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Mechanical and microstructural characterization of AA6061 reinforced with SiC particles

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Abstract

AA 6061 reinforced with four different volume fractions of SiCp (5, 10, 15, and 20%) were produced by powder metallurgy processing using hot compaction (HC) temperature ranging from 400-500ºC. The effect of HC temperature and the volume fraction of the SiC reinforcement were investigated for the degree of consolidation, hardness profile, and microstructural evolutions. Microhardness measurement were taken to assess the variation in hardness across the diameters of the disks and following a rectilinear grid pattern to give color-coded maps of the hardness distributions. The highest Vickers hardness results were produced for AA6061 reinforced with 15% SiC. Increasing SiC volume fraction impeded grain boundaries diffusion, which resulted in lower grain coarsening of the AA6061 matrices. Comparing the relative densities and Vickers hardness of the hot compacted samples, the HC temperatures ranging from 400 -500 ºC had insignificant influence on the densification and hardness results.

1. Introduction

Aluminium alloys have a wide variety of industrial applications because of their low density and good workability. Although, aluminium alloys offer important advantages in terms of their specific strength, corrosion resistance and thermal conductivity, their use is limited by their relatively low yield strength, and poor tribological characteristics [1-3]. Aluminium alloys are one of the most important groups of structural materials in various industries, the low hardness and low wear resistance, however, have limited the applicability of aluminium alloys in certain cases [4]. The aim to increase aluminium strength for applications in the aerospace and aeronautics industries has motivated the study of aluminium matrix composites. Recently, a number of composites have presented excellent mechanical properties at both, medium (473 K) and room temperatures [5-8]. It is well known now that aluminium, aluminium alloys, and aluminium composites can be strengthened by dispersing hard particles such as carbides, oxides or nitrides into the aluminium matrix by using different techniques in the solid or liquid state [9]. In particular aluminium composites can be prepared in the solid state by powder metallurgy (PM), which additionally presents versatility and lower production costs. This type of composite production process involves the mixing of reinforcement particles with the metallic powder, followed by consolidation and sintering processes. Other methods also include mechanical alloying (MA) and mechanical milling (MM), which renders composites with fine and homogeneous distributions of the particles [10-11].

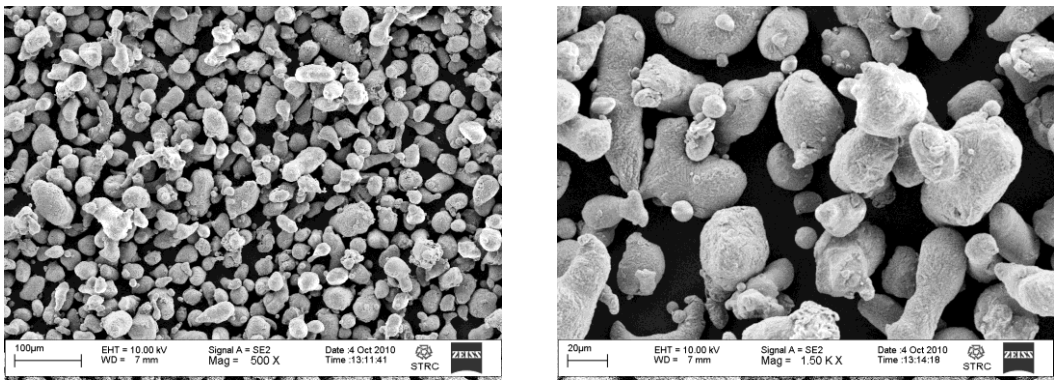
A number of researches investigations have been carried out in recent years to develop engineering materials that are stronger, stiffer, and more wear-resistant than the presently available commercial materials [12-15]. Metal matrix composites (MMCs) are regarded as excellent materials to obtain properties that are superior to those of the constituent phases and also to satisfy the above requirements. However, the higher cost of processing the composites limits their use. MMCs have become increasingly used for critical structural applications in industrial sectors because of their excellent stiffness to density and strength to density ratios. Aluminum is the most popular matrix for the metal matrix composites. MMCs can be reinforced with continuous fibre or discontinuous particles or whiskers [16]. Particle-reinforced MMCs possess distinct advantages over fibre reinforced composites in terms of low cost and isotropic mechanical properties considerations. In general, ceramic particulates are prepared independently prior to composite fabrication. The particulates are introduced into the matrices via ingot casting and powder metallurgy (PM) processes. In the latter route, the scale of the reinforcing phase is limited by the starting powder size, which is typically of the order of microns to tens of microns and rarely below 1 μm. It is generally known that agglomeration of ceramic particulates could occur during PM processing of the MMCs. Agglomeration of reinforcement could lead to the composites having poorer mechanical strength and toughness. Uniform distribution of ceramic particulates in the matrices of MMCs is essential to achieve effective load-bearing capacity of the reinforcement. Moreover, possible interfacial chemical reactions between the reinforcements and the matrix could also degrade the mechanical properties of ex-situ MMCs [17-19].

2. Materials and Experimental Procedure

2.1 Materials

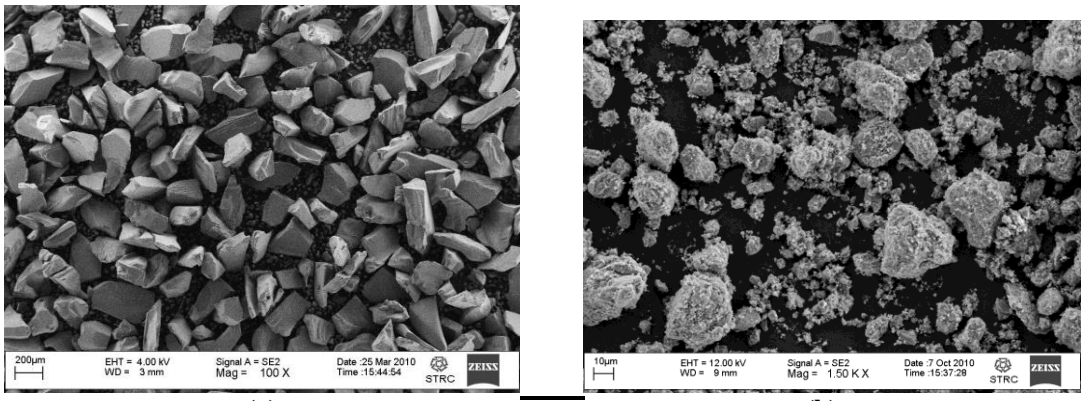
The investigated aluminium alloy 6061 (AA6061) was received in the form of powder with 30 Micron average size, as shown in Fig. 1a at low magnification.

AA6061 particles were characterized by uniformity in shape with variation in size from 10 to 45 µm as shown in Fig1b at high magnification. SiC intermetallic powder with average particles size of 100 µm was milled using high energy Planetary ball mill at a rotation speed of 500 rpm, ball -to- powder ratio of (30:1) for 72 hours duration at room temperature in agate jars and agate balls (10 mm in diameter). After milling, the SiC powder particles size was reduced to ≈ 1µm, while clustered particulate were found to be 25 Micron. Fig.2a, 2b shows SEM images for the SiC powder before and after milling. Figure 3 shows the particles size distribution of AA6061, Fig.4 shows the clusters size distribution of SiC powder after milling. The milled powder was used for AA6061 reinforcement. Four different volume fractions of SiC (5, 10, 15, and 20%) were chosen for the reinforcement of AA6061 matrices.



(a) **(b)**

Fig.1 SEM images for AA6061 powder at: (a) low magnification; (b) high magnification.



(a) **(b)**

Fig.2 SEM images for SiC powder: (a) as received powder; (b) milled powder.

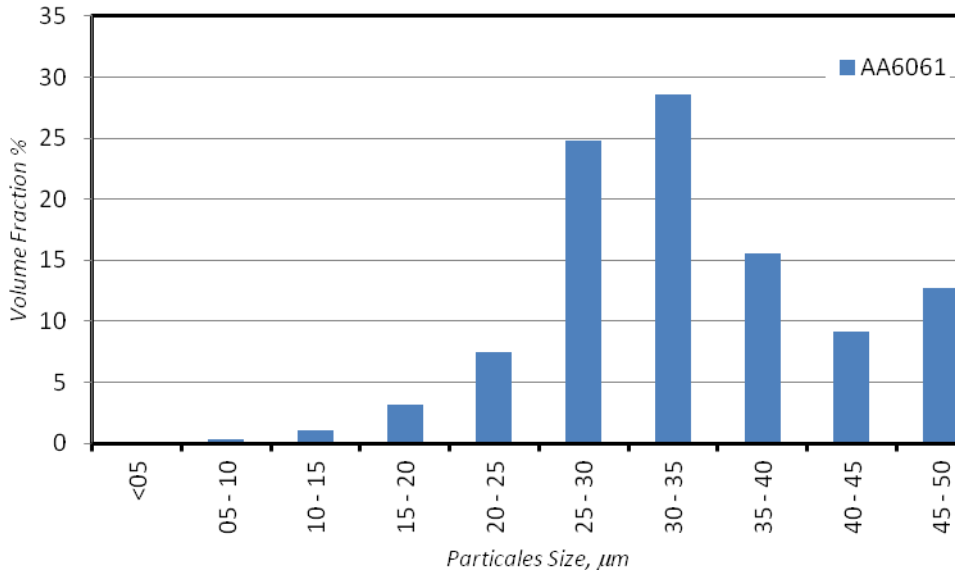


Fig.3 Particles size distribution of AA6061.

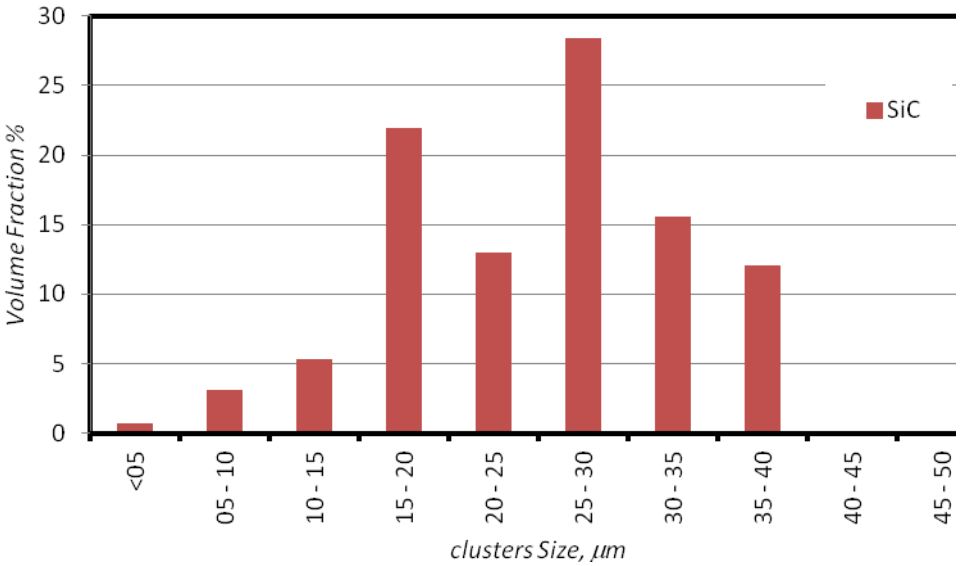


Fig.4 SiC clusters size distribution.

2.2 Mixing

To fabricate the AA6061-SiC composite, the required fractions of AA6061 and SiC powders were mixed under vacuum in Argon atmosphere in a glove box followed by mixing in a turbula blender operating at a rotation speed of 96 rpm for 3 hrs.

2.3 Compaction and sintering

The obtained mixtures were uniaxially hot compacted into cylindrical sample 10 mm in diameter and 10 mm in height. The compaction process was carried out at compaction pressure of 525 MPa at temperatures of 400, 450, and 500 ºC for 30 min. Variable temperatures were investigated so that the lowest compaction temperature suitable for producing an intact solid samples is obtained to minimize grain coarsening associated with sintering as a primary processing stage. Table 1 lists the hot compaction conditions for the various composite mixtures investigated in the current research.

Table 1 AA6061/SiC composite condition at constant pressure of 525 MPa for 30 min as a function of temperature and SiC volume fractions.

Condition No.	Temperature(°C)	SiC%
1	400	0
2	450	0
3	500	0
4	400	5
5	450	5
6	500	5
7	400	10
8	450	10
9	500	10
10	400	15
11	450	15
12	500	15
13	400	20
14	450	20
15	500	20

3.4 Characterization

Density of the specimens was measured using Archimedean principle using Mettler Toledo densitometer by determining the specimens mass and volume, based on the apparent loss of weight after immersing the specimen in Xylene. Relative density of the composite was determined as a function of the theoretical density. Sample preparation was conducted through consecutive steps of grinding using Buehler SiC grinding paper with grits of 240, 320, 400, 600, 800, and 1200, then polished using 1.0 micron Al_2O_3 powder (Buehler ltd) as a polishing media. Keller's reagent and a 0.5 % HF solution were used as etchant [.

Macrohardness measurements were conducted on the polished surfaces without etching using digital metallic Vicker's hardness tester (TH 721). Testing was carried out on the surfaces under applied load of 10 N for 15 sec dwell time. Vickers macro hardness HV measurements were recorded on the polished surfaces so that a rectilinear grid pattern defined by the two arbitrary axis X and Y was produced to show the hardness profile across the surface of the samples. These two axes were established so that they lie parallel to two perpendicular diameters on the surface of each disk with the position (0, 0) representing the centre of each sample as shown in Fig 5. The macrohardness measurements were taken using two different procedures. First, individual values of HV were recorded across the diameter of each disk in incremental steps of 0.5 mm. At each selected point, the average hardness was obtained by taking individual measurements of HV at four separate points uniformly positioned around the selected point at equal distances from the point of 0.15 mm. These measurements provided detailed quantitative information on the precise variation of HV across the diameter of each disk under different testing conditions, and by taking four separate values at each point it was possible to estimate the associated error bars at the 95% confidence level. Second, individual measurements of HV were recorded on the surface of each disk following a regular grid pattern with a spacing of 0.5 mm between each separate point. Following the procedure introduced in earlier experiments, these individual values of HV were then plotted as color-coded contour maps depicting the variation of the local hardness across the surface of each sample.

Microstructural characterization of the prepared surfaces of the samples was carried out using a Lica optical microscopy (OM) on the etched surfaces.

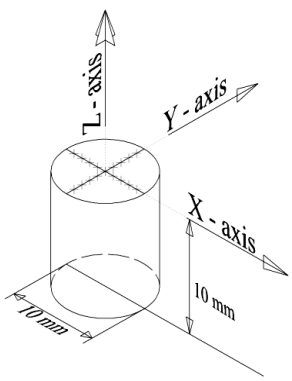


Fig. 5 Schematic drawing showing the hardness measuring points relative to X and Y axis.

3. Results

3.1. Density

Figure 6 shows the relative density variation as a function of hot compaction temperatures for of SiC content (0%, 5%, 10%, 15%, and 20%). It showed that the relative density slightly decreased with increasing the hot compaction temperature. From Fig. 6 it is obvious that the lower the SiC content, the higher of the densification for all compaction temperatures. However, it is clear that hot compaction temperature of 400-500ºC had insignificant influence on the densification. Accordingly, 400ºC compaction temperature was selected as the lowest temperature that is most suitable for producing intact compact disks.

3.2. Macrohardness measurements

It is convenient to take the hardness measurements and plot them in a three dimensional form where by the individual values of HV are plotted against the position of each point defined in terms of X and Y axes. These 3-D displays provide simple pictorial display of the hardness distribution throughout the surface of each sample; also, color- coded contour maps showing the Vickers macro hardness across the surface of samples were done. Hardness profiles of the unreinforced AA6061 and their composites containing different volume fraction of SiC (5, 10, 15, and 20%) using different hot compaction temperature are shown in Figs 7-11. It is apparent from Fig. 7 that the macrohardness distribution of the unreinforced sample is homogeneous, with average macrohardness value of (HV ~63 as Fig. 7a, HV~61 as Fig. 7b, and HV~60 as Fig. 7c). The hardness increased when using reinforcement of 5% SiC and the distribution still uniform as seen in Fig. 8, with average hardness value of (HV ~78 as Fig. 8a, HV ~76 as Fig. 8b, and HV ~72 as in Fig. 8c). The variation of hardness using reinforcement of 10% SiC shown in Fig. 9, with average hardness value of (HV ~88 as Fig. 9a, HV ~82 as Fig. 9b, and HV ~77 as in Fig. 9c). Fig. 10 shows the hardness distribution in case of using 15% SiC content, the average hardness became (HV ~96 as Fig. 10a, HV ~10 as Fig. 10b, and HV~ 78 as in Fig. 10c). With using reinforcement of 20% SiC the average hardness was (HV ~89 as Fig. 11a, HV ~87 as Fig. 11b, and HV~87 as in Fig. 11c). The value of the Vicker's macrohardness that, recorded across the diameter of each sample against the distance from the centre were plotted in Fig. 12, these data delineate the results obtained when conducting hot compaction of samples of the unreinforced AA6061 and their composites containing different volume fraction of SiC (5, 10, 15, and 20%) using different hot compaction temperature. From the results shown in Figs. 7-12, it is clear that the hardness increase in the centre of the disc and decrease as the point of measuring be close to the edge. We can conclude from these figures that the hardness increase by increasing the SiC content, and that for the samples with the same SiC volume fraction, the hardness is slightly decreased by the increase of hot compaction temperature.

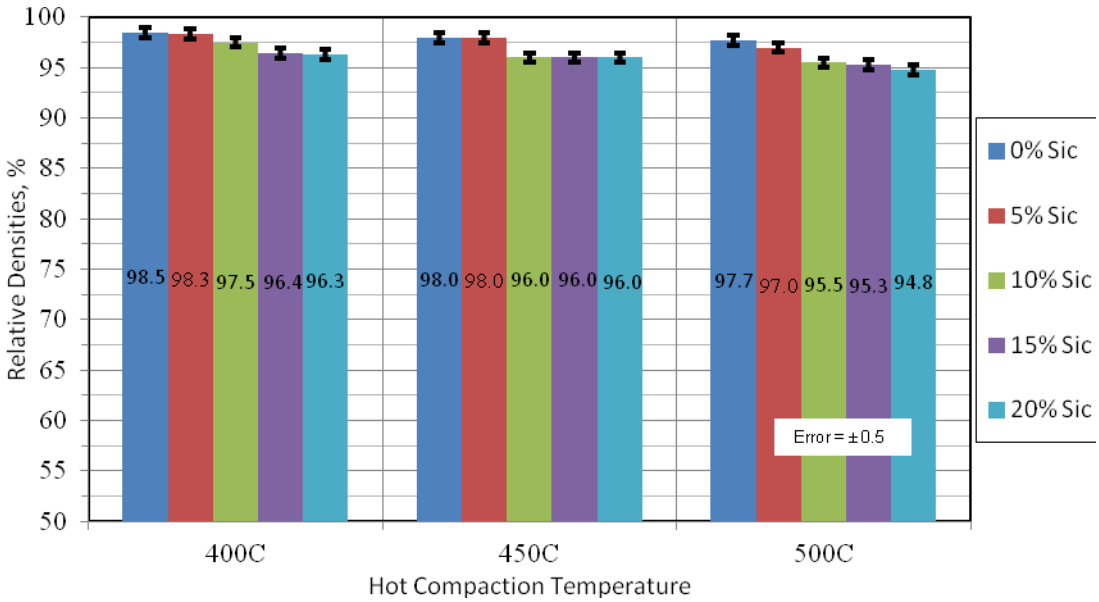
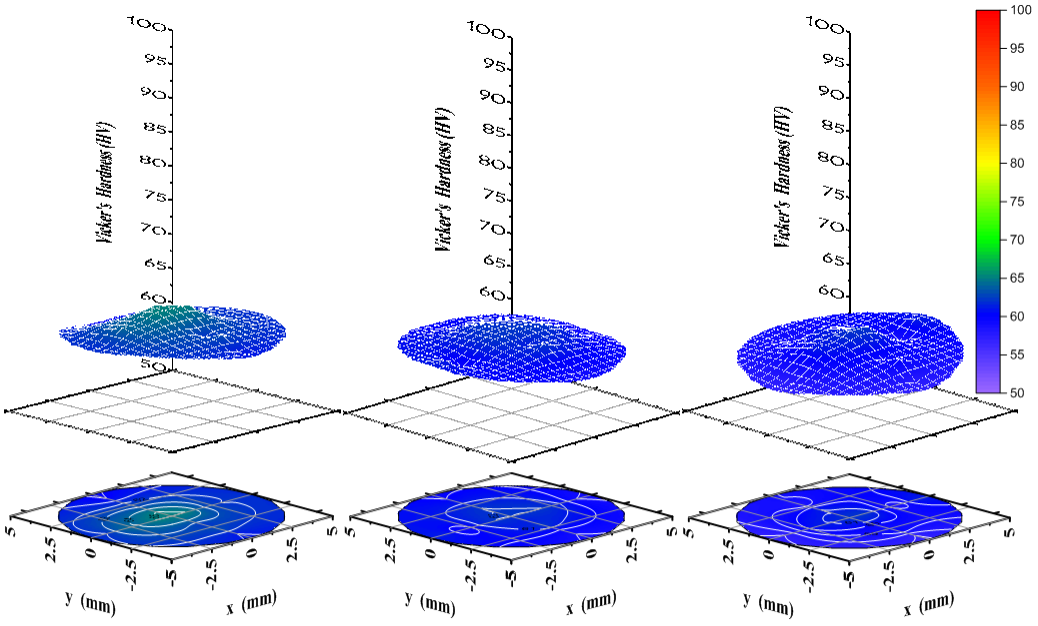
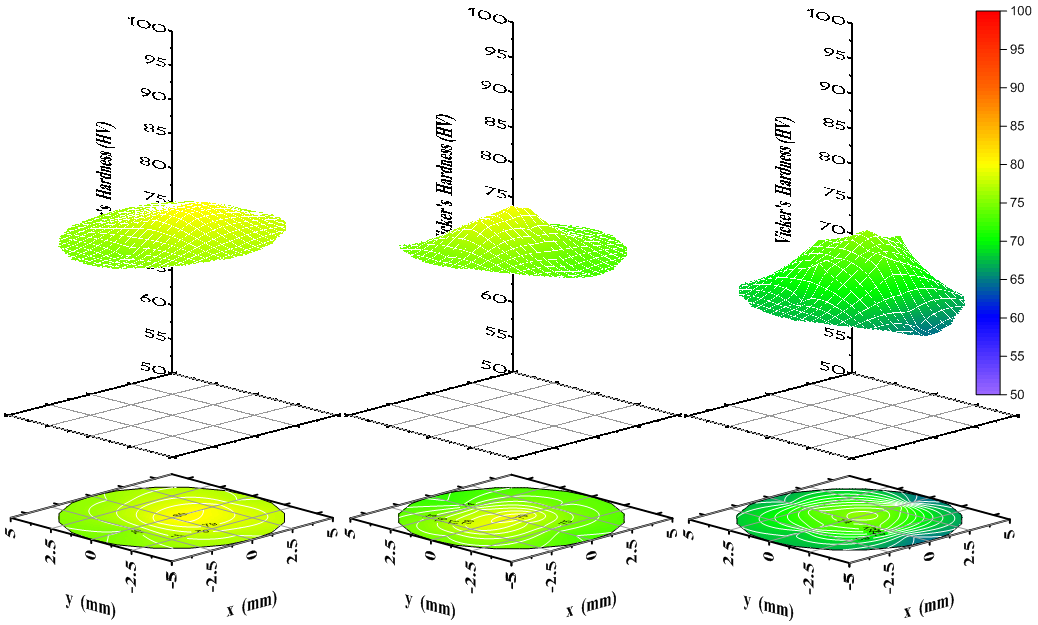


Fig.6 The relative density of AA6061 samples with different volume fraction of SiC reinforcements.



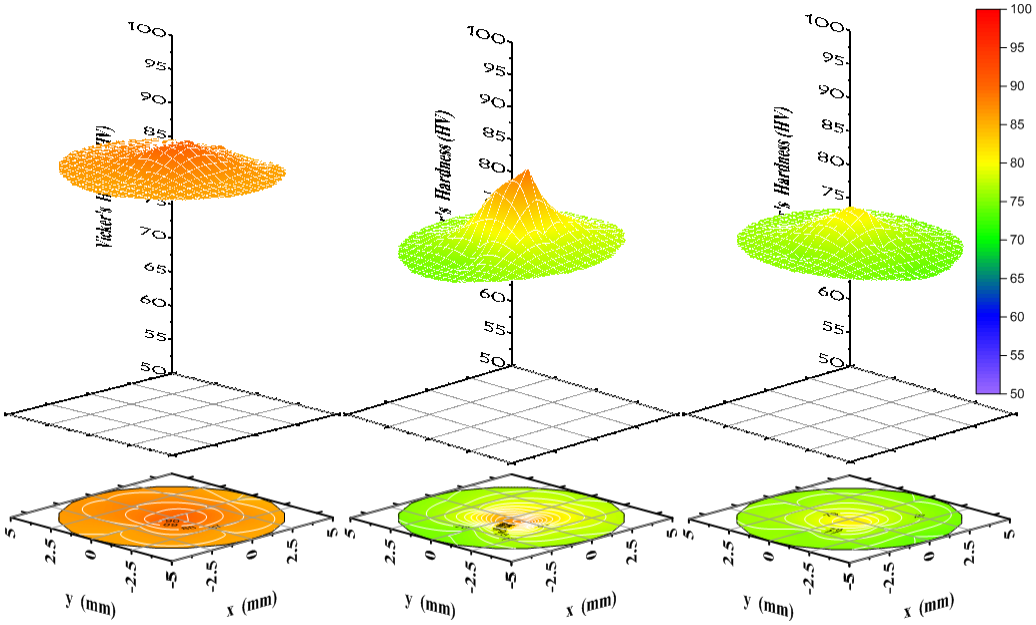
Sample No. 01 (a) *Sample No. 02* (b) *Sample No. 03* (c)

Fig. 7 Three dimensional representation and color-coded contour maps showing hardness distribution across the surface for 0% SiC samples.



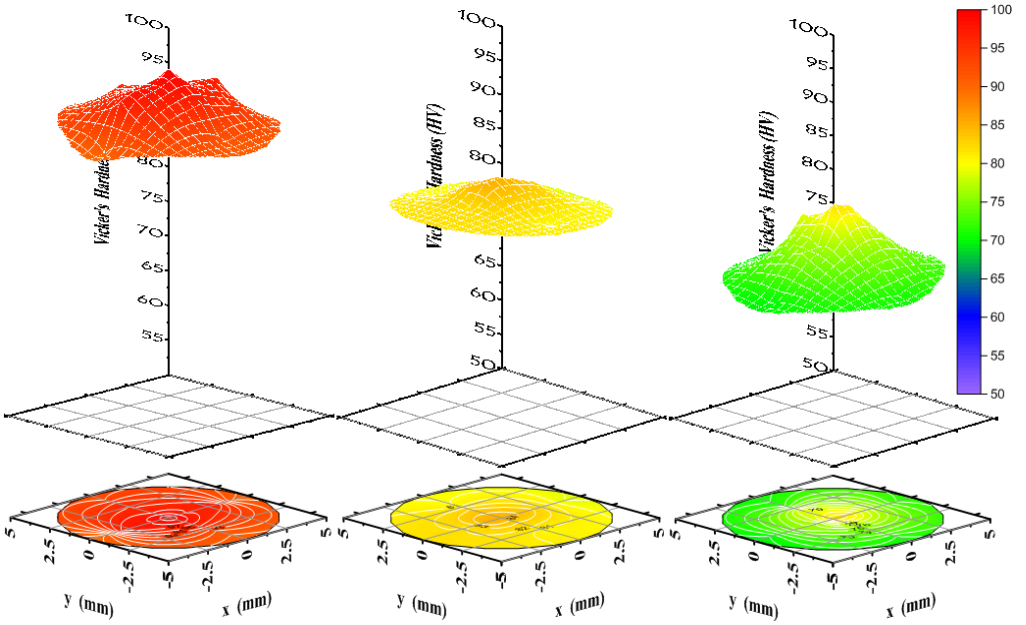
Sample No. 04 (a) *Sample No. 05* (b) *Sample No. 06* (c)

Fig. 8 Three dimensional representation and color-coded contour maps showing hardness distribution across the surface for 5% SiC samples.



Sample No. 07 (a) *Sample No. 08* (b) *Sample No. 09* (c)

Fig. 9 Three dimensional representation and color-coded contour maps showing hardness distribution across the surface for 10% SiC samples.



Sample No. 10 (a) *Sample No. 11* (b) *Sample No. 12* (c)

Fig. 10 Three dimensional representation and color-coded contour maps showing hardness distribution across the surface for 15% SiC samples.

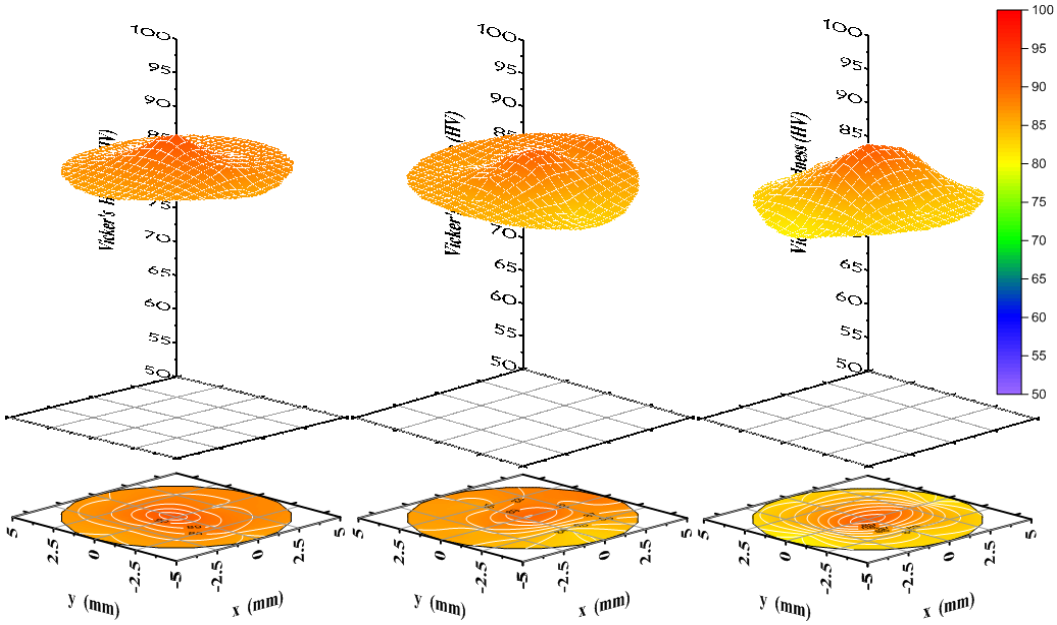


Fig. 11 Three dimensional representation and color-coded contour maps showing hardness distribution across the surface for 20% SiC samples.

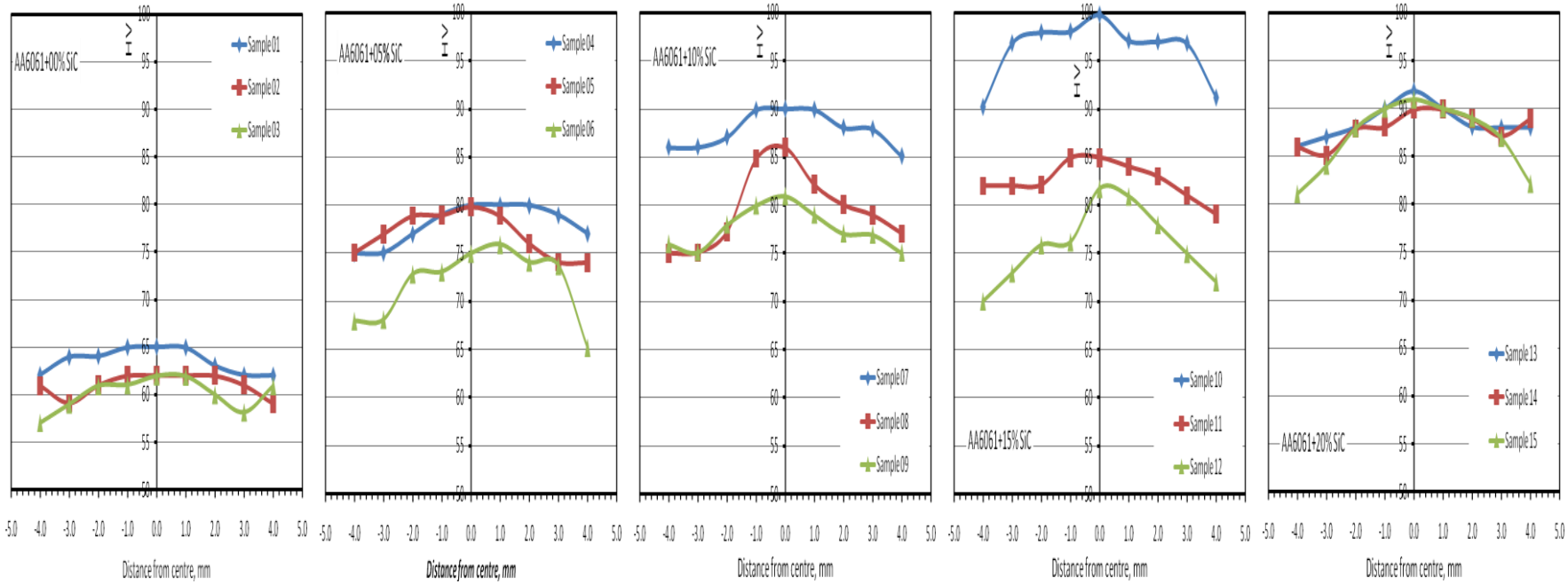
3.3 Microstructural evolutions

Optical micrographs of both pure AA6061 aluminium alloy and its reinforced composites containing different volume fractions of SiC in the as hot compact condition are shown in Fig. 13 at high magnification. It is observed that SiC particles were distributed with the AA6061 matrices along their boundaries and at triple junctions. Some of the segregated SiC particles were associated with voids as shown in Figs. 13(d-o) for all reinforced matrices conditions. In addition, the volumetric voids increased by increasing the SiC content. It was clear that, the coarsening of the grain size increased by increasing the hot compaction temperature. Table 2 shows the average grain size for the different samples. It was shown that increasing HC temperature increases the grain size; however, for the same HC temperature increasing the SiC content resulted in a decrease in grain size.

4. Discussion

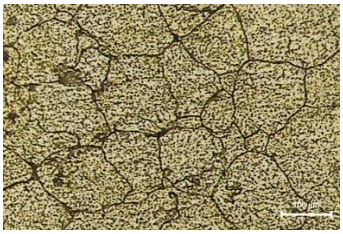
As shown from Fig. 6, increasing of SiC content leads to a decrease in relative density [21]. This can be attributed to the introduction of the brittle of SiC into the ductile matrix of AA6061 which leads to increasing the segregation between the reinforcement and matrix by increasing the SiC reinforcement content. This could be verified by the microstructure, where increasing the amount of cavitations is proportional to the increase in amount of reinforcement. The possible mechanism may be explained by means of porosity evolution such that the fine pores at the particles interfaces have prevented the progress of densification which agreed with [22]. Comparing the results produced at different temperatures, the applied temperatures had insignificance influence on the densification took place. As the melting temperature of SiC is 2830 C^{o}, it is anticipated that there will be no coarsening accompanied during compaction where as for the matrix of alloy AA6061 coarsening was obvious by increasing of hot compaction temperature.

It is important to note that the hardness profile plots provide information on the degree of hardness homogeneities across the compact disks cross section. Numerous earlier reports demonstrated a direct correlation between the measured values of the Vickers macro hardness and the internal microstructures either observed directly by transmission electron microscopy and optical microscope or interpreted through the use of X-ray diffraction measurements [23]. Accordingly, it is reasonable to anticipate that measurements of hardness represent a simple and expedient procedure for the influence of HC on the homogeneity of structure produced of each content.

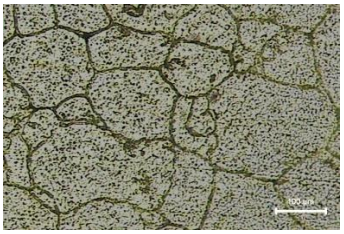


(a) **(b)** **(c)** **(d)** **(e)**

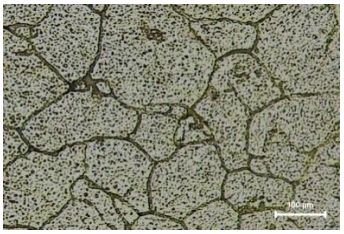
Fig. 12 Variation of VHN, with distance from the centre of the HC specimen as a function of volume fraction of SiC: (a) 0% SiC (b) 5% SiC(c) 10% SiC (d) 15% SiC (e) 20% SiC



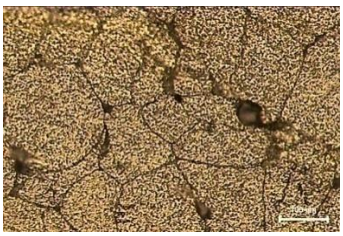
a- (0% SiC, 400Cº)



b- (0% SiC, 450Cº)

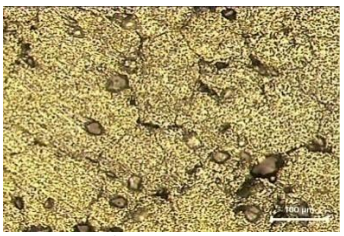


c- (0% SiC, 500Cº)

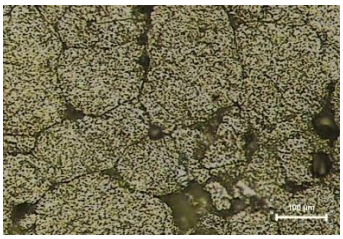


d- (5% SiC, 400Cº)

e- (5% SiC, 450Cº)

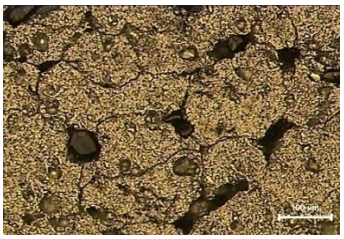


f- (5% SiC, 500Cº)



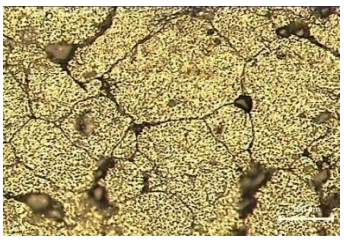
g- (10% SiC, 400Cº)

h- (10% SiC, 450Cº)

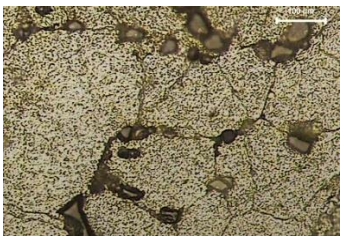


i- (10% SiC, 500Cº)

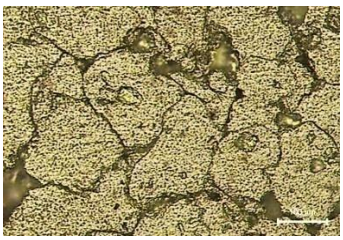
j- (15% SiC, 400Cº)



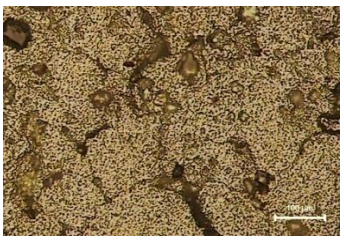
k- (15% SiC, 450Cº)



l- (15% SiC, 500Cº)



m-(20% SiC, 400Cº)



n- (20% SiC, 450Cº)

o- (20% SiC, 500Cº)

Fig. 13 OM micrographs at magnification 500x for AA6061-SiC composite hot compacted at 525 MPa for 30 min at (a-c) 0% SiC, (d-f) 5% SiC, (g-h) 10% SiC, (j-l) 15% SiC, (m-o) 20% SiC

Table2 Average grain size of AA6061-SiC composites after hot compaction.

Condition	Average Grain Size (μm)
AA6061, 400°C	18.11
AA6061, 450°C	19.11
AA6061, 500°C	20.60
AA6061+5%SiC, 400°C	14.22
AA6061+5%SiC, 450°C	14.55
AA6061+5%SiC, 500°C	16.31
AA6061+10%SiC, 400°C	14.08
AA6061+10%SiC, 450°C	14.68
AA6061+10%SiC, 500°C	14.91
AA6061+15%SiC, 400°C	13.74
AA6061+15%SiC, 450°C	14.40
AA6061+15%SiC, 500°C	14.48
AA6061+20%SiC, 400°C	13.21
AA6061+20%SiC, 450°C	13.88
AA6061+20%SiC, 500°C	14.02

Accordingly, these important remarks can be deduced. First, all composite alloy are characterized by a higher hardness compared to the non-reinforced one and it is to the fact that the matrix AA6061 reinforced with SiC posses higher hardness [24]. Hardness of composite materials increases with increasing content of the reinforcement materials in the metal matrix (HV≈ 96 in the samples that contain 15% SiC) which agreed with [25], but at high volume fraction of SiC (20%), the hardness slightly decreased which, could be attributed to the decreasing compressibility of the composite leading to the increased voids fractions and a decrease in density. At high volume fraction, the insufficiency of the imposed pressure (525 MPa) resulted in the segregation of the metal matrix which will be a source of brittleness and resulted in decreasing the density and deterioration of the hardness.

As the volume fraction of SiC decreases, the diffusion during pressing between the SiC and aluminium powder reduces. Therefore, in order to increase the incidence of diffusion, the SiC particle size should be reduced [26]. Consequently, the aluminium powder size must also be reduced to maintain the SiC particle size to aluminium powder size relationship. Due to the highlighted importance of powder particle size and SiC volume fraction, it should be noted that as powder particle size decrease and SiC volume fraction increases the compaction pressure required to achieve higher specific density should increases. Therefore, the selection of a suitable compaction pressure must be based on these parameters for any given composite, so the deterioration of the relative density and of the HV at relatively higher SiC volume fraction suggests increasing the HC pressure up to 650 MPa. The selection of aluminium powder size, to be used for any composite, should be based on the SiC particle size and volume fraction being used for that composite [22]. The average size of the aluminium particles should approximately be the same size, or smaller than that of the SiC average particle size selected. Also, as the SiC volume fraction increases the available space between SiC particles decreases. Therefore, the aluminium average powder size should be decrease with increasing SiC volume fraction. Second, SiC works as a grain coarsening obstacle, so the increase of SiC volume fraction result in grain size refining as shown in table 2, which agree with [27-28], this also leads to increasing the hardness and improving the mechanical properties. Third, it was clear from Figs. 7-12, that, the hot compaction temperature range from 400- 500ºC had insignificant influence on the Vicker's macrohardness for the processed condition and its numerical values were very close. This behaviour could be due to the grains coarsening exhibited with increasing the HC temperature could have resulted in strain softening, which caused the observed reduction in hardness.

5. Conclusions

SiC particles reinforced AA6061 matrix composites were fabricated using PM technique. Results from the present investigation show that:

1- Hot compaction pressure of 525 MPa is suitable for the densification of the AA6061 powder reinforced with low content of SiC up to 15%, increasing the SiC content to 20% results in increasing the Al-matrices resistance to compressibility and hence, produces lowers densities after HC.
2- Deterioration of HV values at relatively higher SiC volume fraction suggests increasing the HC pressure up to 650 MPa.
3- Comparing the relative densities and Vickers hardness values of the hot compacted samples, the HC temperatures ranging from 400 -500 ºC

had insignificant influence on the densification or on the hardness.

4- Accordingly, the most suitable compaction temperature is 400 ºC.
5- The highest hardness values produced corresponding to the AA6061 + 15% SiC composite.
6- Increasing HC temperature up to 500 ºC results in the strain softening due to grain coarsening.
7- Increasing SiC content retards grain coarsening.

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