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RESEARCH PAPER

Microstructural, Electrochemical Corrosion, and Antibacterial Evaluation of Nanostructured TiO_2–Ni Composites for Potential Biomedical Applications

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ABSTRACT

The creation of metallic nanocomposites that offer both improved electrochemical stability and antibacterial properties have received much attention as they can be used in biomedical applications. In this work, a titanium-nickel (TiO_2-Ni) nanocomposite was created via powder metallurgy utilizing titanium and nickel nanopowders. The nominal composition of the powders was 79.89 wt.% TiO_2 and 20.11 wt.% Ni. The powder blend was compacted and then sintered at 900 °C for one hour in an inert argon environment. The crystalline structure was determined via x-ray diffraction (XRD). Electrochemical evaluation was conducted through Tafel Polarization, Open Circuit Potential (OCP), Electrochemical Impedance Spectroscopy (EIS), and Cyclic Polarization. The antibacterial properties against Staphylococcus Aureus were evaluated via the inhibition zone technique. XRD analysis showed a single strong diffraction peak at roughly 2θ = 42.60°, with another much weaker diffraction peak at approximately 77.80°. These results indicated that the composite developed during the powder metallurgy process is crystalline. Tafel polarization analysis showed a corrosion current density of 3.46 × 10-6 A/cm^2. Based upon these results, the corrosion rate calculated for the composite is 0.04063 mm/year. OCP measurements displayed a slight decrease in potential from approximately -0.114 to -0.147 V over a period of 600 seconds. EIS analysis demonstrated a wide, non-ideal capacitive response which indicates that there are electrochemical reactions taking place at the boundary between the composite and the electrolyte solution. The antibacterial testing performed provided yet another way to determine how well the composite interacted with S. Aureus. This work represents a first step toward evaluating the structural and electrochemical characteristics of powder-metallurgy-produced TiO_2-Ni nanocomposites and determining if they will find use in biomedical applications in the near future.

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INTRODUCTION

Biomedical engineering has paid close attention to metallic biomaterials as they are very crucial in developing orthopedic implants, dental implants, surgical instruments and many other medical devices. When choosing which metallic materials will be best used in biomedical applications there are a number of factors that must be considered such as: mechanical strength; corrosion resistance; surface stability; and biological performance. Specifically, materials that will be implanted into a person's body must be able to remain physically and chemically stable while in a physiological environment (i.e. water, dissolved oxygen, chloride ions, etc.) that could lead to electrochemical degradation. As a result, improving the corrosion resistance of metallic materials and adding antibacterial properties is one of the major research areas of study within the field of modern biomaterials science [1,2].

Titanium (TiO_2) has gained recognition as one of the best biomaterials among all metals due to its low weight-to-volume ratio, high strength-to-weight ratio, superior corrosion resistance and acceptable biological behavior. The ability of titanium to resist corrosion is primarily related to the natural occurrence of a very stable and protective titanium dioxide (TiO_2) passive layer on its outer surface. This oxide layer provides a physical barrier preventing additional electrochemical reactions from occurring, thus reducing the contact between the underlying metal and the surrounding biological environment. For these reasons, titanium and its various forms have received much attention as materials for orthopedic and dental implants. However, there is still great interest in developing ways to enhance the functional characteristics of titanium-based materials by incorporating other metals or utilizing advanced processing technologies [3-5].

The introduction of nanosized metallic powders into the development of nanocomposites has opened up new possibilities for achieving the desired control over the microstructure of nanocomposites and possibly improved mechanical properties. Metallic nanoparticles may alter the way particles interact, their diffusion rate, their densification process, and ultimately the formation of phases during the material processing steps. An example of this is the combination of titanium and nickel nanopowders to produce TiO_2-Ni nanocomposites with potential modifications in surface and electrochemical properties. A practical method of forming these nanocomposites is through powder metallurgy; a process that involves mixing the powders together, compacting them, and then heating the compacted mixture (sintering) to create a solid body. Through the use of powder metallurgy, the researcher can create relatively homogeneous powder mixtures and study how variations in composition and sintering conditions affect the final microstructure and resulting properties of the material [6,7].

A major problem in using metallic biomaterials is that they tend to degrade by electrochemistry when exposed to body fluids. Corrosion can make implants unstable over time and can cause toxic metal ions to enter the body through fluid from around the implant. Because of this, it is very important to do thorough electrochemical testing on new metallic biomaterials so we know how they will corrode and if they will protect themselves. Open Circuit Potential (OCP) tests tell us how a material's surface potential changes while it is sitting in an electrolyte. Tafel polarization testing is done to find out some of the most important things about how a material corrodes such as what its corrosion potential is and how fast it corrodes. Also, Electrochemical Impedance Spectroscopy (EIS) gives us a lot of useful information about how much charge is being transferred at the interface between the metal and the electrolyte and whether or not the film formed on top of the metal protects it. Finally, cyclic polarization testing can also help us see how stable the passive film is on a material and if it is likely to undergo localized corrosion like pitting corrosion. Doing all four types of electrochemical testing will give us a much better idea of how well titanium-based nanocomposites resist corrosion [8].

Bacterial contamination is a major issue related to the use of metal medical devices and implant surfaces; in addition to corrosion resistance, bacterial contamination is a significant problem. Implant-associated infections are caused by bacterial colonization of the implant surface and subsequent biofilm formation. Biofilms can lead to inflammation of surrounding tissues, implant failure, and additional surgery to correct these issues. Of all the bacteria involved in implant-associated infections, Staphylococcus aureus is perhaps the most significant. Because of its prevalence in orthopedic and implant-related

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infections, research into new metallic materials that have antimicrobial properties is needed to determine whether they will help reduce the number of colonies that form on implants. An early indicator of antimicrobial activity is provided by the agar diffusion test (expressed as inhibition-zone diameter) for some bacteria. This test alone cannot identify the mechanisms of action that prevent colony formation or demonstrate that a material is resistant to biofilm formation [9,10].

Structural and morphological evaluation is also critical to understand the link between composite's composition, micro-structural organization, and functional capabilities. X-ray diffraction (XRD) evaluation will allow for the identification of the crystalline phases present and the structural modifications occurring due to the introduction of nickel in the titanium matrix as well as the sintering procedure. Scanning Electron Microscopy (SEM) will provide details regarding surface morphology, particle dispersion, porosity, and microstructural characteristics. Utilizing both analytical methods along with evaluation of the electrochemical and antibacterial responses of the nanocomposite will provide a more complete assessment of the composite being evaluated and aid in identifying possible correlations between the composite's structural attributes and its performance capabilities [11].

Although there has been significant research on titanium based biomaterials and nickel-titanium (Ni-TiO_2); additional experimental work is needed to determine the correlation among: 1) the chemical make up of nano-sized Ni-TiO_2 powder; 2) the resulting sintered microstructure; 3) the electrochemical corrosion behavior; and 4) the anti-bacterial effectiveness of the material. Specifically, evaluating all four aspects simultaneously will help us assess if TiO_2-Ni nano-composites produced by powder metallurgy have characteristics that would make them suitable as biomaterials in the near future. Also, a focus must be placed upon corrosion behavior since the integrity of the surface and potential release of nickel ions are both directly related to the biological safety of the material [12].

Therefore, this research was focused on fabricating titanium-nickel (TiO_2-Ni) nanocomposites via the use of nanosized powders via compression and heat treatment. The specimens produced were examined systematically by x-ray diffraction (XRD) and scanning electron microscopy (SEM) to evaluate the crystalline structures and surface morphology. The specimens were evaluated for electrochemical behavior via Open Circuit Potential (OCP), Tafel Polarization, Electrochemical Impedance Spectroscopy (EIS) and Cyclic Polarization. Antibacterial properties of the nanocomposites towards Staphylococcus aureus were evaluated via the inhibition zone method. It is anticipated that the combined data will provide an assessment of the structural, electrochemical and antibacterial characteristics of the fabricated TiO_2-Ni nanocomposites as well as a preliminary evaluation of the potential of these nanocomposites for biomedical applications.

MATERIALS AND METHODS

Materials

The two main raw materials utilized in the fabrication of the TiO_2-Ni nanocomposite samples were Titanium (TiO_2) and Nickel (Ni) nanopowders. The reason behind selecting both powders was to explore how the addition of Nickel to the Titanium-based matrix affects the structural, electrochemical and antimicrobial characteristics of the final product. The nano-sized forms of both starting powders were chosen to allow for the production of nanostructured composites via powder metallurgy processes.

The titanium and nickel powders were weighed exactly as per the required composition and thereafter blended together to form the preferred TiO_2-Ni powder blend. The resulting powder blend was compacted and heated in a vacuum furnace (thermal sintered) so that solid composite samples could be produced for future analysis and assessment of performance.

The crystalline structure of the manufactured specimens was analyzed through the use of X-ray diffraction (XRD) and the morphological features of the specimens' surfaces were examined via the use of scanning electron microscopy (SEM). Corrosion characteristics of the prepared specimens were investigated through the use of open circuit potential (OCP), Tafel polarization, electrochemical impedance spectroscopy (EIS), and cyclic polarization methods. Finally, the ability of the prepared specimens to inhibit bacterial growth was determined by measuring zones of inhibition against Staphylococcus Aureus.

Titanium and nickel nanopowders were employed as raw materials in order to synthesize the Ti**O_2**-Ni nanocomposite. A nominal composition

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was established through the use of the initial weights of the powders. This composition consisted of approximately 79.89 wt.% titanium and 20.11 wt.% nickel. Correspondingly, a nominal atomic composition was established with approximately 82.96 at.% TiO_2 and 17.04 at.% Ni. These powders were then compacted and thermally sintered to form the composite specimens used for structural, electrochemical, and antibacterial studies.

The TiO_2-Ni nanocomposite developed for investigation during this project was produced through a physical mixing process of commercially sourced TiO_2 nanopowder and commercially sourced Ni nanopowder. As such, the TiO_2 nanopowder was utilized as the ceramic matrix material, while the Ni nanopowder was utilized as the metallic reinforcing component. Both powders were blended together in a dispersion medium of ethanol, then subjected to both magnetic stirring and ultrasonic mixing to promote homogeneity of the blended powder and reduce the likelihood of particles aggregating. Following consolidation of the blended powder via drying in an oven to remove the ethanol, the resulting product was a dry blended TiO_2-Ni powder. Therefore, when referring to a TiO_2-Ni nanocomposite, we are referring to a composite formed by combining and consolidating a physical blend of titanium dioxide and metallic nickel.

Preparation of TiO_2–Ni Nanocomposite

The nanocomposite samples containing TiO_2 and Ni were produced by employing a powder metallurgy process. Initially, the exact quantities of TiO_2 and Ni nanopowders were measured based upon the required composition. Then, ethanol was introduced as a dispersing agent to assist with the blending of the two types of powders and to provide uniform dispersion of the Ni particles throughout the TiO_2 matrix.

The powder mixture underwent a first round of magnetic stirring for 10 minutes to obtain initial homogenization. A second round of ultrasonic mixing was done for 15 minutes to increase powder dispersion and decrease powder agglomeration. At the end of both mixing processes, the resulting suspension was dried in an oven for 1 hour at 150°C in order to remove all of the ethanol, resulting in a dry and homogeneous TiO2-Ni powder mixture.

The compact was then made from the dried powder mixture by placing it in an appropriate die and pressing with a standard manual hydraulic press capable of applying a total load of up to 10 tons. After compaction, the green compacts were sintered in a vacuum tube furnace. During sintering, the temperature of the samples was increased at a rate of 10 °C/min until the sintering temperature of 900 °C was reached; once at this level, the samples were kept in the furnace for one hour while still under vacuum and presence Ar as inert gas. At the end of the sintering cycle, the samples were allowed to cool within the furnace prior to their use in characterizing the material's structure, electrochemical behavior, and antibacterial characterization.

Characterization and Experimental Procedure

The TiO_2–Ni nanocomposite specimens fabricated by us have been investigated using a variety of structural, morphological, electrochemical, and biological studies to assess their capability to be used as biomaterials. We followed an experimental process involving powder compaction, thermal sintering, characterization of the resulting materials, and evaluation of the performance of those materials using several analytical methods.

Structural and Morphological Characterization

X-ray diffraction (XRD) was employed to characterize the crystalline structures and phases present in the sintered Ti–Ni nanocomposites. XRD is used to determine which crystalline phases have been created as a result of the sintering process, as well as whether there are any structural changes occurring due to the addition of Ni into the TiO_2 matrix. Surface morphology and microstructure of the manufactured materials were studied by scanning electron microscope (SEM). Special care was taken when examining surface characteristics, particle distributions, and the existence of pores or microstructural defects.

Electrochemical Corrosion Measurements

To assess the corrosion resistance and electrochemical stability of the fabricated Ti**O_2**-Ni nanocomposite materials, several types of electrochemical testing methods were used. To develop a clear and complete picture of how well the composites performed in terms of corrosion during the chosen test procedures, several different electrochemical testing methods were utilized.

The measurement of open-circuit potential

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(OCP) was used to study how an electrode's potential changes with respect to how long it has been immersed in the test electrolyte and to assess when the surface of the sample becomes electrochemically stable within the test electrolyte [13].

The Tafel polarization measurements were then completed to find both the corrosion potential (E_corr) and the corrosion current density (I_corr). Both of these values were used to assess how much the specimens would corrode, as well as to estimate the rate at which they would corrode.

EIS was used to study the electrical behavior of the interface between the material and the electrolyte. EIS allowed for studying both the electrical resistance of the thin layer of oxide/film on the sample and the charge transfer reactions that occur on the sample's surface. The EIS data were fit with a suitable equivalent electrical circuit model [14].

In addition, to evaluate the long-term effectiveness of the passive film that covers the surface of the specimen, and to determine how susceptible the material is to localized corrosion, cyclic polarization tests were conducted. The polarization curves obtained from these tests were analyzed to characterize the anodic characteristics of the material, as well as whether or not there would be potential for pitting corrosion.

Antibacterial Activity Evaluation

The anti-bacterial effectiveness of the prepared TiO_2-Ni nano-composites was assessed using Staphylococcus aureus (a Gram positive bacteria) which is most often responsible for infection related to implants. The "inhibition zone" technique was utilized to examine the anti-bacterial reactions to the specimens being studied. After exposure to the bacteria during the experimental procedures, the existence of a zone of inhibition around each specimen was analyzed. The size of this zone of inhibition was used as an indication of the anti-bacterial properties exhibited by each of the specimens tested [15].

Overall Experimental Assessment

The results of XRD, SEM, electrochemical measurements and antibacterial tests have been used together to determine if there are relationships between the structure characteristics, corrosion

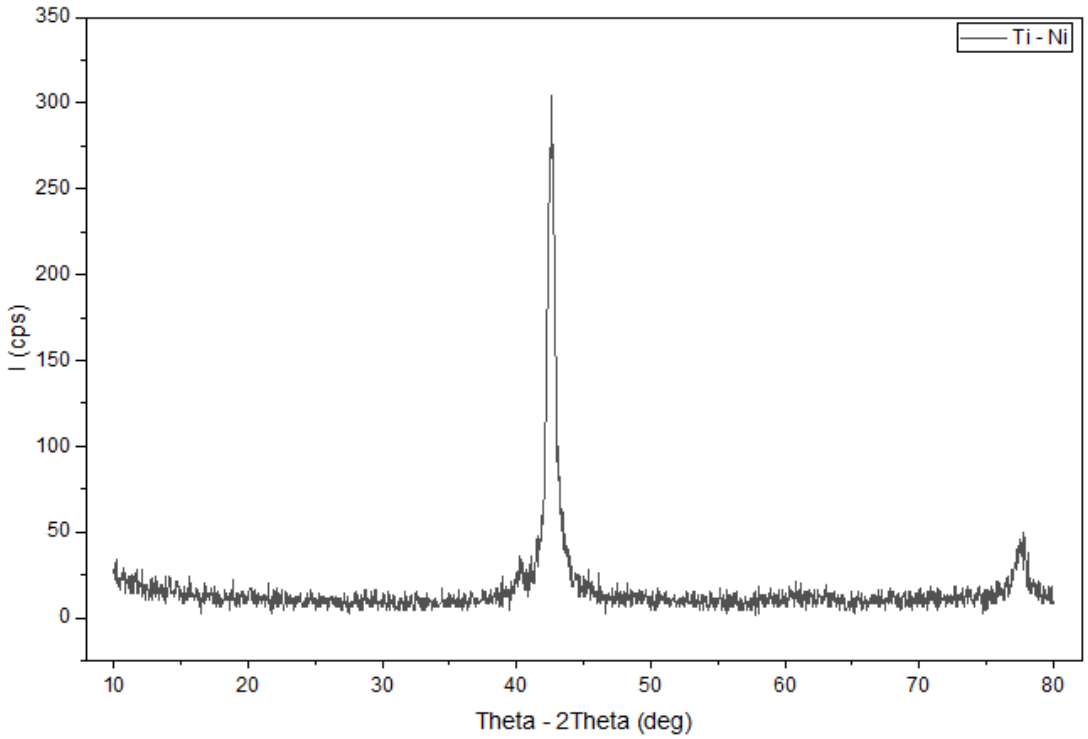

Fig. 1. XRD Analysis of Materials samples.

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performance and antibacterial performance of the TiO_2-Ni nanocomposite materials. This comprehensive evaluation is expected to be a first step in evaluating these materials for use in biomedical applications that require both corrosion resistance and antibacterial properties of the surfaces.

RESULTS AND DISCUSSION

X-ray Diffraction (XRD) Analysis

The XRD pattern of the TiO_2–Ni nanocomposite shown in Fig. 1 has two main diffraction peaks. One peak is found in the range from 42.60° to 43.10° (2θ). This peak may be assigned to the (200) crystallographic plane of nickel oxide (NiO). Another peak is found in the range from 77.80° to 78.40° (2θ). This second peak is close to other high angle reflections which are associated with nickel containing crystalline phases. Both of these peaks indicate that there are crystalline nickel related phases present in the composite.

The appearance of these reflections can be attributed to the thermal treatment at 900°C, which encourages solid state diffusion and interaction between the TiO_2 and Ni particles. As the temperature rises to 900°C, changes in the local chemical environment and surface interaction may alter the crystalline structure of the nickel-containing phase. Specifically, partial oxidation of nickel particles can create nickel oxide phases, as long as there is enough oxygen available during both powder preparation and thermal processing [16].

The higher intensity of the diffraction peak at

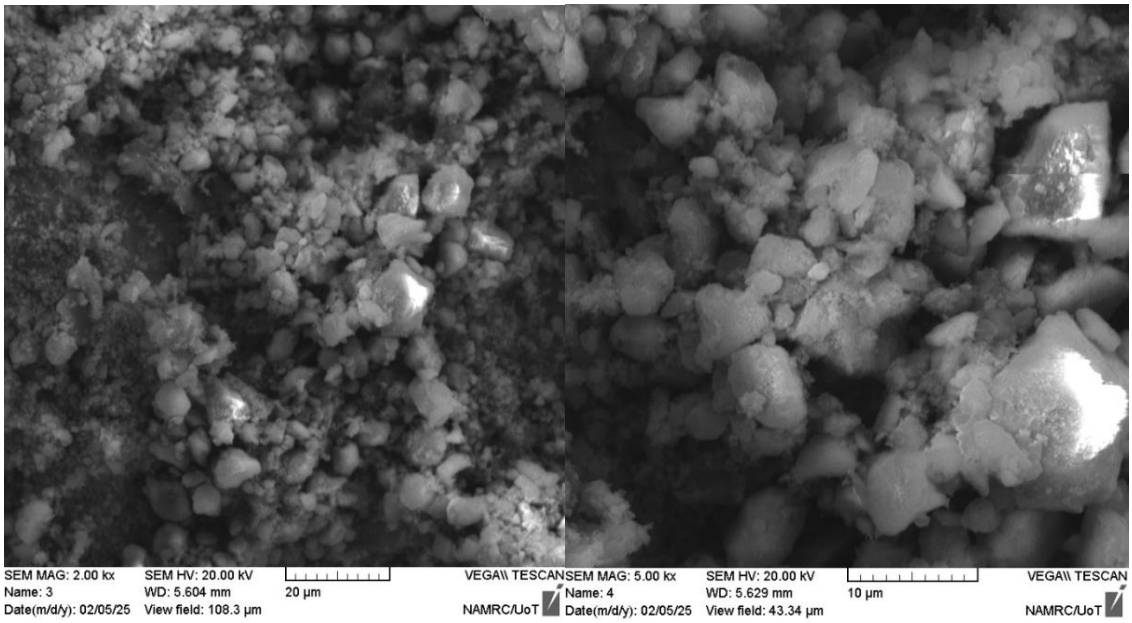

Fig. 2. Sem of Samples.

Table 1. Corrosion parameters of Materials.

	E_{corr}-	i_{corr}	b_c-	b_a+	C_R
	(mV)	($^{Y-}$A.cm)	$^{\backslash-}$mV.dec		(mm/a)
Ni-TiO_2	0.19408	3.46E-06	158.87	114.8	0.04062916307692310000

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42.60 degrees relative to the much lower intensity of the diffraction peak at 77.80 degrees suggests that there is a preferential contribution of the corresponding crystallographic reflection to the overall diffraction pattern. The variation in peak intensities may be related to the crystallographic orientation, phase distribution, and/or the relative contributions of the different crystalline phases present in the sintered composite.

The overall conclusion from the XRD analysis is that a crystalline TiO2-Ni composite was formed through the process of powder mixing, compaction, and then sintering. The diffraction patterns present in this analysis are representative of both the structural aspects of the nickel-based materials and how these materials interact with the TiO2 matrix during the thermal treatment [17].

SEM Analysis

Scanning electron microscopy (SEM) was used to analyze the surface morphology and microstructural characteristics of the manufactured Ti–Ni nanocomposite. A specimen made from titanium and nickel nanopowders had a nominal composition of 79.89 wt.% TiO_2 and 20.11 wt.% Ni. After being compacted, the specimen was sintered at 900 °C for one hour in an inert argon (Ar) atmosphere [18].

A scanning electron microscope (SEM) was used to study the morphology of the surfaces, how the particles are distributed on them, whether the materials have been compacted uniformly, if there are any pores or other types of defects that could be created as a result of the powder being compacted and then sintered. A special focus was put into studying the microstructural aspects related to the way the titanium and nickel particles interact during heat treatment. The thermal treatments at 900 °C would allow for diffusion of atoms between the different constituent particles; this would help create bonds between the particles, allowing for the formation of a consolidated composite material.

The surface features that have been observed are very relevant to being able to relate what the material's microstructural characteristics are with respect to its electrochemical properties. More specifically, how the material's surface is porous;

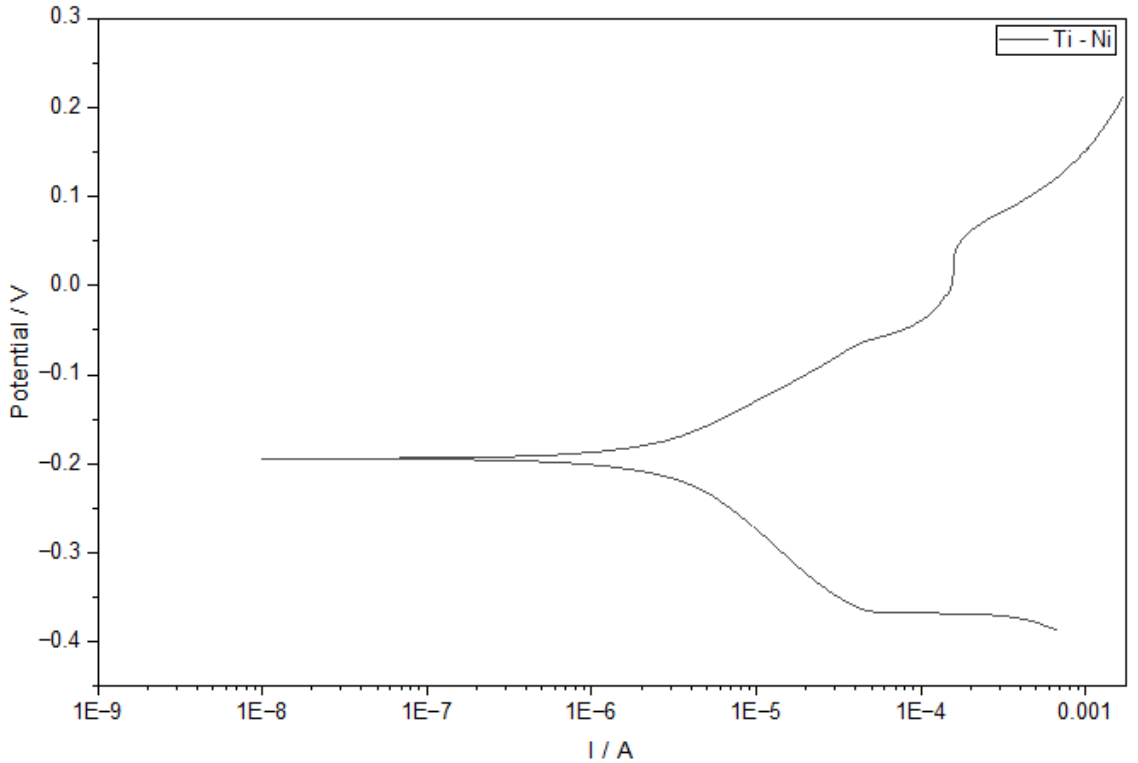

Fig. 3. Tafel polarization curves of TiO_2-Ni in Ringer's solution at 37 °C.

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how the material's particles are distributed on the material's surface; and how well-defined the interface is between the material and the surrounding environment could all be factors that will determine how much of the material is exposed to the electrolyte during electrochemical tests; how easily the electrolyte can penetrate the material; and whether or not protective film(s) form on the material's surface as a result of those electrochemical tests. Also, those same surface characteristics may play a role in how the material's surface interacts with the bacterial cells when the material is evaluated for its ability to prevent the growth of Staphylococcus aureus [19].

Therefore, SEM analysis offers crucial morphologic data to aid in understanding the corrosion resistant and antibacterial properties of the prepared Ti**O**$_2$-Ni nanocomposite and evaluating its initial feasibility for possible use in biomedical fields.

Tafel Polarization Analysis

Tafel polarization was used to assess the corrosion performance of the manufactured Ti**O**$_2$-Ni nanocomposite in order to obtain the relevant electrochemical corrosion characteristics such as corrosion potential (E_corr), corrosion current density (I_corr), anodic Tafel slope (β_a), cathodic Tafel slope (β_c), and corrosion rate (CR). These are key properties that characterize the electrochemical stability and the corrosion rate of the studied material [20].

As shown in Table 1, the Ni-TiO_2 sample has a corrosion potential (Ecorr) of 0.19408 mV and a corrosion current density (I_{corr}) of 3.46 x 10^-6 A/cm^2. The anodic and cathodic Tafel slopes are found to be 114.8 and 158.87 mV/decade, respectively. Based on these values, the corrosion rate of the sample is calculated as 0.04063 mm/year. While the corrosion potential measures the electrical potential of the sample when subjected to the chosen testing conditions, the corrosion current density is a measure of the corrosion kinetics occurring at the interface between the metal and the electrolyte.

The obtained anodic and cathodic Tafel slopes

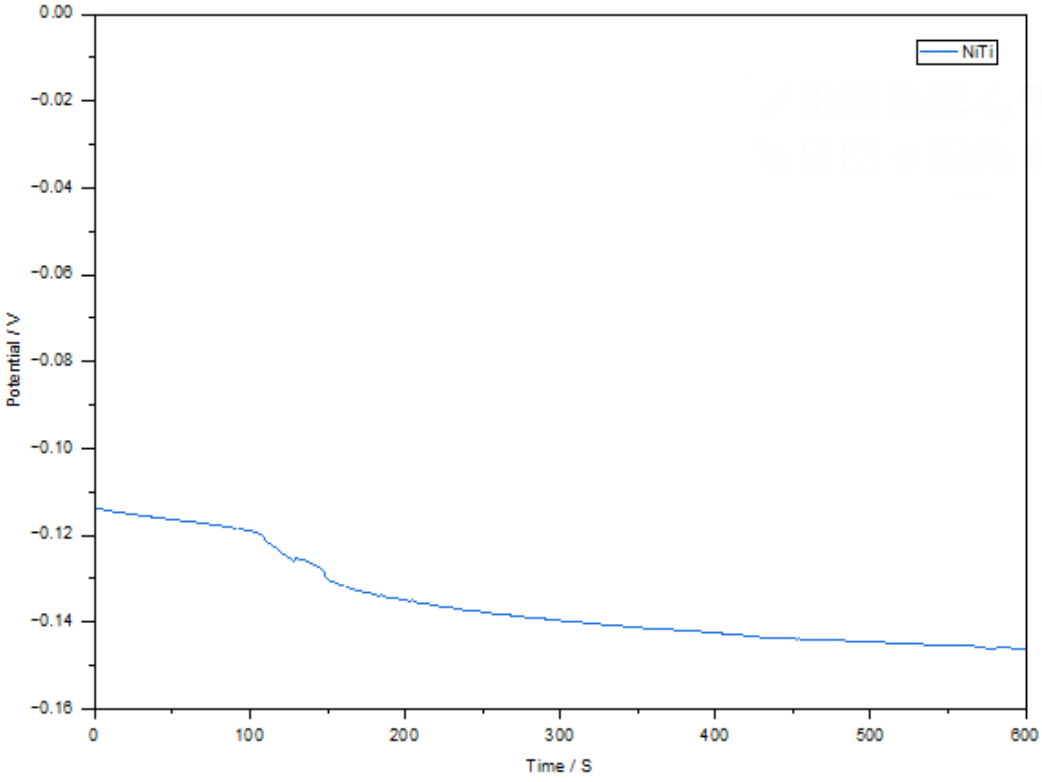

Fig. 4. Open circuit potential (OCP) evolution of stainless steel TiO_2-Ni over 24 hours in Ringer's solution at 37 °C.

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describe how fast the anodic dissolution of the metal and the cathodic reduction reaction occur. The corrosion current density (Icorr) is particularly significant as it is directly proportional to the corrosion rate of the material. A low Icorr indicates a relatively low electrochemical dissolution rate under the experimental conditions used. This provides an initial assessment of the corrosion behavior of the fabricated Ti**O**$_2$-Ni composite, and should be examined in conjunction with the OCP, EIS, and cyclic polarization results to develop a complete picture of its electrochemical performance [21].

Open Circuit Potential (OCP) Analysis

The electrochemical behavior of the prepared TiO_2-Ni nanocomposite was evaluated using open circuit potential (OCP) techniques by recording changes in electrode potential with respect to immersion time. As seen in Fig. 4, the OCP curve continuously moves toward more negative values throughout the testing period; this indicates that after being placed in contact with the test electrolyte, the electrochemical condition of the sample's surface changes.

The potential of the sample was initially about -0.114V when the measurement began. Over the first 100 seconds, there was a fairly slow decrease in potential (negative). From approximately 100 to 160 seconds, there was a much faster decrease in potential. After that, the potential decreased at a slower rate, until it reached about -0.147V after the 600 second measurement period. This slow decrease in potential is indicative of continued electrochemical reactions occurring on the surface of the sample with the electrolyte surrounding the sample [22].

The negative displacement of the OCP curve could be caused by either an increase in activity of the surface of the metal being tested; the dissolution of some of the unoxidized parts of the metal which are now exposed; or a change in the composition of the oxide film on the metal as it was immersed. No positive shift of the OCP curve

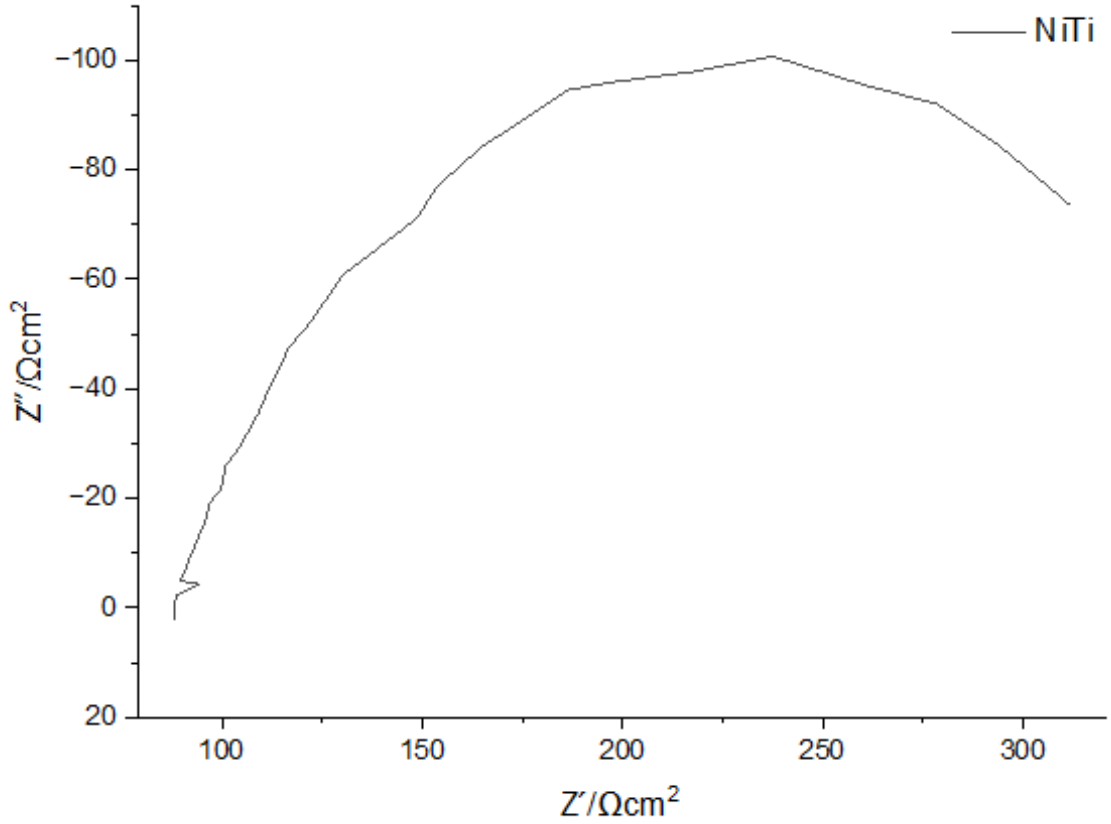

Fig. 5. Nyquist plots from electrochemical impedance spectroscopy (EIS) for TiO_2-Ni in Ringer's solution at 37 °C.

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was seen, nor did the OCP curve reach a steady-state level during the recording interval. Thus, it appears that the electrode potential of the sample was still changing at the end of the test. As a result of this, it can be concluded that the samples will need longer immersion times than those used in this study to allow them to achieve a more stable OCP value prior to making further polarization measurements.

In summary, the OCP data can offer some initial knowledge regarding how the prepared TiO_2-Ni nanocomposite initially reacts electrochemically to being placed in contact with the electrolyte. Therefore, when discussing the corrosion behavior and surface stability of the investigated material, the OCP data must be considered in conjunction with the results of Tafel polarization and EIS tests for a more complete picture [23].

Electrochemical Impedance Spectroscopy (EIS) Analysis

The Nyquist plot shows a large, flattened capacitive semicircle, indicating that the electrochemical response at the TiO_2-Ni/electrolyte interface was not ideal. The primary source of the measured impedance response appears to be related to both the charge transfer process and the capacitive properties of the surface layer. At an intermediate level of real impedance, we see the largest amount of imaginary impedance. As frequency decreases from this point, the imaginary impedance continues to drop off. This partial semicircle may be indicative of multiple electrochemical processes taking place simultaneously and/or non-ideal interfacial behaviors [24].

The charge transfer resistance (Rct), used to assess corrosion resistance, is typically linked to the size of the capacitive semi-circle. In general, larger semi-circles correspond to higher charge transfer resistance, thus resulting in slower rate of electrochemical corrosion. Also, any deviation from the ideal semi-circular form could be due to heterogeneous surface, varied microstructures,

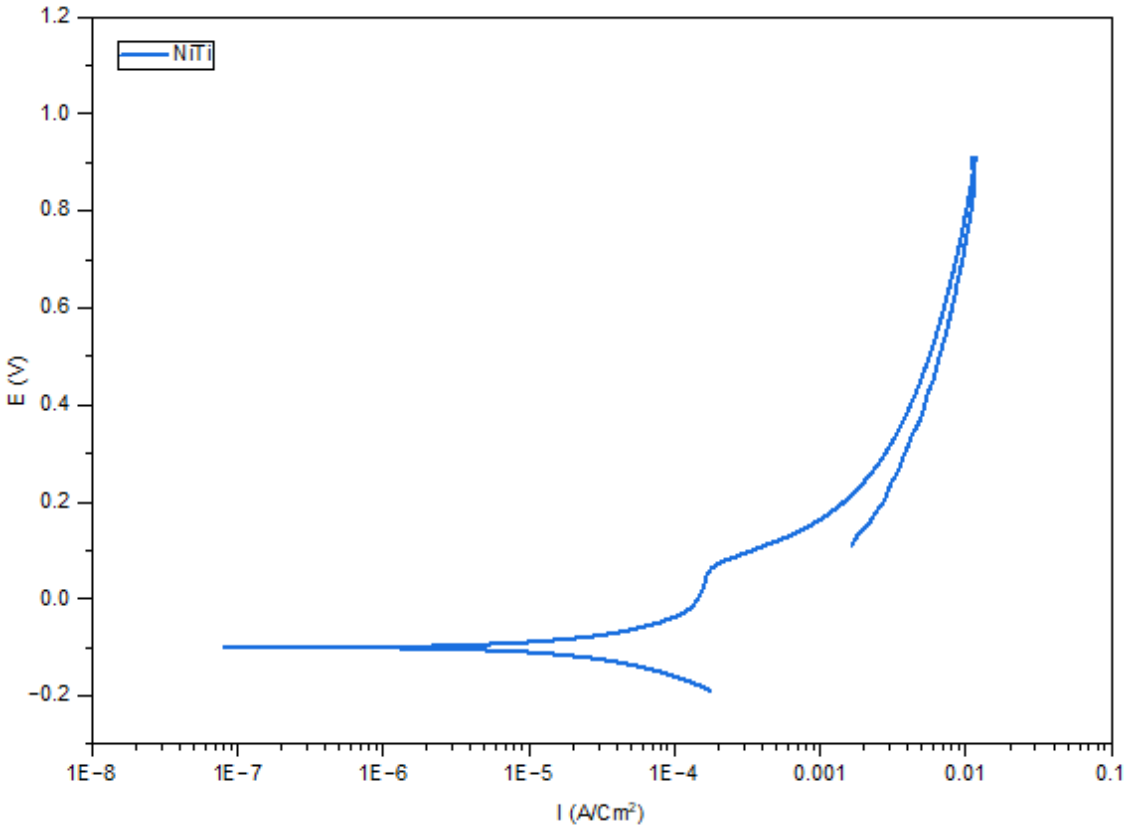

Fig. 6. Cyclic polarization curves of TiO_2-Ni in Ringer's solution at 37 °C.

and uneven electrochemical characteristics within the composite material created.

The EIS data was used to complement the Tafel polarization and OCP measurement data to further enhance the understanding of the electrochemical behavior of the TiO_2-Ni nanocomposite. Overall, the Nyquist response shows that there are interfacial electrochemical reactions taking place which affect the corrosion resistance of the material in Ringer's solution at 37°C [25].

Cyclic Polarization Analysis

Fig. 6 shows the cyclic polarization of the TiO_2-Ni in Ringer's solution (37 °C). This graph gives us an idea of how well this sample would hold up to the physiological environment, and how resistant it would be to corrosion. For a long period of time, the potential remains very close to zero, showing that there is little or no electrochemical reaction occurring. We believe that this is due to a passive oxide layer that forms on the surface of the sample. When the potential starts to increase, so does the current density. When the potential reaches even higher levels, the current density rises rapidly. These results lead us to believe that the passive oxide layer is breaking down, and that there is more anodic dissolution taking place. There is also a hysteresis loop shown on the polarization curve. This means that after scanning in one direction (forward) and then reversing direction (reverse), the current density does not return to its original value. We believe that this may indicate that the sample is susceptible to localized corrosion, and that the surface can repair itself when scanned in the opposite direction. It appears that the primary mechanism for the electrochemical response of TiO_2-Ni is the formation of a surface oxide film, mostly made of titanium oxide. We believe that this film acts as a barrier to prevent corrosion in the chloride-rich Ringer's solution. Based upon our observations of the polarization behavior of the TiO_2-Ni [26].

Antibacterial Activity Evaluation

In this study, the antibacterial properties of the fabricated TiO_2-Ni nanocomposite were tested using Staphylococcus aureus, a gram positive bacterium that is often found in association with medical device and/or implant related infections. To determine the antibacterial activity of the TiO_2-Ni composite, the inhibition zone method was used. After exposing the bacterial culture to the TiO_2-Ni specimen for the designated experimental condition(s), the growth inhibition of the bacteria near the specimen was measured by looking at whether there were areas of "clear" growth on

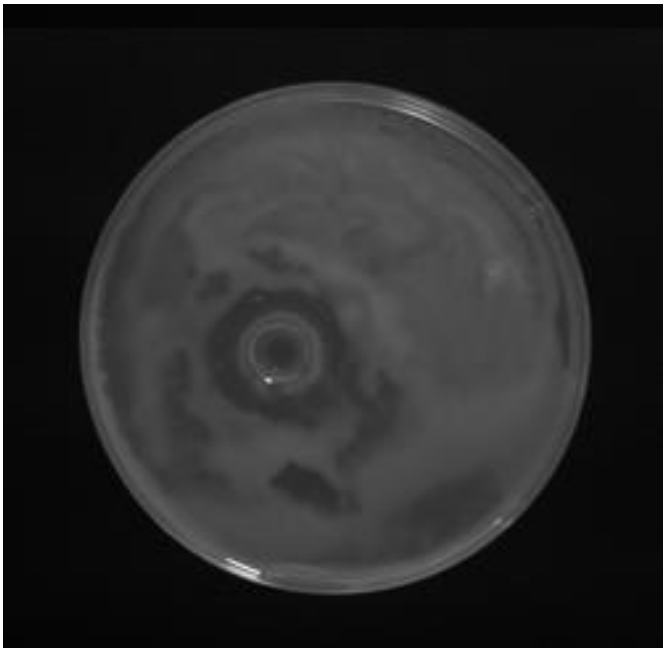

Fig. 7. Inhibition-zone of TiO_2-Ni.

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the agar plate. The size of the inhibition zone was then used as an indication of the antibacterial activity of the composite. Larger inhibition zones indicate greater suppression of the bacterial growth under the specific test conditions. This evaluation gives us some initial data on how the TiO_2-Ni composite surface interacts with bacterial cells. These findings are especially important since they provide potential solutions for the use of the new material in biomedical applications; as well as helping to prevent contamination from bacteria and other types of implants [27].

CONCLUSION

This research has demonstrated the successful fabrication of a TiO_2-Ni Nanocomposite through the use of Powder Metallurgy (PM). This nanocomposite was produced using Titanium (TiO_2) and Nickel (Ni) Nanopowders that had nominal composition values of 79.89 wt.% TiO_2 and 20.11 wt.% Ni, respectively. The resulting composite specimens were then compacted and sintered at 900°C for 1 hour within an inert Argon atmosphere. The structural and electrochemical investigation carried out in this study have given insight into both the characterization of the composite and how it behaves when exposed to corrosive environments. X-Ray Diffraction (XRD) confirmed the composite's crystalline nature, with the most significant diffraction peak being found at approximately $2\theta = 42.60°$, with a second peak located near 77.80°. Tafel Polarization measurements demonstrated a corrosion current density of 3.46 x 10-6 A/cm^2, and a calculated corrosion rate of 0.04063 mm/year; these results suggest that the nanocomposite is susceptible to electrochemical dissolution under the chosen testing parameters. Additionally, Open Circuit Potential (OCP) measurements demonstrated a gradual negative potential shift from approximately -0.114 V to -0.147 V over a 600-second immersion period, indicating changes in the nanocomposite's surface electrochemical conditions. Electrochemical Impedance Spectroscopy (EIS) analysis demonstrated a broad capacitive response in the Nyquist Plot, indicating that there may be interfacial electrochemical processes occurring between the composite's surface and the electrolyte. Lastly, Cyclic Polarization and Antibacterial Investigation were carried out against Staphylococcus aureus to assess the passive-film behavior and antibacterial response of the nanocomposite. In summary, the combined structural, electrochemical, and antibacterial investigations conducted in this study have provided an initial assessment of the TiO_2-Ni Nanocomposite as a viable option for biomedical applications. However, additional studies will need to be completed evaluating cytotoxicity, nickel ion release, biocompatibility, and mechanical properties before the safety and efficacy of the TiO_2-Ni Nanocomposite can be determined for particular biomedical applications.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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