

MANUFACTURING AND CHARACTERIZATION OF Al-xMg-xMgO COMPOSITES USING STIR CASTING PROCESS

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Abstract

In this work, the Al-xMg-MgO composites were fabricated via stir casting method. The different amounts of Mg (1, 3 and 5 wt%) and MgO (0.5, 1.0 and 1.5 wt%) were added to the aluminum matrix, and the composites were casted at various temperatures of 700, 800 and 900 °C. The effects of the casting temperature (°) and the Mg (wt%) and MgO (wt%) ratios on the microstructure, physical and mechanical properties of the composites were investigated. The scanning electron microscope with electron-dispersive spectrum, density (g/cm^3), porosity (%), hardness (HR-15T) and compression (MPa) test analyses were conducted on the composites. The results were also analyzed with the Taguchi experiment design method with ANOVA. The properties of the composites changed depending on the process parameters and ratios of Mg element and MgO

particles. The minimum density and porosity contents were obtained as 2.62 g/cm^3 and 0.6%, respectively. The increase in the casting temperature contributed to the wettability and so the properties of the samples to some extent. The additions of Mg and MgO improved the hardness (72.8 HR-15T) and compression strength (646.4 MPa) of the composites. It can be said that the main strengthening mechanisms of the Al-xMg-xMgO composites for this study were the solid solution and dispersion strengthening mechanisms.

Keywords: aluminum, composite, MgO, Taguchi, ANOVA, AMCs

Introduction

Rapid development of technology and industry, modern production and manufacturing systems increased the need for new and improved materials. One of these new and improved materials is composite materials which are a structural material that consists of two or more combined constituents. The composite materials can be classified according to the geometry of the reinforcement as flake, particulate and fibers and according to the type of matrix as metal, polymer and ceramic matrix composites.¹

Metal matrix composites (MMCs) have great attention due to their excellent dimensional stability, poor expansion coefficient, high hardness value and high specific strength as well as their low cost.² MMCs can be produced with solid- and liquid-state processes. The liquid-state process which is one of the most important composite production methods is very attractive in terms of being simple, inexpensive and a rapid production technique. The technique is generally classified into six categories: squeeze casting, compo-casting, spray deposition, pressure infiltration, in situ processing and stir casting.³ However, a significant disadvantage of these methods is the poor wettability of ceramic particles by liquid phase.⁴

In MMCs, aluminum and its alloys are most commonly used matrix materials due to high specific strength, low density, high thermal conductivity, high toughness, superior corrosion resistance and good machinability.⁵ Aluminum alloys reinforced with particles are known as aluminum matrix composites (AMCs). Due to their superior properties, AMCs have replaced with single-structured materials. AMCs have the potential to be applied in areas where low weight and strength are needed together, such as automotive, aircraft and marine industries, due to their properties such as low density, high hardness, high thermal and electrical conductivities and good corrosion and wear resistances.

The addition of hard and strong ceramic particles into aluminum alloys has emerged to create a material with adaptive properties. Most of the ceramic materials, e.g., CNTs, TiC, SiC, B₄C and Al₂O₃, are generally used to reinforce matrix materials.⁶ Excellent properties of these ceramic materials such as high compressive strength and hardness, wear resistance and refractoriness make them convenient to use as a reinforcement material in MMCs.

Ceramic materials have much high properties such as compressive strength, hardness and thermal stability. The mechanical properties of A356/SiC composites produced by casting method improved with the addition of nano-SiC.⁷ Ugur et al.⁸ investigated the effects of the Al₂O₃ on the mechanical and microstructure of A356 alloy. They declared that the optimum size and ratio of the reinforcement were 79 nm and 0.5 wt%, respectively, and the mechanical properties of composites were advanced with the addition of the reinforcement particles. AlSi₅Cu₃-TiB₂ composites were produced using different fabrication methods and under various processing temperatures.⁹ It is observed that the mechanical properties of the composites were improved under given conditions. The Al-Al₂O₃-Al₃Ni hybrid composites were fabricated using stir casting method.¹⁰ The ultimate tensile strength and hardness of the hybrid composites enhanced significantly owing to the reinforcements and homogenous distribution of the particles.

Magnesium oxide (MgO), which has a melting point of about 2800 °C, is a refractory material with good properties such as high thermal shock resistivity, poor thermal conductivity, high compression strength, superior thermodynamically stable, hardness (910 HV) and density (3.58 g/cm³).¹¹ The microstructure, hardness and compression properties of A356.1 reinforced with different volume fractions of nano-MgO and produced via powder method are studied.¹² Authors claimed that the hardness and compressive strength of samples increased with the addition of MgO, the sintering temperature improved the strength, and the density of composites increased with the increase in temperature. The A356.1-MgO composites are produced with stir casting method, and hardness and wear properties of the composites are investigated.¹³ They

declared that the wear and hardness of composites are advanced by adding nano-MgO particles with the ratio of 2.0 wt%. The A356-MgO composites are produced with stir casting and powder metallurgy methods.¹⁴ The authors reported that the addition of MgO into the matrix contributed to improving the mechanical properties of the composites, and homogeneous distribution of the reinforcements and higher mechanical properties are obtained with casting method. The hardness and wear resistance of Al-MgO composites increased with the increase in the volume fraction of MgO particles.¹⁵

The alloying elements such as Si, Gd and Mg can be added to the matrix to improve the properties of the matrix.¹⁶ The effect of Mg addition on mechanical and microstructure properties of Al-xMg-10Al₂O₃ composites was investigated by authors.¹⁷ They claimed that by increasing the Mg content up to 15% by weight, the crystallite size decreased, the lattice strains increased and microhardness increased to 230 HV.

Despite the presence of MgO-containing composites in the literature, there has been no detailed study on the production and analysis of MgO reinforcement-containing composites produced with different process parameters, as well as Mg element. However, none of the studies published to date regarding Al matrix composites with MgO particles have considered the effects of Mg addition together with MgO ratios and various casting temperatures within a systematic process. Thus, in this study, we have produced the Al-Mg-MgO composites via stir casting technique with different casting temperatures and ratios both Mg and MgO. In order to optimize the effects of process parameters on the properties of the composites, the Taguchi design and ANOVA were also adopted.

Materials and Methods

The highly pure Al (99.95%) and Mg (99.95%) metals and magnesium oxide (MgO; from Nanografi Nano Tech. Com.) particles were used to prepare Al-Mg/MgO_p composites. MgO with high melting point (2800 °C), compressive strength, hardness and also excellent thermodynamic stability is an appropriate choice for

Table 1. Chemical Composition of Aluminum (wt%)

Cu	Fe	Mg	Mn	Si	Zn	Other	Al
0.005	0.015	0.001	0.005	0.020	0.001	0.002	Rem.

Table 2. Chemical Composition of Magnesium (wt%)

Cu	Fe	Al	Mn	Si	Zn	Other	Mg
0.005	0.005	0.010	0.010	0.050	0.010	0.009	Rem.

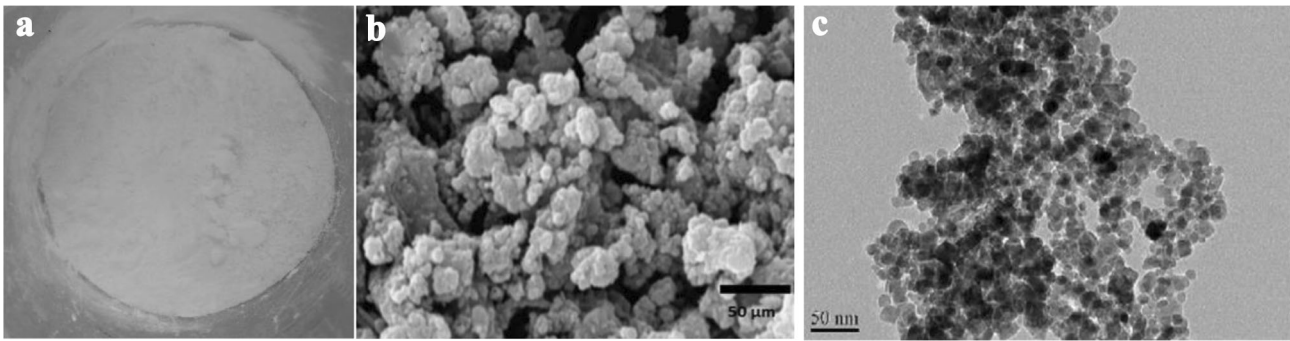


Figure 1. (a) Macroscopic, (b) SEM and (c) TEM images of MgO particles.

Table 3. The Levels and Factors

Level	Factors		
	Casting temperature (°C)	Mg (wt%)	MgO (wt%)
1	700	1	0.5
2	800	3	1.0
3	900	5	1.5

reinforcement. Mg was added due to effects both solid solution and to increase to wettability characteristic of MgO particles. The chemical compositions of the materials are given in Tables 1 and 2. The MgO powders have a purity of 99.80% and the average size of 40 μm. The macroscopic, SEM and TEM images of the MgO particles which have a circular shape are shown in Figure 1.

In this study, the Taguchi experimental design method was established to optimize fabrication condition and mechanical properties of the composites. Table 3 represents the levels and factors of design of experiments (DOE) which are used to produce the samples according to the mentioned factors and their levels. The factors are the casting temperature (°C), Mg ratio (wt%) and MgO ratio (wt%), and their levels are interfered into the Taguchi method in MINITAB program to get the experimental run layout. A total of nine samples were produced according to the parameters given in Table 3.

The design of experiment (DOE) is a powerful statistical technique introduced by Fisher.¹⁸ The DOE is used to design the experimental run layout, to investigate the effect of level change in the process parameters on the output performance. The input and output variables in the approach are casting temperature (°), Mg (wt%) ratio, MgO (wt%) ratio, hardness (HR-15T), compression strength (MPa), density (g/cm³) and porosity (%) for this study. It is known that any change in the input parameters affects the output functional performance. It is important to know that all factors do not effect on the performance in the same manner. The aim of a carefully planned DOE is to find the

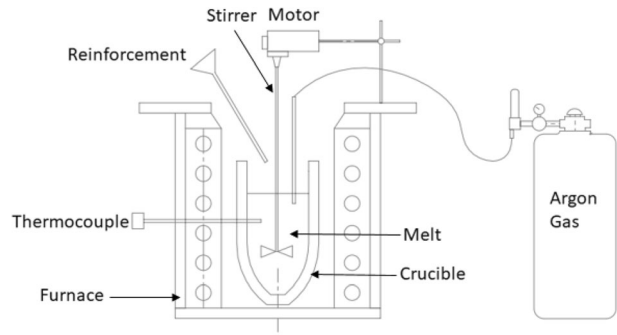


Figure 2. Typical stir casting experimental setup.

effect of process parameters on the output product and also to find which of the selected parameters has the greatest effect on the output performance and then to determine the best set level for these parameters to obtain a high-quality performance products. The level combination of optimum casting factors can be determined by examination of the signal-to-noise (*S/N*) ratio for each experimental run. The level of importance of the casting factors is determined by using ANOVA. The Taguchi method which was used especially for product development in 1980 and afterward is one of new studies. Experimental designs are made easier by using linear graphs and orthogonal array in the Taguchi method. Taguchi has developed an approach using the orthogonal array (OA) systems, which decreases the experiment variance significantly to an optimum number. The OA offers well-distributed factor levels to give a minimum experimental run.¹⁷

The Al and Mg ingots were cut to fit in a small SiC crucible (with 1 kg capacity), and Al was melted in electrical resistance furnace using a graphite crucible, equipped with a mechanical stirring system and inert gas injection instrument. The typical setup of stir casting method is shown in Figure 2. For each casting, the desired amounts of Mg metal (1, 3 and 5 wt%) and MgO (0.5, 1.0 and 1.5 wt%) were added to the molten alloy at 700, 800 and 900 °C, respectively. The MgO particles were pre-heated at 300 °C for 1 hour in order to increase the wettability. The particles were wrapped to aluminum foil to prevent oxidation.

Besides, the use of highly pure argon gas (99.99%) was started with the closure of the furnace cover to prevent oxidation. The molten alloy was stirred with a rod at rate of 300–350 rpm for about 5 min, to ensure complete mixing. The stirring speed was performed according to the result of the literature.¹⁹ It is well known that the increase in the stirrer time and speed leads to the air entrainment and so the oxygen content and oxide formation rise which increase the porosity and deteriorate the mechanical properties of the composites. Degassing and cleaning were conducted by using tablets degasal enviro DM20 and aluflux enviro. After stirring and cleaning off the dross, the composites were poured into a steel mold pre-heated up to 200 °C. The mold was prepared according to ASTM standard.²⁰ At the final stage, the extra Mg (10 wt%) was added to the melt to compensate the Mg loss.

For metallographic analysis, the samples were firstly ground with SiC paper and then polished with diamond paste. After sanding and polishing, the samples were chemically etched in Keller's reagent (1 vol% HF, 1.5 vol% HCl, 2.5 vol% HNO₃ and 95 vol% distilled water) for 30 s. Microstructures and EDS analyses were performed with a scanning electron microscope (ZEISS EVO 50). The theoretical and bulk (measured) densities of the samples were calculated by mixture law and Archimedes' principles using Eqns. 1 and 2, respectively.

$$\rho_t = \rho_{Al} \times m_{Al} + \rho_{Mg} \times m_{Mg} + \rho_{MgO} \times m_{MgO}. \quad \text{Eqn. 1}$$

Where ρ_t is t theoretical density of the composites, ρ_{Al} , ρ_{Mg} and ρ_{MgO} are the densities of the Al, Mg and MgO, respectively, and m_{Al} , m_{Mg} and m_{MgO} are the weights of the Al, Mg and MgO, respectively.

$$\rho_b = \frac{m_1}{m_1 - m_2} \times \rho_w \quad \text{Eqn. 2}$$

where ρ_b is the bulk density, m_1 and m_2 are the measured weights of the specimens in air and in distilled water, respectively, and ρ_w is the water density, respectively. Porosity percentage of the samples was determined with Eqn. 3.

$$\text{Porosity(\%)} = \left(\frac{\rho_t - \rho_b}{\rho_b} \right) \times 100 \quad \text{Eqn. 3}$$

where ρ_t is the theoretical density of the composites and ρ_b is the bulk density of the composites. Hardness and compression tests were conducted on the specimens to determine the mechanical properties. Hardness tests were carried out by using Matsuzawa dxt-3 universal hardness tester. The hardness values of the composites were 265 measured with the Rockwell 15T hardness method according to ASTM E18-15 standards and the results were obtained by the averaging of the ten reading.²¹ Compression test samples were prepared according to ASTM E9-09 standards.²² The compression test was carried out on a computer-controlled Shimadzu AGX

universal test device with a 300-kN capacity at a constant cross-head speed of 1 mm/min and at room temperature, and the results were obtained by averaging the three measurements.

Results and Discussion

In this study, a series of experiments subsequently were conducted on samples and stir casting method was adopted to produce the composites. The Taguchi approach gives an orthogonal array (3³) L9, and this array was selected based on three parameters with three levels as given in Table 4.

Density and Porosity

Table 5 shows the density values of the composites. The bulk density of composites which were obtained from the average of the three test specimens of each group reduced with the increase in the casting temperature. The decrease can be attributed to air entrapment or enforcement agglomeration by casting of the composites well above the melting point. It is well known that casting temperature

Table 4. L9 Taguchi Orthogonal Array Design

Code	Experiment no.	Temperature (°C)	Mg (wt%)	MgO (wt%)
A1	1	700	1	0.5
A2	2	700	3	1
A3	3	700	5	1.5
B1	4	800	1	1
B2	5	800	3	1.5
B3	6	800	5	0.5
C1	7	900	1	1.5
C2	8	900	3	0.5
C3	9	900	5	1

Table 5. The Bulk and Theoretical Densities of the Composites

Code	Bulk density (g/cm ³)	Theoretical density (g/cm ³)	Porosity (%)
A1	2.68	2.70	0.60
A2	2.65	2.68	1.35
A3	2.63	2.67	1.62
B1	2.68	2.70	0.62
B2	2.62	2.69	2.55
B3	2.63	2.66	1.18
C1	2.67	2.71	1.33
C2	2.64	2.68	1.37
C3	2.62	2.66	1.78

plays an important role in rising the wettability of particles and the mechanical properties of the composites. The minimum and maximum densities were obtained at B2 and C3 coded samples and A1 and B1 codes samples as 2.62 g/cm³ and 2.68 g/cm³, respectively. The Mg and MgO have a density of 1.74 g/cm³ and 3.58 g/cm³. According to the mixture law, when higher-density MgO particle added in lower-density pure Al (2.70 g/cm³), the theoretical density of the composites increased. However, by adding low-density Mg to samples, the density of resultant composite reduced. It is well known that by increasing the content of MgO reinforcements, the density of composites increases and decreases by increasing the content of Mg metal. The minimum and maximum porosity contents were observed at A1 and B2 coded samples as 0.60 and 2.55%, respectively. The porosity contents of the composites generally affect by the casting process. This can be attributed to the effect of low wettability and agglomeration at high content of reinforcement led to the formation of porosity.¹⁴ Additionally, the surface area of reinforcement particles in the molten matrix plays an importance role at pore nucleation at ceramic particulate sites.²³ Because of the lower particle size, higher contact surface forms between the molten matrix and the reinforcement particles. The difference in thermal expansion coefficient mismatch between matrix and reinforcement can also be formed defects such as porosity and dislocations around the particles.²⁴ On the other hand, during the stirring process, a quantity of gas can be penetrated to the molten composite and this can cause porosity formation.

Mechanical Properties

All hardness values are presented in Figure 3. It is obvious that the additions of Mg and MgO directly increased the hardness values for all temperature ranges. The highest hardness value was obtained as 72.8 at A3 coded sample which contains 5 wt% Mg and 1.5 wt% MgO. This may be due to solid solution of Mg element, a hard reinforcement particle of MgO and also its role in enhancement of the density of dislocations and prohibition of Al grain growth.²⁵ It is clear that that hardness values are directly proportional to the increase of the Mg metal and MgO particles in AMCs samples. Additionally, the hardness of composite materials increases with the increased proportion of hard particles and the homogenous distribution of these particles. A lot of studies revealed that the increase in the reinforcement content increased the hardness of the composite material.^{26,27}

Figure 4 illustrates the compression test results of the composites. The analysis of the values highlighted that the highest compression strength was obtained at B2 coded samples (800 °C, Mg 3 wt%, MgO 0.5 wt%) as 646 MPa although B2 coded sample has the maximum porosity content. It can be said that the casting temperature and the

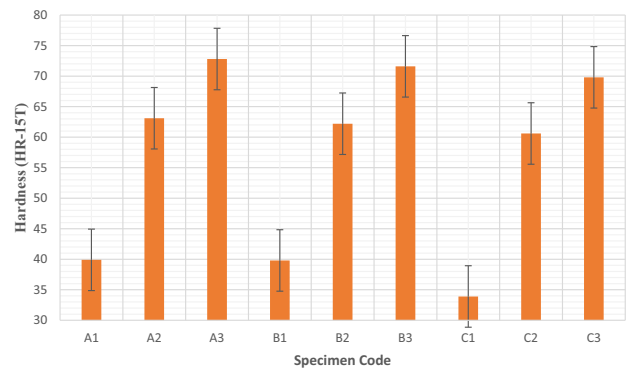


Figure 3. Hardness test results of the composites.

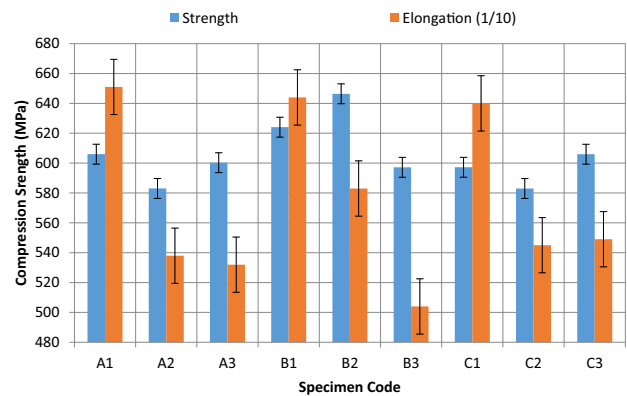


Figure 4. Compression test results of the composites.

additions of Mg and MgO affected the mechanical properties of MMCs. Improving the mechanical properties of the produced composites is due to the following phenomena: (i) elastic properties of the matrix and reinforcement, (ii) various thermal expansion coefficients of the matrix and reinforcement, (iii) mass fraction of MgO and (iv) solid solution of Mg.²⁸ The particles act as a barrier against dislocation movement; furthermore, they can cause new dislocations.²⁹ On the other hand, as a primary alloying element for aluminum alloys, magnesium creates point defects within the lattice and act as a barrier to dislocation motion.³⁰ It is found that there are a better wettability between the matrix and the particle and an increase in the homogeneous distribution of the particles when the Mg ratio is increased. Magnesium is known to strengthening element for aluminum alloys through solute solution strengthening.³¹ Mg element was used to make both alloying and to increase the wettability and hence improve to mechanical behavior.³² It is well known that the wettability of ceramic surfaces by metals and alloys is affected by some parameters such as time, temperature, composition, alloying elements, and volume fraction of the oxides. Also, the interface between the matrix and reinforcement plays a crucial role in determining the properties of AMCs. It is well known that increasing the Mg content increases the wetting.³³ The different thermal expansion coefficients of matrix ($21.50\text{--}25 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$) and MgO

($14.45 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$) result in stress concentration at the matrix and reinforcement materials interface and therefore high density of dislocations and so the strength of the composite increases accordingly.¹² It is clearly stated in the literature that the addition of alloying element, especially Mg element added to aluminum and its alloys, is an important method used to increase the wettability of ceramic strengtheners. Mg reacts with the oxygen formed on the particle surface and wettability increases and agglomeration tendency decreases.³⁴ It is declared that in addition to the wettability, pouring condition, stirring speed and solidification rate also play an important role in the distribution of reinforcement particles in the matrix in the stir casting method.³⁵

Microstructure

The microstructure images and EDS spectrums of the composites are depicted in Figure 5. The specimens were selected to the obtained some properties of the composites such as minimum porosity, minimum hardness, maximum elongation and maximum strength. When the microstructure pictures are examined, the presence of MgO particles in the matrix is clearly seen. The bright regions existing in the figure represent the MgO particles, while the dark regions are matrix materials. The EDS results are presented in Figure 5e–f which prove the Al, Mg and MgO particles.

It can be said that the homogeneous distribution of the particles generally formed in the microstructure of the composites. However, the agglomerations were also observed in some regions of a few composites, because particles have tendency for agglomeration, which can deteriorate the homogeneous distribution of reinforcement particles and mechanical properties of MMCs.³⁶ Because when size of the particles reduces or the ratio of the particles increases the wettability and dispersion of the reinforcement particles become difficult.³⁷ It is known that better mechanical properties are obtained by providing homogeneous distribution of reinforcement particles.²³ Therefore, when microstructures of the samples are examined, the homogeneous dispersion of the MgO particles confirms this information. However, the rate of porosity in this sample is relatively higher compared with that in other samples. It is well known that the porosity is a casting defect and negatively affects the mechanical properties of MMCs.³⁸ The increase in hardness and compression strength with increasing temperature may be due to the positive effect of temperature on increasing the wettability and strengthening metal–ceramic reinforcement binds at interfaces. Additionally, the coating of the reinforcement with a material or element such as nickel, cobalt and copper could be improved the wettability of reinforcement by the matrix.³⁹ It is also well known that the MgO has a higher wettability characteristic.

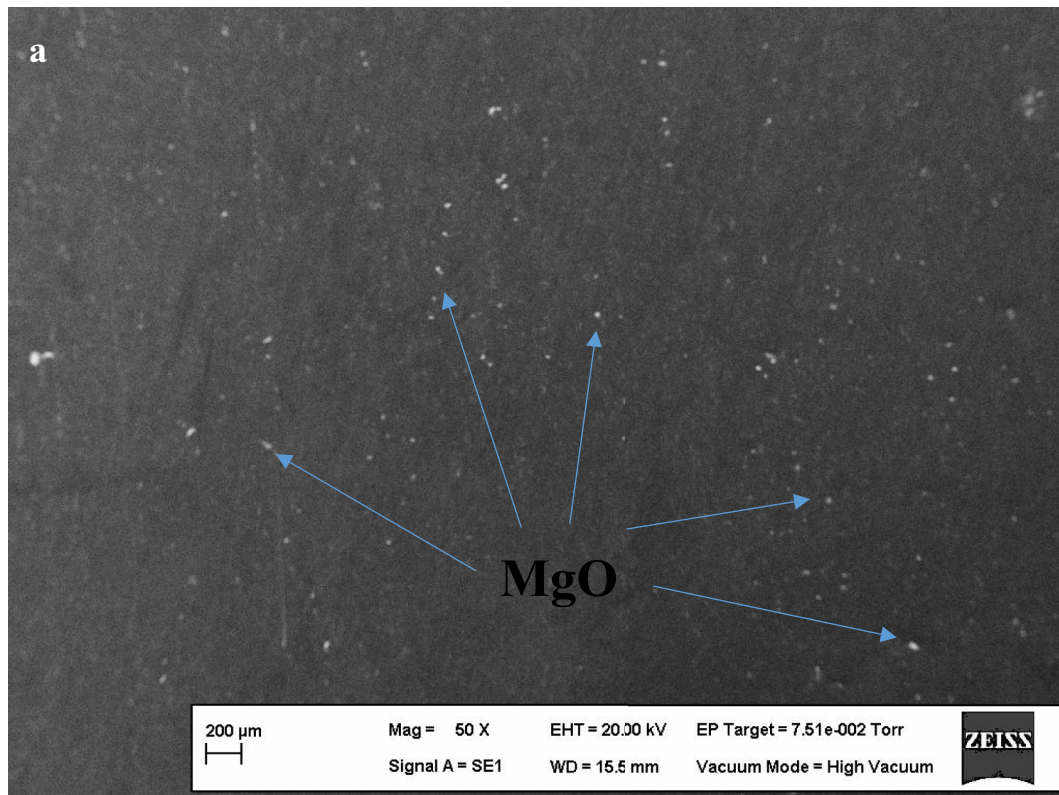


Figure 5. SEM images of samples (a) A1, (b) A2, (c) C1, (d) C2 (e) B2, EDS spectrums of samples (f) A1 and (g) A2.

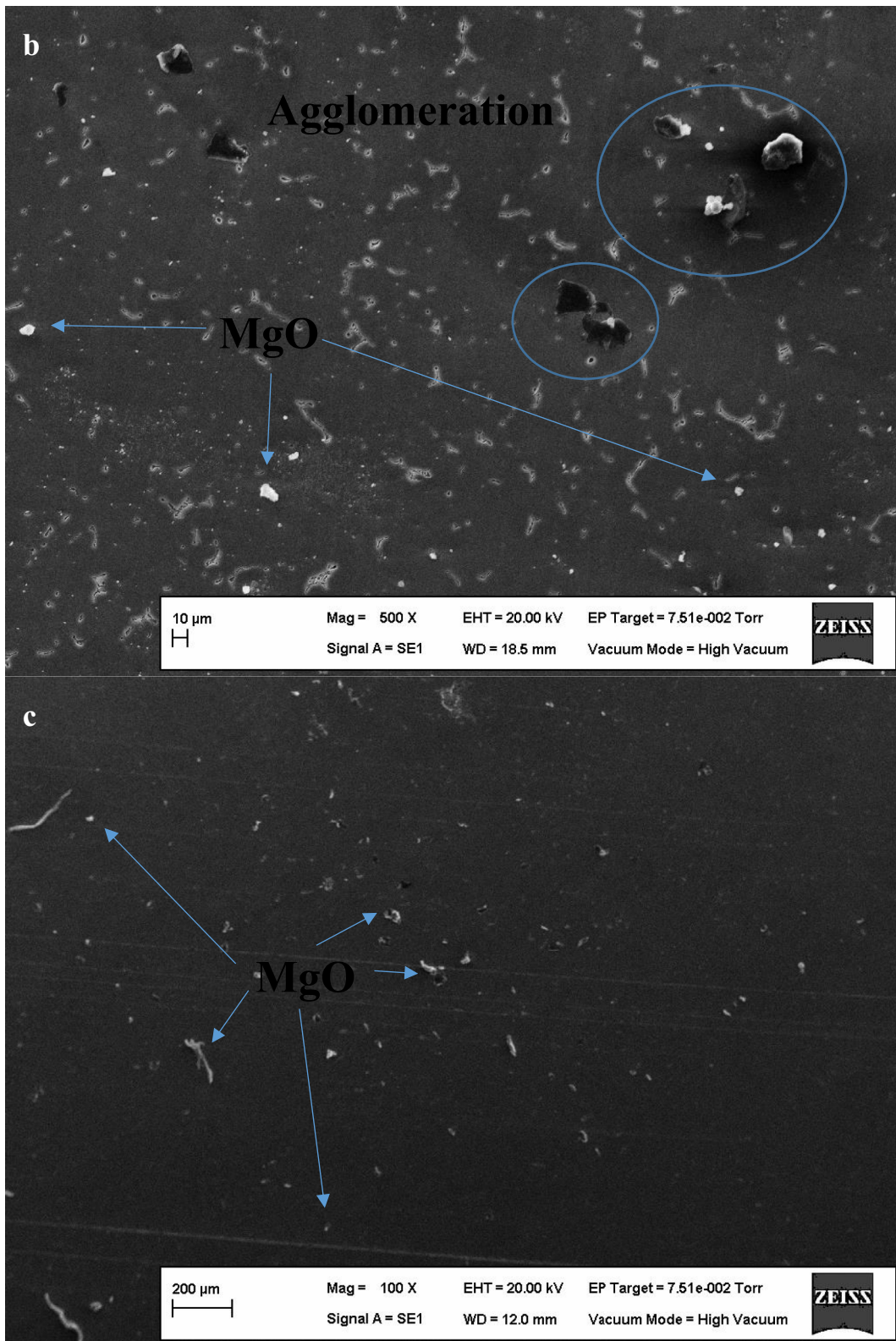


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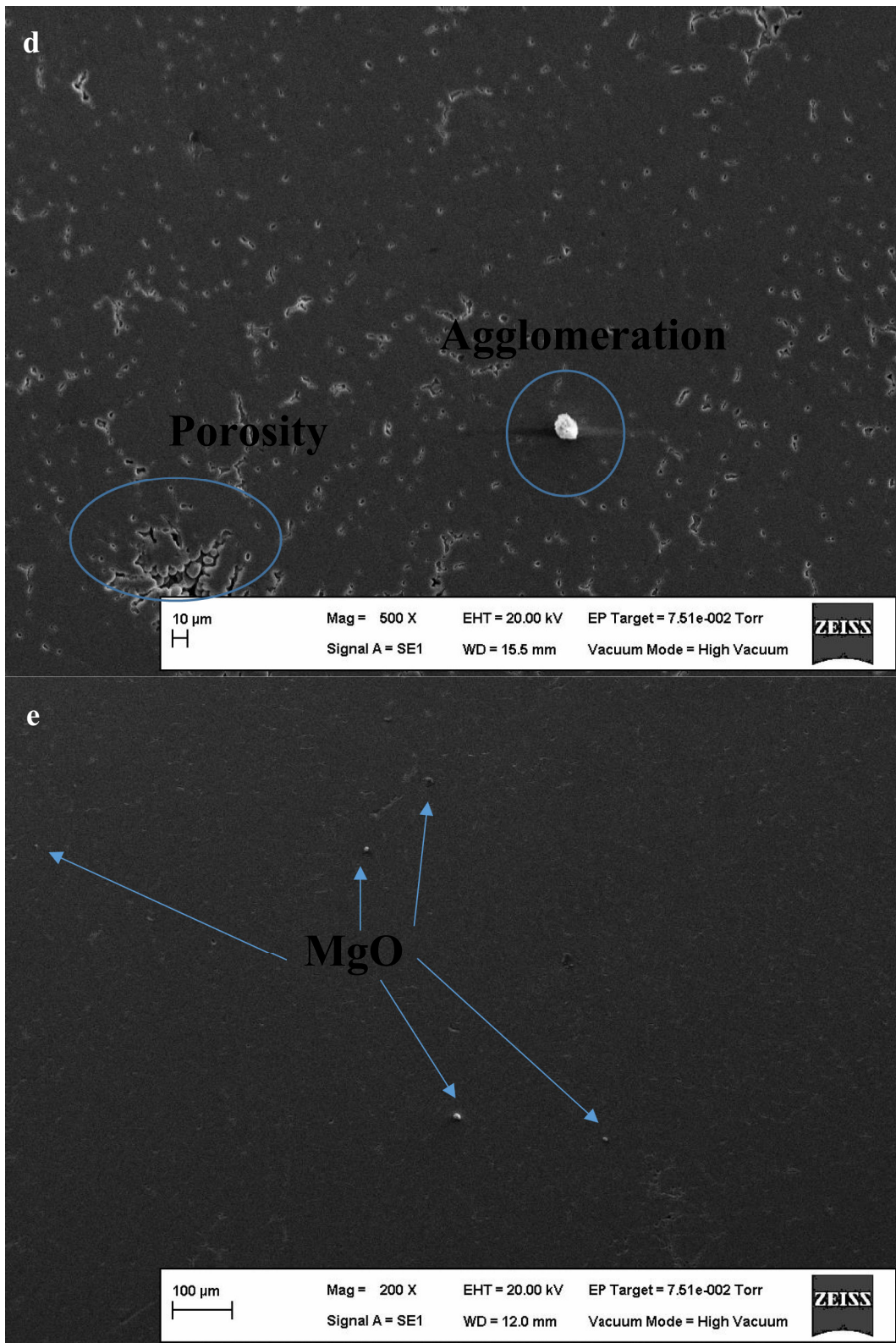


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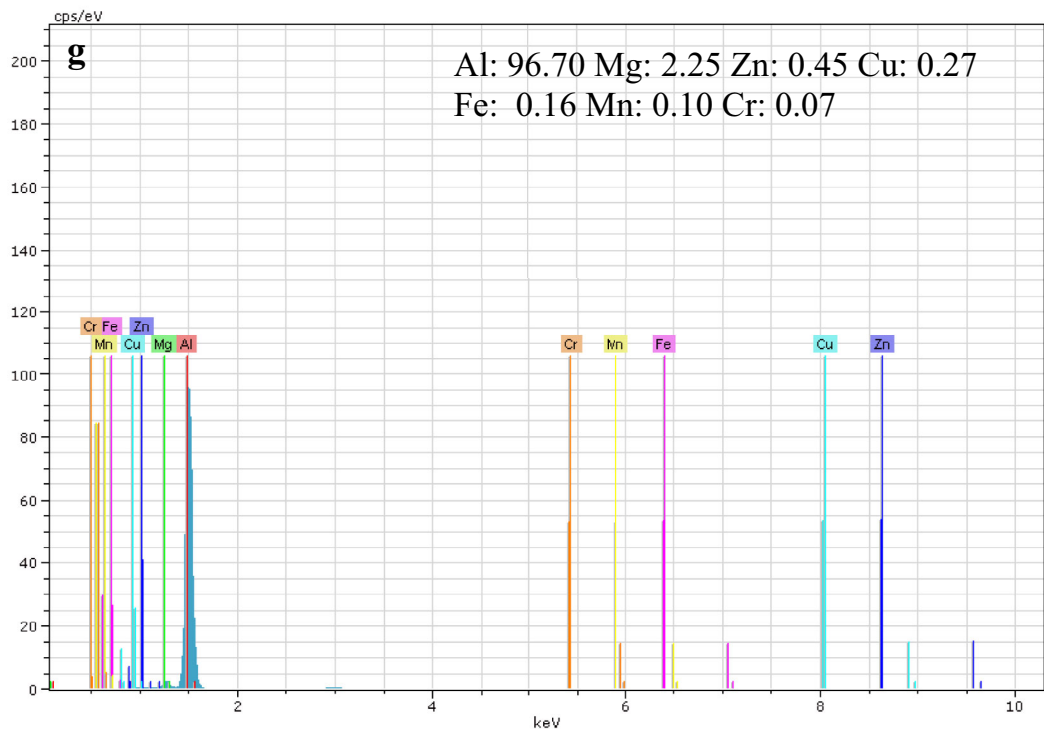
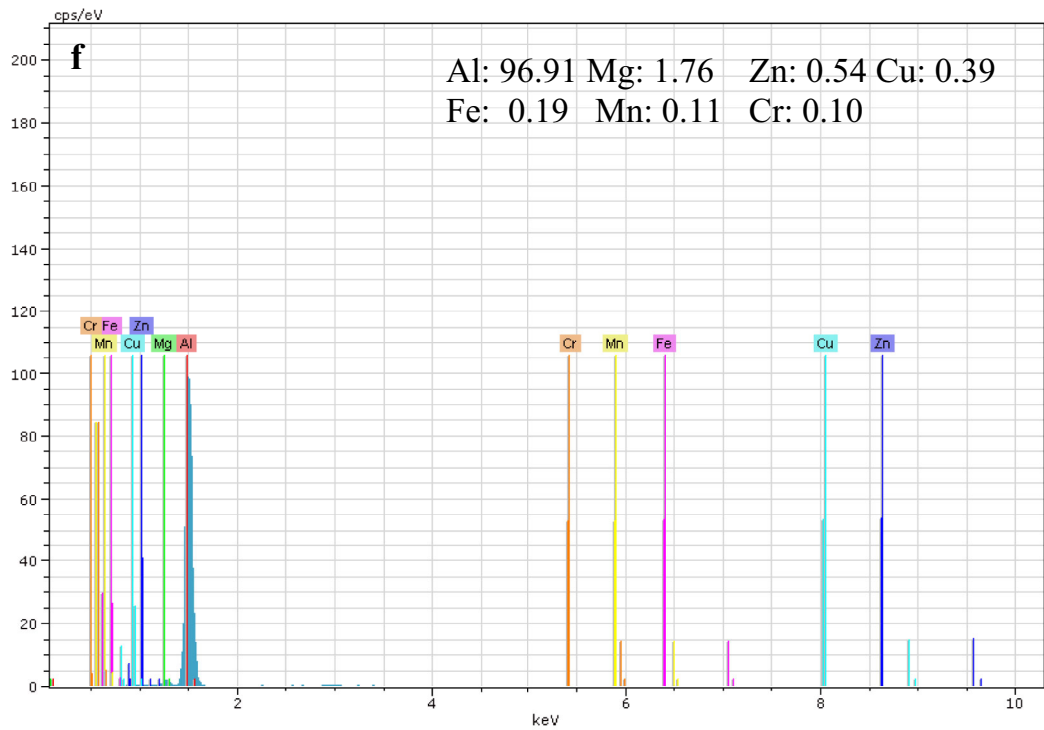


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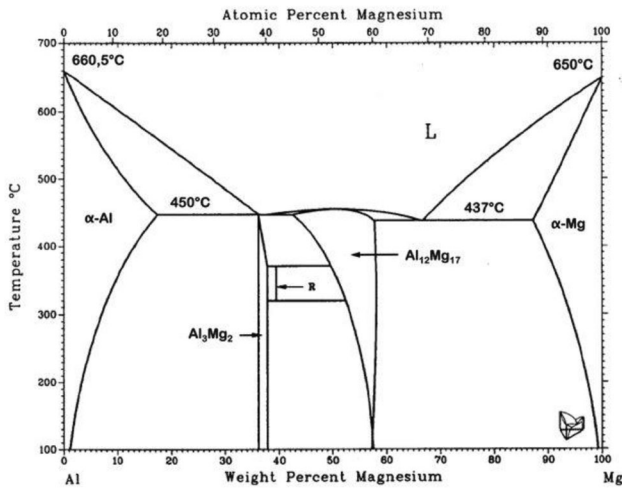


Figure 6. Al–Mg binary phase diagram.

The binary Al–Mg phase diagram is shown in Figure 6. The Al–Mg alloys that are a wrought commercial alloy are known as a high-strength alloy. According to Al–Mg binary phase diagram, the Al–Mg (1, 3, 5) alloys contain primary α -Al phase and eutectic structure. It is well known that the solubility of Mg in Al is theoretically 17.4 wt% at 450 °C. The addition of more Mg (> 6 wt%) to Al improves its castability and strength, and the presence of brittle intermetallic reduces its toughness, corrosion resistivity and workability. The β -Al₃Mg₂ intermetallic compound generally forms when Mg content is higher than 6 wt%. In this work, the matrix materials consist of the α -Al phase and eutectic structure which show the Mg element is mainly dissolved into the matrix. This is due to the lower concentrations of Mg in the alloy system. It is known that the α -solid solution is most commonly observed in the microstructures of Al alloys with Mg.⁴⁰ Furthermore, the Mg-rich particles was not observed in the microstructure. It is well known that the theoretical solid solubility of Mg in the Al matrix is 17.4%.⁴¹ The authors noted that the compounds of Mg₂Al₃ are not formed in the Al–Mg (6–8 wt%) alloy.⁴² Also, the formation of some porous structures in the alloys can be attributed to a higher Mg content.

It is declared that the wettability plays an important role in the distribution of reinforcement particles in the matrix. Additionally, the process parameters such as casting temperature, stirring speed and time, solidification rate and mold temperature have importance effects on the distribution of reinforcements in the matrix, fabricated by stir casting.³⁵ It can be concluded that composites with 3 and 1.5 wt% Mg and MgO contents, respectively, cast at 800 °C represent maximum compression strength and they can be selected as optimum samples. It is well known that in the MMCs, incorporating fine particles into the matrix represents higher tendency toward agglomeration. Therefore, optimum particle size, amount of reinforcement and

Table 6. S/N ratios for Compression Strength of the Composites

Parameters	Level 1	Level 2	Level 3	Delta	Rank
Casting temperature (°C)	55.51	55.88	55.50	0.38	1
Mg (wt%)	55.69	55.61	55.58	0.11	3
MgO (wt%)	55.49	55.62	55.77	0.28	2

Table 7. S/N Ratios for Hardness Values of the Composites

Parameter	Level 1	Level 2	Level 3	Delta	Rank
Casting temperature (°C)	35.09	34.99	34.38	0.71	2
Mg (wt%)	31.54	35.84	37.07	5.53	1
MgO (wt%)	34.92	34.96	34.58	0.38	3

Table 8. Mean Response Values for Density of the Composites

Parameter	Level 1	Level 2	Level 3	Delta	Rank
Casting temperature (°C)	2.653	2.643	2.643	0.010	3
Mg (wt%)	2.677	2.637	2.627	0.050	1
MgO (wt%)	2.650	2.650	2.640	0.010	2

Table 9. Mean Response Values for Porosity of the Composites

Parameter	Level 1	Level 2	Level 3	Delta	Rank
Casting temperature (°C)	1.190	1.450	1.493	0.303	3
Mg (wt%)	0.850	1.757	1.527	0.907	1
MgO (wt%)	1.050	1.250	1.833	0.783	2

processing parameters, precise optimization of reinforcement content, casting temperature, stirring velocity, etc., should be determined for each technique and matrix. It is hard to control all parameters. For example,

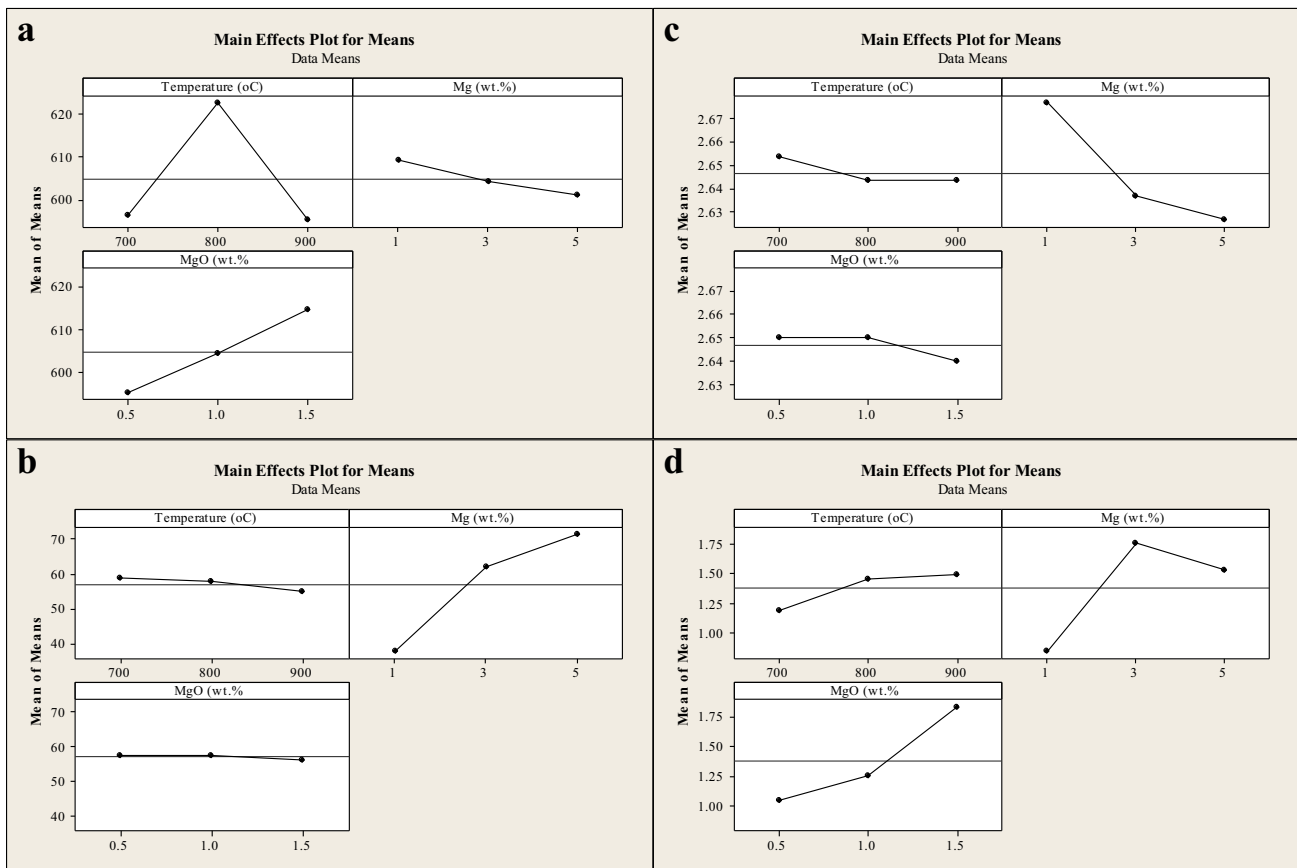


Figure 7. Main effects plot for (a) compression strength, (b) hardness, (c) density, (d) porosity.

- (i) Temperature plays an important role in increasing the wettability of particles.
- (ii) Temperature can cause air absorption and so increase porosity and decrease the mechanical properties.
- (iii) The high rate of reinforcement can increase the agglomeration.

Design of Experiment

Tables 6, 7, 8 and 9 show the signal-to-noise ratios and mean effects of the composites for compression strength, hardness, density and porosity results, respectively. Additionally, the mean effect plots of composites are shown in Figure 7. The S/N ratio for each experiment was calculated according to “the larger is the better” formula for compression strength and hardness and “the smaller is the better formula” for density and porosity, respectively, as given in Eqns. 4 and 5. Because the higher compressive strength means that the composite exhibits the higher mechanical performance.

$$\frac{S}{N} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \left(\frac{1}{y^2} \right) \right) \quad \text{Eqn. 4}$$

$$\frac{S}{N} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n (y_i)^2 \right) \quad \text{Eqn. 5}$$

For all properties given in the tables, the minimum delta values were obtained which show the results have a high accuracy and compatible. A higher rank for a factor is a higher influence of the parameter on the mechanical performance of specimens. This is due to the same change in controllable factor causing a higher effect on the output characteristic being measured than the other factors. The following rank values show the contribution of parameters on the properties of the composites. The Mg ratio has a higher rank value for hardness, density and porosity, while casting temperature has for compression strength. Accordingly, the casting temperature has a greater effect on the response characteristic followed by MgO and Mg for compression test results. The reason for this can be explained by the wettability. It is well known that the high casting temperature is an important parameter to increase the wettability of particles and stirring contributes to uniform dispersion of reinforcement particles in the molten material.⁶

Figure 7 demonstrates that the properties of the composites change with the variation of process parameters. The compression strength and hardness are essential test

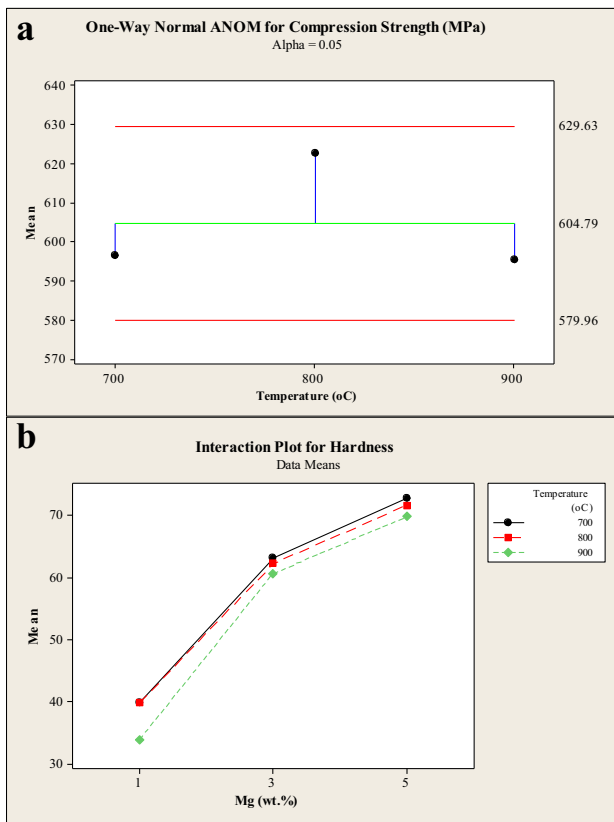


Figure 8. ANOM plot for (a) compression strength and interaction plot for (b) hardness.

techniques for evaluation of the mechanical properties of the materials. The setting of the optimum level of casting factors is the level that shows the maximum value of signal-to-noise ratio. The addition rate of Mg and MgO and casting temperature present different results for the composites. These parameters effect in different scales the properties of the composites. Among three different characteristics, the optimum values were observed as the casting temperature of 800 °C, Mg addition of 1 wt% and MgO addition of 1.5 wt%, for the compression strength. The maximum value for hardness and the minimum density were obtained with the Mg addition of 5 wt%. As expected, the minimum porosity was obtained with the minimum temperature and minimum ratios of Mg and MgO to main effects plot. The higher casting temperature, agglomeration of reinforcements and a higher ratio of reinforcement cause to air entrapment and so the increase in the porosity

content.¹⁴ In Figure 8, one-way normal ANOM plot for the compression strength and the interaction plot for hardness were demonstrated. The effect of the casting temperature on the compression strength of the composites can easily be seen in Figure 8a. The casting temperature of 800 °C is the optimum parameter for the compression strength. The curve shown in Figure 8b is parallel to each other and the change carries out linearly. This shows the hardness of the composites for the given all casting temperatures carried out to an increase in the hardness of the composites with the increasing Mg element. This can be attributed to solid solution strengthening mechanism of Mg element.²⁵ Solid solution mechanism is the attainment of an increase in matrix strength through the addition of different soluble elements. The distortion of atomic lattice inhibits dislocation movement. The difference between the atomic sizes increases the effects of solid solution hardening.

In Table 10, the statistical results of ANOVA are given for hardness, compression strength, density and porosity in detail. The correlation values of hardness, compression strength, density and porosity are 0.97, 0.45, 0.91 and 0.78, respectively. The correlation values of the hardness, density and porosity are quite high and acceptable level but it for compression strength is not appropriate. Although the experimental results are fairly well, the continece between the experimental and theoretical results is not good. This can be attributed the system, software or the difference of dataset. The degrees of freedom (DF) are the amount of information of the given dataset such as casting temperature, Mg and MgO ratio, respectively. The sums of squares (SS) and mean squares (MS) are the measures of variation for different components of the model. It is clear that the SS and MS values for the hardness and compression strength which have bigger dataset are higher compared with those for density and porosity. The *F*-statistic is simply a ratio of two variances. The variances are a measure of dispersion or how far the dataset are scattered from the mean. It is well known that the larger values represent greater dispersion. The minimum and maximum dispersions are observed at the compression strength and hardness values. The *p*-values show that the hardness and density results are more significant to comparison of the strength and porosity results. The minimum standard deviation (SD) and mean values of the one-way ANOVA are obtained with the minimum level at density and porosity results because of the used smaller data group. It is

Table 10. Statistical Results of ANOVA

	DF	SS	MS	F	P	SD	Mean
Hardness (HR-15T)	3	1710.47000	570.16000	24.750	0.0020	15.11	57.08
Compression strength (MPa)	3	651.30000	217.10000	0.430	0.7420	19.97	604.79
Density (g/cm ³)	3	0.00405	0.00135	9.000	0.0019	0.02	2.65
Porosity (%)	3	1.74530	0.58180	2.720	0.1550	0.59	1.38

concluded that the used data and the difference between the experimental results affect the statistical results.

Conclusions

In this work, Al- x Mg/MgO_p composites were produced with stir casting method. The Mg and MgO ratios in the composites were changed. The microstructure and mechanical properties of the composites were investigated by SEM, hardness, compression, density and porosity analysis. The following conclusions from this study can be drawn:

- The SEM analysis of the composites demonstrated a homogenous distribution of the reinforcement. The agglomeration of the particles in some region happened with a higher ratio of the particles.
- The addition ratios of MgO particles and Mg metal have a significant influence on microstructure and mechanical properties of MMCs. Therefore, the compression strength and hardness of the composites varied depending on the additions of reinforcement particle and Mg element.
- The maximum compression strength was obtained at B2 coded sample as 646.4 MPa. The optimum parameters for this composite are the casting temperature: 800 °C, Mg ratio: 3 wt% and MgO ratio: 1.5 wt%.
- The hardness of composites was enhanced by increasing the addition of Mg and MgO contents. The maximum hardness was observed at A3 coded sample as 73.8. The optimum parameters for this composite are the casting temperature: 700 °C, Mg ratio: 5 wt% and MgO ratio: 1.5 wt%.
- The minimum porosity content (0.6%) is obtained with the lower casting temperature but the minimum density (2.62 g/cm³) with the higher casting temperature.
- According to ANOVA model which is associated with the compression strength, casting temperature has a greatest role in casting process and followed by content of MgO and content of Mg, respectively. However, any variation in Mg element will affect the hardness, density and porosity values of the composites more.

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Author Contributions MY was involved in investigation, casting and writing. HIK was involved in investigation, casting, writing—

review and editing and co-supervision. NFY was involved in review and editing and supervision.

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