

The Effect of Adding Alumina Particles on Niobium-Zirconium Alloy Mechanical Properties

Salih Jawad Hamza¹, Haydar H. J. Jamal AlDeen², Zainab Al-Khafaji^{3,4*}

¹Department of Materials Engineering, College of Engineering, University of AL-Qadisiyah, Iraq

²College of Materials Engineering, University of Babylon, Babylon 51013, Iraq

³Imam Ja'afar Al-Sadiq University, Qahira, Baghdad, Iraq

⁴Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

ARTICLE INFO

Article history:

Received 27 August 2025

Revised 22 April 2026

Accepted 10 June 2026

Published 15 September 2026

Keywords:

Niobium-zirconium

Niobium alloy

Surgical implants

DOI:

10.24191/jmeche.v23i3.8677

ABSTRACT

Niobium–zirconium (Nb–Zr) alloys are emerging as promising candidates for biomedical implants owing to their excellent corrosion resistance, biocompatibility, and lower modulus of elasticity compared with those of common metallic biomaterials. However, their mechanical strength and wear resistance need to be improved for load-bearing purposes. In the present work, the Nb-1 wt% Zr matrix composites having different alumina (Al_2O_3) contents of 0.5–6 wt%, prepared by the powder metallurgy process, have been synthesized at 1200 °C for 6 hours and examined systematically to determine their effect on porosity, hardness, compressive strength, elastic modulus, and dry sliding wear behavior. The porosity decreased initially until the Al_2O_3 reached 0.5 wt%, then increased slowly at higher contents. The best mechanical properties were obtained by 6 wt% Al_2O_3 , where the compressive strength was enhanced from 134 to 234 MPa (74.6%), while the hardness increased by more than 90%, and the wear rate decreased by up to 92.5% at a load of 25 N. Meanwhile, the elastic modulus reduced from 70.6 GPa to 22.2 GPa (69% reduction) to be closer to that of cortical bone and to limit the stress-shielding effect at the same time. These results indicate that the controlled Al_2O_3 reinforcement can effectively enhance the mechanical and tribological performance of Nb–Zr alloys while demonstrating biomechanical compatibility, making them prospective candidates for next-generation load-bearing surgical implants.

Introduction

Niobium–zirconium (Nb–Zr) alloys have been considered one of the most favorable candidates for biomedical implants based on their outstanding corrosion resistance, high biocompatibility, and lower

^{4*} Corresponding author. E-mail address: p123005@siswa.ukm.edu.my
<https://doi.org/10.24191/jmeche.v23i3.8677>

Young's modulus compared to the present accepted metallic implant materials, such as Ti–6Al–4V or Co–Cr alloys (Hanawa & Nomura, 2022; Radhi & Al-Khafaji, 2018; Zhang et al., 2022). Nb–Zr increases the mechanical stability and corrosion resistance of niobium, providing a nontoxic, inert surface without significant changes that are inappropriate for implantable applications (Abed et al., 2022; Radhi et al., 2020). However, despite these benefits, the mechanical strength and wear resistance of Nb–Zr alloys remain unsatisfactory for aggressive biomedical applications that require long-term performance under cyclic loads and abrasive contact (Huang et al., 2021).

In addition to addressing these concerns, the emergence of biomedical metallic–ceramic composites has provided an alternative route to achieving improved mechanical strength, wear resistance, and functional reliability (Jack & Szpunar, 2023; Nam & Kim, 2010). Alumina (Al_2O_3) has been employed as the reinforcing phase due to its high hardness, chemical stability, good wear resistance, and well-documented biocompatibility (Ardila et al., 2017; Liu et al., 2021). The dispersion of Al_2O_3 particles in a metallic matrix enhances load transfer, impedes grain growth via Zener pinning, and introduces dispersion-strengthening mechanisms, thereby enhancing hardness, strength, and tribological performance (Ells, 1974; Wang et al., 2018). Furthermore, ceramic reinforcements can be incorporated explicitly and controlled to affect porosity and interfacial compliance, which, in turn, can aid in tuning the elastic modulus more closely to that of cortical bone ($\approx 10\text{--}30$ GPa), thus helping alleviate stress shielding phenomena associated with longevity in implantation (Griffiths, 1988; Topping et al., 2018).

Powder metallurgy represents a precise, controlled one-step process for the production of metal–ceramic composites with specific composition and microstructure (Christensen et al., 2014; Christien & Barbu, 2009; Radhi et al., 2024). Powder metallurgy is a highly suitable method for fabricating such devices, ensuring uniform distribution of Al_2O_3 particles in the Nb–Zr matrix and minimizing material waste to produce high-performance biomedical materials with custom properties. The reinforcement of other Nb and Ti alloys with particles has previously been found to improve hardness and wear resistance. However, the effect of Al_2O_3 on the mechanical, tribological, and elastic properties of Nb–Zr alloys tailored for biomedical applications was not systematically studied until now (Angelo et al., 2022; Radhi et al., 2023; Sallal et al., 2024). The development of powder metallurgy is ongoing, facilitating the continual emergence of new applications and improvements in contemporary production technologies. Moreover, it is a driving force in the materials science discovery process. Many researchers used this technique to add different metal powders to alloys such as Aluminum (Al-khafaji et al., 2018; Jasim et al., 2020; Radhi & Al-Khafaji, 2018), Fe_2O_3 (Radhi et al., 2023, 2024), Zinc (Jasim et al., 2020), Titanium (Hidalgo et al., 2017; Salih & Al-Khafaji, 2023), TiO_2 , and SiO_2 (Hussein et al., 2024; Sattar et al., 2023a, 2023b).

Nam & Kim (2010) showed that as the niobium (Nb) content is increased from 0 wt. % to 0.10 wt. % decreases the corrosion rate in sulfuric acid. This change was attributed to changes in the electrochemical behavior of steel. Passive resistance was found to be enhanced, and the charge-transfer resistance increased in niobium-containing steels. A passivating protective layer of relatively inert Nb oxides forms on the steel surface during oxidation, improving the steel's corrosion resistance (Ardila et al., 2017). Liu et al. (2021) reported that corrosion resistance improves with an appropriate Nb content in microalloyed steels due to the precipitation of NbC, which results in a more homogeneous microstructure. Therefore, NbC precipitates effectively inhibit the rapid anodic dissolution of steel, thereby increasing its corrosion resistance. Wang et al. (2018) conducted a surface morphological analysis and noted that corrosion product films formed on 0.079 wt. % Nb addition is more abraded than non-treated steels after saltwater exposure. Compression of the material increases its resistance to ion migration in an electrochemical reaction, such as that between steel and chloride ions, leading to reduced rate and extent of steel degradation.

Ells (1974) observed that Zr–Nb alloys exhibit greater hardening under irradiation than Zircaloy-2. This effect can be attributed to the smaller atomic radius of niobium (Nb) relative to zirconium (Zr). Nb's smaller size enables it to alleviate compressive strain fields around clusters of interstitials when it substitutes for Zr atoms. This substitution facilitates the accumulation of defects and the formation of dislocation structures, leading to irradiation-induced strengthening. However, Nb also inhibits the annealing of these defects.

Topping et al. (2018) demonstrated that Nb-containing alloys exhibit greater resistance to annealing. According to Topping's findings, these defect structures should typically anneal out at this temperature; however, in Nb-containing alloys, the defects remain observable. Griffiths (1988) further noted that the addition of Nb to Zr decreases the size of a-type dislocation loops and increases their concentration. Christensen's research also indicated that Nb has a strong affinity for and immobilizes self-interstitial atoms (SIAs). This pinning action inhibits interstitial migration, thereby preventing the formation of interstitial loops (Christensen et al., 2014). Based on studies by Griffiths and Christensen, it is expected that irradiated Zr-Nb alloys will exhibit small dislocation loops with high densities, primarily characterized by vacancies (Christien & Barbu, 2009). Bartolomé et al. (2016) studied these innovative zirconia/Nb biocermet implants in vivo and in vitro to assess biological tolerability.

First, human bone marrow mesenchymal stem cells were grown on polished, sintered biocermet discs, and their reactivity to niobium metal was examined. In vitro, biocermet did not affect cell shape, extracellular matrix production, or proliferation. Bioceramics also supported cell growth faster than Nb metal. The bones' reactivity to these new zirconia/Nb biocermet was studied. The tibiae of New Zealand white rabbits were implanted with biocermet cylinders and a commercial Nb rod. All animals were killed after six months. Processing yielded thin specimen slices. The slides were examined under a conventional transmitted-light microscope. A freshly formed bone was observed near the material surfaces. There were no inflammatory or multinucleated cells. Zirconia/Nb composites are osteoconductive and biocompatible, according to the research. The ceramic-metal composite outperforms pure Nb in osteointegration.

Dotta et al. (2021) measured the tribological and mechanical properties of spark plasma-made niobium-alumina (Nb- Al_2O_3) composites at 50 MPa. The crystalline phases and microstructure of sintered materials were characterized by X-ray diffraction and scanning electron microscopy. Instrumented and Vickers indentation tests measured stiffness, hardness, and fracture toughness. Tribology was conducted on ball-on-disc Al_2O_3 , Al_2O_3 -15%Nb, and Al_2O_3 -25%Nb materials at room temperature under dry reciprocating sliding conditions. A mix of material compositions and applied load (5, 10, and 15 N) was considered in three-level factorial wear studies for 52100 steel and Al_2O_3 counterbodies. Niobium increased the wear resistance and fracture toughness of alumina matrix composites. More niobium reduced the materials' stiffness, hardness, and fracture toughness, lowering the brittleness index. Composites exhibited moderate wear behavior ($k < 10\text{--}6 \text{ mm}^3/\text{N.m}$) and wear resistance two orders of magnitude higher than monolithic alumina when sliding against a steel counterbody. Due to material transfer from the 52100 steel counterbody surface, tribofilm deposition in worn areas increased the composite's wear resistance. When sliding against the Al_2O_3 counterbody at higher loads, alumina wore out faster than composites with niobium due to brittle fracture. Wear-regime maps as a function of contact severity and brittleness index showed the higher wear resistance of Nb- Al_2O_3 composites and distinguished the wear processes of the materials involved.

The present study aims to develop and characterize Nb–1 wt% Zr alloys reinforced with varying Al_2O_3 contents (0.5–6 wt%) via powder metallurgy, with a focus on their suitability for load-bearing surgical implants. The novelty lies in the integrated evaluation of porosity, microstructure, hardness, compressive strength, elastic modulus, and wear resistance, establishing direct correlations between reinforcement content, microstructural evolution, and functional performance. Emphasis is placed on achieving an elastic modulus that approaches that of cortical bone while significantly enhancing surface hardness and wear resistance. The results provide insights into optimizing Nb–Zr– Al_2O_3 composites for next-generation orthopedic and dental implants, thereby bridging a critical gap in the development of mechanically compatible, wear-resistant biomedical materials.

Experimental Work

Materials and apparatus

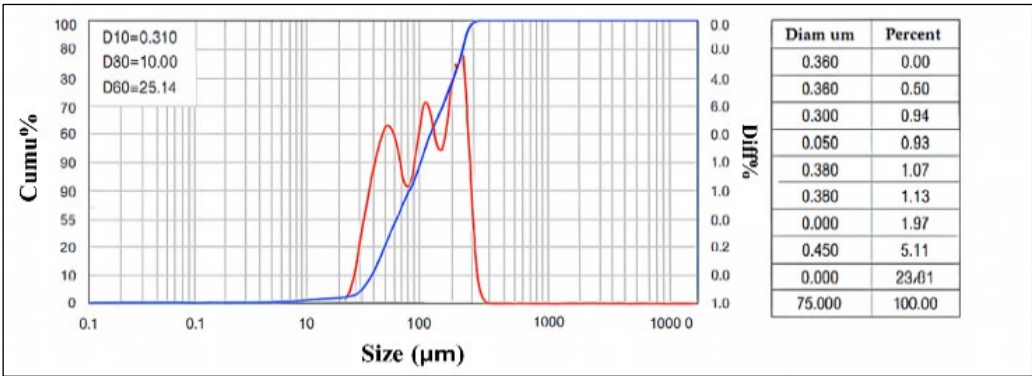
Basic powder

High-purity elemental powders of niobium (Nb), zirconium (Zr), and alumina (Al₂O₃) were used for the preparation of Nb–1 wt% Zr–xAl₂O₃ composites with x ranging from 0.5 to 6 wt%. The powders were obtained from a certified supplier and identified by their mean particle size and purity (Table 1). Particle sizes were measured using a Battersize 2000 laser particle size analyzer.

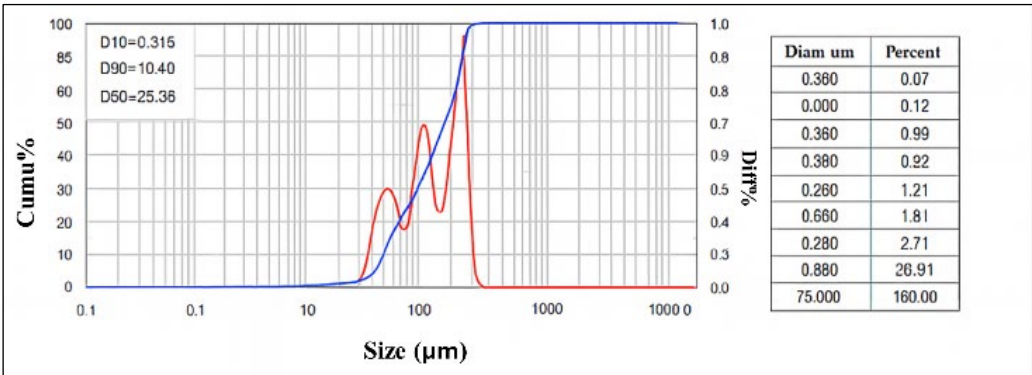
Table 1. The powder utilized in this research has a mean particle size

Powders	Mean particle size (μm)	Purity %
Niobium	28.83	99.95
Zirconium	29.08	98.25
Aluminum oxide	5.311	99.96

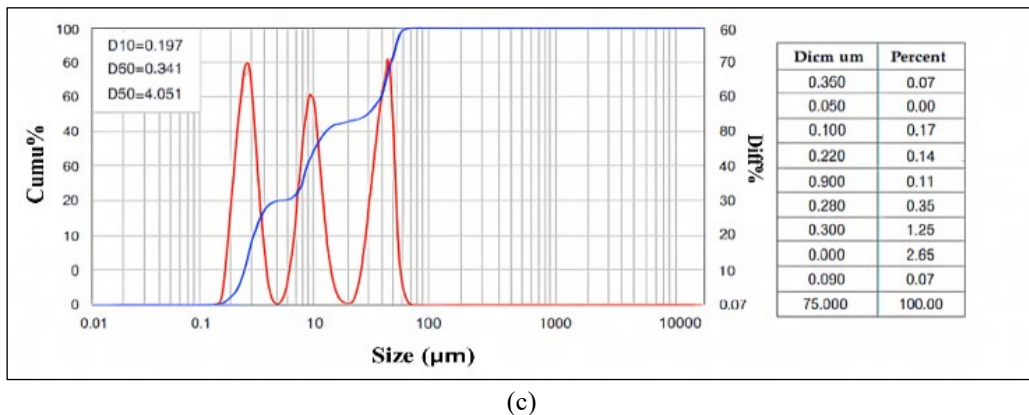
The particle size distributions of the starting powders (a) Nb (b) Zr, and (c) Al₂O₃ by laser diffraction are shown in Fig. 1. The D50 of the Nb and Zr particles are in the 28–29 μm range, with that of Al₂O₃ having a finer one, indicating ~5.3 μm as average size. The fine ceramic particles result in good dispersion and interfacial bonding between to the metallic matrix for effective load transfer. Table 2 displays the typical particle size for powdered materials.



(a)



(b)



(c)

Fig. 1. Particle size analysis: (a) Nb, (b) Zr, and (c) Al_2O_3 .

Table 2. Mean particle size for used materials

Materials (powders)	Mean particle size (μm)
Nb	28.75
Zr	29.60
Al_2O_3	5.311

Powder preparation

The weighed powders were mixed using a planetary ball mill with stainless steel balls of varying diameters in ethanol as the milling medium. Milling was performed for 5 hours to ensure homogeneous dispersion of Al_2O_3 particles. The ball-to-powder weight ratio and rotation speed were selected to avoid excessive particle fracturing.

Compaction

The mixed powders (3.5 g per specimen) were uniaxially compacted into disc-shaped green compacts of 13 mm diameter and 3 mm thickness at 650 MPa using an electrically driven hydraulic press. Graphite was applied as a die lubricant to minimize friction during compaction. The holding time at peak pressure was 2 min.

Sintering

The green compacts were sintered at 1200 °C for 6 hours under a controlled argon atmosphere (to maintain oxidation and phase stability), with a heating rate of 10 °C min⁻¹ and furnace cooling in argon. This heat-treatment schedule was deliberately adopted to encourage good solid-state diffusion and neck growth in the Nb–Zr metallic matrix, while keeping Al_2O_3 as a chemically inert dispersed reinforcement. Increasing the temperature to conventional alumina sintering temperatures would probably accelerate grain growth, increase thermal-mismatch stress and interfacial reactivity, and promote oxygen pick-up or microstructural degradation, potentially challenging mechanical integrity and biomedical reliability. Therefore, sintering at 1200 °C in an inert atmosphere is a conservative yet satisfactory compromise between consolidating the metal matrix and preserving its microstructural stability, including during use.

Preparation of samples for the testing

Sintered specimens were ground sequentially using silicon carbide abrasive papers of 180, 400, 600, 800, 1000, 1200, 1500, and 2000 grit, followed by polishing with diamond paste to a mirror finish. Etching was carried out at room temperature using a solution of 5 mL HF and 25 mL HNO₃. The etched samples were rinsed with deionized water and dried in warm air. Table 3 shows the chemical composition of the etching solution. Following the etching procedure, the specimens underwent a water wash and drying.

Table 3. Chemical analysis of the etching solution

No.	Constituent	ml.
1	HF	5
2	HNO ₃	25

Microstructure examination

Light optical microscope (LOM)

Grain boundaries include features such as form, size, and identification and measurement of the phases. Every one of them has unique qualities. The microstructure was examined utilizing a Japanese-made Olympus microscope at magnifications of 100x, 200x, and 400x.

X-ray fluorescent analysis (XRF)

The chemical analysis of powders and alloys is explained using a handheld (XRF) analyzer of the American type DS-2000.

X-ray diffraction analysis

X-ray diffraction methods have been applied to the alloys using XRD equipment. For both the green compacted specimens and the identical samples after sintering, X-ray diffraction was performed. The Cu target XRD generator operated at 40 KV, 30 mA, with a scanning speed of 5° per minute.

Mechanical tests

To achieve statistical reliability and reproducibility of the experimental results, at least three samples ($n = 3$) were tested for each composition and for each mechanical and physical characterization procedure, unless otherwise specified. All values are the arithmetic mean, and the scatter, too, was within experimental limits for powder-metallurgy materials.

Macro-hardness measurement

The macro-hardness of the sintered samples was measured using a Brinell hardness tester (31.25 kg/mm² load with a 3 mm diameter hardened steel indenter). The load was held for 10 s to obtain stable plastic deformations and well-defined indent locations. Three individual indentations were made at different positions on the sample surface for each composition to reduce the impact of local microstructural inhomogeneity. The selected hardness values are the average of the three measurements and provide a representative characterization of the hardness response across all alloy systems studied.

Dry sliding wear test

Prior to the wear test, the specimens were vacuum dried in a furnace at 100 °C for 2 hours, then cooled. To ensure total drying, the samples were then stored in well-knit boxes lined with silica gel. Utilizing the pin-on-disk approach as shown in Fig. 2, dry sliding wear is investigated at 400 rpm, constant radius (4 mm), and varying sliding distances with loads of 20 N and 25 N. Prior to testing, the specimen is weighed

utilizing an electronic balance with (0.0001) precision. After 5, 10, 15, 20, and 25 minutes, the sample is weighed, and Equation 1 is used to calculate the dry sliding wear rate. ASTM G99 was followed in developing the test protocol. The wear rate was calculated using the following formula:

$$\text{Wear Rate} = \frac{\text{Weight loss (g)}}{\rho \left(\frac{\text{g}}{\text{cm}^3} \right)} \quad (1)$$

where wear rate represents the volume loss of the specimen due to wear (cm^3), weight loss is the decrease in the specimen mass during the wear test (g), and ρ is the density of the specimen material (g/cm^3).

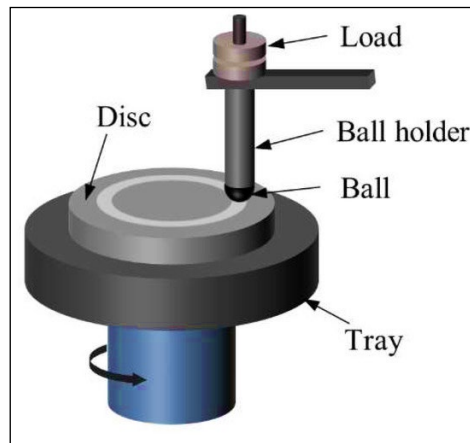


Fig. 2. Pin-on-disc wear testing apparatus.

Compressive strength test

The compressive strength of sintered Nb–1 wt% Zr–x Al_2O_3 composites was measured to determine their load-bearing capacity in uniaxial compression, an important criterion for biomedical implant materials. Subsequently, the 10 mm-diameter and 20 mm-high cylindrical specimens were machined to the standard dimensions for metallic compression testing. Specimens were also refined at their ends by grinding to ensure parallelism and uniform load distribution before testing. Compressive testing. The compression tests were performed at the College of Materials Engineering labs, University of Babylon, at room temperature using a computerized universal testing machine (model: WDW-200, 200 kN capacity). The crosshead move rate was fixed at 0.5 mm min^{-1} throughout the test to ensure quasi-static loading and minimize dynamic effects. Applied compressive load was monitored as the specimens failed or developed significant plasticity.

The compressive strength (σ_c) was calculated using the maximum applied load ($F_{\max}$) divided by the original cross-sectional area (A) of the specimen, according to Equation 2:

$$\sigma_c = \frac{F_{\max}}{A} \quad (2)$$

Elastic modules

The non-destructive ultrasonic pulse velocity method, commonly used for the evaluation of elastic properties of powder metallurgy and biomedical materials, was chosen to assess the processing effects on the elastic modulus of the sintered Nb–1 wt% Zr–x Al₂O₃ composites (Nie et al., 2014). This approach allows a reliable determination of elastic stiffness, accounting for microstructure, porosity, and reinforcement content. Room-temperature ultrasonic measurements were conducted using a pulse–echo ultrasonic testing system equipped with longitudinal and shear wave transducers operating at the corresponding frequencies, providing sufficient signal penetration and resolution. A coupling medium was used between the transducer and the specimen to reduce signal loss. Three replicate specimens for each composition were tested, and three replicate measurements of longitudinal (VL) and transverse wave velocities (VT) were obtained to ensure repeatability. Mean velocity values were used in further computations. The ultrasonic examination was performed according to commonly used techniques for determining the elastic properties of metallic materials, as outlined in ASTM E494-25. The specimen size and surface finish were accurately controlled so that time-of-flight measurements are as precise as possible and wave propagation is homogeneous.

Poisson's ratio (ν) was calculated from the measured ultrasonic velocities using Equations 3 and 4:

$$\nu = \frac{1 - 2 \left(\frac{V_T}{V_L} \right)^2}{2 - 2 \left(\frac{V_T}{V_L} \right)^2} \quad (3)$$

The elastic modulus (E) was then determined according to:

$$E = \frac{V_L^2 \rho (1 + \sigma)(1 - 2\sigma)}{(1 - \sigma)} \quad (4)$$

Whereas

- ν : Poisson's proportion
- VT : Shear (transverse) velocity (m/s)
- VL : Longitudinal velocity (m/s)
- E : Modulus of elasticity (GPa)
- ρ : Density (kg/m³)

Porosity measurement

The porosity of the compacted and sintered Nb–1 wt% Zr–xAl₂O₃ specimens was determined in accordance with (ASTM B962-23) using Archimedes' principle. For each specimen, three masses were measured: the dry mass in air (M_e), the saturated mass in air (M_s) after immersion in distilled water to fill open pores, and the apparent mass while suspended in water (M_i).

The bulk density (ρ_{bulk}) of the sintered specimens was calculated using the following relation:

$$\rho_{bulk} = \frac{M_d}{M_s - M_i} \quad (5)$$

Whereas $M_s - M_i$ represents the volume of displaced water, assuming a water density of 1 g/cm³ at room temperature.

The theoretical density (ρ_{th}) of the Nb–Zr–Al₂O₃ composites was calculated using the rule of mixtures according to Equations 5 to Equation 7:

$$\rho_{th} = \left(\sum \frac{w_i}{\rho_i} \right)^{-1} \quad (6)$$

Whereas w_i and ρ_i are the weight fraction and theoretical density of each constituent phase (Nb, Zr, and Al₂O₃), respectively.

The total porosity percentage (P%) was then determined by comparing the measured bulk density with the theoretical density as follows:

$$P(\%) = \left(1 - \frac{\rho_{bulk}}{\rho_{th}} \right) \times 100 \quad (7)$$

For each composition, three specimens were tested, and the reported porosity values represent the average of the measured results. This method provides a reliable quantitative assessment of densification behavior in powder metallurgy materials and enables direct correlation between porosity and the mechanical and elastic properties of the investigated composites.

Results and Discussion

X-ray diffraction for powders

The XRD pattern of the raw niobium (Nb) powder (Fig. 3) exhibits sharp, intense diffraction peaks, with the dominant reflection corresponding to the (110) plane of the body-centered cubic (BCC) Nb phase, accompanied by minor peaks from higher-index planes. These peaks match the reference pattern in the ICDD card no. 01-089-2450, confirming the high crystallinity and phase purity of the starting Nb powder.

Following sintering at 1200 °C, the base Nb–1 wt% Zr alloy (Fig. 4) retained the BCC crystal structure, with observable peak broadening. This broadening can be attributed to solid-state diffusion between Nb and Zr, which promotes lattice distortion and potential nanoscale grain refinement. Residual internal stresses generated during sintering may also contribute to the observed peak broadening. Such microstructural changes are consistent with diffusion-driven solid-solution formation in Nb–Zr systems, as reported in prior studies on powder metallurgy-fabricated refractory alloys (Aboulkhair et al., 2016).

The discrepancy between the XRD patterns in Figs. 5 and 6 is justified by instrumental detection limits of X-ray diffraction on the one hand and by different apex values, percentage dispersion, and volume fraction of Al₂O₃ reinforcement on the other hand. In the Nb–1 wt% Zr–5.5 wt% Al₂O₃ composite (Fig. 5), the Al₂O₃ content is low, and ceramic particles are nicely distributed within the Nb–Zr metallic matrix. The diffraction intensity of the Al₂O₃ peaks is below the instrument detection limit and is masked by the body-centered cubic Nb–Zr solid solution's major diffraction peaks. Thus, in the XRD pattern, only the matrix-related peaks are significantly observed. In contrast, the high-volume fraction of ceramic (Fig. 6) provides a concomitant increase in diffracting Al₂O₃ crystallites such that weak but discernible diffraction patterns are observable from the alumina. Notably, no further peaks that can be attributed to intermetallic compounds or reaction products are observed in both patterns, indicating that Al₂O₃ remains chemically stable and inert during the sintering process at 1200 °C and does not react with the Nb–Zr matrix. Thus, the

discrepancy between Figs. 5 and 6 does not arise from phase incoherence or experimental errors but rather reveals that XRD is sensitive to reinforcement content and dispersion, as well as particle size, as commonly accepted by detecting low-volume ceramic phases in metal–ceramic composites.

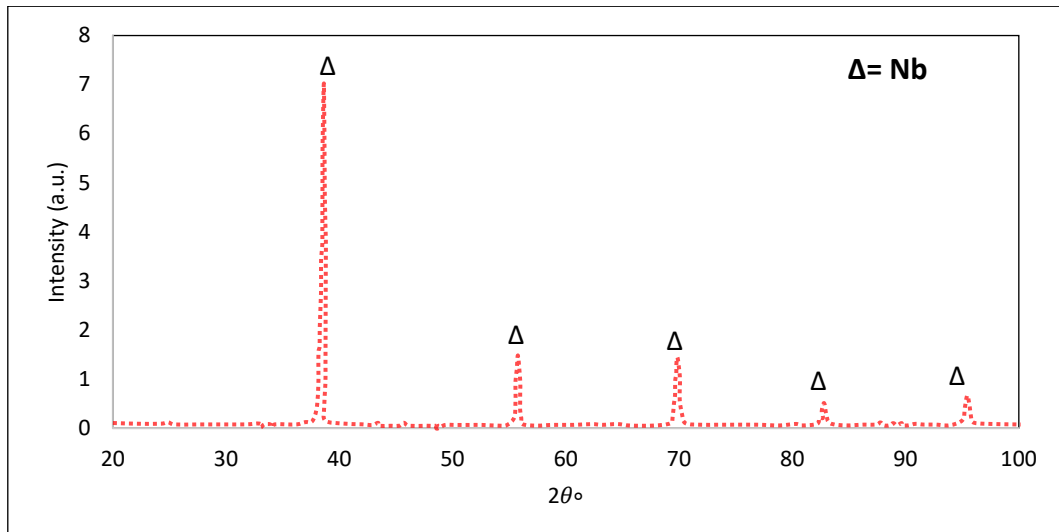


Fig. 3. XRD patterns for Nb powder.

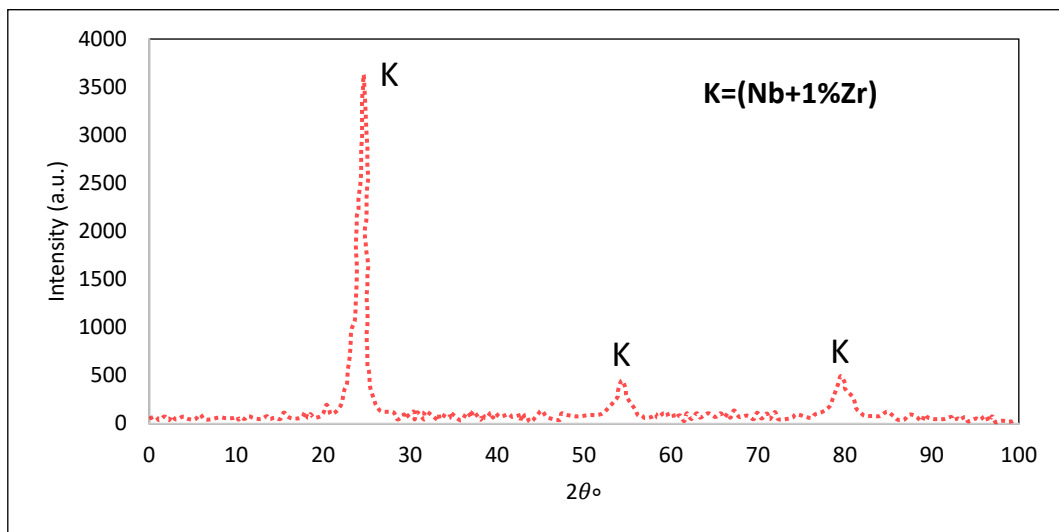


Fig. 4. XRD of base alloy (Nb-1%Zr) after sintering.

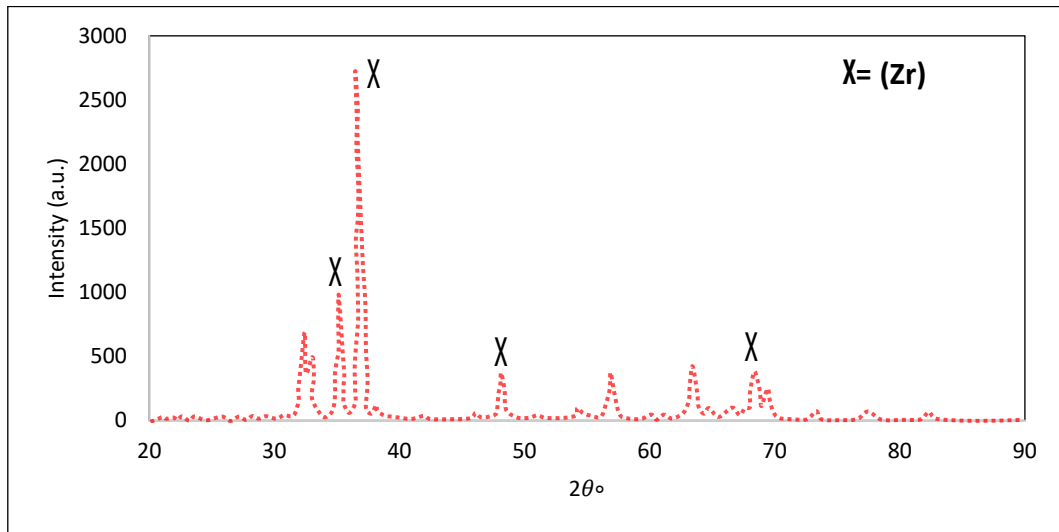


Fig. 5. XRD for (Nb-1%Zr-5.5% Al_2O_3) alloy after sintering.

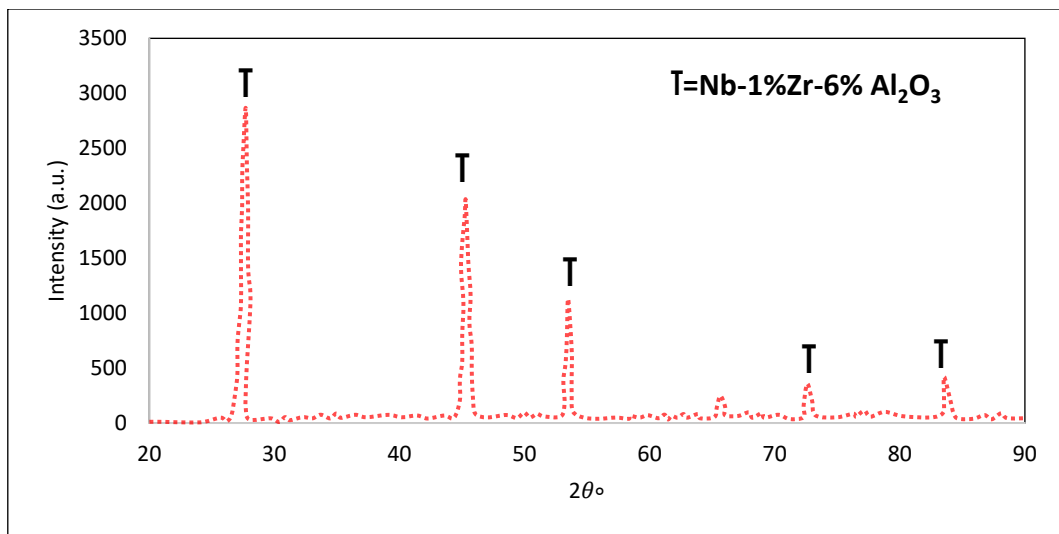


Fig. 6. XRD of (Nb-1%Zr-6% Al_2O_3) alloy after sintering.

Porosity of sintered alloys

The relationship between porosity and the Al_2O_3 addition in sintered Nb–1 wt% Zr alloys is shown in Fig. 7. At lower reinforcement contents (≤ 0.5 wt% Al_2O_3), a significant drop in porosity is observed, likely due to greater solid-particle filling and rearrangement during compaction. The smaller alumina particles fill the intergranular regions between the coarser Nb and Zr grains, thereby increasing the green density prior to sintering. Porosity increases gradually with increasing ceramic loadings above 0.5 wt% Al_2O_3 . This tendency is proposed to be related to the intrinsically non-sinterable behavior of alumina at the adopted sintering conditions, which disrupts particle contact continuity and impedes the formation of diffusion necks. The presence of the ceramic phase acts as a physical barrier to mass transfer, leading to continued incomplete densification. This behavior corresponds to densification in oxide-reinforced P/M alloys, in

which excessive ceramic content impairs both sinterability and matrix cohesiveness (German, 2014). From a biomedical standpoint, porosity control is of extreme importance, as it directly affects the mechanical properties and osseointegration of the implant material. The remaining porosity at the lowest Al_2O_3 levels is associated with improved strength and wear resistance. However, higher porosities at higher Al_2O_3 levels can impact mechanical stability, even though they are beneficial for bone ingrowth. As such, optimizations of reinforcement content are required to balance densification, mechanical performance, and biological functionality.

The correlation between porosity and Al_2O_3 content reveals a key virtuous circle of trade-offs among densification, mechanical properties, and biological performance in the Nb–Zr composites. Fine Al_2O_3 particles increase packing efficiency and diffusion bonding, reducing porosity and resulting in higher strength and wear resistance at low reinforcement levels. In contrast, a high Al_2O_3 content acts as a sintering inhibitor due to its inert behavior; residual porosity increases, and interfacial bonding becomes weaker, resulting in reduced mechanical stability. Still, controlled porosity is beneficial for osseointegration and for reducing modulus. Consequently, optimizing the reinforcement material content is crucial to achieve a satisfactory microstructure that meets structural and biomedical requirements.

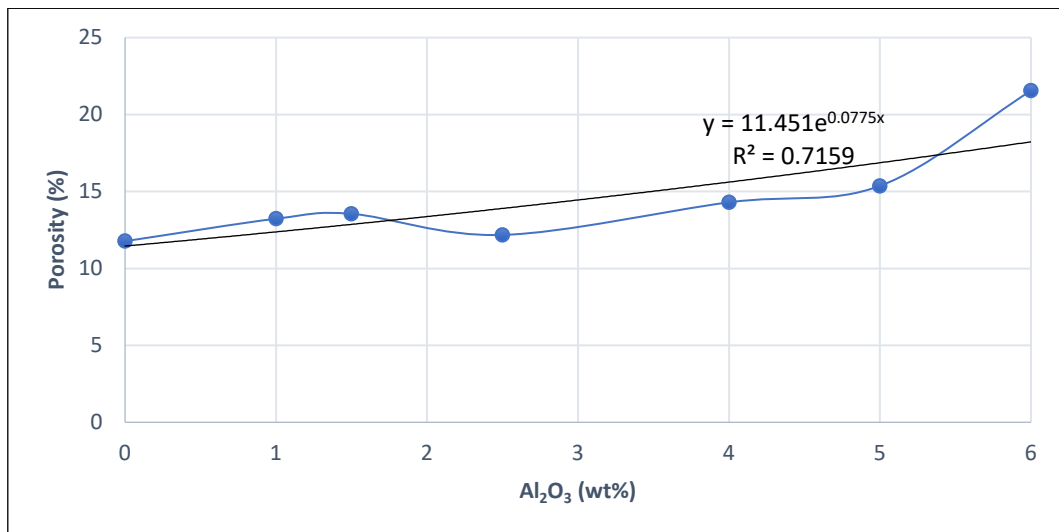


Fig. 7. Impact of (Al_2O_3) amount on the (Nb-1%Zr) alloys porosity.

Microstructure representation

The etched optical micrographs for the sintered Nb–1 wt% Zr– $x\text{Al}_2\text{O}_3$ alloys are provided in Fig. 8. The micrographs show a predominantly homogeneous grain structure, with Al_2O_3 particles evenly dispersed throughout the metal matrix. The presence of these inert, non-deformable ceramic particles at grain boundaries significantly impedes sintering-induced grain growth, as explained by the Zener pinning mechanism. Second-phase particles in this mechanism form a drag force on moving grain boundaries, inhibit their movement, and help form a finer, more stable microstructure. The obtained grain refinement is significant for improving mechanical properties. The finer the grains, the greater the total grain boundary area (which opposes dislocation motion), resulting in greater hardness and strength through the Hall–Petch relation. The uniform distribution of Al_2O_3 also reduces stress concentration and ensures more uniform load transfer between the alloy matrix and the reinforcement particles. Biomechanically, controlled microstructural refinement not only improves wear resistance and load-bearing capacity but also results in an elastic modulus closer to that of cortical bone, potentially leading to stress shielding. The interplay

between microstructure control and mechanical compatibility is thus an important issue for the long-term performance of implants (Kamarád et al., 2014).

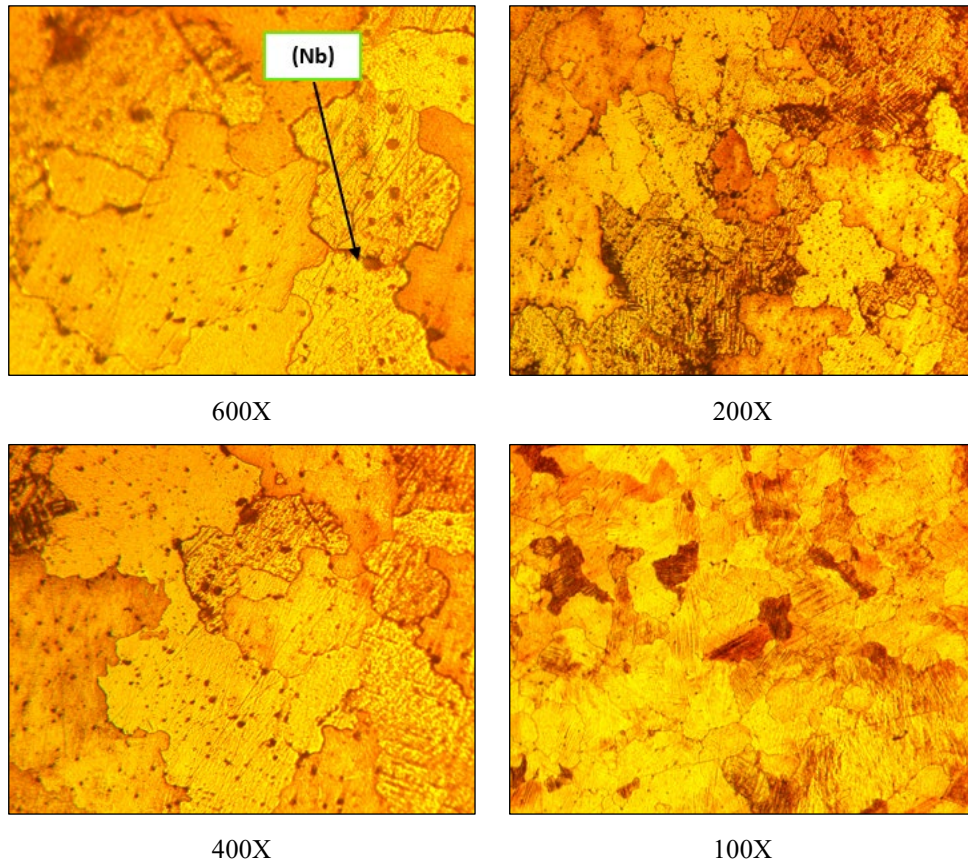


Fig. 8. Microstructure after sintering for etched alloys with various magnifications.

Mechanical tests results

Hardness

As illustrated in Fig. 9, the Brinell hardness of Nb–1 wt% Zr alloys significantly increased with increasing Al_2O_3 loadings. It showed an improvement of more than 90% at 6 wt% reinforcement compared to the non-reinforced alloy. This improvement is attributed to a combination of strengthening mechanisms. First, dispersion strengthening is due to hard, inert Al_2O_3 particles, which physically restrict dislocation motion in the metallic matrix. Secondly, it is known that thermal-expansion-mismatch strengthening arises from the difference in the coefficients of thermal expansion between ceramic (reinforcement) inclusions and the Nb–Zr matrix, leading to a high concentration of dislocations at particle–matrix interfaces (Bartolomé et al., 2008). Third, microstructural refining enhances grain boundary strengthening, as Al_2O_3 particles obstruct grain boundary migration via Zener pinning, thereby enlarging the barrier area and hindering dislocation slip, according to the Hall–Petch equation. These results support previous reports by Dasgupta (2012) on Al– Al_2O_3 composites, in which oxide dispersion contributed significantly to increased hardness through similar strengthening mechanisms. Biomedically, higher hardness is beneficial for load-bearing implants, directly improving wear resistance during joint articulation and cyclic contact, thereby

prolonging implant service life. Increased hardness, along with the other reported mechanical enhancements in this work, shows that Al_2O_3 reinforcement has the potential to tune Nb–Zr alloys for orthopedic and dental applications.

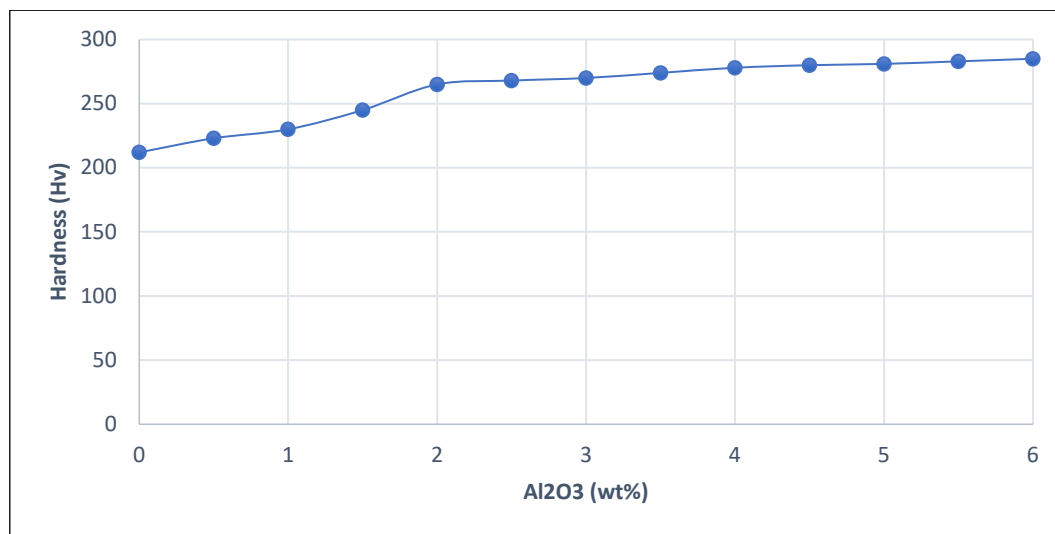


Fig. 9. Effect of Al_2O_3 on hardness.

Elastic modules

The elastic properties can be determined, and the value of the Elastic modulus of the pure Nb–1 wt% Zr composite (Table 4) showed that the elastic modulus exhibited a significant and gradual decrease with the addition of Al_2O_3 , showing it was reduced from 70.6 GPa for the non-reinforced alloy to 12.2 GPa at 6 wt%, equal to an 84% reduction. The interaction of porosity evolution, interface compliance, and load-transfer inefficiency essentially drives this behavior. The addition of fine Al_2O_3 particles above 0.5 wt%, however, interferes with metallic–particle contact during sintering as the ceramic is incapable of being sintered, resulting in hindrance in diffusion neck growth and higher residual porosity—known to decrease stiffness for powder metallurgy materials consistent with the Gibson–Ashby model for cellular solids that relates relative density to elastic modulus (German, 2014). Furthermore, although bulk alumina has a high intrinsic modulus (380 GPa), its discontinuous distribution in the Nb–Zr matrix and the resulting particle–matrix interfaces create localized regions of elastic compliance that effectively reduce stiffness through strain accommodation, as observed in similar metal–ceramic composites (Chawla, 2012). For higher reinforcement contents, particle agglomeration and increased particle–particle contact degrade elastic load transfer to a greater extent, as predicted by percolation theory in discontinuously reinforced composites. The grain-refining effect caused by Zener pinning increases hardness and strength. However, it modestly increases the volume of grain boundary regions, which are more compliant than the crystalline interior and therefore contribute slightly to the softening (Gladman, 2002). Significantly, the previous assumption based on Vegard's law and atomic radii does not hold, since Al_2O_3 remains an inert phase with poor solubility in Nb–Zr at the sintering conditions applied; hence, no substantial lattice expansion due to substitutional solute can be attributed. From a biomedical standpoint, this intentional reduction in elastic modulus is favorable because it brings the stiffness closer to that of cortical bone (10–30 GPa) and avoids stress shielding, an important cause of peri-implant bone resorption and long-term failure in load-bearing implants (Long & Rack, 1998; Niinomi, 2002). As a result, the property profile of the Nb–Zr– Al_2O_3 system high wear resistance, significant hardness, and biomechanically compatible modulus render it highly promising as a next-generation orthopedic and dental implant material.

Table 4. The modulus of elasticity of the produced alloys

Al ₂ O ₃ %	Modulus of elasticity (GPa)	Improvement %
0	70.55	/
0.5	69.441	1.56
1	65.74	7.95
1.5	63.654	10.91
2	44.27	38.47
2.5	37.45	48.17
3	34.81	51.92
3.5	27.36	59.68
4	25.93	61.71
4.5	24.45	65.41
5	21.615	70.68
5.5	15.87	78.86
6	12.22	84.04

Wear rate

Figs. 10 to 13 show the wear rate at different loads and durations. The presence of Al₂O₃ reduced the wear rate by 92.5% compared with the base alloy (Table 5). The increase in wear resistance is mainly attributed to the enhanced hardness, improved load distribution, and barrier effect of Al₂O₃ particles, which hamper surface deformation and direct material loss under a sliding environment. Findings on dry sliding wear of ceramic-reinforced metal matrix composites have also been consistent with these observations by Zhang et al. (2011), which corroborated the effect of oxide dispersions on reducing COF and enhancing surface stability.

It can be observed from Figs. 10 to 13 that as Al₂O₃ content increases, a remarkable decrease (maximum = 92.5%) in wear rate is observed for Nb–1 wt% Zr–xAl₂O₃ composites as compared to the base alloy. The improvement is mainly due to dispersion strengthening, higher surface hardness, and the barrier effect of hard Al₂O₃ particles, which effectively inhibit plastic deformation and material removal during sliding. Nevertheless, a significant rise in wear rate is seen after the first 5 min under the increased applied load (25 N). This behavior could be linked to the decomposition of the tribolayer formed during the initial period and to a shift from mild to severe wear. In the initial period, surface polishing and oxide layer formation decrease friction and wear; in contrast, continued sliding on a given contact under higher load increases the temperature of the contact area, which promotes microfracture of asperities, delamination, and third-body abrasion initiated by debris accretion. As a result, the synergistic effect of thermal softening, a larger real contact area, and an unstable tribofilm causes accelerated material removal at loads greater than 5 min.

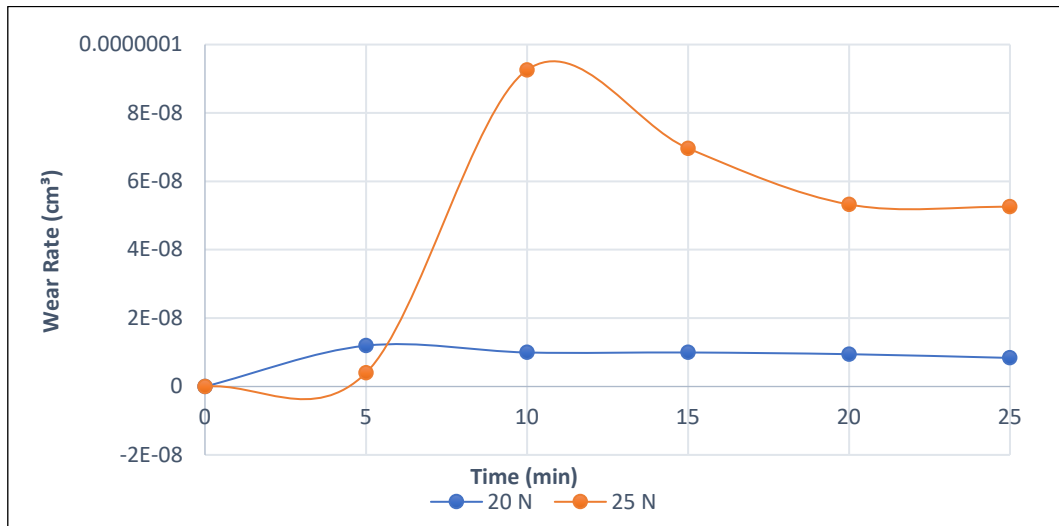


Fig. 10. Wear rate against time for base alloy under (20 & 25) N.

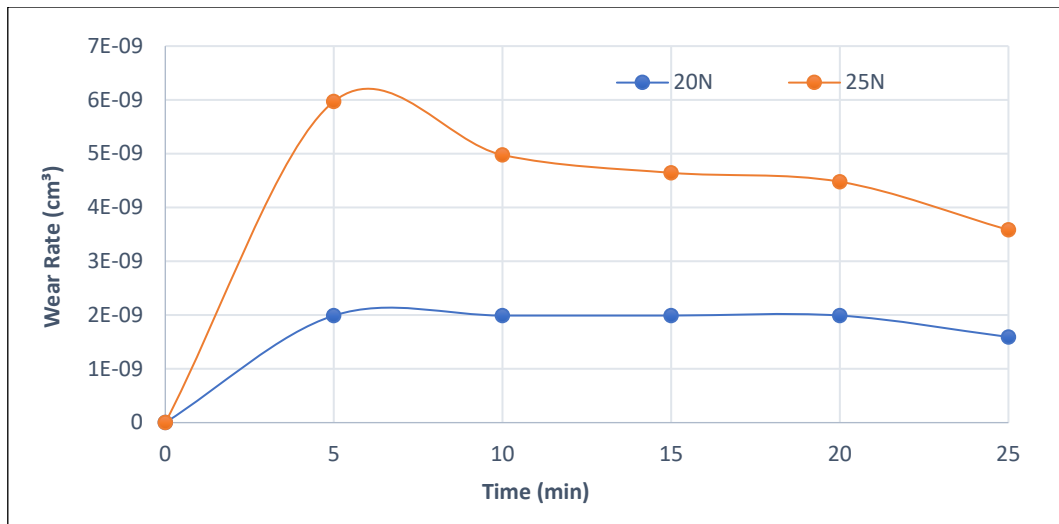


Fig. 11. Wear rate against time for (Nb-1%Zr-5% Al_2O_3) alloy under (20 & 25) N.

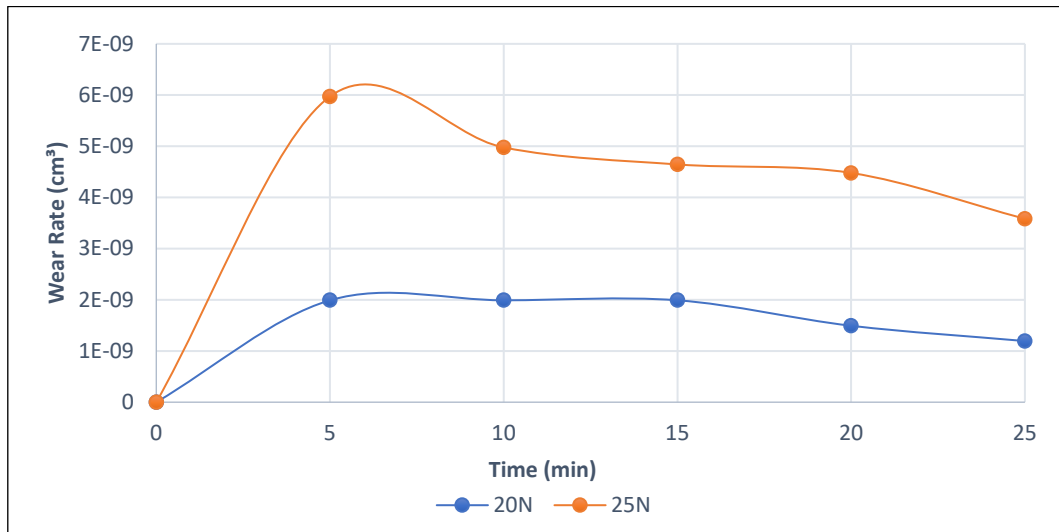


Fig. 12. Wear rate against time for (Nb-1%Zr-5.5% Al₂O₃) alloy under (20 & 25) N.

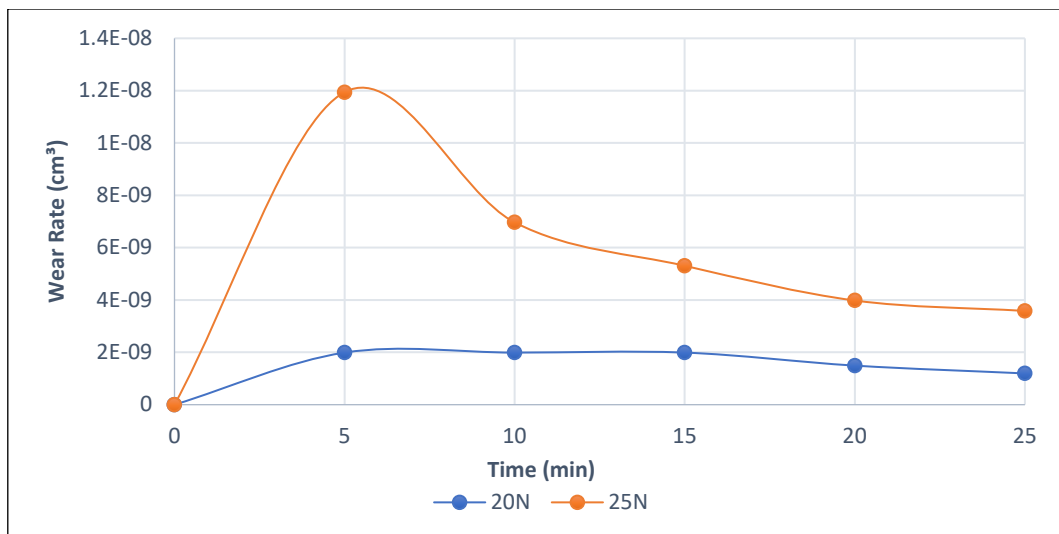


Fig. 13. Wear rate against time for (Nb-1%Zr-6% Al₂O₃) alloy under (20 & 25) N.

Table 5. Wear rate and improvement %

Seq.	Alloy	Wear Rate (cm³)	Improvement in Wear Rate %
1	Base (Nb-1%Zr)	4.26E-08	/
2	(B+0.5% Al ₂ O ₃)	1.07E-08	74.77
3	(B+1% Al ₂ O ₃)	6.37E-09	85.047
4	(B+1.5% Al ₂ O ₃)	3.18E-09	92.52
5	(B+2% Al ₂ O ₃)	3.18E-09	92.52
6	(B+2.5% Al ₂ O ₃)	3.58E-09	91.59
7	(B+3% Al ₂ O ₃)	6.77E-09	84.11

8	(B+3.5% Al ₂ O ₃)	3.98E-09	90.65
9	(B+4% Al ₂ O ₃)	3.58E-09	91.59
10	(B+4.5% Al ₂ O ₃)	3.58E-09	91.59
11	(B+5% Al ₂ O ₃)	3.58E-09	91.59
12	(B+5.5% Al ₂ O ₃)	3.58E-09	91.59
13	(B+6% Al ₂ O ₃)	3.58E-09	91.59

Compressive strength

As shown in Fig. 14 and Table 6, the compressive strength increased from 134 to 234 MPa with the addition of Al₂O₃ (6 wt%), corresponding to a 74.6% increase. The strengthening is expected to result from the combined effects of solid-solution strengthening, load transfer from the matrix to ceramic particles, and densification-induced microstructure refinement. Furthermore, the inverse relationship between porosity and strength is consistent with the Gibson–Ashby model for cellular solids, which predicts that reducing porosity improves load-bearing capacity (Lee, 2000). A similar mechanical behavior was also noticed for Ti–Al₂O₃ composites synthesized by powder metallurgy (Kaykilarli et al., 2024).

Table 6. Effect of Al₂O₃ contents on alloy properties

Al ₂ O ₃ %	Porosity %	Compressive Strength (MPa)	Improvement in Compressive Strength (%)
0	25.96	134	-
0.5	22.17	137	10.42
1	20.85	140	20.83
1.5	18.78	143	22.92
2	16.4	150	29.17
2.5	15.2	155	32.1
3	13.45	158	34.17
3.5	13.23	163	35.42
4	11.77	170	37.5
4.5	10.23	185	40.41
5	8.32	190	41.67
5.5	5.5	215	42.92
6	4.28	234	44.17

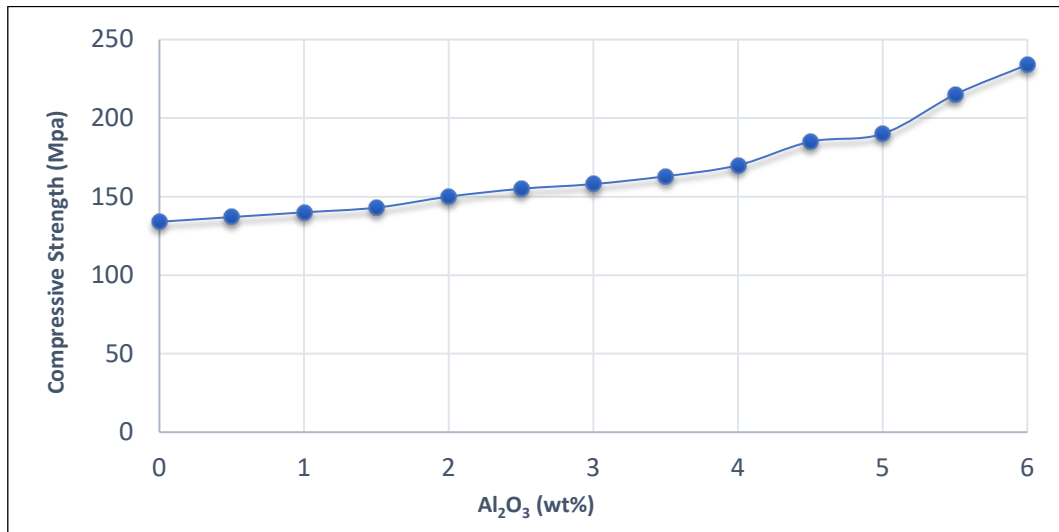


Fig. 14. Compressive strength test results for various Al₂O₃.

Conclusion

In this work, it was shown that alumina (Al₂O₃)- reinforced Nb–1 wt% Zr alloys prepared by powder metallurgy can indeed improve the mechanical and tribological properties of these materials and modulate their elastic modulus for biomedical applications.

- Sintering at 1200 °C for 6 h produced a dense, multi-phase microstructure with Al₂O₃ particles distributed homogeneously to prevent the grain growth by Zener pinning. Similarly, the porosity showed a non-linear variation—first decreased up to 0.5 wt% Al₂O₃ with enhanced packing and then increased at higher contents due to the ceramic's non-sinterable nature.
- The best combination of properties was obtained at 6 wt% Al₂O₃, with enhancement in the compressive strength from 134 to 234 MPa (74.6%), over 90% improvement in hardness, and up to a 92.5% reduction in wear rate under a load of 25 N as compared to the unreinforced alloy.
- Meanwhile, the elastic modulus decreased from 70.6 GPa to 12.2 GPa (84% reduction), like that of cortical bone, potentially minimizing the risk of stress shielding with load -bearing implants.

Acknowledgement

The authors would like to thank the Ministry of Higher Education, University of AL-Qadisiyah, University of Babylon and Imam Ja'afar Al-Sadiq University. This work was conducted in the laboratory at the University of Babylon.

Funding

No external funding.

Conflict of Interest

The authors declare that no conflict of interest.

Authors' Contribution

Salih Jawad Hamza conceived the research idea, designed the experimental methodology, and conducted experimental work. Haydar H. J. Jamal AlDeen carried out the tests results analysis and Supervisor. Zainab Al-Khafaji performed manuscript preparation and critical revision of the final manuscript.

Data Availability

All data generated or analysed during this study are included in this published article.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of University of Babylon.

Reference

- Abed, K. M., Radhi, N. S., Jasim, A. H., Al-Khafaji, Z. S., Radhi, S., & Hussien, S. A. (2022). Study the effect of adding zirconia particles to nickel–phosphorus electroless coatings as product innovation on stainless steel substrate. *Open Engineering*, 12(1), 1038–1045. <https://doi.org/10.1515/eng-2022-0364>
- Aboulkhair, N. T., Maskery, I., Tuck, C., Ashcroft, I., & Everitt, N. M. (2016). Improving the fatigue behaviour of a selectively laser melted aluminium alloy: influence of heat treatment and surface quality. *Materials & Design*, 104, 174–182. <https://doi.org/10.1016/j.matdes.2016.05.041>
- Al-khafaji, Z. S., Radhi, N. S., & Mohson, S. A. (2018). Preparation and modelling of composite materials (polyester-alumina) as implant in human body. *International Journal of Mechanical Engineering and Technology*, 9(4), 468–478.
- Angelo, P. C., Subramanian, R., & Ravisankar, B. (2022). *Powder metallurgy: science, technology and applications*. (2nd Ed.). PHI Learning.
- Ardila, M. A. N., Labiapari, W. S., & Mello, J. D. B. (2017). The influence of crystallographic texture and niobium stabilisation on the corrosion resistance of ferritic stainless steel. *Materials Research*, 20(3), 576–583. <https://doi.org/10.1590/1980-5373-MR-2016-0622>

- American Society for Testing and Materials. (2023). Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes Principle (ASTM-B962). ASTM International.
- American Society for Testing and Materials. (2025). Standard Practice for Measuring Ultrasonic Velocity in Materials by Comparative Pulse-Echo Method (ASTM-E494). ASTM International.
- Bartolomé, J. F., Beltrán, J. I., Gutiérrez-González, C. F., Pecharromán, C., Muñoz, M. C., & Moya, J. S. (2008). Influence of ceramic–metal interface adhesion on crack growth resistance of ZrO₂–Nb ceramic matrix composites. *Acta Materialia*, 56(14), 3358–3366. <https://doi.org/10.1016/j.actamat.2008.03.021>
- Bartolomé, J. F., Moya, J. S., Couceiro, R., Gutiérrez-González, C. F., Guitián, F., & Martínez-Insua, A. (2016). In vitro and in vivo evaluation of a new zirconia/niobium biocermet for hard tissue replacement. *Biomaterials*, 76, 313–320. <https://doi.org/10.1016/j.biomaterials.2015.10.058>
- Chawla, K. K. (2012). Metal matrix composites. *Composite Materials: Science and Engineering* (pp. 197–248). Springer.
- Christensen, M., Wolf, W., Freeman, C. M., Wimmer, E., Adamson, R. B., Hallstadius, L., Cantonwine, P. E., & Mader, E. V. (2014). Effect of alloying elements on the properties of Zr and the Zr–H system. *Journal of Nuclear Materials*, 445(1–3), 241–250. <https://doi.org/10.1016/j.jnucmat.2013.10.040>
- Christien, F., & Barbu, A. (2009). Cluster dynamics modelling of irradiation growth of zirconium single crystals. *Journal of Nuclear Materials*, 393(1), 153–161. <https://doi.org/10.1016/j.jnucmat.2009.05.016>
- Dasgupta, R. (2012). Aluminium alloy-based metal matrix composites: a potential material for wear resistant applications. *International Scholarly Research Notices*, 2012(1), 594573. <https://doi.org/10.5402/2012/594573>
- Dotta, A. L. B., Serafini, F. L., Ordoñez, M. F. C., Machado, I. F., & Farias, M. C. M. (2021). Mechanical and tribological properties of spark plasma sintered Nb–Al₂O₃ composites. *Ceramics International*, 47(5), 6800–6812. <https://doi.org/10.1016/j.ceramint.2020.11.023>
- Ells, C. E. (1974). Deformation of irradiated zirconium-niobium alloys. *Zirconium in Nuclear Applications*. ASTM International. <https://doi.org/10.1520/STP32123S>
- German, R. (2014). *Sintering: from empirical observations to scientific principles*. Butterworth-Heinemann.
- Gibson, L. J. (2003). Cellular solids. *MRS Bulletin*, 28(4), 270–274. <https://doi.org/10.1557/mrs2003.79>
- Gladman, T. (2002). *The physical metallurgy of microalloyed steels*. Taylor & Francis.
- Griffiths, M. (1988). A review of microstructure evolution in zirconium alloys during irradiation. *Journal of Nuclear Materials*, 159, 190–218. [https://doi.org/10.1016/0022-3115\(88\)90093-1](https://doi.org/10.1016/0022-3115(88)90093-1)
- Hanawa, T., & Nomura, N. (2022). Zirconium and zirconium alloys for biomedical use. *Advances in Materials Science Research*, 52, 107–144. Nova Science Publisher.
- Hidalgo, A. A., Frykholm, R., Ebel, T., & Pyczak, F. (2017). Powder metallurgy strategies to improve properties and processing of titanium alloys: a review. *Advanced Engineering Materials*, 19(6), 1600743. <https://doi.org/10.1002/adem.201600743>
- Huang, S., Wu, H., Zhu, H., & Xie, Z. (2021). Effect of niobium addition upon microstructure and tensile properties of CrMnFeCoNi_x high entropy alloys. *Materials Science and Engineering: A*, 809, 140959. <https://doi.org/10.1016/j.msea.2021.140959>

- Hussein, E. Y., Al-Murshdy, J. M. S., Radhi, N. S., & Al-Khafaji, Z. (2024). Surface modification of titanium alloy by titania / silver multilayers coating for biomedical application. *Journal of Advanced Research in Micro and Nano Engineering*, 20(1), 66–78. <https://doi.org/10.37934/armne.20.1.6678>
- Jack, T. A., & Szpunar, J. (2023). Effect of Nb-induced microstructure on pipeline steel corrosion and stress corrosion cracking performance in acidic environment. *Corrosion Science*, 218, 111196. <https://doi.org/10.1016/j.corsci.2023.111196>
- Jasim, A. H., Joudi, W. M., Radhi, N. S., & Saud, A. N. (2020). Mechanical properties and wear characteristics of (aluminum-zinc oxide) metal matrix composite prepared using the stir casting process. *Materials Science Forum*, 1002, 175–184. <https://doi.org/10.4028/www.scientific.net/MSF.1002.175>
- Kamarád, J., Albertini, F., Arnold, Z., Fabbri, S., & Kaštil, J. (2014). Extraordinary magnetic and structural properties of the off-stoichiometric and the Co-doped Ni₂MnGa Heusler alloys under high pressure. *Acta Materialia*, 77, 60–67. <https://doi.org/10.1016/j.actamat.2014.06.011>
- Kaykilarli, C., Uzunsoy, D., & Yeprem, H. A. (2024). Role of process control agent in the production of Al₂O₃-reinforced titanium matrix composites. *Ceramics International*, 50(9), 16452–16462. <https://doi.org/10.1016/j.ceramint.2024.02.130>
- Liu, X., Wang, H., Liu, Y., Wang, C., Song, Q., Cui, H., Zhang, C., & Huang, K. (2021). The effect of Nb content on microstructure and properties of laser cladding 316L SS coating. *Surface and Coatings Technology*, 425, 127684. <https://doi.org/10.1016/j.surfcoat.2021.127684>
- Long, M., & Rack, H. J. (1998). Titanium alloys in total joint replacement - a materials science perspective. *Biomaterials*, 19(18), 1621–1639. [https://doi.org/10.1016/S0142-9612\(97\)00146-4](https://doi.org/10.1016/S0142-9612(97)00146-4)
- Nam, N. D., & Kim, J. G. (2010). Effect of niobium on the corrosion behaviour of low alloy steel in sulfuric acid solution. *Corrosion Science*, 52(10), 3377–3384. <https://doi.org/10.1016/j.corsci.2010.06.010>
- Nie, L., Zhan, Y., Hu, T., Chen, X., & Wang, C. (2014). β -Type Zr–Nb–Ti biomedical materials with high plasticity and low modulus for hard tissue replacements. *Journal of the Mechanical Behavior of Biomedical Materials*, 29, 1–6. <https://doi.org/10.1016/j.jmbbm.2013.08.019>
- Niinomi, M. (2002). Recent metallic materials for biomedical applications. *Metallurgical and Materials Transactions A*, 33(3), 477–486. <https://doi.org/10.1007/s11661-002-0109-2>
- Radhi, N. S., & Al-Khafaji, Z. (2018). Investigation biomedical corrosion of implant alloys in physiological environment. *International Journal of Mechanical and Production Engineering Research and Development*, 8(4), 247–256. <https://doi.org/10.24247/ijmpredaug201827>
- Radhi, N. S., Jasim, A. H., Al-Khafaji, Z. S., & Falah, M. (2023). Investigation of hematite nanoparticles according to mechanical characteristics of aluminium matrix composite. *Nanosistemi, Nanomateriali, Nanotehnologii*, 21(4), 769–778. <https://doi.org/10.15407/nnn.21.04.769>
- Radhi, N. S., Marza, M., & Al-Khafaji, Z. S. (2020). Modification of nickel-phosphor electroless coatings by adding particles of zirconia. *Solid State Technology*, 63(2), 1179–1186.
- Radhi, N. S., Nattah, A. M., & Al-Khafaji, Z. S. (2024). Identify the effect of Fe₂O₃ nanoparticles on mechanical and microstructural characteristics of aluminum matrix composite produced by powder metallurgy technique. *Open Engineering*, 14(1), 20220519. <https://doi.org/10.1515/eng-2022-0519>
- Salih, E. M. S., & Al-Khafaji, Z. (2023). Effect of surface treatments by ultrasonic on NiTi biomaterials. *Academic Journal of Manufacturing Engineering*, 21(3), 77–81.

- Sallal, H. A., Mahboba, M. H., Radhi, M. S., Hanif, A., Al-Khafaji, Z. S., Ahmad, S., & Yaseen, Z. M. (2024). Effect of adding (ZrO₂-ZnO) nanopowder on the polymer blend (lamination and methyl vinyl silicone) in a hybrid nanocomposite material. *Journal of King Saud University-Science*, 36(2), 103061. <https://doi.org/10.1016/j.jksus.2023.103061>
- Sattar, S., Alaiwi, Y., Radhi, N. S., & Al-Khafaji, Z. (2023a). Numerical simulation for effect of composite coating (TiO₂ + SiO₂) thickness on steam turbine blades thermal and stress distribution. *Academic Journal of Manufacturing Engineering*, 21(4), 86-99.
- Sattar, S., Alaiwi, Y., Radhi, N. S., Al-Khafaji, Z., Al-Hashimi, O., Alzahrani, H., & Yaseen, Z. M. (2023b). Corrosion reduction in steam turbine blades using nano-composite coating. *Journal of King Saud University-Science*, 35(8), 102861. <https://doi.org/10.1016/j.jksus.2023.102861>
- Topping, M., Ungár, T., Race, C. P., Harte, A., Garner, A., Baxter, F., Dumbill, S., Frankel, P., & Preuss, M. (2018). Investigating the thermal stability of irradiation-induced damage in a zirconium alloy with novel in situ techniques. *Acta Materialia*, 145, 255–263. <https://doi.org/10.1016/j.actamat.2017.11.051>
- Wang, Z., Wu, J., Li, J., Wu, X., Huang, Y., & Li, X. (2018). Effects of niobium on the mechanical properties and corrosion behavior of simulated weld HAZ of HSLA steel. *Metallurgical and Materials Transactions A*, 49(1), 187–197. <https://doi.org/10.1007/s11661-017-4391-4>
- Zhang, D., Shen, Y., Xu, L., & Ge, S. (2011). Fretting wear behaviors of steel wires in coal mine under different corrosive mediums. *Wear*, 271(5–6), 866–874. <https://doi.org/10.1016/j.wear.2011.03.028>
- Zhang, N., Xia, C., Qin, J., Li, Q., Zhang, X., & Liu, R. (2022). Research progress of novel zirconium alloys with high strength and toughness. *Journal of Metals, Materials and Minerals*, 32(4), 23–36. <https://doi.org/10.55713/jmmm.v32i4.1526>



© 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC-SA) license (<https://creativecommons.org/licenses/by-nc-sa/4.0/>)