ARCHIVES of FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 15
Special Issue
1/2015

99 – 102

21/1

Mechanical Properties and Microstructure of WE43 Magnesium Matrix Composite Reinforced SiC Particles

T. Rzychoń*, B. Dybowski, A. Gryc, M. Dudek
Faculty of Materials Science and Metallurgy, Silesian University of Technology,
Krasińskiego 8, 40-019 Katowice, Poland
*Corresponding author. E-mail address: tomasz.rzychon@polsl.pl

Received 28.04.2015; accepted in revised form 05.05.2015

Abstract

Magnesium alloys containing yttrium and neodymium are known to have high specific strength, good creep and corrosion resistance up to 250°C. The addition of ceramic particles strengthens the metal matrix composite resulting in better wear and creep resistance while maintaining good machinability. In the present study, WE43 magnesium matrix composite reinforced with SiC particles were fabricated by stir casting. The microstructure of the composite was investigated by optical microscopy, quantitative metallography, scanning electron microscope and XRD analysis. Microstructure characterization of WE43 MMC showed homogeneous reinforcement distribution and presence of the small amount of porosity at the interface. A thin layer consists of zirconium-rich particles was observed at the interface. In the microstructure, inclusions of the yttrium oxide were found. The presence of SiC particles assisted in improving hardness and in decreasing the ultimate tensile strength, yield tensile strength and elongation.

Keywords: Magnesium matrix composite, Microstructure, WE43 alloy, Stir casting

1. Introduction

In recent years, magnesium alloys have been used in a variety of structural applications due to their high specific strength at ambient temperature and good castability. On the other hand, the major drawbacks in using magnesium alloys are their limited mechanical properties at high temperatures and low corrosion resistance [1-4].

One possible way to increase the high-temperature mechanical properties of cast magnesium alloys is the addition of the expensive rare earth metals such as yttrium, neodymium or gadolinium. The WE43 and WE54 alloys (Mg-Y-Nd system) exhibit the best creep resistance among the commercial magnesium alloys. Moreover, these alloys shows good specific strength, castability and corrosion resistance. The good high-temperature strength is achieved by the precipitation of fine intermetallic phases within the magnesium grains [5-7].

Considerable improvement of mechanical properties of WE alloys can be achieved through reinforcing with ceramic particles. The incorporation of particles causes a substantial increase of strength and stiffness as well as the creep and wear resistance. Silicon carbide (SiC) particles are the most preferred reinforcements primarily because enhanced properties can be easily achieved with little or no penalty on the low density of magnesium alloys [8-10].

Magnesium matrix composites have been produced by different methods, such as stir casting, powder metallurgy and squeeze casting Among these methods, stir casting would be considered an easily adaptable and most used method. An additional benefit of this process is the near net-shape formation of the composites by conventional foundry processes [9].

2. Experimental procedure

WE43 (Mg - 4% wt. Y – 3% wt. RE – 0.4% wt. Zr) magnesium matrix composites reinforced with different weight fraction of SiC (0.3, 2, 5 and 10%) with an average size of 45 μm were produced by the stir casting process in argon atmosphere. A charge of 1 kg of WE43 alloy was placed in a mild steel crucible preheated to 450°C, in an electric resistance furnace. Thereafter, argon gas was allowed to pass avoid burning of WE43 alloy during melting. The furnace temperature was raised to 720°C and the melt was homogenized for about 20 min. The Mg-Y, Mg-Zr and Mg-Nd hardeners was added in order to compensate the chemical composition. Afterwards, preheated (up to 200°C) SiC particles were added into the vortex of the melt during stirring. The composite melt was stirred with stainless steel impeller at 150 rpm for 10 min and poured from 720°C into a graphite mould to form cast having a diameter of 4 cm. The unreinforced WE43 alloy was poured from 720°C into graphite mould.

Microstructural observations of the alloys studied were carried out using light microscopy (LM) and scanning electron microscopy (SEM). Microanalysis of intermetallic compounds were performed by using energy-dispersive X-ray spectroscopy (EDS). The accelaration voltage was 15 keV. The phase identification was performed by X-ray diffraction analysis (XRD) and selected area electron diffraction (SAED). The detailed results from the XRD and SAED analysis will be published elsewhere

Mechanical properties of as cast and heat treated samples were evaluated in terms of their hardness, creep properties and tensile properties. Hardness measurement were carried out on Vickers hardness tester (Duramin A5) at a load of 2 kg. The tensile tests and creep tests were carried out on a Zwick Kappa 50DS machine. The creep tests were performed at 250°C under constant stress 90 MPa.

3. Results and discussion

3.1. Microstructure

Microstructure of WE43 magnesium alloy without reinforcement is composed of primary α-Mg phase and eutectic equilibrium β phase (Mg_5RE isomorphic to Mg_5Gd) along the grain boundaries [11]. Moreover Zr-rich particles are observed within α-Mg grains. Hardness of this alloy in as-cast state is 59 HV2.

The LM micrographs of SiC/WE43 composites are presented in Fig. 1, which shows uniform distribution of SiC particles in the matrix, however the agglomerations of SiC particles were sporadically observed in some areas. In these areas, it was also found the presence of shrinkage porosity. A homogenous distribution of reinforced particles in composite is confirmed by the low value of variability index of volume fraction of SiC particles (detailed results will be published elsewhere). The uniform distribution of SiC particles results from the good wettability of SiC by molten magnesium.

Microscopic observations at higher magnifications showed that the interfacial products are visible at the interface between the α-Mg matrix and SiC particles (Fig. 2). A thin layer with a thickness of about 1 μm was found at the interface. This layer consists of fine particles of zirconium-rich phase, which was identified as the $ZrSi_2$ compound (it should be emphasized that the identification of this compound is ambiguous). The presence of these particles in the composite is undesirable due to the zirconium depletion in molten metal and the lack of the heterogeneous nucleation of α-Mg grains. This factor will lead to grains growth in the composite. On the other hand, the SiC particles may act as heterogeneous nuclei due to similar values of the interplanar spacing *d* in the low index crystallographic planes between hexagonal magnesium matrix and hexagonal SiC compound (disregistry δ). It should be stressed that the SiC particles have a lower thermal conductivity and heat diffusivity than the magnesium melt. Hence if the temperature of SiC particles in magnesium melt is equal to that of the surrounding magnesium melt before composite casting, then during the cooling process the temperature of SiC particles will be somewhat higher than that of the surrounding magnesium melt. The hotter SiC particles would heat up the surrounding magnesium melt, and thus delay the solidification process of the surrounding melt. In such a case, it is very difficult for primary magnesium phase to nucleate at the SiC particle surfaces [12].

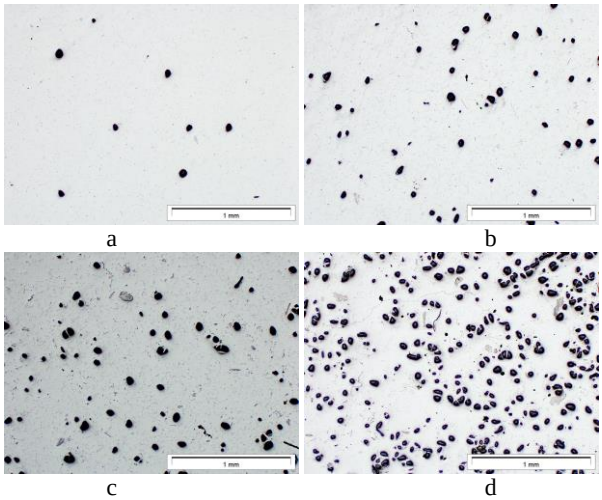

Fig. 1. LM of SiC particles distribution in the WE43-SiC composites: (a) 0.3 vol.% SiC, (b) 2 vol.% SiC, (c) 5% vol. SiC, (d) 10 vol.% SiC

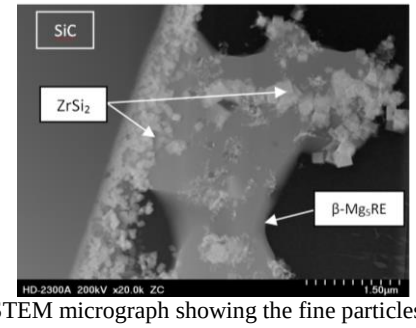

Fig. 2. STEM micrograph showing the fine particles of $ZrSi_2$ compound and β phase at the interface between the α-Mg matrix (dark color) and SiC particles (grey color - left side)

In the vicinity of the particles, the eutectic of α-Mg+β phase is often observed (Fig. 2). The equilibrium β phase should be dissolved in the magnesium matrix after the typical T6 heat treatment. In the composite the numerous, thin layers of Y_2O_3 were visible in the microstructure (Fig. 3). In the melting process the thin film of yttrium oxide is formed on the surface of the liquid metal. When the SiC particles are incorporated into the liquid metal and the intensive stirring of molten composite is carried out, the yttrium oxide is broken and drawn into molten metal, thus the numerous inclusions of Y_2O_3 are visible in the microstructure after the solidification. Moreover the small amount the porosity at the interface was observed in the microstructure of composites (Fig. 4).

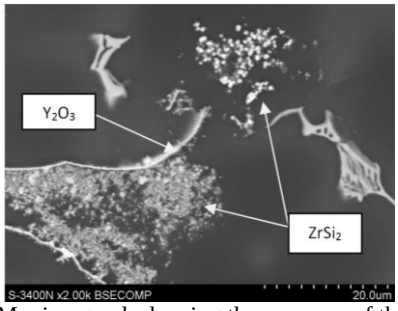

Fig. 3. SEM micrograph showing the presence of thin layer of Y_2O_3 and clusters of $ZrSi_2$ compounds

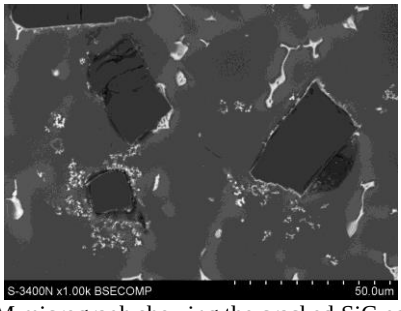

Fig. 4. SEM micrograph showing the cracked SiC particles and porosity at the interface between the α-Mg matrix and SiC particles

3.2. Mechanical properties

The hardness and tensile properties of as-cast WE43 matrix composites reinforced with SiC particles are given in Table 1. Obviously, the hardness of composites increases with increasing the content of SiC particles because the ceramic particles are harder than WE43 magnesium alloy.

Tensile properties of the base alloy and composites are also reported in Table 1. Generally, mechanical properties of composites are reduced in relation to the as-cast WE43 alloy. Ultimate tensile strength and elongation are significantly decreased, whereas the yield tensile strength is comparable to the base alloy. The lower mechanical properties of composites with the SiC particles addition can be attributed to the following reasons: (a) the presence of the fine particles of $ZrSi_2$ compound at the interface between the SiC particles and magnesium matrix, (b) the large grain size resulting from the formation of Zr-rich compounds, (c) large size of particles (about 45 μm) which are not effective in blocking dislocations, (d) the presence of little amount of porosity, (e) the presence of yttrium oxide Y_2O_3 in the microstructure.

Table 1.
Mechanical properties of as-cast WE43 matrix composite reinforced with SiC particles

Material	Hardness HV2	R_m [MPa]	$R_{p0.2}$ [MPa]	A_5 [%]
WE43 unreinforced	59±4	166±18	113±9	4.7±1.5
WE43 + 0.3% SiC	61±5	150±0,7	112±10	2.2±1.3
WE43 + 2% SiC	64±7	151±13	116±6	2.2±1.3
WE43 + 5% SiC	68±5	146±7	110±6	1.3±0.4
WE43 + 10% SiC	71±6	149±16	125±14	1.0±0.1

It should be noted that the high dispersion of the results of tensile tests were observed. During the tensile tests, it was observed that the ultimate tensile strength of some specimens is close to only 100 MPa. Macroscopic observation of the fracture surfaces of the tensile specimens with very low values of ultimate tensile strength revealed that the main reason of the decrease the mechanical properties is the presence of thin layer of yttrium oxide (Fig. 5).

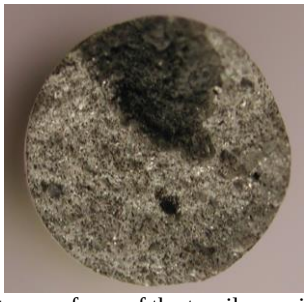
Fig. 5. The fracture surfaces of the tensile specimens with large Y_2O_3 inclusion (dark color). Identification of Y_2O_3 was performed by XRD and SEM-EDS analysis. The diameter of specimen is 6 mm

WE43 magnesium alloy is designated for heat treatment (T6) consisting of solution treatment at 525°C, holding time 8 hours, quenching in warm water and ageing at 250°C for 16 hours. This precipitation hardening allows to improvement the hardness, ultimate tensile strength and yield tensile strength as a result of the formation of fine precipitates of β' phase [11]. Therefore, the T6 heat treatment was carried out and results of tensile tests for heat treated composites are shown in Table 2.

Table 2.
Mechanical properties of heat-treated WE43 matrix composite reinforced with SiC particles

Material	UTS [MPa]	YTS [MPa]	El. [%]
WE43 unreinforced	222±4	153±6	7.7±1.3
WE43 + 0.3% SiC	198±10	147±3	4.0±2.0
WE43 + 2% SiC	181±20	146±6	2.0±1.5
WE43 + 5% SiC	173±16	148±6	1.9±1.3
WE43 + 10% SiC	142±24	115±2	1.4±2.2

Mechanical properties of unreinforced WE43 magnesium alloy are increased significantly after T6 heat treatment due to precipitation process of metastable β' phase. According to the literature data the ultimate tensile strength after T6 process should be 265 MPa, tensile yield strength should be 185 MPa and elongation 7%. In our case, the mechanical properties are lower, probably due to a thick section of casting and large size of α-Mg grains.

Mechanical properties of composites are also improved after the T6 heat treatment due to precipitation process in the α-Mg matrix. Moreover, relationship between the volume fraction of SiC particles and mechanical properties is observed (Table 2). Generally, the presence of SiC particles in WE43 alloy cause a decrease in the mechanical properties of heat-treated WE43 composites. The increase in R_m, $R_{p0.2}$ and A_5 after T6 treatment is observed only for composites consisting up to 5% wt. of the SiC particles. In case of the heat-treated composite containing 10% wt. of particles, the mechanical properties are comparable with the untreated composites (Table 1). It is associated with a high content of interface between the SiC and matrix, which is the point of nucleation of microcracks during tensile test. Moreover, the porosity at the interface is higher in composite with 10 % wt. SiC and additionally porosity increases during solution treatment (525°C, 8h, warm water) due to the expansion of the gas contained in the pores and deformation of the matrix in the vicinity of pores at elevated temperatures.

4. Conclusions

1. Microstructure of WE43 composite consists of α-Mg grains, β eutectic compound at the grain boundaries, SiC particles located at the grain boundaries and the within the α-Mg grains.
2. Microstructure characterization of WE43 MMC showed homogeneous reinforcement distribution and presence of the small amount of porosity at the interface. A thin layer consists of zirconium-rich particles was observed at the interface. In the microstructure, inclusions of the yttrium oxide were found.
3. The hardness of composites increases with increasing the volume fraction of SiC particles.
4. Ultimate tensile strength and elongation of as-cast WE43 composites are significantly decreased, whereas the yield tensile strength is comparable to the base alloy.
5. Mechanical properties of composites are improved after the T6 heat treatment. The increase in R_m, $R_{p0.2}$ and A_5 after T6 treatment is observed only for composites consisting up to 5% wt. of the SiC particles. In case of the heat-treated composite containing 10% wt. of particles, the mechanical properties are comparable with the as-cast WE43 composite.

Acknowledgements

The present work was supported by the National Centre for Research and Development under the project LIDER/29/198/L-3/11/NCBR/2012

References

[1] Cabibbo, M. & Spigarelli, S. (2011). A TEM quantitative evaluation of strengthening in an Mg-RE alloy reinforced with SiC. *Mater. Charact.* 62, 959-969.
[2] Braszczyńska, K.N., Lityńska, L., Zyska, A. & Baliga, W. (2003). TEM analysis of the interfaces between the components in magnesium matrix composites reinforced with SiC particles. *Mater. Chem. Phys.* 81, 326–328.
[3] Dybowski, B., Kiełbus, A. & Jarosz, R. (2014). Effect of mould components on the cooling rate, microstructure, and quality of WE43 magnesium casting alloy. *Arch. Metall. Mater.* 29, 1527-1532.
[4] Rzychoń, T., Kiełbus, A. & Lityńska-Dobrzyńska, L. (2013). Microstructure, microstructural stability and mechanical properties of sand-cast Mg-4Al-4RE alloy. *Mater. Charact.* 83, 21-34.
[5] Garcés, G., Rodríguez, M., Pérez, P. & Adeva, P. (2010). Microstructural and mechanical characterisation of WE54–SiC composites, *Mater. Sci. Eng.* A527, 6511–6517.
[6] Dybowski, B., Kiełbus, A., Jarosz, R. & Paśko, J. (2014). The Microstructure of Elektron21 and WE43 Magnesium Casting Alloys After Subsequent Melting Process Operations. *Solid State Phenom.* 211, 65-70.
[7] Rzychoń, T., Szala, J. & Kiełbus, A. (2012). Microstructure, castability, microstructural stability and mechanical properties of ZRE1 magnesium alloy. *Arch. Metall. Mater.* 57(1), 254-262. DOI: 10.2478/v10172-012-0018-3.
[8] Trojanova, Z., Szaraz, Z., Chmelik, F. & Lukac, P. (2010). Acoustic emission from deformed Mg–Y–Nd alloy and this alloy reinforced with SiC particles. *J. Alloys Compd.* 504, L28–L30.
[9] Gui, M., Han, J. & Li, P. (2003). Fabrication and Characterization of Cast Magnesium Matrix Composites by Vacuum Stir Casting Process, *J. Mater. Eng. Perform.* 12(2), 128-134.
[10] Poddar, P., Srivastava, V.C., De, P.K. & Sahoo, K.L. (2007). Processing and mechanical properties of SiC reinforced cast magnesium matrix composites by stir casting process. *Mater. Sci. Eng.A* 460–461, 357–364.
[11] Rzychoń, T, Kiełbus, A. & Bierska-Piech, B. (2007). Characterization of β phase in WE54 magnesium alloy. *Solid State Phenom.* 130, 155-158.
[12] Cai, Y., Tan, M.J., Shen, G.J. & Su, H.Q. (2000). Microstructure and heterogeneous nucleation phenomena in cast SiC particles reinforced magnesium composite, *Mater. Sci. Eng.* A282, 232–239.
[13] Olszówka-Myalska, A., McDonald, S.A., Withers, P.J., Myalska, H. & Moskal, G. (2012). Microstructure of in situ Mg metal matrix composites based on silica nanoparticles. *Solid State Phenom.* 191, 189-198.