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Mechanical Properties of A356 Matrix Composites Reinforced with Nano-SiC Particles

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Механические свойства композитов с матрицей из сплава A356, упрочненных наночастицами карбида кремния

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Композиты с металлической матрицей образуют группу новых искусственно спроектированных материалов, в металлическую матрицу которых вводятся керамические упрочняющие компоненты с целью улучшения ее механических свойств, включая удельную прочность и удельную жесткость, а также износостойкость, и обеспечения высокой коррозионной устойчивости и высокого модуля упругости. Метод композиционного литья использовался для введения наночастиц SiC в алюминиевый сплав и изготовления нанокомпозитов с металлической матрицей и однородным распределением упрочняющих компонентов. Микроструктурный анализ композитов, полученных методом композиционного литья, показал однородное распределение наночастиц, уменьшение размеров зерен матрицы из алюминиевого сплава и минимальную пористость материала. Установлено, что наличие наночастиц карбида кремния существенно повышает твердость, условный предел текучести и предел прочности при сохранении исходной пластичности алюминиевой матрицы.

Ключевые слова: матрица из алюминиевого сплава, карбид кремния, нанокомпозиты с металлической матрицей, прочность.

Introduction. There has been a great upsurge in using aluminum alloys for structural applications, particularly in aerospace and automotive industries, owing to their low density, high thermal conductivity and high specific strength, which leads to the weight reduction resulting in a considerable economic advantage. However, their low hardness and poor wear resistance are the main obstacles for their high performance tribological applications. To overcome this problem, hard reinforcement phases such as particulates, fibres, and whiskers are introduced into Al-based matrix in order to improve their high specific strength, stiffness, wear resistance, fatigue resistance and elevated temperature applications [1–3].

Aluminum matrix composites (AMCs) have been transformed from a topic of scientific and intellectual interest to a material of broad technological and commercial significance. Important AMC applications in the ground transportation (auto and rail), thermal management, aerospace, industrial, recreational and infrastructure industries have been enabled by functional properties that include high structural efficiency, excellent wear resistance, and attractive thermal and electrical characteristics. While in composites reinforced with continuous fibers, strengthening is associated with load transfer from the matrix to the fiber, it is associated with the high dislocation density in the matrix of composites reinforced with whisker and particulate [4–7].

Microsize ceramic powders and fibers were widely used in fabrication of Al-based composites to improve the ultimate tensile and the yield strengths of the metal. However, the ductility of the metal matrix composites (MMCs) deteriorates significantly with high ceramic particle concentration. Application of nano-sized ceramic particles is increasing since it strengthens the MMCs and maintains the ductility of the matrix alloy. The most popular nano-sized reinforcements are silicon carbide and alumina. Aluminium, titanium and magnesium alloys are commonly used as the matrix phase. However, it is extremely difficult to obtain uniform dispersion of nano-sized ceramic particles in liquid metals due to high viscosity, poor wettability in the metal matrix, and a large surface-to-volume ratio [6–8].

Currently, there are several fabrication methods of metal matrix nanocomposites (MMNCs), including in situ technique [1, 2], disintegrated melt deposition [3] powder metallurgy [4, 5], vortex process [6], ultrasonic method [7, 8]. SiC nano-particles (np) have been added to the Al 356 alloy using the ultrasonic method [8]. Experimental results showed a relatively uniform distribution of nano-particles and more than 50% improvement in yield strength of A356 alloy only with 2.0 wt.% of nano-sized SiC particles. Zhao characterized the properties and deformation behavior of $(Al_2O_3+Al_3Zr)$np/Al nanocomposites produced by magneto-chemical melt reaction. It is reported that elongation, ultimate tensile strength and yield strength of nanocomposites are enhanced with increasing of particulate volume fraction, and are markedly higher than that of Al composites synthesized by micro size particles [2]. Solidification processing such as stir casting that utilizes mechanical stirring is a widely used technique of producing Al matrix composites that are reinforced by micro ceramic particles. However, it is extremely challenging for the conventional mechanical stirring method to distribute and disperse nano-scale particles uniformly in metal melts because of the poor wettability and higher specific surface areas of nano-particles which lead to agglomeration and clustering.

From the available literature on MMNCs, it is clear that the morphology, distribution and volume fraction of the reinforcement phase, as well as the matrix properties, are all factors that affect the final properties of the composites, but as yet relatively few works related to the optimization of the productivity process have been published [9–12]. In the present article, we will evaluate and report the experimental results of mechanical properties in nano-SiC reinforced A356 matrix composites.

Experiments. Nano-SiC particles with average particle size of 50 nm was used as the reinforcement. The metal matrix composites have been produced by using both vortex and compocating method. Experiments were carried out using a relatively simple experimental set-up which consists of several parts. The main part, which allows temperatures of up to 1000℃ to be reached, is surrounded by a 50 mm thick layer of kaowool insulator to minimize heat loss. Inside the heater band is a graphite crucible for holding the materials, which has a lid. Weighed quantity of Al alloy was charged into the crucible and heated up to 750℃ (above the alloy liquidus temperature) for melting. The mixture of nano-particles were then added into the melt. There is a nitrogen supply to the crucible in order to minimize the oxidation of molten aluminum, and a graphite stirrer mounted on a graphite shaft passes through small hole out of the crucible lid.

For the comparison, semi-solid agitation was also employed. The temperature of the alloy was first raised to about 700℃ and then stirred at 800 rpm using an impeller fabricated from graphite and driven by a variable ac motor. The temperature of the furnace was gradually lowered until the melt reached a temperature in the liquid solid range (i.e., 590℃) while stirring was continued. Then the stirrer was positioned just below the surface of the slurry and the particles were added uniformly at a rate of 50 g/min over a time period of approximately 3 min. The slurry was allowed to mix in the semisolid state isothermally for another 30 min while the stirrer was positioned near the bottom of the crucible. The slurry was then heated to 750℃ to properly maintain the fluidity of the molten metal and kept at this temperature for 5 min while being continuously stirred.

To examine the morphology of the grains and reinforcement distribution, macro- and microstructural characteristics the materials were investigated. The specimens were prepared by grinding through 120, 400, 600, and 800 grit papers followed by polishing with 6 μm diamond paste, and etched with Keller's reagent (2 ml HF (48%), 3 ml HCl (conc.), 5 ml HNO_3 (conc.) and 190 ml water). TEM specimens were machined to 0.5 mm thickness and cut using a wire electro discharge machine. The specimens were then ground down (350 to 1200 grit) and perforated using double spew with methanol solution. The porosity of the cast alloy and the composite was determined by comparing the measured density with that of their theoretical density.

The tensile tests were used to assess the mechanical behavior of the composites. The tensile specimens were machined from composite rods according to ASTM B 557 standard. For each volume fraction of SiC particles, three specimens were tested. To study the hardness, the Brinell hardness values of the specimens were measured on the polished specimens using a ball with 2.5 mm diameter at a load of 31.25 kg.

Results and Discussions. Comparison of the measured density of the cast alloy and the composites with their theoretical density determined the material porosity. Figure 1 shows the variation of porosity with the volume fraction of nano-SiC particles. It is noted that compocast composites have less porosity than the sir cast ones. Stir casting of MMNCs is an attractive processing method for these advanced materials since it is relatively inexpensive, and offers a wide variety of material and processing condition options. Generally, these composites consist of a metal matrix, which is melted during casting, and ceramic reinforcement added to the molten matrix material by a mechanical stirrer. In order to overcome some of the drawbacks associated with the conventional stir casting techniques, semisolid agitation processes can be employed. The benefits include reduced solidification shrinkage, lower tendency for hot tearing, suppression of segregation, settling or agglomeration and faster process cycles. These advantages are accompanied with lack of superheat (lower operating temperatures), as well as a lower latent heat which results in a longer die life together with a reduced chemical attack of the reinforcement by alloy, also a globular, non-dendritic structure of the solid phase which then explains the thixotropic behavior of the material. Figure 1 also shows higher degree of defects and micro-porosity at higher SiC content which is the result of increase in the amount of interface area [11, 12].

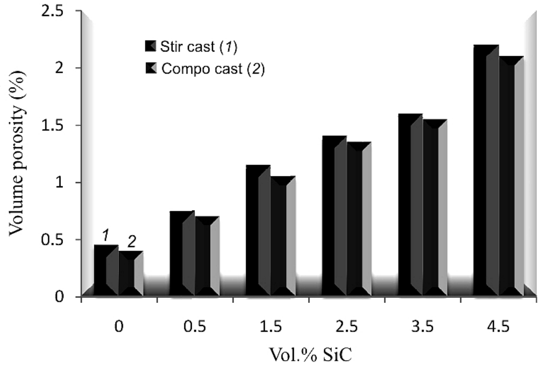


Fig. 1. Variations of porosity with the nano-SiC content.

The mechanical properties of the nano-SiC reinforced Al-matrix composites have been also investigated in this study. Good wetting between the solid ceramic phase and the liquid metal matrix is an essential condition for the generation of a satisfactory bond between these during casting and creating high mechanical properties. Hardness tests were performed using a Brinell hardness machine. In order to obtain the average values of hardness, areas predominant in the soft matrix or the hard reinforcing phase should be avoided so that the average values of hardness are attained from these measurements. The variation in hardness with volume fraction for Al/nano-SiC composites is depicted in Fig. 2. It is clear from the graph that the hardness of the composites is higher than that of the non-reinforced alloy. The higher hardness of the composites could be attributed to the fact that SiC particles act as obstacles to the motion of dislocation. The hardness increment can also be attributed to reduced grain size. As shown, hardness increases with the amount of SiC present particles. It is believed that since SiC particles are harder than aluminum alloy, their inherent property of hardness is rendered to the soft matrix [13, 14].

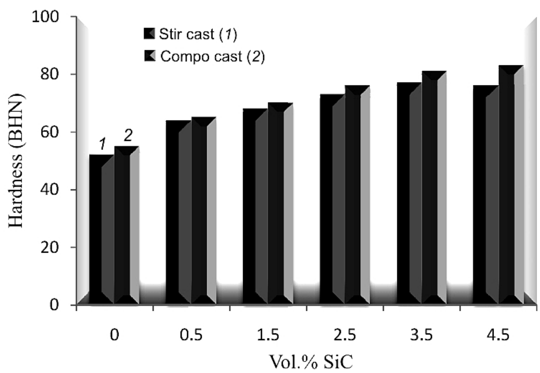


Fig. 2. Variation of hardness as a function of vol.% SiC particulates.

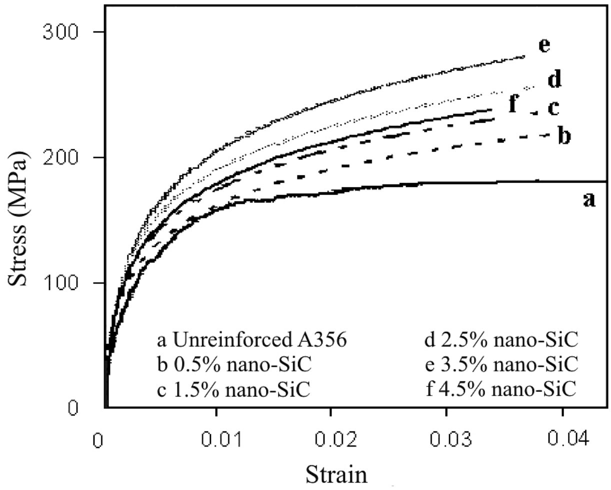


Fig. 3. Flow curves in tensile deformation of the composites.

Figure 3 displays the tensile flow curves of the stir cast composites. It could be noted that the flow curves do not show any sharp yield point irrespective of the material and the strength values increase with the addition of nano-SiC particles. It is believed that the great enhancement in tensile flow stress observed in these composites is due to good distribution of the nano-SiC particles and low degree of porosity which leads to effective transfer of applied tensile load to the uniformly distributed strong SiC particulates. The grain refinement and strong multi-directional thermal stress at the Al/SiC interface are also important factors, which play a significant role in the high strength of the composites. SiC particles have grain-refined strengthening effect, since they act as the heterogeneous nucleation catalyst for aluminum which is improved with increase in the volume fraction [9–15]. The difference between the coefficient of thermal expansion (CTE) values of matrix and ceramic particles generates thermally induced residual stresses and increases dislocations density upon rapid solidification during the fabrication process. The interaction of dislocations with the non-shearable nano-particles increases the strength level of composite specimens. According to the Orowan mechanism, the nano-SiC particles act as obstacles to hinder the motion of dislocations near the particles in the matrix. This effect of particles on the matrix is enhanced gradually with the increase of particulate volume fraction [2, 10].

Figures 4 and 5 display yield strength and UTS of the composites, respectively. According to the results of this experiment, quite significant improvement in strength is noted initially when particles are added; however, further increase in SiC content leads to reduction in strength values of stir cast composites. The weakening factors of mechanical properties might be responsible for this including particles clusters and porosity. Hereby, it is believed that strengthening and weakening factors of mechanical properties could neutralize the effect of each other and thus, the stir cast composite containing 3.5 vol.% SiC exhibits the maximum tensile yield stress. Normally micron-sized particles are used to improve the ultimate tensile and yield strengths of the metal. However, the ductility of the MMCs deteriorates significantly with high ceramic particle concentration [16–18].

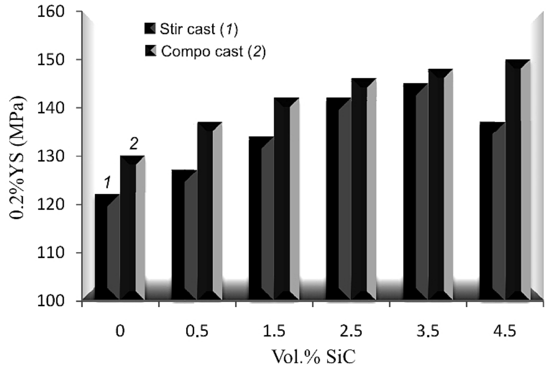


Fig. 4. Variations of yield strength as a function of vol.% nano-SiC particulates.

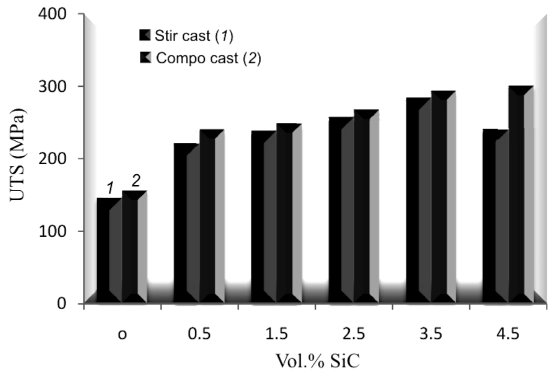


Fig. 5. Variations of UTS as a function of vol.% nano-SiC particulates.

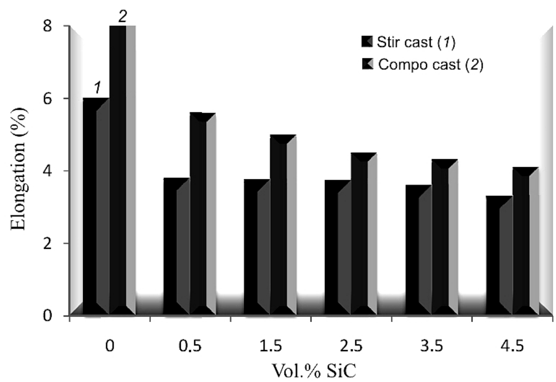
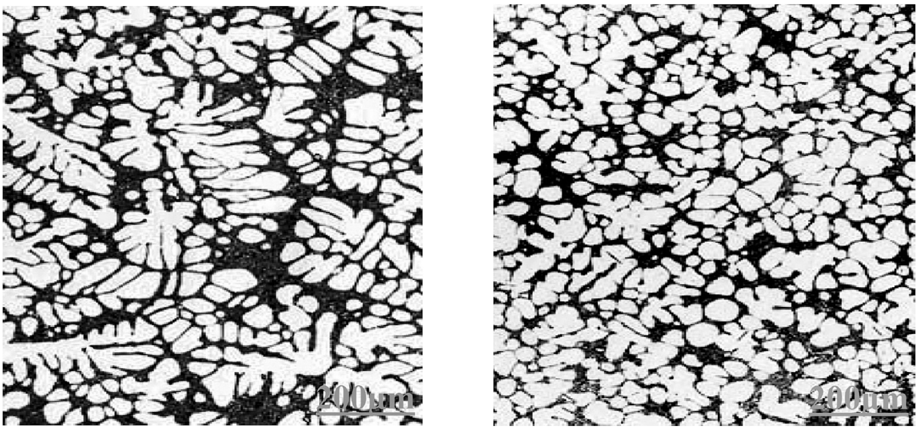


Fig. 6. Variations of elongation as a function of vol.% nano-SiC particulates.

It is of interest to use nano-sized ceramic particles to strengthen the metal matrix, while maintaining good ductility [6, 19]. It is inferred from Fig. 6 that the addition of nano-particles deteriorates the ductility of A356 alloy. The stir casting method that is used in the present work to produce the nanocomposites can most probably create different interfaces between nano-particles and matrices and thus, encourage crack initiation and propagation [10]. It is also noted that the elongation remains constant with the addition of nano-particles. This is consistent with the findings of Hassan and Gupta [20, 21].

The uniformity in distribution of particles within the specimen is a microstructural feature which determines the in-service properties of particular AMCs. A non-homogeneous particle distribution in cast composites arises as a consequence of sedimentation (or flotation), agglomeration and segregation. Optical micrographs of stir and compocast composites reinforced with SiC particles are shown in Fig. 7. Dendritic microstructure, as the result of casting process, is clearly revealed in this figure. This trend was observed in previous works [9, 10].



a b

Fig. 7. Optical photomicrographs: (a) stir cast A356 reinforced with 4.5 vol.% SiC; (b) compo cast A356 reinforced with 4.5 vol.% SiC.

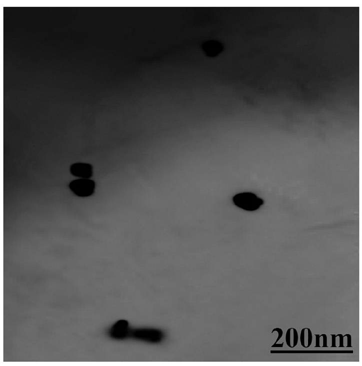


Fig. 8. TEM bright field image of composites with 3.5 vol.% nano-SiC particles.

High-magnification bright field TEM of compocast composites shows the uniform distribution of SiC particles through the matrix alloy (Fig. 8). It is reported in previous studies that during the solidification process of the composite slurries, the reinforcing particles are pushed to the interdendritic or intercellular regions and tend to segregate along the grain boundaries of matrix alloy. Figure 9 shows the grain morphology results of the composites. It is assumed that the uniform dispersion of nano-particles provides some heterogeneous nucleation sites during solidification, resulting in a more refined microstructure. Higher grain refinement of compocast composites can be attributed to the restricted movement of particles within the melt during solidification as a consequence of the increased effective

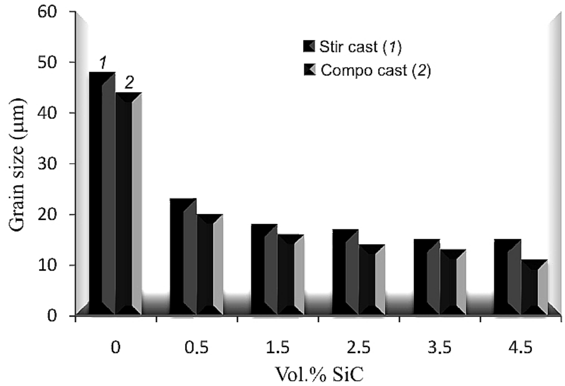


Fig. 9. Results of grain morphology.

viscosity of the slurry and the less pronounced coarsening effects resulting in a finer matrix microstructure which, in turn, causes a more uniform ceramic particle distribution.

Conclusions. It is concluded that a careful control of processing conditions is required to produce defect-free castings with fine microstructure which, in turn, may exhibit a more uniform particle distribution. In this research, nano-sized SiC particles were successfully incorporated into the aluminum matrix. Optical microscope examination revealed the grain refining effect of nano-particles. A reasonably uniform distribution of SiC nano-particles in the Al matrix was observed by electron microscope. Porosity level increased slightly with increasing particulate content which can be attributed to the increased surface area of the nano-SiC particles. The addition of nano-particles resulted in significant improvements in hardness, yield strength and UTS of the composites. Different strengthening mechanisms contributed in the obtained strength improvements including Orowan strengthening, grain refinement, accommodation of CTE mismatch between the matrix and the particles, and the load-bearing effects.

Резюме

Композити з металічною матрицею утворюють групу нових штучно спроектованих матеріалів, у металічну матрицю яких вводяться керамічні зміцнювальні компоненти з метою покращання її механічних властивостей, включаючи питомі міцність і жорсткість, а також зносостійкість, та забезпечення високої корозійної стійкості і високого модуля пружності. Метод композиційного лиття використовувався для введення наночастинок SiC у алюмінієвий сплав та виготовлення нанокомпозитів із металічною матрицею й однорідним розподілом зміцнюваних компонентів. Мікроструктурний аналіз композитів, що отримані методом композиційною лиття, показав однорідний розподіл наночастинок, зменшення розмірів зерен матриці з алюмінієвого сплаву та мінімальну пористість матеріалу. Установлено, що наявність наночастинок карбіду кремнію суттєво підвищує твердість, умовну границю текучості і границю міцності при збереженні початкової пластичності алюмінієвої матриці.

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