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LASER MICROMACHINING OF TiB_2 NANOSTRUCTURED CERAMICS

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Abstract: *Laser micromachining of TiB_2-based composite materials is extensively studied for its ability to produce precise and clean cuts without inducing deformations or cracks, vital for various industrial and military applications. This paper analyzes a nanostructured TiB_2 ceramic obtained through microwave hybrid sintering, with a microhardness around 15 GPa. Laser micromachining is necessary to create cavities or complex internal structures in the TiB_2 sample for sensor integration in defense applications. The primary objective of this research is to monitor the behavior of TiB_2 during the laser cutting process, emphasizing the maintenance of structural integrity and the improvement of processing efficiency. The results will contribute to the optimization of laser applications for advanced processing of TiB_2 nanoceramics.*

Key words: *laser micromachining, TiB_2, nanostructured ceramics, penetration depth, energy, footprint.*

1. INTRODUCTION

Laser processing has become an indispensable technique in modern manufacturing due to its versatility, allowing its application on a wide range of materials, including metals, plastics, glass, wood, ceramics, and composite materials. This technology stands out for its high processing speed, precise control of cutting depth or welding, and the ability to create complex patterns, making it widely used in various industries such as military, metallurgical, electronics, medical, automotive, aerospace, and artistic fields [1-6].

Another major advantage of laser processing is its ability to perform operations without direct contact with the material, thereby reducing the risk of contamination or deformation. Additionally, the process can be automated and integrated into production lines, significantly enhancing efficiency and productivity [7].

The precise control of processing parameters, such as laser power, speed, and beam focus, is important for achieving the desired results. Compared to other processing methods, laser processing can be more energy-efficient, as the energy is directed precisely to the work area, minimizing losses and optimizing energy consumption.

Accurate micro-machining of ceramic composites is critically important due to their application in various advanced technologies. However, this process presents significant challenges due to the inherent properties of ceramics, such as high hardness, extreme brittleness, and low fracture toughness. These characteristics make it difficult to achieve precise control during machining, often leading to difficulties in maintaining the integrity of micro-features. As a result, optimizing the parameters and techniques used in laser micromachining is essential to overcome these challenges and ensure high-quality outcomes.

TiB_2 is well known as a ceramic material with a hexagonal crystal structure and has been extensively utilized in various industrial and military applications due to its exceptional properties, as illustrated in figure 1 [8-12]. Furthermore, TiB_2's ability to maintain structural integrity under extreme conditions makes it ideal for high-performance components

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in aerospace and defense industries. Its robust performance in high-temperature and abrasive environments further underscores its value in advanced manufacturing processes and the development of cutting-edge technologies.

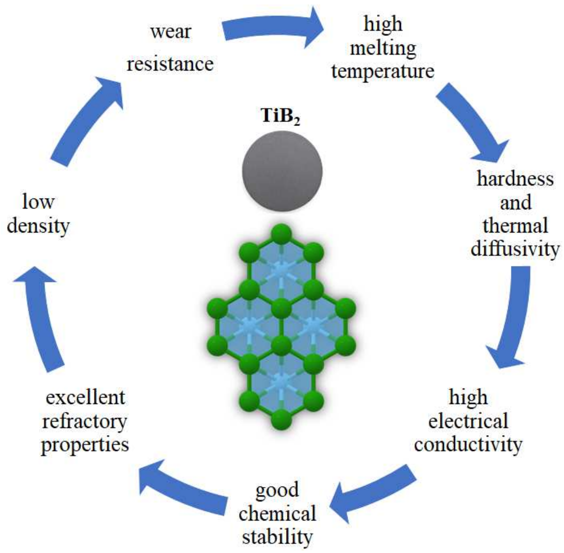


Fig. 1. TiB_2 properties

The primary motivation for this research is to address the specific challenges associated with laser micromachining of TiB_2, with a focus on creating cavities and complex internal structures for sensor integration in military applications. This study aims to investigate the behavior of TiB_2 during the laser cutting process, emphasizing the maintenance of structural integrity and the improvement of processing efficiency. Thermal management during the laser micromachining process is also a critical factor. TiB_2's high thermal conductivity aids in dissipating heat, but careful control of the laser's energy input is required to prevent overheating and potential cracking.

The findings from this research are expected to contribute significantly to the field of advanced manufacturing, offering practical guidelines for the effective use of laser micromachining in processing TiB_2 and similar advanced ceramics. These insights will enhance the precision and efficiency of manufacturing processes and expand the potential applications of TiB_2 in various high-performance sectors, including aerospace, defense, and electronics.

Moreover, the integration of sensors into TiB_2 structures via laser micromachining could lead to the development of smart materials with embedded sensing capabilities. This advancement holds promise for a range of applications, from structural health monitoring to the creation of intelligent systems in military and industrial environments. The ability to precisely machine TiB_2 without compromising its intrinsic properties opens new avenues for innovation in the design and manufacture of advanced ceramic components.

2. MATERIALS AND METHODS

The material used in the experimental activities was titanium diboride (TiB_2), consolidated through a microwave hybrid field sintering process.

The initial material was micron-sized TiB_2 powders, acquired from Sigma-Aldrich. These powders were mechanically milled to achieve a nanometric scale. The milling procedure is detailed in references [13,14].

For the sintering process in the microwave hybrid field, the knowledge from previous studies was applied [15-18].

The micromachining of TiB_2 samples was performed using an integrated laser processing system, equipped with a Yb TruDisk 3001 laser source (Trumpf, Germany) with a maximum power of 3 kW. The laser beam was focused onto the sample with a spot size of 0.8 mm.

To ensure precise control over the machining process, the system was configured to adjust key parameters such as laser power, cutting depth and scanning speed. These parameters were used to achieve high-quality machining with minimal thermal damage to the material. The use of a Yb laser allowed for efficient energy absorption and precise material removal, which is important for maintaining the integrity of the nanostructured TiB_2.

Figures 2 and 3 highlights the important aspects of the laser micromachining process for TiB_2 sample, including the laser footprint, laser machining direction and penetration depth of the laser beam into the sample. In addition, the figures present a detailed analysis of the interaction between the laser and the material, illustrating the thermal effects and material removal mechanisms during the laser micromachining process. This analysis highlights the importance of achieving clean penetration of the laser beam into the TiB_2 sample without causing any structural damage.

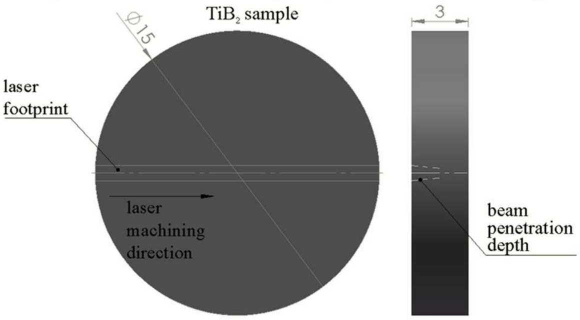


Fig. 2. TiB_2 sample dimensions and laser processing details

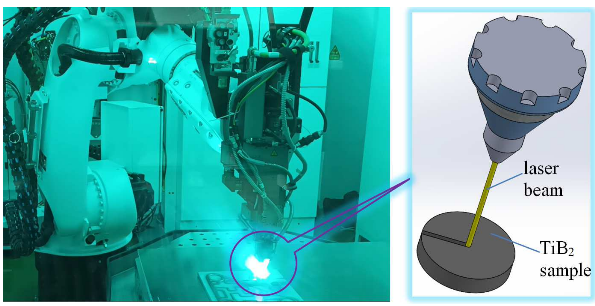


Fig. 3. Laser micromachining process of TiB_2 sample

The study aimed to ensure precise and controlled material removal, thereby preserving the integrity of the sample. This comprehensive depiction underscores the critical role of thermal management and precise control in maintaining the quality of micromachined features in TiB_2 ceramics.

In the laser machining process, power levels ranging from 100 to 1000 W and a speed of 25 mm/s were used.

All laser-processed samples were examined using an MA 100 Nikon optical microscope (NIS-Elements software) to determine the penetration depth of the laser beam into the TiB_2 sample, as shown in figure 2. Additionally, the microscopic analysis aimed to identify any surface or subsurface features, such as microcracks or thermal effects, resulting from the laser interaction. This examination provided important insights into the quality and uniformity of the micromachining process, enabling a comprehensive assessment of the material's response to laser processing.

In the paper, coding of the laser-micromachined samples was implemented to ensure efficient organization and identification. Table 1 presents the coding system used, detailing the method for assigning unique codes to each specimen.

Table 1

Laser microprocessed samples coding

Sample No.	Code
1.	T1_100_25
2.	T2_500_25
3.	T3_1000_25

For the first laser micromachining of titanium diboride, the code T1_100_25 was used, where "T1" represents the first cutting attempt, "100" denotes the laser power in watts, and "25" indicates the laser beam's travel speed in mm/s. The second sample was coded as T2_500_25, with "T2" indicating the second cutting attempt, "500" being the laser power, and "25" remaining constant as the travel speed. Similarly, the third sample was designated with the code T3_1000_25, where "1000" corresponds to the laser power used.

The laser parameters used in the micromachining of TiB_2 are shown in table 2.

Table 2

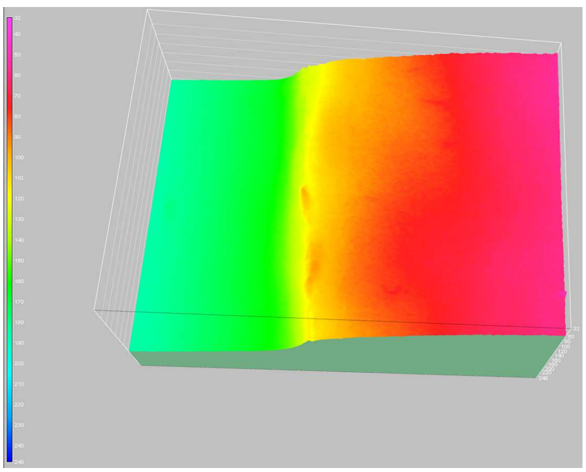
Laser parameters for TiB_2 microprocessing

Laser parameters / Laser regime	Power [W]	Energy [J]	Speed mm/s]
T1_100_25	100	93	25
T2_500_25	500	470	25
T3_1000_25	1000	941	25

3. RESULTS AND DISCUSSIONS

To investigate the behavior of the titanium diboride sample during laser micromachining, low laser parameters were utilized. Specifically, a power of 100 W, energy of 93 J, and a beam travel speed of 25 mm/s were applied. These settings were chosen to minimize the risk of damage to the sample and to allow for a detailed analysis of the interaction between the laser beam and the material. The depth of penetration of the laser beam was assessed by examining the sample under an optical microscope, focusing on both ends of the processed area. The resulting images are presented in figures 4 and 5, highlighting the morphological characteristics of the treated zones.

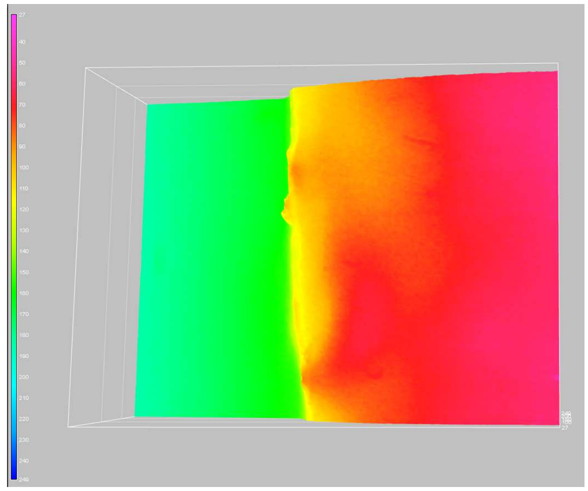
a)



b)

Fig. 4. Microscopic image of the laser-processed sample, T1_100_25 (view at one end of the sample):
a) penetration depth, b) 3D image.

a)



b)

Fig. 5. Microscopic image of the laser-processed sample, T1_100_25 (view at the other end of the sample):
a) penetration depth, b) 3D image.

From the above microscopic images and the 3D maps of the laser-micromachined area, it is evident that at a power setting of 100 W, the laser beam penetrated only to a shallow depth of 0.1 mm into the body of the sample. The laser left only discontinuous thermal and structural marks in several areas along the laser's trajectory, as shown in figure 6. At one end of the sample, a thin layer of melted material was identified, with dimensions ranging from 72 to 148 micrometers, as illustrated in figure 7. This suggests that the applied power was insufficient to achieve deeper material penetration, resulting in localized melting and a limited impact on the sample's overall structure.

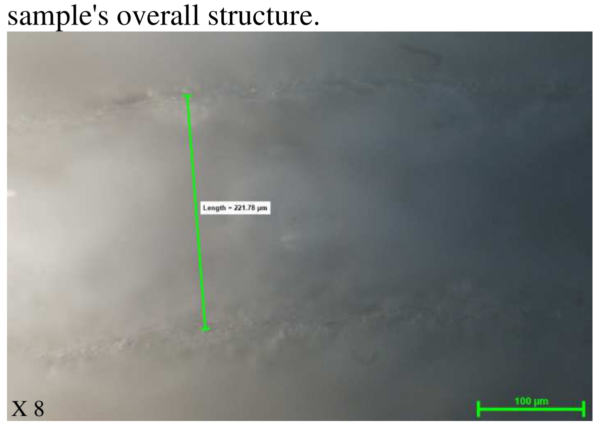


Fig. 6. Laser footprint for T1_100_25 sample

Based on this experience and the initial results, the laser power was increased to 500 W while maintaining the same working speed of 25 mm/s. The recorded energy was 470 J, as shown in figure 8.

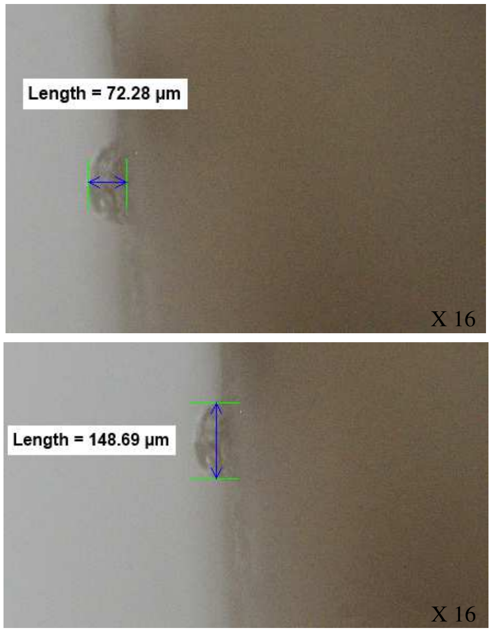
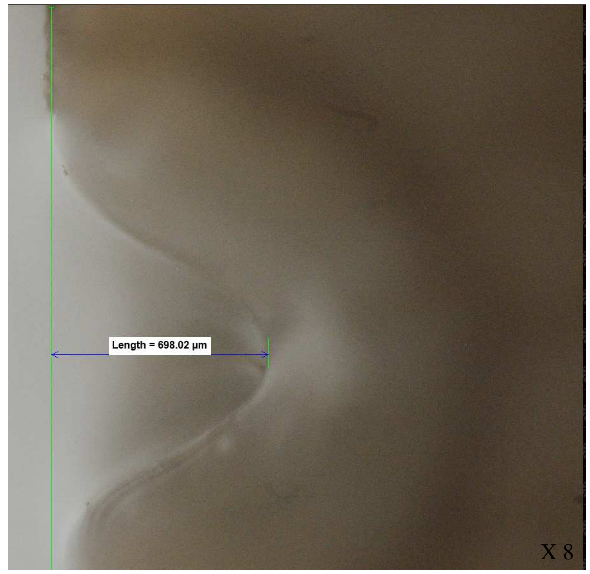


Fig. 7. Dimensions of the molten material for T1_100_25 sample

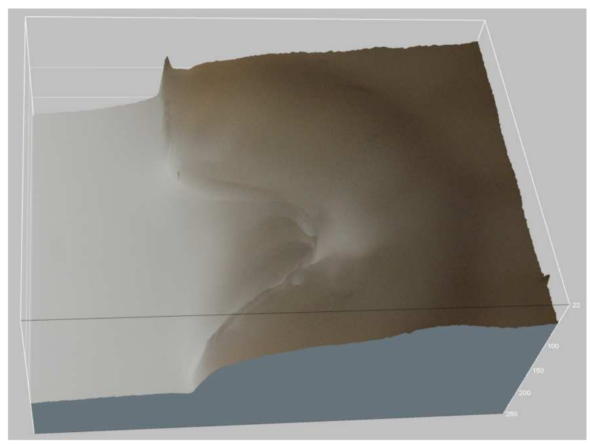
Fig. 8. Recorded energy for T2_500_25 sample

The laser-processed sample was subsequently examined under a microscope, and the resulting images are presented in figure 9. This adjustment aimed to achieve deeper penetration and a more pronounced structural effect on the sample, allowing for a more comprehensive analysis of the laser's interaction with the TiB_2 material. The images captured provide a detailed view of the modifications induced by the increased laser power, highlighting changes in both surface morphology and subsurface features.

At a power of 500 W, it can be observed that the laser beam penetrated the thickness of the titanium diboride to a depth of 0.69 mm.



a)



b)

Fig. 9. Microscopic image of the laser-processed sample, T2_500_25: a) penetration depth, b) 3D image.

This significant penetration indicates a more intense interaction between the laser and the material, highlighting the increased capability of the beam to penetrate deeper into the sample and induce substantial structural changes. These observations are important for understanding the material's behavior under stronger processing parameters and for optimizing subsequent processing steps.

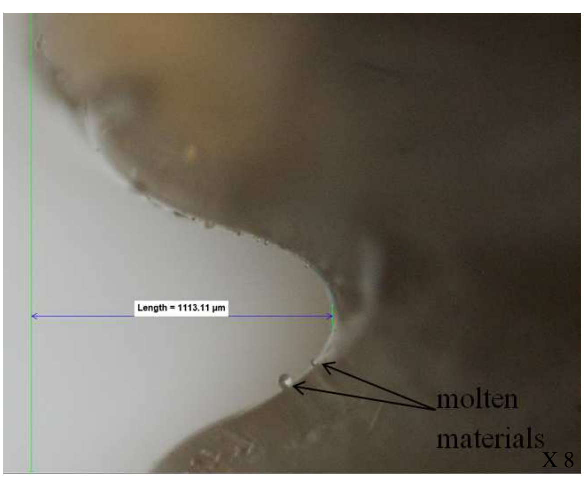
The structural mark along the laser's trajectory is presented in figure 10. It shows a penetrated layer width of approximately 0.8 mm.

Fig. 10. Laser footprint for T2_500_25 sample

Fig. 11. Recorded energy for T3_1000_25 sample

For the third laser micromachining operation, designated as T3_1000_25, the working power was doubled while maintaining the same scanning speed of 25 mm/s. The energy obtained during the laser micromachining process at a power of 1000 W was 941 J, as can be seen in figure 11.

The images obtained from the metallographic microscope examination are presented in figure 12. The observed depth of penetration was 1.11 mm, significantly greater than in the previous case.



a)

b)

Fig. 12. Microscopic image of the laser-processed sample, T3_1000_25: a) penetration depth, b) 3D image.

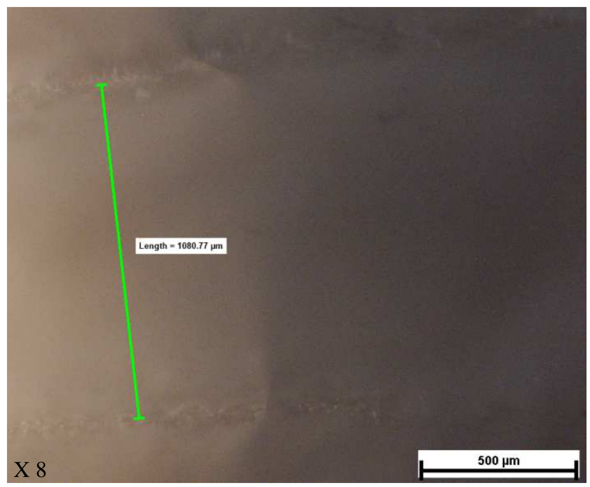


Fig. 13. Laser footprint for T3_1000_25 sample

Additionally, small spherical layers of melted material were noted on the surface of the sample, resulting from the passage of the laser beam. These spherical features ranged in size from 20 to 60 micrometers, indicating a more intense thermal interaction at this increased power level. The laser footprint is presented in figure 13, showing a penetrated layer width of approximately 1 mm. The laser micromachining process was stopped at a depth of 1.1 mm on the titanium diboride sample, which has a total thickness of 3 mm, to analyze the material's intermediate response. This preliminary depth was chosen as an initial phase of the study, allowing for a detailed analysis of the partial penetration effects on the material. This allows for a detailed study of the microstructural changes and mechanical impacts at this depth before proceeding with further machining in future research.

4. CONCLUSION

Based on the research conducted in the field of laser micromachining of TiB_2 samples and the data presented in the graph in figure 14, the following conclusions can be drawn:

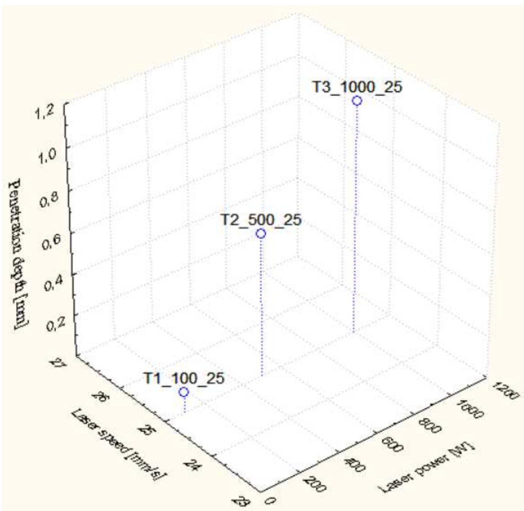


Fig. 14. Influence of laser speed and power on penetration depth

-The results highlight the critical importance of optimizing laser parameters in the micromachining of TiB_2 composites. Variations in laser power significantly affected the penetration depth, impacting both the quality of the cut and the structural integrity of the samples.

-Microscopic observations revealed substantial differences between the results obtained at low and high laser power levels. At lower power settings, the laser beam produced only superficial effects, with minimal penetration into the material. In contrast, higher power settings enabled deeper penetration into the TiB_2 samples.

-For the first sample, T1_100_25, the laser achieved a penetration of 3.3% of the sample thickness. The second sample exhibited a penetration rate of 23%, while the third sample reached 37%. Notably, the penetration depth for the T3_1000_25 sample was 38% greater than that of the T2_500_25 sample and 91% greater than that of the T1_100_25 sample. The difference in penetration between the T2_500_25 and T1_100_25 samples was 86%.

- Laser micromachining technology offers a precise and efficient method for processing TiB_2 composites. However, optimizing the process requires a detailed understanding of the laser beam's interaction with the material to achieve the desired outcomes.

Further studies are needed to explore the effects of laser parameters on the microstructure and properties of the material.

5. REFERENCES

[1] Xia, H., Zhao, G., Mao, P., Hao, X., Li, L., He, N., *Improved machinability of TiB_2–TiC ceramic composites via laser-induced oxidation assisted micro-milling*, Ceramics International 47, pp. 11514–11525, 2021.

[2] Liu, L., Minasyan, T., Ivanov, R., Aydinyan, S., Hussainova, I., *Laser beam micromachining (LBMM)-A review*, Optic Laser. Eng., 73, pp. 89–122, 2015.

[3] Wang, Q.Z., Lin, X., Kang N., Wen, X.L., Cao, Y., Lu, J.L., Peng, D.J., Bai, J., Zhou, Y. X., Mansori, M. El, Huang, W.D., *Effect of laser additive manufacturing on the microstructure and mechanical properties of TiB_2 reinforced Al-Cu matrix composite*, Materials Science & Engineering A, 840, 142950, 2022.

[4] Guimarães, B., Guedes, A., Fernandes, C.M., Figueiredo, D., Bartolomeu, F., Miranda, G., *WC-Co/316L Stainless Steel Joining by Laser Powder Bed Fusion for Multi-Material Cutting Tools Manufacturing*, Int. J. Refract. Met. Hard Mater., 112, 106140, 2023.

[5] Liu, H., Yu, Y., Wang, X., Gao, Zhao, J., Wang H., *Microstructure and Properties of CoCrNi/Nano-TiC/Micro-TiB_2 Composite Coatings Prepared via Laser Cladding*, Materials, 16, 7016, pp. 1-14, 2023.

[6] Vlasova, M., Kakazey, M., Aguilar, P. A. M., Tapia, R. G., Hernandez A. C., Mel'nikov, I., Fironov, Y., Uribe D. B., *Processes Connected With Local Laser Heating of TiB_2 Armor Ceramics*, Science of Sintering, 51, pp. 125-134, 2019.

[7] Manikandan Rajam, P.K. – Nampoothiri, J., *Investigation of Laser Ablative Micromachining of Al/TiB_2 Nanocomposite*, Journal of Mechanical Engineering, 68(12), pp. 735-745, 2022.

[8]Mishra, S., Yadava, V., *Selective laser melting of TiB_2-Ti composites with high content of ceramic phase*, Ceram. Int., 46, pp. 21128–21135, 2020.

[9] Apparao, D., *Optimization of Milling Process Parameters for Machining of Aluminium-TiB_2 Metal Matrix Composite*, The International journal of analytical and experimental modal analysis, 12 (2), pp. 2695–2701, 2020.
[10] Wang, W., Fu, Z., Wang, H., Yuan, R., *Influence of hot pressing sintering temperature and time on microstructure and mechanical properties of TiB_2 ceramics*, Journal of the European Ceramic Society, 22 (7), pp. 1045–1049, 2002.
[11] Ma, L., Yu, J., Guo, X., Xie, B., Gong, H., Zhang, Y., Zhai, Y., Wu, X., *Preparation and sintering of ultrafine TiB_2 powders*, Ceramics International, 44 (4), pp. 4491–4495, 2018.
[12] Cao, Y., He, Q., Wang, W., *Microstructure, Mechanical, and Thermal Properties of B4C-TiB2-SiC Composites Prepared by Reactive Hot-pressing*, Journal of Wuhan University of Technology-Mater. Sci. Ed., 35 (6), pp. 1031–1037, 2021.
[13] Stefan I., Benga G. C., Olei A., *Elaboration and characterization of the nanometric titanium diboride powders by the mechanical milling*, Annals of "Dunarea de Jos" Univ. of Galati, Fascicle XII, 31, pp. 55–58, 2020.
[14] Stefan I., Benga G. C., et al., *Impact of planetary ball milling parameters on the particle size of TiB_2 powders*, Acta Technica Napocensis, 65 (2S), pp. 449–455, 2022.
[15] Savu, S.V., Ghelsingher, C.D., Stefan, I., Sîrbu, N.-A., Tarnita, D., Simion, D., Savu, I.D., Bucșe, I.G., Țunescu, T., *Microwave Soldering of Low-Resistance Conductive Joints—Technical and Economic Aspects.*, Materials, 16, pp. 1–21, 2023.
[16] Ghelsingher, C.D., Simion, D., et al., *Microwave heating of composite material reinforced with natural ceramics – technical and economical aspects*, Acta Technica Napocensis, 65 (II), pp. 351–358, 2022.
[17] Savu, S.V., Tarnita, D., Benga, G.C., Dumitru, I., Stefan, I., Craciunoiu, N., Olei, A.B., Savu, I.D., *Microwave Technology Using Low Energy Concentrated Beam for Processing of SolidWaste Materials from Rapana thomasiana Seashells*, Energies, 14, pp. 1–25, 2021.
[18] Savu, I.D., et al., 2021. Composite polymer for hybrid activity protective panel in microwave generation of composite Polytetrafluoroethylene-Rapana Thomasia na. *Polymers*, *13*(15), p.2432.

Microprelucrarea cu laser a ceramicelor nanostructurate pe bază de TiB_2

Microprelucrarea cu laser a materialelor compozite pe bază de TiB_2 este studiată pe scară largă datorită capacității sale de a produce tăieturi precise și curate, fără a induce deformații sau fisuri, aspecte iimportante pentru diverse aplicații industriale și militare. Această lucrare analizează o ceramică nanostructurată din TiB_2 obținută prin sinterizare hibridă în câmp de microunde, cu o microduritate de aproximativ 15 GPa. Microprelucrarea cu laser este necesară pentru a crea cavități sau structuri interne complexe în proba de TiB_2 pentru integrarea senzorilor în aplicațiile militare. Obiectivul principal al acestei cercetări este monitorizarea comportamentului materialului TiB_2 în timpul procesului de tăiere cu laser, punând accent pe menținerea integrității structurale și îmbunătățirea eficienței procesului. Rezultatele vor contribui la optimizarea aplicațiilor laser pentru procesarea avansată a nanoceramicelor din TiB_2.
Cuvinte cheie: *microprelucrare laser, TiB2, ceramică nanostructurată, adâncime de penetrare, energie, amprentă.*

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