EFFECT OF HOT EXTRUSION TEMPERATURE ON PARTICLE BREAKAGE AND FRACTOGRAPHY OF SILICON CARBIDE-REIFNORCED AL-6061 ALLOY COMPOSITE MATERIALS

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ABSTRACT

6061 aluminum matrix composites reinforced with oxidized SiC particles were fabricated by the vortex method and were extruded at 450ºC, 500ºC and 550ºC with the objective of understanding the effect of hot extrusion temperature on particle fragmentation and fractography of the composite materials. For this purpose, metallography investigations and image analyzing were performed on longitudinal sections of the specimens, tensile tests were carried out at room temperature and SEM fractography was used. The results show that the reinforcement particles were refined by the extrusion process and increasing the extrusion temperature decreased the extent of the fragmentation. The fracture surfaces of as-cast specimens revealed agglomerations of reinforcement particles leading to brittle fracture but these clusters were eliminated after applying the extrusion process and a more ductile fracture behavior was observed.

Keywords: Al/SiC composites; Extrusion; Fractography; Metallography; Particle fragmentation; Vortex method.

1. INTRODUCTION

Discontinuously reinforced aluminum alloy metal matrix composites (MMCs) based on particulate, whisker or short-fiber reinforcements in a 2XXX-, 6XXX- or 7XXX- series aluminum alloy matrix comprise a technologically maturing materials system capable of competing with conventional aluminum and titanium alloys and organic matrix composites. In the time period spanning the last two decades, MMCs have emerged as promising structural materials solution [1-2]. In particular, incorporation of discontinuous particulate reinforcement in aluminum alloy matrices have been shown to provide noteworthy attributes such as high strength, excellent stiffness, superior wear resistance, increased elevated temperature strength, improved creep rupture properties, good micro-creep performance, good corrosion resistance and improved fatigue crack initiation resistance compared with the unreinforced matrix alloys. Moreover, the MMCs based on particulate reinforcements are attractive because they can be made with properties that are near isotropic in three orthogonal directions or in a plane [2].
Basically there are three types of fabrication techniques available to manufacture MMC materials. These are solid phase processes, liquid phase processes and semi-solid fabrication processes [3]. Liquid phase processing has attractive economic aspects. Chopped fibers, porous ceramic compacts and particulates can ben incorporated into molten matrix alloys. In

some cases, pressure assistance has been used to infiltrate the reinforcement with the molten matrix. These methods result in microstructures dictated by the solidification of the molten metal [4]. Stir casting of MMCs generally involves producing a melt of the selected matrix material, followed by the introduction of a reinforcing material into the melt and obtaining a suitable dispersion through stirring. Its advantages lie in its simplicity, flexibility and applicability to large scale production [5]. It has been reported that, the cost of preparing composite materials using a casting method is about one third to one half that of competing methods, and for high volume production, it is projected that costs will fall to one tenth [6]. However, due to poor wetting of the ceramic particles by molten alloy, the introduction and uniform dispersion of the reinforcement into the liquid matrix is difficult [7]. Moreover, structural defects such as interfacial reactions, formation of porosity and nonhomogeneous particle distribution arise from the unsatisfactory casting techniques [8].
Particulate reinforced aluminum alloys can be formed by conventional plastic deformation processes such as rolling, extrusion or forging, among which extrusion has been used as the most common secondary processing because of its excellent preferential axial alignment of discontinuous fibers as well as large compressive hydrostatic state of stress [9].
The observations in microstructures of extruded composites by many investigators [10-12] have shown that the number of resolvable pores is reduced, some particle fragmentation is noticeable, some particle orientation into the direction of extrusion has taken place and considerable improvements in mechanical properties of the composites were monitored with the application of the hot-extrusion process.
However it is necessary to note that the presence of brittle and nearly nondeformable reinforcements such as particulates, whiskers or short fibers as in Al/SiC or Al/Al_2O_3 composites can results in undesirable phenomena such as fracture of reinforcement, debonding of interface or surface cracking in extruded product unless appropriate process design is employed [13].

2- MATERIALS AND EXPERIMENTAL PROCEDURES

Aluminum 6061 alloy and SiC particles of 46 µm average size were utilized to prepare 10 Vol. % composite ingots by the stir casting technique. The composition of the Al6061 alloy used in the present study (unreinforced material) is given in Table 1.

Table 1. Chemical composition of the aluminum alloy 6061.

Alloy Type	Composition (wt.%)						
6061	Mn	Cr	Fe	Cu	Si	Mg	Al
	0.01	0.05	0.17	0.33	0.71	1.12	Balance

The irregular shaped SiC particles used in this research were artificially oxidized in air at 950ºC for 120 minutes to form a very thin layer of SiO_2 on their surface in order to improve wettability with molten aluminum and prevent the potential attack of the SiC reinforcements by liquid aluminum to form Al_4C_3 at the Al/SiC interface which could be harmful to the mechanical properties of the composite.
In order to produce the composite the following steps were taken: The alloy was melted in a graphite crucible with the capacity of 10Kg Al-melt by the use of an electrical resistance-heated laboratory furnace. The temperature was raised to 750ºC and the melt was stirred at 680 rpm using a graphite impeller attached to a variable speed AC motor. After 30 seconds a specific quantity of oxidized silicon carbide particles equal to 10 vol. % was added to the matrix alloy at a low rate for about 5 minutes while stirring was continued. The slurry was

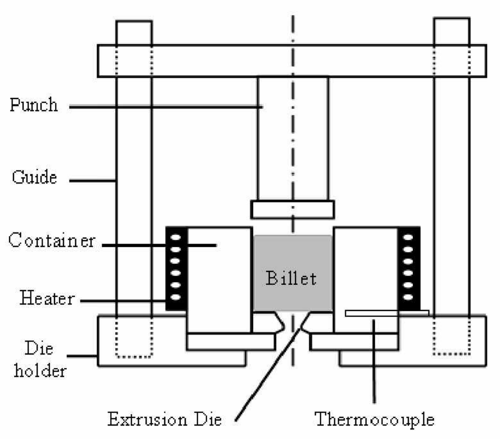

Figure1. Geometry of the extrusion equipments.

allowed to mix isothermally for another 15 minutes, then the impeller was taken out of it and the composite slurry was poured into metallic molds. The produced ingots were cut into approximately 1Kg pieces. Then they were separately remelted and cast in cylindrical metallic permanent molds of low-carbon steel having 44mm diameter, 50 or 100mm height and 7mm wall thickness with an inner 3° tilt.

The 50mm height-billets were then hot extruded by using a hydraulic press and a graphite-based high temperature lubricant at a ram speed of 1mm/s, temperatures of 450ºC, 500ºC and 550ºC and with the extrusion ratio of 12:1. A Schematic diagram of extrusion equipments used in the present work are shown in Fig. 1.

The microstructures of the MMCs in as-cast and extruded states were examined using an image analyzer coupled to an Olympus optical microscope to determine the size and distribution of the SiC particles. For each metallographic sample 10 fields were analyzed at a magnification of 20 times.

Round tensile samples were machined along the extrusion direction According to ASTM E8, and room temperature uniaxial tension tests were carried out in a fully automated MTS tensile testing machine at a constant cross head speed of 1mm/s.

Fracture surfaces of the deformed tensile specimens in both as-cast state and after the extrusion process were examined in a scanning electron microscope (SEM) to determine the predominant fracture mode.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Typical microstructures of the as-cast and extruded composites are shown in Fig. 2. The microstructure investigation of the as-cast composites generally revealed that SiC particles were not distributed evenly in the matrix, regional clusters of particles exist and some pores are resolvable in the as-cast samples. But after applying the extrusion process the number of resolvable pores is reduced, some particle fragmentation is noticeable and some particle orientation into the direction of extrusion has taken place.

The decreased porosity of MMCs during extrusion is due to the compressive forces generated by the interaction of the composite billet with the extrusion container and die, resulting in the flow of the matrix alloy under the applied shear forces and filling the voids.

It is believed that non-uniformity in the particle distribution of the as-cast structures is mainly caused by segregation and clustering of ceramic particles at grain boundaries. But while the extrusion process is being executed, the applied shear stress breaks up these clusters resulting in a more uniform particle distribution.

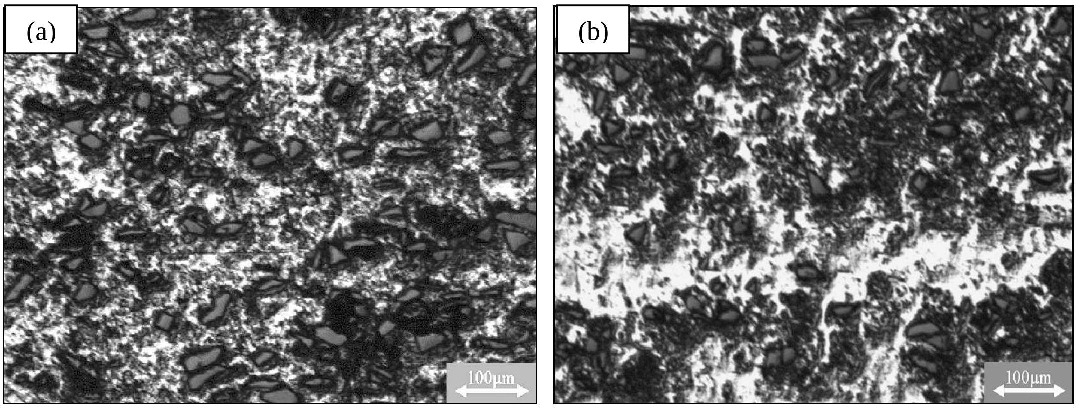

Figure2. Microstructures of Al6061/SiC/10p: (a) as-cast, (b) extruded at the ratio of 12:1.

Strain-rate effects during the extrusion process were also responsible for the break-up of the particle clusters. Variations in the local strain rate within the composite billet during extrusion and differences in the strain rate sensitivities of the particle-rich and particle- poor regions of the composite lead to the partitioning of strain during flow and the subsequent shearing of the clustered regions [14]. Extrusion thus produced a more homogeneous distribution of the SiC particles.

The influence of the extrusion temperature on the average size of the SiC particles is shown in Fig. 3. In this figure the average sizes of the SiC particles in the as-cast condition are also presented for comparison.

It should be noted that there is a difference between the sizes of the SiC particles in the as-cast condition when measured by laser diffraction (i.e. D = 46 µm) and when measured on the metallographic sections of as-cast samples by image analyzer (i.e. D_{ave} = 35.4 µm). These differences can be partially attributed to the different techniques used for particle size measurement as well as the possible breakage of SiC particles during the primary stages of the composite production (for instance slurry stirring). It is evident from this figure that the average size of the SiC particles is reduced during extrusion indicating particle fragmentation and the extent of particle breakage is decreased by increasing the extrusion temperature.

The microstructural changes caused by extrusion are a direct consequence of the stresses developed in the composite during deformation. The tensile stresses arise primarily from the extrusion load whereas the hydrostatic component of the stress state arises due to the compressive forces generated by the interaction of the composite billet with the extrusion container and die [14].

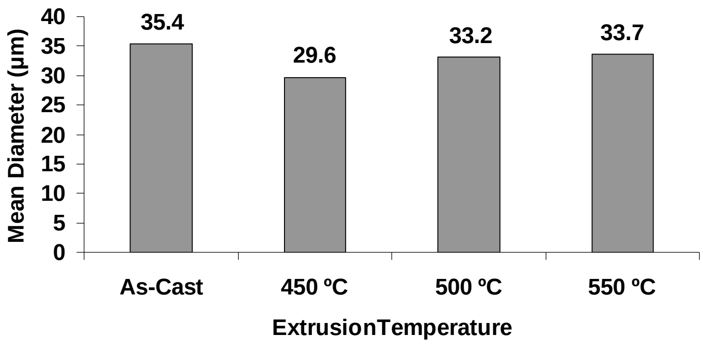

Figure3. The variation in average particle diameter of Al-6061/SiC/10p composites with extrusion temperature.

During the reduction of the cross-section of the composite billet in the extrusion die, the metal matrix is deformed in a plastic manner. In contrast, the hard and brittle ceramic particles tend only to fragment since they are rigid and non-deformable. Furthermore, finite element simulations by Christman et al. [15] have shown that the presence of brittle reinforcements in a ductile matrix leads to a significant building up of triaxial stresses in the matrix during plastic deformation. A particle would fracture when the local stress acting on the particle exceeds its fracture strength. It has also been documented that shear forces during the extrusion process can result in particle breakage [16].
Fig. 3 demonstrates that SiC particle breakage has occurred more severely during extrusion of the Al/SiC composites at lower temperatures as compared with higher temperatures. These results are in agreement with literature [12] and can be ascribed to the easier movement and rotation of the SiC particles as a result of the reduced flow stress at higher extrusion temperatures resulting in decreased particle fragmentation. Moreover, at lower extrusion temperatures larger extrusion loads are required which cause more severe deviatoric stresses that lead to the increased breakage of the particle reinforcements and the formation of further smaller particles in the microstructure.

3.2 Fractography

Fractographs of tensile fracture surfaces are always useful in clarifying microstructural effects on fracture properties of metal matrix composites. Particle reinforced metal matrix composites are almost always far less tough than their unreinforced matrices. It is well known that the fracture of pure aluminum or its alloys in the absence of reinforcement phase is associated with void nucleation and growth [15].
But presence of ceramic particles causes a strong acceleration of internal damage build-up, and damage is highly localized in front of the crack tip, thus forming a distinct fracture process zone [17]. Various micromechanisms for fracture of MMCs have already been reported including: (i) particle fracture, (ii) debonding or cracking along the interface of reinforcement/matrix, (iii) matrix failure by microvoid nucleation, growth and coalescence, and (iv) failure in the matrix by shear. It should be noted that while these damage processes may operate simultaneously in a particular composite, one mode is often dominant.
SEM fractographs of the composite in as-cast condition are shown in Fig. 4. On a macroscopic scale the fracture surfaces were relatively rough and evidence of porosity were observed on the surface (Fig. 4a).

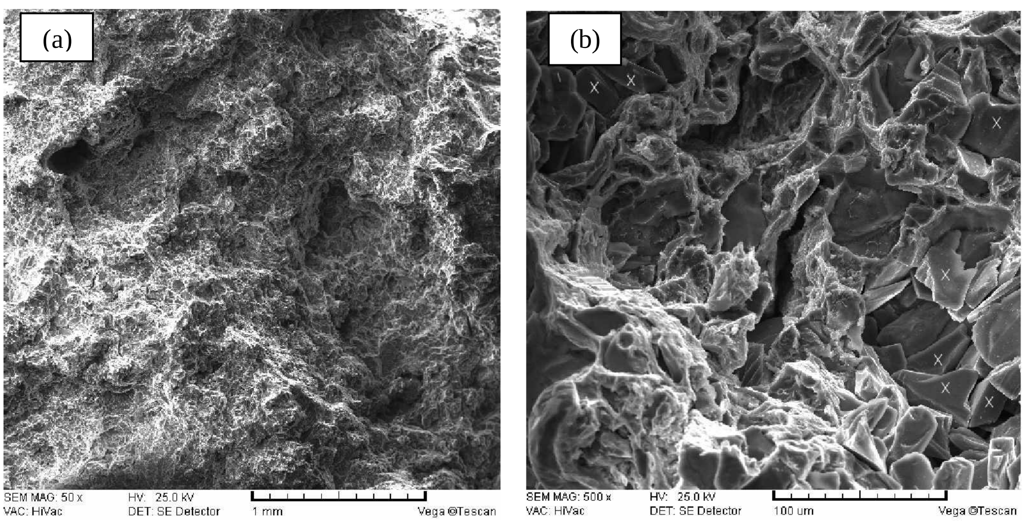

Figure4. SEM micrographs of the tensile fracture surfaces of the as-cast Al6061/SiC/10p composite, showing :(a) overall morphology; (b) non-uniform distribution of particles.

When viewed on a microscopic scale, the fracture surfaces revealed agglomerations of reinforcement particles which caused local stress concentrations in the composite and led to crack formation in the matrix (Fig. 4b). It also shows fractured particles on the fracture surface.

Presence of hard and brittle SiC particles in the ductile aluminum matrix exerts constraints on the plastic flow of the matrix. When combined with concentration and triaxiality of stress in clustered particles regions, the composite undergoes brittle fracture without showing appreciable ductility.

Fractographs of the extruded composites at 450ºC, 500ºC and 550ºC are shown in Fig. 5. These figures demonstrate that clusters of reinforcement particles are eliminated after applying the extrusion process, thus some ductility is expected in the absence of those highly stress raisers. The fracture surfaces in Fig. 5a reveal cracked and fractured particles surrounded by ductile regions called tear ridges. These hallow and featureless dimples on the fracture surface are related to ductile failure. The lack of formation of ductile dimples, as a dominant fracture mode, is attributed to be due to constraints on plastic flow in the composite matrix caused by the presence of the discontinuous SiC_p reinforcement and not to limited ductility of the aluminum alloy.

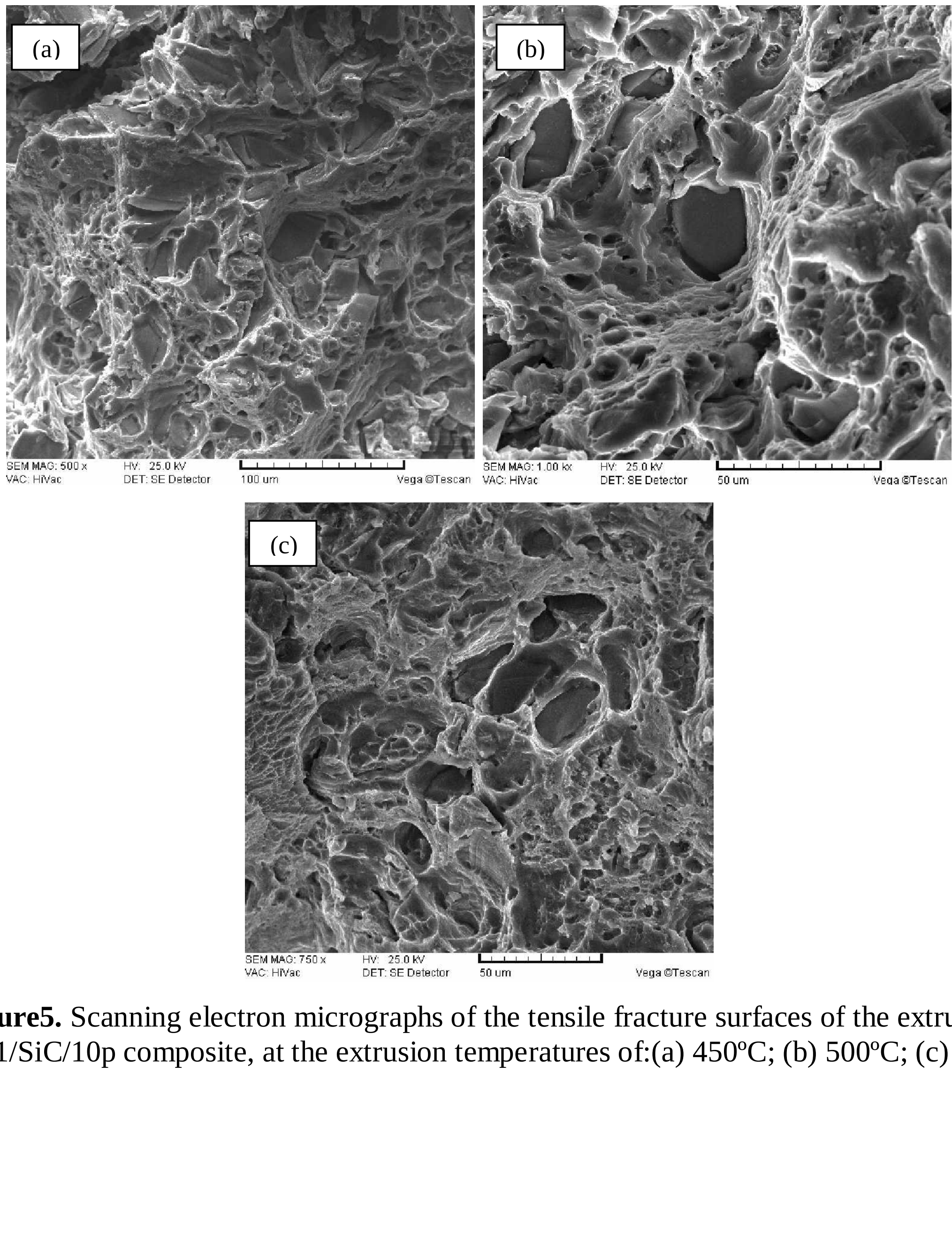

Figure5. Scanning electron micrographs of the tensile fracture surfaces of the extruded Al6061/SiC/10p composite, at the extrusion temperatures of:(a) 450ºC; (b) 500ºC; (c) 550ºC.

Generally, particle cracking and fracture is associated with the following factors: 1- Residual stresses caused by the difference between the coefficients of thermal expansion of the reinforcement and the matrix material. 2- Local stress concentrations caused by the constraints in plastic deformation. 3- Applied stress during the tensile test and 4- The brittle nature of ceramic particles. When particle fracture occurs, microvoids are nucleated and then by growth and coalescence of these voids, crack propagation would occur.

During tensile deformation, as the strain increases, the larger-sized reinforcing particles fracture first, followed by fracture of the smaller-sized reinforcing SiC particles. In regions of particle clustering, or agglomeration, the short interparticle distance facilitates linkage between microscopic cracks and neighboring voids as a direct result of decreased propagation distances between the cracked SiC particles.

According to Srivatsan et al [2], the stress adjacent to any SiC particle is a combination of stress components imposed by the macroscopic applied stress and the stress component that develops on a microscopic scale. The microscopic scale components arise as a result of the conjoint influence of strain incompatibility between the reinforcing particle and the deforming matrix, individual stresses arising from thermal expansion mismatch between the second phase particles and the matrix, and load sharing by the reinforcing particulates. Observation of the fracture surface shows that the fracture plane of cracked SiC particles is almost always perpendicular to the loading axis, suggesting the importance of the tensile stress in inducing particle fracture.

Figs. 5b and 5c demonstrate that increasing the extrusion temperature led to less cracked particles on the fracture surfaces of the composite specimens. It can be attributed to the better distribution of ceramic particles in the matrix at higher extrusion temperatures which reduces localized stress concentration in tensile samples. It is also noticed that many broken particles are found at the bottom of existing dimples on the surface, confirming that these voids are nucleated by broken particles.

By looking carefully at the Figs. 5a and 5c, a very noticeable difference can be distinguished between fracture surfaces of samples extruded at lower temperatures and at higher temperatures. In Fig. 5c very fine aluminum dimples on the surface of many particles can be discerned, which exhibit a strong bonding between the matrix and the particles. It is also seen that in the extruded samples at higher temperatures, the aluminum matrix has been able to flow more properly and it has filled the possible gaps between the adjacent particles more appropriately which can account for the better bonding in the interface. Therefore, in spite of the differences in the microscopic fracture surfaces of the samples extruded at different temperatures, the main micromechanism responsible for the failure of the Al-6061/SiC_p in uniaxial tensile test was particle fracture. However, interface debonding can also partly account for the failure of the composite material, being more pronounced in specimens extruded at lower temperatures.

4. CONCLUSION

1. Reinforcement particles were refined by the hot extrusion. The reduction in particle size was due to fracture of the larger particles which was a result of the high shear stresses inherent in the extrusion process and the non-deformability of hard ceramic particles.
2. The degree of particle refinement was greater at the lower extrusion temperatures due to the larger extrusion loads required for deformation which led to higher shear stresses acting on the reinforcements.
3. SEM fractographs of the as-cast composite revealed agglomerations of reinforcement particles which caused local stress concentrations and stress triaxiality, leading to particle fracture and a too low ductility in the material.

4. Clusters of reinforcement particles were eliminated after applying the extrusion process, thus some ductility was achieved in the absence of those highly stress raisers.
5. Increasing the extrusion temperature led to less cracked particles on the fracture surfaces of the composite specimens, which can be attributed to the reduced localized stress concentration in tensile samples because of the better distribution of the particles in the matrix at higher extrusion temperatures.
6. Samples extruded at higher temperatures showed more proper flow of the matrix between adjacent particles which can result in better bonding at the matrix/reinforcement interface.

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