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Studying the Effect of Thickness on the Properties of Ti-6Al-4V Films Prepared by Magnetron Sputtering Plasma Deposited on Stainless Steel Substrates

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ABSTRACT

In this study, magnetron sputtering was used to deposit Ti-6Al-4V thin films onto stainless steel substrates. A high-purity (99%) Ti-6Al-4V target and a DC magnetron sputtering system were employed. Deposition occurred at a base pressure of 10^{-5} bar, a working pressure of 4 Torr, room temperature (27 °C), and a target-to-substrate distance of 5 cm. Film thickness was controlled by varying deposition time to 3, 6, and 9 minutes. AFM and FESEM analyses showed thicknesses of 18, 42, and 13 nm for the first, second, and third samples, respectively. AFM revealed that the 18 nm sample had a smooth, uniform surface, while the 42 nm and 13 nm films showed poorer surface quality and structural changes. FESEM indicated that nanoparticle size and surface morphology varied with thickness. A clean surface was observed in the 18 nm film, whereas the 42 nm and 13 nm samples exhibited irregular deposition profiles and particle-size differences. Controlling film thickness during deposition is essential for achieving desired properties. Mechanical and electrical behavior change significantly with thickness and surface structure. Thinner films show modified optoelectronic and mechanical characteristics due to increased surface aggregation. Surface variations are crucial for sensor and electronic device development. Ti-6Al-4V films produced by magnetron sputtering exhibited nanoparticles of 33–43 nm and improved corrosion resistance, mechanical durability, thermal stability, and optical performance. These properties make them suitable for sensors, microdevices, and electronic medical applications. Furthermore, precise thickness optimization enables tailored functionality for advanced coatings, biomedical implants, and durable electronic surface engineering solutions worldwide.

Keywords: Magnetron sputtering, Ti-6Al-4V, Nanostructure properties, Stainless steel, Plasma sputtering

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دراسة تأثير السُمك على خصائص أغشية Ti-6Al-4V المُحضرة بواسطة بلازما الرش الماغنتروني المترسبة على ركائز من الفولاذ المقاوم للصدأ

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قسم الفيزياء، كلية العلوم، جامعة تكريت، تكريت، العراق

الملخص

في هذه الدراسة تم استخدام طريقة الترسيب الماكنتروني وترسيب اغشية رقيقة من سبيكة Ti-6Al-4V على قواعد من الفولاذ المقاوم للصدأ باستخدام منظومة الرش الماكنتروني الذي يعمل بالتيار المستمر DC باستخدام هدف من سبيكة Ti-6Al-4V عالية النقاوة (99 %) وتحت ضغط (10^{-5} bar) وضغط (4 Torr) وبدرجة حرارة المختبر (27 °C) والمسافة بين الهدف والركيزة (5 cm). ان المتغير في هذه الدراسة هو سُمك الأغشية المحضرة الناتج من تغيير أزمنة الترسيب، حيث كانت أزمنة الترسيب (3, 6, 9 min). اظهرت نتائج فحوصات مجهر القوة الذرية والمجهر الالكتروني الماسح الباعث للمجال ان سمك العينة الاولى (18 nm) والعينة الثانية ذات سمك (42 nm) اما العينة الثالثة كانت بسمك (13 nm) اما فحص المجهر الالكتروني الماسح الباعث للمجال فقد اظهر تأثير السمك على بنية السطح وحجم الجسيمات النانوية بينما تمثل العينة الأساسية ذات السمك (18 nm) سطحًا نقيًا، تشير العينتان العينة الثانية ذات سماكة (42 nm) والعينة الثالثة ذات سمك (13 nm) إلى تفاعلات مختلفة أثناء الترسيب، مما يؤدي إلى تباين في حجم الجسيمات النانوية الناتجة. تؤكد هذه النتائج على أهمية التحكم في سمك الغشاء أثناء الترسيب لتحقيق خصائص محددة في الأغشية الرقيقة. يمكن أن تؤثر الاختلافات في السمك وبنية السطح بشكل كبير على الخصائص الميكانيكية والكهربائية. على سبيل المثال، أظهرت الأغشية الرقيقة خصائص بصرية وميكانيكية متميزة بفضل تراكمات سطحها الأكبر. تُعد هذه الاختلافات السطحية بالغة الأهمية لتطبيقات مثل أجهزة الاستشعار والأغشية الرقيقة في الإلكترونيات. أظهرت أحجام الجسيمات النانوية المقاسة (33 – 43 nm) في أغشية Ti-6Al-4V المترسبة بواسطة الرش المغناطيسي تحسينات كبيرة في تطبيقات إلكترونية مختلفة. تُحسّن هذه الأغشية الأداء من حيث مقاومة التآكل والمتانة الميكانيكية والكفاءة الحرارية والخصائص البصرية، مما يجعلها مناسبة لتطبيقات مثل أجهزة الاستشعار والأجهزة الدقيقة والأجهزة الطبية الإلكترونية..

INTRODUCTION

Nanotechnology enables industry-wide adoption due to its exceptional physical properties, which provide compact weight and strong mechanical resistance, making it suitable for aerospace applications [1, 2]. Ti-6Al-4V shows exceptional compatibility with human body tissues, and scientists use it particularly for implant engineering applications[3, 4]. Magnetic sputtering enables precise control of thin-film composition and substantial control of film thickness. Research shows that film thickness plays an essential role in managing corrosion resistance, hardness, and fatigue resistance in different applications, thereby defining film performance optimization [5]. The properties of thin films can be tailored to application needs by controlling film thickness through proper processing. The development of Ti-6Al-4V enables its employment in several diverse environments that require high temperatures and high pressures. Ti-6Al-4V alloy is the primary choice for engineering applications and biomedical use because it offers top-tier strength, low weight, and outstanding corrosion protection. Magnetron sputtering provides the optimal solution for thin-film deposition on metal substrates. The target material is bombarded with plasma to create uniform layers.

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Through this process, researchers can achieve specific control over film thickness while determining its composition, as both characteristics directly influence material properties, including hardness and corrosion resistance [6]. The physical and mechanical properties change significantly with variations in film thickness. Research indicates that increasing thickness measurements alters the microscopic characteristics. Research on titanium films demonstrates that thickness management improves final material properties, making the material applicable to diverse uses [7, 8]. A research team studied the role of plasma thickness in magnetron sputtering for the deposition of Ti-6Al-4V films. The research aims to enhance the film structure, mechanical performance, and surface characteristics for multiple applications that require strong corrosion resistance and superior substrate bonding.

MATERIALS AND METHODS

Thin films of Ti-6Al-4V alloy were prepared using plasma sputtering technology inside a high-vacuum chamber. The initial vacuum pressure (10-5 bar) was maintained, and a high-voltage power supply was used. Stainless steel substrates were used and carefully cleaned in an ultrasonic bath to remove contaminants and surface impurities that might affect deposition quality. The magnetron sputtering system used to prepare the thin films consists of the following components:

1) Vacuum chamber: Operates in a high-vacuum environment to reduce interference from other gases, improving the quality of thin films. The internal structure includes a cathode, where the target material is fixed, and a positive electrode (anode), where the thin films are deposited.

2) High-voltage power supply: Provides the power needed for spraying.

3) Control systems: These include electronic systems for measuring pressure, temperature and voltage, allowing precise adjustment of operating conditions.

4) Cooling system: Maintains the system temperature within a certain range, especially during prolonged deposition processes.

These components work together seamlessly to produce thin films with tailored and desired properties. The deposition process was carried out under the following conditions: working pressure during deposition (10-5 bar), distance between the target and the substrate (5 cm), deposition was carried out at room temperature (27 ° C), and deposition times were (3, 6, and 9 min).

RESULTS AND DISCUSSION

Atomic energy microscopy imaging showed that the first sample, with a thickness of 18 nm and deposited within 3 minutes, exhibited specific surface properties (Figure 1).

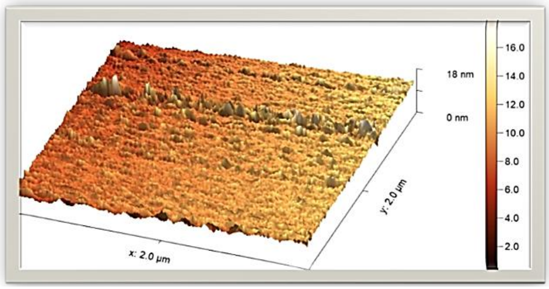

Fig. 1: Atomic energy microscope image of the prepared sample at the time of deposition (3 min).

Based on Figure 1, the surface structure shows slight variations in roughness, with a maximum height difference of approximately 18.3 nm. The surface appears relatively uniform, indicating that the layer deposited at this thickness is smoother. This smoothness enhances properties such as wear resistance and layer adhesion. Lower roughness improves properties such as corrosion resistance and biocompatibility. Layers with smooth surfaces (18 nm) are particularly suitable for applications requiring high biocompatibility or good wear resistance. The second sample has a thickness of 42 nm with a deposition time of 6 min. Increasing the thickness may cause the layer to lose its homogeneity, as shown in Figure 2, due to grain growth or defect accumulation during deposition, resulting in increased surface roughness. Rougher layers (42 nm) may be suitable for other

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applications, such as mechanical stabilization or improved adhesion to other materials. This topographic map indicates the presence of subtle surface features that may result from the material preparation process, such as physical deposition, or from the material's inherent nature. The maximum surface roughness (41.7 nm) is relatively high in nanotechnology applications and may affect material properties, such as adhesion. These findings are important for understanding surface roughness and topographic analysis, which are used to assess material quality in industries such as nanocoatings, solar cells, and semiconductors. Surface heights can directly influence interactions with light or fluids, as demonstrated in the study.

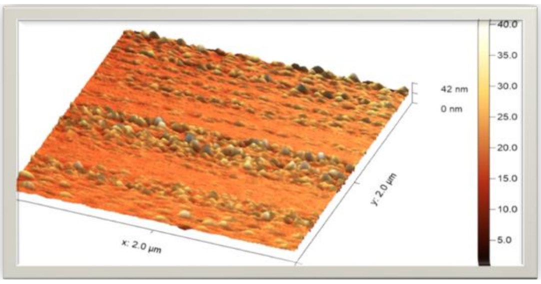

Fig. 2: Atomic energy microscope image of the prepared sample at the time of deposition (6 min).

Figure (3) represents an AFM image of the third sample with a thickness of (13 nm), where the deposition time was (9 min). In general, three-dimensional topographic analysis using AFM reveals subtle differences, as confirmed by a study of nanomaterial topography. These results are consistent with previous studies. [8-11] . AFM analysis reveals fine details of the material's surface, which helps evaluate its physical and chemical properties, such as adhesion and chemical activity. This is also consistent with [12] . These results are important, as nanoscale surface roughness can affect the performance of materials in applications such as nanocoatings, semiconductors, and optical devices. [13] .

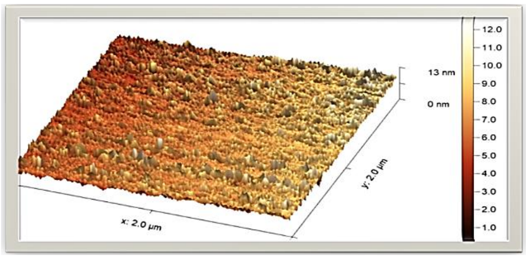

Fig. 3: Atomic energy microscope image of the prepared sample at the time of deposition (9 min).

Figure 4 shows the FESEM results for films deposited for 3 minutes, which appear flat with no noticeable nanoscale features. The absence of a nanoscale layer is evident because the process did not yield one. Therefore, FESEM did not detect any nanoparticles, as the surface lacked nanoscale deposits.

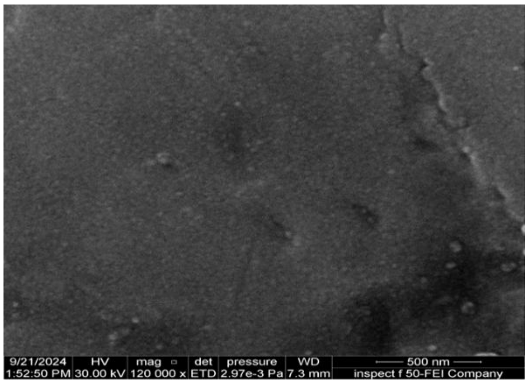

Fig. 4: FESEM image of the prepared sample at deposition time (3 minutes).

Figure 5 shows FESEM results for films deposited for 6 minutes, with measured particle sizes ranging from 33 to 43 nm. These sizes play an important role in electronic applications, especially in applications that require superior surface properties, such as corrosion resistance and high-temperature tolerance.

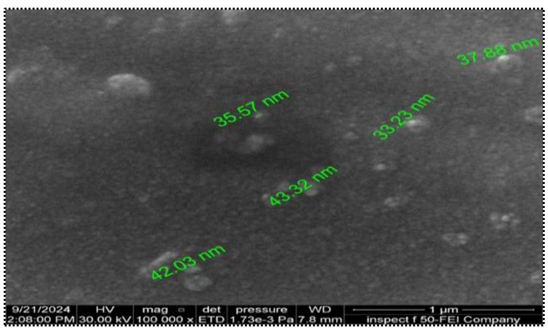

Fig. 5: FESEM image of the prepared sample at deposition time (6 minutes).

Figure 6 represents the FESEM results of the films deposited with a deposition time of 9 minutes. The results showed a range of particle sizes, with an average of 51.11 nm.

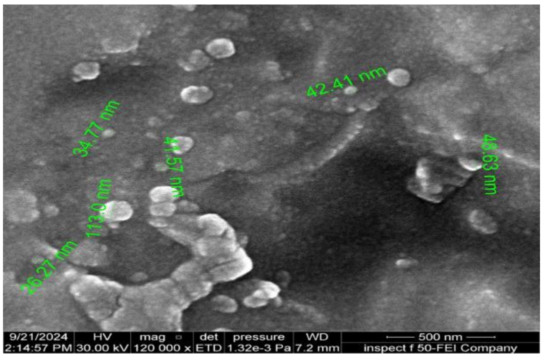

Fig. 6: FESEM image of the prepared sample at deposition time (9 minutes).

Ti-6Al-4V coatings offer high corrosion resistance, which is critical for electronic devices operating in harsh environments (such as marine, humid, or industrial environments). In electronic devices, metal components may corrode due to environmental factors or chemical reactions. These coatings provide greater corrosion resistance and improved material durability in applications that require high endurance under heavy use or friction.

CONCLUSION

Higher working pressures tend to increase particle size, while higher temperatures promote crystallinity and reduce particle dimensions, consistent with previous studies. The variability in particle sizes suggests potential heterogeneity in particle distribution. These differences may affect the film's mechanical properties, including toughness and hardness. Larger particles may introduce structural defects that affect corrosion resistance. In comparison, smaller particles can enhance electrical conductivity and improve wear resistance, potentially increasing film performance in both electronic and environmental applications. However, a wide range of particle sizes may lead to non-uniform film properties, potentially negatively affecting thermal efficiency or electronic response. Microscopic analysis confirms that layer-thickness control during magnetic sputtering is critical for determining the surface structure and influencing the film's mechanical and chemical properties. The combined use of AFM and FESEM provided high-resolution multidimensional analysis of the structures.

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Author contribution: Authors contributed equally to the study.

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