies have been performed with precipitates effects on the mechanical property's enhancement and the alloying elements' additions [10, 11]. It was reported that there are several intermetallic phases, like $MgZn_2$ and $Al_2Mg_3Zn_3$ are formed in the commercial alloy of Al-Zn-Mg-Cu and might exist below the solidus temperature [12, 13].

Moreover, aluminum alloys are typically fabricated using casting, forging, extrusion, and semisolids [14]. The mechanical characteristics of aluminum alloys developed by the powder metallurgy process have been increasingly stated recently. Powder metallurgy is a method of production used to manufacture the final shape or near to shape components [15]. Moreover, it is easier and cheaper to manufacture complex engineering components with this method. Combined with various powder particle sintering, which is used successfully in small component production for different industrial applications [16]. Light metals such as aluminum are used in the automobile industry to minimize the weight of vehicles in order to minimize fuel consumption. Since the mid-1990s, industrial applications for automotive components, like camshafts and bearing caps, have been made of aluminum via powder metallurgy methods. Because of its high strength, 7XXX series aluminum alloys are increasingly used in powder metallurgy nowadays [17].

The literature review revealed that the second phase's formation could increase the strength of aluminum alloys. Still, the relationship between various percentages and microstructures has not been studied yet. This study thus attempts to explain the effects of the second phase (intermetallic compounds), which formed in the structure according to the additive percentage of powder metallurgy Al alloys' behavior in terms of density and porosity microstructure and microhardness.

EXPERIMENTAL PROCEDURE

A 99.9% purity of Mg and Zn rods were purchased from Sigma Aldrich used in this study. A 5 g of the Zn and 0.93 g of Mg were melted in a Zirconia crucible using an electric induction furnace under a vacuum atmosphere. The casted MgZn alloy was then crushed using a hammer and followed by a ball milling at 300 rpm for 3 hrs to obtain $MgZn_2$ powder with fine particle size. The aluminum powder with a purity of 99.9% was also purchased from Sigma Aldrich, mixed with the produced $MgZn_2$ powder at different volume fractions of 2.5%, 5%, 10%, and 20%, shown in Table 1. Then, the mechanical ball milling was carried out in an argon atmosphere at a rotation speed of 300rpm for 18h. The mixed powder was compacted into green samples using a hydraulic press with an applied 5 tons of load. The produced samples were in the shape of a cylinder with a 20 mm diameter and 3 mm thickness dimension. The green samples were then sintered in a vacuum furnace at 575 oC for 3 hrs, followed by polishing. The density of the porosity and sintered samples were calculated according to Archimedes' principles [18]. The average value (3 trials) of porosity density was calculated using the following equation [19]:

$$P = (1 - {}^{\rho}/_{\rho_a}) \times 100;$$

Where ρ is the experimental density (based on Archimedes' principles) and ρa is the theoretical density Al.

Table 1. The Experimental chemical composition used

Alloy	Additive weight (g)	
	Al	**$MgZn_2$**
Pure Al (Bare alloy)	5.00	0
2.5% $MgZn_2$ + Al	5.00	0.125
5% $MgZn_2$ + Al	5.00	0.250
10% $MgZn_2$ + Al	5.00	0.500
20% $MgZn_2$ + Al	5.00	1.00

The microstructure and phase composition due to the different volume fractions of $MgZn_2$ addition were characterized using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), respectively. Fully recrystallized grains with average sizes through above alloying (the average grain size was measured by the "line intercept method", according to the microstructures observed by Scanning electron microscopy (SEM); all the high-angle grain boundaries, including twin boundaries were counted). For the phase analysis, X-ray diffraction (XRD-600, Japan) with Cu Ka radiation at 40 kV and 100 mA was used. The microhardness measurements were calculated using a Shimadzu microhardness tester with an applied load of 0.2 Newton for 30 sec. The calculated values are the average of five measurements at different locations.

RESULTS AND DISCUSSION

Effect of $MgZn_2$ content on sintering density and porosity of Al alloys

Figure 1 shows the sintering relative density of Al samples with different $MgZn_2$ contents. The relative density of Al increased from 78.9% to 95.1% as the percentage of $MgZn_2$ risen from 2.5% to 5%. However, adding $MgZn_2$ with 10% and 20% reduced the relative density by 86% and 82.3%, respectively. The enhancement of the relative density is attributed to the optimum percentage of the Zn (which smaller particle than Mg) filled the interval space (porosity) during the compaction process, resulting in a higher relative density. Furthermore, as the particles' spacing becomes closer, the diffusion process takes a shorter time to produce a completed bonding between the particles and makes a homogenized microstructure. Nevertheless, when the $MgZn_2$ addition was increased to 10% and 20%, the relative density was reduced due to the partial replacement of Mg by Zn atoms, which lead to a decrease in the mismatching of the lattice of aluminum [20, 21]. These results were also confirmed by measuring the porosity (Figure 2), which shows the same variation trend as the percentage of $MgZn_2$ added.

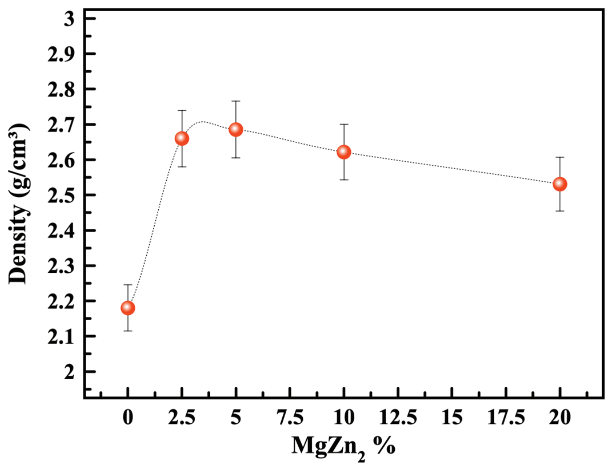

Figure 1. The density of the sintered Al alloy with different $MgZn_2$ contents.

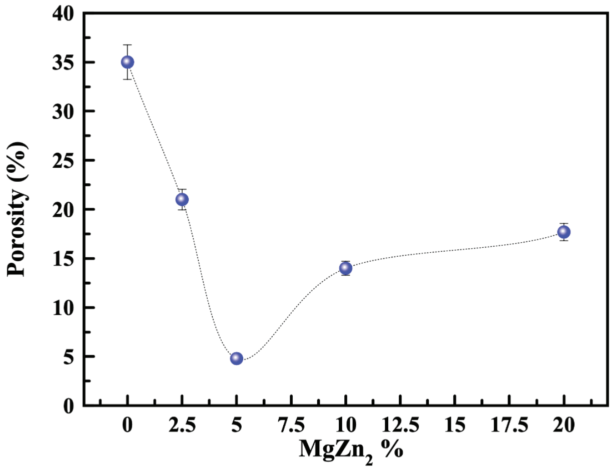

Figure 2. Porosity volume fraction of the sintered Al alloy with different $MgZn_2$ contents.

Effect of $MgZn_2$ content on microstructure and phase structure of Al alloys

Figure 3(a-e) shows the optical micrographs of Al samples with the different $MgZn_2$ addition contents. It can be seen that with increasing the $MgZn_2$ contents from 2.5% to 5%, the pore size of the sintered Al sample is reduced. This result is also consistent with the density and volume fraction of the porosity discussed earlier. The grain refinement process changes the planar or cellular interface to an equiaxed structure, which minimizes porosity [22], diminishes hot tearing, improves feeding, and reduces volumetric shrinkage [23]. This phenomenon raises the fracture toughness significantly [22] with the decrease in the grain size of aluminium alloy [24]. Figure 3a shows the characteristic microporous microstructure of the sintered Al alloy. The addition of 2.5 wt.% $MgZn_2$ (Figure 3b) shows micro-segregation and coarse grains of the $MgZn_2$ phase, which is non-uniformly distributed in the aluminium matrix. Furthermore, the Al alloys' grain size slightly decreased as the addition of the $MgZn_2$ increased from 2.5% to 5% along with uniform distribution in the formed particles (see in Figure 3c) than other further additions (i.e., 10% and 20%), as shown in Figure 3d and e. These reductions in the grain size may be attributed to the structure of the Mg and Zn, as both of them belong to a close-packed hexagonal structure. The Zn atoms diffusion rate is considered faster than Mg atoms due to the difference in the atom size, whereby it diffuses in the aluminum matrix and produces a solid solution or intermetallic compounds [25]. Despite this, the particle size distribution mainly affects the powder properties, affecting the sinterability of the prepared alloys. Liu et al. [26] found that the optimum sintering density was achieved within a particle size for the Al powder nearly ~100 μm.

Figure 4(a-e) shows the SEM micrographs of the Al alloys with and without $MgZn_2$ addition; it was found that the $MgZn_2$ was mainly distributed at the Al particles' boundaries along with few particles were formed at the intragranular of Al particles. The SEM also shows that the sintering precipitates have formed at both center and boundaries of grains, as shown in Figure 4d. The elemental analysis was conducted by EDX to determine the composition of the area scanning and found that the composition of Mg and Zn varied according to the added contents. Besides that, the presence of these precipitates (marked with magnified scanned area in Figure 4f) could be seen clearly as the content of $MgZn_2$ increased. The second phase on the grain boundary impedes the grain boundary movement and prevents grain growth [27, 28]. In consequence, the Al grains refined with the increased $MgZn_2$ content.

Figure 5 shows the XRD patterns of the Al samples with and without $MgZn_2$ addition. It can be seen that the bare sample is composed of the α-Al phase, while with the addition of $MgZn_2$, there are three phases were obtained; α-Al phase, $Al_5Mg_{11}Zn_4$, and $AlMg_4Zn_{11}$. The intermetallic compounds $Al_5Mg_{11}Zn_4$ and $AlMg_4Zn_{11}$ were formed with different volume fractions, and their related XRD peaks were increases as the $MgZn_2$ increased. The main reason for the intermetallic formation is that with increasing the amount of $MgZn_2$ addition, the Mg and Zn atoms will be diffused at a higher rate. However, due to the Zn atoms

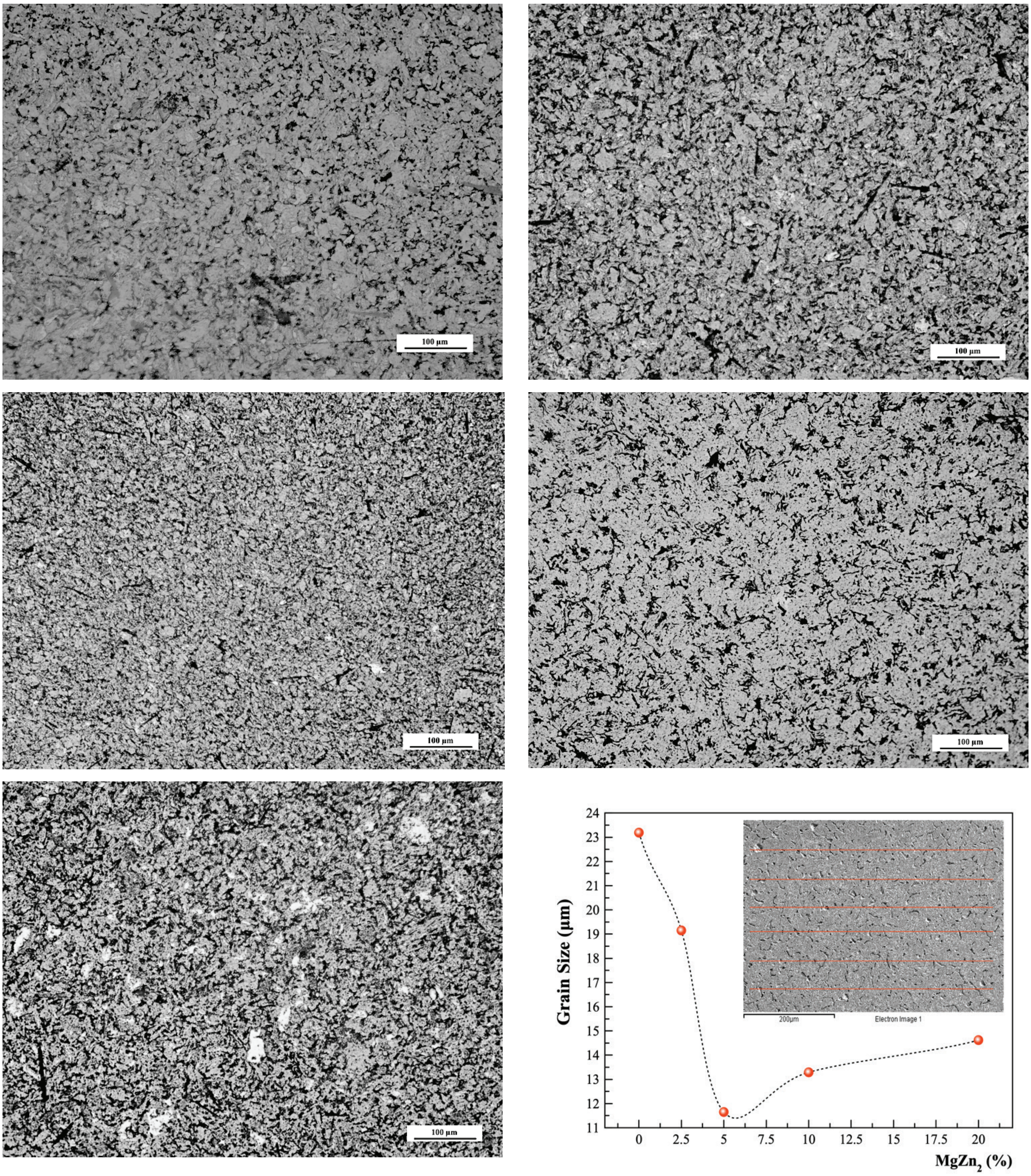

Figure 3. Optical micrographs of (a) Al, (b) Al +2.5% $MgZn_2$, (c) Al +5% $MgZn_2$, (d) Al +10% $MgZn_2$, (e) Al +20% $MgZn_2$, and (f) grain size measurement.

diffusion ability limitation [28], the Zn atoms particulate near the sintered necks and distort the Al matrix. Moreover, during the transformation of the sintered necks to form grain boundaries, the $MgZn_2$ particles are situated near the grain boundaries, which results in double-confirming the microstructure presence in Figure 4.

Effect of $MgZn_2$ content on microhardness of Al alloys

Figure 6 shows the variation of the microhardness values corresponding to the amount of $MgZn_2$ addition. It can be seen that the hardness of the Al samples was increased drastically as the $MgZn_2$ was added. The highest hardness was obtained from the Al sample with 5% of $MgZn_2$, achieving

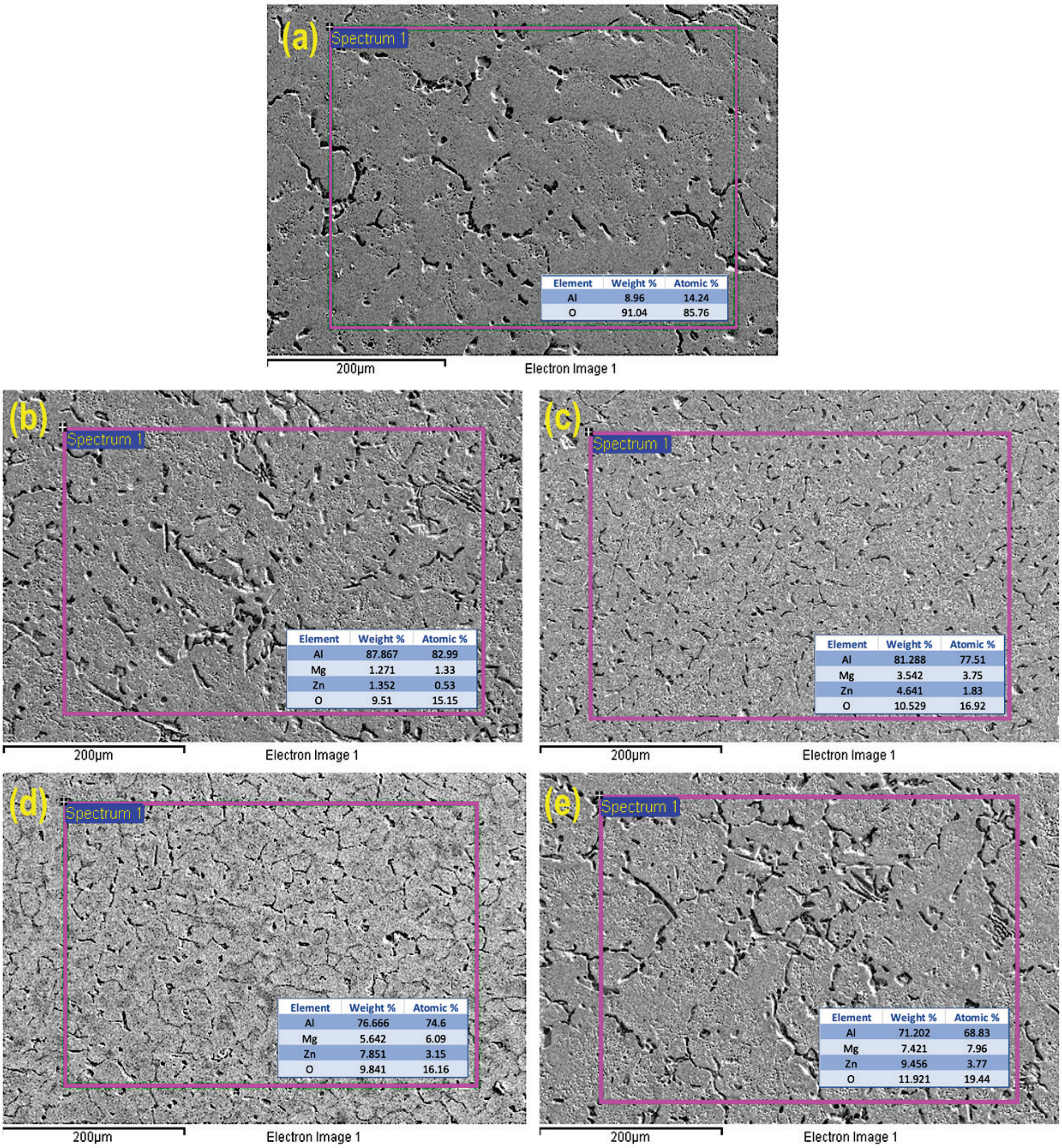

Figure 4. SEM surface morphology and EDS analysis of (a) Al, (b) Al +2.5% $MgZn_2$, (c) Al +5% $MgZn_2$, (d) Al +10% $MgZn_2$, (e) Al +20% $MgZn_2$ and (f) magnified precipitates formation.

a hardness of 112.4 HV. The hardness improvement may be attributed to the strength hardening as well as the presence of the precipitates, which it hinders the movement of dislocations and thus increases the hardness [29]. As a result of porosity and grain size reduction associated with the existence of intermetallic compounds, the mechanical properties in terms of hardness improved. However, the hardness decrement for the 10% and 20% samples may result as a consequence of the increment in the size of precipitates formed in the structure (oversaturation).

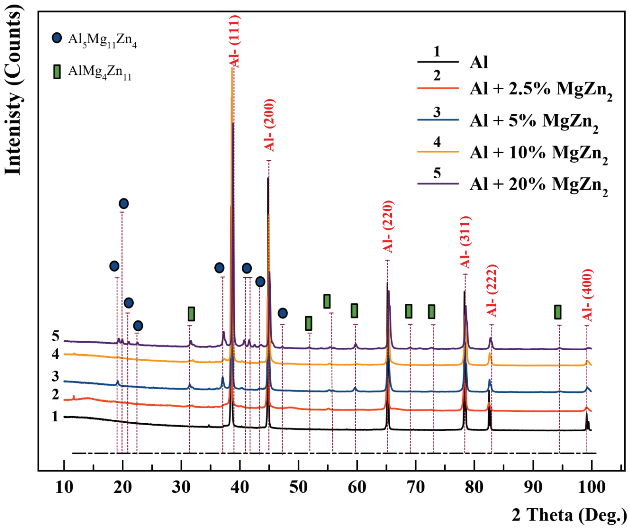

Figure 5. XRD diffraction patterns of Al with different $MgZn_2$ contents.

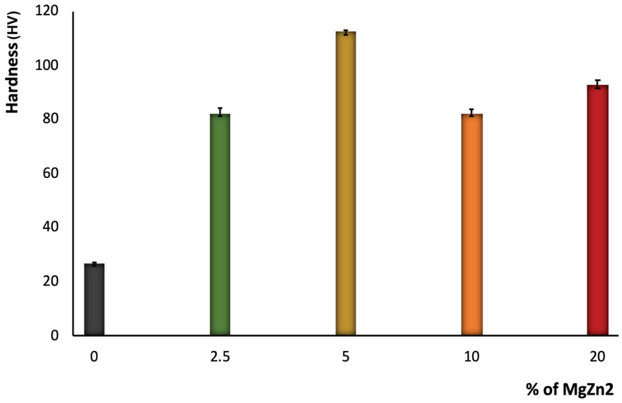

Figure 6. Microhardness of Al with different $MgZn_2$ contents.

CONCLUSION

This study investigated the effect of $MgZn_2$ additions to the Al alloy prepared by powder metallurgy. It can be concluded that as the $MgZn_2$ was added, the intermetallic compounds were formed in the matrix of Al alloys along with decreases in the grain size that achieved the smallest grain size with a 5% addition. Furthermore, the relative density of the Al powder metallurgy tends to increase as the $MgZn_2$ addition increased with obtaining the highest relative density of 95.1% at a 5% addition of $MgZn_2$. The porosity of the sintered samples achieved the lowest volume fraction with a 5% addition of $MgZn_2$, and thus the highest value of hardness was obtained.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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