

*Research Article*

Mechanical and Surface Characterization of Titanium–29Niobium–13Tantalum–4.6Zirconium Alloy Coated with Hydroxyapatite using High-Velocity Oxy-Fuel Spraying for Biomaterial Applications

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Abstract: The β -titanium alloy Ti-29Nb-13Ta-4.6Zr (TNTZ) is a highly promising orthopedic implant material due to its exceptional biocompatibility, corrosion resistance, and favorable mechanical properties; however, its bioinert nature restricts direct osseointegration. Although hydroxyapatite (HA) coatings can significantly enhance surface bioactivity, optimizing deposition parameters to achieve desirable surface topography and mechanical stability remains a critical challenge. This study investigates the influence of high-velocity oxygen fuel (HVOF) spray distance on the physical and mechanical properties of HA coatings deposited on TNTZ substrates. The coatings were synthesized at varying spray distances (20, 25, and 30 cm) and characterized using surface profilometry and nanoindentation. The results reveal a distinct trade-off between the surface roughness and mechanical properties governed by the spray distance. Specifically, a 25 cm stand-off distance yielded the highest surface roughness ($R_a = 5.48 \mu\text{m}$), which is highly conducive to initial cellular attachment. Conversely, the maximum coating hardness was achieved at a distance of 20 cm, attributed to elevated particle impact energy, whereas Young's modulus peaked at 187.49 GPa at a distance of 30 cm. A comprehensive analysis identified 25 cm as the optimal deposition distance, providing the most favorable balance between coating morphology and mechanical response derived from nanoindentation. Overall, these findings indicate that the HVOF spray distance is a critical processing parameter influencing the morphological, surface, and nanomechanical characteristics of HA-coated TNTZ coatings, thereby providing valuable guidance for coating optimization.

Keywords: Coating; High-Velocity oxygen fuel; Hydroxyapatite; Osseointegration; Titanium

1. Introduction

Biomaterials are engineered to interact with biological systems to repair or replace damaged tissues in the human body (Todros et al., 2021). With the aging global population, the demand for biomaterials is steadily increasing, and the number of elderly people is projected to reach approximately 1.6 billion by 2050 (Oladele et al., 2023). Orthopedic implants are commonly used to treat osteoporosis and joint degeneration in older patients. Among metallic biomaterials, titanium-based alloys have become the primary choice due to their superior mechanical strength, light weight, excellent corrosion resistance, and good biocompatibility (Anene et al., 2021).

Ti-29Nb-13Ta-4.6Zr (TNTZ), a β -type titanium alloy with excellent mechanical properties, has a low Young's modulus of approximately 55–60 GPa, which is close to that of human cortical bone (Niinomi et al., 2016). This characteristic is crucial for minimizing the effects of stress shielding. In addition, TNTZ is free of toxic elements and exhibits high strength and superior corrosion resistance (Anderson et al., 2022).

TNTZ is inherently bioinert and exhibits limited direct interaction with surrounding bone tissue, which may restrict early-stage cell attachment, proliferation, and bone formation at the implant surface (Xu et al., 2022). Consequently, the osseointegration process may be slower than desired, potentially affecting the implant's long-term stability and clinical success. While surface properties, particularly roughness and chemistry, are critical for regulating cellular responses (Zhu et al., 2022), conventional modification methods, such as ultraviolet radiation, plasma radiation (Takematsu et al., 2016), anodizing (Liu et al., 2019), and hydrothermal treatment (Zuldesmi et al., 2015), often exhibit drawbacks, such as limited coating thickness, non-uniform layers, and inferior adhesion, because of the processing conditions and intended application. To address these limitations, HA was selected as the optimal coating material. As a structural analogue of the mineral phase of natural bone, HA creates a highly bioactive interface that promotes direct bone–implant integration and ensures long-term stability (Nuswantoro et al., 2024). In addition, HA coating offers the advantage of forming a direct chemical bond with living bone tissue compared with other surface modification techniques. Furthermore, HA layer deposition via the high-velocity oxygen fuel (HVOF) process ensures low porosity, superior interfacial adhesion, and minimized thermal degradation, effectively resolving the drawbacks of conventional surface modifications and significantly enhancing the overall clinical performance of TNTZ implants.

The deposition technique significantly influences the coating's efficacy. While HA can be incorporated via sol-gel, chemical precipitation, or hydrothermal methods (Mondal et al., 2020), the high-velocity oxy-fuel (HVOF) process was used in this study (Shankar et al., 2024). HVOF is a thermal spray technique in which a high-pressure oxygen-fuel combustion flame heats and accelerates powder particles before impacting the substrate at high velocity to form a dense coating. HVOF operates at a lower particle temperature while maintaining a much higher particle velocity than atmospheric plasma spraying. This results in coatings with low porosity, high adhesion strength, and reduced HA thermal degradation (Wang et al., 2022). However, although electrochemical coating techniques preserve the HA phase due to their low processing temperature, they generally produce thinner coatings with lower adhesion strength and often require post-treatment to improve mechanical performance. Therefore, HVOF provides an optimal balance between coating density, adhesion strength, HA phase stability, and mechanical reliability, making it highly suitable for load-bearing biomedical applications. Although HVOF has been successfully applied to HA and zinc oxide (ZnO) coatings on cobalt-chromium (Co-Cr) alloys to enhance hardness and osseointegration (Bansal et al., 2020), its application to biomedical implant coatings, particularly on TNTZ, remains relatively limited, highlighting a clear gap in available reference data.

Recent studies have also highlighted the potential of apatite-based materials, particularly carbonate apatite, for enhancing the biological integration and mechanical performance of implants (Yotsova & Peev, 2024). For example, in magnesium–carbonate apatite composites, processing routes such as sintering and extrusion markedly influence density, mechanical strength,

and degradation behavior, which in turn govern the overall in vivo performance (Setyadi et al., 2024). These findings underscore the importance of precisely controlling apatite layer formation and properties in the development of next-generation biomaterials.

The feedstock properties and HVOF processing parameters govern the final coating characteristics. HA particle size affects melting, in-flight behavior, and solidification, thereby influencing coating microstructure, crystallinity, porosity, and adhesion (Li et al., 2000). Meanwhile, the spray distance controls the particle temperature, velocity, and impact energy, which determine splat deformation, coating densification, surface roughness, thickness, porosity, and mechanical properties (Górnik et al., 2021; Sosa et al., 2010). For HA coatings, the stand-off distance also influences the in-flight particle state, coating formation, crystallinity, and resulting properties (Hermann-Muñoz et al., 2019).

The mechanical integrity and functional performance of HA-coated TNTZ are governed by hardness, Young's modulus, coating thickness, and surface roughness, as mechanical mismatches between the coating and substrate may affect interfacial integrity (Sinnott et al., 2022). Despite previous studies on HVOF-deposited HA coatings, systematic evaluation of the combined effects of spray distance on coating thickness, surface roughness, and local mechanical properties of HA coatings on TNTZ remains limited. This study addresses this gap by integrating surface and local mechanical characterization to establish a process–structure–property relationship between HVOF spray distance and coating characteristics. The objective of this study was to determine the effect of spray distance on coating thickness, surface roughness, hardness, and Young's modulus and to identify a suitable processing range for tailoring HA-coated TNTZ surfaces for biomedical applications.

2. Methods

2.1 Specimen Preparation

This study used a Ti-29Nb-13Ta-4.6Zr (TNTZ) alloy bar supplied by Daido Steel Co., Ltd., Japan. Table 1 shows the chemical composition of TNTZ.

Table 1 Chemical composition of Ti-29Nb-13Ta-4.6Zr (TNTZ) (mass %)

Ti	Ta	Zr	Fe	C	N	O	Nb
Bal.	12.2	4.3	0.05	0.02	0.04	0.10	29.2

Kuroda et al. (2000) reported that high-frequency induction melting produced a practical-size ingot of Ti-29Nb-13Ta-4.6Zr (TNTZ). The resulting ingot was subsequently subjected to HIP at 1447 K and 172 MPa for 14.4 ks to obtain a homogeneous alloy structure, followed by hot forging and cold rolling to achieve the desired material form (Figure 1). The reported TNTZ ingot had a mass of approximately 17 kg and exhibited a homogeneous distribution of alloying elements.

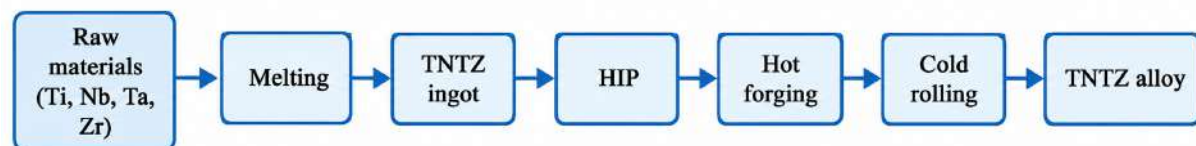


Figure 1 Schematic illustration of the processing sequence used to fabricate the TNTZ alloy

Subsequently, the as-received bulk material was machined into cylindrical specimens measuring 10 mm in diameter and 5 mm in thickness for experimental use, as detailed in Figure 2.

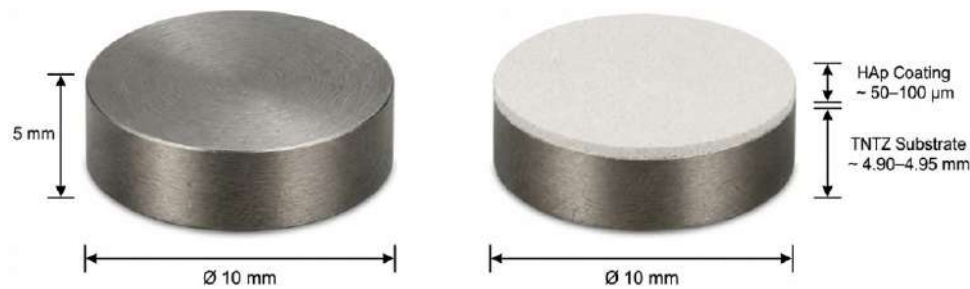


Figure 2 Schematic illustration of a. TNTZ substrate geometry and b. HA-coated TNTZ specimen prepared by HVOF spraying

The specimens were mechanically ground using silicon carbide (SiC) abrasive papers with sequential grit sizes of 400, 800, 1200, and 2000 mesh and then polished to obtain a uniform surface finish. Subsequently, the specimens were sandblasted using alumina (Al_2O_3) abrasive particles (1.2 mm particle size) to increase surface roughness and enhance coating adhesion.

Medical-grade bovine hydroxyapatite (HA) powder (BHANEX[®], PT Inovasi Bioproduk Indonesia, Surabaya, Indonesia) was selected as the primary coating material for its exceptional bioactivity and structural homology to natural bone. The particle size distribution was characterized using a Cilas 1190 Particle Size Analyzer (PSA) (Cilas, Orléans, France). This powder (average particle size: 43.68 μm) was applied to the substrates via HVOF thermal spraying (Figure 3) at controlled standoff distances of 20, 25, and 30 cm, which were selected based on the typical standoff distance range reported for HVOF coating processes and preliminary experimental trials. These distances were chosen to evaluate the effect of particle flight characteristics on the deposition behavior of HA coatings on TNTZ substrates (Hermann-Muñoz et al., 2019). At shorter spray distances (20 cm), particles are expected to impact the substrate at higher temperatures and velocities, promoting coating densification and stronger interfacial adhesion. Conversely, increasing the spray distance to 30 cm may reduce particle temperature and kinetic energy due to prolonged exposure to the surrounding atmosphere, thereby affecting coating growth, porosity, and bonding quality. The intermediate distance of 25 cm was selected to assess the evolution of coating characteristics between these two extreme conditions and to determine the optimum spraying distance for achieving desirable coating performance (Lih et al., 2000). After coating, each coated plate was sectioned into three specimens, which were used as replicate samples for subsequent characterization and nanoindentation testing.

The HA coating was deposited using a custom-built HVOF thermal spray system developed in-house by the Research Center for Electric Power and Mechatronics, Indonesian Institute of Sciences (LIPI), during 2006–2007. The HVOF process was performed under the following conditions:

- HA powder was pre-dried to minimize residual moisture before HVOF deposition.
- Before spraying, the HVOF torch and nozzle were calibrated. Propane and oxygen were used as fuel gases, and nitrogen was used as the carrier gas for feeding the HA powder.
- The spraying parameters were as follows: oxygen flow rate: 270 L/min; LPG flow rate: 65–75 L/min (start: 70 L/min); compressed air flow: 180–220 L/min (start: 200 L/min); carrier gas (N_2): 20–30 L/min (start: 25 L/min); powder feed rate: 20–30 g/min (start: 25 g/min); spray angle: 90°; substrate temperature: <180 °C. Oxygen pressure of 3.5 bar, propane pressure of 5 bar, nitrogen pressure of 3 bar, combustion temperature of 3100 °C, and particle velocity of 800 m/s.
- The HA particles were injected into the high-velocity flame, where they were partially melted and subsequently propelled toward the TNTZ substrate.

- The coatings were deposited until the desired thickness was achieved (three passes), then cooled to room temperature for 30 min and stored in a dry environment before characterization.

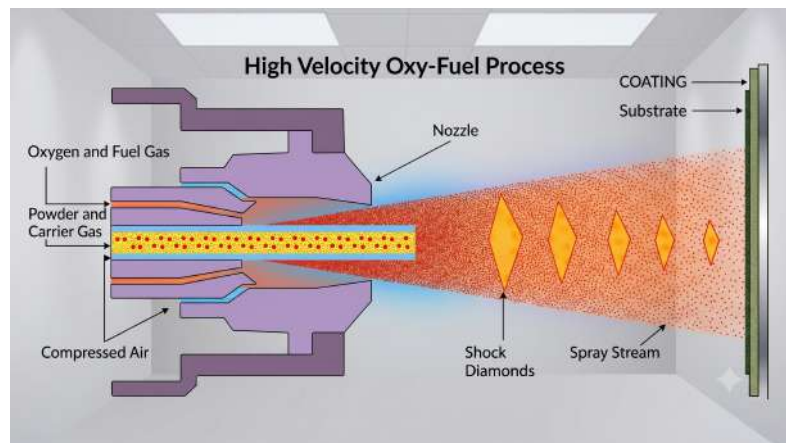


Figure 3 Schematic of the HVOF coating process used to deposit HA onto the TNTZ substrate

2.2 Coating Surface Characterization

The surface topography was quantified using a Keyence VHX-7100 three-dimensional optical microscope (Keyence Corporation, Osaka, Japan) to determine the mean surface roughness (R_a). Coating thickness and microstructural morphology were examined from cross-sectional images obtained using a Hitachi SU3500 Scanning Electron Microscope (SEM) (Hitachi High-Tech Corporation, Tokyo, Japan) at an accelerating voltage of 15 kV and a beam current of 10–100 pA to characterize the coating morphology and determine its thickness. The coating thickness was measured at several representative locations from the outer coating surface to the coating–substrate interface, and the average value was reported. FTIR spectroscopy (ALPHA II Eco-ATR, Bruker) was performed over the range 4000–400 cm^{-1} to detect the characteristic functional groups of HA, notably phosphate (PO_4^{3-}), hydroxyl (OH^-), and carbonate (CO_3^{2-}).

The mechanical properties of the coating, coating–substrate interface, and substrate were evaluated using a nanoindentation testing machine (BRUKER HYSITRON TI 990) to determine the hardness and Young's modulus values. Nanoindentation was used to characterize the local mechanical properties of the coating by continuously pressing a sharp indenter into the surface while recording the applied load and penetration depth. Hardness was measured using a Berkovich diamond indenter and determined from the load–displacement data according to the Oliver–Pharr method, with hardness calculated as the ratio of the maximum applied load to the projected contact area at peak load. The indentation load was selected to maintain the maximum indentation depth below approximately 10% of the coating thickness, thereby minimizing the effects of the substrate on the measured hardness and elastic modulus. Measurements were repeated to confirm reproducibility, and the resulting data were analyzed to clarify how spray distance influences the TNTZ-HA coating system's surface morphology, microstructure, and mechanical properties.

2.3 Data Analysis

Measurements were performed on three replicate specimens for each experimental condition. The experimental data were analyzed using quantitative and descriptive approaches based on three samples ($n = 3$). The mean values and standard deviations were calculated for the coating thickness and surface roughness, and the hardness and Young's modulus were evaluated for the coating, coating–substrate interface, and TNTZ substrate. The coating thickness

was determined from cross-sectional SEM micrographs by measuring the distance between the outer coating surface and the coating–substrate interface at several locations across the cross-section, and the average value was reported. Correlation analysis was performed to assess the relationships between mechanical and surface properties, while scanning electron microscopy (SEM) observations were used to evaluate coating morphology, structural uniformity, and interface characteristics. The results were summarized in tables and graphs to assess the effect of HVOF spray distance on the HA-coated TNTZ substrate.

3. Results and Discussion

3.1 Characteristics of the Coating Surface

Figure 4 shows the FTIR spectra of the HA powder before and after the HVOF deposition. Prior to coating, the characteristic absorption band of the phosphate group (PO_4^{3-}) was observed in the wavenumber range of $1020\text{--}1100\text{ cm}^{-1}$, indicating the presence of a well-crystallized apatite structure (Mondal et al., 2020). In addition, the hydroxyl (OH^-) stretching vibration appeared at $3550\text{--}3570\text{ cm}^{-1}$, confirming the stoichiometric nature of HA (Mondal et al., 2020). Carbonate (CO_3^{2-}) absorption bands were also detected at $1400\text{--}1450\text{ cm}^{-1}$ and $870\text{--}890\text{ cm}^{-1}$, suggesting carbonate substitution within the apatite lattice, a characteristic commonly found in natural bone mineral that contributes to improved bioactivity (LeGeros, 2008; Mondal et al., 2020). These spectral features confirm that the HA powder used in this study can be classified as carbonated hydroxyapatite (CHA).

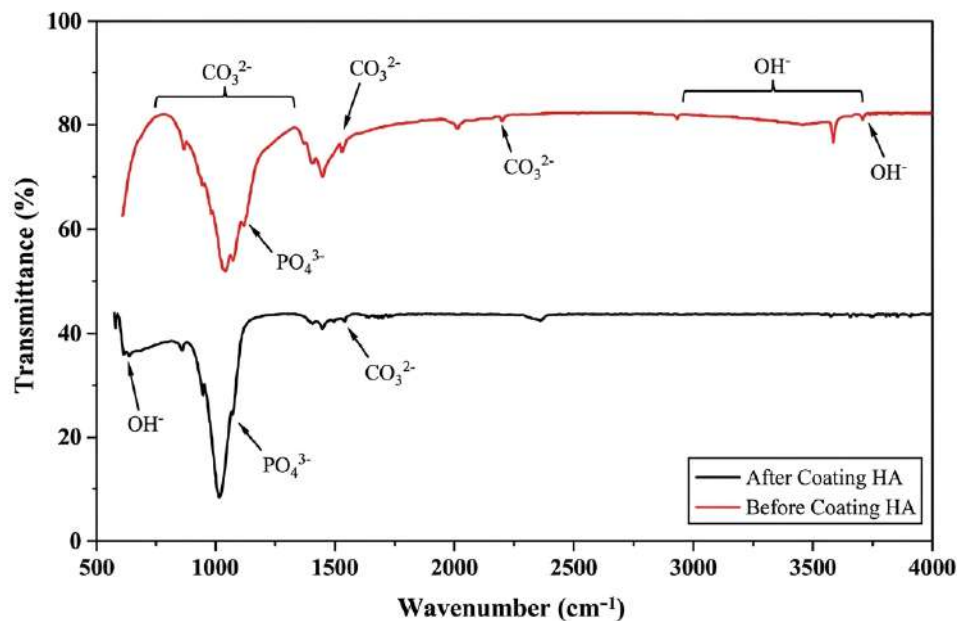


Figure 4 FTIR spectrum of HA powder before and after coating

Comparison of the FTIR spectra before and after coating revealed a noticeable reduction in the intensity of the OH^- absorption band. This behavior is attributed to dehydroxylation occurring during the HVOF process, where the high spraying temperature promotes the release of hydroxyl groups and the partial formation of oxyapatite (Bulina et al., 2023). In addition, the rapid cooling experienced by molten HA particles upon impact with the substrate suppresses the reincorporation of OH^- groups into the crystal lattice, resulting in a nonequilibrium structure (Henao et al., 2020). Although the reduction of hydroxyl groups may slightly decrease bioactivity and crystal stability, the preservation of the characteristic phosphate bands indicates that the fundamental HA structure remains intact and retains its potential for bone interaction (Trzaskowska et al., 2024). Furthermore, changes in the hydroxyl content are closely associated with the degree of crystalline-to-amorphous transformation during dehydroxylation, which sub-

sequently influences the coating's mechanical properties, particularly its hardness (Osuchukwu et al., 2021).

3.2 Surface Roughness

Figure 5 shows the surface roughness of the sandblasted substrate (TNTZ) and coating layers as a function of the spraying distance. The initial sandblasting process, in which high-pressure abrasive particles were propelled onto the surface, generated a microtopography characterized by peaks and valleys, with an area surface roughness value (R_a) of 3.21 μm . This morphology increases the effective surface area and enhances the mechanical interlocking between the substrate and HA coating.

When the spraying distance was varied, an increase in surface roughness was observed at a distance of 20 cm compared with the as-sandblasted substrate. The HA particles retained relatively high kinetic and thermal energies upon impact with the substrate at this spraying distance (Lima & Marple, 2007). The highest roughness peak was obtained at a spraying distance of 25 cm, where the semi-molten state of the powder particles allows for their optimal deformation into more complex splat and lamellar structures, resulting in a rougher surface texture (Gross et al., 2012). In contrast, at a spraying distance of 30 cm, the surface roughness decreased due to the loss of kinetic energy and premature cooling of the powder particles within the flame jet before they reached the substrate, resulting in a smoother coating morphology. However, this study did not directly measure particle temperature, velocity, or splat morphology; therefore, these mechanisms should be regarded as a plausible interpretation rather than direct experimental evidence.

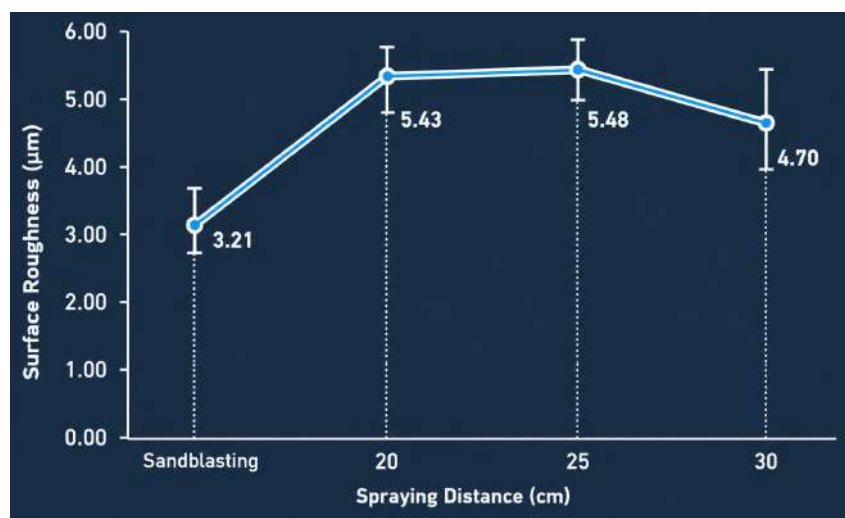


Figure 5 Surface roughness (R_a) of the sandblasted TNTZ substrate and HA coatings sprayed with HVOF as a function of spray distance

The surface roughness values in this study ranged from 4–6 μm . This range is consistent with the standard surface roughness of 4–7 μm reported in the literature for HA coatings using a thermal spray method (Singh et al., 2014). The coating exhibited the highest roughness at a spraying distance of 25 cm, providing a surface morphology favorable for protein adsorption and biological interactions. Such surface characteristics are expected to support the osseointegration process in biomaterial implant applications (Dehghanpour & Rouhi, 2025). Therefore, the alignment between spray distance control and surface topography appears to be a key factor in optimizing postimplantation stability (Gross et al., 2020).

In this study, the surface roughness analysis is crucial because the topography of the HA coating influences implant osseointegration. Surfaces with appropriate roughness have been reported to enhance the initial adsorption of proteins, such as fibrinogen and extracellular matrix components, thereby facilitating early blood clot formation and provisional matrix establish-

ment on the implant surface (Dehghanpour & Rouhi, 2025). This protein layer then supports osteoblast adhesion and proliferation, which accelerates the formation of new bone tissue and ultimately contributes to the stable osseointegration of the implant within the host bone (Dehghanpour & Rouhi, 2025).

3.3 Coating Thickness

Variations in spraying distance affect the thickness of the resulting coating (Figure 6). At a distance of 20 cm, the average coating thickness was 21.70 μm , followed by 24.55 μm at a distance of 25 cm. However, at a distance of 30 cm, the coating thickness increased significantly to 62.32 μm .

The nearly threefold increase at 30 cm, compared with the relatively modest change between 20 and 25 cm, indicates a nonlinear response of coating deposition to spray distance, which was not accompanied by similar changes in surface roughness or hardness, suggesting that distinct aspects of the HVOF deposition process govern coating thickness.

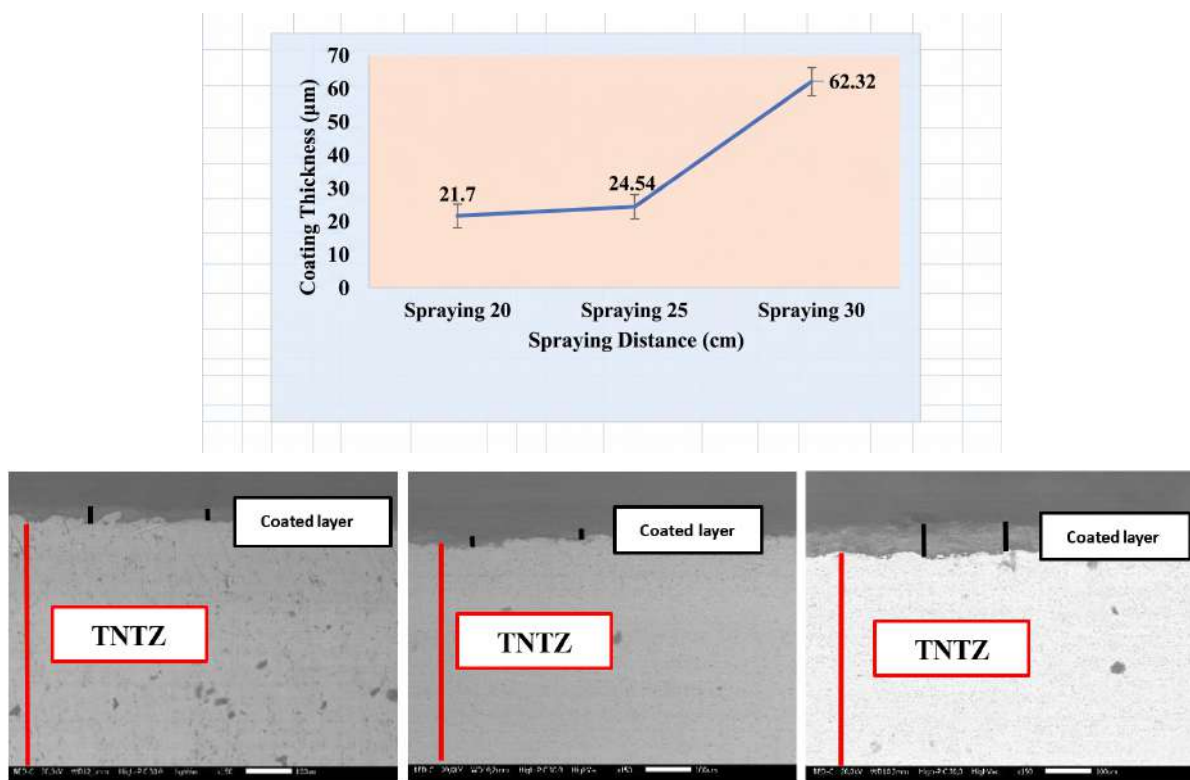


Figure 6 (a) Variation in coating thickness with spraying distance, and (b) cross-sectional scanning electron microscopy (SEM) images of the HA coating on the TNTZ substrate at spraying distances of 20, 25, and 30 cm

The longer spray distance may alter particle flight and deposition behavior, potentially affecting splat formation and material accumulation at 30 cm. This interpretation is consistent with previous reports describing the influence of particle thermal state, impact behavior, and splat formation on HVOF coating deposition (Blum et al., 2021; Lima & Marple, 2007; Vats et al., 2021). Nevertheless, the markedly higher thickness at 30 cm may reflect the combined effects of particle–substrate interactions and deposition efficiency under the specific HVOF conditions employed, rather than spray distance alone. Although the longer spray distance reduced particle temperature and velocity, the associated changes in particle impact and deposition behavior may have favored greater material retention and coating build-up, resulting in the observed increase in thickness.

Test results indicated that variations in spray distance affect HA coating thickness on TNTZ

substrates. The coating thickness in this study was within the 10–100 μm range, consistent with literature standards for orthopedic and dental implant applications (Anusha et al., 2023). This range is considered ideal because it balances the adhesion strength between layers with the bioactivity required to support osseointegration. Appropriate coating thickness is crucial for the long-term performance of implants, particularly in facilitating effective attachment and growth of new bone tissue on the material surface (Nuswantoro et al., 2024). Therefore, optimizing the firing distance is key to producing functional coatings for biomaterial applications.

3.4 Hardness

Figure 7 shows the nanoindentation testing area on the specimen surface. The black dot indicates the indentation locations selected for local measurement of hardness and Young's modulus.

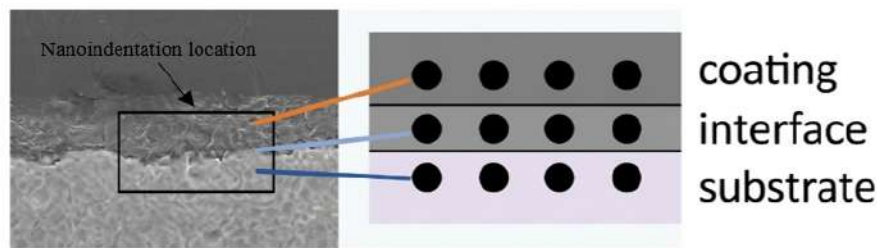


Figure 7 Cross-sectional micrograph showing the nanoindentation locations within the HA coating, coating–substrate interface, and TNTZ substrate

The hardness test results are displayed in color and contour maps, as shown in Figure 8. The color maps show a heterogeneous hardness distribution, with values grading from low (blue) to high (red). Unlike the contour method, this representation allows a more distinctive separation of the three zones—substrate, interface, and coating—because the value distribution is presented in a separate format. Areas dominated by blue and green represent the substrate, yellow to brown represent the interface zone, and the red spectrum indicates the coating region. This visual distinction reflects the influence of the HVOF process parameters on each layer's hardness distribution profile. Meanwhile, contour maps depict a continuous hardness distribution, where the low (blue-green) and high (yellow-red) zones appear more unified through smooth transitions. These contour maps do not define the boundaries between zones but rather emphasize the value gradation and the overall hardness distribution. However, for more specific identification of testing area boundaries, the color maps still provide more definitive information.

The hardness test data, consisting of three areas—namely, the coating, interface, and substrate areas—presented in Figure 9, show that the highest hardness value was recorded in the coating area, followed by the interface, and the lowest on the substrate for all variations of the spray distance. In the coating zone, the hardness decreased with increasing spray distance, with values of 14.03 GPa (20 cm), 12.62 GPa (25 cm), and 9.66 GPa (30 cm). These results are consistent with the HA hardness reference range of 4–14 GPa (Barabashko et al., 2022), indicating that a denser and harder coating is produced by a closer spray distance.

The increased hardness of the coating indicates the effectiveness of the HA coating in enhancing the mechanical properties of the TNTZ surfaces. The maximum hardness observed at a spray distance of 20 cm can be attributed to the higher particle impact velocity, which promotes better splat deformation, lower porosity, and greater resistance to localized plastic deformation (Raza et al., 2022). In addition, the high density achieved through the HVOF process promotes the formation of a dense and compact coating microstructure, which can contribute to the enhanced hardness of the coating (Jonda et al., 2020). The decrease in hardness at a distance of 30 cm suggests that sufficient particle energy, as achieved at a distance of 20 cm, is crucial for forming compact and stable interlamellar bonds (Katranidis et al., 2019). Conversely, long

distances lead to increased porosity and weakened interparticle bonds, thus reducing the density and hardness of the coating (Hermann-Muñoz et al., 2019).

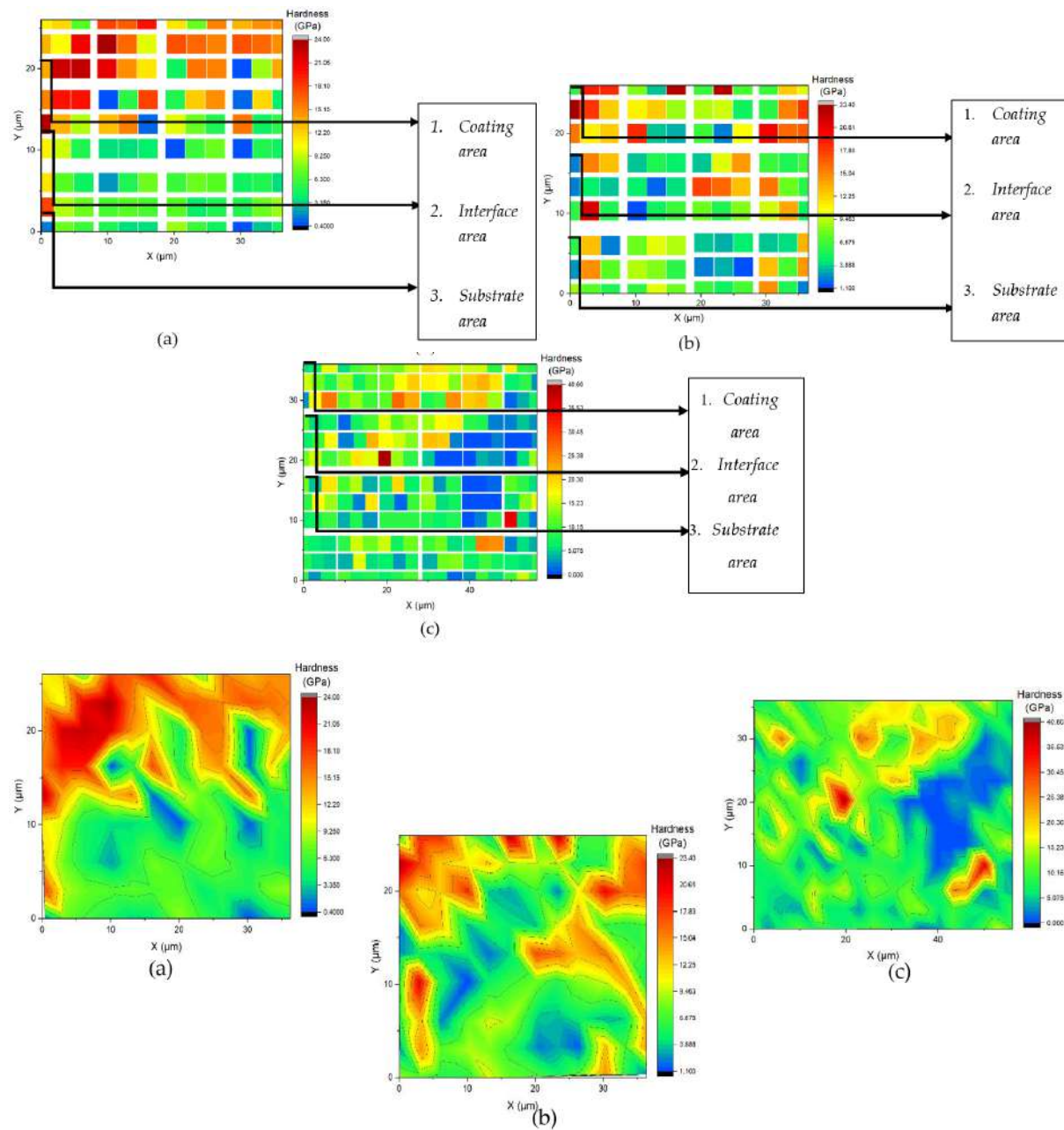


Figure 8 Hardness color maps and contour maps showing the spatial distribution of hardness across the HA coating, coating–substrate interface, and TNTZ substrate at spray distances of (a) 20, (b) 25, and (c) 30 cm. The X- and Y-axes represent the measurement positions (m) in the mapping area (μm)

These findings show that the structural quality of the material is a more dominant factor in determining hardness than thickness alone. The high hardness of HA coatings is crucial for implant resistance to load, which directly supports stability and osseointegration (Nuswantoro et al., 2024). Conversely, interface hardness exceeding that of the substrate indicates good mechanical transition. This occurs due to the mechanical interlocking formed by sandblasting, resulting in tighter interparticle bonds, reduced porosity, and increased hardness in the transition zone (Górnik et al., 2021; Yang et al., 2023). The substrate hardness value is within the reference range of 2–6 GPa (Barabashko et al., 2022).

3.5 Young's Modulus

In Figure 10, the highest Young's modulus value was consistently found in the coating layer, followed by the interface zone, and the lowest in the substrate for all spray distance variations. As the HVOF spray distance increased, the Young's modulus value of the coating increased to 167.39 GPa (20 cm), 179.81 GPa (25 cm), and up to 187.49 GPa (30 cm). This increase illustrates the effectiveness of the HVOF method in modifying the surface's mechanical properties, especially since HA is a ceramic material with high intrinsic stiffness (Nuswantoro et al., 2024).

Differences in Young's modulus values between zones reflect the characteristics of the constituent materials. The HA coating has maximum stiffness, whereas the TNTZ substrate has a low modulus for bone compatibility. The interface zone acts as a mechanical transition between the two. The higher modulus measured at 30 cm may be associated with improved elastic response resulting from changes in microstructural homogeneity, inter-splat bonding, and residual stress relaxation during particle flight (Górník et al., 2021).

The elastic modulus values obtained from nanoindentation (167–187 GPa) are higher than those commonly reported for bulk sintered hydroxyapatite and should therefore be interpreted as local indentation-derived values rather than the intrinsic bulk modulus of HA. Nanoindentation probes a highly localized material volume, and the resulting modulus can be affected by local microstructural characteristics, deformation and stress conditions beneath the indenter, as well as testing parameters (Filippov & Koch, 2019; Hardiman et al., 2016; Mokhtari et al., 2022; Mook & Gerberich, 2007). In thermally sprayed coatings, local porosity, inter-splat bonding, and other microstructural features may further influence the measured mechanical response (Gindl & Schöberl, 2004; Guidoni et al., 2010). The HA coating thickness in the present study was approximately 62.32 μm ; therefore, the possible contribution of the underlying TNTZ substrate must be considered in relation to the actual indentation depth. Although the TNTZ substrate has a substantially lower elastic modulus than the measured coating values, which would tend to reduce rather than increase the apparent modulus if substrate interaction occurred, the absence of a directly measured indentation depth prevents the substrate effect from being quantitatively excluded. Representative load–displacement curves obtained during nanoindentation are therefore provided to illustrate the measured indentation response and support assessment of the consistency of the mechanical behavior. Accordingly, the measured values are considered localized elastic modulus values of the HVOF-sprayed HA coating rather than intrinsic bulk HA properties. Complementary mechanical characterization at a larger scale would be beneficial in future studies to further validate the effective elastic modulus of the coating (Guidoni et al., 2010; Oyen & Ko, 2004).

Figures 9 and 10 show the contrasting responses of hardness and Young's modulus to increasing spray distance, with hardness declining and Young's modulus increasing. These trends reflect the different mechanical responses represented by the two properties: hardness indicates resistance to localized plastic deformation, whereas Young's modulus characterizes elastic stiffness. In this study, the hardness was highest at 20 cm and decreased with increasing spray distance, while the Young's modulus reached 187.49 GPa at 30 cm. This behavior may be related to changes in particle temperature, impact velocity, and splat formation. These mechanisms remain plausible interpretations because the particle temperature, impact velocity, splat morphology, and residual stress were not directly characterized in this study.

Although the Young's modulus of the coating is relatively high compared with that of bone (10–30 GPa), it remains essential as a bioactive surface for enhancing osseointegration and implant stability (Nuswantoro et al., 2024). This high modulus is a result of the coating's dense microstructure, minimal porosity, and residual stress formed during the fabrication process (Owoseni et al., 2020).

3.6 Limitations and Future Work

This study has several limitations. We evaluated the mechanical performance of the HA coating using nanoindentation, which provides localized measurements of hardness and Young's modulus. Although these parameters are useful for assessing the coating's local mechanical response, they do not fully represent its overall mechanical performance under physiological loading conditions. Coating adhesion strength, fracture toughness, wear resistance, fatigue behavior, and long-term durability were not investigated. Furthermore, the relationship between the nanoindentation results and coating microstructure, such as porosity, residual stress, and inter-splat bonding, was not quantitatively evaluated. Future work should include comprehensive mechanical characterization, detailed microstructural analysis, and in vitro and in vivo biological evaluations to better establish the suitability of HVOF-sprayed HA coatings on TNTZ alloys for load-bearing biomedical applications.

4. Conclusions

Based on the findings of this study, the spraying distances in the HVOF process play a critical role in determining both the mechanical properties and surface characteristics of HA coatings deposited on TNTZ substrates. The results showed that the highest hardness, 14.03 GPa, was achieved at a spraying distance of 20 cm, whereas the maximum Young's modulus, 187.49 GPa, was obtained at 30 cm. Furthermore, the spraying distance significantly influenced the coating surface morphology, as evidenced by variations in surface roughness and coating thickness. The highest surface roughness was observed at a spraying distance of 25 cm, measuring 5.48 μm , while the thickest coating was produced at 30 cm, with an average thickness of 62.32 μm . Although individual properties reached their maximum values at different spraying distances, the 25 cm condition provided the most balanced combination of surface morphology and mechanical performance. However, since this study focuses exclusively on surface and mechanical characterizations, further investigations into the adhesion strength of the coating and comprehensive biological validation (in vitro and in vivo) are required before any definitive claims regarding its clinical suitability for biomedical applications can be established.

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Author Contributions

Zuldesmi Mansjur: planning, coordinating, and evaluating research activities. Soenandar Milian Tompunu Tengker: assisting in the preparation of test specimens and data processing. Andril Arafat: assisting in the preparation of test specimens and data processing. I Nyoman Jujur: assisting in the preparation of test specimens and data processing. Mirza Wibisono: assisting in the preparation of test specimens and data processing. Suryadi: assisting in the preparation of test specimens and data processing. Xui Ching Angelika Hutasoit: methodology, formal analysis, editing. Gunawarman: supervision, writing—review & editing, formal analysis, conceptualization. Mitsuo Niinomi: supervision, writing—review & editing, formal analysis, conceptualization. Toshikazu Akahori: writing—review & editing, supervision, formal analysis, data curation, conceptualization.

Conflict of Interest

The authors have no financial or non-financial relationships that could be perceived as a conflict of interest.

Declaration of AI

This article is the original work of the authors without using AI tools for generating text or creating/editing tables and figures.

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