Peer-reviewed version available at Bioengineering 2018, 5, 10; doi:10.3390/bioengineering5010010

Type of the Paper: Article

Di-Silicate Dental Ceramic Surface Preparation by 1070 nm Fiber Laser: Thermal and Ultrastructural Analysis

Carlo Fornaini [1,2,*], Federica Poli [1], Elisabetta Merigo [2], Nathalie Brulat-Bouchard[2], Ahmed El Gamal [2], Jean-Paul Rocca [2], Stefano Selleri [1] and Annamaria Cucinotta [1]

1 Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy
2 Micoralis Laboratory, Faculty of Dentistry, University of Cote d'Azur, 24 Avenue des Diables Bleus, 06357 Nice, France
* Correspondence: carlo@fornainident.it; Tel.: +39-338-2014393

Abstract:

Background

Lithium di-silicate dental ceramics bonding, realized by using different resins, is strictly dependent on micro-mechanical retention and chemical adhesion. The aim of this *in vitro* study was to investigate the capability of a 1070 nm fiber laser for their surface treatment.

Methods

Samples were irradiated by a pulsed fiber laser at 1070 nm with different parameters (Peak Power from 5 kW to 5 kW, RR 20 kHz, speed from 10 to 50 mm/s, total Energy Density from 1.3 to 27 kW/cm^2) and the thermal elevation during the experiment was recorded by a Fiber Bragg Grating (FBG) temperature sensor. Subsequently, the surface modifications were analysed by optical microscope, Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Spectroscopy (EDS).

Results

With a Peak Power of 5 kW, RR of 20 kHz and speed of 50 mm/s, the microscopic observation of the irradiated surface showed increased roughness with small areas of melting and carbonization. EDS analysis revealed that, with these parameters, there are no evident differences between laser-processed samples and controls. Thermal elevation during laser irradiation ranged between 5 °C and 9 °C.

Conclusions

1070 nm fiber laser can be considered as a good device to increase the adhesion of Lithium di-silicate ceramics.

Keywords: di-silicate ceramics; fiber lasers; Fiber Bragg Grating; Energy Dispersive X-ray Spectroscopy

1. Introduction

The demand of ceramic prosthetic restorations has increasingly become common in daily dentistry. Moreover, the continuous need for increased precisions level, particularly in cosmetic dentistry. where new materials, such as feldspathic ceramics, play an important role in prosthetic rehabilitations, is considered crucially important. Unfortunately, failure resulting from porcelain fracture has been reported as ranging from 2.3% to 8%. Nevertheless, it seems to be a function of a multi-factorial reason [1-3], with the key cause attributed to the composite resin adhesion with porcelain. Therefore, it is necessary to condition the ceramic surface which is considered very interesting [4,5].

The inside surface of the ceramic prosthetics must be conditioned for optimized micro-mechanical retention by the resin penetration into the ceramic micro-roughness; this treatment enhances the mechanical retention of cement by enlarging the surface in contact with the tooth structure through the creation of micro-porosities. [6,7].

For producing surface roughness and for promoting micro-mechanical retention, different treatment methods such as diamond roughening, air-particle abrasion with aluminium oxide and acids etching have been proposed in the literature [6,7]. All these techniques have been investigated under *in vitro* conditions [8-10].

The use of laser technology for surface treatment has already been successfully applied in many industrial applications by the utilization of high power sources. Today, this technology represents a controllable and flexible technique for the modification of surface properties for different various materials [11,12], since laser parameters have the capability to influence and alter the surface microstructure [13].

The *in vitro* study here reported has the aim to verify the possibility of performing the surface treatment of Lithium di-silicate ceramic specimens by the irradiation of a 1070 nm pulsed fiber laser.

2. Materials and Methods

The circular faces of twelve cylinders of Lithium di-silicate ceramics (e.max Press, Ivoclar, Italy) with 10 mm diameter and 8 mm length were processed into three 3 x 3 mm square zones by using a 1070 nm pulsed fiber laser (AREX 20) provided by Datalogic, Italy. This source has a maximum average output power of 20 W and a fixed pulse duration of 100 ns, thus providing a maximum peak power of 10 kW for a repetition rate of 20 kHz. Each square zone on the sample faces has been processed with different laser parameters. Particularly, the output power and speed have been varied from 100% to 30% and 50 to 5 mm/s.

After a preliminary pilot study using different parameters, it was decided to conduct all the tests at RR of 20kHz.

The lens used with the AREX 20 laser has a focal length of 160 mm. In this configuration, the laser beam has a spot-size of 80 μm. Each square zone on the sample surface has been processed using a meshed filling pattern with a distance between lines of 0.03 mm.

The laser beam focalization was checked by a metal cylinder of the same dimension of the samples.

The Power per unit area deposited on the material ranged between 1.3 and 27 kW/cm^2.

The specimens were subsequently observed by an optical microscope (Olympus MTV-3, Japan), then metallized and analysed by a SEM (Ion sputter Jeol JFC 1100E, USA) and an EDS system (JSM-35CF, Jeol Ltd., Japan).

During the irradiation of the sample with the best laser parameters, the thermal elevation was recorded by a FBG-based temperature sensor connected to an interrogator. The fiber sensor was positioned into the groove in the middle of the sample. Dynamic Optical Sensing Interrogator sm130-500 (Micron Optics Inc, Atlanta, USA) was used to measure the FBG wavelength shift induced by the temperature increase). This device is also considered as a compact, industrial grade, dynamic optical sensor interrogation module, field proven for robust, reliable, and long term operation. The software included with the sensing interrogator system provides a single suite of tools for data acquisition, computation, and analysis of optical sensor networks. A 25 mm-long FBG with centre wavelength of 1550 nm, reflectivity of 96% and acrylate coating, imprinted in a standard SMF (AOS GmbH, Germany), has been connected to the interrogator for performing the temperature change measurement. A temperature-induced wavelength shift of about 13 pm/°C has been considered for the FBG at 1550 nm.

3. Results

3.1.SEM observation

By comparing at higher magnification, the control group (non-irradiated samples) to the cylinders processed by the fiber laser, greater differences can be noticed (Fig. 1).

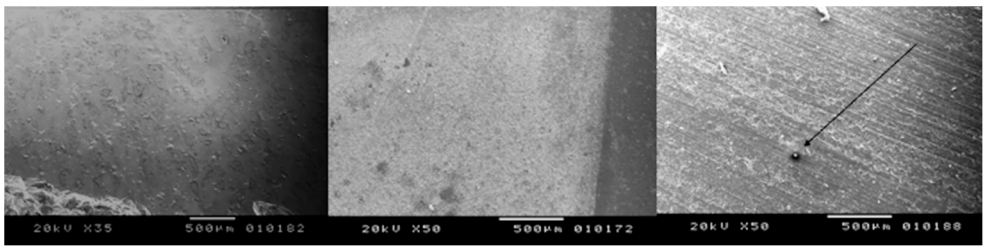


Figure 1. (Left): Non-irradiated sample. (center): peak power of 7.5 kW and 50 mm/sec speed. (right): peak power of 7.5 kW and 10 mm/sec speed with a carbonization spot. (left: X35; center and right: X50)

In fact, all the treated surfaces show a rough surface with many holes and irregularities. It is evident that the samples irradiated at different lasing parameters experienced some areas of melting and burning when the highest energy level was used, due to the cumulative effect of the laser energy. The presence of some cracks with variable intensities are also found, due to the thermal effects of laser irradiation (Figs. 2-3-4-5).

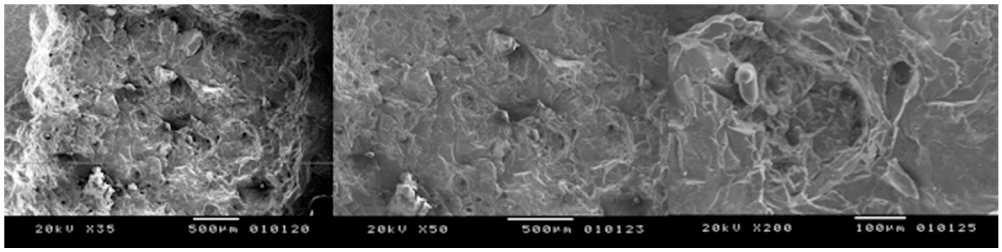


Figure 2. Peak power of 10 kW, speed of 10 mm/s: many zones with melting and carbonization are shown. (left: X35, center: X200, right: X500)

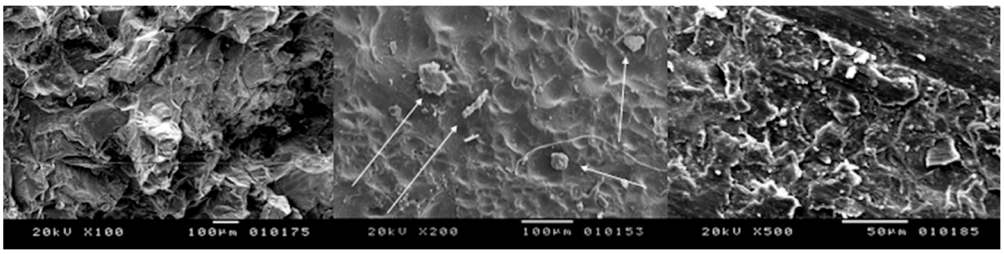


Figure 3. Peak power of 10 kW, speed of 50 mm/s: some points with melting are shown. (left: X100, center: X200, right: X500)

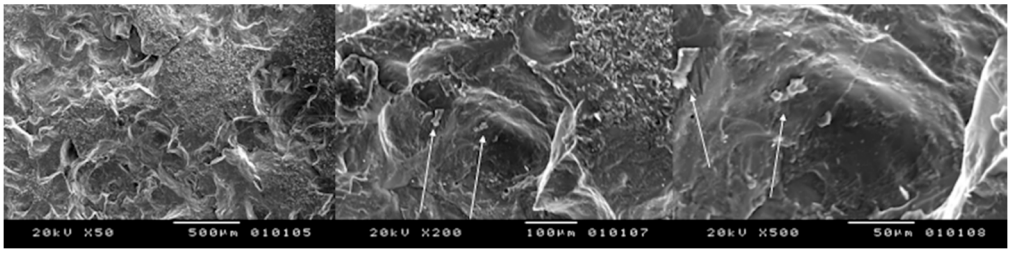


Figure 4. Peak power of 7.5 kW, speed of 50 mm/s: presence of melting and carbonization in some areas of the sample. (left: X35, center: X50, right: X200)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 November 2017 doi:10.20944/preprints201711.0029.v1

Peer-reviewed version available at Bioengineering 2018, 5, 10; doi:10.3390/bioengineering5010010

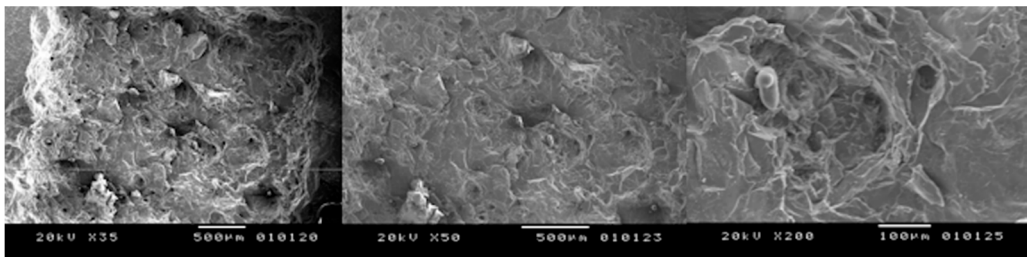


Figure 5. Peak power of 5 kW, speed of 10 mm/s: evidence of some zones with melting (left: X50, centre: X100, right: X500).

The laser parameters which seem to be the most effective for surface conditioning of the materials without causing any damages are peak power of 5 kW, repetition rate of 20 kHz and speed of 50 mm/sec. In fact, the samples irradiated with these parameters revealed a rough surface with holes, irregularities, cavities and recesses, while the presence of thermal damaging effects, such as melting, burning and cracks, were not evident (Fig.6).

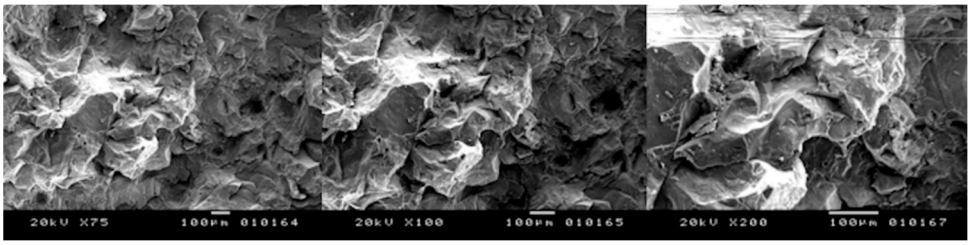
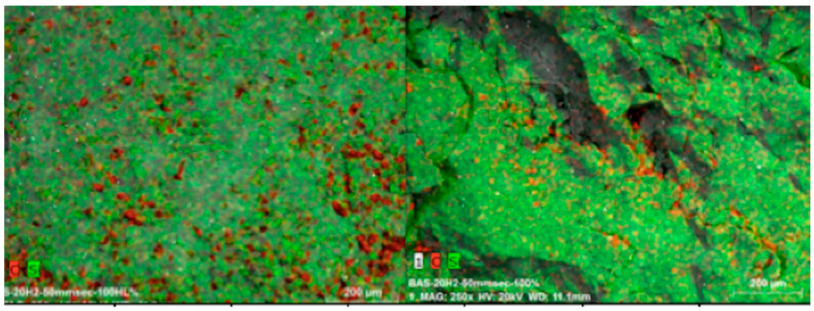


Figure 6. Peak power of 5 kW, speed of 50 mm/s: no evidence of carbonization and melting zones. (left: X75, center: X100, right: X200)

3.2. EDS analysis

The EDS analysis consists of the percentage recording of chemical elements in the point where the probe is placed. Analyzed samples showed, in general, slight differences in the chemical composition between control groups and irradiated samples, even smaller variations by changed lasing parameters were detected thus confirming the information given by the SEM observation.
The differences of elemental composition between the non-irradiated areas in the different samples may be explained by the structure of the ceramic which is not homogeneous, thus resulting in structural variations of the tested zones. (Fig.1, Left)
The samples treated with laser operating at peak power of 10 kW, repetition rate of 20 kHz and speed of 50 mm/s experienced some zones (red spots) of lower percentage of C when compared to the control group. On the other hand, O and Al elements were slightly higher in the affected zones (Fig. 7).

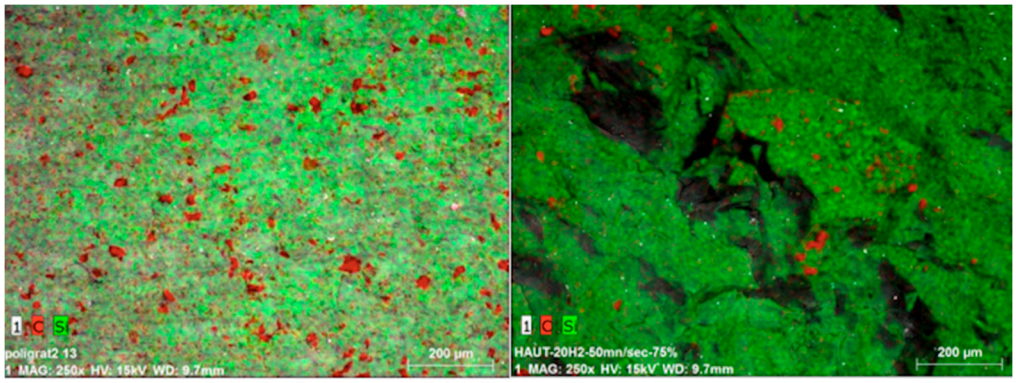


Concentration (%) of some elements before and after laser irradiation (10 kW, 50 mm/sec)

	C	O	Si	K	Al	Na
non-irradiated	16.70	41.40	25.70	6.10	4.30	3.40
irradiated	7.40	44.40	23.70	8.00	6.70	5.50

Figure 7. (Left) Control group and (right) samples irradiated with peak power of 10 kW and speed of 50 mm/s: in red the C concentration.

The samples irradiated with peak power of 7.5 kW, repetition rate of 20 kHz and speed of 50 mm/s showed that only the Carbon concentration was higher in the control group (13.6%), while all the other elements, such as O, Si, K, Al and Na, presented higher concentration values on the treated surfaces (Fig. 8).



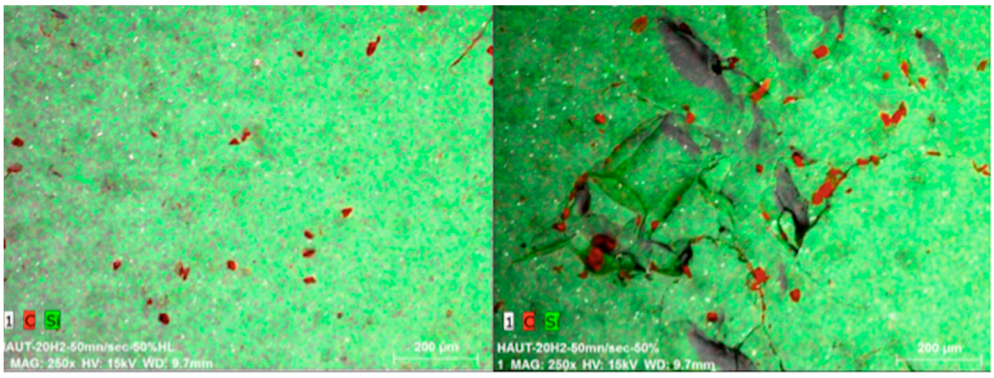
Concentration (%) of some elements before and after laser irradiation (7.5 kW, 50 mm/sec)

	C	O	Si	K	Al	Na
non-irradiated	13.60	41.20	27.10	7.40	4.50	3.40
irradiated	3.80	44.40	27.10	8.90	5.90	4.70

Figure 8. (Left) Control group and (right) samples irradiated with peak power of 7.5 kW and speed of 50 mm/s: in red the C concentration.

Carbon is one of chemical ceramic composition of lithium di-silicate. The presence of carbon on ceramic surface is due to the high energy of laser irradiation that leads to the burning and melting of ceramic surface.

SEM observations of the samples irradiated with the parameters such as peak power of 5 kW, repetition rate of 20 kHz and speed of 50 mm/s demonstrated the best results. The analysis, in this case, was conducted in four different zones. Results showed slight differences for all the elements concentration in each analyzed zone. These data, confirmed also by SEM observation, demonstrated a poor modification of the ceramic chemical structure caused by laser operating with the optimum parameters (Fig. 9).



Concentration (%) of some elements before and after laser irradiation (5 kW, 50 mm/sec)

	C	O	Si	K	Al	Na
non-irradiated	5.70	43.10	27.50	9.50	6.10	4.40
irradiated	4.30	43.50	28.00	9.50	6.40	4.50

Figure 9. (Left) Control group and (right) samples irradiated with peak power of 5 kW and speed of 50 mm/s: in red the C concentration.

3.3. Thermal analysis

The temperature increase during the laser irradiation has been measured only when the source operates with the best parameters as per the observation of SEM and EDS analysis. The aim of this measurement was to provide the maximum value of the temperature rise, induced by laser, that the di-silicate ceramic material can withstand, without being damaged. Higher energy laser treatments provide more significant temperature change, which is associated with the detrimental surface modifications as shown by SEM and EDS analysis.

Thermal elevation of the sample during the irradiation with the laser operating at a peak power of 5 kW, repetition rate of 20 kHz and speed of 50 mm/s, has been recorded with a FBG connected to an interrogator. The FBG wavelength shift obtained in a time interval of 120 s, during the laser processing, is reported in Fig. 10. The temperature measurement has been repeated three times, by processing three square regions on the sample surface. The fiber sensor was placed in the centre of the sample, approximately at the same distance from all the areas irradiated by the laser. Notice that the wavelength shift measured by the interrogator is between 65 pm and 115 pm, respectively, in the first and the third test. Consequently, the temperature rise due to the laser processing is between 5°C and 9°C. The slight growth of the temperature value measured in the second and the third test can be due to the gradual heating of the sample, originating from the previous laser processing. Moreover, slight differences in the distance of the three zones irradiated by the laser with respect to the sensitive part of the fiber sensor must be taken into consideration.

The measure of temperature rise during laser irradiation may throw some light on the explanation behind the crack formations. after laser irradiations which could be explained through the high thermal effects of laser processing, along with the consequence of an extreme physical stress in the re-hardening ceramic surface.

It must also be underlined that the importance of the very short pulse duration given by the fiber laser used in this study (100 ns) which may explain the greater difference between the fluences of these tests, compared to those given in the cited works where irradiation had been performed in CW or in μs.

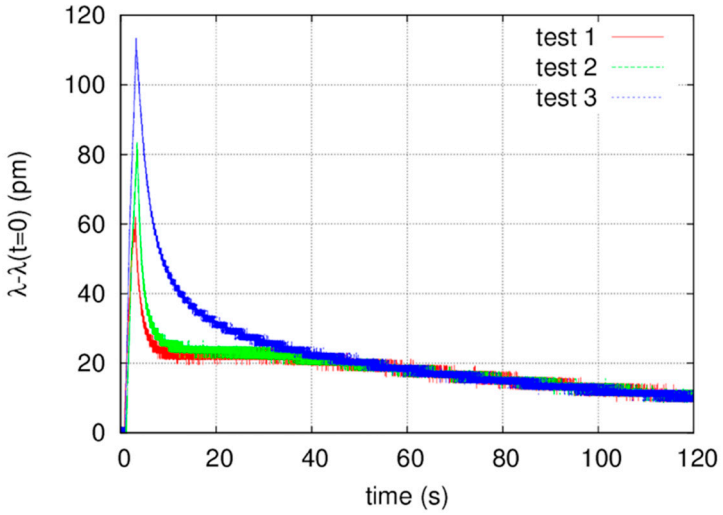


Figure 10. FBG sensor wavelength shift induced by temperature variations during and after the laser irradiation with the best parameters (peak power of 5 kW, repetition rate of 20 kHz, speed of 50 mm/s).

4. Discussion

As contrast to the different surface treatment methodology mentioned in the introduction, this study focused on the laser treatment of the ceramics materials. In current study, laser irradiation demonstrated the capability to roughen ceramic surfaces which increases the contact area with the

tooth structure, by creating micro-porosities, and therefore enhancing the potential for mechanical retention of the cement.

Although different techniques used for ceramic surface conditioning have demonstrated several major limitations, the utilisation of laser is not free of problems, too. Particularly, some tests conducted on lithium-di-silicate [14] and CAD-CAM ceramics [15] with CW CO_2 laser at 10.6 μm confirmed the presence of micro-cracks and melting textures, due to the thermal effect of the laser irradiation at output powers higher than 10 W CW (3184.7 W/cm²). Moreover, the observation of the ceramics structure irradiated by a 10 W (14185 W /cm²) pulsed Nd:YAP laser at 1340 nm exhibited the presence of holes, micro-cracks and melted grains [14,15]. This is probably caused by the effect of high quantity of radiation energy given in a well-defined portion of the ceramic surface over a short period, thus leading to a very high energy density accumulation. Micro-cracks formation on ceramics after CO_2 and Nd:YAP laser irradiations may be related to the high thermal effects of laser processing which leads to an extreme physical stress in the re-hardening ceramic surface [16,17]. Also Er:YAG laser was used for surface treatment of feldspathic porcelain, however its effect resulted in significantly weaker surface than that of the HF treated surface The probable assumption is that the laser energy from an Er:YAG laser is not well absorbed in porcelain and, therefore, not sufficient to create a micro-mechanical retention pattern for more favourable bonding [18]. In agreement with this study, some authors affirmed that, even at a very high energy (500 mJ), Er:YAG laser is not able to cause on the porcelain surface a roughness sufficient to promote reliable adhesion to the resin composite [19]. Recently, the so-called "ultra-short pulses" lighted up a greater interest in the field of mean roughness value [20]. However, due to the higher expense associated with this laser source, to date, it is still utilized only in few laboratories.

Fiber lasers act as sources whereas, the active medium is an optical fiber with core doped with active ions, such as Nd (Neodymium), Yb (Ytterbium), Er (Erbium), Tm (Thulium) [21]. Fiber lasers differ from traditional solid-state lasers mainly by the form of the gain medium: in fact, bulk crystal lasers are typically based on conventional rod or slab geometries while in the case of fiber lasers, active ions are added into the core of an optical fiber, often with a length of many metres [22]. These lasers operating in continuous wave (CW) or pulsed mode and emit in a wide range of wavelengths, which is a function of the dopants and host materials. CW output powers of several kW [23] and pulse energies up to around 30 mJ [24,25] can be currently obtained with Yb-doped fiber lasers.

The most common applications of fiber lasers regard the industrial field, where they are used mainly for material processing (i.e., for cutting and marking). The main utilizations of fiber lasers in medicine are related to the lithotripsy [26], the surgical treatment of vascular lesions [27], the non-surgical skin aesthetic procedures [28, 29] and the eye surgery [30].

Recently also its use in the dental field started to be considered, particularly in the soft oral tissues surgery where it demonstrated to get some advantages consisting on the scanty overheating of the target, and consequently scanty tissue damages, probably also due to the shorter pulse duration (ns), compared to the emission normally used in dentistry (μs) [31].

This is also the reason of the great differences in the Power Densities utilised in this study (1.3 /27 kW/cm²), compared to those used in the similar cited works [14,15] performed with different wavelengths.

The data here reported, according to Gamal et Al [32] confirmed that ceramic laser-irradiated surfaces show higher roughness values, when compared to non-irradiated surfaces, liable to enhance mechanical retention due to the extreme physical stress originating in the re-hardening ceramic surface by the characteristic photo-ionization.

5. Conclusions

This *in vitro* study demonstrated that the utilization of 1070 nm pulsed fiber lasers for the Lithium di-silicate ceramics surface conditioning is effective and damage-free. In fact, the results obtained using the proper laser parameters (peak power of 5 kW, repetition rate of 20 kHz and speed of 50 mm/s) show that it is possible to create an important ceramic rough surface, ready to incorporate in its cavities through the bonding agent. Moreover, thermal elevation recorded during irradiation was

found to be very low, thus explaining the few damages evidenced and, overall, the poor modifications in the ceramic structure, as shown by the EDS analysis.

The use of a pulsed fiber laser at 1070 nm represents a new approach in dentistry, especially in the field of prosthetics, opening new perspectives, which shall be confirmed by further *ex vivo* studies. Further analysis will have to be done for studying the mechanical properties of irradiated ceramic surface (micro-hardness, roughness) and the adhesion characteristics after ceramic sealing (wettability, shear bond strength and micro-leakage), to confirm the capacity of improving the adhesion of laser processed di-silicate ceramics to the dental tissues.

Acknowledgments: The Authors would like to thank Datalogic S.p.A. and, particularly, Dr. Lorenzo Bassi for providing the fiber laser source.

Author Contributions: S.S. and A.C. conceived and designed the experiments; E.M, C.F. and F.P. performed the experiments; JP. R. and N.B. analyzed the data; A.G. contributed materials; C.F. wrote the paper."

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ulusoy M, Toksavul S: Fracture resistance of five different metal framework designs for metal-ceramic restorations. *Int J Prosthodont* (2002) **15**, 571-574.
2. Kang MS, Ercoli C, Galindo DF, Graser GN, Moss ME, Tallents RH: Comparison of the load at failure of soldered and non-soldered porcelain-fused-to-metal crowns. *J Prosthet Dent* (2003) **90**, 235-240. DOI: 10.1016/S0022391303004190.
3. Michalakis KX, Stratos A, Hirayama H, Kang K, Touloumi F, Oishi Y: Fracture resistance of metal ceramic restorations with two different margin designs after exposure to masticatory simulation. *J Prosthet Dent* (2009) **102**, 172-178.
4. Appeldoom RE, Wilwerding TM, Barkmeier WW: Bond strength of composite resin to porcelain with newer generation porcelain repair systems. *J Prosthet Dent* (1993) **70**, 6-11
5. Demirel F, Muhtaroğullari M, Yüksel G, Cekiç C: Microleakage study of 3 porcelain repair materials by autoradiography. *Quintessence Int* (2007) **38**, 285-290.
6. Giordano R, McLaren EA: Ceramics overview: classification by microstructure and processing methods. *Compend Contin Educ Dent* (2010): **31**, 682–4.
7. Albakry M, Guazzato M, Swain MV Fracture toughness and hardness evaluation of three pressable all-ceramic dental materials. *J Dent* (2003): **31**, 181–8.
8. Chung KH, Hwang YC: Bonding strengths of porcelain repair systems with various surface treatments. *J Prosthet Dent* (1997) **78**, 267-274.
9. Suliman AH, Swift EJ Jr, Perdigao J: Effects of surface treatment and bonding agents on bond strength of composite resin to porcelain. *J Prosthet Dent* (1993) **70**, 118-120.
10. Diaz-Arnold AM, Schneider RL, Aquilino SA: Bond strengths of intraoral porcelain repair materials. *J Prosthet Dent* (1989) **61**, 305-309.
11. Holand W, Schweiger M, Frank M, Rheinberger V: A comparison of the microstructure and properties of the IPS empress 2 and the IPS empress glass ceramics. *J Biomed Mater Res* (2000) **53**, 297–303.
12. Della Bona A, Mecholsky JJ Jr, Anusavice KJ: Fracture behavior of lithia disilicate and leucite based ceramics. *Dent. Mater* (2004) **20**, 956–62. DOI: 10.1016/j.dental.2004.02.004.
13. Piwowarczyk A, Ottl P, Lauer HC, Kuretzky T: A clinical report and overview of scientific studies and clinical procedures conducted on the 3 M ESPE lava all-ceramic system. *J Prosthodont* (2005) **14**, 39–45. DOI: 10.1111/j.1532-849X.2005.00003.x.
14. Rocca J-P, Fornaini C, Brulat-Bouchard N, Bassel Seif S, Darque-Ceretti E: CO_2 and Nd:YAP laser interaction with lithium disilicate and Zirconia dental ceramics: A preliminary study. *Optics & Laser Technology* (2014) **57**, 216-223.
15. El Gamal A, Fornaini C, Rocca JP, Muhammad OH, Medioni E, Cucinotta A, Brulat-Bouchard N: The effect of CO_2 and Nd:YAP lasers on CAD/CAM Ceramics: SEM, EDS and thermal studies. *Laser Ther* (2016) **25**(1), 27-34. DOI: 10.5978/islsm.16-OR-02.
16. Liu L, Liu S, Song X, Zhu Q, Zhang W: Effect of Nd: YAG laser irradiation on surface properties and bond strength of zirconia ceramics. *Lasers Med Sci* (2015) **30**, 627-634. DOI: 10.1007/s10103-013-1381-7.

17. Ural C, KalyoncuoGlu E, Balkaya V: The effect of different outputs of carbon dioxide laser on bonding between zirconia ceramic surface and resin cement. *Acta Odontol Scand* (2012) **70**, 541–546. DOI: 10.3109/00016357.2011.600718.
18. Sadeghi M, Davari A, Abolghasami Mahani A, Hakimi H: Influence of Different Power Outputs of Er:YAG Laser on Shear Bond Strength of a Resin Composite to Feldspathic Porcelain. *J Dent (Shiraz)* (2015) **16**, 30-6.
19. Shiu P, De Souza Zaroni WC, Eduardo Cde P, Youssef MN: Effect of feldspathic ceramic surface treatments on bond strength to resin cement. *Photomed Laser Surg* (2007) **25**, 291–296. DOI: 10.1089/pho.2007.2018.
20. Erdur EA, Basciftci FA: Effect of Ti:Sapphire-femtosecond laser on the surface roughness of ceramics. *Lasers Surg Med* (2015) **47**, 833-8. DOI: 10.1002/lsm.22432.
21. Tuchin V: *Biomedical Optics and Biophotonics*, SPIE Press, USA (2012)
22. Pierce M, Jackson S, Golding P, Dickinson B, Dickinson M, King T, Sloan P: Development and application of fibre lasers for medical applications. *Proc. SPIE 4253* (2001) Optical Fibers and Sensors for Medical Applications, 144
23. Shiner B: The Impact of Fiber Laser Technology on the World Wide Material Processing Market. *CLEO: 2013, OSA Technical Digest (online) (Optical Society of America,)* (2013) paper AF2J.1
24. Zheng C, Zhang H, Yan P, Gong M: Low repetition rate broadband high energy and peak power nanosecond pulsed Yb-doped fiber amplifier. *Optics & Laser Technology* (2013) **49**, 284-287
25. Stutzki F, Jansen F, Liem A, Jauregui C, Limpert J, Tünnermann A: 26 mJ, 130 W Q-switched fiber-laser system with near-diffraction-limited beam quality. *Optics Letters* (2012) **37**, 1073-1075.
26. [26] R. Li, D. Ruckle, M. Keheila, J. Maldonado, M. Lightfoot, M. Alsyouf, A. Yeo, SR. Abourbih, G. Olgin, JL. Arenas, DD. Baldwin. High-Frequency Dusting Versus Conventional Holmium Laser Lithotripsy for Intrarenal and Ureteric Calculi. *J Endourol* 13 (2016)
27. [27] JA. Park, SW. Park, IS. Chang, JJ. Hwang, SA. Lee, JS. Kim, HK. Chee, IJ. Yun, The 1,470-nm bare-fiber diode laser ablation of the great saphenous vein and small saphenous vein at 1-year follow-up using 8-12 W and a mean linear endovenous energy density of 72 J/cm, *J Vasc Interv Radiol*, 25(11) (2014) 1795-800
28. [28] DC. Wu, DP. Friedmann, SG. Fabi, MP. Goldman, RE. Fitzpatrick, Comparison of intense pulsed light with 1,927-nm fractionated thulium fiber laser for the rejuvenation of the chest, *Dermatol Surg.* (2014) 40(2) 129-33
29. [29] P. Wattanakrai, S. Pootongkam, S. Rojhirunsakool, Periorbital rejuvenation with fractional 1,550-nm ytterbium/erbium fiber laser and variable square pulse 2,940-nm erbium:YAG laser in Asians: a comparison study, *Dermatol Surg.* (2012) 9
30. [30] F. Morin, F. Druon, M. Hanna, P. Georges, MicroJoule femtosecond fiber laser at 1.6 μm for corneal surgery applications, *Optics Letters* (2009) 34(13)
31. Carlo Fornaini, Elisabetta Merigo, Federica Poli, Chiara Cavatorta, Jean-Paul Rocca, Stefano Selleri, Annamaria Cucinotta: Use of 1070 nm fiber lasers in oral surgery: preliminary ex vivo study with FBG temperature monitoring. Laser Therapy (2018), vol. 27 No. 1 (in press)
32. El Gamal A, Medioni E, Rocca JP, Fornaini C, Muhammad O, Brulat-Bouchard N: Shear bond wettability and AFM evaluations on CO2 laser-irradiated CAD/CAM ceramic surfaces. *Lasers Med Sci* (2017) doi:10.1007/s10103-017-2171-4