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Study the Effect Nanomaterial Al Addition on the Structural and Mechanical Properties of TiO₂ via Nano-Powder Metallurgy Method

Murtadha H. Gatea , Alaa Y. Ali ^{a,b} , Ayad M. Tahatoh, Mustafa Y. Ali^a

^a *Electrical Department, Engineering College Alshirqat, Tikrit university, Iraq.*

^b *Natural Resources Research Center, Tikrit University, Iraq.*

Corresponding author : alaa.y.ali@tu.edu.iq , <https://orcid.org/0000-0002-7095-2328>

Abstract:

The addition of nano-Aluminum (Al) to Titanium Oxide (TiO₂) using the powder metallurgy method led to significant improvements in the mechanical and structural properties of the resulting composite material. Mechanically, a significant increase in the hardness of the composite material was observed with an increase in the percentage of added Al, reaching a peak value of (80.36 HV) when 20% Al was added. Compressive strength also increased significantly from (33.76 MPa) at 3% Al to 61.29 MPa at 20% Al. Structurally, a decrease in the total porosity of the composite material was observed with an increase in the proportion of Al added, decreasing from 10.91% at 3% Al to (7.17%) at 20% Al. This change in porosity is associated with improved homogeneity and uniformity in the crystal structure of the composite material, which was confirmed by the results of the scanning electron microscope test. It can be said that the addition of Al to TiO₂ using the powder metallurgy method has led to clear improvements in the mechanical and structural properties of the composite material, making it more suitable for various engineering applications. XRD analysis confirmed that all composites retained the Monoclinic TiO₂ phase, while the diffraction peaks gradually shifted to higher 2θ values and broadened as the Al content increased—evidence of lattice contraction and reduced crystallite size. These nanostructure changes, revealed by peak broadening and peak-position shifts, correlate directly with the observed rise in hardness and compressive strength in the Al–TiO₂ composites.

Keywords: powder metallurgy, composite materials, hardness, sintering, compressive strength.

Introduction:

Titanium oxide (TiO_2) is a ceramic material commonly used in many industrial and technological applications due to its outstanding properties such as chemical stability [1,2], corrosion resistance, and optical and electrical properties [3,4]. However, there are some aspects that need improvement in the properties of TiO_2 , such as mechanical and thermal properties [5,6]. Nano-Powder metallurgy method One of the effective ways to improve the properties [7,8] of TiO_2 is the development of composite materials consisting of TiO_2 and other elements [9,10]. These composite materials combine the characteristic properties of TiO_2 and the additive, improving the physical, chemical and mechanical properties of the resulting material [10].

Some of the elements used to produce materials composite with TiO_2 include other ceramics (e.g. Alumina, Silica), metals (e.g., Aluminum, Copper), and polymers. Powder metallurgy is one of the popular methods for preparing these composite materials in a structured and targeted manner [11,12]. By preparing TiO_2 composite materials using the powder metallurgy method, advanced materials with improved mechanical and thermal properties can be obtained compared to pure TiO_2 . These composite materials have promising applications in fields such as mechanical engineering, energy, and nanotechnology [13,14].

The experimental work:

For nanomaterials used, the weights of the mixture of each component were prepared following the volumetric ratios in Table (1), as the volumetric ratios were relied upon due to the difference in density between nanomaterial Aluminum powder and Titanium Oxide. The weighing was carried out using a Japanese-origin sensitive electric balance (sartorius) with an accuracy of(0.0001) .

Table 1: Materials used and their ratios

TiO₂%	Al%
97	3
90	10
80	20

In powder preparation, the metal or alloy powder to be used is carefully prepared, including checking the size and appropriate granular distribution. The powder is also well mixed to improve the forming properties. Press process, the prepared powder is placed in a mold made of heat-resistant materials such as steel. The powder is pressed using high mechanical force using a pressing tool to give the product the desired final shape, as the pressure (80MPa) was shed, in Figure (1) shows the piston used in the process.

Fig. 1: Piston used in the pressing process.



In measurements and examinations, Vickers hardness is a method for measuring the hardness of metals and alloys. This method is mainly used for hard and brittle metals. This method is based on measuring the area of the fingerprint of a compressed area on the surface of the sample using a low load. The sample to be measured is placed on the base of the hardness measuring device. The fingerprint is loaded by a cone-shaped diamond needle with a specific load (usually 1 kg or 10 kg). The area of the fingerprint formed on the surface of the sample is measured using a microscope integrated into the device.

The hardness value of Vickers HV is calculated by the following equation [15]:

$$Hv = 1.854 \times \frac{F}{d^2} \dots \dots (1)$$

Where F = applied load (N) , d = average diagonal of footprint (mm).

Compressive strength is a measurement of the force required to destroy or deform a sample of a material under the action of an axial compressive force. This method is commonly used to evaluate the properties of engineering materials such as concrete, stone, and composite materials. A test sample is prepared with specific dimensions and regular shape (cube or cylindrical). The sample is placed between compressor plates on the compression tester. The axial compressor load is applied to the sample at a constant rate until collapse occurs.

Compressive strength is calculated using the following equation[16]:

$$\text{Compressive strength} = \frac{\text{maximum load}}{\text{cross – sectional area of the sample}} \dots \dots (2)$$

porosity is the ratio of the size of the pores (voids) to the total volume of the material. The immersion method is a simple and commonly used method for measuring porosity in materials such as concrete, rock, and other porous materials. A representative sample of the material is taken in a known size. Clean the sample and dry in the oven to remove any moisture present. The dry sample is weighed and the weight is recorded. The sample is placed in a bowl and the container is filled with water until the sample is completely covered. The sample is left under water for a sufficient period (24 hours) to allow water to absorb and fully immerse the sample. After immersion, the sample is taken out of the water and wiped the outside with a damp cloth to remove excess water. The water-saturated sample is weighed and the weight recorded [17].

Porosity is calculated using the following equation:

$$\text{Porosity} = \frac{\text{weight of saturated samp} - \text{weight of dry sample}}{\text{weight of saturated} - \text{weight of sample suspended in water}} \times 100\% \dots (3)$$

For Scanning electron microscope (SEM) characterization, clean and carefully prepare the sample to be clean and free of contaminants. Adjust the vacuum inside the sample chamber and adjust other parameters such as electric acceleration. Modified the focus and lenticular dimension to get a clear image of the sample. Take pictures of the sample were at different zoom levels. Scroll and scan across the sample surface was doing for a comprehensive image.

Results and Discussion:

In hardness test results, from Figure 2, the positive effect of Aluminum addition on Titanium Oxide hardness can be observed. The higher the percentage of Aluminum added, the higher the hardness value (Hv) of the composite material and this can be explained by the addition of Aluminum to Titanium Oxide leads to the formation of a solid solution between the two components. This solid solution has a more uniform atomic arrangement compared to pure Titanium Oxide, which leads to increased resistance against crystal slippage and thus increased hardness, and Aluminum has a larger atomic size than Titanium, which leads to distortions in the crystal structure of Titanium Oxide when added. These crystalline abnormalities hinder the movement of crystalline abnormalities and thus increase hardness [13,18]. Accordingly, it can be said that the increase in the proportion of Aluminum added to Titanium Oxide leads to an improvement in the mechanical properties of the composite material, specifically an increase in the hardness value.

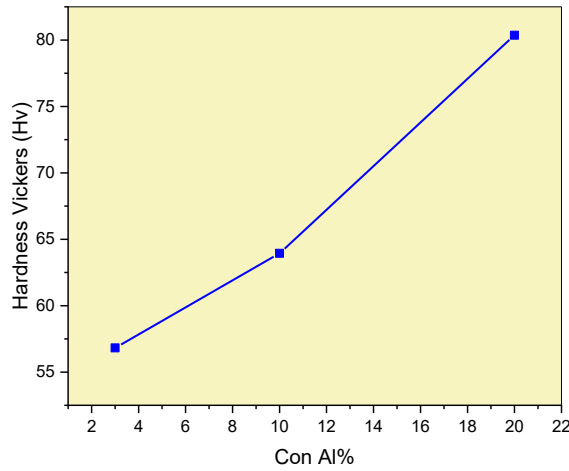


Fig. 2: Relationship between the content of aluminum addition and the hardness of Vickers

The results of the compressive strength test through Figure 3, that the addition of Aluminum to Titanium Oxide has improved the compressive strength of composite materials. This observation enables the explanation that the addition of Aluminum to Titanium Oxide increases the cohesion of the intermolecular bond, which leads to an increase in the compressive strength of the composite material. In general, the addition of Aluminum to Titanium Oxide improves the structural and mechanical properties of the composite material, resulting in a significant increase in compressive strength [18,19]. This resistance increases with the proportion of Aluminum added.

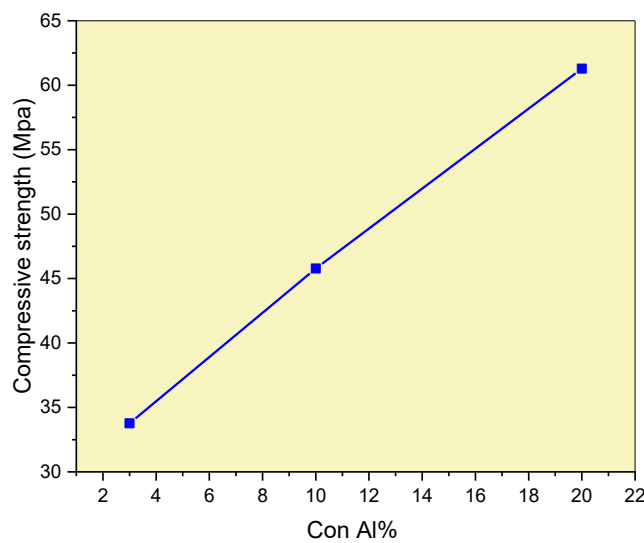


Fig. 3: Relationship between aluminum content and compressive strength

Porosity test, Figure 4 shows a decrease in porosity values by increasing Aluminum, increasing the percentage of Aluminum leads to a decrease in the size and size of pores because Al fills the pores in TiO_2 and reduces the formation of new pores [20]. This is because Al has a larger atomic size than Ti, which causes the crystal lattice to shrink and clog pores.

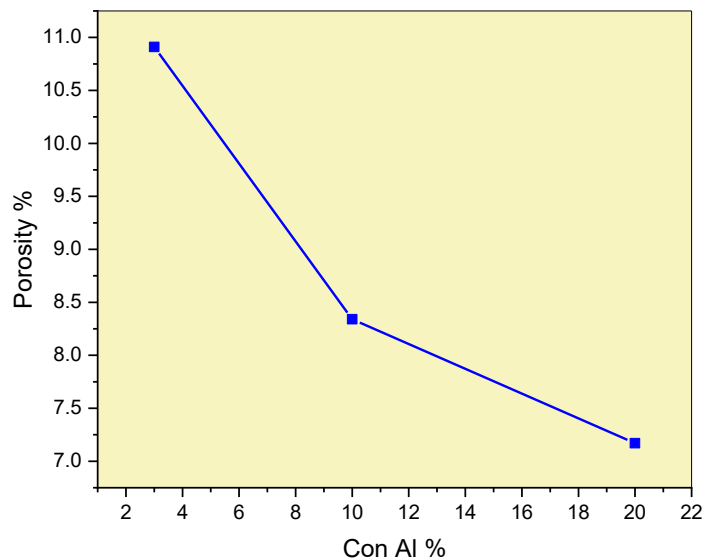


Fig. 4: Relationship of aluminum content with porosity

For SEM analysis, Figure 5 shows the results obtained from the SEM, which indicate that the images improved and that the surfaces were smooth and not cracked with an increase in the proportion of Aluminum added to Titanium Oxide (TiO_2), because the addition of Aluminum to TiO_2 leads to improved homogeneity and uniformity in the surface crystal structure[20]. Aluminum fills cracks and defects in the surface structure, resulting in a more uniform and smooth surface.

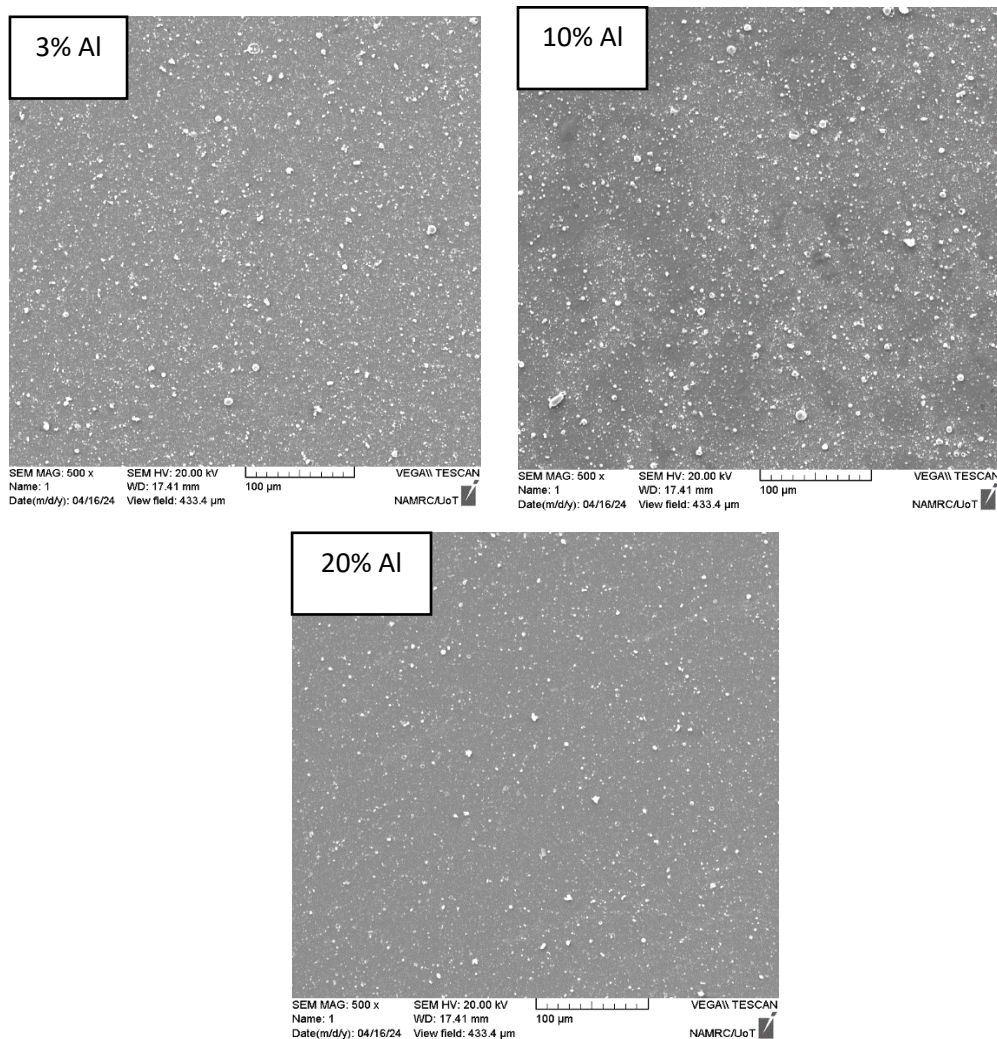


Fig. 5: Scanning electron microscope images of nano-Aluminum (Al) added to Titanium Oxide (TiO₂).

The X-ray diffraction results (XRD), Figure 6 shows the X-ray diffraction results. The main peaks appear at angles of approximately 25.3°, 37.8°, and 48.0°, corresponding to Miller indices (101), (004), and (200), respectively. This confirms that the predominant crystalline phase is monoclinic for TiO₂, with cubic Al. Then, as the Al content increased from 3% to 20%, a slight shift in the positions of these peaks toward larger angles was observed. This subtle shift indicates a slight contraction in the lattice constant, resulting from the replacement of Ti⁴⁺ ions with smaller Al³⁺ ions, partially compressing the crystal lattice.

A gradual decrease in the intensity of the (101) peak was observed as the Al content increased. At 3%, the intensity was highest, then decreased at 10%, reaching its lowest value at 20%. This decrease indicates that the degree of crystallinity has begun to grow in the material.

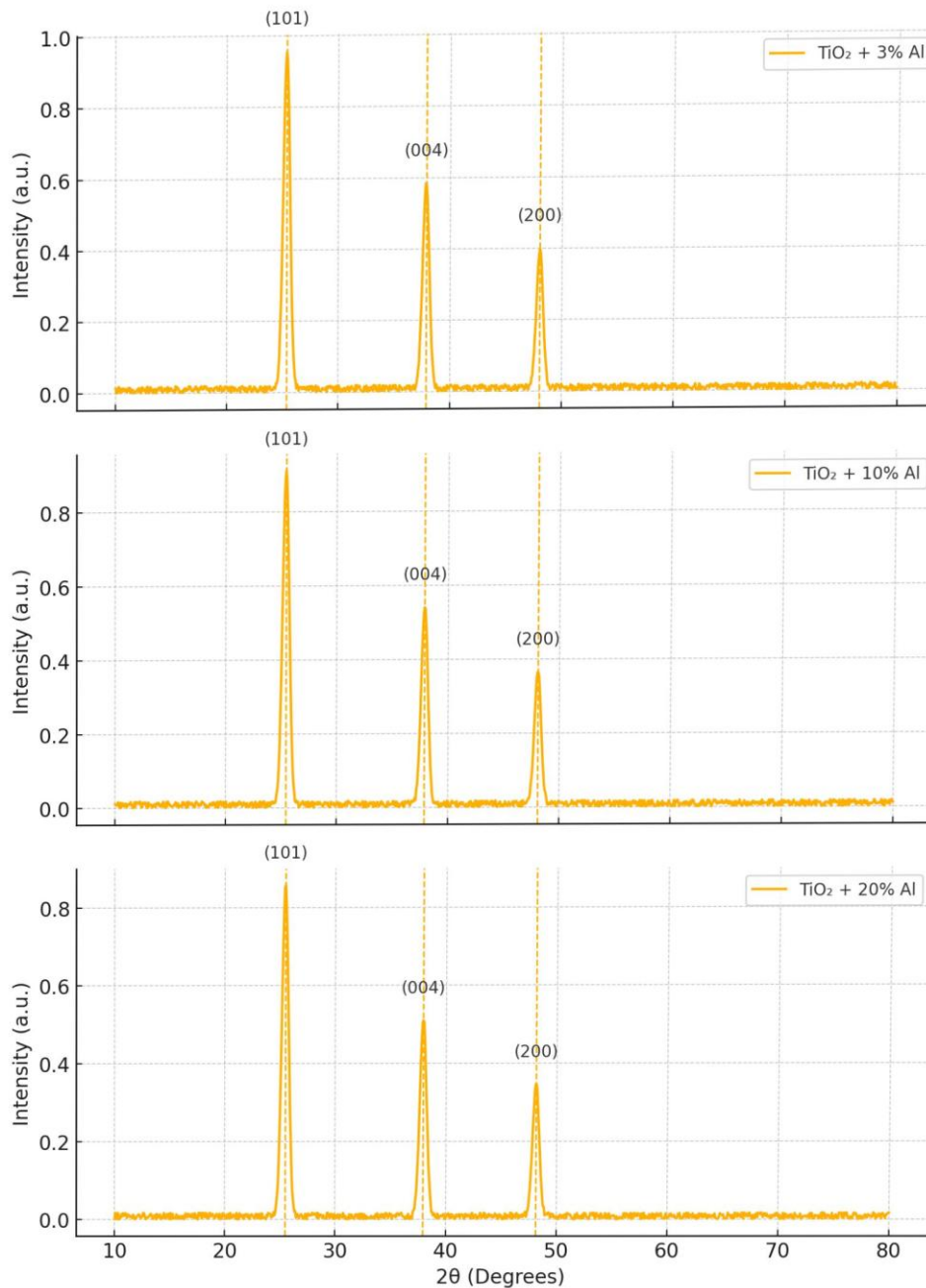


Fig. 6: X-ray diffraction of the material (TiO₂ + Al).

Conclusions:

The addition of Aluminum to Titanium Oxide (TiO₂) leads to improved mechanical properties by entering Aluminum into the crystalline structure of TiO₂ and strengthening the interbonds, resulting in increased hardness and compressive strength. This also improves the homogeneity and uniformity of the crystal structure, resulting in a decrease in the overall porosity of the composite material. The improvement in surface composition is reflected in the quality of images taken with Scanning Electron Microscopy (SEM).

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