Temperature effect on mechanical and tribological characterization of Mg–SiC nanocomposite fabricated by high rate compaction

To cite this article: G H Majzoobi et al 2018 Mater. Res. Express 5 015046

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Temperature effect on mechanical and tribological characterization of Mg–SiC nanocomposite fabricated by high rate compaction

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Keywords: Mg–SiC nanocomposite, dynamic compaction, wear, mechanical properties, powder

Abstract

In this paper, dynamic compaction is employed to produce Mg–SiC nanocomposite samples using a mechanical drop hammer. Different volume fractions of SiC nano reinforcement and magnesium (Mg) micron-size powder as the matrix are mechanically milled and consolidated at different temperatures. It is found that with the increase of temperature the sintering requirements is satisfied and higher quality samples are fabricated. The density, hardness, compressive strength and the wear resistance of the compacted specimens are characterized in this work. It was found that by increasing the content of nano reinforcement, the relative density of the compacted samples decreases, whereas, the micro-hardness and the strength of the samples enhance. Furthermore, higher densification temperatures lead to density increase and hardness reduction. Additionally, it is found that the wear rate of the nanocomposite is increased remarkably by increasing the SiC nano reinforcement.

1. Introduction

Over the past decades, the need to reduce the fuel consumption in automotive and aircraft industries has prompted new developments in lightweight metals, alloys and composites [1]. Among the lightweight metals, Mg has gained more attentions as this material exhibits excellent castability, machinability at low temperatures of 250 °C–300 °C [2]. Attempts have been made to improve the stiffness and wear resistance, of Mg by adding harder and stiffer ceramic particle reinforcements to produce Mg composites [3, 4].

Mg-matrix composites (MMCs) are fabricated using different techniques in form of liquid or solid, such as stir casting [5], powder metallurgy (PM) [6], squeeze casting [7], and spray deposition [8]. PM is a preference for fabrication of nanocomposites by many researchers mainly due to its simplicity, near-net shape products, and low cost [9]. Among the ceramic reinforcements, SiC is is widely used to reinforce the metallic matrices [10].

Most of the PM methods utilize quasi-static loading for the powder compaction. These methods generally require hot sintering during or after the powder compaction to consolidate the powder particles and to produce the composite or nanocomposite samples. In return, powder particles can be consolidated using dynamic compaction techniques. The major benefit of high velocity or dynamic powder compaction (HVC) methods is that hot sintering stage is mostly omitted from the production cycle. In high rate compaction methods, normally an explosive or high pressure gas are employed as propellants to fire a projectile for densification of the powder. The energy required for the compaction can also be supplied by a drop hammer [11]. The concept of HVC was initially developed in 1960s [12]. Höganäs developed a novel hydraulic impact machine to compact some electrolytic copper powders [13]. Some other researchers [14, 15] also studied different cases of dynamic compaction techniques. The dynamic compaction requires lower sintering temperature and shorter sintering duration. Although, dynamic compaction methods enjoy some advantages, their imposed damage on the molds decreases the mold life and therefore, cannot be used for mass production.

Many studies on quasi-static powder compaction can be found in the literature [16, 17]. However, only few studies can be found on dynamic compaction [14], shock consolidation [18], or explosion consolidation [19].
Volger et al [20] reported higher density for dynamic compaction. It has been found that as the compaction temperature increases, mechanical behavior of the compact improves compared to the conventional double compaction and sintering techniques [21]. However, less attention has been paid to warm compaction of non-ferrous powders particularly Mg powder [22]. In warm compaction methods, elevated temperature plays the role of high impact to enhance mechanical behavior and density [23]. Recently, Arian et al [11, 24] and Majzoobi et al [23, 25] investigated the effect of temperature on high rate densification of Al-matrix composite. Their results showed that warm dynamic compaction increased the relative density and reduced the micro-hardness.

The use of Mg is usually limited by its low wear behavior. However, the Mg-matrix nanocomposite are popular for their wear properties which have application in various industries particularly automobile industry [26, 27]. Aatthisugan et al [28] studied the wear mechanisms of nanostructured AZ91D alloy. Sharma et al [5] studied the wear resistance of feldspot reinforced AZ91 composite. Their results indicated that the wear resistance decreased as the reinforcement content increased. Majzoobi et al [27] studied tribological behavior of Al7075/SiC nanocomposite produced by hot dynamic compaction. Similar investigations were carried out by Srinivasan et al [29], Wang et al [30] and Wei et al [31].

In the present study, dynamic powder compaction method is employed utilizing a mechanical dropping hammer to fabricate Mg–SiC nanocomposites. The main objective of this paper is to study the simultaneous influence of compaction temperature and the content of SiC nano particles on mechanical, microstructural, and tribological behaviors of the compacted samples.

2. Material

The commercially pure Mg powder (99.5% purity, irregular morphology, size of 60–150 μm, Merck Co., Germany) as the matrix and nano-sized SiC particles (irregular morphology, size of 50–100 nm, NAM Inc., USA) as the reinforcement were used in this study. The powders were milled in a glove box to reduce the effects of moisture and contamination that may affect the mechanical behavior of the nanocomposites [32]. About 0.12 g (0.5% wt) stearic acid (99% purity) as the process control agent was added to 25 g of the powder mixture. A Retsch PM-400 planetary ball mill with a ball-to-powder mass ratio of 3:1 was used to gain a uniform distribution of the nano reinforcement within the matrix at room temperature. In the present work, 0, 1.5, 3, 5, and 10 vol% of nano-sized SiC were added to the matrix. The process was performed for 1 h with 200 rpm rotational speed and in the presence of inert argon gas. Figure 1 shows the morphology of Mg and SiC nano particles.

3. Dynamic compaction using drop hammer

High rate compaction is normally conducted using impacting devices and in particular projectile launchers like gas gun [33], hydropulsor device [34] or dropping hammer which is used in this work. The schematic view of the device is depicted in figure 2(a). The compaction energy is supplied by dropping a 60 kg hammer from a height of 3.5 m. So, using the relation $V = \sqrt{2gh}$, the velocity of the hammer at the instant of impact is worked out to be around 8 m s$^{-1}$. This impact velocity corresponds to a kinetic energy of 2 kJ calculated from $E = \frac{mv^2}{2}$.

The schematic view of the die is shown in figure 2(b). The die and the punch are made of Mo40 (1.7225) and VCN150 (1.6582) steel, respectively to resist against thermal and impacting loads. Two tablets (5 mm length) of
VCN150 steel were also mounted on top and beneath of powder to reduce the spring-back and to preserve the surface quality of the compact [35]. The clearance between the tablets and the die wall was adjusted to around 0.10–0.15 mm. This was to prevent the powder to flee from the 0.25–0.3 mm clearance between the die wall and the tablets, during the dynamic compaction [11]. The required temperature (maximum about 450 °C) was supplied by a 1200 W furnace. The impact on the powder was accomplished when the powder temperature reached to a steady state. After compaction, the samples were ejected out of the die and were cooled at ambient temperature.

In order to lubricate the interfaces between the punches and the die, MoS₂ spray was applied. In addition, to explore the effects of temperature and nano reinforcement content, a number of experiments, as given in table 1, were designed. Cylindrical specimens (with the length of 11–12 mm and the diameter of 15 mm) of nanocomposites containing 0, 1.5, 3, 5, and 10 vol% of SiC were fabricated at 25 °C, 250 °C, and 450 °C. In each experiment, 3.5 g of the powder with a tap density of around 55% of the theoretical density was compacted using the drop hammer. The theoretical densities of Mg-1.5 vol% SiC, Mg-3 vol% SiC, Mg-5 vol% SiC, and Mg-10 vol% SiC samples were computed using the rule of mixture having \( \rho (\text{Magnesium}) = 1740 \, \text{kg} \, \text{m}^{-3} \) and \( \rho (\text{SiC}) = 3220 \, \text{kg} \, \text{m}^{-3} \) equal to 1762, 1784, 1814, and 1888 kg m⁻³, respectively. It is worth mentioning that the maximum applied temperature, 450 °C, is the sintering temperature of Mg that is roughly around 75% of melting temperature of its solid state [36].

### Table 1. The experimental design.

<table>
<thead>
<tr>
<th>Dynamic compaction</th>
<th>Temperature (°C)</th>
<th>SiC content (vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>25</td>
<td>0, 1.5, 3, 5, 10</td>
</tr>
<tr>
<td>Warm</td>
<td>250</td>
<td>0, 1.5, 3, 5, 10</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>0, 1.5, 3, 5, 10</td>
</tr>
</tbody>
</table>

![Figure 2. Schematic views of (a) the drop hammer and (b) the die.](image)
4. Characterization tests

The density of compacted specimens was measured using the Archimedes’ principle. Microstructural characteristics including morphology and distribution of powder and porosities were examined using optical microscopy and field emission scanning electron microscopy. For this purpose, the specimens were polished up to 0.05 μm finish and were etched for 7 s using 70 ml ethanol solution, 4.2 g picric acid, 10 ml acetic acid and 10 ml water according to the ASTM E 407-99 [37]. X-ray diffraction analysis was performed on polished specimens utilizing a Philips X’PERT PW3040 diffractometer (40 kV/30 Ma, λ = 0.154 059 nm) and scanning speed of 2° min⁻¹. Wear tests were also performed under dry conditions using a pin-on-disc tester according to ASTM G99-05 [38]. The tests were then performed for a total sliding distance of 500 m, normal load of 20 N, and sliding speed of 0.09 m s⁻¹. Prior to testing, pins and disc surfaces were cleaned with acetone. AISI 52100 carbon steel pins with the hardness of 63 RC were used as the counter faces. After each test, the weight of the specimens was measured using a scale with 0.1 mg precision and the weight loss of the specimen was calculated. Having measured the weight loss and the sliding distance the wear rate can easily be determined.

Mechanical behavior of the nanocomposite samples was also investigated by measuring the micro-hardness and compressive strength of the samples. The Vickers micro-hardness was measured as suggested by the ASTM E384-99 [39] and the compressive strength was obtained according to ASTM E9-89a [40] using a Santam testing machine at the rate of 1 mm min⁻¹. The test cylindrical samples had a 15 mm diameter and a length of 12 mm. For each test conditions given in tables 1, 3 samples were tested to make sure of the repeatability of the tests [41].

5. Results and discussion

5.1. Density

The results for relative density and porosity measurements of the compacted samples at 450 °C are shown in table 2. The porosity is measured using the following equation [42]:

\[
\% \text{porosity} = \left( \frac{\text{Theoretical density} - \text{Experimental density}}{\text{Theoretical density}} \right) \times 100.
\]  

(1)

The theoretical density in this equation is calculated using the rule of mixture as follows:

\[
\rho_{\text{theoretical}} = \rho_m \varphi_m + \rho_r \varphi_r.
\]  

(2)

where \(\varphi_m\) and \(\varphi_r\) represent the volume fraction of matrix and reinforcement, respectively. \(\rho_m\) and \(\rho_r\) are also density of matrix and reinforcement, respectively. As the results indicate, the experimental and theoretical densities increase with the SiC content. The increase is due to the higher density of SiC nanoparticles than Mg particles. Relative density indicates the porosity of sample and is an important measure to qualify the compaction technique [43].

Variation of the relative density versus temperature and nanoparticles contents are shown in figure 3. As the figure suggests, temperature and the content of nanoparticles exhibit opposite effects on the relative density. As it is seen, while the relative density is improved at elevated compaction temperatures, it is reduced when the content of nanoparticles increases. The reason is that at elevated compaction temperatures, the strength and the strain hardening of the powder are reduced and higher densifications may be obtained [44]. In contrast, the addition of SiC nanoparticles results in the enhancement of strain hardening and strength of the nanocomposite and consequently lead to the reduction relative density and porosity [45].

Density measurement is a benchmark for powder compaction quality and has been a key parameter in nearly all investigations in the field of PM. Khalil [46] showed that relative densities of Mg-HAp nanocomposite decreased with the increase of nano-hydroxyapatite (HAp) addition. He attributed the reduction behavior of relative density to nanoparticles clustering. Sankaranarayanan et al [41] and Thakur et al [16] also reported the same results for their fabricated composites. The results of this work implied that by using the compaction
technique used in the current work, near dense materials with porosities less than 1.8% for the compactions at 450 °C can be obtained. However, for the samples compacted at room temperature higher porosity of about 3% was observed. High relative density obtained in the current research is attributed to the type of adopted procedure. During high rate densification, the kinetic energy delivered to the powder rises as the impact speed increases, according to the equation \( E = \frac{mv^2}{2} \). The energy delivered to the powder during compaction process causes large strain rates and therefore, the process is considered as an adiabatic process. This implies that the internal heat due to large deformations cannot be dissipated and gives rise to local temperature increase in the nanocomposite and consequently softening the particles surfaces which is known as thermal softening phenomenon. On the other hand, the friction due to the movement of the particles accelerates the localized temperature rise that in turn causes plastic deformation and softening the surface layer of particles. This phenomenon improves the bonding between the particles and brings about further increase in the green density [24].

### 5.2. SEM examination

Figure 4 shows the morphology of Mg and the milled mixture. Figure 5 clearly illustrates that the surface of Mg micro-particles are sufficiently covered by SiC nano-particles after 1 h of mechanical milling.

SEM pictures of densified specimens at 450 °C are illustrated in figure 6. As the figure shows, the volume and number of porosities and voids increases as the volume fraction of SiC nano-reinforcements increases.

Typical optical pictures of samples depicted in figure 7 exhibit less voids and porosities at elevated temperatures. It is worth mentioning that the specimens consolidated at lower temperatures exhibited voids with sharp corners. This implies that the samples have not been sintered appropriately. Nevertheless, as illustrated in figure 7(c), at higher temperatures the particle are welded and bonded together and less porosities can be observed. This is due to thermal softening of the powder that happens when the powder is compacted at a specific temperature. In this case, the strength and work hardening of the powder decrease and the powder particles become softer.
Figure 5. (a) A Mg particle after milling with SiC nano particles, (b), (c) x-ray maps of SiC particles.

Figure 6. Dynamically compacted specimen at 450 °C: (a) Mg ($\rho = 1.7236$), (b) Mg-1.5 vol% SiC ($\rho = 1.7430$), (c) Mg-3 vol% SiC ($\rho = 1.7613$) (d) Mg-5 vol% SiC ($\rho = 1.7852$) (e) Mg-10 vol% SiC ($\rho = 1.8458$) (f) EDS point analysis of the region around the agglomeration of nano-SiC particles shown in (d), (e).
5.3. X-ray diffraction examinations

XRD of the compacted specimens was performed to study the structural evolution of the powders after mechanical milling and during hot compaction. The crystallite size of Mg matrix was estimated from the broadening of XRD peaks using Williamson–Hall (W–H) method [47]. Figure 8 illustrates the XRD patterns of Mg powder and Mg-1.5 vol% SiC compacted samples at different temperatures. It is clear that no new phases were produced after dynamic compaction even at elevated temperatures. It is well known that temperature affects the microstructure and may lead to grain growth under uncontrolled thermal conditions [48]. In this regard, W–H approach [11] was employed to assess the lattice strain and crystallite size of the Mg matrix. W–H analysis showed that the Mg crystallite size increased from 49 to 462 nm when the compaction temperature increased from 25 °C to 450 °C. Moreover, the lattice strain also increased from 0.19% to 0.43% during this temperature rise. As stated before, this behavior can be attributed to grain growth induced by temperature rise [49]. More details about W–H analysis and the computational procedure can be found in [11]. Ahmed et al [49] reported similar increase in grain size of Al7075-SiC nanocomposites produced by hot static compaction. They attributed this grain coarsening to the lower degree of precipitation.

5.4. Hardness measurement

Variations of Vickers micro-hardness (HV) versus SiC volume fractions at different temperatures for compacted samples are illustrated in figure 9. As the figure suggests, the SiC reinforcement has enhanced the Vickers micro-hardness particularly at elevated temperatures. This improvement can primarily be due to the relatively uniform distribution of SiC nano reinforcement [50]. The hardness improvement can be due to two reasons: (a) the intrinsic hardness of the nanosized SiC reinforcements, (b) the hardening effects of SiC nano particles (the presence of harder SiC reinforcements serves as constraint to localized deformation during indentation). Similar observations on composite micro-hardness have also been reported by Tun [51] and Thakur [16]. As stated at
early lines of this paragraph, SiC reinforcement play a more influential role at higher temperatures. This is obviously associated to better consolidation of the samples at elevated temperatures, which provides a favorable condition for hardening effects of ceramic reinforcements. In other words, the spaces between the powder particles disappear at elevated temperatures and a more qualified sintering is obtained \[^{22}\]. However, the samples compacted at room temperature remain porous to some extent \((\text{figure 10})\). Under such conditions, the addition of SiC nanoparticles, which is inherently a hard material, to the substrate is useless and cannot make any contribution to the hardness of material.

In order to examine the uniformity of hardness distribution, the Vickers micro-hardness was measured on the longitudinal and transverse sections of the dynamically compacted samples as illustrated in \(\text{figure 11}\). As \(\text{figure 12}\) indicates, the hardness measurements follow nearly a uniform distribution trend in transverse and longitudinal cross sections of the sample (less than 1% deviation). This may be interpreted that SiC reinforcement particles are distributed uniformly throughout the microstructure during the dynamic compaction process.

5.5. Stress–strain curves

Uniaxial compressive tests were carried out at the velocity of 1 mm min\(^{-1}\) and ambient temperature using a SANTAM universal testing apparatus. Figure 13 illustrates typical engineering stress strain diagrams of dynamically compacted specimens at ambient temperature. As the figure suggests, reinforcing Mg matrix with SiC nano particles has improved the compressive strength by about 26% and has reduced the ductility by around 37%. Variations of the ultimate compressive strength (UCS) of nanocomposite samples compacted at different temperatures are depicted in \(\text{figure 14}\). As the figure suggests, depending on the SiC content, the UCS of the nanocomposites increases by about 83% and 47% for 250 °C and 450 °C temperatures, respectively. The increase of UCS is definitely partly due to the strengthening influence of SiC.

Moreover, a layer of Mg oxide which usually covers the Mg particles, can act as a strengthening phase \[^{52}\]. Some evidences about the presence of Mg oxide are discussed in section 5.6. As \(\text{figure 14}\) demonstrates for all
compaction temperatures, the highest improvement in UCS is obtained for the 5 vol% SiC reinforced sample. Further addition of SiC will cause reduction in the UCS. The reason is that as the reinforcement content increases, the sample porosity will also increase, as discussed in section 5.1. Furthermore, higher contents of hard ceramic SiC nano particles increases the chance of nano particles agglomeration inside the sample (see figure 6(e)).

Figure 15 typically shows the effects of compaction temperature on compressive flow stress of the non-reinforced samples. It is clear that the temperature has significantly improved the UCS and elongation of the
samples by about 113% and 109%, respectively. Variation of UCS versus SiC content for various temperatures is shown in figure 16. As the figure indicates, the improvement of UCS, as the temperature approached 450 °C, is about 122%, 150%, 147%, and 120% for Mg-1.5 vol% SiC, Mg-3 vol% SiC, Mg-5 vol% SiC, and Mg-10 vol% SiC, respectively. Generally, reinforcing a metal matrix with ceramic particles does not increase the strength of the composite continuously with the increase of the particles content. Rather, the initial positive effect on the strength which usually changes in a linear fashion, has an optimum beyond which adding more reinforcement
may lead to the composite degradation. The reason for this behavior is partly due to stress concentration and crack propagation that normally take place in reinforcing particle clusters [53]. Akbarpour et al [54] demonstrated that the increase of nano SiC content from 4% to 6% in copper/SiC nano composite diminishes the yield stress of the compacted powder. They attributed this behavior to weak bonding between particles in nano particle clusters. Some researchers [55, 56] also believed that this behavior was due to weak bonding in nano particle clusters as well as non-uniform dispersion of reinforcing particles. Figure 16 shows how the compaction temperature can improve the strength of the samples. This improvement is believed be due to higher consolidation and sintering quality of the samples fabricated at elevated temperatures, as discussed previously in section 5.1.

### Table 3. Compressive properties of fabricated samples at different temperatures.

<table>
<thead>
<tr>
<th>Sample/parameter</th>
<th>0.2 CYS (MPa)</th>
<th>UCS (MPa)</th>
<th>Failure strain (%)</th>
<th>Toughness (MJ m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg</td>
<td>45</td>
<td>75</td>
<td>112</td>
<td>75</td>
</tr>
<tr>
<td>Mg-1.5%SiC</td>
<td>50</td>
<td>80</td>
<td>116</td>
<td>80</td>
</tr>
<tr>
<td>Mg-3%SiC</td>
<td>65</td>
<td>82</td>
<td>130</td>
<td>82</td>
</tr>
<tr>
<td>Mg-5%SiC</td>
<td>77</td>
<td>100</td>
<td>153</td>
<td>95</td>
</tr>
<tr>
<td>Mg-10%SiC</td>
<td>72</td>
<td>95</td>
<td>118</td>
<td>88</td>
</tr>
</tbody>
</table>

![Figure 17. Variation of weight loss versus sliding distance in nanocomposite samples.](image17)

![Figure 18. The effect of SiC vol% on wear rate.](image18)
Under compressive loads, the addition of SiC nano reinforcement enhanced the UCS about 26% and 47% at room and 450 °C, respectively. The compressive properties of the fabricated samples are shown again in table 3. Generally, the fracture strain (elongation) of pure Mg were found to decrease with addition of SiC nanoparticles. The increase in the UCS of the nanocomposites is believed to be influenced by (a) Orowan strengthening due to the presence of nano SiC [24] and (b) mismatch in the coefficient of thermal expansion (CTE) values (CTE of Mg is $24 \times 10^{-6} \text{K}^{-1}$ and SiC is $4 \times 10^{-6} \text{K}^{-1}$) leading to generation of dislocations [23]. Temperature plays an important role in strengthening of nanocomposites through thermal mismatch phenomenon [57]. Different thermal properties of the reinforcing particles and the matrix generally causes thermal stresses in the interface regions during the cooling stage of compaction process. The thermal mismatch stress gradient is sufficiently large to produce plastic deformation at the boundaries. However, the stress decreases sharply when moving away from the particles border. Moreover, small defects such as dislocation buildup in the vicinity of nano inclusions may be generated by this high stress gradient [57, 58] giving rise to enhancement of the strength of composite. Zhang and Chen [57] believed that thermal mismatch stresses were the most significant cause for strength improvement of nanocomposites with higher content of nano-reinforcement.

It was found that reinforcement decreased ductility and energy absorbability of the powder (toughness), which is equal to the area under the stress–strain curve. The hard and non-deformable ceramic reinforcements are believed to be responsible for increasing the brittleness and reducing the toughness and fracture strain of the nanocomposite samples.

5.6. Wear resistance behavior

Variation of weight loss versus sliding distance for nanocomposite samples is shown in figure 17. Variation of wear rate against the SiC content is also shown in figure 18. As the figure suggests, for the 20 N applied load and 500 m distance, the wear rate decreases from 3.55 to 1.48 mg m$^{-1}$ depending on the SiC volume fraction. Lim et al [59] reported that wear resistance of SiCnp-reinforced MMC was improved with respect to monolithic Mg samples. Abachi et al [60] also reported similar results for QE22 magnesium alloy reinforced with SiC under different sliding conditions. The decreased wear rate observed in this work may be due to stronger bonding between Mg and SiC particles during high rate compaction and hardness effects of the ceramic reinforcements [15]. The decreasing behavior of the wear rate and the increasing trend of the wear resistance of the reinforced samples is associated to the enhanced hardness of the nanocomposite.
In order to have a deeper insight into the wear mechanism, the worn surfaces of the Mg–SiC nanocomposite samples were examined using SEM. Figures 19 and 20 show the SEM pictures of the worn surfaces of the samples of different SiC volume fraction.

Figures 19(a), (b) clearly indicate delamination and craters on the worn surface. This implies that delamination is one of the major wear mechanism on the worn surface [60]. With regard to the fact that no significant metal flow on the surface are visible and only some craters are observable, another wear mechanism can be the mild adhesive [61]. During the adhesive wear, small parts of material separates from the surface due to adhesion to the pin and therefore, some craters are created. Abachi et al. [60] reported that delamination reduces wear resistance of the samples. The narrow grooves evident in figures 19(b) and (c) imply that abrasion can also be a prevailing wear mechanism [60, 61]. This can be featured to the existence of hard SiC nano particles which confine the material flow during sliding [61]. These hard particles behave as abrasive agent and create most of the

Figure 20. Wear track in dynamically compacted sample, (a) Mg-0 vol% SiC (b) Mg-5 vol% SiC (c) Mg-10 vol% SiC.
narrow grooves displayed in figure 19(c). As a result, the effective load is increased while transferred from the matrix to the hard ceramic particles, and accordingly, as SiC fraction increases, the wear rate decreases \[62\]. Presence of Mg oxide is evident in figure 19(a) as small bright points. These oxides that have been identified using EDS analysis are produced during mechanical milling and wear test due to generated frictional heat. Mg oxides clearly contribute to the material strengthening and to the governing wear mechanism as well so that, delamination is usually accompanied by oxidation wear mechanism \[63\].

Figure 20 illustrates the SEM pictures of the worn surfaces of pure Mg, Mg-5 vol% SiC and Mg-10 vol% SiC nanocomposite, respectively. Apparently, the wear track of pure Mg sample (figure 20(a)) is relatively rough whereas the wear track of the nanocomposite sample (figures 20(b) and (c)) are relatively smooth due to the resistance of the reinforcing SiC to indentation. A comparison between figures 20(a)–(c) clearly reveals a strong interfacial bonding between the SiC particles and Mg matrix which in turn gives rise to improvement of the wear tolerance \[15\].

Variation of friction coefficient (FC) versus sliding distance is illustrated in figure 21. As the figure suggests, in all cases, FC varies initially in a nonlinear fashion and gets asymptotes to a constant level afterward. The extent
of the nonlinear segment and the constant level differ with the Mg content. For the pure Mg sample, FC has the highest mean value of around 0.9. For Mg-5 vol% SiC and Mg-10 vol% SiC this mean value is about 0.27 and 0.23, respectively. The figures indicate again that higher levels of SiC reinforcements improve the wear behavior which in turn, decrease the FC mean value. Lower FC for Mg–SiC samples is believed to be due to their higher hardness. As a matter of fact, when the hardness increases, the actual contact area between the steel pin and the sample surface diminishes and therefore, the magnitude of FC reduces [64].

6. Conclusion

Based on investigations presented in this paper, the following conclusions may be derived:

1. Adding nanoscale SiC reinforcements increased the Vickers micro-hardness from 45 to 58 (28% increase). This increase was more remarkable for samples fabricated at higher temperatures and was about 35%.

2. XRD analysis showed that the increase of the compaction temperature from 25 °C to 450 °C led to Mg matrix grain coarsening from 49 to 462 nm. The lattice strain also increased from 0.19% to 0.43% during this temperature rise.

3. By increasing the temperature up to 450 °C the UCS of Mg–5%SiC np sample increased around 150%.

4. The wear rate of Mg–SiC nanocomposite decreased up to 58% with the increase of the SiC content.

5. The governing wear mechanisms of nanocomposites were delamination and mild adhesive.

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