Nanoindentation studies and analysis of the mechanical properties of Ti-Nb$_2$O$_5$ based composites

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Abstract. In this study, nanoindentation tests were used to evaluate the mechanical properties of spark plasma sintered Ti based composites containing 5, 10 and 15 wt.% Nb$_2$O$_5$, targeted for potential use as biomedical material. Nanoindentation tests were performed on the samples using indenter loads of 20 and 100 mN, while the microstructures were characterized using scanning electron microscopy. It was noted that with increasing Nb$_2$O$_5$ wt.%, there is transition from the lamellar structure of pure Ti to fully bimodal structures for the Ti-10 wt.% Nb$_2$O$_5$ and Ti-15 wt.% Nb$_2$O$_5$ composites. The hardness (6.0–40.67 GPa (20 mN) and 2.4–12.03 GPa (100 mN)) and reduced elastic modulus (115–266.91 GPa (20 mN) and (28.05–96.873 GPa (100 mN)) of the composites increases with increase in the Nb$_2$O$_5$ content, attributed to contributions of load transfer from the Ti matrix to the relatively harder Nb$_2$O$_5$ particles, particle and dispersion strengthening mechanisms. The elastic recovery index also improved with increase in Nb$_2$O$_5$ content, while the inverse was noted with respect to plasticity index. The elastic strain to failure and yield pressure both improved with increase in Nb$_2$O$_5$ content, which suggests that the antiwear properties and resistance to impact loading equally improves with Nb$_2$O$_5$ addition.

Keywords: titanium based composites / niobium pentoxide / nanoindentation / microstructure / mechanical properties / biomedical applications

1 Introduction

Presently, Ti has gained glowing reputation as specialist structural material for high tech and sensitive applications such as in aerospace, automobile and biomedical applications [1,2], which is largely due to the spectrum of properties possessed by Ti and its alloys. Load bearing properties such as high specific strength and stiffness, reasonable ductility [3,4]; resistance to environment induced failures such as high corrosion resistance [5]; and biological qualities such as biocompatibility, osteointegration and osteoconductivity [6,7] are some of functional properties it combines, which has given it an edge over several conventional structural materials for specialized applications and environments.

In applications such as orthopedic biomedical applications, Ti and Ti alloys though possessing the closest combination of properties needed in load bearing orthopedic applications (strength, low elastic modulus, biocompatibility, and corrosion resistance), are deficient in adequate wear resistance [8,9]. This has been ascribed to the resistance to plastic shearing and the poor protection provided by the surface oxide sheathing [10]. Several problems have been identified to be consequent on this deficiency — namely, increased wear debris/particles from the implants during usage in the physiological environments of the body, which results in complications such as inflammation of the tissues within the vicinity of the implant, acute pains, infections and shortened life span of the implant due to accelerated loosening and failure of the implant, in vivo [11–13].

As a mitigation measure, the development of Ti based composites reinforced with biocompatible and refractory materials have been advanced [14]. The state-of-the-art shows that several metallic oxides (TiO$_2$, SrO$_2$, ZrO$_2$), phosphates, and hydroxyapatite have been investigated for potential use as reinforcement in Ti based composites for load bearing orthopedic applications [15–19]. The consideration of niobium pentoxide (Nb$_2$O$_5$) has been the subject of recent interest [20]. Niobium pentoxide has been reported to be biocompatible and still preserves the good

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biocompatibility qualities of the base metal Ti when added as reinforcement. Nonetheless, the mechanical properties and wear behaviour have not been extensively investigated, which could be instructive in appraising its all-round reliability for orthopedic applications; and also forecast the other potential applications of the Ti-Nb$_2$O$_5$ based composites.

The present study attempts to address this identified research gap by assessing some of the vital mechanical properties and antiwear properties of the Ti-Nb$_2$O$_5$ based composites processed by spark plasma sintering, using nanoindentation method. The SPS process was selected based on its optimal processing and sintering efficiency and improved material properties imparted over conventional powder metallurgy techniques [21–23]. The use of nanoindentation is equally justified as it has been established to be a more amenable and reliable method of assessing mechanical and related properties at small length/size scales than conventional mechanical testing methods [24,25]. The conventional mechanical testing methods often require bulk materials and standard geometries, which are not applicable for nanoindentation testing. Also, the nanoindentation testing is non-destructive as the microstructures are essentially not significantly distorted by testing. Furthermore, it is possible to generate data for the evaluation of a broad range of mechanical and related properties (such as the hardness, elastic modulus, the elastic index, plastic index, fracture toughness, visco-elastic properties, creep rate, and wear resistance), which can hardly be derived from a single conventional mechanical testing data analysis [26,27].

The corpus of literature on the use of nanoindentation indicate that there is hardly any work from authoritative sources which has adopted this technique to study the mechanical and related properties of Ti-Nb$_2$O$_5$ based composites, thus the motivation for this study.

2 Materials and methods

2.1 Materials

The starting powders utilized for this investigation were commercial pure titanium powder (APS 25 µm; 99.8% purity) and niobium pentoxide powder (APS 50 µm; 99.9% purity) used as the reinforcement. The CpTi and Nb$_2$O$_5$ powders were supplied by TLS Technik GmbH & Co and Sigma-Aldrich, respectively. The Cp Ti based composites were designed to contain 5, 10 and 15 wt.% niobium pentoxide powder as reinforcement, with the unreinforced Cp Ti serving as the control composition.

2.2 Method

2.2.1 Composite production

The rule of mixture was used to determine the amount of Cp Ti and Nb$_2$O$_5$ powders required for the designed compositions to be achieved. The powders were mixed using a Retch 100 PM planetary ball milling machine with milling time of 4 hours, and speed of 100 rev/mins, without balls. In order to avoid cold welding and reactions of the powders when milling, 10 mins relaxation time was adopted for each 20 mins milling. The morphologies of the starting and milled powders were assessed using JEOL JSM-7600 F field emission scanning electron microscope and are presented in Figure 1.

The sintering of the mixed powders was performed using an automated spark plasma sintering machine (model HHPD-25, FCT GmbH Germany) following standard spark plasma sintering working principles [26]. The Ti-Nb$_2$O$_5$ based composites were sintered in vacuum, using pressure, sintering temperature, heating rate, and sintering holding time of 50 MPa, 1100°C, 100°C/min, and 10 min, respectively before cooling to ambient temperature. For ease of removal, the powders were shielded from the die upper and lower punches, using graphite sheets. After sintering, graphite contamination on the products surfaces, were removed by sand blasting. The relative density of the Cp Ti and Ti-Nb$_2$O$_5$ composites were measured using Archimede’s principle [23]. The relative density of the samples on determination were within the range 99.57–99.94%.

2.2.2 Microstructural evaluation

For microstructural evaluation, Cp Ti and Ti-Nb$_2$O$_5$ based composites were metallographically prepared by grinding with silicon carbide papers, after which they were polished with colloidal silica suspension to flat mirror finished surfaces. Thereafter, etching of the polished samples was performed using Carpenter’s reagent. The microstructures of the Cp Ti and Ti-Nb$_2$O$_5$ based composites were then
examined, using JEOL Scanning Electron Microscope (FESEM, JSM-7600F).

2.2.3 Nanindentation
The nanindentation tests were performed with Anton Paar ultra-Nanoindenter (UNHT) fitted with a diamond Berkovich indenter. The indentation experiments were performed in accordance with ISO 14577 [23], with the test run under constant load to reach possible maximum depth. The indentation experiments were performed using the user defined profile, using two different loads of 20 and 100 mN to make the indents at a loading rate of 10 mN/min and held for 10 s. A minimum of five indents were made per sample and the average of these indentations served as basis for analyses of the data generated. The user defined profile (with the assistance of a built-in microscope which offers three sets of magnification), permits the selection and proper delineation of areas within the samples where the indents are to be made. The hardness and elastic modulus of the samples were evaluated using Oliver-Pharr analysis [28].

Basically, the hardness (H) is defined as [29]:

\[ H = \frac{P_{\text{max}}}{A_c}, \]

(1)

where \( P_{\text{max}} \) is the maximum load, and \( A_c \) is the projected area of the indentation.

The reduced elastic modulus (\( E_r \)), is considered as the elastic modulus which factors the elastic contributions of the specimen and the indenter tip, and is determined using the relation [1]:

\[ \frac{1}{E_r} = \frac{1 - \nu_s^2}{E_s} + \frac{1 - \nu_i^2}{E_i} \]

(2)

where, \( E_i \) and \( E_s \) are the elastic modulus of the indenter and sample, respectively; while \( \nu_i \) and \( \nu_s \) are the Poisson’s ratio of the indenter and the specimen, respectively.

From the hardness and reduced elastic modulus, the elastic strain to failure \( \varepsilon_{\text{failure}} \) and yield pressure \( P_y \) were determined using the expressions [24]:

\[ \varepsilon_{\text{failure}} = \frac{H}{E_r}, \]

(3)

\[ P_y = \frac{H^3}{E_r^2}. \]

(4)

The nanindentation load-displacement curves of the Cp Ti and Ti-Nb2O5 based composites subjected to indentation loads of 20 mN and 100 mN, respectively are presented in Figure 3. From Figure 3, it is observed that the Cp Ti and Ti-Nb2O5 based composites have similar loading and unloading behaviours that are smooth with no pop-in effect at indentation loads of 20 mN and 100 mN. It is seen that generally, the penetration depth increased with increase in indenter loading from 20 mN to 100 mN. However, the load-displacement curves show that the Cp Ti has a high penetration depth, that is, the indenter penetrates into the material easily, while the penetration depth decreased with increase in Nb2O5 content at indenter loads of 20 mN and 100 mN, respectively. The decrease in penetration depth with increase in Nb2O5 content is indicative of increased hardness of the Ti-Nb2O5 based composites. Similarly, the penetration-depth vs time profiles of the Cp Ti and Ti-Nb2O5 based composites when subjected to indentation of 20 mN and 100 mN, are shown in Figure 4. It was observed that after an initial rise, the penetration depth decreased with increasing time, and increase in Nb2O5 content. The reduced penetration depth, is an indication of decreased plastic deformability with increasing Nb2O5 content.

3 Results and discussion
3.1 Microstructural characterization
The SEM images of the Cp Ti and Ti-Nb2O5 based composites are presented in Figure 2. Figure 2a shows the lamellar (\( \alpha \)) structure of pure titanium (without the addition of the reinforcement) and the corresponding EDS (Fig. 2a1) which shows peaks of Ti and O2, with the O2 likely due to oxidation. It is noted that with increasing Nb2O5 wt.%, there is transition from the lamellar structure of pure Ti to a bimodal (\( \alpha + \beta \)) structure for the Ti-Nb2O5 based composites (Figs. 2(b1), 2(c1) and 2(d1)) that Nb and O2 were identified, alongside elements such as Al, Si, O2, and Na. The Al, Si, and Na are likely trace impurities from the processing and characterization environment.

3.2 Nanomechanical analysis
3.2.1 Load-displacement and depth-time curves of the Cp Ti and Ti-Nb2O5 based composites
The nanindentation load-displacement curves of the Cp Ti and Ti-Nb2O5 based composites subjected to indentation loads of 20 mN and 100 mN, respectively are presented in Figure 3. From Figure 3, it is observed that the Cp Ti has a high penetration depth, that is, the indenter penetrates into the material easily, while the penetration depth decreased with increase in Nb2O5 content at indenter loads of 20 mN and 100 mN. It is seen that generally, the penetration depth increased with increase in indenter loading from 20 mN to 100 mN. However, the load-displacement curves show that the Cp Ti has a high penetration depth, that is, the indenter penetrates into the material easily, while the penetration depth decreased with increase in Nb2O5 content at indenter loads of 20 mN and 100 mN, respectively. The decrease in penetration depth with increase in Nb2O5 content is indicative of increased hardness of the Ti-Nb2O5 based composites. Similarly, the penetration-depth vs time profiles of the Cp Ti and Ti-Nb2O5 based composites when subjected to indentation of 20 mN and 100 mN, are shown in Figure 4. It was observed that after an initial rise, the penetration depth decreased with increasing time, and increase in Nb2O5 content. The reduced penetration depth, is an indication of decreased plastic deformability with increasing Nb2O5 content.
3.2.2 Hardness and reduced elastic modulus of the Cp Ti and Ti-Nb2O5 based composites

The hardness and reduced elastic modulus of the Cp Ti and Ti-Nb2O5 based composites are shown in Figures 5a,b and 6a,b. From both Figures, it is observed that there is a progressive increase in hardness and reduced elastic modulus with an increase in Nb2O5 for both indenter loads of 20 mN to 100 mN. This improvement maybe associated to the load transfer from the Ti matrix to the relatively harder Nb2O5 particles. It is also linked to increased particle and dispersion strengthening offered by the Nb2O5 particles, which serve as barriers to dislocation motion [30].

3.2.3 Mechanical and anti-wear behaviour of the Cp Ti and Ti-Nb2O5 based composites

Further insight on the mechanical behaviour of the Cp Ti and Ti-Nb2O5− based composites and their anti-wear properties, were assessed from the elastic recovery index \( U_e / U_t \), the plastic recovery index, \( U_p / U_t \), the Elastic strain to failure \( H / E \), and the yield pressure \( H^3 / E^2 \). The elastic recovery index corresponds to the amount of energy released by the material under the influence of load, and is also a measure of the materials resistance to impact loading; while the plastic recovery index is dependent on the intrinsic plasticity of the material [24,31]. Furthermore, the nano-hardness to elastic modulus ratio \( H / E \), dictates the ability of the material to resist elastic strain to failure at nanometer length scales whereas the yield pressure \( H^3 / E^2 \), serves as a measure of the resistance to plastic deformation loaded contact and anti-wear resistance of materials [32,33]. Figure 7a,b shows the elastic recovery for the Cp Ti and the Ti-Nb2O5 based composites for indentation loads of 20 mN and 100 mN. From Figure 7a, it was observed that the Cp Ti with 20 mN has the least elastic recovery while the value generally improved for the Ti-Nb2O5 based composite, albeit the Ti-10 wt.% Nb2O5 based composite, had the highest value. The same trend of improved elastic recovery for the Ti-Nb2O5 based composites for the 100 mN load was also observed (Fig. 7b), although the increase was not progressive with wt.% of Nb2O5− which could be due to slight inhomogeneous dispersion of the Nb2O5 particles in the Ti matrix. Conversely, the plasticity index as shown in Figures 8a,b reduces with the increase in Nb2O5 content in the Ti based composites for the indenter loading of 20 mN and 100 mN, respectively. This is an affirmation that with increasing Nb2O5 content, the composites undergo less plastic deformation on account of the lower intrinsic plasticity of the composites. Notwithstanding the lower plasticity index of the composites, they are still potentially reliant as hard tissue replacements, as hard tissue implants from biomechanics assessment, are hardly exposed to significant plastic strains based on the typical stress/strain states involved in static and dynamic loads applied on the human body. Figure 9 shows the resistance to elastic strain to failure of the Cp Ti and the Ti-Nb2O5 based composites. It is observed that the resistance to elastic strain to failure

Fig. 2. SEM micrographs (a) Pure Cp Ti with lamellar structure (a1) EDS showing the chemical composition of Cp Ti. (b) Ti – 5 wt.% Nb2O5 (b1) EDS showing the chemical composition of the Ti – 5 wt.% Nb2O5 (c) Ti – 10 wt.% Nb2O5 (c1) EDS showing the chemical composition of the Ti – 10 wt.% Nb2O5 (d) Ti – 15 wt.% Nb2O5 (d1) EDS showing the chemical composition of the Ti – 15 wt.% Nb2O5.
largely improved with the Nb₂O₅ addition. Specifically, the Ti based composite containing 15% Nb₂O₅ had the highest resistance to elastic strain to failure at 20 mN and 100 mN, while the Cp Ti showed the least resistance at both loads. It is also noted that the elastic strain to failure values were highly sensitive to the magnitude of the indenter load, as the values for 20 mN were significantly lower than that for 100 mN. Similarly, from Figure 10, it is noted that the yield pressure of the Ti-Nb₂O₅ based composite improved with increase in the Nb₂O₅ content, with the 15 wt.% Nb₂O₅ having the highest yield pressure. The implication of the improvement of the elastic strain to failure and yield pressure indicates good resistance to impact loading and wear of the composites [25]. Summarily, based on the

Fig. 3. (a) the load at 20mN (b) the load at 100mN.

Fig. 4. (a) Penetration depth with time at 20mN (b) Penetration depth with time at 100mN.

Fig. 5. (a) showing hardness of the material at 20mN (b) hardness at 100mN.
The analysis of Figures 7–10, the use of Nb₂O₅ as reinforcement in Ti, offers improved mechanical and antiwear properties which are desirable for orthopedic implants and a number of technological applications where Ti based composites find usefulness. Also, the trends established for these nanomechanically derived mechanical and antiwear properties of the composites, are consistent with findings from related studies [24,33].
4 Conclusion

In this study, nanoindentation analysis was used to evaluate the mechanical properties and predict the wear behaviour of Ti based composites containing 5, 10 and 15 wt.% Nb2O5, developed using spark plasma sintering. The results show that:

- The lamellar structure of the pure Ti transformed to a mixed structure of lamellar and bimodal structure for the Ti-5 wt.% Nb2O5 composite, to fully bimodal structures for the Ti-10 wt.% Nb2O5 and Ti-15 wt.% Nb2O5 composite compositions.
- The hardness (6.0–40.67 GPa (20 mN) and 2.4–12.03 GPa (100 mN)) and reduced elastic modulus (115–266.91 GPa (20 mN) and (28.05–96.873 GPa (100 mN)) of the composites increased with increase in the Nb2O5 content.
- The combination of load transfer from the Ti matrix to the relatively harder Nb2O5 particles, particle and dispersion strengthening mechanisms, were linked to the improved hardness and elastic modulus with increase in the Nb2O5 content.
- The elastic recovery index also improved with increase in Nb2O5 content, while the inverse was noted with respect to plasticity index.
- The elastic strain to failure and yield pressure both improved with increase in Nb2O5 content, which suggests that the antiwear properties and resistance to impact loading equally improves with Nb2O5 addition.

References

1. H. Attar, S. Ehtemam-Haghighi, D. Kent, I.V. Okulov, H. Wendrock, M. Bönisch, A.S. Volegov, M. Calin, J. Eckert, M. S. Dargusch. Nanoindentation and wear properties of Ti and Ti-TiB composite materials produced by selective laser melting, Mater. Sci. Eng. A 688 (2017) 20–26
2. S. Ehtemam-Haghighi, K. Prashanth, H. Attar, A.K. Chauhey, G. Cao, L.C. Zhang, Evaluation of mechanical and wear properties of Ti-xNb-7Fe alloys designed for biomedical applications, Mater. Des. 111 (2016) 592–599

3. P.A.B. Kuroda, M.L. Lourenco, D.R.N. Correa, C.R. Grandini, Thermomechanical treatments influence on the phase composition, microstructure, and selected mechanical properties of Ti-20Zr-Mo alloys system for biomedical applications, J. Alloys and Comp. 8125 (2020) Article 152108

4. F.D. Quadros, P.A.B. Kuroda, K.d.J. Sousa, T.A.G. Donato, C.R. Grandini, Preparation, structural and microstructural characterization of Ti-25Ta-10Zr alloy for biomedical applications, J. Mater. Res. Tech. 8 (2019) 4108–4114

5. T.M. Manhabosco, S.M. Tamborim, C.B. dos Santos, I.L. Muller, Tribological, electrochemical and tribo-chemical characterization of bare and nitrided Ti6Al4V in simulated body fluid solution. Corros. Sci. 53 (2011) 1786–1793

6. T. Lee, S. Lee, I. Kim, Y.H. Moon, H.S. Kim, C.H. Park, Breaking the limit of Young’s modulus in low-cost Ti-Nb-Zr alloy for biomedical implant applications, J. Alloys Comp. 828 (2020) 1541401

7. I.V. Okklov, A.Volegov, H. Attar, M. Bönisch, S. Ehtemam-Haghighi, M. Calin, J. Eckert, Composition optimization of low modulus and high-strength TiNb-based alloys for biomedical applications, J. Mech. Behav. Biomed. Mater. 65 (2017) 866–871

8. M. Fellah, N. Hezil, M. Z. Touhami, A. Obrosov, S. Weiß, E. B. Kashkarov, A.M. Lider, A. Montagne, A. Iost, Enhanced structural and tribological performance of nanostructured Ti-15Nb alloy for biomedical applications, Results Phys. 15 (2019) 102767

9. N.B. Hua, Z.L. Liao, W.Z. Chen, Y.T. Huang, T. Zhang, Effects of noble elements on the glass-forming ability, mechanical property, electrochemical behavior and tribocorrosion resistance of Ni- and Cu-free Zr-Al-Co bulk metallic glass, J. Alloys Compd. 725 (2017) 403–414

10. Y. Liu, S. Pang, W. Yang, N. Hua, P.K. Liaw, T. Zhang, Tribological behaviors of a Ni-free Ti-based bulk metallic glass in air and a simulated physiological environment, J. Alloys Compd. 766 (2018) 1030–1036

11. A. Ataeef, Y. Li, C. Wen, A comparative study on the nanoindentation behavior, wear resistance and in vitro biocompatibility of SLM manufactured CP-Ti and EBM manufactured Ti64 gryoid scaffolds, Acta Biomater. 971 (2019) 587–596

12. A. Srivastav, An overview of metallic biomaterials for bone support and replacement, in: A. Laskovsky (Ed.), Biomedical Engineering, Trends in Materials Science, IntTech 2011, pp. 153–168

13. M. Geetha, A. Singh, R. Asokamani, A. Gogia, Ti based biomaterials, the ultimate choice for orthopaedic implants—a review, Prog. Mater. Sci. 54 (2009) 397–425

14. H. Attar, S. Ehtemam-Haghighi, N. Soro, D. Kent, M.S. Dargusch, Additive manufacturing of low-cost porous titanium-based composites for biomedical applications: advantages, challenges and opinion for future development, J. Alloys Comp. 827 (2020) Article 154263

15. G. Singh, N. Sharma, D. Kumar, H. Hegab, Design, development and tribological characterization of Ti-6Al–4V hydroxyapatite composite for bio-implant applications, Mater. Chem. Phys. 243 (2020) Article 122662

16. Prakash, S. Singh, S. Ramakrishna, G. Królczyk, C.H. Le, Microwave sintering of porous Ti-Nb-HA composite with high strength and enhanced bioactivity for implant applications, J. Alloys Comp. 824 (2020) Article 153774

17. H.Y. Hu, L. Zhang, Z.Y. He, Y.H. Jiang, J. Tan, Microstructure evolution, mechanical properties, and enhanced bioactivity of Ti-13Nb-13Zr based calcium pyrophosphate composites for biomedical applications, Mater. Sci. Eng. C 98 (2019) 279–287

18. Y. Wang, C. Wong, C. Wen, P. Hodgson, Y. Li, Ti-SrO metal matrix composites for bone implant materials, J. Mater. Chem. B 2 (2014) 5854–5861

19. Han, Y. Li, X. Wu, S. Ren, X. San, X. Zhu, Ti/SiO2 composites fabricated by powder metallurgy for orthopedic implant, Mater. Des. 49 (2013) 76–80

20. Y. Li, K.S. Munir, J. Lin, C. Wen, Titanium-niobium pentoxide composites for biomedical applications, Bioact. Mater. 1 (2016) 127–131

21. J.O. Abe, A.P.I. Popoola, O.M. Popoola, Consolidation of Ti6Al4V alloy and refractory nitride nanoparticles by spark plasma sintering method: Microstructure, mechanical, corrosion and oxidation characteristics, Mater. Sci. Eng. A 774 (2020) 138920

22. W.R. Matizhmkuna, Spark plasma sintering (SPS) – an advanced sintering technique for structural nanocomposite materials, J. S. Afr. Inst. Min. Metall. 16 (2016), 1171–1180

23. M.E. Maja, O.E. Falodun, B.A. Obadele, S.R. Oke, P.A. Olubambi, Nanoindentation studies on TiN nanoceramic reinforced Ti-6Al–4V matrix composite, Cer. Int. 44 (2018) 4419–4425

24. M.O. Okoro, R. Machaka, S.S. Lephuthing, S.R. Oke, M.A. Awotunde, P.A. Olubambi, Nanoindentation studies of the mechanical behaviours of spark plasma sintered multilayer carbon nanotubes reinforced Ti6Al4V nanocomposites, Mater. Sci. Eng. A 765 (2019) 138320

25. S. Ehtemam-Haghighi, G. Cao, L. Zhang, Nanoindentation study of mechanical properties of Ti based alloys with Fe and Ta additions, J. Alloys Comp. 692 (2017) 892–897

26. A.S. Namini, M. Azadbeh, M.S. Afs, Effect of TiB2 content on the characteristics of spark plasma sintered Ti–TiB composites, Adv. Powd. Tech. 28 (2017) 1564–1572

27. N. Fujiwasa, M. ukomski, Nanoindentation near the edge of a viscoelastic solid with a rough surface, Mater. Des. 184 (2019) Article 108174

28. W.C. Oliver, G.M. Pharr, An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments, J. Mater. Res. 7 (1992) 1564–1583

29. M. Masanta, S.M. Shariff, A. Roy Choudhury, Evaluation of modulus of elasticity, nano-hardness and fracture toughness of TiB2–TiC–Al2O3 composite coating developed by SHS and laser cladding, Mater. Sci. Eng. A 528 (2011) 5327–5335

30. K.K. Alaneme, E.A. Okotete, A.V. Fajemisin, M.O. Bodunrin, Applicability of metallic reinforcements for mechanical performance enhancement in metal matrix composites: a review, Arab J. Bas. Appl. Sci. 26 (2019) 311–330

31. O.E. Falodun, B.A. Obadele, S.R. Oke, M.E. Maja, P.A. Olubambi, Effect of sintering parameters on densification and microstructural evolution of nano-sized titanium nitride reinforced titanium alloys, J. Alloys Comp. 736 (2018) 202–210.
32. J. Xu, G.d. Wang, X. Lu, L. Liu, P. Munroe, Z.H. Xie, Mechanical and corrosion-resistant properties of Ti-Nb-Si-N nanocomposite films prepared by a double glow discharge plasma technique, Ceram. Int. 40 (2014) 8621-8630

33. A. Hynowska, A. Blanquer, E. Pellicer, J. Fornell, S. Surinach, M.D. Baro, S. Gonzalez, E. Ibanez, L. Barrios, C. Nogues, Novel TiZrReHfFe nanostructured alloy for biomedical applications, Mater. 6 (2013) 4930-4945

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