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Research Article

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Surface Modification of Ti6Al4V Alloy by Q-switched Nd: YAG Laser

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Abstract: In this study, Ti6Al4V alloy was exposed to a Q-switched Nd:YAG laser (wavelength 1064 nm, 6 Hz repetition rate, 10 ns pulse duration, and 4 mm spot size) with energies of (280-460) mJ. This process is referred to as laser surface modification (LSM). The effect of laser energy on crystalline structure, surface wettability, hardness, and topography was systematically evaluated using appropriate measurement techniques such as (XRD, contact angle, Vickers micro hardness tester, SEM). Significant increases were observed in hardness and wettability during the decrease in the contact angle and along with an enhancement in other surface properties.

Keywords: Surface modification, laser energy, wettability, microhardness, Ti6Al4V, Nd:YAG laser.

1. Introduction

Titanium alloys are frequently implanted into the human body to enhance physiological processes[1, 2] . The field of biomaterial study is multidisciplinary, encompassing elements of chemistry, physics, biology, medicine, and materials science. A biomaterial is a non-viable substance used in medical devices that are meant to interact with biological systems to assess, treat, enhance, or replace any bodily tissue, organ, or function[3].

The development of biomedical implants and tissue engineering heavily depends on the functionality and uses of biomaterials in biological systems. The human body can employ a wide range of biomaterials, including metals (such as stainless steel, cobalt alloys, and titanium alloys), ceramics (such as aluminum oxide, zirconium, and calcium phosphates), and synthetic and natural polymers [4]. Among these, titanium (Ti) and titanium alloys are regarded as some of the most important biomaterials because of their high corrosion resistance, great tensile strength, flexibility, and resistance to the effects of bodily fluids. This particular combination of strength and biocompatibility [5, 6] makes them appropriate for use in medical applications. For instance, the most common material for dental implants is commercially pure titanium (c.p.Ti), whereas Ti-6Al-4V alloy is employed for orthopedic applications[7-9].

Bioactive surface coatings have been widely explored to enhance the biological performance of titanium-based implants. Coatings such as hydroxyapatite (HA) and titanium oxide (TiO_2) layers are known to improve cell adhesion, osseointegration, and corrosion resistance. These coatings act as a complement to physical surface modification methods and have been successfully applied in various biomedical

applications, providing a favorable environment for bone integration and long-term implant stability[10]. Despite concerns regarding the potential biological effects of alloying elements such as aluminum and vanadium, Ti-6Al-4V remains one of the most widely used titanium alloys in biomedical applications. This widespread use is attributed to its excellent mechanical strength, high corrosion resistance, favorable fatigue behavior, and long-term clinical performance[11].

Numerous in vitro and in vivo studies have demonstrated that Ti-6Al-4V exhibits acceptable biocompatibility and minimal ion release under physiological conditions, particularly when a stable oxide layer is present on the surface. Consequently, Ti-6Al-4V continues to be extensively employed in orthopedic and dental implants, with surface modification techniques commonly applied to further enhance its biological response[12].

Therefore, this study aims to investigate the effects of laser surface modification (LSM) on the Ti6Al4V alloy, focusing not only on surface properties such as roughness, wettability, and hardness, but also on their potential impact on cell adhesion and osseointegration, which are critical for biomedical applications. It should be noted that the present study focuses exclusively on Ti6Al4V alloy, and no comparative evaluation with commercially pure titanium (CP-Ti) or other biomaterials, such as polymers or ceramics, was conducted. The main objective is to investigate the effects of LSM on the surface properties of this alloy, while comparative studies with other materials could be considered in future research.

2. Materials and Methods

2.1 Specimen Preparation

Ti6Al4V alloy specimens were prepared by sequential grinding and mirror polishing [13]. The specimens were first ground using a series of silicon carbide (SiC) papers with grain sizes of 180, 400, 600, 800, 1000, 1200, and 2500 μm, employing the KNUTH-ROTOR 2 system (Denmark). Polishing was then carried out using DP-cloth and DP-suspension (1 μm and ¼ μm) to achieve a mirror-like surface finish as shown in Fig.1.

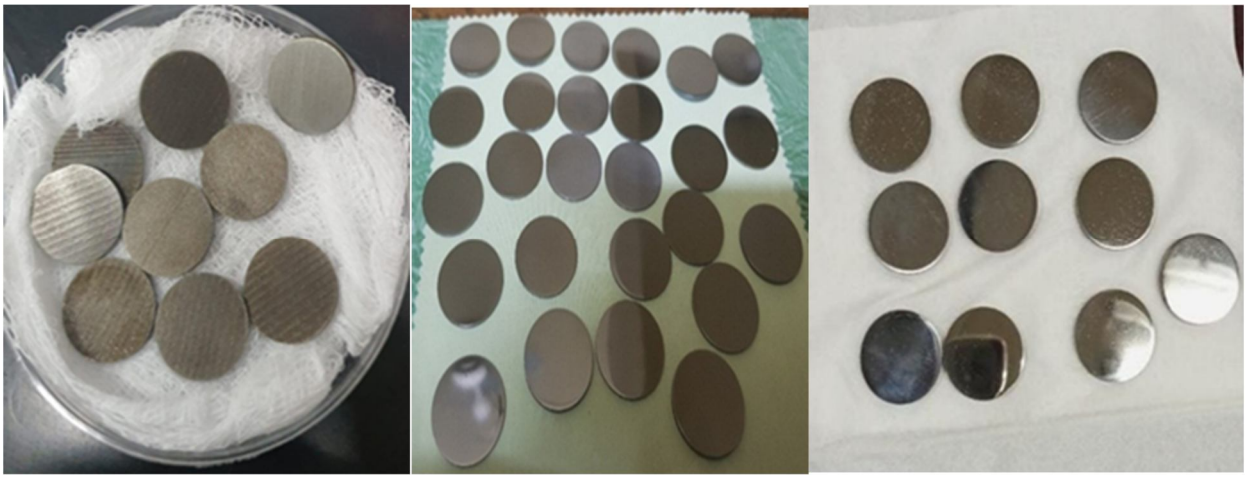

Fig.1: Photograph of mirror-polished Ti6Al4V alloy specimens after sequential grinding and polishing, showing smooth reflective surfaces used for laser surface modification experiments.

2.2 Experimental Setup for Laser-Induced Plasma (LIP) System

Surface treatment of Ti6Al4V specimens was performed using a Q-switched Nd:YAG laser with the following parameters:

- Wavelength: 1064 nm
- Pulse duration: 10 ns
- laser energies: 280, 340, 400, and 460 mJ
- repetition rate: 6 Hz
- spot size: 4mm

All experiments were conducted in air. The laser beam was focused onto the sample surface using a lens positioned at a 45° angle relative to the beam direction, with a working distance of approximately 10 cm. Plasma emission from the laser-treated surface was collected using an optical fiber (125 µm core diameter) positioned 10 cm from the target, and analyzed with a spectrometer, as shown schematically in Fig.2.

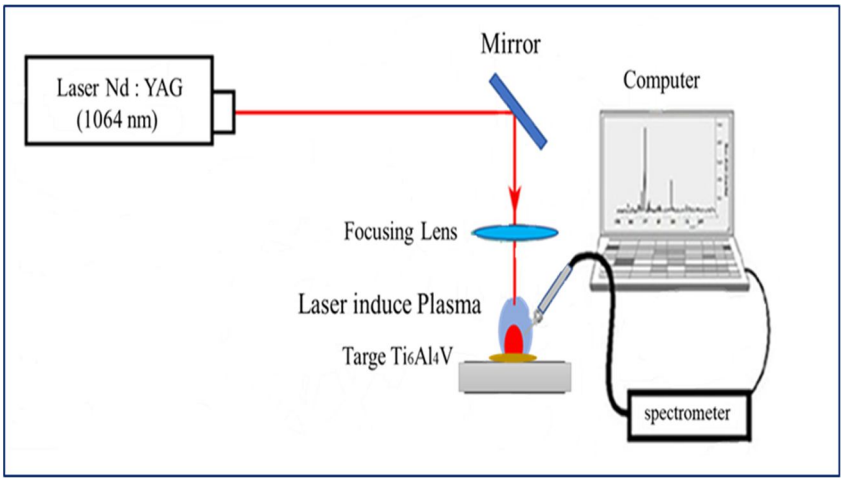

Fig.2: Schematic illustration of the laser-induced plasma system used for surface modification of Ti6Al4V alloy.

3. Results and Discussion

3.1. X-Ray Diffraction (XRD) measurements

XRD analysis of untreated and laser-treated Ti6Al4V samples (laser energies: 280, 340, 400, 460 mJ; repetition rate: 6 Hz) confirmed that all diffraction peaks correspond to the α-Ti phase with a hexagonal close-packed (HCP) structure. Peaks at 2θ angles of 35.6, 38.7, 40.6, 53.5, 63.7, 71.3, 75.2, and 78.8° correspond to the (010), (002), (011), (012), (110), (013), (112), and (021) planes of Ti, with no additional peaks indicating secondary phases (Fig. 3). Average crystallite sizes, calculated using the Debye–Scherrer equation [14], were assigned as follows: untreated sample (32.08 nm), 280 mJ (31.81 nm), 340 mJ (22.5 nm), 400 mJ (26.9 nm), and 460 mJ (31.05 nm).

$$D = \frac{k\lambda}{(\beta \cos\theta)} \quad (1)$$

Where λ is the X-ray wavelength, β is the full width at half maximum (FWHM) of the peaks at the θ diffracting angle with respect to Bragg's angle position, D is the crystallite size and k is the Scherer's constant (k = 0.9).

The reduction in crystallite size at lower laser energies indicates grain refinement due to rapid melting and resolidification induced by laser irradiation. This refinement is associated with increased defect density and enhanced surface activity. At higher laser energies, a slight increase in crystallite size is observed, likely

due to crystal rearrangement. Peak broadening is mainly attributed to reduced crystallite size and residual strain, while instrumental broadening was minimized through standard calibration. A noticeable reduction in peak intensity is observed after laser treatment compared to the untreated sample, which is attributed to grain refinement and stress generated during the rapid laser-induced thermal process. Although lattice parameters and residual stresses were not calculated in this study, these factors may be considered in future work to provide a more comprehensive structural analysis.

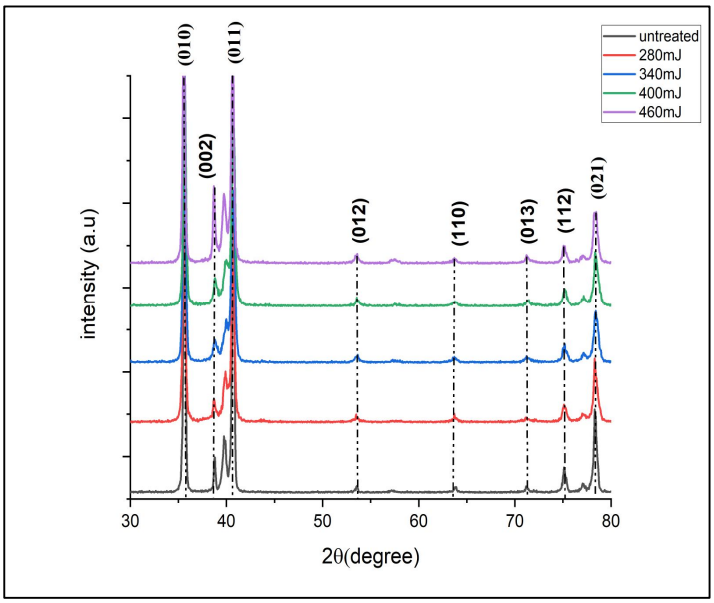

Fig. 3: XRD patterns of untreated and laser-treated Ti6Al4V samples at various laser energies.

3.2. Surface Wettability

Contact angles were measured by placing a 2 μL water droplet on the sample surface and photographing the droplet (Fig. 4). The laser-treated Ti6Al4V samples exhibited a modest decrease in contact angle compared to the untreated sample. The untreated surface showed the highest contact angle, indicating relatively low surface energy and the absence of significant topographical or chemical modifications. Although surface roughness measurements (e.g., AFM or profilometry) were not performed, the observed trend is consistent with the expected effect of laser-induced surface roughness on wettability, as described by Wenzel's model. The measurement was performed twice for each sample and at different locations on the surface.

Table 1. show how laser energy affects the contact angle of the Ti6Al4V alloy.

Condition		Contact angle	
Repetition Rate	**Energy**	**CA left [°]**	**CA right [°]**
Untreated	Untreated	103.92	103.72
6Hz	280mJ	94.6	94.89
6Hz	340mJ	94.49	94.28
6Hz	400mJ	92.64	91.02
6Hz	460mJ	92.39	92.66

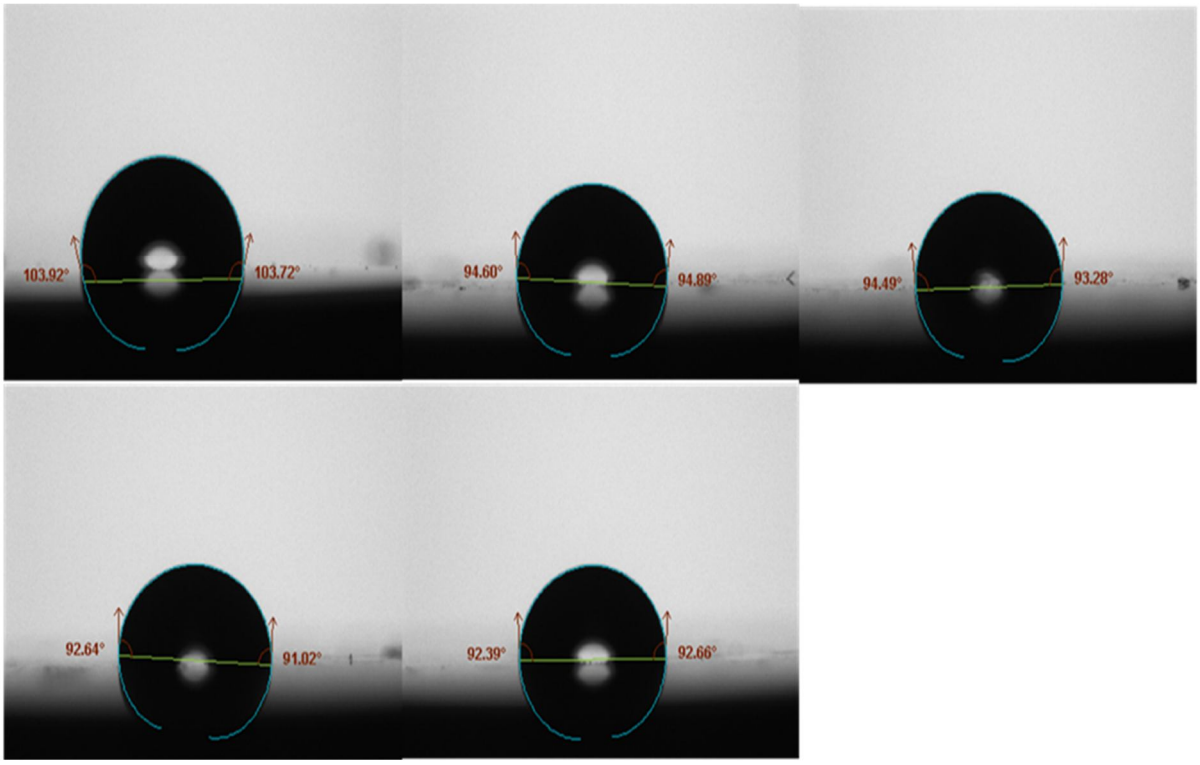

Fig. 4: Variation of water contact angle on Ti6Al4V surfaces treated with different laser energies, showing a decrease in contact angle and enhanced surface wettability due to laser-induced microstructural modifications.

3.3. Hardness

Microhardness measurements were performed using a digital Vickers microhardness tester (HVS-1000, China) under a load of 4.9 N for 15 s. The untreated sample exhibited the lowest hardness (240 HV). Increasing the laser energy from 280 to 460 mJ resulted in a gradual increase in hardness, reaching 301 HV at the highest energy. This enhancement is attributed to surface melting followed by rapid cooling, which produces a fine microstructure, refines grains, and increases dislocation density and residual stresses, thereby limiting plastic deformation and improving hardness. Each hardness value represents the average of three measurements. Based on the data mentioned above, a graph can be created to illustrate the effect of laser energy on the microhardness of the samples.

Table 2. Microhardness (HV) of the Ti6Al4V alloy as a function of laser energy

Repetition Rate	Energy (mJ)	Hardness (HV)
Untreated	Untreated	240 ± 3
6 Hz	280	247 ± 2
6 Hz	340	261 ± 4
6 Hz	400	285 ± 3
6Hz	460	301 ± 2

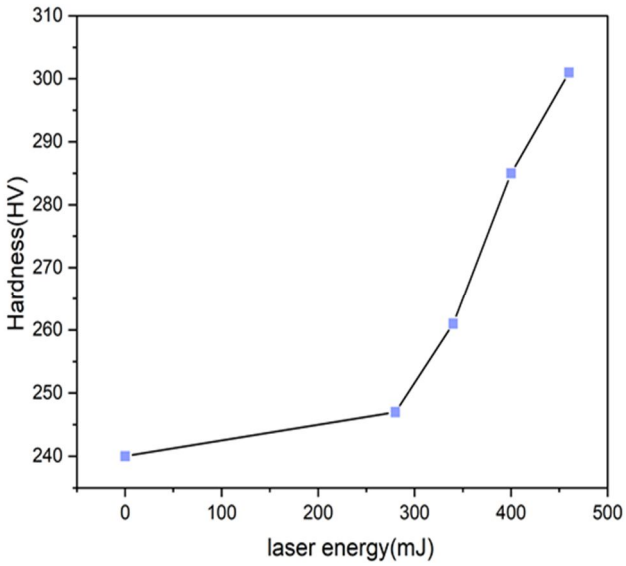

Fig. 5: Effect of laser energy on Vickers microhardness of Ti6Al4V alloy. Hardness increases with laser energy, reflecting grain refinement, higher dislocation density, and residual stresses from rapid surface melting and solidification.

3.4. Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) image of the untreated sample of Ti6A4V alloy shows a relatively smooth and homogeneous surface with fine, directional scratches resulting from mechanical preparation processes such as grinding and polishing. No signs of surface melting, re-solidification or thermal damage are observed, indicating that the surface remained in its original state and serves as a reference condition for comparison, as shown in Fig.6.

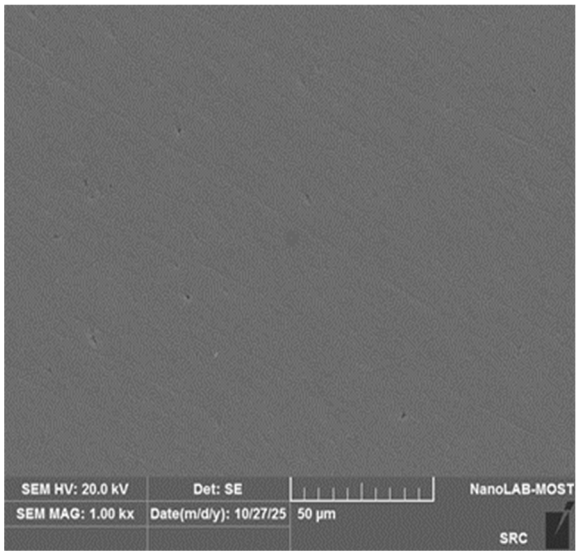

Fig. 6: SEM image showing the as-received Ti6Al4V surface with smooth morphology and minimal topographical features before laser treatment.

After laser treatment at energy of 280 mJ, initial surface modification becomes evident. The surface exhibits slight melting features and shallow surface ripples, accompanied by a modest increase in surface roughness. These changes suggest partial surface melting without inducing severe thermal effects. At laser energy of 340 mJ, the surface morphology shows more pronounced modification. The density of surface ripples and grooves increases, and the melted regions appear more uniform. This behavior is attributed to enhanced laser–material interaction, leading to more effective melting and rapid re solidification of the surface layer. When the laser energy is increased to 400 mJ, the surface undergoes significant modification, characterized by deeper grooves and a rougher surface texture. The microstructural features become more distinct due to higher thermal input, resulting in intensified melting and faster cooling rates, which promote noticeable surface restructuring. At the highest applied laser energy of 460 mJ, the surface exhibits the most severe modification, with dense and deep ripples, increased surface roughness, and signs of localized thermal stress. These features indicate excessive energy input, which enhances surface deformation and may introduce local non-uniformity due to rapid heating and cooling.

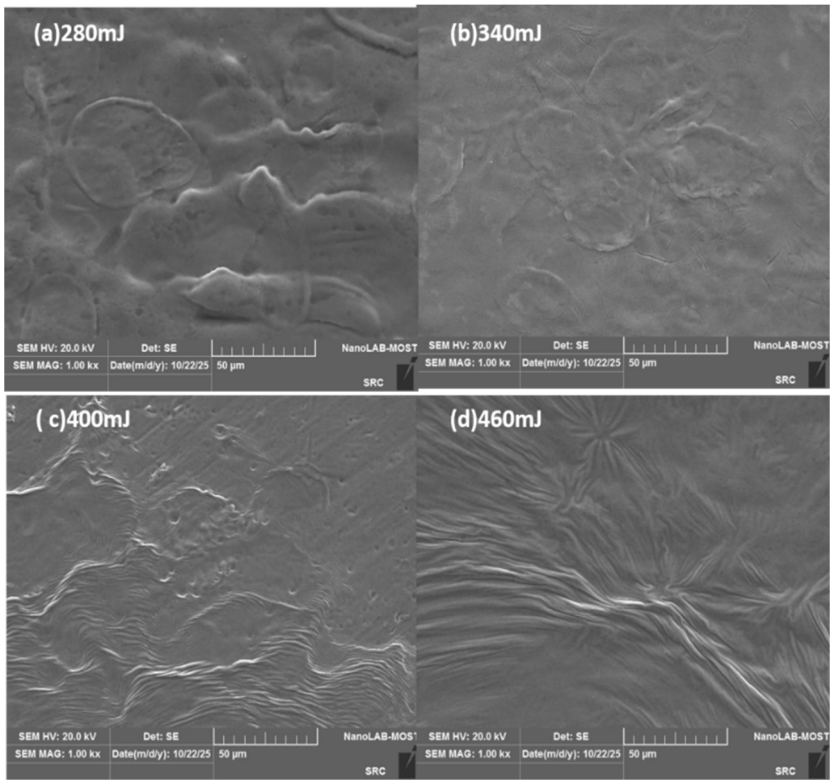

Fig. 7: SEM images of Ti6Al4V surfaces treated with increasing laser energies. Progressive surface modification is observed, from slight melting and shallow ripples at 280 mJ to dense, deep ripples and higher roughness at 460 mJ, indicating the effect of laser energy on surface morphology and microstructural restructuring.

4. Conclusion

Laser surface modification (LSM) of Ti6Al4V alloy significantly alters its surface properties. Increasing the laser energy within the tested range led to enhanced surface wettability, as indicated by a decrease in water contact angle and a corresponding increase in surface roughness. Additionally, microhardness measurements showed a gradual increase in surface hardness with increasing laser energy, which can be attributed to grain refinement and higher dislocation density resulting from rapid surface melting and

solidification. These results demonstrate the potential of LSM to modify surface characteristics; however, further studies are required to evaluate biological performance and corrosion behavior.

References

[1] O. Bialas, A. Kunwar, A. Taratuta, M. Skonieczna, K. Matus, and M. Adamiak, "Surface Engineering of Ti13Zr13Nb Biomaterial Alloy with Gold Via Laser Melting for Enhanced Biocompatibility and Functional Performance," *Metallurgical and Materials Transactions A*, 1–17 (2025).
[2] M. Balazic, J. Kopac, M. J. Jackson, and W. Ahmed, "Titanium and titanium alloy applications in medicine," *International Journal of Nano and Biomaterials*, 1 (1), 3–34 (2007).
[3] D. F. Williams, "On the nature of biomaterials," *Biomaterials*, 30 (30), 5897–5909 (2009).
[4] D. Mihov and B. Katerska, "SOME BIOCOMPATIBLE MATERIALS USED IN MEDICAL PRACTICE," *Trakia Journal of sciences*, 8 (2010).
[5] D. F. Williams, "On the mechanisms of biocompatibility," *Biomaterials*, 29 (20), 2941–2953(2008).
[6] H. Y. Hammod and T. J. Mossa, "Influence of optical fiber diameters on the performance of surface plasmon resonance sensor," *Baghdad Science Journal*, 19 (6), 34 (2022).
[7] D. M. Brunette, P. Tengvall, M. Textor, and P. Thomsen, *Titanium in medicine: material science, surface science, engineering, biological responses and medical applications*. Springer, (2001).
[8] H. J. Ali, M. K. Khalaf, B. M. Ahmed, and H. M. Fadhel, "Enhancing Ti6Al4V biomedical alloy's corrosion resistance with tin, TiO2, and TiO2/TiN multilayer coatings using DC reactive sputtering technique," in *AIP Conference Proceedings*, 3282 (1), 050024, (2025).
[9] N. H. Harb, "Preparation and characterization of NiONPS sensor Prepared by Different Q-switched Nd: YAG Laser parameter: energy pulse and wavelength," *Baghdad Science Journal*, 22 (2), (2025).
[10] K. Homa *et al.*, "Surface functionalization of titanium-based implants with a nanohydroxyapatite layer and its impact on osteoblasts: a systematic review," *Journal of Functional Biomaterials*, 15 (2), 45 (2024).
[11] Y. K. Balasubramanian Gayathri, R. L. Kumar, V. V. Ramalingam, G. S. Priyadharshini, K. S. Kumar, and T. R. Prabhu, "Additive manufacturing of Ti-6Al-4V alloy for biomedical applications," *Journal of Bio-and Tribo-Corrosion*, 8 (4), 98 (2022).
[12] E.-S. M. Sherif, S. A. Ragab, and H. S. Abdo, "Role of vanadium additions on the corrosion mitigation of Ti-6Al-xV alloy in simulated body fluid," *Metals*, 10 (7), 903 (2020).

تعديل سطح سبيكة Ti6Al4V بواسطة ليزرQ-switched Nd:YAG

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الخلاصة : اجري في هذه الدراسة تعريض سبيكةTi6Al4V الى ليزر Q-switched Nd:YAG (ذو الطول الموجي 1.064 نانومتر,معدل تكرار 6 هرتز ,عرض النبضة 10 نانوثانية,وحجم البقعة 4 مم) مع طاقات تتراوح بين (280-460) مللي جول . ويشار الى هذه العملية بأسم تعديل السطح بالليزر(LSM) .تم تقييم تأثير طاقة الليزر على البنية البلورية وقابلية التبلل السطحي والصلابة والتضاريس بشكل منهجي وباستخدام تقنيات القياس المناسبة مثل (XRD , زاوية الميل,اختبار الصلادة الدقيقة فيكرز, SEM) .وقد لوحظ زيادة كبيرة في الصلابة وقابلية البلل اثناء انخفاض زاوية الميل بالاضافة الى تحسن في خصائص السطح الاخرى.