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: The data supporting the findings of this study are available upon request from the corresponding author.

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Writing—original draft preparation, [Salih Y. Darweesh]; Writing—review and editing, [Ghazi F. Mahal]. All authors have read and approved the final manuscript.

ORIGINAL STUDY

Effect of Adding Nano Silica on Some Structural and Thermal Properties of Aluminum

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Abstract

The powder metallurgy method was employed to fabricate aluminum-based composite samples reinforced with nano silica at varying weight fractions of 2, 4, 6, 8, and 10 wt. %. The powders were mixed, dried, and compacted using a hydraulic press at 7 tons of pressure for 1 min, followed by thermal sintering in an oven at 600 °C for 2 h. Structural characterization was conducted using scanning electron microscopy (SEM) and X-ray diffraction (XRD), while thermal analysis included thermal conductivity, heat capacity, thermal diffusivity, thermal flux, and thermal resistance. The results revealed that the optimal nano silica reinforcement ratio was 10 %, yielding notably improved properties. SEM images confirmed surface homogeneity and strong granular cohesion, whereas XRD and energy-dispersive X-ray spectroscopy (EDX) identified aluminum in the cubic crystal system, while nano silica exhibited partial crystallization and a broad maximum peak at ($2\theta = 22-25^{\circ}$) with a Miller index of (111). Thermal analysis indicated a gradual decline in thermal conductivity as the nano silica content increased, with the lowest thermal conductivity recorded at 112 W/m.K and the lowest thermal effusively at 265.990 W $s^{1/2}/m^2$.K. Similarly, the thermal diffusivity reached a minimum of 0.1098 mm^2/s at 10 wt. % silica reinforcement. Furthermore, the thermal capacity decreased, whereas thermal resistance increased with higher reinforcement ratios, reaching a minimum heat capacity of 302.251 J/kg.K and a maximum thermal resistance of 3.366×10^{-6} W/m^2.K at 10 wt. % silica. These findings highlight the potential of nano silica reinforcement in enhancing the thermal performance of aluminum-based composites.

Keywords: EDX, SEM, Thermal conductivity, Thermal effusion

1. Introduction

Composite materials have been used since ancient times. The Mesopotamian civilization was the first to use composite materials [1]. They built ziggurats by reinforcing layers of construction with reed fibers to stabilize the construction. They also built houses by strengthening clay with sawdust [2]. Examples of composite materials found in nature are cellulose fibers with wood. Composite materials consist of different materials, so their manufacturing methods differ from those of metals and polymers [3]. Therefore, the manufacture of composite materials requires high skill and cost to complete [4]. One of the methods of manufacturing composite materials is powder metallurgy technology. Composite materials are a broad science that cannot be covered by simply knowing the basic principles of the subject. Rather, it must be supported by a large practical aspect [5]. It should be noted that the study of composite materials aims to find a composite material that meets the design requirements at the lowest possible cost. Powder metallurgy technology is used to manufacture products from metal or ceramic powders by mixing these powders to obtain a homogeneous distribution of particles and then placing these powders in molds and pressing them with an appropriate pressure to obtain pistons with dimensions close to the design dimensions [6]. Examples of products produced in this way include grinding wheels, magnets, welding wires, self-lubricating bearings, electrical conductors, and high-temperature resistant turbine

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blades. Powder metallurgy technology goes through several processes, namely mixing the powders, pressing them in molds, and then sintering them at temperatures below the melting point of the base material. Sintering the pistons is to increase the bonding between the particles in addition to improving the material's resistance and other properties. Metal-based composites are considered one of the most important types of composite materials and are called advanced engineering materials [7]. These materials have distinctive properties that have made them at the forefront of composite materials. The base material is a metal material such as aluminum, copper, magnesium, etc. And reinforced with one of the strengthening phases such as particles, fibers, or hairs, etc. such as silicon carbide, graphite, and other strengthening materials. Compared to metal materials, metal-based composites have good specific strength, good specific stiffness, and good wear resistance [8]. The disadvantages of metal-based composites compared to metals are their high manufacturing cost, in addition to their low ductility and durability [9]. Due to the good properties of metal-based composites, they have been widely used in industry, such as the manufacture of some parts of aircraft and satellites, as well as the manufacture of some parts of cars [10]. The current work aims to study some structural and thermal properties of aluminum-based composites reinforced with nano-silica, and the main goal is to obtain a consistent, homogeneous, and low-porosity surface, with low thermal conductivity values for the purpose of using these composites in insulating applications or those with high-temperature tolerance, such as some parts of cars, aircraft, and satellites.

2. Raw powders

The base material was aluminum powder with a particle size of 75 μm and a purity of 99.3 % manufactured by Sulzer Metco of Switzerland. The reinforcement material was nano silica with a nano size of 35 nm and a purity of 99.8 % manufactured by Changsha Santech Co. of China.

3. Expremental part

The practical side included the preparation of the compressed materials by powder metallurgy using a Chinese-made hydraulic press at a pressure of 7 tons for 1 min. The powders were mixed with aluminum base and supported by volumetric ratios of nano silica with values of (2,4,6,8,10) wt. %. All mixtures were dried after mixing to get rid of some impurities or moisture formed in the laboratory, then mixed with a laboratory mixer. The compression process was carried out using a compression mold with a diameter of 1 cm so that the final models were 0.7 cm high. The compressed materials were prepared according to the required type of examination. The resulting compressed materials suffer from a weak crystalline structure that needs to be strengthened by the necessary heat treatments. The sintering process was carried out in a Korean-made Muffle type thermal oven at a temperature of 600 °C for 2 h and left until the next morning. The melting point of the basic materials was taken into consideration during sintering. The samples coming out of the thermal furnace were cleaned and subjected to post-operation processes in terms of polishing and cleaning in order to prepare them for the upcoming structural and thermal tests. Fig. (1) shows samples after the powder pressing process.

Fig. 1. Models after powder pressing and thermal sintering process.

4. Theoritacal part

4.1. Stracture crystalline (SEM and XRD)

The scanning electron microscope is one of the important electron microscopes in evaluating the surface topography, examining the surface structure, and calculating the grain size. It is also possible to know the proportions of the elements that make up the compound through (EDX), where a scanning electron microscope type (MIRA3 TESCAN) of Belgian origin was used. Through it, a beam of electrons is directed at the atoms present on the surface of the sample, thus producing several different signals that provide information about the shape and topography of the external surface of the samples used. As for the results of the X-rays, they were calculated using a device of the type (X'Pert High Score Plus). The tube used is (Cu) kα, and the examination was carried out at room temperature. Table (1) shows the examination results in terms of specifications. The British scientist William Lawrence Bragg (W.L. Bragg) developed a mathematical equation that helped determine the distances between the atomic levels within crystals through the phenomenon of X-ray diffraction. Bragg relied on the fact that when X-rays fall on a crystal, they are deflected in multiple directions as a result of their interaction with the crystal levels. This equation is used to determine the crystal phases and analyze the type of material. The equation is as follows [11]:

$$2d\,Sin\theta = n\lambda \tag{1}$$

Where: d: the distance between the atomic planes, θ: the angle of diffraction,

λ: the wavelength of the X-rays, n: an integer expressing the order of diffraction.

4.2. Thermal properties

Thermal conductivity is a property of materials that shows their ability to conduct heat, and its calorific value is measured in units of ($w.m^{-1}.k^{-1}$). The device used to measure thermal conductivity is (Mathis TC i) type (MPTS). Conductivity can be determined using the following formula [12–15]:

Table 1. X-ray measurement specifications.

Applied voltage	40 KV
Applied current	30 mA
Scan speed	5 deg/min
Scan range	5°–80°
Wavelength	1.54060 A°

$$Q = \frac{dH}{dt} = -\frac{\lambda A\, dT}{dx} \tag{2}$$

Where:

Q: Amount of heat per unit time (watt), H: Heat (J), t: Time (sec (,λ: Thermal conductivity ($w.m^{-1}.k^{-1}$), T: Temperature value (K), X: Height of the test sample (m), A: Cross-sectional area of the sample (m^2),

The thermal diffusion equation (m^2/s) δ is:

$$\delta = \frac{\lambda}{Cp\,.\rho} \tag{3}$$

Cp: Specific heat capacity (J/g.k), ρ: Density of the sample (g/cm^3),

The heat flux relationship Ɛ ($ws^{½}/m^2$. K) is:

$$\varepsilon = \sqrt{\lambda\,.\,\rho\,.\,C_p} \tag{4}$$

The thermal resistance $R_{thermal}$ (W/m^2.K) is:

$$R.thermal = \frac{dX}{\lambda} \tag{5}$$

5. Discuss the compositional and thermal results

5.1. XRD & SEM tests

Fig. (2) shows the X-ray diffraction pattern of (Al), (%SiO_2) compounds after heat treatment. The results of the X-ray diffraction (XRD) of the aluminum sample, also shown in the figure, show the face-centered cubic (FCC) crystal system, which is the known crystal structure of aluminum. The main peaks can be observed at different diffraction angles, where a prominent peak appears at 38° representing the (111) level, which is the peak with the highest intensity, indicating the preferred crystal orientation in the sample. Other peaks appear at 44.5° for the (200) level, at 65° for the (220) level, and at 78° for the (311) level. This crystal distribution reflects a high degree of formation, where the sharp and high-intensity peaks indicate the purity of the material and its crystalline homogeneity [16]. The appearance of these peaks alone and the absence of additional large peaks indicate that the material is mainly composed of pure aluminum with a very small percentage of impurities or secondary materials, which indicates the success of the pressing method for manufacturing pistons in obtaining high purity and regular crystal structure. As for the nano-reinforcement material, it is silica [17]. The results of X-ray diffraction (XR D) of nano-silica, as shown in the results, show a broad and distinct peak at an

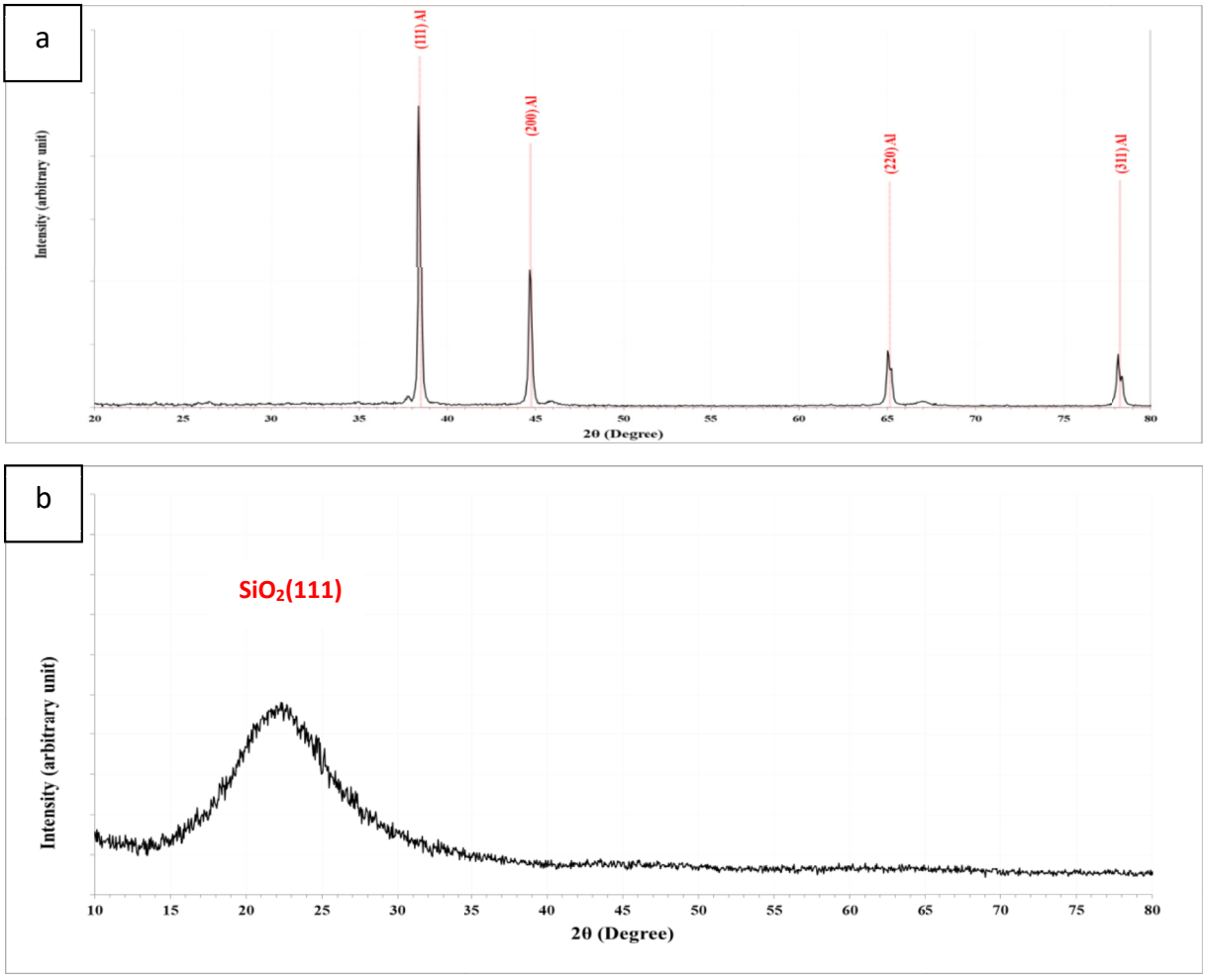

Fig. 2. XRD of the raw powders (a-Al, b-SiO_2).

angle of 2θ about 22–25°, which is attributed to the (111) plane of SiO_2. The appearance of this broad peak indicates that the material has a partially amorphous nature with some semi-crystalline properties. This behavior reflects a limited and short-range arrangement of SiO_2 atoms, as no clear crystalline values are seen as shown in fully crystalline materials. The (111) plane indicates the presence of a local structure organized at the nanoscale, but it does not extend significantly throughout the material [18]. The non-crystalline randomness of nano-silica exhibits a material with distinctive properties, such as high porosity and ability to undergo any chemical reaction, which makes it suitable for application in composite materials [19,20].

Encouraging results were obtained from scanning electron microscopy (SEM) testing at a depth of 10 μm and a magnification power of 5KX, as shown in Fig. (3). This figure presents images of the added percentages of nano-silica: (a-2 %, b-4 %, c-6 %, d-8 %, e–10 %), where the electronic results reflect the properties of (Al–%SiO_2) composites at different reinforcement percentages after thermal sintering. These results highlight the evolution of the microscopic structure and properties of the material as the nano-reinforcement percentage increases. Increasing the nano-silica content has a noticeable effect on the microscopic structure, as nano-silica contributes to filling voids and reducing porosity within the crystalline structure of aluminum, enhancing the material's hardness, thermal stability, and mechanical performance [21]. At higher percentages, silica acts as an effective barrier against cracks by distributing stresses and improving crystal bonding [22]. The optimum ratio (90 % Al - 10 % SiO_2) achieves a balance between hardness and structural cohesion, ensuring defect reduction and improving the overall material properties [23]. These improvements are attributed to the good interpenetration between aluminum and silica atoms, leading to the formation of a cermet alloy

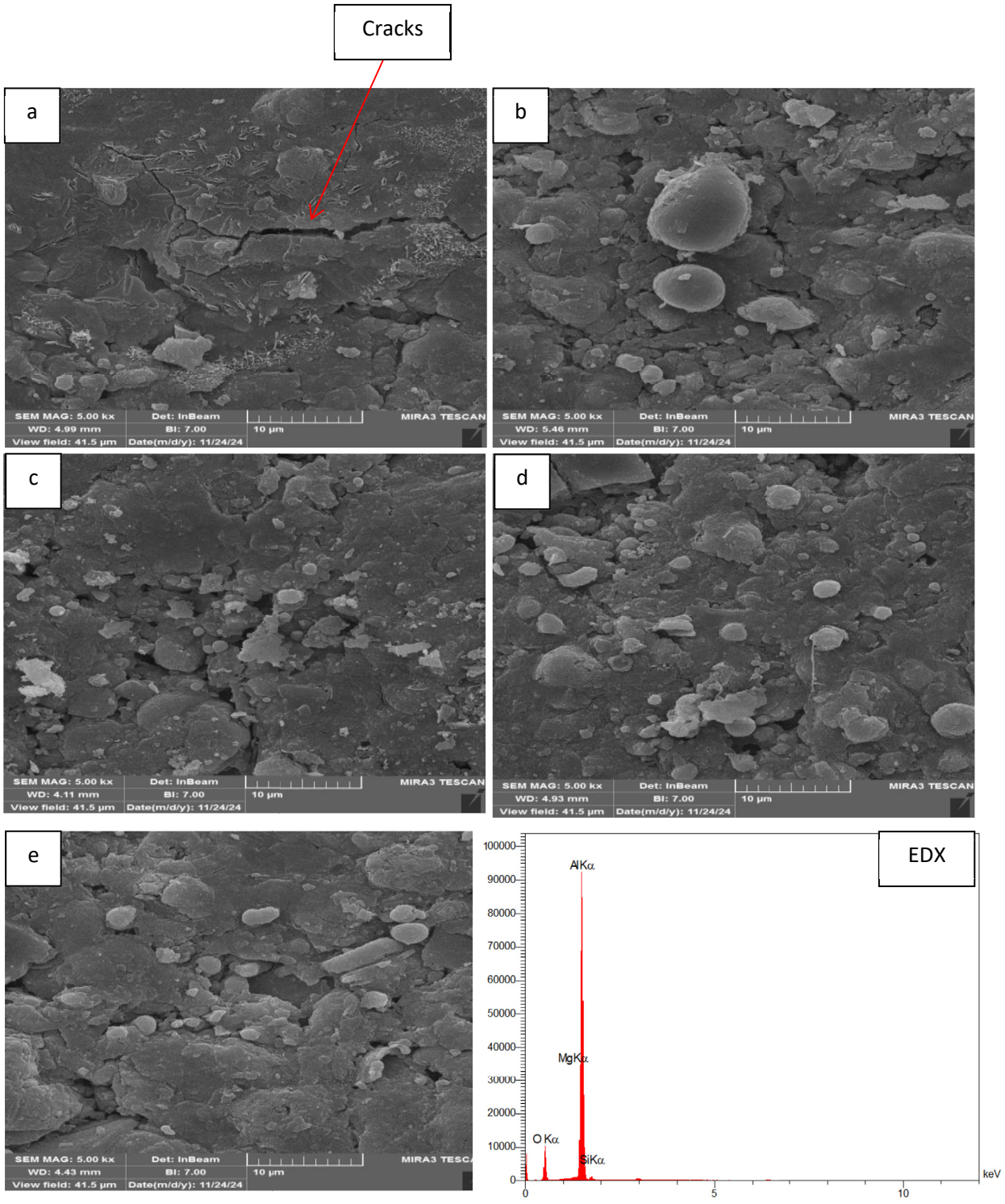

Fig. (3). Scanning electron microscope (SEM) and EDX images of (Al–%SiO_2) composites at different reinforcement ratios (a-2 %, b-4 %, c-6 %, d-8 %, e–10 %).

that combines the hardness of nano-silica with the ductility of aluminum, making it suitable for applications requiring high strength and advanced thermal properties [24]. Furthermore, Fig. (3) also includes energy-dispersive X-ray spectroscopy (EDX) analysis, which confirms the presence of aluminum as the base material along with silicon and oxygen representing nano-silica. Additionally, a few grille-like features appear naturally due to the incomplete resistance of materials to structural

imperfections, which is a common characteristic in composite materials [25].

5.2. Thermal tests

Figs. (4)–(8) show the relationship of conductivity, capacitance, diffusion, flow, and resistance with the addition ratios of nano-silica at reinforcement ratios (2, 4, 6, 8, 10 %) after heat treatment. We find in Fig. (4) that there is a clear decrease in the thermal conductivity values from (200 w/m.k) to (112 w/m.k) from reinforcement ratio (2 %) to (10 %) respectively, i.e. the inverse proportion between the thermal conductivity (λ) and the increasing reinforcement ratios. Due to the insulating nature of silica compared to high thermal conductivity aluminum. Silica acts as a barrier to heat transfer through the material. The second reason is attributed to the presence of pores that greatly affect conductivity, and this is what was found in the previous structural interpretations, where the increase in porosity values has a significant effect on the decrease in thermal conductivity in an inverse proportion [26]. As shown in Fig. (5), we notice a decrease in the heat capacity from (700.379 J/kg.k) to (302.251 J/kg.k) from the reinforcement ratio (2 %) to (10 %), respectively. The reason for the decrease in the heat capacity (Cp) with the increase in the percentages added to the reinforcement powder of nano-silica is due to the behavior of the composites as semiconductors, i.e. a compound of a base material (aluminum) is a conductor and silica is an insulator. The result showed a semiconductor material, i.e. with a low thermal capacity, and this is consistent with the researchers [27]. This behavior is similar to thermal conductivity. Also, the amount of heat capacity, the specificity depends on the

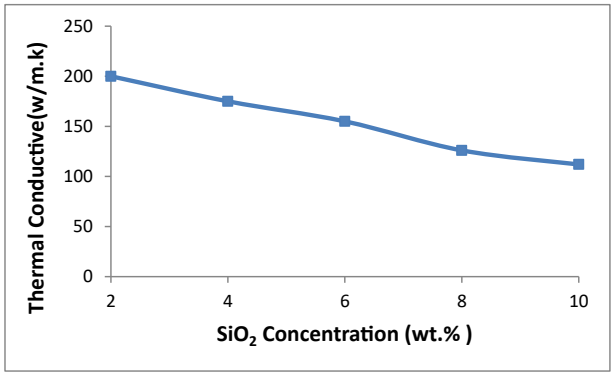

Fig. 4. The relationship between the increase in the volume fraction of silica nanoparticles and thermal conductivity.

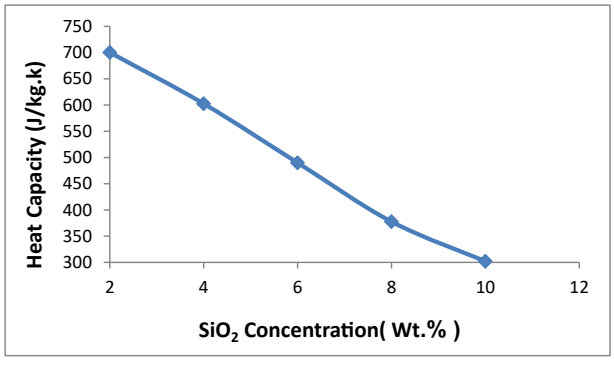

Fig. 5. The relationship between the increase in the volume fraction of silica nanoparticles and the heat capacity.

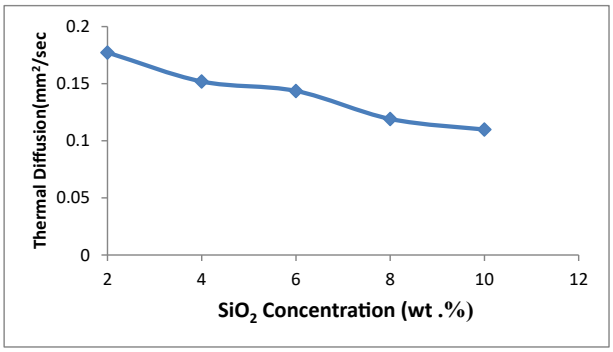

Fig. 6. The relationship between the increase in the volume values of silica nanoparticles and thermal diffusion.

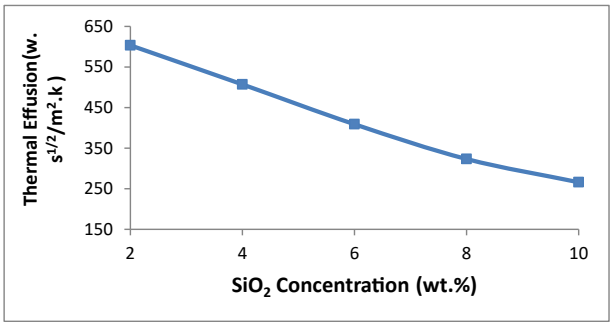

Fig. 7. Increase in the volumetric values of silica nanoparticles and thermal effusion.

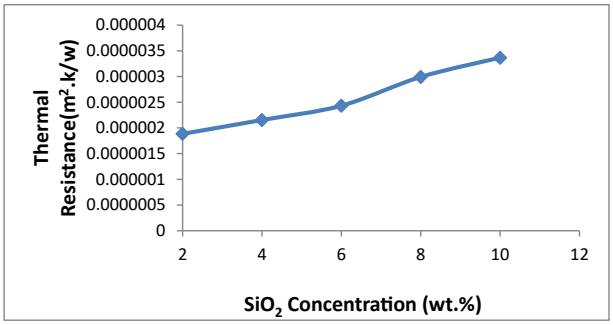

Fig. 8. The relationship between the increase in the volume fraction of silica nanoparticles and thermal resistance.

constituent materials, as nano-silica has a lower specific heat capacity than aluminum, so it decreases naturally. As for Fig. (6), we find that the thermal diffusion values (δ) begin to decrease gradually with each nano addition of silica, as we find a decrease in the amount of heat diffusion by an amount proportional to (0.177 mm^2/s) to (0.109 mm^2/s) from a reinforcement ratio of (2 %) to (10 %). This decrease in thermal diffusion values is expected and the reason is attributed to the decrease in thermal conductivity with the increase in silica ratios, as the decrease in thermal diffusion leads to a direct negative effect on thermal diffusion [28,29]. As for Fig. (7), we notice a decrease in the thermal flux from (603.371w. $s^{1/2}/m^2.k$) to (265.990 $w.s^{1/2}/m^2.k$) from a reinforcement ratio of (2 %) to (10 %). This decrease is proportional to the thermal conductivity and thermal diffusion and for the same reasons when mixing a material with low thermal conductivity with a metal such as aluminum [30]. While Fig. (8) shows where We notice an increase in thermal resistance from (0.0000188 $w/m^2.k$) to (0.00000336 $w/m^2.k$) from reinforcement ratio (2 %) to (10 %) respectively. Thus, we find that thermal resistance changes inversely with respect to thermal conductivity, thus thermal resistance increased with any addition of nano-silica, as well as the occurrence of cracks and separations during pressing, which in turn acts as thermal resistance [31–33].

6. Conclusions

The scanning electron microscope (SEM) analysis revealed clear homogeneity and strong adhesion between the aluminum powder and nano silica, along with a uniform distribution of silica grains within the aluminum matrix. The optimal diffusion rate was observed at a 10 % reinforcement ratio, whereas lower reinforcement levels exhibited increased porosity, cracks, and crystal separations. Regarding the thermal conductivity tests, the results confirmed a gradual decline in thermal conductivity with increasing silica reinforcement. The lowest thermal conductivity was recorded at 112 W/m.K, with a corresponding minimum heat flux of 265.990 W $s^{1/2}/m^2.K$ and thermal diffusivity of 0.1098 mm^2/s at 10 % silica reinforcement. Additionally, an inverse relationship was observed between thermal capacity and thermal resistance, where an increase in silica content led to reduced heat capacity and enhanced thermal resistance. The lowest thermal capacity was recorded at 302.251 J/kg.K, while the highest thermal resistance reached 3.366×10^{-6} $W/m^2.K$ at 10 % silica reinforcement. These findings demonstrate that increasing the nano silica content enhances the thermal insulation properties of aluminum-based composites, making them suitable for applications requiring low thermal conductivity and high thermal resistance.

Ethics information

We confirm that this study adheres to the ethical guidelines required by the journal. No human or animal subjects were involved in this research, and there are no ethical concerns related to this study. Additionally, there are no conflicts of interest to declare.

Source of Funding

None.

Conflict of Interest

No conflicts of interest.

Data Availability

The data supporting the findings of this study are available upon request from the corresponding author.

Author Contributions

Writing—original draft preparation, [Salih Y. Darweesh]; Writing—review and editing, [Ghazi F. Mahal]. All authors have read and approved the final manuscript.

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