Fabrication and Characterizations of Mg/SiC Composite Via Compo-Casting Technique

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Abstract: The present work deals with applying compo-casting technique for fabrication of magnesium matrix composite under an inert gas atmosphere. A 15 Micrometer average diameter size of -SiC particulate was used as a reinforcement material with different volume fractions. The effect of processing technique on SiC distribution within alloy matrix was investigated using light optical microscope and scanning electron microscope. Also, microstructural characterization studies conducted on the composites produced by compo-casting technique revealed a uniform distribution of SiC particulates (at the microscopic scale) and less porosity content. The mechanical properties of pure Mg and Mg-SiC composites have been evaluated. The results show a remarkable increasing in hardness value, tensile strength and 0.2% yielding strength. The increasing in overall mechanical properties revealed to SiC addition to base matrix. However, it is also evident that the strain to failure significantly decreased as the volume fraction of the particulate increased. Also, a good bonding between Mg matrix and SiC reinforcement material was observed in fracture surface SEM micrograph.

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1. Introduction

Metal matrix composites (MMCs) are a range of advanced materials that can be used for a wide range of applications within the aerospace, automotive, nuclear, biotechnology, electronic and sporting goods industries.

MMCs consist of a non-metallic reinforcement incorporated into a metallic matrix which can provide advantageous properties over base metal alloys. These include improved thermal conductivity, abrasion resistance, creep resistance, dimensional stability, exceptionally good stiffness-to-weight and strength-to-weight ratios. They also have better high temperature performance. [1]

In recent years, there has been an increasing growth of light-weight materials which can be used as structural materials in the engineering applications where weight saving is critical for improved performance. Magnesium (Mg) and its alloys owing to their attractive physical properties have been potential candidates for light-weight structural materials. However, Mg alloys have been limited for use in high performance applications, such as in the aircraft and automotive industries due to their low mechanical properties. It has been demonstrated that Mg alloys composites reinforced with different particulates may provide superior properties. [2]

Magnesium alloys present a great potential as structural materials in the aerospace and automobile industries mainly because of their low density and high specific strength. However, because of their rapid loss of strength at temperatures above ambient and their poor creep resistance at elevated temperatures, they are rarely used above 190 °C (half the melting point), unlike aluminum alloys with a similar melting temperature. The addition of ceramic particles improves the creep resistance at intermediate and high temperatures. A second harder phase leads generally to an increase in the tensile strength, Young's modulus and hardness, particularly at room temperature, and to a reduction of the coefficient of thermal expansion (CTE). [3]

Compo-casting is a liquid state process in which the reinforcement particles are added to a solidifying melt while being vigorously agitated. It has been shown that the primary solid particles already formed in the semi-solid slurry can mechanically entrap the reinforcing particles, prevent their gravity segregation and reduce their agglomeration [4−6]. These will result in better distribution of the reinforcement particles.

The lower porosity observed in the castings has been attributed to the better wettability between the matrix and the reinforcement particles as well as the lower volume shrinkage of the matrix alloy. [7]

In order to improve the wettability between base matrix and reinforcement materials, the reinforcement particles pretreated by heat treating (artificially oxidized). For SiC oxidation, different workers have used varying temperatures and times. [8-10]

The purpose of this study is to investigate the feasibility of the fabrication of Mg MMCs reinforced with different SiC volume fractions using compo-casting technique. The microstructures, porosity, hardness and tensile strength of the composites are also discussed.

2. Experimental procedure

2.1. Materials

A pure magnesium metal used in the present work . The chemical analyses and properties of SiC particulates, which used in the present work are listed in Tables 1 and 2, respectively.

Table 1. The chemical analysis of the SiC particles (wt.%).

SiC	C	Si	SiO_2	Fe	Al_2O_3,	CaO,	MgO
99.3	0.20	0.05	0.1	0.005	<0.01	<0.01	<0.01

Table 2. Some physical and mechanical properties of the SiC particles.

Density g/cm^3	Modulus GPa	Tensile strength GPa	Yielding strength GPa	Thermal expansion coefficient (10^{-6}/K)
3.2	480	3	21	4.7

2.2. Processing

2.2.1. Alteration of SiC surface

The adsorbed gas layer that covers the SiC particles surface is responsible for poor wetting of the SiC particles with Mg base matrix as well as for the agglomeration. This may lead to the total rejection of reinforced particles. Also, the presence of gases after casting composite materials leads to undesirable voids, which influence on the density of the obtained composite. In order to improve the wettability between the base matrix and reinforcement materials, SiC particles were artificially oxidized in air at 900 ºC for 180 minutes to remove the adsorbed gases from the surface and to make the entire surface uniformly active, hence to enhance the wettability with the molten magnesium. [10]

2.2.2. Casting Procedures

About 200 gm of pure magnesium metal was melted in a electric heat resistance furnace, using a carbide crucible and three-blade graphite stirrer driven by speed motor at 900-1200 rpm. Argon gas with a flow rate of 1 L/min. was poured at the surface of molten Mg to avoid oxidation/ignition and to remove the undesirable gases, which takes place during melting and stirring processes.

In the compo-casting process, the magnesium metal was heated above its melting temperature and stirring was initiated to homogenize the temperature. Then, all inclusions are removed and degassing is completed, the temperature was then lowered gradually until the alloy reached a semi-solid state. At this temperature (650 ºC) the reinforcing SiC particles were introduced into the slurry. The high viscosity of the slurry combined with the action of stirring helps in minimizing the tendency for floating, settling, or agglomeration of SiC particles.

During the addition of the SiC particles, the temperature was raised gradually and stirring was continued until the interface between the particles and the matrix promoted wetting. Then, the melt was superheated above its liquidus temperature (about 100 ºC) and stirred by a speed motor at 900 r.p.m. At 700°C the composites slurry were poured into permanent steel mould (30 mm dia. and 120 mm height). Figure 1 presents a schematic illustration of the compo-casting apparatus which was used in the present work .

2.2.3. Microstructural Characterizations

The as-cast ingots were sectioned, polished and etched for microstructural analysis by optical microscope and scanning electron microscope (DSM 950 Der Firma Zeiss). The etchant is a solution mixture of 1ml NHO_3 (conc.), 24 ml water, 75 ml ethylene glycol.

2.2.4. Mechanical Properties

The macro-hardness was established by means of Vickers hardness testing using 10 Kg load. At least 10 macro-hardness measurements were made for each specimen to ensure accurate results. the macro-hardness values have also been checked for reproducibility with 3 specimens. the results cited are the average value from such multiple test.

Tensile tests of pure Mg and Mg-SiC composites were performed on flat specimen of 65 mm gauge length, 10 mm width, and 5 mm thickness with threaded ends, in accordance with standard DIN 50 125 requirements. Tensile test were done using a testing machine (com-ten with program software 2.1.25, U.S.A.).The tests were carried out at an applied strain rate of 0.20 mm/min. The reported results of the tensile tests are the average of three individual tests for three different samples.

3. Results and Discussion

3.1. Microstructural characterizations

In order to examine the effect of the fabrication process on composite quality, the microstructures of the composites obtained using compo-casting technique, with different SiC volume fraction were analyzed. The unreinforced Mg base matrix and reinforced material structures that solidified under the same solidification condition shown in Fig.2.

Figure 2 (a) shows the typical microstructures of Mg matrix prior to mixing. Typical solidification microstructure of SiC particles reinforced magnesium composite are shown in Figure 2 (b, c, and d) . It is noted that the grain boundaries of the magnesium matrix are decorated with a cluster of SiC, at the same time few SiC particles captured within the magnesium grains can be also observed.

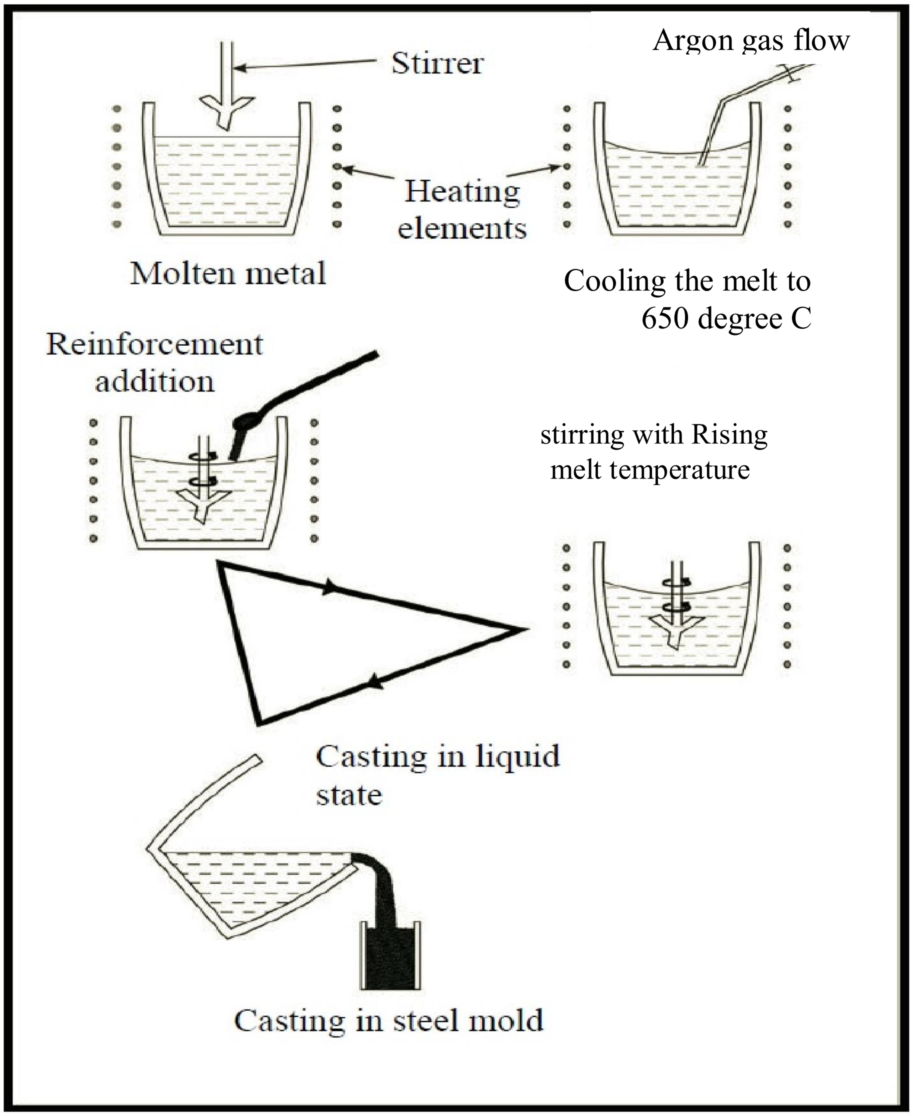

Fig.1. Schematic illustration of the compo-casting apparatus.

It is generally believed that in metals and alloys, solid particles in a solidifying melt which have low energy solid-liquid interfaces provide favorable sites for heterogeneous nucleation. [11]

This suggests that during solidification process of magnesium composite, most SiC particles were pushed by the primary magnesium phases into the last freezing regions, then entrapped in this area.

It can be also noted that the SiC particles are entrapped in a magnesium grain. This observation suggests that the SiC particle might act as the substrate for heterogeneous nucleation of primary magnesium.

On the other hand, it can be noted that the formation of the composite microstructure can discussed from the perspective of cooling rate depending on the fact that SiC particles have a lower thermal conductivity and heat diffusivity than the magnesium melt. During the cooling process the temperature of SiC particles is somewhat higher than that of the surrounding magnesium melt. The SiC particles with the higher temperature would heat up the surrounding magnesium melt, and thus retard its solidification. In such a situation, primary magnesium could not nucleate at the SiC particle surfaces, and the latter would be pushed by the solidifying primary magnesium. [12]

This good distribution of SiC particles into Mg base matrix refers to the fabrication method compo-casting technique, as described above. In a semi-solid state, primary Mg phase exists, so agitation can apply large forces on the SiC particles through abrasion and collision between the primary Mg nuclei and particles. This process helps to break the gas layers and perhaps the oxide layers as well and to spread the liquid metal onto surfaces of the particles, leading to achieve a good wettability.

The common advantage of using semisolid slurries is the increase in the apparent viscosity and the prevention of the buoyant migration of particles.

In the present study, the breaking of particle-surface gas layers is emphasized. When the gas layers are broken and the particles are wetted, the particles will tend to sink toward the bottom (due to higher specific weight) rather than float to the surface. However, this does not ensure a uniform particle distribution.

To improve the particle distribution, the second step is needed, i.e., to heat the slurry to a temperature above the liquidus and then to stir the melts using mechanical device. It was found that the compo-casting method leads to a homogeneous particle distribution in the alloy matrix.

The presence of SiC particles within Mg metal matrix act as a grain refiner as shown in Fig.2.

Figure 2 shows no reaction layer was observed at the particle/matrix interfaces. This clearly suggests that the method of preparation used in this study is effective, resulting in a near uniform distribution of the reinforcing phase in the metal matrix.

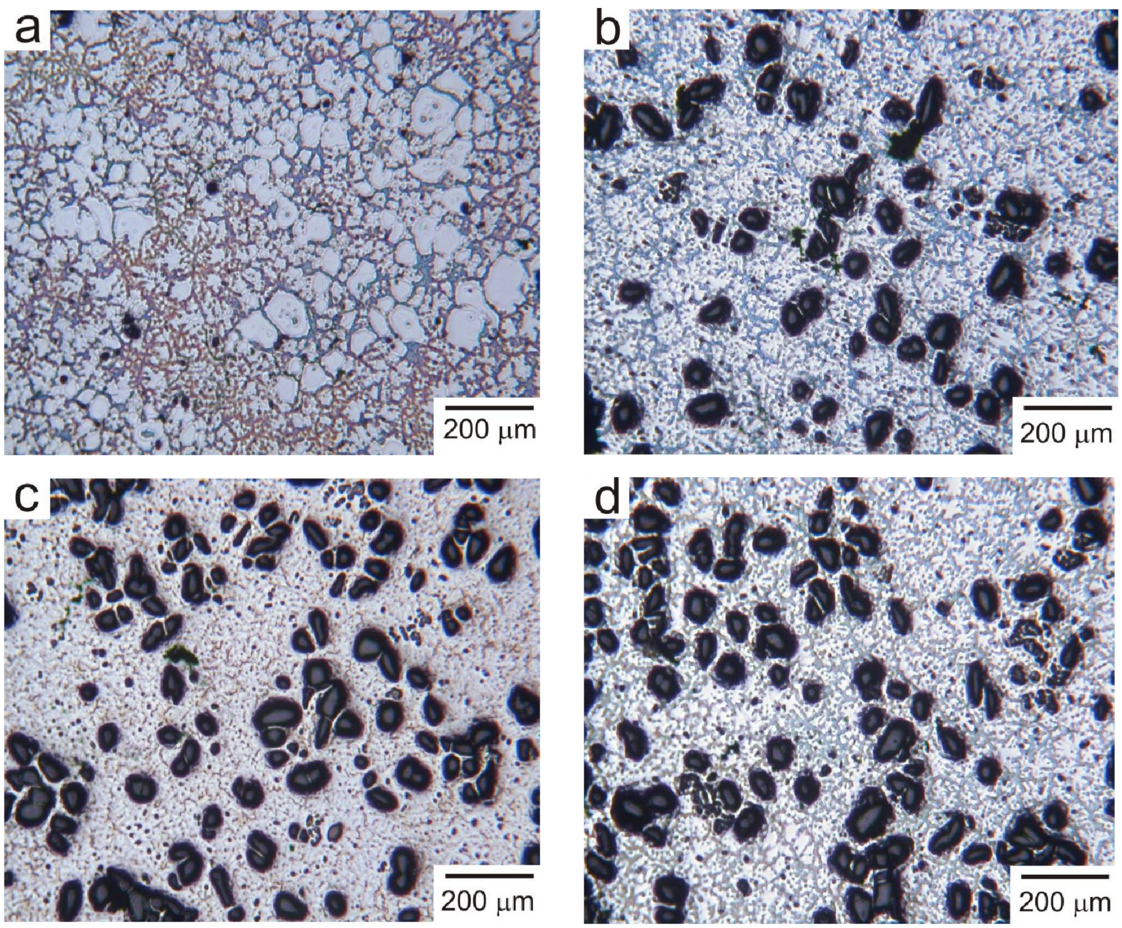

Fig.2. Optical micrograph of as-cast Mg-SiC composite, (a) unreinforced Mg metal, (b) Mg-10% SiC, (c) Mg-20% SiC, and (d) Mg-30% SiC.

3.2. Mechanical properties

Mg metal matrix and SiC particles are the main contributors for hardness of the obtained composites. The hardness, tensile strength, 0.2% yielding strength and elongation percent values obtained for Mg-SiC composites applying compo-casting techniques as a function of SiC contents have been listed in Table 3.

Table 3. Results of VH10, Tensile Strength, 0.2% Yielding Strength, and E% tests for as-cast Mg- SiC composites as a function of SiC content.

Composite Materials	Hv10	Max. Tensile strength (Mpa)	0.2% Yielding strength (Mpa)	E%
Mg-0% SiC	68.6	155	95	5
Mg-10% SiC	84.2	170	140	3
Mg-20% SiC	95.5	240	190	1.8
Mg-30% SiC	112.5	255	225	0.8

The correlation between the Vickers hardness number (HV10) and the SiC contents of as-cast Mg-SiC composites that were obtained by compo-casting are shown in Fig.3. It can be notice that a remarkable increase in the HV10 of composites Mg-SiC materials that were obtained by compo-casting technique.

The hardness of composites increases from HV10 = 68.6 to 112.5 (around %64) with increasing the volume fraction of SiC - particles from 0 % to 30 %.This remarkable increase can be attributed to the presence and good distribution of a harder SiC particles in the metallic Mg matrix, as shown in Figs. 2.

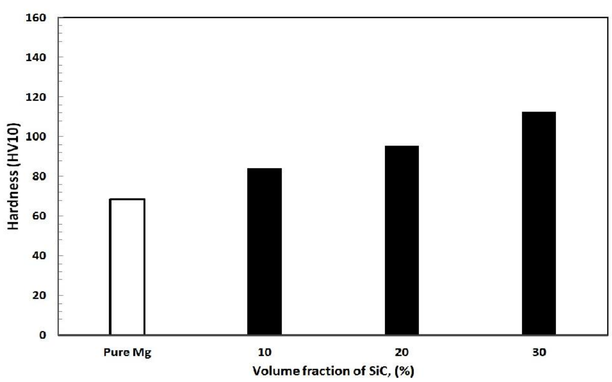

Fig.3 : Varition of the hardness value of Mg base composite with different percentage of SiC particles

Tensile and yielding strength properties of as-cast Mg-composite materials are shown in Fig.4. With the addition of a reinforcement phase, both tensile and yielding strength of the magnesium base metal are, in general, increased but considerably reduces the strain to failure Fig.5.

Particle strengthening, work hardening, load transfer, and grain refinement of the matrix alloy by the reinforcement phases are the key strengthening mechanisms in magnesium composites. The dispersion of fine and hard particles in the matrix drastically blocks the motion of dislocations and thus strengthens the material.

Work hardening takes place when the composite is strained. The strain mismatch between the matrix and the reinforcement usually generates a higher density of dislocation in the matrix around the reinforcement, thus strengthening the material.

magnesium strength is highly sensitive to its grain size. Thus, grain refinement contributes to the great strength at room temperature for both Mg alloys and the Mg matrix composite. [12,13]

However, it is also evident that the strain to failure significantly decreases as the volume fraction of the particulate increases, (Fig.5). This means that the matrix probably does not have sufficient internal ductility to redistribute the very high localized internal stresses. It is also obvious that the resistance to the dislocation motion of the hard particles reduces the ductility of the composite materials. Moreover, the presence of the SiC-particulates impedes the plastic flow of the matrix, initiating failure at low strains by the formation of cavities in the vicinity of the particulate.

In related studies conducted on as cast AZ91-SiC composites [14] , it was proposed that the presence of SiC particulate lead to localized damage, such as interface de-bonding and particulate breakage, resulting in lower elongation value. In fact it has pointed out by a number of authors [15, 16] that high matrix strength results in more particle related damages, while the material with lower matrix strength exhibited a smaller percentage of reinforcement damage at the fracture strain.

Generally, the strengthening effects, which can occur in the composite material, can be divided into direct and indirect strengthening. Direct strengthening mechanism includes the ability to transfer stress from the matrix to the stronger reinforcing particles. [17] This, in turn, depends on achieving a strong interfacial bond between the matrix and the reinforcement.

Therefore, If the bonding between the matrix and the reinforcement is strong enough, the applied stress can be transferred from the soft matrix to the hard particle phases. If the interfacial bond is weak, the interface will fail before any effective stress transfer to the particle can occur, and no strengthening is achieved. Indirect strengthening mechanisms include increased initial work hardening of the composite, grain refinement of the matrix alloy caused by the reinforcement phases, and the generation of a high dislocation density in the matrix as a result of difference in the coefficient of thermal expansion (CTE) of the Mg matrix ($26 \times 10^{-1}\ K^{-1}$) and the SiC reinforcement ($4.7 \times 10^{-1}\ K^{-1}$) which are the key strengthening mechanisms in magnesium composites. [12,13] Also the strain mismatch between the matrix and the reinforcement usually generates a higher density of dislocation in the matrix around the reinforcement, thus strengthening the material.

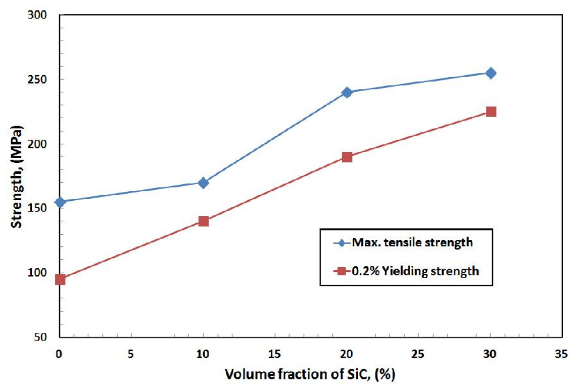

Fig.4 : The change in the 0.2% yielding and tensile strength of Mg base composite as a function of volume fraction of SiC

Also, it can be noted that at elevated temperature, ultimate tensile strength of obtained composite was increased with the presence of SiC reinforcement as shown in Fig.6.

Figure 7 shows the surface topography viewed from scanning electron microscope of the tensile fracture surface. It shows that the main reasons for the fracture surface was found to be the same for all SiC volume fractions.

The embedded hard particles in the matrix act as a barrier that resists the plastic flow of composites when it is subjected to strain. This can explain the improvements of the tensile properties in SiC composites, and others mechanical properties such as tensile strength and hardness.

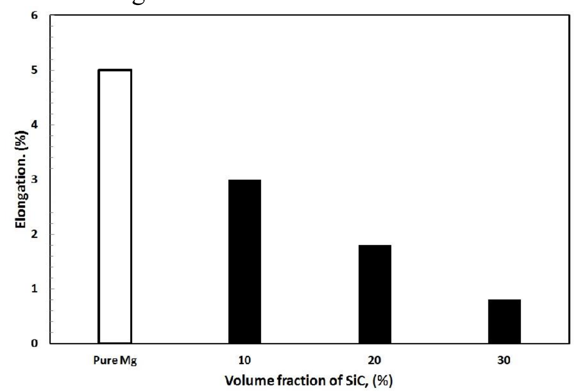

Fig. 5 : Varition of the tensile elongation of Mg base composite with different percentage of SiC particles

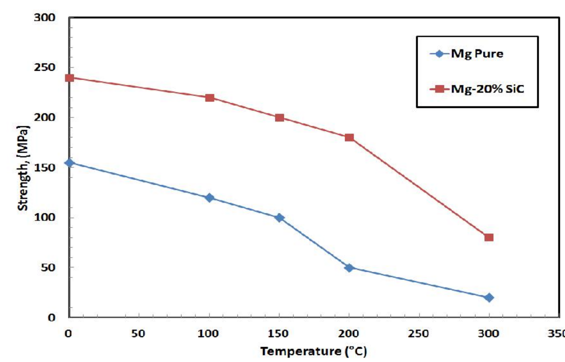

Fig. 6 : Affecting of temperature on Pure Mg base matrix and Mg-20% SiC composite material.

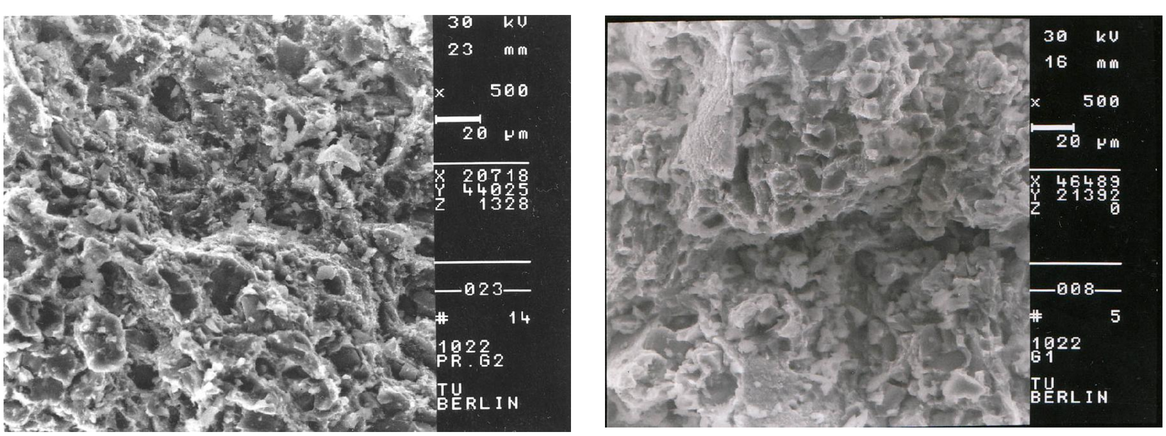

Fig.7. SEM micrograph of fracture surface of as-cast Mg-SiC composite.

The presence of hard particles in a soft matrix increases the dislocation density. The low ductility of the investigated composites could be attributed to the susceptibility to the effect of stress raiser.

4. Conclusion

The conclusions derived from this study can be summarized as follows:

1. Compo-casting technique was used successfully to produce Mg composites reinforced with 10% and up to 30% SiC particles volume fraction utilizing 50 µm of SiC particle size.

2. The heat treatment technique utilized (900 ºC + 3Hrs) enhanced the wettability of the composite components.

3. The composites produced by compo-casting technique showed good reinforcement distribution within Mg base matrix, and presence of SiC particles in the Mg base matrix affects the matrix microstructure. The grain structure of the composites is refined compared to the Mg base matrix.

4. The hardness of un-reinforced Mg metal matrix increases from HV10 = 68.6 to 112.5 (around %64) with increasing the volume fraction of SiC - particles from 0% to 30%.

5. The casting composites ultimate tensile strength and 0.2 yielding strength slightly increased with increasing of the SiC volume fraction, However the elongation is lower in the composites with increasing the volume fraction of SiC particulate.

6. At elevated temperature, ultimate tensile strength of obtained Mg-SiC composite was increased compared to unreinforced Mg metal matrix.

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