Investigating the Impact of Shot Materials on Surface Roughness in Ti6Al4V Alloy-Based Bone Implants treated by Shot Peening Process

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Abstract - This study explores the impact of different shot materials on the surface roughness of Ti6Al4V alloy-based bone implants treated with shot peening. Shot peening is a prevalent surface treatment method in the biomedical field used to enhance implant osseointegration. The choice of shot material can significantly influence surface morphology and, consequently, biological responses. This research examines the effects of various shot materials, including mild steel, stainless steel, glass beads, and alumina, on the surface roughness of Ti6Al4V alloy-based bone implants subjected to shot peening. Surface roughness measurements reveal distinct outcomes: glass beads result in the lowest roughness at 1.45 µm, while stainless steel leads to a higher roughness of 6.27 µm. These findings highlight the critical role of shot material selection in modulating surface characteristics essential for implant integration and performance. Understanding these variations provides valuable insights for optimizing implant design and enhancing biomedical applications.

Key Words: shot peening, shot materials, surface roughness, Ti6Al4V alloy

1.INTRODUCTION

The surface properties of orthopedic implants play a crucial role in determining their long-term success in clinical applications. The long-term prognosis for dental implants is remarkably positive, with exceptional survival rates. However, despite the generally high success rates observed in patients who are missing teeth, a minority may experience implant failures either during or after the process of osseointegration [1]. Primary implant failure, attributed to inadequate osseointegration, occurs in a small percentage of cases, estimated at 1–2% of patients [2]. On the other hand, secondary failures, often stemming from peri-implantitis, may manifest several years after successful osseointegration, affecting approximately 5% of patients [2-3]. The tissue response to the implant is predominantly influenced by the composition and texture of the implant surface. Textured surfaces, in contrast to smooth ones, offer a greater area for interaction with bone through the osseointegration process. Additionally, textured surfaces facilitate tissue in growth [4-5]. In order to improve osseointegration after insertion, there is a demand for novel technologies for modifying implant surfaces [6]. Various surface modifications have been implemented on implants through subtractive and additive techniques, encompassing physical methods such as turning and blasting, chemical approaches like acid etching and alkali treatments, electrochemical processes such as electropolishing and anodizing, deposition techniques like plasma-spraying and sol-gel coating, and biochemical methods involving the application of proteins.

Histomorphometric analyses have revealed enhanced bone apposition on surfaces subjected to sandblasting and acid etching. These investigations suggest that surface modifications contribute to improved osseointegration between the implant surface and bone. Additionally, a synergistic mechanism is proposed, highlighting the combined effects of macro-topographical alterations induced by sandblasting and micro-textural changes resulting from acid etching on the implant [7-8]. The surface of a machined implant typically features grooves and valleys that are predominantly aligned along the machining direction, as observed in various studies. Additionally, the surface layers undergo plastic deformation during the machining process. Depending on the specific machining parameters employed, the surface roughness values varied [9]. Grinding typically results in relatively coarse surface topographies. Utilizing an abrasive grade of 60 during grinding yields Ra values approximately around 1micron, while employing the coarsest grade may lead to high surface roughness [10]. In their study, Wang et al. [11] examined the effects of electron beam melting (EBM) processing parameters on the surface roughness of fabricated components. Additionally, Szymczyk et al. [12] explored the impact of surface modifications like polishing, sandblasting, and acid-polishing applied to Ti6Al4V implants manufactured via EBM, on critical biological properties. Their findings underscored the significant influence of surface modification on these biological properties. In numerous experimental investigations, the incorporation of various ions—such as Ca, P, Sr, F, NaOH, and Mg—into the implant surface has demonstrated a robust bone response [13-18]. Plasma treatment elevates the surface energy of the implant which increase wetting characteristics than the traditional surface clean [19-20]. In the ion implantation method, ions penetrate to 0.1 to 1 microns depth. This technique finds utility in certain dental implants to augment corrosion resistance by forming a titanium nitride layer [21]. Laser treatments offer a clean and straightforward method of surface modification and roughness measured in the range of 2.28 microns [22]. Clinical investigations have reported that laser-treated implants increased bone formation surrounding [23-24].

In recent years, 3D printing technology replaces traditional methods such as powder metallurgy, wrought, and casting processes for producing Ti64 medical implants [25-26]. In this study, the surface roughness results revealed distinct differences in surface roughness among the various manufacturing processes.

Among various surface modification techniques, shot peening has emerged as a promising method to enhance the

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mechanical and biological performance of implants, particularly those made from Ti6Al4V alloy, a widely used material in orthopedic surgery due to its excellent biocompatibility and mechanical properties [27-29].

However, beside the surface roughness influence on osteointegration, other key parameters such as fatigue, wear, and corrosion resistances must be evaluated for ensuring the implant permanency in the body for a long time [30]. For a more comprehensive understanding of the aforementioned points, Cappellini et al. [31] provided detailed explanations in their article with fig.1.

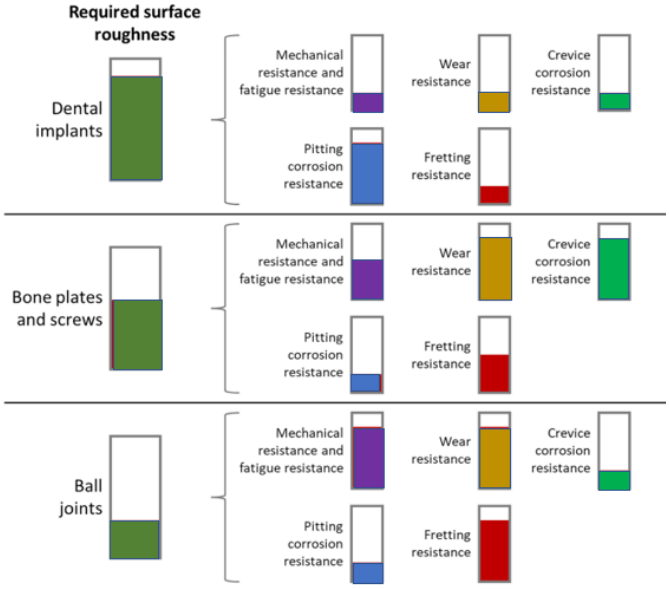

Fig -1: Surface roughness requirements [31]

Fig. 1 illustrates a comparative analysis of required surface roughness for dental implants, bone plates and screws, and ball joints, along with five essential parameters crucial for each application's success. These parameters both impact and are influenced by optimal surface roughness. Higher surface roughness compromises wear and fretting resistance, as observed in dental implants, while lower roughness mitigates fretting-related degradation and debris formation. Certain parameters, such as high pitting resistance, seemingly contradict high surface roughness requirements, necessitating alternative strategies for enhancing resistance without relying solely on surface finishing. A comprehensive analysis of osseointegration variables is imperative for devising effective strategies.

From the literature review, it is evident that surface roughness is required according to types of implant, viz, dental implants, bone plates and screws, and ball joints. Shot peening is generating such type of desired surface property by means of proper shot materials. The choice of shot material used in the peening process has been recognized as a key factor influencing surface roughness and, consequently, the biological response of the implant.

In this context, this study aims to explore the effect of different shot materials, including mild steel, stainless steel, glass beads, and alumina, on the surface roughness of Ti6Al4V alloy-based bone implants subjected to shot peening

2. EXPERIMENTAL METHODS

2.1 Materials

This study centers on the Ti6Al4V alloy, chosen as the primary material for its versatility in biomedical fields. Table 1 details the chemical composition of the base material.

Table -1: Chemical elements of the base material

Chemical elements	Al	V	Fe	C	Ti
Wt%	5.8	3.9	0.4	0.15	balance

2.2 Shot peening processes

The experimental methods, a pressure blaster machine is employed for shot peening, as shown in Figure 2. The precise parameters chosen for the shot peening process are listed in Table 2. The nozzle was oriented perpendicular to the specimen throughout the procedure.

Table -2: Shot peening parameters

Sl.No	Parameters	units
1	Peening pressure	4 Bar
2	Peening distance	100 mm
3	Peening duration	10 sec

Fig -2: Shot peening machine

2.3 Shot materials

Four different shots materials used for this investigation, viz, mild steel, stainless steel, glass beads and alumna. These shots materials are shown in fig.3. The properties of shots materials are presented in table 3.

Table -3: Properties of shots materials

Sl.No	Shots material	Specific gravity (g/cc)	Hardness
1	Mild steel shots	7.8	130 BHN
2	Stainless steel shots	7.9	250 BHN
3	Glass beads	2.6	7 Mohs
4	Alumina shots	3.9	9 Mohs

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Fig -3: Shots materials

2.4 Microstructure and surface roughness measurements

A scanning electron microscope (SEM) was employed to magnify the surface enabling a detailed comparison of the effects of shot peening and without shot peening on the surface characteristics. A Mitutoyo roughness tester, featuring a stylus with a length of 4 mm and operating at a driving speed of 0.2 mm/s, was employed to assess the surface roughness, specifically the average roughness (Ra).

3. RESULTS AND DISCUSSIONS

Figure 4 presents SEM images of the Ti6Al4V alloy under four different shot peening conditions: mild steel shots, stainless steel shots, glass beads, and ceramic shots. In the SEM images, the untreated surface exhibits consistency, regularity, and uniformity. However, the surfaces subjected to shot peening display roughness and irregularities, indicating damage to the Ti6Al4V alloy surface caused by the shot peening process. Further investigation into the surface roughness of these specimens reveals noticeable differences among them, highlighting the influence of different shot types on surface characteristics.

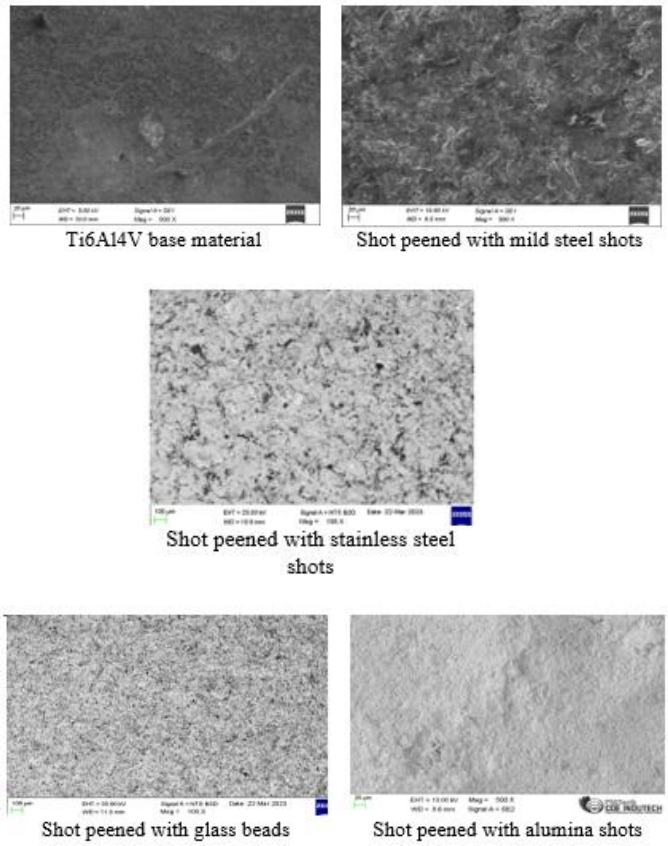

Fig -4: SEM images of Ti6Al4V and Shot peened of Ti6Al4V with different shots materials

The surface roughness values for the base material Ti6Al4V alloy is shown in Table 4 and fig.5. The average surface roughness value is 0.49 µm.

Table -4: Surface roughness of Ti6Al4V alloy

Condition of sample	Trial No.	Roughness value (R_a)	Average (R_a)
Ti6Al4V sample	1	0.42	0.49
	2	0.46	
	3	0.57	
	4	0.40	
	5	0.64	

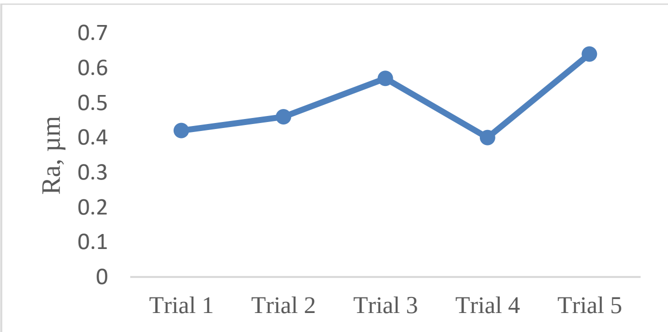

Fig -5: R_a for Ti6Al4V alloy

The surface roughness values for the specimen subjected to shot peening using mild steel shots is shown in Table 5 and fig.6. The average surface roughness that can be produced by shot peening using mild steel shots is 2.3 µm.

Table -5: Surface roughness of Ti6Al4V alloy peened with mild steel shots

Condition of sample	Trial No.	Roughness value (R_a)	Average (R_a)
Ti6Al4V peened with mild steel shots	1	2.24	2.3
	2	2.32	
	3	2.66	
	4	2.29	
	5	2.23	

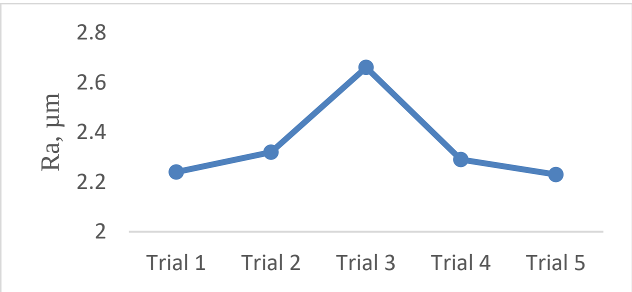

Fig -6: R_a for Ti6Al4V alloy peened with mild steel shots

The surface roughness values for the specimen subjected to shot peening using stainless steel shots is shown in Table 6 and fig.7. The average surface roughness that can be produced by shot peening using stainless steel shots is 2.73 µm.

Table -6: Surface roughness of Ti6Al4V alloy peened with stainless steel shots

Condition of sample	Trial No.	Roughness value (R_a)	Average (R_a)
Ti6Al4V peened with stainless steel shots	1	6.25	6.27
	2	6.28	
	3	6.26	
	4	6.29	
	5	6.28	

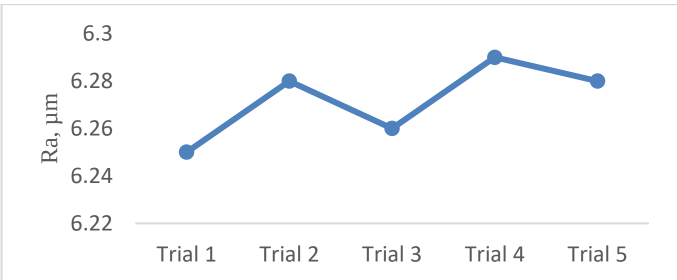

Fig -7: R_a for Ti6Al4V alloy peened with stainless steel shots

The surface roughness values for the specimen subjected to shot peening using glass beads is shown in Table 7 and fig.8. The average surface roughness that can be produced by shot peening using glass beads is 1.26 µm.

Table -7: Surface roughness of Ti6Al4V alloy peened with glass beads

Condition of sample	Trial No.	Roughness value (R_a)	Average (R_a)
Ti6Al4V peened with glass beads	1	1.49	1.45
	2	1.43	
	3	1.45	
	4	1.48	
	5	1.42	

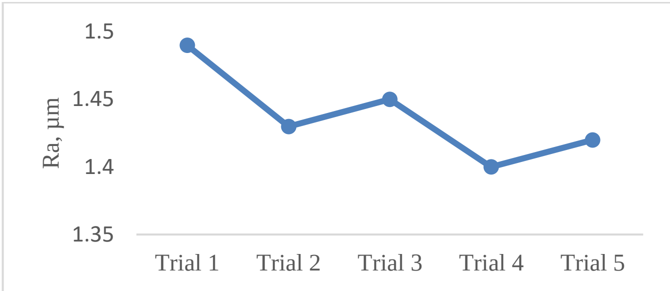

Fig -8: R_a for Ti6Al4V alloy peened with glass beads

The surface roughness values for the specimen subjected to shot peening using alumina shots is shown in Table 8 and fig.9. The average surface roughness that can be produced by shot peening using alumina shots is 1.72 µm.

Table -8: Surface roughness of Ti6Al4V alloy peened with alumina shots

Condition of sample	Trial No.	Roughness value (R_a)	Average (R_a)
Ti6Al4V peened with alumina shots	1	1.73	1.72
	2	1.71	
	3	1.75	
	4	1.76	
	5	1.71	

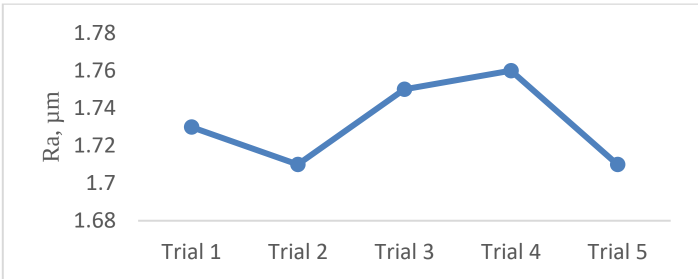

Fig -9: R_a for Ti6Al4V alloy peened with alumina shots

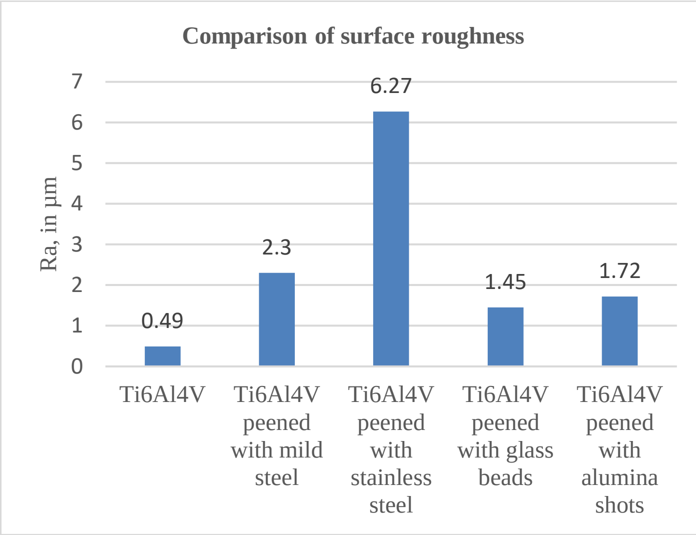

Fig -10: surface roughness of shot peened samples

Figure 10 presents the surface roughness (Ra) of untreated and shot peened samples with different shot materials. The untreated sample exhibited a smooth surface with an Ra value of 0.49 µm, indicating good initial surface finish. In contrast, shot peened samples displayed higher surface roughness, with Ra values ranging from 1.45 µm to 6.27 µm. Among the shot peened samples, those treated with stainless steel shots exhibited the highest surface roughness (6.27 µm), followed by mild steel (2.3 µm), alumina (1.72 µm), and glass beads (1.45 µm). The observed differences in surface roughness can be attributed to the hardness and specific gravity of the shot materials. Stainless steel shots, with higher hardness and specific gravity, resulted in deeper surface penetration and more pronounced surface modifications, leading to increased roughness. Conversely, shot peening with glass beads, characterized by lower hardness and specific gravity, yielded comparatively lower surface roughness.

Referring to fig.1, Indeed, elevated surface roughness values often correlate with diminished resistance to fatigue, wear, crevice corrosion, and fretting. However, they can enhance resistance to pitting corrosion, as exemplified in the context of dental implants. Certainly, diminished surface roughness values typically correlate with decreased resistance to pitting and crevice corrosion. Conversely, they enhance resistance to wear, fatigue, and fretting, as observed in ball joints.

3. CONCLUSIONS

Shot peening was conducted on a Ti6Al4V alloy utilizing various shot materials including mild steel, stainless steel, glass beads, and alumina shots, leading to the following conclusions:

- Substantial variances were observed in the surface roughness of specimens subjected to shot peening with various shot materials.
- The untreated specimen displayed a polished surface, boasting an Ra value of 0.49 µm, denoting a commendable initial surface quality.
- Within the shot peened samples, those treated with stainless steel shots showcased the most elevated surface roughness at 6.27 µm, trailed by mild steel at 2.3 µm, alumina at 1.72 µm, and glass beads at 1.45 µm.
- The necessity for surface roughness is higher for dental implants compared to ball joints, where the requirement is lower.

Moreover, comprehending the impact of shot materials on surface roughness aids in pinpointing suitable implant applications, thereby fostering progress in biomaterials science and orthopedic surgery.

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