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| RESEARCH ARTICLE

Development of Composite Materials Using Magnesium Matrix with Variations in the Addition of Volume Fractions of Nano-Al_2O_3 Reinforcement Results of the Stir Casting Method

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| ABSTRACT
Magnesium matrix composites were developed as a form of material selection that can save fuel use due to excess magnesium, which has very low specific gravity and still has good mechanical properties. In this study, a magnesium matrix composite with nano-Al_2O_3 reinforcement was successfully fabricated using the stir casting method. When compared with magnesium monolithic, the addition of nano-Al_2O_3 particles of 0.05, 0.10, 0.15, 0.20, and 0.25 %Vf in magnesium composite casting was investigated to improve the mechanical properties of Mg/nano-Al_2O_3 composites. Magnesium composites with 0.20% Vf reinforcement were found to be the best composition of impact price, wear rate, density, and porosity. This is because the more reinforcement given, the more mechanical properties increase, but the agglomeration tendency of nano-Al_2O_3 particles is higher so that at a composition of 0.25 %Vf, there is a mechanism anomaly because the reinforcement carried out is less homogeneous. In addition to the number of amplifiers, the improvement of mechanical properties is influenced by the fabrication process, i.e. stir casting. This study uses chemical characterization of OES, EDS, and XRD, hard damage, impact, wear, density and porosity testing, and metallographic observations using OM and SEM.

| KEYWORDS

Magnesium Composite, nano-Al_2O_3, stir casting.

| ARTICLE INFORMATION

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1. Introduction

Indonesia is a country with population growth that has an increasing trend. This can be seen from the expansive population pyramid, which has a higher number of births than the number of deaths. This expansive population trend is the attraction of transportation-related industries, especially motor vehicles or automotive and aerospace, both abroad and domestically, to improve and develop their industries and products in Indonesia. This can be seen from the growth data of the four-wheeled market, which will increase sales in the country by 50 thousand in 2017. The Association of Indonesian Automotive Industries (Gaikindo) is confident that it will achieve the target of 1.1 million units of cars from all brands (Purnama, 2017). However, along with the increasing growth of the automotive market, so does the demand for economical use of energy/fuel sources that are difficult to renew. In addition, soaring crude oil prices and tighter controls on emissions to reduce environmental impact are fueling industries today to aggressively seek new and cutting-edge materials as alternatives to conventional materials. Soaring world crude oil prices and the use of fuels that have a difficult renewable source encourage studies related to the development of materials for transportation applications, especially automotive and aerospace, that can reduce energy and fuel consumption. One way that energy conservation in the automotive and aerospace fields is becoming a concern is the choice of light metals.

Magnesium is the lightest metal structural material. Magnesium has a specific gravity of 1.74 g/cm3, which is lighter than aluminum, which has a density of 2.7 g/cm3, and is close compared to plastic, which is 0.97-2.17 g/cm3 [Baldwin 2004].

Metal matrixed composites made from magnesium would provide an attractive alternative to aluminum metal matrixed composites. This is because, in addition to being the lightest metal structural material, magnesium matrix composites exhibit many advantages over monolithic magnesium or magnesium alloys, such as high elasticity modulus, high strength, creep resistance and superior wear at high temperatures. However, their ductility is reduced, which limits their wide application. The desired properties can be achieved by careful selection of the type and size of reinforcing particles. So based on this exposure, in this final project, the author tries to examine composite materials with a magnesium base matrix reinforced with nano-Al_2O_3 particles using the stir casting method as a development in improving mechanical properties of cutting-edge materials for automotive or aerospace application materials as well as reducing harmful emissions, fuel consumption and energy efficiency.

2. Method

Research Flow Chart

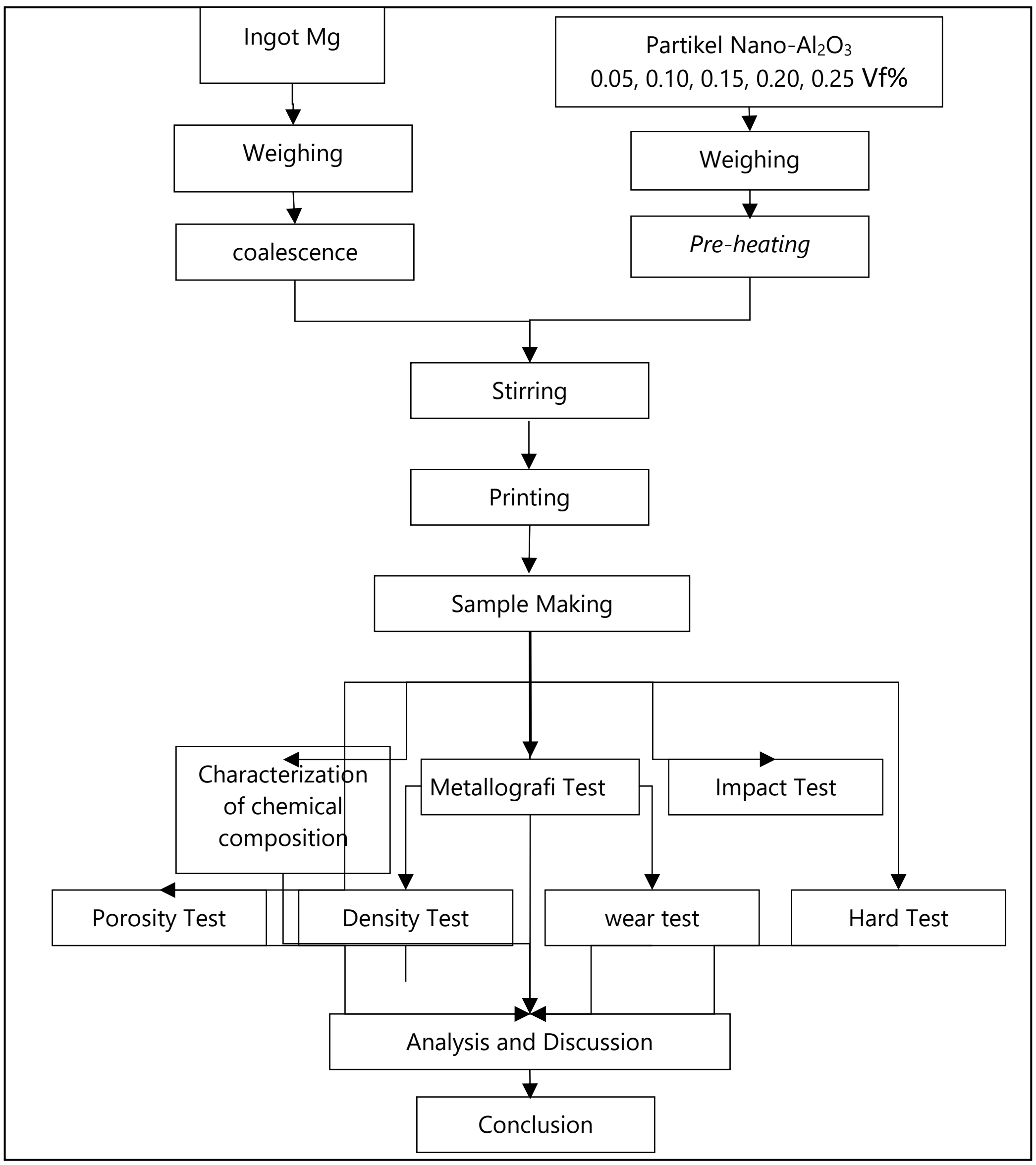

Figure 1 Research Flow Chart.

3. Results and Discussion

3.1 Analysis of Density and Porosity Test Results of Magnesium/nano-Al_2O_3 Composites with %Vf Variation of Nano-Al_2O_3 Reinforcement

Density and porosity tests were carried out to determine the effect of the casting process and the addition of nano-Al_2O_3 reinforcement on the difference in actual density and theoretical density of magnesium composites and porosity obtained by magnesium composites. The calculation of theoretical density is carried out by applying *the calculation of the Rule* of Mixture (ROM) and the calculation of actual density using the principle of Archimedes. The results of the test can be seen in Figure 4.6 and Figure 4.7.

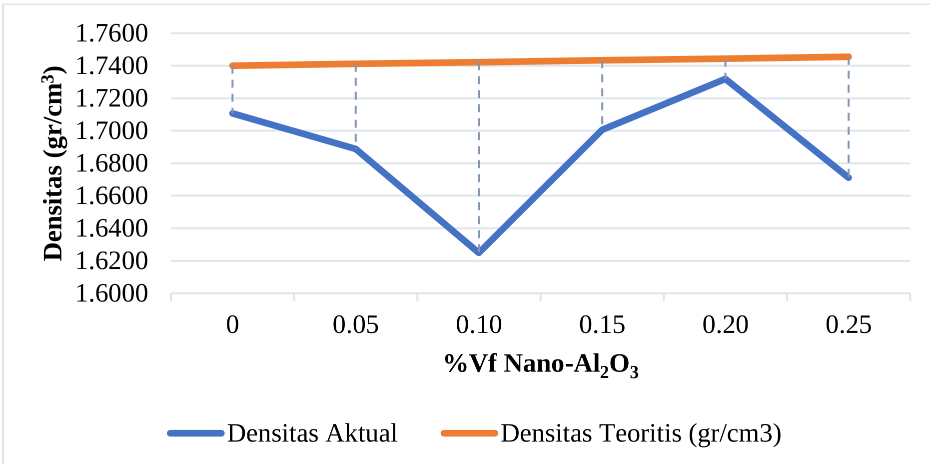

Figure 4. 1 Graph of Comparative Value of Actual Density with Theoretical Density of Nano-Al_2O_3 Reinforced Magnesium Composite with %Vf Variation of Nano-Al_2O_3 Reinforcement

From Figure 4.6 and Figure 4.7, it can be concluded that according to theory, the density produced by composite materials increases as the amount of nano-Al_2O_3 reinforcement given increases. This is due to the higher density of nano-Al_2O_3 (3.94 gr/cm3) compared to pure magnesium (1.74 gr/cm3) [Hassa et al., 2007; Hassan et al., 2008]. While the actual density is obtained at a lower level than the theoretical density. This is due to the porosity produced both from the poor casting process and the addition of the number of nano-Al_2O_3 reinforcement particles. The casting process is one of the largest porosity contributions due to the trapping of gases in the molten magnesium metal when it enters the mold due to turbulence from the pouring process. Porosity can also be seen from the resulting casting sample, namely the number of holes both on the surface and inside the magnesium composite sample. The resulting porosity will create empty space and will certainly reduce the density of the magnesium composite so that it does not match its theoretical density. In addition to the poor casting process, the addition of nano-Al_2O_3 reinforcing particles also plays a role in increasing the amount of porosity because the addition of reinforcing particles in the semi-solid state and proper stirring causes an increase in viscosity and a decrease in melt fluidity. Gas bubble trapping causes porosity to increase with an increase in the percentage of reinforcement volume (Aravindan et al., 2015). In addition, it is also due to the low wetability and agglomeration tendency in the number of nano-Al_2O_3 reinforcing particles that are getting higher (Raturi et al., 2017). Nanoparticles, as reinforcement, increase porosity due to the presence of interstitial cavities in the agglomeration pool (Yadav et al., 2017).

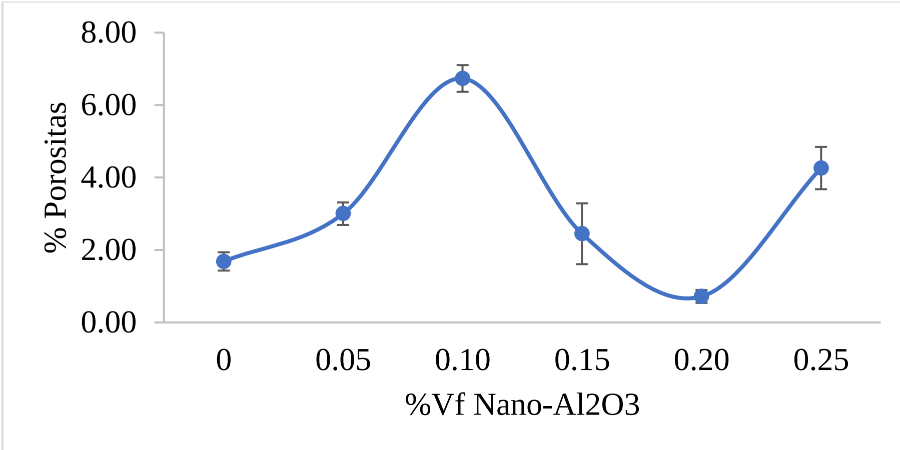

Figure 4. 2 Graph of Actual Porosity Amount in Magnesium and Nano-Al_2O_3 Reinforced Magnesium Composites with %Vf Variation of Nano-Al_2O_3 Amplifier

3.2 SEM-EDS-Mapping Analysis of Magnesium/nano-Al_2O_3 Composites with %Vf Variation of Nano-Al_2O_3 Reinforcement

Tests for SEM-EDS analysis were carried out on samples derived from magnesium without reinforcement and Mg/nano-Al_2O_3 composites that had optimum and minimum mechanical and physical properties values to be compared, namely in composites with %Vf nano-Al_2O_3 of 0.15%, 0.25%, and 0.05%. Shooting using SEM was carried out with two shots at 500x magnification and once at 1000x magnification, shown in figure 4.19, figure 4.20, figure 4.21, and figure 4.22, to clarify the topography to be observed. Then, EDS testing was carried out with the aim of determining the possibility of elements formed in the phase seen in this Mg/nano-Al2O3 composite, in reference to the results of the previously carried out element mapping.

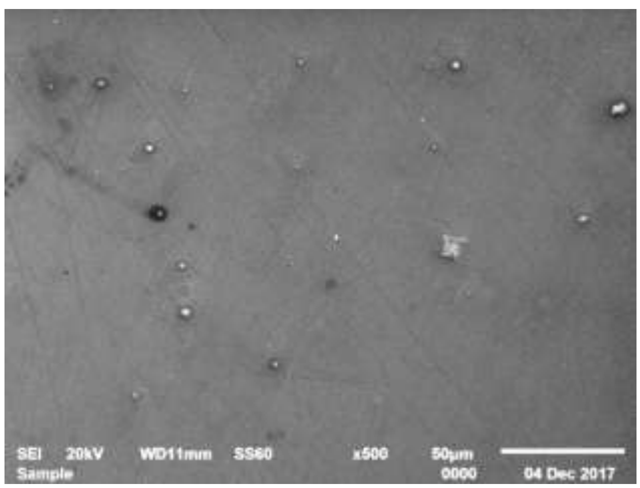

Figure 4. 3 Results of SEM Magnesium Without Reinforcement and Mg/Nano-Al2O3 Composite Using 500x Magnification.

When compared with nano-Al_2O_3-reinforced magnesium in Figures 4.18, 4.19, and 4.20, magnesium materials without reinforcement showed no collection of nano-Al_2O_3 reinforcing particles.

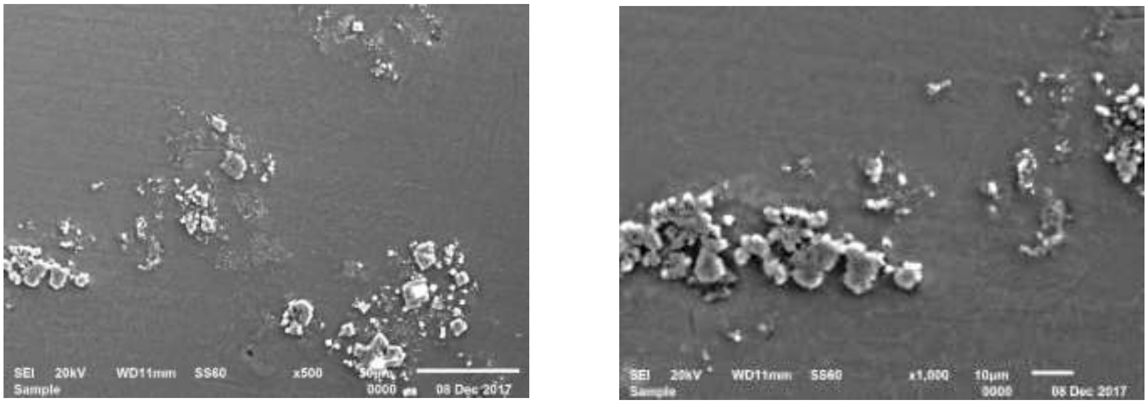

Figure 4. 4 Results of SEM Composite Mg/nano-Al_2O_3 with Amplifier of 0.05 %Vf Using 500x (left) and 1000x (right) magnifications.

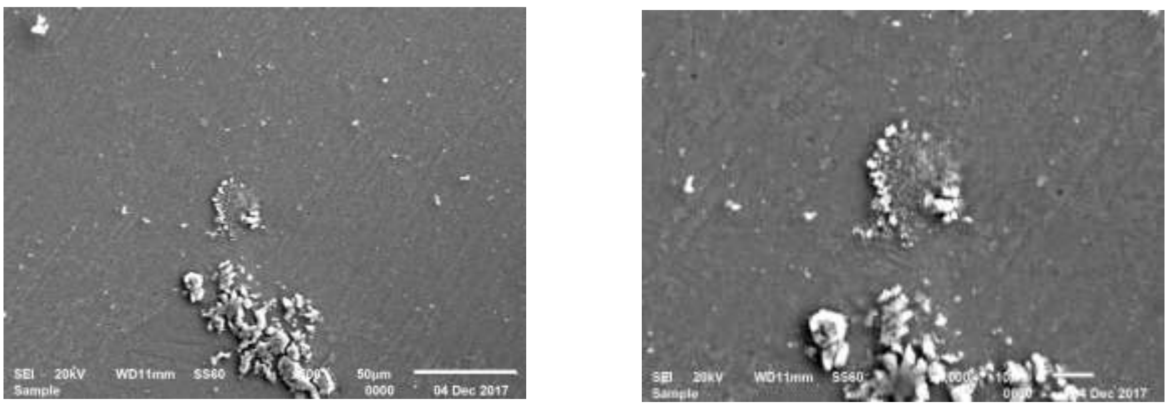

Figure 4. 5 Results of SEM Composite Mg/nano-Al_2O_3 with Amplifier as Much as 0.15 %Vf Using Magnification 500x (left) and 1000x (right).

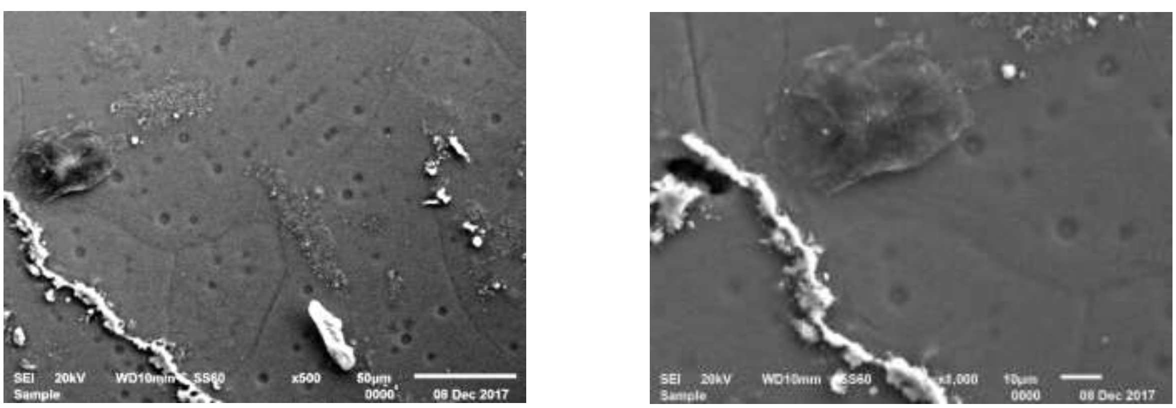

Figure 4. 6 Results of SEM Composite Mg/nano-Al_2O_3 with Amplifier of 0.25 %Vf Using 500x (left) and 1000x (right) magnification

This is in accordance with the previous research conducted by M. Gupta et al. in Figure 4.21. Meanwhile, the results of the Mg/nano-Al_2O_3 composite SEM in Figures 4.18, 4.19, and 4.20 all found white objects indicated as a collection of reinforcing particles and magnesium oxide reacted during casting. It is this collection of reinforcing particles that makes the improvement of mechanical properties not so significant. The phenomenon of collecting reinforcing particles is caused by poor methods and parameters of stirring and *pretreatment* of nano-Al_2O_3 reinforcing particles.

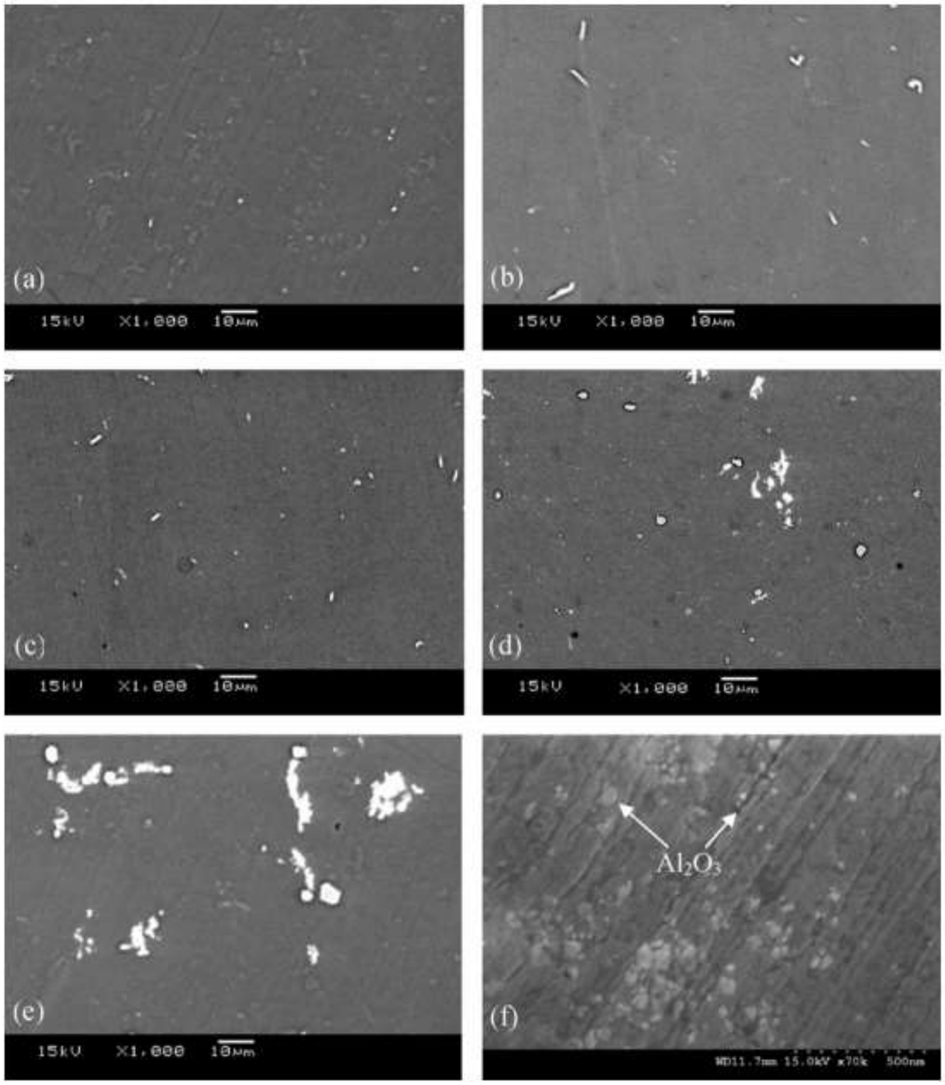

Figure 4. 7 SEM Results Show Second Phase Distribution and Reinforcement Particles on (a) AZ31, (b) AZ41, (c) AZ51, (d) AZ41-Al2O3 and (e) AZ51-Al2O3 Samples. (f) FESEM Results of Nano-Sized Alumina Distribution in AZ41-Al_2O_3 Samples (Hassan &; Gupta, 2007)

Figure 4.22 shows the results with 500x magnification on the entire sample with 4 arrows as a clue to the location to be carried out EDS. Before EDS is carried out, element mapping is carried out first to determine the distribution of elements at that location, which can be seen in Figure 4.23.

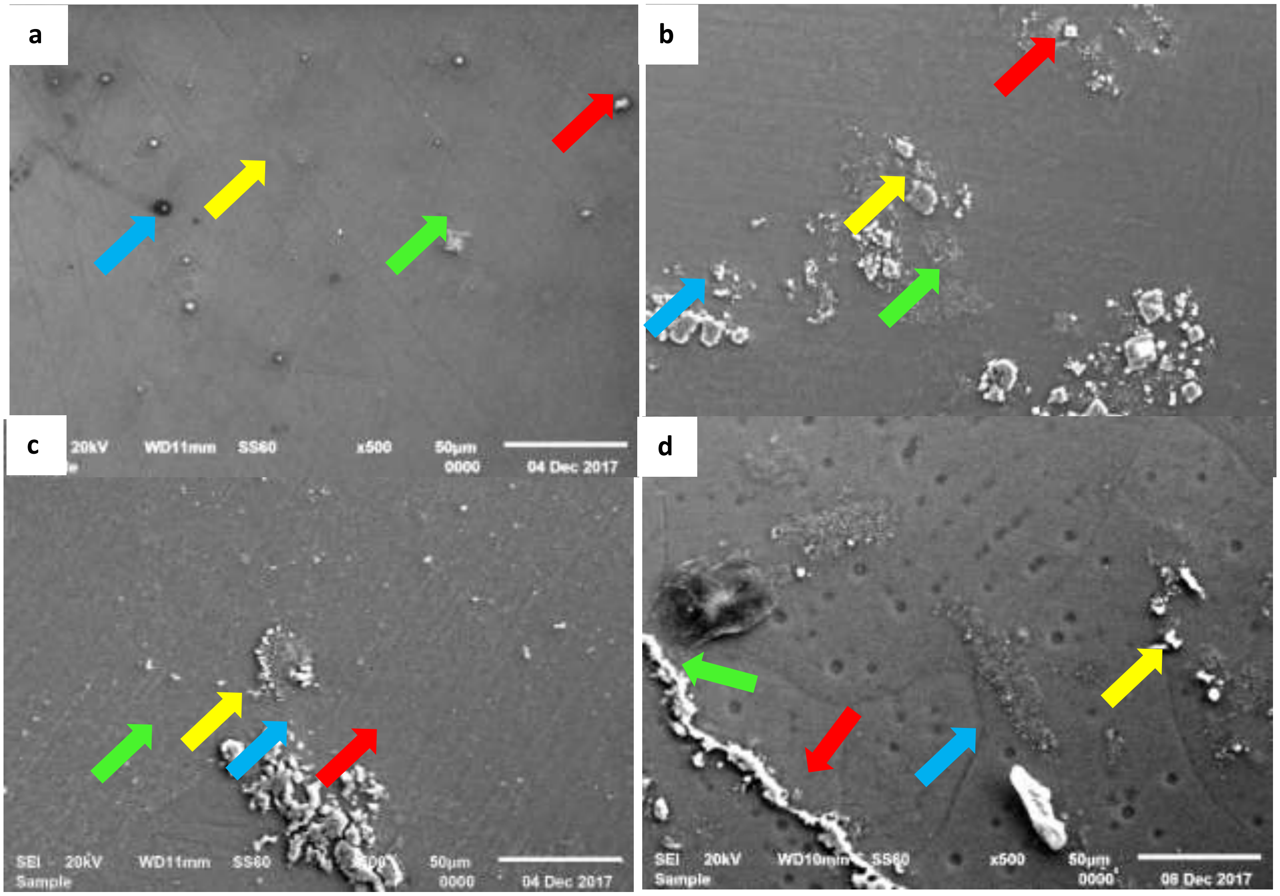

Figure 4. 8 SEM Results on (a) Magnesium Without Reinforcement and Mg/Nano-Al_2O_3 Composite with Amplification as Much as (b) 0.05 %Vf, (b) 0.15 %Vf, and 0.25 %Vf Using 500x Magnification

The results of the EDS test can be seen in Table 4.4 below. Based on the EDS results in all samples, almost the main elements were found, namely Mg, Al, O, and C. Mg, Al and O elements are predicted as a result of the formation of phases MgO, Al_2O_3, and Mg2Al2O4 derived from the reaction between nano-Al_2O_3 reinforcement particles with Magnesium based on reactions (4.1) and (4.2) (Lloyd, 1994) and as a reaction of molten magnesium with highly oxidative oxygen gas to form MgO.

$$3\ Mg + Al2O3 \leftrightarrow 3MgO + 2Al \tag{4.1}$$

$$3\ Mg + 4Al2O3 \leftrightarrow 3Mg\ Al2O4 + 2Al \tag{4.2}$$

While element C is predicted from inclusions derived from the fall of the crucibels used, namely graphite, the crucibels used fall out due to the unsuitable conditions of metal melting with crucibel properties that are alkaline, while molten magnesium tends to be acidic. The crucibel condition is also porous, allowing slag penetration from the magnesium fuse to enter the crucible and react to erode the crucibels and mix into the metal melt.

Table 1 EDS Results on Magnesium and Magnesium Composites Reinforced 0.05, 0.15, and 0.25%Vf Nano-Al_2O_3, 500x Magnification.

Material	Arrow	Element Content (wt.%)						Possible Phases
		Mg	To the	Or	Yes	Cr	C	
Mg	Blue	80.46	-	3.50	-	-	16.05	MgO
	Yellow	94.12	-	2.07	-	-	3.81	MgO
	Green	88.15	-	7.56	0.24	-	4.05	MgO
	Red	68.82	4.51	19.19	0.24	-	7.44	$MgO, Al_2O_3, MgAl_2O_4$
Mg/0.05 %Vf Nano-Al_2O_3	Blue	49.95	14.39	6.25	0.66	-	4.96	$MgO, Al_2O_3, MgAl_2O_4$
	Yellow	66.95	-	24.57	0.31	-	8.15	MgO
	Green	87.99	-	8.21	-	0.31	3.66	MgO
	Red	50.53	-	41.10	0.07	-	8.15	MgO
Mg/0.15 %Vf Nano-Al_2O_3	Blue	81.63	-	14.22	0.12	0.03	4.01	MgO
	Kuning	58.23	1.28	34.84	0.43	-	4.78	$MgO, Al_2O_3, MgAl_2O_4$
	Green	84.98	0.90	5.52	0.10	-	8.50	$MgO, Al_2O_3, MgAl_2O_4$
	Red	89.43	-	0.82	-	-	9.75	MgO
Mg/0.25 %Vf Nano-Al_2O_3	Blue	59.49	-	39.17	-	0.02	1.32	MgO
	Yellow	59.23	-	39.0	-	0.03	1.74	MgO
	Green	52.94	6.29	40.62	0.15	-	-	$MgO, Al_2O_3, MgAl_2O_4$
	Red	59.29	-	39.08	0.04	0.01	1.58	MgO

Based on Figure 4.23, the results of element mapping in the four samples show that the distribution of Al and O elements is only present in certain parts and not spread across the SEM observation surface. This confirms that the agglomeration phenomenon of nano-Al_2O_3 reinforcing particles occurs and supports the cause of the lack of effectiveness in improving the mechanical properties of Mg/nano-Al_2O_3 composites.

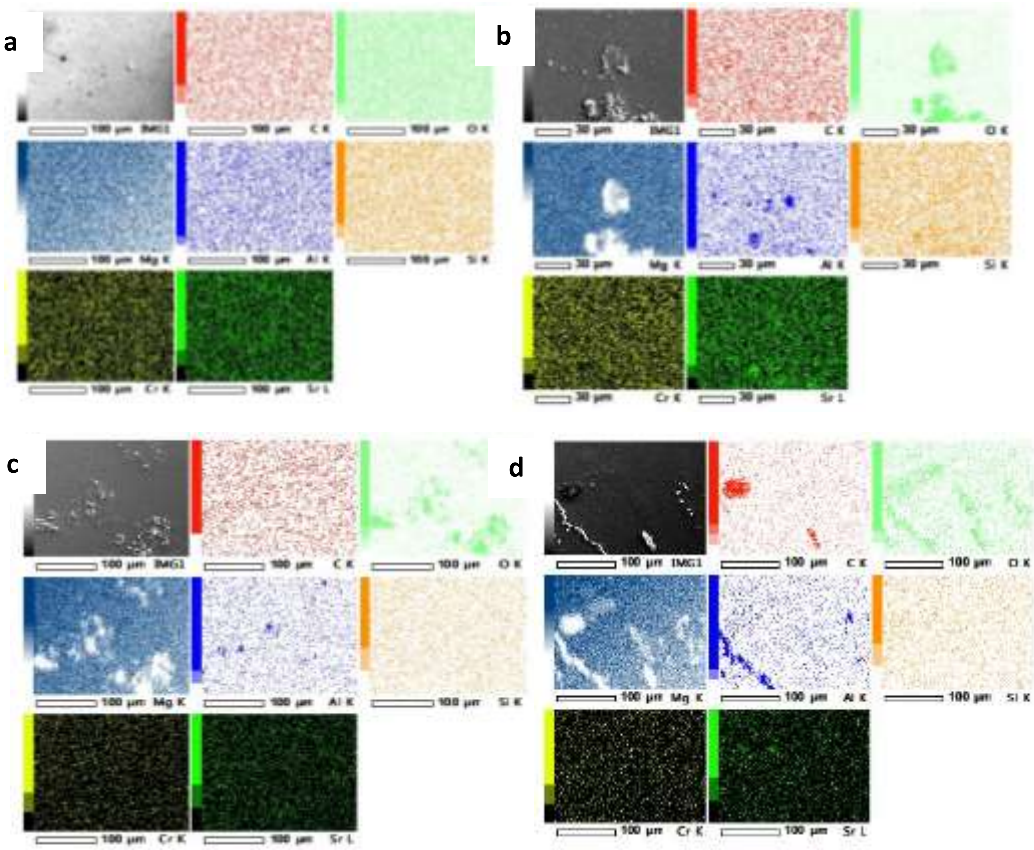

Figure 4. 9 Results of Element Mapping on (a) Magnesium Without Reinforcement and Mg/Nano-Al_2O_3 Composites with Amplifiers as Much as (b) 0.05 %Vf, (b) 0.15 %Vf, and 0.25 %Vf Using 500x Magnification

3.3 Analysis of XRD Test Results of Magnesium/nano-Al_2O_3 Composites with %Vf Variation of Nano-Al_2O_3 Reinforcement

XRD testing on Magnesium composites reinforced with nano-Al_2O_3 particles was carried out on samples with nano-Al_2O_3 particle composition of 0.15%Vf, where the sample had the highest tensile strength value. To process the data generated after testing, *X'Pert HighScore Plus* software is used to see the phases indicated to appear in the composite sample. Table 4.5 shows a list of detected phases along with the scores for each.

Tabel 4. 1 Identifikasi Senyawa pada Sampel Komposit Magnesium Berpenguat 0.15%Vf Nano-Al_2O_3

No.	Ref. Code	Score	Compound Name	Chemical Formula
1	98-016-6274	20	Magnesium Aluminium Oxide (0.25/0.5/1)	$MgAl_2O_4$
2	96-901-3272	27	Periclase	MgO
3	98-016-1061	1	Aluminium Oxide	Al_2O_3
4	98-005-3767	27	Magnesium	Mg

Based on the *score* figures in Table 4.5, it can be seen that the most compounds detected are the $MgAl_2O_4$ phase and periclase or MgO. This condition is in accordance with the previous analysis, where the phases $MgAl_2O_4$ and MgO will form a lot because these two compounds are stable compounds formed when reacting with Mg according to equations 2.1 and 2.2. In addition, the element Mg is very reactive and easily reacts with Oxygen to form MgO as a compound that is widely found. In addition, the persistence of the Al_2O_3 phase, even in small amounts, indicates that the distribution of reinforcing particles is not good and tends to collect in a certain area or agglomerate as previously predicted and described. Figure 4.24 shows the top ten peaks of the XRD results of a Mg/0.15%Vf nano-Al2O3 composite sample.

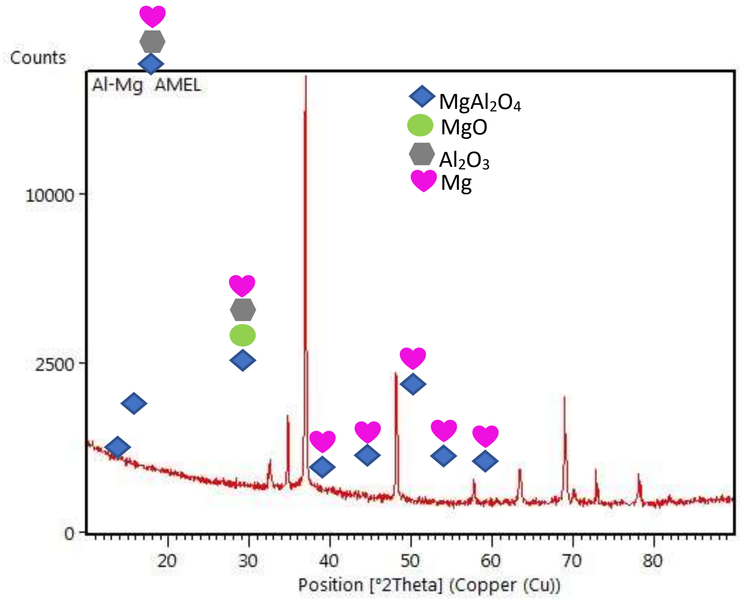

Figure 4. 10 XRD Test Results on Magnesium Composites with the Addition of 0.15%Vf Nano-Al_2O_3 Booster.

Furthermore, a comparison between *the peak list* of composite samples and *reference peaks* can be seen in Figure 4.25. The peak comparison is then complemented by a pattern identification analysis that will produce a *score*. *The score* can be used as a reference to determine the indication of the existence of a phase. The higher the score obtained in a phase, it can be indicated that the existence of the phase is better.

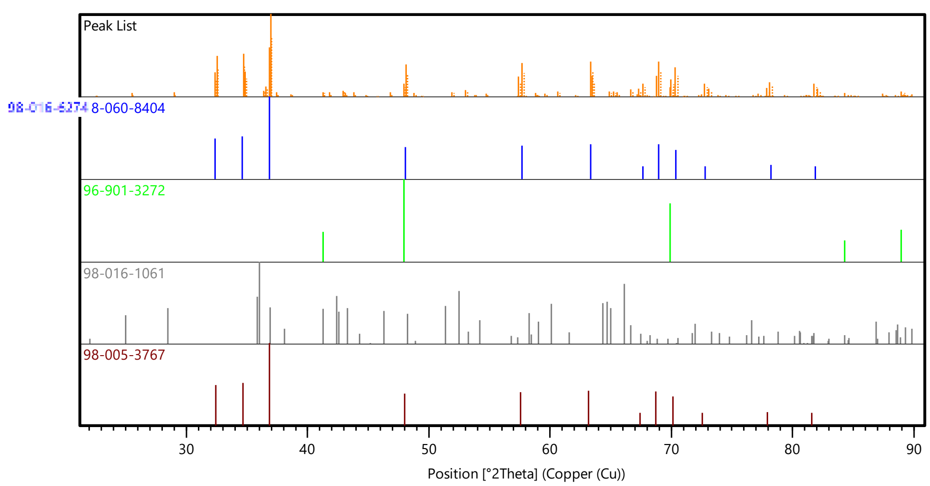

Figure 4. 11 Comparison between *Peak List of* 0.15%Vf Nano-Al_2O_3 Reinforced Magnesium Composite Samples with *Reference Peak*

4. Conclusion

Unstable stirring speeds and less stirring times result in inhomogeneous dispersion of reinforcement particles and turbulence-prone conditions and leave more gases trapped in the composite sampling process, resulting in high amounts of porosity and insignificant increases in mechanical strength.

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Conflicts of Interest: The authors declare no conflict of interest.
Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.

References

[1] Aravindan, S., Rao, P. V., & Ponappa, K. (2015). Evaluation of physical and mechanical properties of AZ91D/SiC composites by two-step stir casting process. *Journal of Magnesium and Alloys*, *3*(1), 52–62. https://doi.org/10.1016/j.jma.2014.12.008

[2] Baldwin, W. (2004). *Metallography and Microstructures 2004*.

[3] Callister, W., & Rethwisch, D. (2007). Materials science and engineering: an introduction. In *Materials Science and Engineering* (Vol. 94). https://doi.org/10.1016/0025-5416(87)90343-0

[4] Dhindaw; R., P., , Stefanescu D. M. S., and Ahuja; B.K., (1992). modeling of particle distribution in equiaxed-grains metal matrix composite. *Processing of Semi-Solid Alloys and Composites*, 406–416.

[5] Garcés, G., Oñorbe, E., Pérez, P., Klaus, M., Genzel, C., & Adeva, P. (2012). Influence of SiC particles on compressive deformation of magnesium matrix composites. *Materials Science and Engineering A*, *533*, 119–123. https://doi.org/10.1016/j.msea.2011.10.103

[6] Gupta, M., & Sharon, N. M. L. (2010). Magnesium, Magnesium Alloys, and Magnesium Composites. In *Magnesium, Magnesium Alloys, and Magnesium Composites*. https://doi.org/10.1002/9780470905098

[7] Hassan, S. F., & Gupta, M. (2007). Development and Characterization of Ductile Mg∕Y[sub 2]O[sub 3] Nanocomposites. *Journal of Engineering Materials and Technology*, *129*(3), 462. https://doi.org/10.1115/1.2744418

[8] Hassan, S. F., & Gupta, M. (2008). Effect of submicron size Al2O3 particulates on microstructural and tensile properties of elemental Mg. *Journal of Alloys and Compounds*, *457*(1–2), 244–250. https://doi.org/10.1016/j.jallcom.2007.03.058

[9] Karthick, E., Mathai, J., Michael Tony, J., & Marikkannan, S. K. (2017). Processing, Microstructure and Mechanical Properties of Al 2 O 3 and SiC Reinforced Magnesium Metal Matrix Hybrid Composites. *Materials Today: Proceedings*, *4*(6), 6750–6756. https://doi.org/10.1016/j.matpr.2017.06.451

[10] Khandelwal, A., Mani, K., Srivastava, N., Gupta, R., & Chaudhari, G. P. (2017). Mechanical behavior of AZ31/Al2O3 magnesium alloy nanocomposites prepared using ultrasound-assisted stir casting. *Composites Part B: Engineering*, *123*, 64–73. https://doi.org/10.1016/j.compositesb.2017.05.007

[11] Lee, Y. C., Dahle, A. K., & StJohn, D. H. (2000). The role of solute in grain refinement of magnesium. *Metallurgical and Materials Transactions A*, *31*(11), 2895–2906. https://doi.org/10.1007/BF02830349

[12] Lim, C. Y. H., Leo, D. K., Ang, J. J. S., & Gupta, M. (2005). Wear of magnesium composites reinforced with nano-sized alumina particulates. *Wear*, *259*(1–6), 620–625. https://doi.org/10.1016/j.wear.2005.02.006

[13] Lloyd, D. J. (1994). Particle-reinforced aluminum and magnesium matrix composites. *International Materials Reviews*, *39*(1), 1–23. https://doi.org/10.1179/imr.1994.39.1.1

[14] Lu, D., Jiang, Y., & Zhou, R. (2013). Wear performance of nano-Al2O3 particles and CNTs reinforced magnesium matrix composites by friction stir processing. *Wear*, *305*(1–2), 286–290. https://doi.org/10.1016/j.wear.2012.11.079

[15] Paramsothy, M., Chan, J., Kwok, R., & Gupta, M. (2012). Al2O3 Nanoparticle Addition to Commercial Magnesium Alloys: Multiple Beneficial Effects. *Nanomaterials*, *2*(4), 147–162. https://doi.org/10.3390/nano2020147

[16] Purnama, R. (2017). Gaikindo Patok Penjualan Mobil Lebih Tinggi di 2017. *CNN Indonesia*.

[17] Raturi, A., Mer, K. K. S., & Kumar Pant, P. (2017). Synthesis and characterization of the mechanical, tribological, and microstructural behavior of Al 7075 matrix reinforced with nano Al2O3 particles. *Materials Today: Proceedings*, *4*(2), 2645–2658. https://doi.org/10.1016/j.matpr.2017.02.139

[18] Sinica, A. M. (2013). *Short Communication*. *15*(November), 625–627. https://doi.org/10.13343/j.cnki.wsxb.2013.11.014

[19] WAGIH, A. (2016). Effect of Mg addition on mechanical and thermoelectrical properties of Al–Al<inf>2</inf>O<inf>3</inf> nanocomposite. *Transactions of Nonferrous Metals Society of China (English Edition)*, *26*(11), 2810–2817. https://doi.org/10.1016/S1003-6326(16)64409-6

[20] Wei-Chao, Z., Shuang-shou, L. I., Bin, T., & Da-ben, Z. (2006). Microstructure and properties of Mg-Al binary alloys. *China Foundry*, 270–274.

[21] Xiang, S. L., Gupta, M., Wang, X. J., Wang, L. D., Hu, X. S., & Wu, K. (2017). Enhanced overall strength and ductility of magnesium matrix composites by low content of graphene nanoplatelets. *Composites Part A: Applied Science and Manufacturing*, *100*, 183–193. https://doi.org/10.1016/j.compositesa.2017.05.011

[22] Yadav, S., Gangwar, S., & Singh, S. (2017). Micro/Nano Reinforced Filled Metal Alloy Composites: A Review Over Current Development in Aerospace and Automobile Applications. *Materials Today: Proceedings*, *4*(4), 5571–5582. https://doi.org/10.1016/j.matpr.2017.06.014

[23] Zhang, Z. F., Zhang, L. C., & Mai, Y. W. (1995). Wear of ceramic particle-reinforced metal-matrix composites - Part I Wear mechanisms. *Journal of Materials Science*, *30*(8), 1961–1966. https://doi.org/10.1007/BF00353018