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Original Article

Influence of Fiber Laser (1064 nm) on Shear Bond Strength of Titanium Abutment and Resin Cement

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Abstract

Introduction: The present study was performed to evaluate the influence of a 1064 nm fiber laser on shear bond strength (SBS) at the interface of titanium and resin cement.

Methods: Forty titanium discs of 6 mm × 3 mm (diameter and thickness respectively) were categorized into four groups (n = 10): control group without any surface treatment and three groups treated with a fiber laser with 81 ns pulse duration, 30 kHz frequency, 10 000 mm/s scanning speed, 0.05 mm spot size, and different average power values (3, 5 and 7 W) depending on the tested group. Titanium disc characterization was performed by the scanning electron microscope (SEM) and surface roughness tester. Phase analysis was achieved using an X-ray diffractometer (XRD). Following these tests, resin cement application to titanium discs was performed. SBS values were determined by the universal testing machine. After debonding, the surface of titanium discs was examined by the stereomicroscope for the determination of failure modes. Data analysis was performed using analysis of variance (ANOVA) and Tukey HSD tests ($\alpha = 0.05$).

Results: A higher surface roughness value was observed in the 7 W group followed by the 5 W and 3 W groups, and the lowest surface roughness was in the control group. Additionally, the lowest SBS value was obtained from the control group and the highest SBS value was obtained from the 7 W group followed by the 5 W and 3 W groups.

Conclusion: SBS between titanium abutment and resin cement can be significantly enhanced by using a fiber laser as a surface treatment considering tested laser parameters; additionally, a positive association between surface roughness and SBS was noted in the experimental groups.

Keywords: Fiber laser; Titanium abutment; Shear bond strength; Resin cement; Surface roughness.

Introduction

Titanium with its exceptional properties and superior biocompatibility made a noticeable entry in dentistry. It is a material with low density and modulus of elasticity and is highly resistant to corrosion; also, it has a suitable strength-to-weight ratio and excellent thermal conductivity.[1,2]

Because of these good properties and tolerance in living tissue with its flexibility for modification and coating, titanium has been widespread to be used in the field of implantology.[3,4] Pure titanium showed a great response and support to different methods of surface modification, including lasers in surface fixture modification.[5] Furthermore, advanced researches considering coating with biological material and stem cells project showed promising results.[6,7]

One of its applications is in the fabrication of implant supported prosthesis.[8] The connection of the final restoration to the implant abutment can be via either a screw or cement. The most important advantages of screw-retained restoration are retrievability and good response of soft tissue,[9,10] while advantages of cement-retained restoration are excellent esthetic, reduced technique sensitivity, ability to compensate improperly inclined implant, fitted passively and easily cleaned,[9] therefore cement retained restoration is more preferable.[11] The security of retention between the implant abutment and crown is the main factor that contributes to the success of cemented restoration.[12] The abutment taper, surface roughness, surface area, and cement type are factors that affect the bonding of cemented restoration.[13] Retention of the cemented restoration is enhanced by surface roughness because of the increased surface area through the creation of micro-retentive grooves and ridges.[14]

Various techniques were used to enhance bonding characteristics by the surface modification of titanium abutment, such as sandblasting, acid etching, electro-discharge machining, grinding with a bur, or a combination of these methods. Studies have shown that these techniques increased the bond strength at various amounts.[11,15,16] With the advancement in technology, lasers have been used for titanium surface modification because

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they are highly efficient and easily used. Laser treatment was suggested by many authors as a substitutional method of surface treatment for increasing the surface roughness of titanium abutments and enhancing their retention.[11,12,15,17]

The modern products of laser technology are fiber lasers, which play a role in dentistry because these lasers are suitable for biomedical applications and they can emit very high power within a short period.[18] Fiber lasers have a powerful effect on the surface of the material, causing less thermal damage when compared with other lasers.[19,20] Fiber lasers have very high repetition rates, which in turn enhance the removal process efficiency by reducing laser pulse energy needed for the ablation process and making the cooling of the ablation process possible.[18] Furthermore, using the fiber laser provides several advantages as the ability to predetermining or selecting the exact area need to be irradiated and sine it perform irradiation according to the set data automatically this results in a more homogenous etching pattern and reduce the need for further equipment or devices usually used for standardization when the manual technique is selected.

The present study aimed to investigate the effect of the 1064-nm fiber laser on the modification of the titanium surface used as an abutment to enhance crown retention. The null hypothesis was that the modification of the surface of titanium with the fiber laser would not positively influence the average surface roughness and shear bond strength (SBS) to resin cement.

Materials and Methods

Forty titanium discs of 6 mm × 3 mm (diameter and thickness respectively) were cut from commercially pure titanium rod grade II (Baoji Jinsheng Metal Material/ China) by the wire cut lathe machine (Bantam, Italy). The discs were ground and polished using silicon carbide papers ranging from 120 to 2400 grit size to obtain a uniform, smooth mirror-like surface. After that, the discs were cleaned ultrasonically with ethanol for 15 minutes and then with distilled water for 10 minutes, and they were left to dry.

Ytterbium (Yb) Q-switched nanosecond 1064-nm fiber laser (Wuxi Raycus Fiber Laser Technologies Co., Ltd/ RFL-P 100Q, China) was used for the surface modification of titanium discs with 81 ns pulse duration, 0.05 mm spot size, 30 kHz repetition rate, and 10 000 mm/s scanning speed, and the average power was 3 W or 5 W or 7 W depending on the tested group (Table 1). The pattern of surface modification was in the form of lines with a 0.1-mm hatch distance.

Titanium discs were arranged into four groups (n = 10) in accordance with the variation in average power of the fiber laser as follows:

1. Control group: without any surface modification.
2. 3 W group: fiber laser application (average power of 3 W and peak power of 1234.5 W)
3. 5 W group: fiber laser application (average power of 5 W and peak power of 2057.6 W).
4. 7 W group: fiber laser application (average power of 7 W and peak power of 2880.6 W).

After laser modification of titanium discs, one disc surface from each group was examined by the scanning electron microscope (SEM) (TESCAN VEGA 2, Czech Republic) with

a magnification of × 1000 to examine the surface morphology of titanium discs and to determine if there were any cracks or defects due to laser treatment.

Phase analysis for titanium discs from each group was performed by the X-ray diffractometer (XRD) (XRD-6000/SHIMADZU, Japan) that operated at a voltage of 40 kV and current of 30 mA, and its scan range was from 10 to 90 degrees and 2Θ.

The average surface roughness (Ra) of titanium discs was examined by the surface roughness tester (SRT-6210, China) which contained a diamond probe pin of 5 µm radius oriented in a perpendicular position to the disc surface, and the cut-off level was 0.25 mm. Three measurements on each disc surface were measured at distinct points, and then Ra was calculated in micrometers (µm).

Following surface treatment, titanium discs were horizontally embedded in a mixed cold cure acrylic mold to about 2 mm in depth, and the remaining 1 mm of titanium disc height was left exposed to ensure that the titanium disc remained intact during the bonding procedure with resin cement. For the application of resin cement, a customized made silicon mold was constructed. This mold was designed in a disc form with 4 mm height and central circular whole; the lower 1mm of the whole was with 6mm diameter continued with 5 mm diameter and 3 mm height. This silicon mold was secured to the acrylic block encounters the titanium disc using adjustable clamp. The cementation process was performed using self-adhesive resin cement (Breeze Self-Adhesive Resin Cement, Pentron, USA) following the manufacturer's instructions. An equal volume of resin cement was automixed by using the disposable mixing

Table 1. Laser Parameters of the Experimental Groups

Group	Average Power (W)	Peak Power (W)	Pulse Duration (ns)	Scanning Speed (mm/sec)	Frequency (kHz)	Spot Size (mm)	Power Density (MW/cm²)	Energy Density (J/cm²)
3 W group	3 W	1234.5	81	10 000	30	0.05	62.9	5.09
5 W group	5 W	2057.6	81	10 000	30	0.05	104.8	8.49
7 W group	7 W	2880.6	81	10 000	30	0.05	146.8	11.8

tip and dispensed into the central opening of the silicon mold, and then resin cement was photopolymerized with a light-curing device for 40 seconds. After cementation, the silicone mold was separated and the discs were kept in a water bath containing distilled water for 24 hours at 37°C.

The SBS test was performed using the universal testing machine (Laryee, WDW-50, 50 KN, China); the chisel-end blade rod was positioned in a perpendicular position to the interface of titanium and cement, and the application of load was performed with 0.5 mm/min crosshead speed until the failure occurred. SBS values (MPa) were determined following this formulation[21]:

$S = F/A$

Where S = Shear bond strength [MPa]; F = Applied force [N] and A = bonding area [mm²].

Deboned surfaces of titanium discs were examined by the stereomicroscope (Hamilton microscope, BLS120, Korea) with a magnification of × 20 in order to determine failure modes. Failure modes are categorized as cohesive failure within resin cement, adhesive failure at the titanium-cement interface, or mixed failure which includes both types together.

Statistical Analyses

Statistical analyses were achieved using Statistical Package for the Social Sciences (SPSS) to analyze the data including descriptive and inferential statistics. The analysis of variance (ANOVA) test was done to detect the significant difference of Ra and SBS between the groups, while the Tukey HSD test was performed to determine the significant differences of Ra and SBS between every two groups at $P < 0.05$.

Results

Average Surface Roughness

A higher Ra value was observed in the 7 W group, followed by the 5 W and 3 W groups. The control group displayed the lowest Ra value as compared with the other groups (Table 2).

The ANOVA test was performed to test the significant difference between the groups. Table 3 shows a highly significant difference between tested groups at ($P < 0.05$).

The Tukey HSD test was done to test the difference between every two groups. Table 4 shows that there is a highly significant difference between the control group and each of the experimental groups and there is a highly significant difference between the laser-irradiated groups.

Shear Bond Strength

Results considering the SBS test showed that the highest value of the SBS mean was obtained at the average power of 7 W, followed by 5 W and then 3 W, while the lowest value of the SBS mean was observed in the control group, as shown in Table 2.

The ANOVA test was performed to test the significant difference between the groups. Table 3 shows a highly significant difference between tested groups ($P < 0.05$) considering SBS.

The Tukey HSD test was done to test the difference between every two groups. Table 4 shows that there is a highly significant difference between the control group and each of the experimental groups and there is a highly significant difference between the laser-irradiated groups.

Modes of Failure

The analysis of failure modes following the SBS test demonstrated that the predominant failure mode in the control group was an adhesive type and that the highest occurrence of cohesive mode was observed in the 7 W group followed by the 5 W group, while the 3 W group revealed that the highest mode of failure was the mixed mode (Table 2).

Scanning Electron Microscope

The photographs of the SEM of the control and irradiated titanium discs with different average power values are illustrated in Figure 1. The SEM photographs of the control specimen appear to be smooth in comparison

Table 2. Descriptive Statistics of Ra (Mean ± SD), SBS (Mean ± SD), and Failure Mode Results

Groups	Surface Roughness Ra (μ)	SBS (MPa)	Failure Modes %		
			Adhesive	Cohesive	Mixed
Control	0.421 ± 0.030	1.585 ± 0.089	90	0	10
3 W	1.539 ± 0.017	3.924 ± 0.159	20	30	50
5 W	2.023 ± 0.042	5.819 ± 0.166	20	40	40
7 W	2.330 ± 0.017	8.001 ± 0.273	10	50	40

Table 3. ANOVA Test of Surface Roughness and SBS Data.

	Surface Roughness			SBS				
	Sum of Squares	Mean square	F	Sum of Squares	Mean square	F	Df	Sign.
Between groups	21.040	7.013	8350.947	223.842	74.614	2212.843	3	0.000
Within groups	0.030	0.001		1.214	0.034		36	
Total	21.070			225.056			39	

Table 4. Tukey HSD Test between groups for surface roughness and SBS.

(I) Groups	(J) Groups	Surface roughness		SBS	
		Mean Difference (I-J)	Significance	Mean Difference (I-J)	*P* Value
Control	3 W	-1.117	0.000	-2.339	0.000
	5 W	-1.603	0.000	-4.234	0.000
	7 W	-1.908	0.000	-6.416	0.000
3 W	5 W	-0.486	0.000	-1.895	0.000
	7 W	-0.790	0.000	-4.077	0.000
5 W	7 W	-0.304	0.000	-2.182	0.000

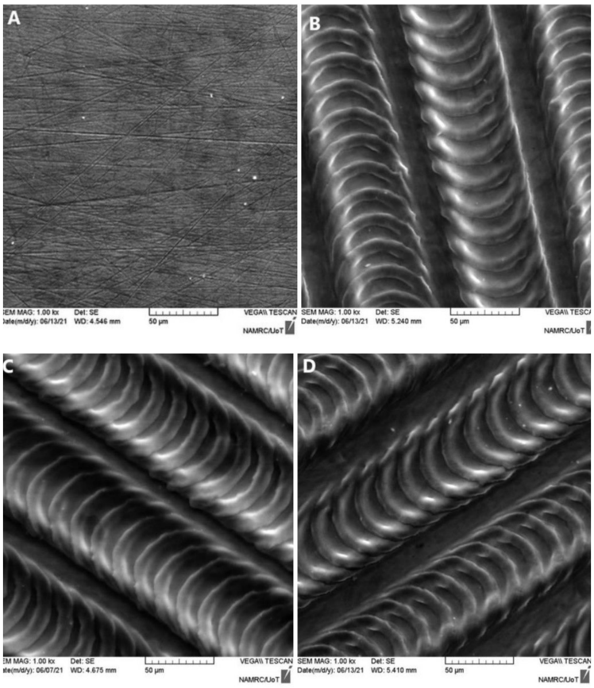

Figure 1. SEM Photographs of Titanium Discs With a Magnification of × 1000 (A) Control, (B) 3 W, (C) 5 W, and (D) 7 W

with laser-irradiated specimens. The texture of the laser-irradiated specimens consists of micro-retentive grooves and displays a uniform roughness pattern and deep penetration areas by the fiber laser beam without the presence of defects or cracks.

Phase Analysis

XRD patterns of titanium discs were indexed to International Centre for Diffraction Data (ICDD). Phase analysis demonstrated that there was no alteration in the phase of titanium discs following laser irradiation, as shown in Figure 2, which is considered an essential condition during titanium treatment with a laser. The diffraction peaks of titanium discs were indexed to 100, 002, 101, 102, 110, 103, 200,112, and 201 and corresponded with hexagonal α-Ti. Following laser treatment, in addition to α-Ti peaks, some new peaks of TiO_2 indexed to 004 and 301 were observed and corresponded with those of tetragonal anatase TiO_2. There was no determination of β-Ti or oxynitrides in any case.

Discussion

The frequent problem associated with the cement-retained type of implant-supported prosthesis is retention loss, which indicates the importance of the essential solution.[10] Reliable bonding between titanium abutment and luting cement is essential to guarantee high prosthesis performance. This study was conducted to investigate the effect of various average power values of the fiber laser on the Ra and SBS of resin cement to titanium. SEM analysis revealed that there is a variation in surface morphology between control specimens and fiber laser irradiated specimens that resulted from the absorption of laser energy by titanium and conversion of optical energy into thermal energy, leading to melting and vaporization.

Methods used to modify the surface of titanium abutment to enhance retention may include chemical or mechanical methods in techniques of adding or removing increments from the surface. Al Ahdal et al showed that lasers have potential for being used as a supplement to the sandblasting procedure in the conditioning of cement-retained titanium alloy implant abutments.[22]

The Fiber laser treatment of the titanium surface improves Ra which leads to an increase in the titanium surface area without any micro-cracks or defects. This modification was seen in a well-controlled pattern indicating reproducibility as well as similarity; this, in turn, ensures the success of the procedure as a method for the mass production of the modified surface implant fixture. This result agrees with Erdoğan et al[23] who described the effect as structuring to indicate the possibility of reshaping the surface in a selected manner or form to establish the goal. The surface area was directly proportionate with retention which was an important condition to improve the longevity of implant-supported prosthesis and enhance the bonding between implant abutment and cement; therefore, the modified surface by the laser increased the surface area more than the flat surface. The results of the present study agree with the study by Korkmaz and Aycan, who reported that the treatment of titanium alloy with the fiber laser led to an increase in surface roughness without any cracks or defects.[18] However, the result of the present study disagree with those of the studies by Kurt et al, Miranda et

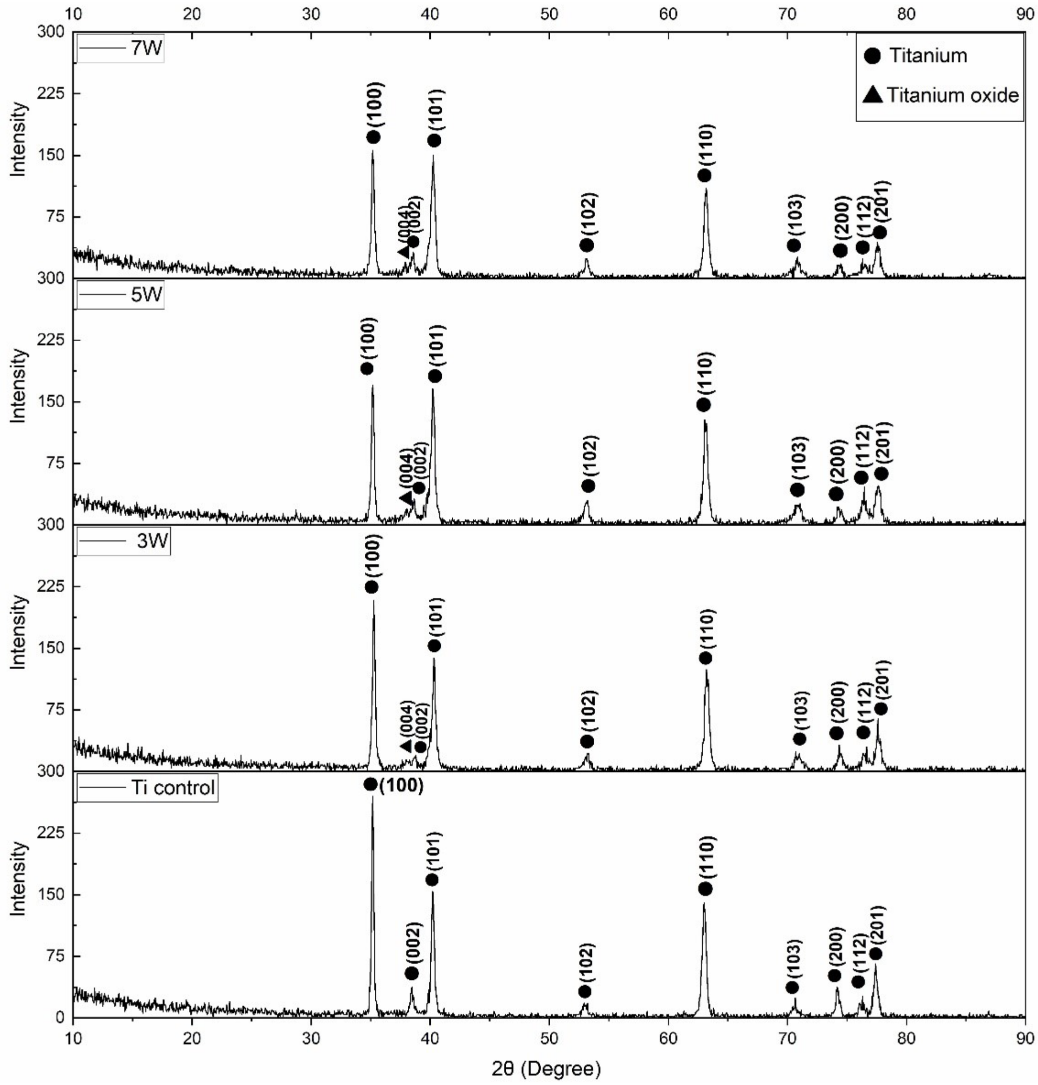

Figure 2. XRD Pattern of Control and Laser-Irradiated Discs

al, and Ustun et al who demonstrated that the irradiation of the titanium surface with CO_2 or Er,Cr:YSGG lasers led to cracks formation.[12,24,25] The reason for crack formation might be due to the fact that they used lasers with longer pulse duration which induced a pronounced heat effect, increased thermal diffusion to the bulk of the material, and increased penetration, resulting in high thermal stresses and that inevitably lead to cracks formation.[26] This disagreement highlights the essential of proper lase type and parameters selection to achieve optimum results with no adverse effects.

The phase analysis of titanium discs showed that there was no change in phase appearing in titanium discs following laser treatment. However, the formation of new peaks of TiO_2 (anatase) in addition to peaks of α-Ti was noticed because the process was performed in an open environment. During laser irradiation, the surface of titanium discs was melted superficially by the fiber laser, and as a result, oxygen diffused into the molten metal which led to the oxidation of the titanium surface.[27] Except for this, no changes in the material composition were detected, and this is very important to ensure the preservation of biocompatibility and chemical properties of the material during use. Changes in the chemical structure could lower the biological and mechanical properties of the material.

The results of the present study demonstrated that the fiber laser modification of the titanium surface resulted in significantly higher Ra and SBS values compared to the control group ($P < 0.05$); thus, the null hypothesis was rejected.

All experimental groups had higher Ra values compared with the control group. The variation in surface roughness among the experimental groups resulted from the variation in the average power of the fiber laser that interacts with the titanium surface, leading to a different degree of melting and vaporization.

All fiber laser-treated groups had higher SBS values compared to the control group, and the SBS value increased with the increase in Ra because the increase in

Ra of titanium leads to an increase in the surface area; also, surface roughness might increase the surface area and create mechanical interlocking sites favorable by the cement material which enhancing the bond between the abutment and cement. This fact is in agreement with the study by Kılıçarslan et al[11,28] which concluded that when the surface roughness of the titanium surface increased, the SBS value also increased.[29]

The results of the SBS test of the 7 W group were higher than the other groups; this result could be attributed to the efficacy of the fiber laser in roughening the surface of titanium through melting and vaporization processes that result in micromechanical irregularities which increase the mechanical interlocking. Whereas specimens treated with the fiber laser at 3 W displayed the lower SBS among the study groups, this could be attributed to the low average power that was used. Several studies have evaluated the effect of laser irradiation on improving the bonding strength between titanium abutments and cement. The results of these studies are in agreement with those of the present study. Ates et al reported that ultrafast fiber laser irradiation increased the surface roughness of titanium and significantly increased the SBS to resin cement and it is considered a substitutional technique to improve the bonding strength.[11] In their study, Venkat et al reported that the Nd:YAG laser treatment of titanium abutment enhances the retention of the crown to the abutment.[30] Additionally, Kurt et al pointed out that the laser treatment of titanium abutment is an effective method for enhancing crown retention, although they used a CO_2 laser.[24]

Conversely, the present study disagrees with the study by Akın and Güney which reported that laser irradiation of the titanium surface with Er:YAG or Nd:YAG lasers did not enhance bonding strength with resin cement. These controversial results could be explicated by different laser types or different types of applied energy and pulse duration.[9] According to Ayobian-Markazi et al, the application of the Er: YAG laser decreased surface roughness, although it did not affect biocompatibility and it increased the wettability of the titanium surfaces.[31]

Essential information related to the bonding quality can be provided by failure mode analysis. In the present study, it was observed that both cohesive and mixed failure types in laser-treated groups were higher than the adhesive type and the predominating failure mode in the control group was the adhesive type because the adhesive type could indicate lower bond strength.[9,32] This result is in agreement with that of Ates and colleagues' study in which the adhesive failure is less in the laser-irradiated group than in the control group.[11] This means that the bonding strength between the laser-treated titanium surface and cement is higher than the cohesive strength of the resin cement; additionally, there is a tendency toward an increase in the cohesive failure with a higher value of bonding strength.

Conclusion

1064-nm fiber laser irradiation of the titanium surface increases surface roughness without any defects or cracks, and it has a significant effect on the SBS between titanium and resin cement. Additionally, there is a positive relationship between surface roughness and SBS, and increasing surface roughness leads to higher SBS.

Conflict of Interests

The authors declare no conflict of interest.

Ethical Considerations

This article does not contain any studies with human participants or animals performed by any of the authors.

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