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ORIGINAL PAPER

Residual Contaminations of Silicon-Based Glass, Alumina and Aluminum Grits on a Titanium Surface After Sandblasting

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Abstract Sandblasting (grit-blasting) is a commonly used surface treatment method for roughening the surface of titanium dental implants. Today, alumina (Al_2O_3) grits with various sizes are widely used for this purpose, due to their good surface roughening effects. However, sandblasting with Al_2O_3 grits also introduces impurities to the surface of the Ti implant, which may adversely affect the osseointegration process of the implant. This raises the question as to the use of Al_2O_3 as the most suitable type of sandblasting grit, considering the contaminations to the titanium implant in addition to roughening effects. This study evaluates Al_2O_3, a silicon-based (silica, SiO_2) glass and Al metal grits in terms of both roughing effects and contamination to the titanium implant surface. Thirty commercially pure grade 2 (CP2) titanium plates were grit-blasted using various grits. Surface roughness average (R_a) of all grit-blasted plate was measured. In addition, SEM/EDX analysis was performed to detect the morphology and elements on the titanium specimen surface before and after sandblasting. Results showed that each type of grits has its own advantages and disadvantages. This said, Al_2O_3 might be the most suitable material among the three tested grit materials for sandblasting a titanium dental implant surface.

Keywords Titanium dental implant · Osseointegration · Sandblasting · Surface analysis · Silica glass · Glass powder

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1 Introduction

Titanium and its alloys are currently the most widely used materials for the fabrication of dental subgingival implants, due to their desirable mechanical properties, extremely high biocompatibility, and the ability to osseointegrate with living bone [1]. Osseointegration leads to stabilization and a strong and direct bonding between the implant surface and adjacent bone, without intermediate layers of scar tissues, or cartilage [2]. Once osseointegration is achieved, the implant is considered to be completely accepted by the host bone, with direct stable, structural and functional connections [2]. Hence, strong and rapid osseointegration is considered to be the key for the success of titanium dental implantation. Previous research has found that implant surface features, such as roughness, chemical composition, cleanliness (purity), wettability and electrical charges, play important roles in the rate and quality of osseointegration [3, 4]. That said, the surface treatment is usually applied on the titanium implant to improve and ensure its osseointegration ability.

Bearing in mind the amount of all the surface factors, titanium dental implant surface roughness is known to be of particular importance in influencing the bone-to-implant contact. Many studies have revealed that roughened titanium implants osseointegrate better than the smooth ones, in terms of both quality and rate [5, 6]. The precise reason is still poorly understood, and more researches are needed to look for the optimum titanium dental implant topography. Sandblasting (grit-blasting) using a silica-coated alumina powder [7], is a commonly used surface pretreatment method for titanium and some other biomaterials for adhesion promotion. This takes place by transferring tribochemically a freshly embedded silica layer onto the

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grit-blasted surfaces. Such silica-coated titanium surfaces are then immediately followed by silanization to enhance resin bonding on them in various dental applications [8, 9]. The main effects of sandblasting include cleansing and roughening the titanium surface, whereas both of them would promote the osseointegration ability of titanium [1, 3]. Our recent studies revealed that sandblasting also modifies the surface charge of the titanium material, which may also promote osseointegration [10].

When a dental implant's surface is sandblasted, it is important to choose an appropriate material and size of the blasting grits to be used. Traditionally, the main consideration for choosing the grits is their surface roughening effects, i.e., whether the grit-blasted titanium implant will develop a clinically suitable surface roughness. Based on this criterion, a common choice of the blasting material is alumina (aluminum trioxide, Al_2O_3), which is understood to create good surface textures on the titanium implant. One often neglected aspect, however, is that sandblasting also has a major drawback: it introduces impurities to the titanium material due to residuals of the blasting grits. Such impurities are believed to negatively affect the biocompatibility, bioactivity, corrosion resistance, mechanical properties and most importantly, the osseointegration of the titanium material [11]. This is in particular a problem for Al_2O_3 grits, because they tend to adhere (embed) onto the titanium surface during sandblasting, and the resulting impurities are rather difficult to remove [11–13]. One type of grit-blasting material that might avoid this problem is titania (TiO_2). However, as TiO_2 is as hard as the titanium surface, its roughening effects are inferior to Al_2O_3 [3]. Consequently, sandblasting with TiO_2 grits is less effective in creating a suitable surface roughness for promoting the titanium implant's osseointegration [3]. So far, we are not aware of a systematic comparison of various blasting materials considering both their roughening effects and the impurities introduced on the titanium surface.

This study aims at comparing and contrasting various powder materials and their grit sizes for sandblasting titanium by evaluating both the surface topography and the residual impurities of the blasted titanium surface. The hypothesis for this study was that using silicon-glass beads or aluminum powders in sandblasting titanium surfaces would introduce less impurities than using Al_2O_3 grits. For a given blasting material, a larger grit size would leave less residues on the titanium surface.

2 Materials and Methods

2.1 Titanium Plates Preparation

A total of 35 commercially pure grade 2 (CP2) titanium plates (15 mm × 15 mm × 1 mm) were machine-cut and polished by abrasive SiC papers in the sequence of 220, 320, 500 and 1000-grits with a polishing machine (LUNN Major, Struers, Ballerup, Denmark) under running water. Next, they were ultrasonically cleansed (Decon Ultrasonics Ltd, Hove Sussex, England) by acetone for 15 min and then dried in an incubator at 37 °C overnight. These 35 plates were randomly divided into 7 study groups with 5 plates in each. One group of polished titanium plates was used as control, while the others were sandblasted by different grits.

2.2 Sandblasting

The blasting materials were 110 μm and 50 μm alumina (Al_2O_3) powders (Renfert GmbH, Germany), 150–300 μm and 45–75 μm silica-glass beads (Langfang Olan Glass

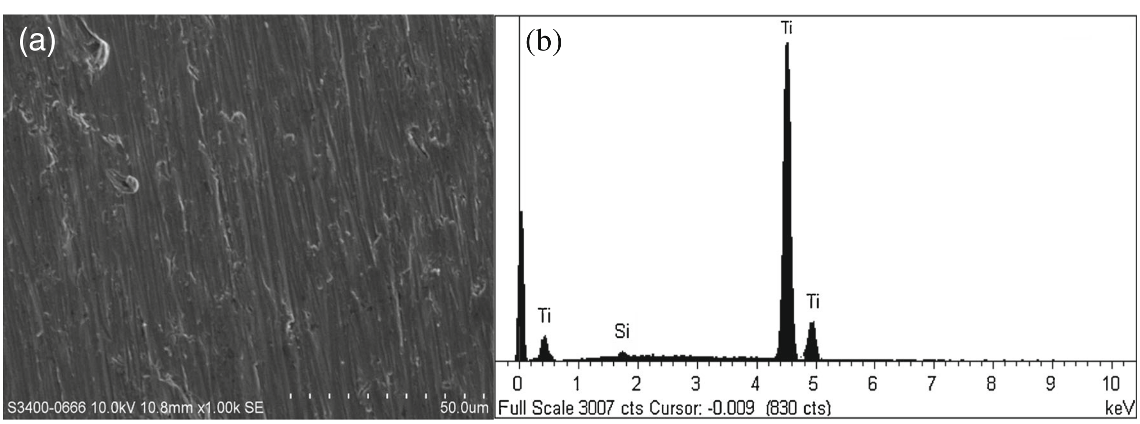

Fig. 1 **a** SEM image (×1000 magnification) **b** EDX analysis of machined and polished titanium plate

Beads Co., Ltd, PR China), and 250 μm and 44 μm aluminum powders (Yee Lee Industrial Chemical Ltd. Hong Kong). The glass beads were claimed to have more than 72 % SiO_2 by the manufacturer.

Sandblasting was powered with a constant air pressure of 3.4 bar by using a pen type hand piece blaster (SMC Corporation, Tokyo, Japan). The duration for an even treatment was set to be 15 s per plate. The blasting nozzle was always held perpendicular to the titanium surface. The distance between the nozzle and titanium plate was fixed at 10 mm [7].

2.3 Surface Analysis for Titanium and Blasting Materials

Scanning electron microscopy analysis (SEM, S-3400N, Hitachi, Tokyo, Japan) was performed at 20.0 kV operating voltage to visualize the surface morphology of the titanium plates before and after sandblasting, as well as of the blasting powders used. Energy-dispersive X-ray spectroscopy (EDX, S-3400N, Hitachi, Tokyo, Japan) was employed for elemental analysis on the titanium surface before and after sandblasting, to determine the impurities on the titanium

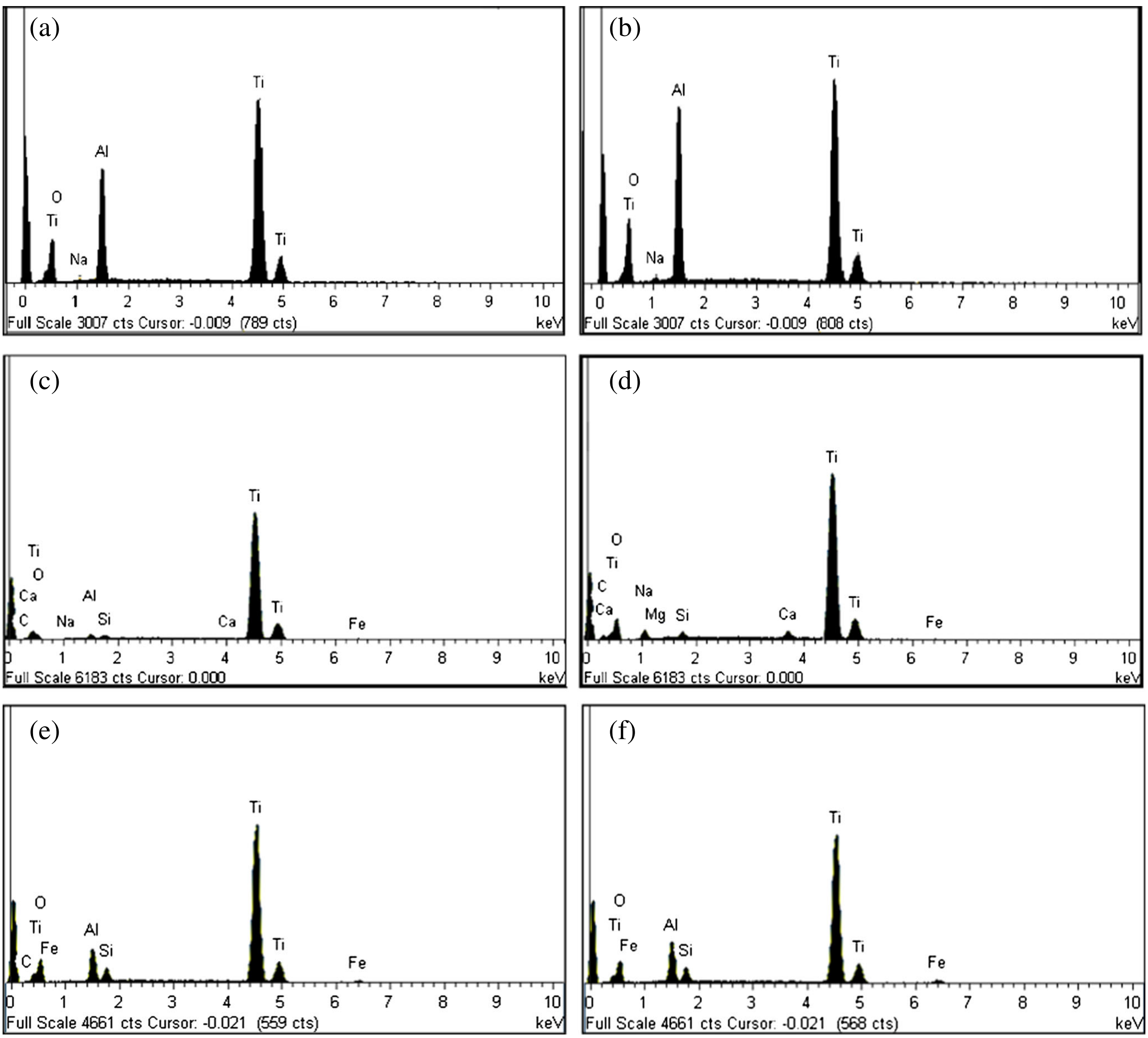

Fig. 2 EDX analysis for the titanium plates sandblasted by: **a** Al_2O_3 grits with average diameter of 110 μm; **b** Al_2O_3 grits with average diameter of 50 μm; **c** glass beads with diameter 150-300 μm; **d** glass beads with diameter 45-75 μm; **e** aluminum grits with diameter 250 μm; **f** aluminum grits with diameter 44 μm

surface introduced by sandblasting. EDX analysis was also performed on the blasting powders to confirm whether the impurities indeed come from the grits.

2.4 Surface Roughness

To contrast and compare the surface roughness of the titanium plates blasted with the powders used, the surface roughness average (R_a) of the smooth and sandblasted titanium plates was measured by a Surtronic 3+ (Taylor Hobson Ltd. Leicester, UK) device. The measuring distance was set at 0.8 mm [14]. Each titanium plate was measured twice in two perpendicular directions. For each group of titanium plates, the average R_a value was reported.

3 Results

3.1 Titanium Surface Analysis before Sandblasting

Figure 1a shows the SEM image of a machine-cut and polished titanium. Figure 1b reveals the EDX results of this titanium plate. It can be observed that the surface is relatively smooth and clean. A small amount of Si (1.39 atomic-%) was found as an impurity on the titanium surface.

3.2 Impurities Introduced by Sandblasting

Results from EDX analysis of titanium plates sandblasted by Al_2O_3 (110 μm and 50 μm), silica-glass beads (150–300 μm and 45–75 μm) and Al grits (250 μm and 44 μm) are shown in Fig. 2a–f. Table 1 shows the elemental analysis results, by atomic percentage, on the surface of the titanium plates before/after sandblasting, and the corresponding blasting grits. They illustrate the types and quantities of the impurities on the titanium surface before and after sandblasting.

For Al_2O_3 blasted titanium, the Si content on the titanium surface before sandblasting had been completely removed. However, a considerable amount (> 13 atomic-%) of Al was found.

Regarding silica-glass beads, a relatively small amount of residues was left on the titanium surface compared to the results of Al_2O_3 grits. Smaller grit sizes lead to a smaller amount of impurities. However, compared to Al_2O_3 grits, sandblasting with silica-glass beads lead to a larger number of elements in the impurities. Iron (Fe) was found on the titanium plates after sandblasting for both of the silica-glass bead blasted groups, in which Fe was not found in the silica-glass beads themselves.

For the Al powders used, the quantities and types of contaminations were between those in the results of Al_2O_3 grits and silica-glass beads. Similar to the other two grit materials, larger Al grits left less residues on the titanium surface. Si was found on the titanium surface after sandblasting with Al powder.

3.3 Titanium Surface Roughness

SEM images for Al_2O_3 grits (110 μm and 50 μm), silica-glass beads (150–300 μm and 45–75 μm) and Al powders (250 μm and 44 μm) are shown in Fig. 3a–f respectively. In Fig. 4a–f are the SEM images of titanium surfaces sandblasted by these powders. They visualize the blasted titanium surface roughness. Table 2 shows the mean values of surface roughness average (R_a) for all experimental groups. Different types of powders showed various effects in roughening titanium.

Table 1 Elemental analysis (atomic-%) on the surface of test titanium and blasting grits (Ti and O not reported)

Group	Procedure	Al	Ca	Na	Si	C	Fe	Mg
0	Machined and polished Ti	——	——	——	1.39	——	——	——
1	Ti blasted by 110 μm Al_2O_3 powder	13.18	——	0.46	——	——	——	——
	110 μm Al_2O_3	39.37	——	1.62	——	——	0.49	——
2	Ti blasted by 50 μm Al_2O_3 powder	15.77	——	0.71	——	——	——	——
	50 μm Al_2O_3	29.13	——	0.32	——	10.07	——	——
3	Ti blasted by 150-300 μm glass beads	1.78	0.11	0.32	1.06	7.39	0.16	——
	150–300 μm glass beads	0.31	1.11	8.71	12.75	8.86	——	1.65
4	Ti blasted by 45–75 μm glass beads	——	0.79	3.05	0.78	9.37	0.06	0.05
	45–75 μm glass beads	0.36	2.34	8.01	19.89	4.92	——	1.65
5	Ti blasted by 250 μm Al grits	6.26	——	——	1.81	4.28	0.52	——
	250 μm Al grits	22.84	——	——	2.19	8.61	6.63	——
6	Ti blasted by 44 μm Al grits	7.92	——	——	2.20	——	0.86	——
	44 μm Al grits	32.31	——	0.10	0.12	1.49	0.44	——

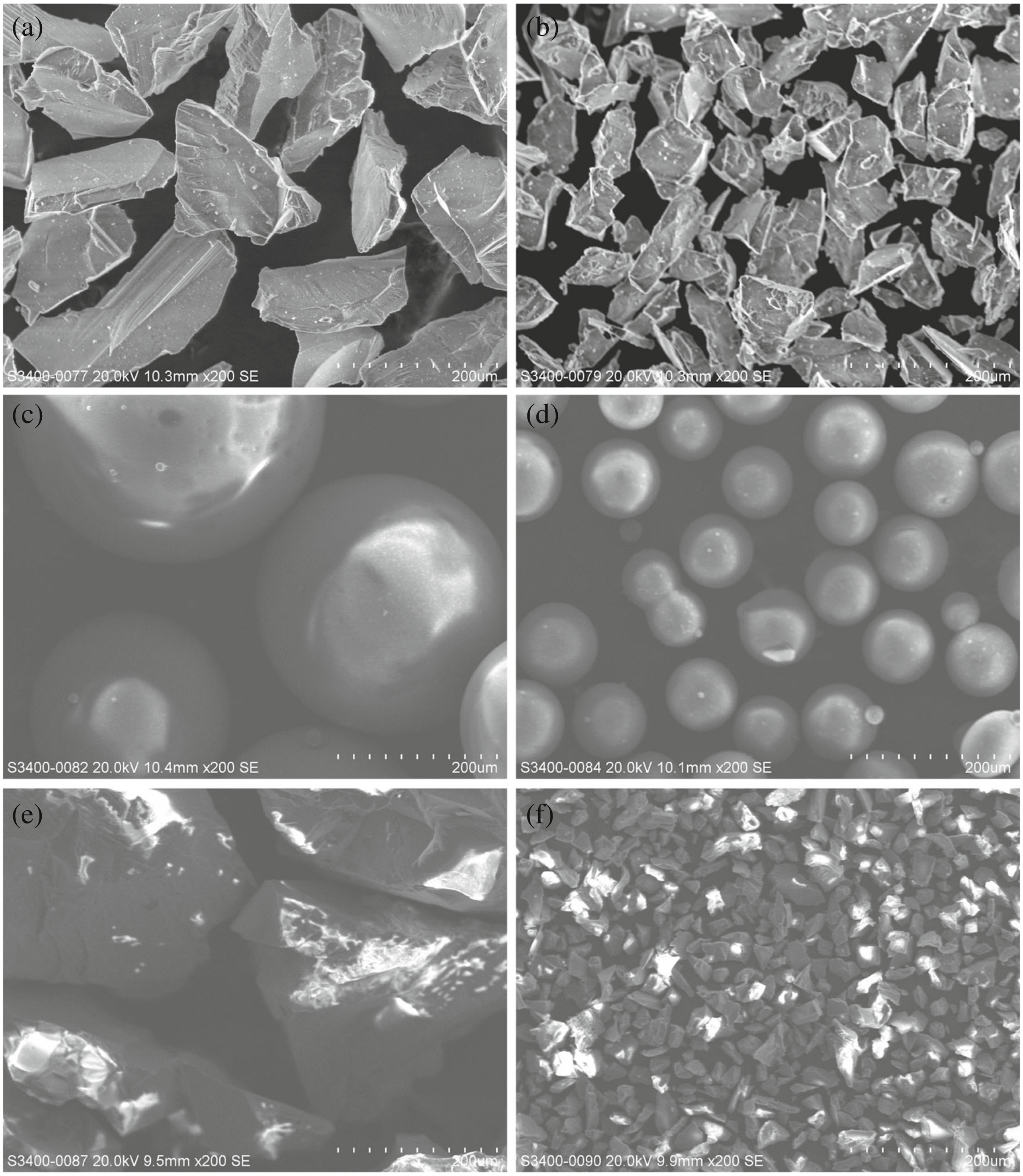

Fig. 3 SEM micrographs (×200 magnification) of blasting materials: **a** Al_2O_3 powder with diameter 110 μm; **b** Al_2O_3 powder with diameter 50 μm; **c** glass beads with diameter 150–300 μm; **d** glass beads with diameter 45–75 μm; **e** aluminum grits with diameter 250 μm **f** aluminum grits with diameter 44 μm

4 Discussion

Numerous studies had demonstrated that Al_2O_3 roughened titanium dental implants obtained better osseointegration with living bones than the smooth ones [15, 16]. In comparison, surface roughness created by silica-glass beads or 44 μm Al powder was much finer and 250 μm Al grits produced rather poor roughness results.

Contamination of titanium dental implants during casting is a well-reported and known problem [17]. Such contamination not only adversely affects the characteristics of the titanium surface, but also causes metal ion release into the host tissues, which may potentially have both local and distant toxic effects [11]. The impurities in the titanium implant surface have been found to be the cause of metallic elements in the surrounding tissues which is a major

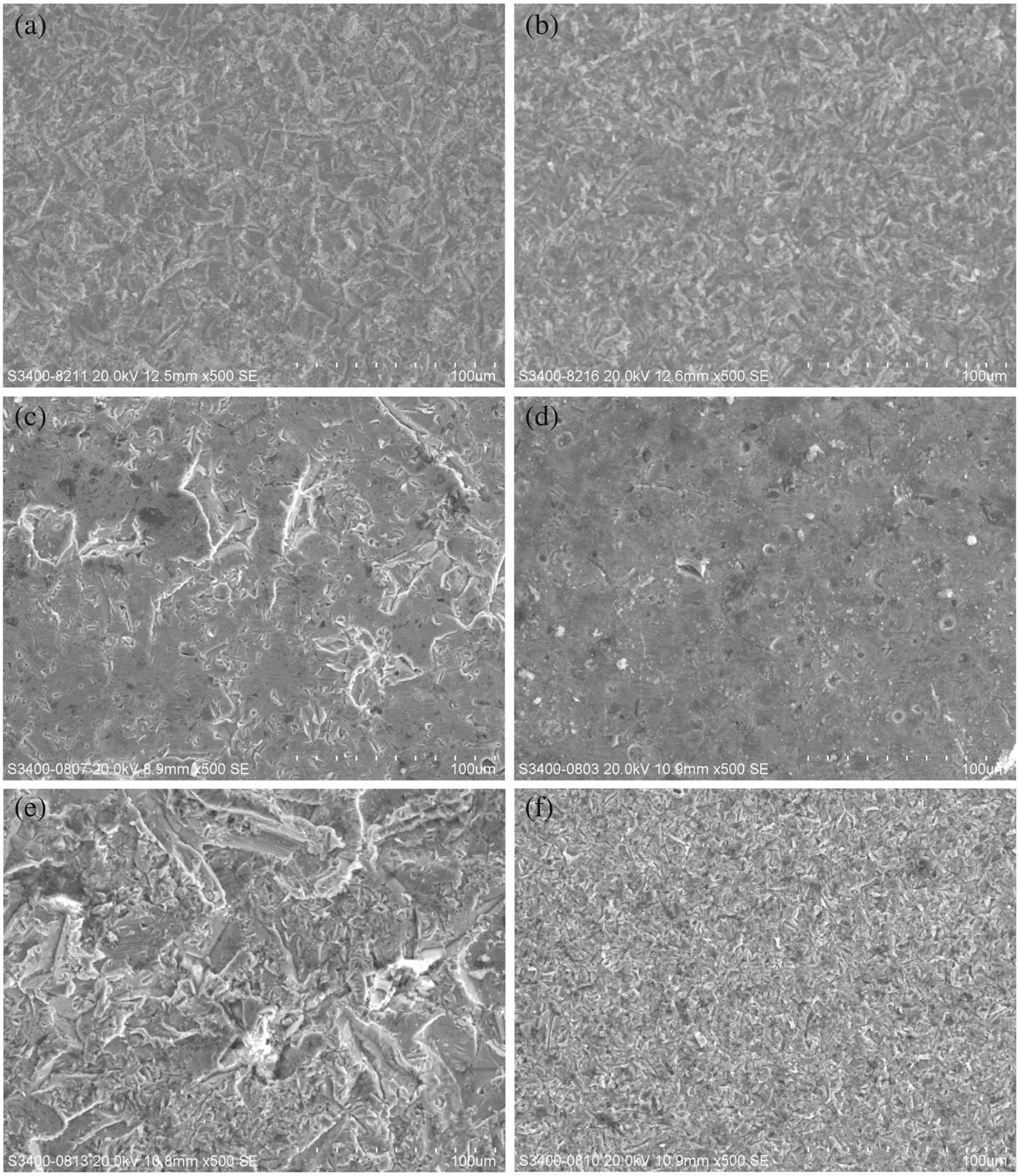

Fig. 4 SEM micrographs ($\times$ 500 magnification) of the titanium plates sandblasted by: **a** Al_2O_3 grits with average diameter of 110 μm; **b** Al_2O_3 grits with average diameter of 50 μm; **c** glass beads with diameter 150–300 μm; **d** glass beads with diameter 45–75 μm; **e** aluminum grits with diameter 250 μm; **f** aluminum grits with diameter 44 μm

Table 2 Average R_a values of titanium surface for all experimental groups

	Machined and polished Ti	Al_2O_3 110μm	Al_2O_3 50μm	Glass beads 150–300 μm	Glass beads 45–75 μm	Al 250 μm	Al 44 μm
R_a (μm)	0.040	0.760	0.551	0.448	0.332	0.856	0.276
SD	0.003	0.060	0.057	0.034	0.078	0.089	0.020

concern [11]. Therefore, cleaning such impurities is an important part in the surface treatment of titanium dental implants.

Sandblasting is a commonly used method to clean a metal surface, to remove the impurities on the metal surface. On the other hand, sandblasting may also introduce new impurities to the metal surface due to the remaining fragments of the blasting grits. The current results showed that among the blasting grits (powders) used in the experiments, Al_2O_3 grits were the most effective in removing existing impurities (in this case mainly Si) off the titanium surface. However, sandblasting with Al_2O_3 also introduced a large amount of Al onto the titanium surface which means the fragments of Al_2O_3 grits tend to embed into the titanium surface. Smaller Al_2O_3 grits introduced more residues than the larger ones. This would be explained as below, i.e., both Si and Al impurities adversely affected the surface of titanium dental implants. Hence, in terms of titanium surface cleaning, Al_2O_3 had no clear advantage over other materials as blasting grits.

For silica-glass beads, as they already contained a certain amount of Si, it was more difficult to describe their ability in removing impurities (such as Si) on titanium. Fe was found on blasted titanium surface and it probably originated from the blasting machine (e.g., the blasting pen), and adhered to the glass beads during sandblasting.

Si was found on the titanium surface after sandblasting with 44 μm Al powder, while the powder itself didn't contain this element. This result indicated that using 44 μm Al was not as effective as Al_2O_3 grits in terms of removing existing impurities on the titanium surface. Given this, 250 μm Al grits created a relatively poor surface roughness, which had a high standard deviation in its R_a values. A likely reason might be that these grits were too large and heavy for the current experimental blasting machine and air pressure. Given the same grit material, a larger grit size leads to a higher surface roughness in average.

In general, Si is an important element and constituent in a vast amount of biomaterials [18]. Si-based dental biomaterials include E-glass fibre reinforced composites [19], the use of E-glass fibres as denture reinforcement [20] and Si-based sand-blasted coatings for adhesion promotion [7] by using synthetic organo-Si compounds for chemical coupling [21]. However, it is believed that the presence of high levels of released Si ions at a local level could be toxic, leading to cell death [22, 23]. It is noteworthy that the exact mechanism of how the Si affects the interaction between the titanium implant surface and its adjacent tissue is still somewhat poorly understood, and merits further investigation [24].

Although Al_2O_3 has been widely used in dentistry in various forms [25, 26] due to its low reactivity in physiological media, the toxicity of soluble aluminum is well known and reported [27]. After implantation, the fragments of Al_2O_3 blasting grits embedded in the titanium substrate may lead to the release of Al ions into the surrounding tissues, due to degradation in the physiological environment [28]. Furthermore, Al_2O_3 impurities are known to compromise the corrosion resistance of titanium in a physiological environment [29]. Al_2O_3 impurities on the titanium surface are also difficult to remove, since they are insoluble in acid, and remain after ultrasonic cleaning and sterilization. In addition, the negative surface charge has been considered as an essential aspect for implant osseointegration [10]. However, when the cations of Al and Si are being adhered on the Ti surface, the overall magnitude of negative charge at the surface would decrease. Thus, the intimate bone-implant bonding after implantation might be compromised.

Besides cleansing the titanium surface, another important effect of sandblasting is obtaining a certain necessary level of surface roughness. Previous research has shown that titanium dental implants with suitably rough surfaces demonstrated superior clinical outcomes than those with smooth surfaces [1]. Sandblasting with Al_2O_3 grits has been shown to produce desirable level of surface roughness on the titanium dental implant [29]. Hence, in this aspect, Al_2O_3 grits still have a clear advantage over other types of blasting materials. Nevertheless, the fact that Al_2O_3 grits introduce large quantities of impurities to the titanium surface suggests that there remains much room for improvements in the sandblasting process as a surface treatment method for Ti-based biomaterials. An interesting direction for further investigations might be to discover better powder materials as blasting grits that could achieve both a desirable level of surface roughness and purity for Ti-based dental implants. The hypothesis of this study has been fully supported by the results.

5 Conclusion

This study suggests that sandblasting the titanium surface with Al_2O_3 grits leaves more impurities than with SiO_2 glass or Al grits. However, Al_2O_3 is more effective in removing existing Si contaminants on the polished titanium surface than SiO_2 glass or Al grits. Given the same material, a larger grit size introduces less residues as observed in this study.

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