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Effect of reinforcement on mechanical characteristics of A356 alloy nanocomposites

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Abstract. Nanocomposites with aluminum base reinforced with nanoparticles, have wide application in many industries, for example, aerospace, marine, automobile, due to its lightweight, high tensile strength and high wear resistance, etc. The study of the microstructure, mechanical and tribological properties of the nanocomposite is very important in order to reliably and optimally carry out the design of new materials. In this study for the mechanical characterization of the A356 composites with a ceramic particle reinforcements nanoindentation was performed. Nanoindentaion is largely used for the analysis of mechanical properties. The samples of the nanocomposites were developed using 0, 0.2, 0.3 and 0.5 wt.% SiC, with an average size of particles of about 50 nm, produced by a compocasting process with pre-processing mechanical alloying. Nanoindentation was carried out based on Berkovich's test method with the indenter in shape of three sided diamond pyramid. The nanocomposite testing showed that the nanocomposites containing 0.5 wt.% of the reinforcement have slightly higher tensile strength and a lower value of the elastic modulus compared to the aluminum alloy base.

1. Introduction

In recent years, many composite materials have been developed that replace monolithic materials in many engineering applications. Composite materials consist of a base and an reinforcement that can be in the form of particles, fibers (long or short), laminates etc. Depending on the requirements of the industry, the properties of the base and the reinforcement are combined in order to respond to the set tasks that cannot be answered by conventional engineering materials. The composite can be with a polymeric, ceramic or metal base. Metal matrix composites (MMCs) are a special group of engineering materials due to the use of a light metal base to which different types of reinforcement are added, thereby improving the characteristics of the material. The most common materials used as base of composites are aluminum (Al) [1-3] magnesium (Mg) [4, 5], copper (Cu) [6], and titanium (Ti) [7] or their alloys.

Recent years great attention is paid to aluminum nanocomposites strengthen with particles due to application in the production of parts in the automotive and airplane industry [8, 9]. Metal matrix nanocomposites are a new class of materials that contain a nano-level reinforcement (1-100 nm), e.g. nanoparticles that are often used as an reinforcement. The most commonly used ceramic nanoparticles are Al_2O_3 and SiC, followed by TiC [10, 11], TiO_2 [12, 13], and TiB_2 [14, 15], which is confirmed by a large number of published researches in previous years [8].

Ceramic particles can be embedded in the base of aluminum alloy with different techniques. The most commonly used are mechanical alloying and casting. The method of making the nanocomposite with a metal base in liquid state is promising in terms of more economical production (shorter processing time and production cost) [16]. However, the efficient supply and dispersion of the nano-reinforcement is still a big challenge for many researchers [17]. Also, one of the useful techniques for achieving an equal distribution of nanoparticles is powder metallurgy technique [8].

In the last decades, testing of nanocomposite materials has been in expansion in order to find a nanocomposite that will meet certain requirements and replace monolithic materials in automotive, airplane, military, and many other industries.

The aim of this paper is the production of aluminum nanocomposites with different content of silicon carbide reinforcements by using an innovative process that represents a combination of mechanical alloying and compocasting process. Examination of the mechanical characteristics of the obtained nanocomposites with the base of the A356 alloy and with the low content of ceramic nanoparticles, is in order to find the dependence of the reinforcement content on hardness, elastic modulus and other feature of these materials. The tribological properties of these nanocomposites were tested and shown in the paper [18].

2. Overview of mechanical properties of nanocomposites with aluminum base

Today, great attention is paid to aluminum composites reinforced with particles in order to detect the best combination of base and reinforcement (type, size and content) and applied production techniques in order to achieve superior mechanical characteristics. Based on mechanical characteristics such as hardness, elasticity, elongation, density, porosity and tensile strength, a overall characteristics of the test material are obtained. A large number of scientists tested tribological characteristics [8], and the mechanical characteristics of nanocomposites with an aluminum base. Due to the diversity of the methods of obtaining and testing, combinations of the type, content and size of the reinforcement in the nanocomposite, as well as the way of displaying the results, the comparative results of the characteristics of the nanocomposite cannot be unified and diagrammatically illustrate. Some researchers carried out tests of the specific, i.e. the required characteristics, while other researchers carried out a complete analysis of the nanocomposite.

Rajmohan et al. carried out mechanical testing of the composite on hardness with the use of the Vickers method. The reinforcements used to form the composites are: CuO and SiC in mass ratio: CuO of 0 - 2 wt.% and SiC of 10 wt.%. The hardness results showed that the hardness increased with the increase of nanoparticles of the reinforcement in an aluminum base [19]. Also, the test of the hardness by the Vickers was carried out by Sharifi and Karimzadeh who then compared the results of aluminum alloys and hybrid nanocomposites with various reinforcement admixtures [20]. Based on the obtained hardness results, they concluded that the hardness increases with increase of the mass ratio of the reinforcement. The hardness test, depending on the mechanical grinding time, when obtaining the nanocomposite with the CNT and nSiC reinforcements, was considered by Kwon et al. [21]. They concluded that the hardness of the nanocomposite increases with the increase in the mechanical grinding time.

R. Taherzadeh Mousavian and others, in the production of an aluminum composite, tried to use micro particles instead of using nanoparticles to form SiC nanoparticles by increasing the grinding time. They concluded that with increase of grinding time the particle size was reduced, but not completely, because the SEM (Scanning Electron Microscopy) analysis revealed the presence of SiC particles of about 10-20 μm. They found that the particle size cannot be completely altered but they recorded an increase in the strength and hardness of the composite [22].

The combination of SiC particles of nano and micro sizes using stir casting technique for the production of composites was carried out by K. Amouri et al. The average particle size of nano and micro-size SiC powders was 50 nm and 5 μm. Testing the strength of the composite with the A356 base and the nano SiC particles of 0.5 and 1.5 wt.% and micro SiC with a content of 5 wt.% recorded a significant improvement in strength. More precisely, the highest strength was obtained in the composite containing 1.5 wt.% nano SiC. With the addition of micro/nano SiC particles the MMC has a significantly increased strength while ductility is reduced. Composite with a content of 1.5 wt.%

nano SiC possesses the highest tensile and compression strengths. The greatest strength of the nanocomposite is attributed to an optimized combination of sizes, equal distribution, and volume of particle fraction [23].

Hassan Tazari et al. carried out mechanical testing of aluminum nanocomposites with different SiC particle content of 1 wt.% to 5 wt.% produced by powder metallurgy [24]. They discovered that micro-hardness increases with an upward trend with the addition of particles up to 3 wt.% and then adding 5 wt.% this trend slightly decreases. In the analysis, they also found an increase in the porosity of the nanocomposite with the content of the reinforcement of 5 wt.%, which was also uncovered by the decrease in relative density. The improvement in micro-hardness values of 95%, 83% and 166% was recorded with an increase in reinforcement content of 1, 3 and 5 wt.%, respectively.

In addition to the hardness of the material, tensile strength monitoring is also important. Poovazhagan and others performed all mechanical tests on the nanocomposite [25]. For the reinforcements, they used SiC and B_4C with mass ratio for both reinforcements: 0.5 wt.%, 1 wt.% and 1.5 wt.%. The results obtained by tension test showed that the maximum tensile strength of the composite with 1 wt.% SiC + 0.5 wt.% B_4C was 265 MPa. While the composite with 1.5 wt.% SiC + 0.5wt.% B_4C had a tensile strength of 200 MPa. Mahmoud et al. [26] performed mechanical testing of nanocomposite samples with the Al_2O_3 and Ni reinforcements in the following ratio: Al_2O_3 of 2, 3 wt.%, and Ni of 5, 10, 15 wt.%. The highest value of the tensile strength of 380 MPa was obtained for the composite with 2 wt.% Al_2O_3 and 5 wt.% Ni, while the significantly lower strengths of 300 MPa were obtained with the composite ratio of the reinforcement from 3 wt.% Al_2O_3 and 5 wt.% Ni.

Comparison of experimental and theoretical results for density was carried out by Muley et al. They used a composite made of only one variation of the mass fraction of the reinforcement [27], while Sharifi and Karimzadeh made a comparison between the density of the composites obtained by experimental paths and between the composites with multiple variations of the reinforcement [20]. Generally, the density values obtained by the experiments and theoretically are very close.

On the basis of the obtained results for density [28, 29] it is noticed that the density of the nanocomposite is mostly influenced by the content of the mass fraction of the material, as well as the choice of the material of the reinforcement because different reinforcements result in different densities of the final nanocomposite. With the increase in the mass fraction of CuO in the composite, the density increases [28]. The stretch test of the nanocomposite and comparison with the base of the nanocomposite [25, 26] led to the conclusion that increasing the reinforcement content may result in more or less elongation of the nanocomposite than in the base alloy.

Based on previous research and literature review, it is noted that the properties of the nanocomposite with the metal base are greatly influenced by the size, shape, uniform distribution, the hardening mechanism, as well as the thermal stability of the nano reinforcement [30]. Also, the great influence on the mechanical behavior of the material depends on the porosity of the materials which is need to be controlled in order to avoid undesirable properties [31, 32]. Researchers tend to achieve an improvement in mechanical properties without affecting ductility by applying certain quantities of particles at the nano level [33].

For nanocomposites strengthened by nanoparticles, strength and ductility can be improved at the same time if the particles are correctly or evenly distributed on the base. Unlike micron particles, nanoparticles with a similar and even smaller particle volume in the base can improve the mechanical properties of the nanocomposite [2, 34]. Moreover, in the previous research, the optimization methods have been observed in order to speed up the research process and optimize the processing parameters and conditions, as well as the nanocomposite testing. Temel Varol et al. [35] created a model for predicting the effect of SiC reinforcement size, reinforcement content, and grinding time on the density and strength of the nanocomposite AA2024-SiC by using a neural network. They have confirmed that the results obtained by the multilayer neural model have consistency with experimental values that they found on the basis of error in results which was less than 1%. The results of this study show that the neuronal network model can be used to predict the density and hardness of the AA2024 nanocomposite with great precision. Also, a powerful means of achieving appropriate data for predicting and optimizing the desired parameters in various processing technologies of advanced materials is possible by using the combination of the artificial neural networks (ANN) and genetic algorithms (GA) method [36] and many other optimization methods.

3. Experiment

3.1. Materials

A356 alloy is selected as the base of the nanocomposites because it possesses high mechanical strength, ductility, hardness, fatigue strength, fluidity and the possibility of light machining and good weldability. The chemical composition of the used hypoeutectic Al-Si alloy A356 is as follows: Si (7.20 wt.%), Cu (0.02 wt.%), Mg (0.25 wt.%), Mn (0.01 wt.%), Fe (0.18 wt.%), Zn (0.01 wt.%), Ni (0.02 wt.%), Ti (0.11 wt.%) and rest is Al.

To obtain the nanocomposite, prior to the compocasting procedure, a pre-treatment was applied - the mechanical alloying of the metal chips of the base alloy with nanoparticles of the SiC reinforcement of about 50 nm. One of the most important ceramic reinforcements for metal matrix composites are SiC particles. The importance of use of SiC particles in MMC is due to its properties such as good thermal stability, low density, high wear resistance, high melting point and high hardness. The SiC nanoparticles were washed in ethyl alcohol before the alloying procedure, and heated to a temperature of up to 400°C in order to free the moisture and possible chemical impurities. The metal chips of the A356 alloy was washed in trichlorethylene and then in ethyl alcohol for degreasing. A more detailed procedure for obtaining the nanocomposite with and the used apparatus is described in [18].

The mechanical properties of the A356 alloy can be improved by thermal treatment. In this study, the applied thermal treatment T6 implied the first solvent irradiation for 8 hours at a temperature of 525°C, followed by tempering in water at 30°C to room temperature. And finally, natural aging for 5 hours in the air or artificial aging (precipitation) for 8 hours at a temperature of 165°C. The goal of thermal treatment is to increase hardness and reduce toughness, to obtain an optimal combination of strength and toughness, as well as removing residual stresses.

3.2. Specimen preparation

The quality of the treated surface greatly influences the exploitation properties of the machine parts, as well as their lifetime. It is generally known that the surface of any machine element after finishing is never absolutely smooth. So before testing the material, it is necessary to prepare the surface of the samples after cutting the castings to certain dimensions.

The application of the grinding and polishing method tended to achieve certain roughness of the surfaces after the milling process. The grinding process was carried out by treating the contour surfaces with abrasive paper grit of 1000, 2000 and 3000, while the polishing was performed with an emulsion with abrasive grains of 1 μm in order to obtain surfaces of the appropriate quality. The preparation of the samples was carried out on the MetaServ 250 polisher. This polisher can be found in the paper [37] in which the analysis of tribological characteristics of nanocomposites was carried out. The computer-assisted device for testing of the mechanical properties of the tested materials is Nanoindenter and Micro Scratch Tester, and this device is shown in figure 1. Technical specification of the used nanoindenter is: maximum load 500 mN, load resolution 0.04 μN, maximum depth 40 μm (optional 200 μm), depth resolution 0.04 nm and movement of measuring table XY, 150 x 80 mm.

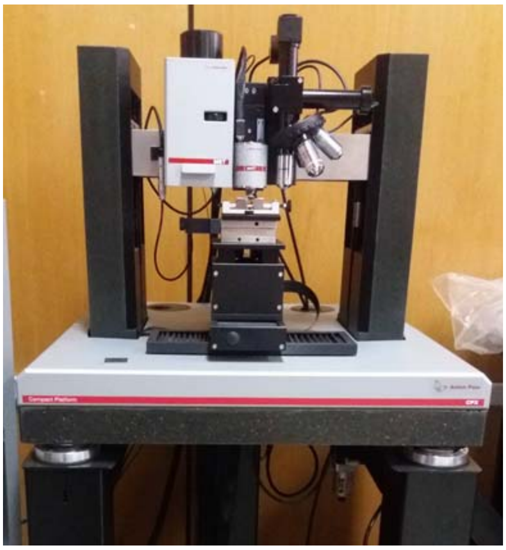

Figure 1. Nanoindenter and Micro Scratch Tester.

With this device is possible to continuously measure normal load and movement of the indenter during the hardness testing. Measurement of the elastic modulus and hardness using this device is possible based on the budget method developed by scientists Pharr and Oliver [38].

3.3. Nanoindentation

The mechanical properties of the nanocomposite and the A356 alloy are tested by penetrating the surface of the test sample. During these tests, Berkovich's three-sided diamond pyramid was used as an indenter. Experimental tests were carried out in the conditions shown in table 1. The chosen type of test is in the form of a matrix, and it is 3x3, which means tests were carried out in 9 points.

Table 1. Conditions of nanoindentation experiments.

Parameter	Unit	Value
Normal load	mN	50
Maximum load holding time	s	15
Loading speed	mN/min	100
Unloading speed	mN/min	100

In this study, the value of the normal load was 50 mN, because the previous research of these materials proved that force variation does not significantly affect the results of hardness. The value of Poison's coefficient in this test was taken as the value for aluminum and it is 0.33.

4. Results and discussion

As the results of nanoindentation a number of representative values can be obtained, in this paper the following will be shown: hardness (HV), elastic modulus (E) and value of maximum indentation depth (hmax). Also, based on the measurements carried out, in figure 2, the diagram of indentation is shown, which represents the dependence of the normal load of the indenter and the maximum depth of penetration. The illustrated diagram of indentation was selected according to the corresponding hardness values that were closest to the mean values of the hardness (figure 3).

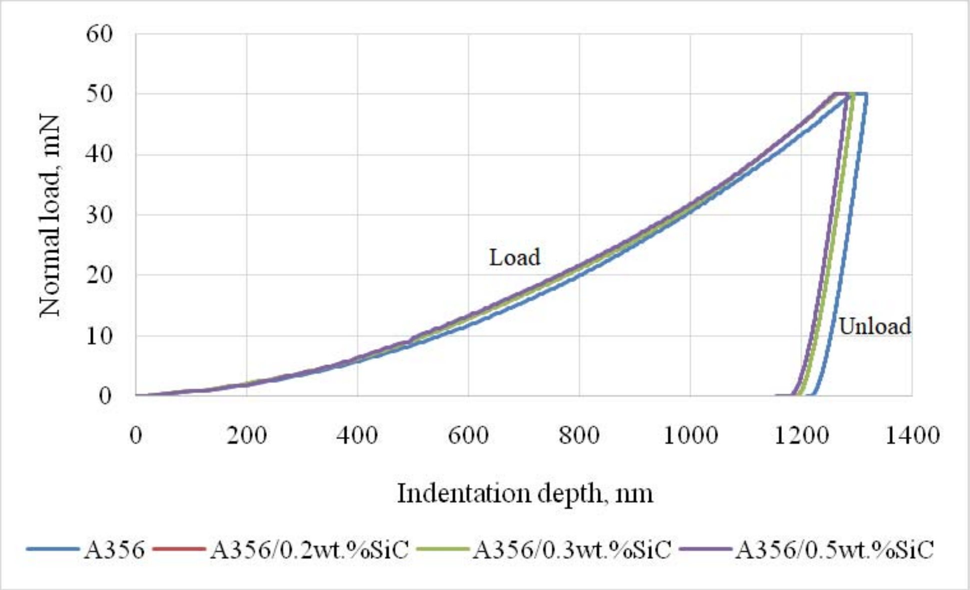

Figure 2. Nanoindentation curves for nanocomposites with SiC reinforcement and A356 alloy.

Based on the trend of indentation curves of all the examined materials, there is no large difference between the tested materials in the appearances of the curves. These curves show the elastic and plastic deformations during and after the process. The first is the result of the elastic deformation of the tested materials and it ends with the indentation depth about ~ 300 nm. Thereafter, there are no significant changes in the curve trends. Also, it is possible to notice two stages in the load process (load and unload), which are denoted in figure 2.

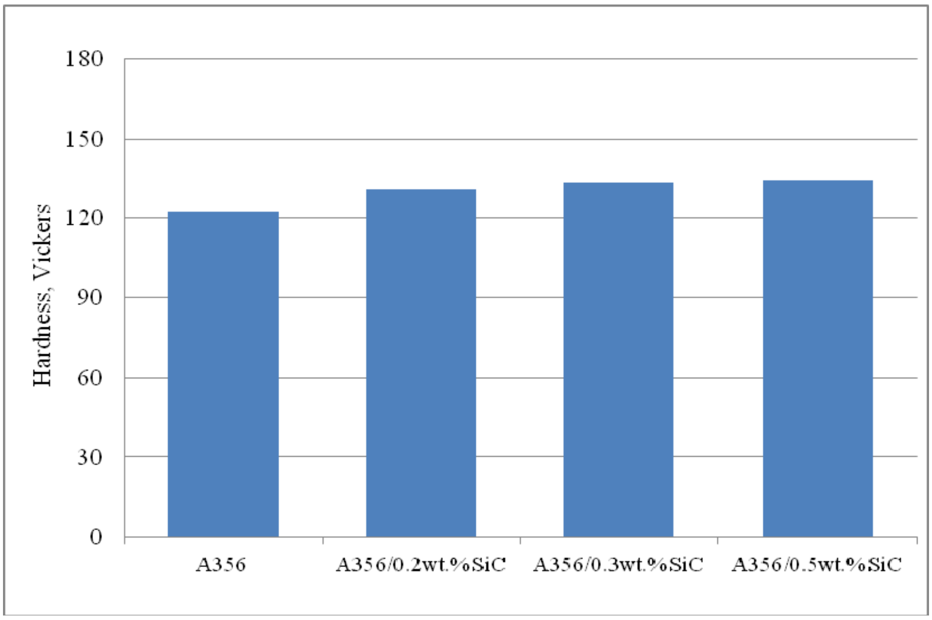

Figure 3. Experimental values of hardness.

Based on the curves obtained by nanoindentation of samples of A356 alloys and nanocomposites with reinforcement content of 0.2, 0.3 and 0.5 wt.% SiC, it can be noticed that the obtained values of the hardness of the nanocomposite are higher compared to the base alloy. The difference in the hardness of the material is evident from the difference in the indentation depths of the indenter into the test samples (figure 4), which means that the greater indentation depth is followed by a lower hardness value.

What has to be noted is that during the implementation of the experiment, it was taken into account that the matrix is positioned in such a way that it is approximately in the same position for each material, more precisely, the same number of imprints are in areas with and without the presence of eutectic silicon on the surface of the material. However, some of the results were not taken into consideration because there was much greater hardness, and this happened when the indenter hit the eutectic silicone. Previously mentioned was done to reduce the dispersion in the averaging of the test results.

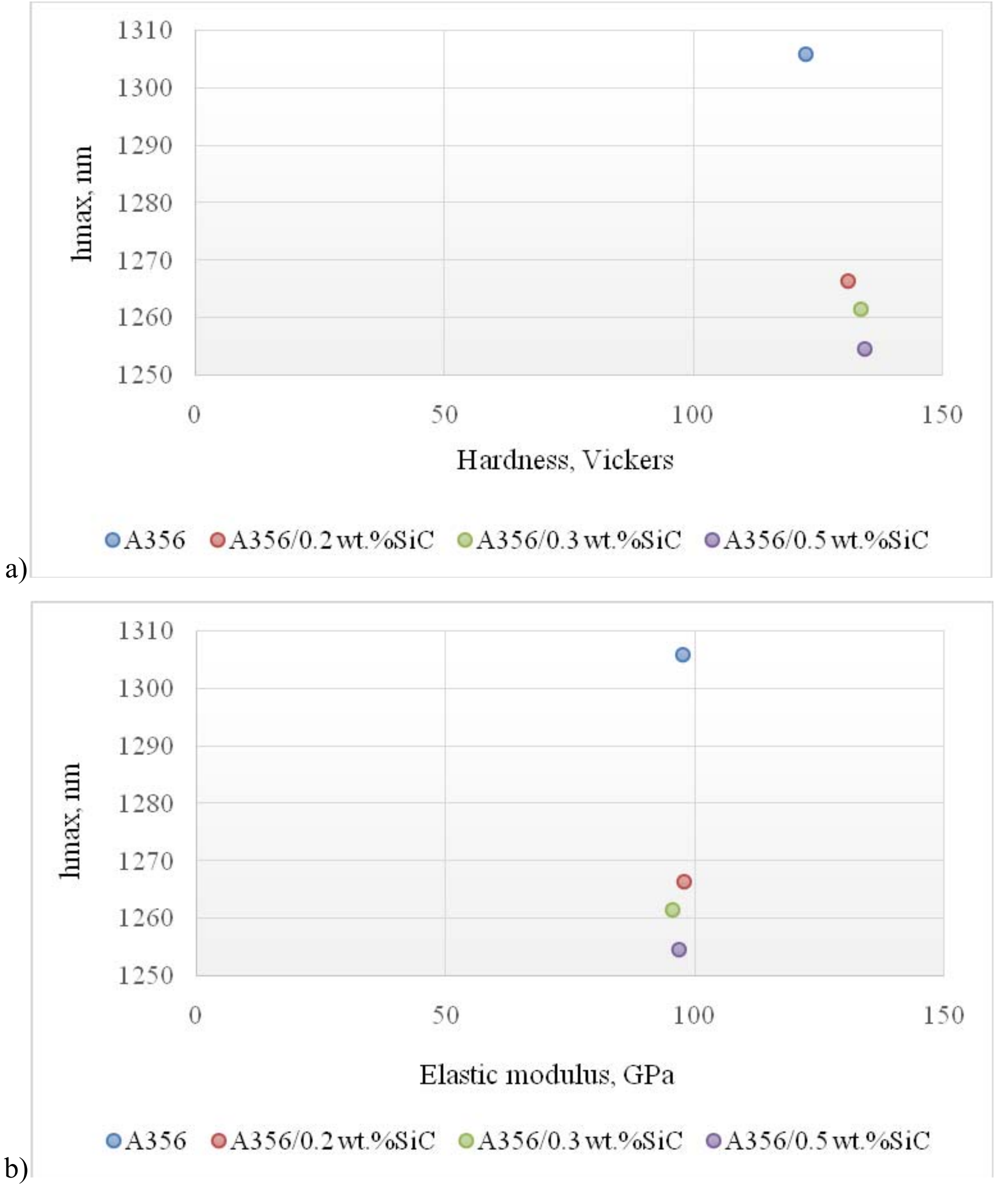

Figure 4. Mechanical properties as a function of the impression depth: (a) hardness; (b) elastic modulus.

Based on the results shown, for the elastic modulus, it can be said that the increase in the percentage content of the reinforcement does not greatly affect the value of the elastic modulus. It can also be concluded that the lower indentation depth indicates the strengthening of the base with silicon carbide, and Behzad Sadeghi and others have come to similar conclusions [39]. It is generally known that the presence of agglomeration and porosity has a negative impact on the mechanical properties of nanocomposite materials [40]. Analyzing the nanocomposite surfaces by SEM analysis in [37], no agglomeration of nanoparticles was observed, which confirms the increase in the hardness of these materials.

5. Conclusions

Hardness tests were conducted with the aim of analyzing the effect of nanoparticles of silicon carbide as a reinforcement in the A356 base. Based on the obtained values of the hardness in surface layer of the nanocomposites, a noticeable increase in hardness was observed in comparison to the base alloy of the nanocomposite. Increasing the reinforcement content of 0.2, 0.3 and 0.5 wt.% increases the hardness of the nanocomposites ~131, 133 and 134 Vickers, respectively. Also, it can be concluded that the elasticity of the material decreases with the increase of reinforcement content. When comparing the hardness and elastic modulus of the tested nanocomposites there is a small deviation in the results, which is due to the small difference in reinforcement content in the nanocomposites.

However, it has to be noted that the extreme values obtained for eutectic silicon have not been taken into consideration and this requires additional research because it has an impact on the hardness values of the surface layers of the material.

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