Characteristics of composite magnesium with micro SiC particle for automotive applications with stir casting method

N R Susilo and A Z Syahrial
Department of Metallurgy and Materials Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia

Corresponding author’s email: anne@metal.ui.ac.id

Abstract. Composite is a promoted material consists of two or more materials to enhance the properties mechanically. In this study, composites were created by mixing a matrix; magnesium and the reinforcement; SiC microstructure with the addition of a volume fraction of: 2 %vf, 4 %vf, 6 %vf and 8 %vf. This magnesium composite fabrication process is stirred casting. The results of this study show that the addition of SiC micro particles will enhance the properties of the composite–mechanical wise–, namely, wear resistance and hardness. The addition of SiC micro-reinforcing particles that produced the best magnesium composite was by adding 8 %vf volume fraction which produced a hardness value of 83 HB and a wear rate of 0.002015706 mm³/m. Increased mechanical properties in magnesium composites is caused by the reducing grain size and Orowan strengthening mechanism.

Keywords: Magnesium composite, micro SiC, stir casting

1. Introduction
Technology in the automotive field is one of the many rapidly developing technology fields. In the automotive world, one factor that continues to be developed is the fuel in vehicles. To reduce the fuel requirements on a vehicle, the weight of the vehicle must be balanced [1]. The weight of vehicles takes a significant part in the fuel efficiency. Since, the heavier the vehicle, leads to a higher usage of fuel for the engine to drive. The weight reduction of vehicle by 10 %, can reduce the fuel usage by 6–8 % [2]. The car skeleton is one parameter that could be taken into consideration. One type of metal that is considered to create a skeleton of a car with a low mass is magnesium [3].

Magnesium is a metal with the lowest density. Because the density is only 1.74 g/cm³ [4], it can reduce the weight and increase the efficiency of the fuel, hence magnesium is the most compatible material to be applied as raw material for high fuel efficiency car skeletons [5]. Magnesium is the sixth most abundant element on earth (2.7 % of the composition of the earth's crust is magnesium) [6], it is possible to use it as a mass production for car skeleton. To make a car skeleton with improved mechanical properties, mixing magnesium with other materials to form magnesium composite material that has better mechanical properties than pure magnesium can be applied.

In composites, two or more materials are involved. Both types the material acts as a matrix and reinforcement. The composite matrix used is magnesium metal. One of the compounds that can be utilized is micro-sized silicon carbide (SiC) ceramic particles [7]. According to the research conducted by Paramshoy et al. [8] ceramic reinforcements have excellent mechanical properties, isotropic properties, chemical hypertension properties, and are stable at high temperatures, as well as the
expansion coefficient can be monitored, therefore the particles of ceramic can be regarded as interesting for fabrication of metal matrix composites. In this study, four variable % volume fractions were used from micro-sized SiC reinforcing particles with magnitudes of 2, 4, 6 and 8. With the addition of reinforcing micro-sized ceramic particles, magnesium composites with low density, specific strength and high stiffness were obtained, as well as the high wear resistance [8].

2. Materials and method

2.1. Materials
Before the trial, mass balance calculation of composite was performed to prepare the required materials. Pure magnesium 90 %wt was applied as the matrix and micro sized SiC particle with 2, 4, 6 and 8 % volume fraction was used.

2.2. Fabrication of magnesium with SiC micro-sized particle composite
The magnesium ingot weighed at the same mass balance of magnesium was cleaned with soap and 96 % alcohol in order to remove inclusion particle and oil that might be left on the surface. SiC (reinforce) was heated in a different furnace with a temperature of 900 °C, for 30 min in order to remove inclusions while the furnace and the mold was coated with mixing thinner and zircon so that the furnace and the melt has a high thermal resistance to avoid cracking. After that, the magnesium and micro SiC were inserted into the furnace, before turned on the heater, they were fluxed for 6 min and argon gas was flowed for 20 sec.

The matrix was melted at 650 °C in the furnace and before pouring into the matrix, the reinforce was pre-heated at 900 °C in the muffle furnace to remove the moist. After the pre-heat process, micro SiC particle was inserted into molten magnesium and then stirred for 1 min to get homogenous mixture. Then, the mixture was poured into the mold and the mold was opened after the composite solidified. Finally, this composite sample was being used for further characterization.

2.3. Characterization
To study the features of microstructure, optical microscope (OM) observation was conducted on the composite samples that were grounded and polished by TiO₂. Scanning electron microscope (SEM) micrographs and X-ray diffraction (XRD) patterns were also recorded to obtain the data regarding the presence of different phases in the microstructure. The chemical properties were determined with optical emission spectroscopy (OES). Mechanical properties were studied by conducting the tensile test based on JIS Z2241; impact test based on Charpy method with ASTM E23 standard, hardness test (Rockwell H) based on ASTM E18 and wear-rate test with pin on disc (Ogoshi) method based on ASTM G99. The density of every sample was also determined with the Archimedes Theory. All mechanical tests were performed at room temperature.

3. Results and discussion

3.1. Chemical composition
OES (Optical Emission Spectrometry) is a test to confirm the presence of elements in magnesium as-cast or non-reinforced magnesium as well as the magnesium composite quantitatively. So that, the effect of the casting process on the metal characterization will be identified. Table 1 below shows the chemical composition of the material. According to the characterization results, magnesium as-cast has 99 % Mg which is in accordance with the mass balance in the first place. Instead, there are other elements that were not supposed to be present in the composite, namely Al, Ti, Be, Cu, Mn, etc. However, these elements would not give a significant effect to the characteristics itself. For the composite, the results show that the increasing of reinforce particles reduces the content of
magnesium. On the other hand, it decreases in the 2 %vf micro SiC which is caused by the porosity, also due to the speed while pouring the liquid into the mold was not fast and quick enough so that the liquid composite reacted too long with the air.

3.2. SEM and EDS
SEM and EDS tests were performed using magnesium as-cast and magnesium composite with 8 %vf to represent all of the composite sample. Based on the figure 1 above, it shows some elements like Mg, Al, Si and O which probably formed some compounds; MgO and Al₂O₃. The oxygen element at some point indicates of products of rust initiation in the form of MgO at most points in the composition of 8 %vf. Just like other compositions, this is because magnesium is a highly reactive metal and oxidized very easily. This carbon impurity originates from the crucible from the melting furnace which is a graphite-based refractory. There is Al₂O₃ at point 10 which is probably derived from polished Al₂O₃ particles which are still attached onto the surface.

| Element | Mg (as-cast) (JIS) | Mg/2 % micro SiC | Mg/4 % micro SiC | Mg/6 % micro SiC | Mg/8 % micro SiC |
|---------|-------------------|-----------------|-----------------|-----------------|-----------------|
| Mg      | 99.8              | > 96.0          | > 98.0          | > 98.0          | > 96.0          |
| Al      | < 0.005           | 1.01            | 0.703           | 1.190           | 1.540           |
| Be      | 0.0001            | 0.00006         | 0.00009         | 0.0001          | 0.00006         |
| Cu      | < 0.001           | < 0.0001        | < 0.0001        | < 0.0001        | < 0.0001        |
| Mn      | 0.0466            | 0.00690         | 0.005           | 0.005           | 0.0086          |
| Zn      | 0.0377            | 0.00710         | 0.023           | 0.011           | 0.0097          |
| Ag      | < 0.001           | 0.00014         | < 0.0001        | 0.0002          | 0.00019         |
| Ca      | 0.0023            | 0.00180         | 0.002           | 0.0022          | 0.0028          |
| Cd      | < 0.001           | < 0.0001        | < 0.00010       | < 0.00010       | < 0.00010       |
| Sn      | 0.0421            | 0.01470         | 0.019           | 0.0125          | 0.018           |
| Sr      | 0.0007            | 0.00016         | 0.0002          | 0.00014         | 0.00025         |
| Si      | 0.134             | 2.83000         | 1.210           | 0.671           | 2.170           |

![Figure 1. The SEM result of Mg micro SiC.](image)
3.3. XRD

XRD is a test to find out which phases are formed in the composite microstructure. In this research, magnesium composite with micro SiC 8 %vf was observed to represent all the composite samples. From the graph of the XRD test results on the magnesium reinforcing composite SiC 8 %vf, it can be concluded that the compounds formed are Mg, MgO, Si, SiC, SiO. Mg compound appears because the matrix of the micro Mg composite SiC is magnesium. Similarly, Si and SiC appear due to the addition of the amplifier from the SiC (figure 2) Meanwhile, MgO compounds appear because of the reaction of magnesium with oxygen which results in the formation of MgO compounds. SiO compounds are formed due to the reaction of SiC amplifiers with oxygen to form SiO compounds.

3.4. Microstructure

In this study, the addition of SiC micro-booster volume fraction of 2, 4, 6 and 8 %vf resulted in a decrease in grain size in magnesium composites thus increasing some mechanical properties namely hardness and wear resistance. In the microstructure Mg image, there is porosity due to the reaction of the molten magnesium with oxygen so that a porosity phenomenon is formed. This is also seen in the addition of the SiC micro amplifier volume fraction at 2 %vf and 4 %vf because the pouring time tends to be longer than the composite with SiC 6 %vf and 8 %vf micro amplifier volume fraction which has less porosity. In the figure 3, there is no porosity in the SiC 6 %vf and 8 %vf micro amplifier volume fraction because it is not included and also has a little porosity. In Mg composite microstructure images with SiC 2, 4, 6 and 8 %vf micro booster volume fraction occurs SiC reinforcement agglomeration phenomenon.

This is because the gathering of SiC amplifiers is caused by several things, namely the stirring is too fast or too slow when casting, so that the micro amplifier SiC will agglomerate. At 8 %vf micro-SiC amplifier volume Mg2C3 precipitates are formed, where precipitates are formed because magnesium as the matrix reacts with SiC as an amplifier where in the 8 % variation SiC micro amplifier, the more SiC amplifier means more carbon will react with magnesium and will form the Mg2C3 phase. According to research conducted by Esmaily M et al. [9] the Mg2C3 phase has good mechanical properties such as strength and hardness. Therefore, the results of microstructure images in accordance with the literature Mg Micro SiC 8 %vf composite has good strength and wear resistance.

Figure 2. The XRD result of MgSiC 8 %vf.
Figure 3. Microstructure images of (a) as-cast 200 x, (b) MgSiC 2 %vf, (c) MgSiC 4 %vf, (d) MgSiC 6 %vf, (e) MgSiC 8 %vf 1000 x.

3.5. Tensile and elongation
Data obtained from the Pull test is Ultimate Tensile Strength (UTS) and % elongation. This test is performed on each variable to determine the effect of changes in SiC content on the tensile strength of the composite. The test results can be seen in figure 4 where in general it can be seen that the more SiC added to the composite, the higher the tensile strength of the composite.

In figure 4a, it can be seen that the tensile strength of magnesium composites added with SiC micro reinforcing particles significantly increases. Besides that, the decrease in strength is caused by the uneven distribution of SiC, so that SiC clumps will appear. SiC accumulation at this point will
certainly reduce the number of interfaces formed, so that the SiC strengthening mechanism that occurs is not maximum and the tensile strength will decrease. The uneven distribution of this SiC can be influenced by two factors, namely the speed and duration of the stirring process during the casting process.

In figure 4b we can see that there was a decrease in % elongation in the composite after the addition of SiC compared to the magnesium cast. The decrease elongation value indicates that the addition of SiC into the material will not only make the material stronger but also make the material more brittle. Plastic deformation process will be more difficult to occur in materials that have reinforcing particles in them when compared to pure metals [10].

Research conducted by Song Min [11] also shows that the more SiC levels are added, the lower is the elongation value. The reduced elongation value when increasing the SiC levels can be because the SiC itself has very brittle properties. In addition, SiC can also be a point of crack initiation. When the bond between the matrix and the SiC amplifier is very strong, then when exposed to the load of the dislocation density it will continue to increase until it reaches the maximum limit, and these SiC particles will break and create cracks on the surface of the magnesium matrix where this crack will continue to propagate. Conversely, when the bond between the matrix and the SiC amplifier is weak, the interface will not be broken, but the SiC will detach from the matrix and leave cracks on the magnesium matrix [10]. However, when interface bonds are formed between the matrix and the amplifier, a strength increase will occur without a significant reduction in the elongation value [12].

3.6. Hardness, wear rate and impact

The composite hardness value increases with the increase of the aging temperature. However, it will decrease after certain temperature when over aging phenomenon takes place. Composite with 200 °C aging temperature achieved the highest hardness value. However, sample with 230 °C, 260 °C aging temperature only shows an insignificant hardness value reduction. When the temperature aging increases to peak age, precipitates will form coarsening which will reduce the strength and hardness of the composite material [6]. Figure 5 of impact value data also shows that the composite with 200 °C achieved the highest impact value. This tendency resembles the hardness test results. Figure 5 of wear rate data also displays the tendency of materials having a higher hardness value to show a lower wear rate, since the materials’ hardness property is straightly corresponded to the capability in preventing the loss of materials as exposed against abrasion, erosion, or other wear mechanism. The hardness increase in the material leads to a decrease in the rate of wear while the decrease in the hardness in the material creates an increase in the rate of wear [4].

![Figure 4. (a) Tensile strength and (b) elongation.](image-url)
3.7. Density and porosity

Figure 6a shows that the actual density of composite samples of all compositions has a smaller value when compared to the theoretical density. The smaller actual density of the composite sample compared to its theoretical density indicates porosity in the composite sample. The greater the difference between the priority density and the actual density shows the more porosity is formed.

Figure 6b shows magnesium as-cast has a lower porosity value than magnesium composites in all variables adding volume fraction. This is because during the process of making magnesium as-cast, the stirring process is not carried out because there is no addition of SiC micro boosters on liquid magnesium. So that, there is no contamination from the atmosphere or metal stirrers which can cause porosity to occur. The microstructure of SiC reinforcement particle at 2 %Vf has a very large amount of porosity due to external factors such as stirring and agglomeration formed from the SiC micro amplifier [13].
Porosity in composite samples can be formed because there are gases such as hydrogen gas trapped and dissolved in the composite sample during the casting process and during the solidification process. Besides, porosity can also be formed due to several factors, namely the contact between air or the outer atmosphere with molten magnesium metal, materials and equipment that are not clean and not dry, the occurrence of turbulence during the stirring process [14] and because of the high temperature during the stirring process [12]. The degassing process during the casting process can be carried out to reduce the formation of porosity by injecting argon gas into molten metal to remove hydrogen gas content dissolved in liquid magnesium [10]. Previously, the vacuum process was carried out on the furnace which aims to form a vacuum environment in the furnace, and when the melting process of argon Mg gas ingots is continuously fed into the furnace to make the furnace environment inert so that the hydrogen gas is not causing porosity casting defects. Porosity during the casting process occurs because when inserting the amplifier into the furnace for too long so that magnesium and SiC micro reinforcing particles react with air causing porosity.

4. Conclusion
The stir casting method may be used to fabricate Mg composite of the micro SiC particle. The addition of micro SiC can increase the UTS value at 8 %Vf specifically, reduce the impact value, increase the hardness, decrease the wear rate, and increase the density of material. The addition of 8 %wt micro SiC was aimed to refine the material’s grain by forming initial nucleation, so that solidification occurs faster and is able to increase the material’s strength as well. The result of the microstructure shows the presence of MgO, Al2O3 and MgO.

Acknowledgments
This work was financially supported by Universitas Indonesia under research grant PIT 9 with grant contract number NKB-0042/UN2.R3.1/HKP.05.00/2019.

5. References
[1] Blawert C, Hort N and Kainer K U 2004 Trans. Indian Inst. Met. 57 397-408
[2] U.S. Department of Energy 2011 2010 Annual Progress Report: Light Weighting Material available at https://www.energy.gov/sites/prod/files/2014/03/f8/2010_lightweighting_materials.pdf
[3] Kiani M, Gandikota I, Rais-Rohani M and Motoyama K 2014 J. Magnes. Alloy 2 99-108
[4] Gupta M and Sharon N M L 2010 Magnesium, Magnesium Alloys, and Magnesium Composites (Singapore: John Wiley & Sons, Inc)
[5] Porro R 1998 The Innovative Use of Magnesium in Car Design and An Analysis of Cost Versus Weight Savings (United States: SAE International)
[6] Clark J B and Nayeb-Hashemi A A 1988 Phase Diagrams of Binary Magnesium Alloys (Metals Park, Ohio, UnitedSA: ASM International)
[7] Dey A, Pandey K M 2015 Rev. Adv. Mater. Sci. 42 58-67
[8] Paramsothy M, Chan J, Kwok R and Gupta M 2011 J. Nanopart. Res. 13 4855-66
[9] Esmaily M, Svensson J E, Fajardo S, Birbilis N, Frankel G S, Virtanen S, Arrabal R, Thomas S and Johansson 2017 Prog. Mater. Sci. 89 92-193
[10] Ibrahim I A, Mohamed F A and Lavernia E J 1991 J. Mat. Sci. 26 1137-56
[11] Song M 2009 T. Nonferr. Metal. Soc.19 1400-4
[12] Srivastava N and Chaudhari G P 2016 Mater. Sci. Eng. A 651 241-7
[13] Ponappa K, Aravindan S, Rao P V, Ramkumar J and Gupta M 2010 Int. J. Adv. Manuf. Tech. 46 1035-42
[14] Aravindan S, Rao P V and Ponappa K 2015 J. Magnes. Alloy. 3 52-62