Prototyping of Dental Structures Using Laser Milling

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Abstract. The results of experimental studies of the effect of an ytterbium fiber laser radiation parameters on processing efficiency and quality of ZrO_2 ceramics widely used in stomatology are presented. Laser operating conditions with optimum characteristics for obtaining high quality final surfaces and rapid material removal of dental structures are determined. The ability of forming thin-walled ceramic structures by laser milling technology (a minimum wall thickness of 50 μm) is demonstrated. The examples of three-dimensional dental structures created in computer 3D-models of human teeth using laser milling are shown.

1. Introduction

Zirconium dioxide is used for making electronic equipment, dielectric and piezoelectric ceramic, solid electrolytes, fuel elements and heat insulators. A variety of applications for ZrO_2 is caused by a unique combination of its thermal, optical, electric and other properties [1-3].

The prosthetics of teeth is dynamically developing medicine area. The market of dental structures which are based on zirconium dioxide is growing every year. Nowadays the computer system of laser scanning of a tooth imprint made by the doctor is used to create a 3D-model. Further, this model is used to create individual dental crowns or dental bridge structures from partially stabilized zirconium dioxide.

Manufacturing constructions is carried out using a device with CAD/CAM-systems by mechanical milling [4]. For ceramic blocks milling diamond bur with water-cooling is required. Process of yttria tetragonal zirconia polycrystal (Y-TZP) mechanical milling is very expensive, it demands a lot of time and it leads to significant wear of diamond burs. Moreover the production of dental structures with thickness of walls less than 400 microns is impossible, and the formation of microcracks in the material structure is possible by mechanical milling.

In this paper we propose an alternative precision laser milling technology of dental structures made of zirconium dioxide. Possibility of decrease in consumption of material on production of zirconium structures, increase of blank processing speed, increase in accuracy of processing and decrease of the ceramic structures minimum thickness to an optimum is considered.

2. Experimental part

Nowadays dental structures are prototyped widely using ZrO_2 ceramics with added yttrium from 1 to 7% (so called partially stabilized zirconia). In the production of a dental ceramic structure the most important factors are the speed of the final material production and roughness of the surface. Since the treated dental blank subsequently is processed with dye solutions and enamels which requires a surface roughness for better adhesion. The optimum value of dental crown surface roughness should be at a level of 10 - 30 microns.

For the experimental determining of the effect of the repetition rate and pulse duration of the laser radiation on the laser milling productivity the fiber laser (λ = 1,068 mkm) with an average power P_{av} =

20 W output radiation was directed onto a flat surface of ceramic blanks with the help of scanning mirrors. The diameter of the laser spot was d = 50 mm, and scanning speed of the ceramic blank surface was v = 1 m / s and was not changed. During the experiment the parameters of laser pulse duration (from 4 to 200 ns) and the pulse repetition frequency (from 1 to 20 kHz) were varied.
The ceramic sample surface was processed by scanning the laser beam over square areas 5×5 mm in size. The scanning square area was progressively filled with laser passes or "paths". Laser "paths" with various degrees of overlap (0, 25, 50 and 75%) were applied to ceramics to determine the effect of this parameter on the material removal rate. The average ZrO_2 ceramics removal rate was estimated at the repetition rate f = 20 kHz and average radiation power P_{av}=20 W. The results are shown in Table 1.

Table 1. Material removal rate (cm^3/h) depending on the pulse duration and the degree of overlap of the elementary "paths".

Degree of "path" overlap, %	***Pulse duration, ns***			
	30	**50**	**100**	**200**
0	0.16	0.70	2.04	3.93
25	0.21	0.80	2.27	4.60
50	0.17	0.54	1.73	4.70
75	0.17	1.26	2.26	3.58

The pictures of surface after laser treatment were taken with an optical microscope at magnifications of 2x and 20x. Typical surface topography is shown in Fig. 1.

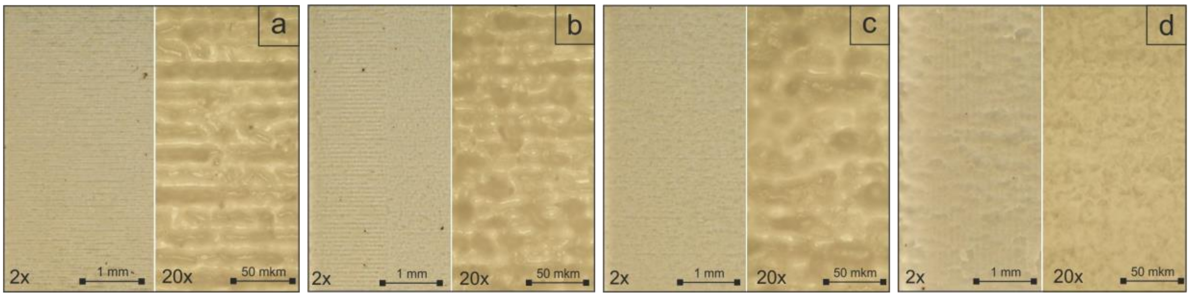

Fig. 1. The characteristic relief of the surface of the ceramic blank after laser treatment. Degrees of overlap: a – 0%, b – 25%, c – 50%, d – 75%.

As one may see from the above data, the degree of overlap slightly affects the material removal rate, while with increasing pulse duration the productivity of the laser milling process increases significantly.
The data obtained were used to construct the dependences of the material removal rate on the laser pulse duration for various degrees of "path" overlap (Fig. 2).

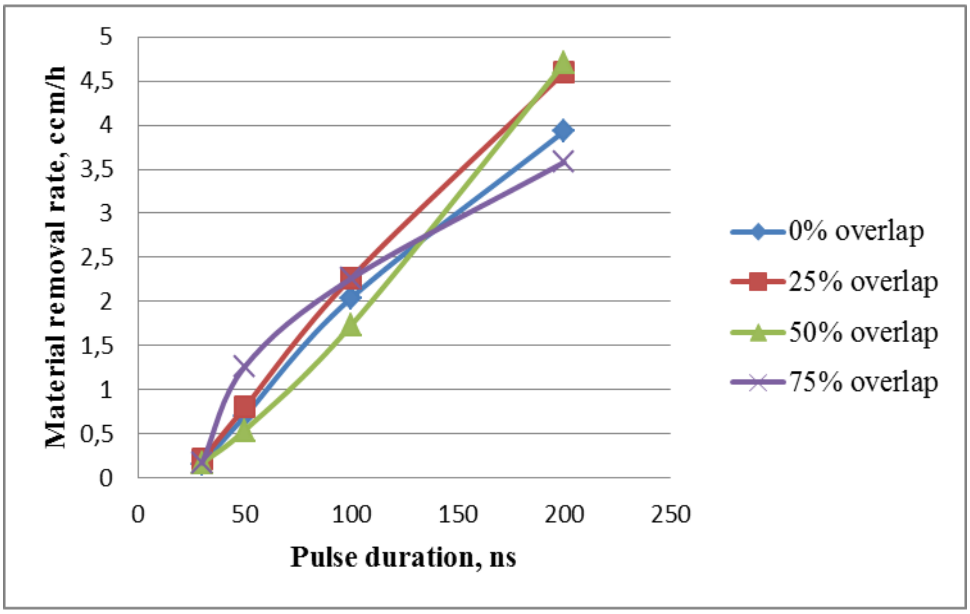

Fig. 2. Dependences of the material removal rate on the laser pulse duration (for various degrees of "path" overlap)

To investigate the influence of the pulse repetition rate and the pulse duration on the surface quality after laser processing, the roughness of processed areas was measured using the mechanical profilometer Dektak 150. During this experiment the parameters of pulse duration (from 30 to 200 ns) and repetition rate (from 2 to 20 Hz) were varied, while the average radiation power (P_{av} = 20 W), the scanning speed (v=1 m/s) and degree of "path" overlap (equal to zero) remained unchanged. The measurement results are shown in Table 2.

Table 2. Measurements of the processed surface roughness (μm) versus the pulse duration and the pulse repetition rate (Pav=20W, v=1 m/s, no overlap)

Repetition rate, Hz	***Pulse duration, ns***			
	30	**50**	**100**	**200**
2	2.31	3.70	4.49	10.36
5	3.65	5.45	9.02	9.01
10	4.61	6.41	8.22	9.35
15	4.90	7.72	7.15	6.49
20	5.38	7.89	7.10	9.51

As seen from the above data, the factor of pulse duration effects greater on roughness of the laser treated surface than the factor of repetition rate. Thus the entire frequency range with increasing pulse duration increases surface roughness.
The data obtained were used to find the dependence of the surface roughness on the repetition rate and pulse duration of the laser radiation (Fig. 3, 4).

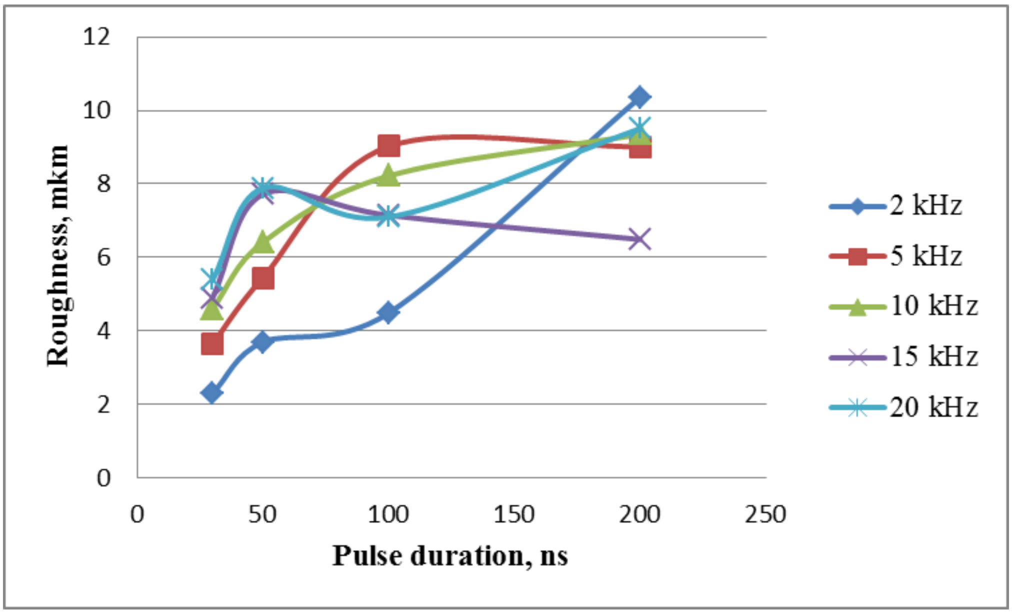

Fig. 3. The dependence of the surface roughness on the pulse duration (different repetition rate).

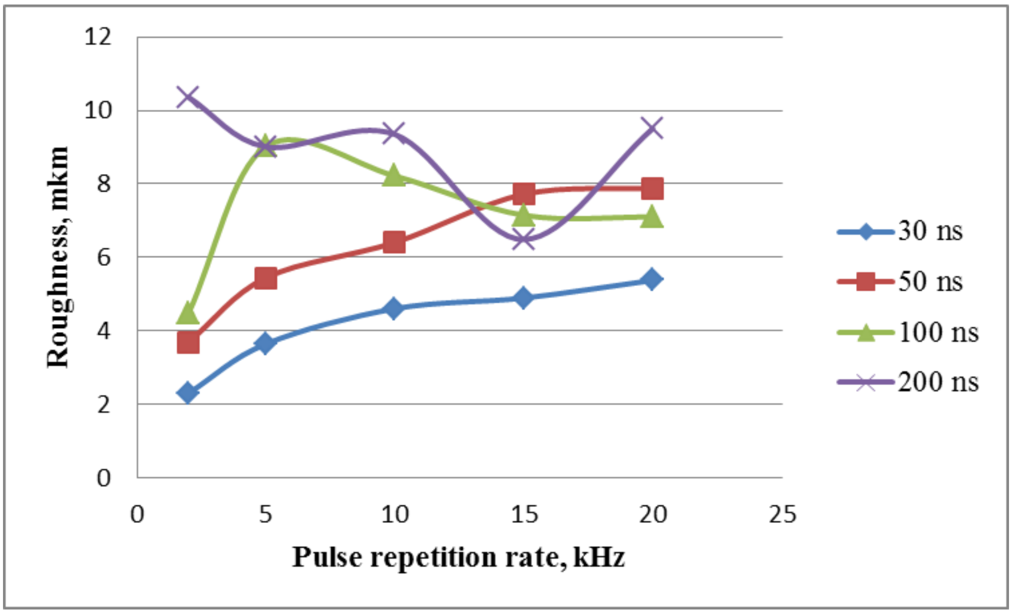

Fig. 4. The dependence of the surface roughness on the pulse repetition rate (different pulse duration).

3. Discussion

For the procedure of forming three-dimensional ZrO_2 ceramics dental structure prototypes the process productivity (material removal rate) and the final surface quality (total roughness) are the determining factors.

The material removal rate increases with the increase of pulse duration (Fig. 2). The dependence is almost linear in the chosen region of pulse durations. Thus, the use of laser pulses with a longer duration increases the material removal rate. The productivity of laser milling technology (at average power P_{av}=20 W) is comparable with the material removal rate using conventional mechanical milling.

The factor of laser pulse duration has a greater effect on the surface quality (roughness) than the factor of the pulse repetition rate. At shorter pulses, the surface remains smoother than at long pulses. However, as noted above, dental structures require a roughness of 10-30 μm, which means the choice of the mode of operation with pulse durations from 100 to 200 ns. The pulse repetition rate affects the surface quality to a lesser extent, and can be chosen in the range of 15-20 kHz for corresponding optimum pulse durations.
The combination of optimum parameters for prototyping of ZrO_2 ceramics dental structures using laser milling technology is as follows (for λ=1,068 μm, P_{av}=20 W, v=1 m/s):

- Pulse duration is 200 ns
- Pulse repetition rate is 20 kHz
- Degree of "path" overlap is 25%

The cross section of the cylindrical structure of ZrO_2 ceramics (thickness of the wall is 50 μm) produced by laser milling technology at optimum parameters given above is shown on Fig. 5. This technology allows the creation of thin-walled dental structures. Walls of dental frameworks with such thicknesses have light transmittance similar to that of human tooth tissue, which is an important esthetic requirement in stomatology.

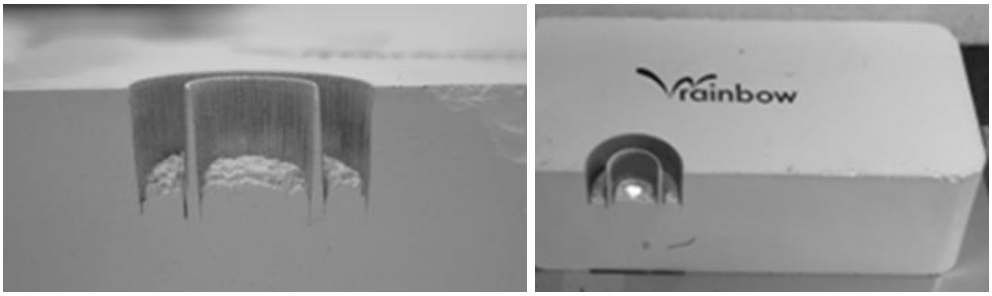

Fig. 5. Half cut section of the cylindrical structure with a wall thickness of 50 μm (side and top views).

Three-dimensional dental structure obtained by laser milling technology are shown on Fig. 6. Processing ZrO_2 ceramic blanks was carried out from pre-prepared 3D-model of a human tooth.

Fig. 6. Three-dimensional dental structure obtained from 3D-model of a human tooth by technology of laser milling.

It must be noted that the technology of laser milling of ceramic articles can be used to produce three-dimensional structures which can find application in other science and engineering fields.
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