

Nd:YVO₄ナノ秒レーザーを使用したジルコニアコーピングの新しい加工法

風間一小出 未来

A new method for fabricating zirconia copings using a Nd:YVO₄ nanosecond laser

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Abstract

The purpose of this work was to fabricate zirconia copings from fully sintered Y-TZP blocks using a Nd:YVO₄ nanosecond laser in order to avoid complicated procedures using conventional CAD/CAM systems. To determine the most appropriate power level of a Nd:YVO₄ laser, cuboid fully sintered Y-TZP specimens were irradiated at six different average power levels. One-way ANOVAs for the average surface roughness and laser machining depth revealed that an average power level of 7.5 W generated a smooth machined surface with high machining efficiency. Y-TZP copings were then machined using the proposed method with the most appropriate power level. As the number of machining iterations increased, the convergence angles decreased significantly ($p < 0.01$). The accuracy of the machined copings was judged to be good based on 3D measurements and traditional metal die methods. The proposed method using the nanosecond laser was demonstrated to be useful for fabricating copings from fully sintered Y-TZP.

Introduction

Recently, dentists and patients have become interested in all-ceramic restorations, which do not contain metals, which block light transmission, and better resemble the natural tooth appearance than any other restorative option¹⁾. In addition, all-ceramic restorations do not cause metal allergy problems. The clinical shortcomings of ceramic materials, such as brittleness, low tensile strength, and marginal inaccuracy, continue to limit their use compared to porcelain-fused-to-metal crowns^{2,3)}. Nevertheless, patients' demand for improved esthetics has driven the development of ceramic restorations. The use of all-ceramic restorations has spread as a result of the application of high-strength ceramics, such as zirconia, to the coping materials.

Zirconia ceramics for dental restorations have high strength and high toughness, which allows these materials to be used as all-ceramic coping materials for long-span bridges. However, machining fully sintered zirconia by milling is very difficult because of its high hardness. The coping is fabricated with an established method using a CAD/CAM system in which a partially sintered zirconia block is milled and subsequently sintered in a furnace. A linear shrinkage of 15 to 30% occurs due to sintering⁴⁾. The increased milling efficiency of the softer partially sintered block has the trade-off of a potentially poorer fit caused by the sintering shrinkage, the scanning process, compensatory software design, and milling⁵⁾. In order to avoid these complicated procedures, we have devised a new simple method by which to machine high-hardness zirconia using a laser. A range of lasers is now available in

dentistry. The Nd:YAG laser can be used in the dental laboratory for laser welding. Metal parts such as frameworks can be joined by self-welding of the parts with combustible acrylic denture base resins and artificial composite teeth, which would be burned by conventional soldering⁶). Noda *et al.* conducted an experiment involving the irradiation of zirconia using this Nd:YAG laser and examined the possibility of welding zirconia⁷). They reported that laser irradiation induced cracking on the surfaces of zirconia so Nd:YAG dental laser welding should not be performed on zirconia⁷). Nd:YAG dental laser irradiation, which produced a millisecond-order pulse width, generated thermal effects on zirconia⁸).

Therefore, we devised a new method by which to machine zirconia copings using an industrial Nd:YVO₄ Q-switched nanosecond laser, which had a smaller pulse width and a power density that was several hundred times higher than that of the conventional Nd:YAG dental laser. The purpose of the present study was to demonstrate the possibility of Nd:YVO₄ Q-switched nanosecond laser machining of zirconia copings.

Materials and Methods

Nd:YVO₄ laser machine

In the present study, fully sintered yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) specimens were machined using a Q-switched Nd:YVO₄ (Neodymium Doped Yttrium Vanadate) laser machine (Lasertec 40, DMG, Berlin, Germany, Fig. 1) for fabricating the Y-TZP copings of all-ceramic restorations. This nanosecond laser machine generated a power density of 2.26×10^4 (kW/mm³), which is several hundred times higher than a dental Nd:YAG laser with a millisecond pulse. The fundamental parameters of the Nd:YVO₄ laser machine are listed in Table 1.

Fully sintered yttria-stabilized tetragonal zirconia polycrystals (Y-TZP)

Two types of fully sintered Y-TZP specimens were prepared as follows. The discs of partially sintered Y-TZP (height: 25 mm, diameter: 98.5 mm, Aadvia Zr disk, GC, Tokyo, Japan) were milled and subsequently sintered at 1,550°C for 18.5 hours in a furnace using a dental CAD/CAM system (GM-1000, GC, Tokyo, Japan). Partially sintered Y-TZP consisted of >91 wt% ZrO₂, 5 wt% Y₂O₃, <3 wt% HfO₂, and <1 wt% Al₂O₃.

One cuboid (13 mm×13 mm×17 mm) fully sintered Y-TZP specimen was used to determine the most appropriate power level of the Nd:YVO₄ laser irradiation condition for fully sintered Y-TZP and another specimen (height: 7 mm, baseline: 10.6 mm), as shown in Fig. 2, was machined to form a Y-TZP coping on an abutment tooth of an imitation lower first molar.

Determination of the most appropriate power level of the Nd:YVO₄ laser

In order to determine the most appropriate power level of the Nd:YVO₄ laser, a cuboid fully sintered Y-TZP specimen was irradiated at six different average power levels (3, 6, 7.5, 9, 12,

and 14 W). The irradiated surface area was square (2 mm×2 mm). The specimen was cleaned in distilled water using an ultrasonic cleaner. The machining depth and the calculated average roughness (Ra in μm) at each of the six power levels were evaluated. The machining depth was measured using a measuring microscope (STM6, OLYMPUS, Tokyo, Japan). The calculated average roughness was also measured using a laser microscope (VK-8500, KEYENCE, Osaka, Japan) with a cut off value of 0.8 mm. One-way ANOVA and Tukey's multiple comparison test were used to analyze the data.

Machining Y-TZP copings using the Nd:YVO₄ laser machine

Machining 3D-CAD data of a Y-TZP coping were constructed using CAD software (Rhinoceros4.0, Robert McNeel & Associates, WA, USA). Y-TZP copings were machined in order to create the final form with a convergence angle of 11°, a cervical width of 10.6 mm, and a shoulder part width of 0.5 mm using 3D-CAD data (Fig. 2). The part that touched the abutment tooth, as shown in Fig. 2, was machined. Y-TZP copings were fabricated from fully sintered blocks using the Nd:YVO₄ laser machine with an optimal machining condition (n=6). Machining each coping required eight hours. Y-TZP copings were machined in 100- μm increments, as measured using calipers integrated into the laser machine for depth control. At first machining, the machining residue in the width direction of Y-TZP coping occurred on the inner surface so that the convergence angle of coping was greater than 11°, as designed based on machining 3D-CAD data. Therefore, the coping was machined two, three, or four times until the machining residue disappeared (Fig. 3).

Machining accuracy

1) Evaluation of machining accuracy by 3D measurement

Machined Y-TZP copings were measured using a non-destructive industrial 3D scanner (ATOS I 2M, GOM mbH, Brunswick, Germany) at every machining, and 3D-CAD data of copings were constructed. Dimensional differences in the height direction and width direction between the 3D-CAD data for machined Y-TZP copings and the target 3D-CAD data of Y-TZP copings were inspected using inspection software (GOM inspect, GOM mbH, Brunswick, Germany). Twelve measurement points were set in the width direction: 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, and 5.5 mm away from the inner cervical line of the Y-TZP coping (Fig. 4). In the height direction, six measurement points were set: -3, -2, -1, 0, 1, 2, and 3 mm away from the occlusal center of Y-TZP coping (Fig. 4). The results for the dimensional differences in the width direction and the machining frequency were analyzed by two-way repeated-measures ANOVA and Sidak's multiple comparison test. One-way repeated-measures ANOVA and Sidak's multiple comparison test were used to analyze the results for the dimensional differences in the height direction. The convergence angle of the inner coping was measured at each machining. One-way repeated measures ANOVA and Sidak's multiple comparison test were used for analyzing the results of the convergence angle

of inner-machined copings.

2) Evaluation of machining accuracy using metal dies

Machined copings at the fourth machining were measured using dies having different cervical widths of 9.60 mm (Abutment 1), 9.58 mm (Abutment 2), and 9.56 mm (Abutment 3). The convergence angle of each die was 11°. Y-TZP copings were placed on the metal die (Fig. 5) without cementation, and the marginal discrepancy (L-L1) was measured using a measuring microscope (STM6, OLYMPUS, Tokyo, Japan). Negative values for L-L1 indicate that copings were machined smaller than the machining CAD, whereas positive numbers indicate that the copings were machined larger than the machining CAD (Fig. 5). One-way ANOVA and Sidak's multiple comparison test were used to analyze the results for the goodness of fit.

Results

Determination of the most appropriate power level of the Nd:YVO₄ laser

The means and standard deviations (SD) of the calculated average roughnesses (Ra) and the machining depths of the irradiated Y-TZP surfaces are shown in Table 2 and Fig. 6.

The values of Ra for average powers of 6 W, 7.5 W, and 9 W were smaller than those for average powers of 3 W and 12 W, and the values of Ra for average powers of 6 W and 7.5 W were smaller than that for an average power of 14 W ($p < 0.05$). Therefore, the Y-TZP surface was machined to be the smoothest at 6 W and 7.5 W using the Nd:YVO₄ laser. As the average power increased, the machining depth tended to increase, but became smaller from 12 W to 14 W. The machining depths per pulse for average powers of 7.5 W, 9 W, 12 W, and 14 W were greater than that for an average power of 3 W ($p < 0.05$), and machining depth per pulse for an average power of 12 W was greater than that for an average power of 6 W ($p < 0.05$). When the above analysis results for the calculated average roughness and the machining depth were put together, the average power level of 7.5 W, at which the smoothest Y-TZP surface could be obtained with high machining efficiency, was decided to be the most appropriate power level.

Machining Y-TZP copings using the Nd:YVO₄ laser machine

An optimal machining condition with an average power of 7.5 W was used to machine Y-TZP copings from fully sintered specimens. At first machining, machining residue was deposited in the width direction on the inner surface of the Y-TZP copings, so that the convergence angle was greater than 11°, which were designed as the machining 3D-CAD data (Fig. 3). The machining residue of Y-TZP copings was measured using an industrial 3D scanner, and the machining data were reacquired. The Y-TZP copings were then machined again using the new data. This process was repeated for the same Y-TZP coping until the fourth machining.

Machining accuracy

1) Machining accuracy using 3D measurement

Figure 7 and Table 3 show the dimensional difference in the height direction for a certain section between the CAD data of the machined Y-TZP copings and the target CAD data for the coping obtained through 3D measurement. The average dimensional difference in the height direction was 73.6 μm . Figure 8 and Table 4 show the dimensional difference in the width direction obtained using 3D measurement. Two-way repeated-measures ANOVA revealed that both main effects were significant ($p < 0.01$). As shown in Fig. 8, the dimensional difference in the width direction decreased as the number of machining iterations increased and as the distance from the cervical line decreased, although the interaction between the two primary effects was also significant ($p < 0.05$). The simple primary effect of the distance from the cervical line was not significant at the third or fourth machining ($p < 0.05$). The dimensional difference in the width direction at the fourth machining was at most approximately 20 μm .

Figure 9 shows the inner convergence angle of machined copings of particular cross sections. The means and standard deviations, which are shown in parentheses, of the inner surface convergence angle were determined to be as follows: 18.5° (0.86°) for the first machining, 13.9° (0.47°) for the second machining, 12.1° (0.34°) for the third machining, and 10.9° (0.18°) for the fourth machining. One-way repeated-measures ANOVA revealed that the number of machinings significantly affected the inner convergence angle of Y-TZP coping. As the number of machining iterations increased, the convergence angle decreased significantly ($p < 0.01$). At the fourth machining, the convergence angle was comparable to the target 3D-CAD data.

2) Machining accuracy using the metal dies

The marginal fits of the Y-TZP copings that were machined four times were measured using metal dies. The means and standard deviations, which are shown in parentheses, of L-L1 were -80.2 (40.0) μm , 4.8 (32.6) μm , and 77.0 (42.0) μm using Abutments 1, 2, and 3, respectively. The larger the cervical width, the smaller the value of L-L1 (Fig. 10). The copings fit accurately on Abutment 2.

Discussion

Determination of the most appropriate power level of the Nd:YVO₄ laser

The average roughness and machining depth were measured in order to determine the most appropriate average power level (W) of the Nd:YVO₄ laser on fully sintered Y-TZP. Excellent lasing performance on Y-TZP, which has high machining efficiency and provides a smooth surface, is most important. As shown in Fig. 6, the six average power levels considered herein were statistically divided into three subgroups (a, b, and c) with respect to average roughness and three subgroups (A, B, and C) with respect to machining depth. The average power level of 7.5 W belonged to both subgroup a (smallest average roughness) and

subgroup A (greatest machining depth). Therefore, the average power level of 7.5 W, at which the smoothest Y-TZP surface could be obtained with high machining efficiency, was considered to be the most appropriate power level for the Nd:YVO₄ laser. High machining efficiency reduces the machining time.

Machining accuracy of Y-TZP copings

The copings, which were extracoronary restorations, were able to be machined from fully sintered Y-TZP using the nanosecond laser. Figure 7 shows that the dimensional difference in the height direction was not uniform. Air was blown from three directions on the Y-TZP coping in order to avoid reattachment of fine particles. However, locational differences were thought to occur as a result of the air being blown non-uniformly against the copings. Controlling the depth direction in machining (Z-axis) using a focused laser beam is generally difficult. Therefore, the copings were machined using an improved method for the depth control. In this experiment, the dimensional difference in the height direction was at most 132 μm for the planned 6.5 mm in the height direction based on machining CAD data, which gives an error of only 2.0%. In the width direction, the dimensional difference was at most 20 μm. The mean and standard deviation of the convergence angles of the inner copings were 10.9° and 0.18°, respectively.

In addition, the inside of the coping might be slightly oval-shaped. Therefore, in order to clinically evaluate the precision, a traditional experiment was conducted in which the dimensional accuracy was evaluated using a die method. We prepared three metal dies having different cervical widths. Since the machining 3D-CAD data (Fig. 2) did not take into account the cement layer or the coefficient of friction, the marginal discrepancy at the cervical line could not be obtained using Abutment 1, the cervical width of which was the same as in the machining 3D-CAD data. Therefore, dies having smaller cervical widths had to be used to measure the marginal discrepancy. The results revealed that the copings fit accurately on the die. The aforementioned discrepancies could be further improved by a slight modification of the design program of the CAD system. Marginal discrepancies of less than 120 μm have been reported to be clinically acceptable⁹⁾. Thus, accurate machining of zirconia coping for clinical use using the Nd:YVO₄ laser is possible.

Laser machining of Y-TZP

At present, Y-TZP copings are fabricated using a dental CAD/CAM system in which a partially sintered Y-TZP block (12HV) is milled and subsequently sintered in a furnace. Machining design can compensate for the approximately 20% volume shrinkage that occurs later during sintering of the zirconia blocks. Therefore, we devised a new method by which to machine a Y-TZP coping directly from a fully sintered Y-TZP block using an industrial Nd:YVO₄ Q-switched nanosecond laser. The use of lasers to machine ceramics presents a

number of advantages over the other methods. Laser machining is a noncontact technique that allows high-precision machining of numerous types of ceramics and eliminates tooling costs, which are expensive.

Generally, the material properties of Y-TZP, specifically its high thermal expansion coefficient ($11 \times 10^{-6} / ^\circ\text{C}$) and low thermal conductivity (2 W/mK)¹⁰⁾, make laser machining of this material difficult. Due to the strong thermal nature of the laser beam-material interaction, especially in the case of long pulse widths, microcracks are generated by dental lasers, which generate millisecond-order pulse widths, as a result of thermal damage. In the present study, we used a nanosecond pulsed laser, which could significantly reduce thermal damage. The formation of cracks in the irradiated surface was seldom observed when using the nanosecond laser, and cracks that observed were extremely small, having depths of approximately $3 \mu\text{m}$. Thus, the use of an ultrashort pulse laser that produces a picosecond pulsed laser or a femtosecond pulsed laser can significantly reduce the above-mentioned thermal effects, such as thermal damage or microcracks. However, such lasers require too much machining time to be adapted for practical application. Therefore, the potential of nanosecond laser machining on Y-TZP was demonstrated herein. Approximately 90% of the material removed through the proposed laser machining is a result of the interaction between the laser beam and the surface of the Y-TZP workpiece being machined. The nanosecond laser used is thus suitable for use in the machining of dental restorations.

The laser machine used herein provided three-axis machining, in which a Y-TZP specimen was irradiated from one direction (Z-axis). In addition, machining a hole with a convergence angle by condensing a laser beam has certain limitations because a focused laser produces a tapered hole. Accurately machined copings for clinical use were obtained after the fourth machining. On the other hand, a five-axis laser machine can instantly machine a taper-less hole because the laser beam can irradiate vertically with respect to the work piece¹¹⁾. In other words, a five-axis machine would provide the Y-TZP copings with improved retention and accuracy for clinical use and reduce costs by reducing the machining and finishing times.

Figure 11 shows a crown coping that was machined at an average power of 7.5 W. A dental restoration more complicated than the simple abutment coping shown in Fig. 2 was successfully machined from a fully sintered Y-TZP block, as shown in Fig. 11.

In comparison with a Nd:YAG laser, the Nd:YVO₄ laser has advantages such as the ability to produce more compact systems, because the Nd:YVO₄ crystal has 5 times higher absorption coefficient than Nd:YAG crystal. In addition to this, the laser has a higher efficiency thanks to a high stimulated emission cross section. A Nd:YVO₄ single crystal can be used for compact, high-efficiency machining, as compared with a Nd:YAG single crystal^{12,13)}.

Darkening of the machined Y-TZP surface and corresponding countermeasures

After ultrasonic cleaning, the machined Y-TZP surface was dark gray. Darkening of Y-TZP irradiated by a nanosecond laser should be a result of oxygen vacancies that were generated at high temperatures due to the release of oxygen atoms after substoichiometric dioxide formation, in which ZrO_2 became ZrO_{2-x} ^{14,15}). Noda *et al.* reported that a surface irradiated by a Nd:YAG laser became darkened and that the oxygen concentration clearly decreased, whereas the zirconium concentration increased⁷). Irradiated Y-TZP disks heated at 1,000°C for 5 minutes in air returned to their original white color. Applying the above reduction reaction to the present study, Y-TZP was heated in the atmosphere to reabsorb oxygen. After heating, the Y-TZP became white again. The high temperature allows oxygen to diffuse back to vacancies in the irradiated surface, rebuilding the crystalline structure and recovering the white color of Y-TZP. This heating is thought not to have an adverse clinical effect because the porcelain is sintered on Y-TZP at higher than 1,000°C. Matysiak *et al.* reported a similar result in which blackening occurred within holes on zirconia irradiated using a HeNe laser¹⁶). After heating at 1,350°C, the sample became white again, and there was no significant variation after the heat treatment. The recovery of the white color of the surface enables the fabrication of esthetic dental prostheses without opaquing using Y-TZP machined with a Nd:YVO₄ laser. The effect of the nanosecond laser on the machined Y-TZP surface was small, and we assume that the mechanical properties will not be adversely affected to a significant degree.

Future development

The primary problems associated with the laser machining of Y-TZP reported herein are a long machining time and high cost. Fabrication of the inner surface of the Y-TZP coping required approximately eight hours. However, sintering a partially sintered zirconia coping fabricated by a CAD/CAM system requires up to 18 hours. Moreover, the long machining time required when using the laser can be shortened by using a prefabricated coping of fully sintered Y-TZP. A nanosecond laser machine that can machine a high-thermal-expansion, low-thermal-conductivity material, such as Y-TZP, will also be able to machine other dental materials, such as resins and metals. If the machine is miniaturized and becomes widely used, the cost may be reduced considerably.

The toughness and high strength of Y-TZP are similar to the characteristics of metallic materials. For this reason, Y-TZP has been used in numerous applications in which previously only metals were believed to be suitable, such as moving parts of engines, valve components, milling and cutting tools, wire-drawing dies, and scissors⁸). Y-TZP is also a popular material for use in bio-medical applications due to its outstanding mechanical properties, reliability, and excellent biocompatibility. The ability to carry out accurate laser machining of Y-TZP would allow its properties to be more widely exploited, in particular for

applications in which uniquely shaped, intricately structured components are required, not only in industry but also in dentistry.

Conclusions

A Y-TZP coping was fabricated using a CAD/CAM system in which a partially sintered Y-TZP block was milled and subsequently sintered in a furnace, because fully sintered Y-TZP is too difficult to machine using milling techniques. Furthermore, the design compensates for the volume shrinkage that occurs during sintering of Y-TZP blocks. Thus, we devised a new method by which to machine Y-TZP copings using an industrial Nd:YVO₄ Q-switched nanosecond laser. The following conclusions were obtained based on the results of the present study.

1. An average power of 7.5 W was determined to be the optimal lasing condition because this condition provided the smoothest surface with high machining efficiency.
2. The convergence angle of the inner coping obtained at the first machining did not adequately agree with the provided machining 3D-CAD data. At the fourth machining, however, the convergence angle of the inner coping was 10.9° (SD=0.18°), which is approximately the same as the provided machining 3D-CAD data.
3. The dimensional difference in the height direction was at most 132 µm (SD=59 µm), and the dimensional difference in the width direction at the fourth machining was at most 20 µm (SD=2.4 µm).
4. The machined copings fit accurately on the metal die.
5. The proposed method using a nanosecond Nd:YVO₄ laser machine was demonstrated to be useful for fabricating a coping directly from fully sintered Y-TZP.

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Figures and Tables



Fig. 1 Nd:YVO₄ laser machine.

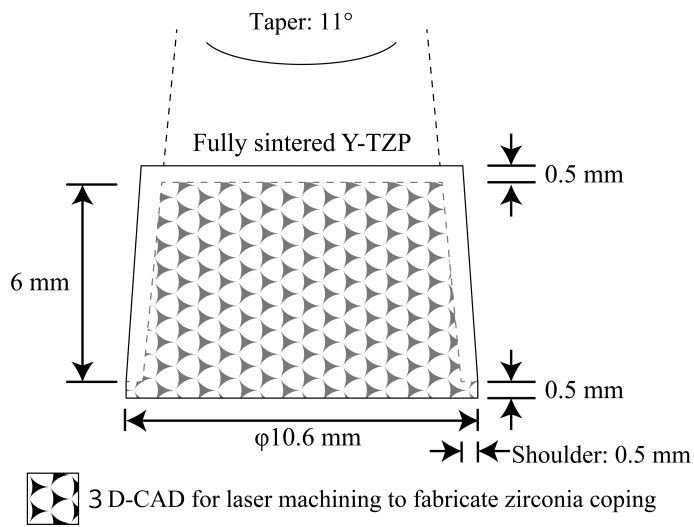


Fig. 2 Dimensions of the fully sintered Y-TZP specimen simulating a lower first molar, and 3D-CAD for laser machining to fabricate zirconia coping.

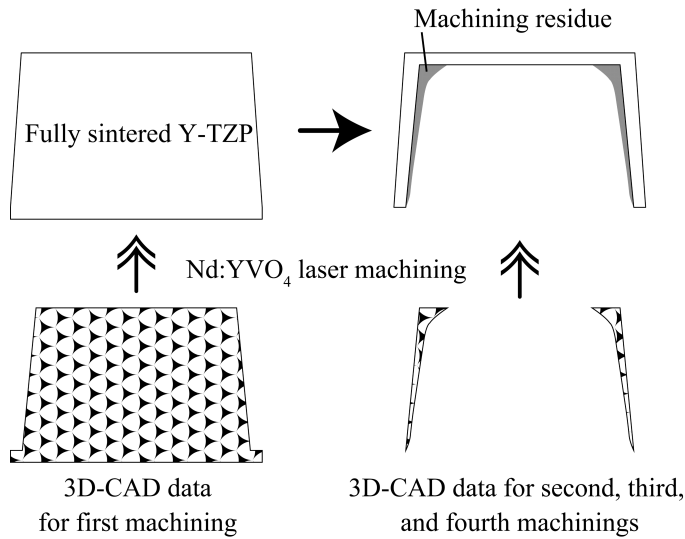


Fig. 3 Method of fabricating a zirconia coping having an inner taper of 11° and a cervical width of 9.6 mm.

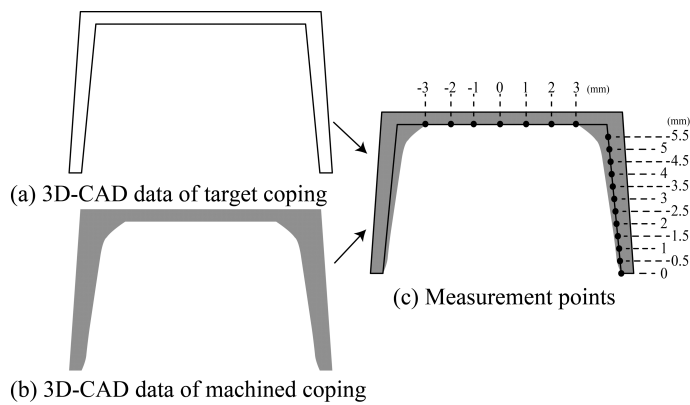


Fig. 4 Schematic diagrams of 3D measurement for machining accuracy. The dimensional differences between (a) and (b) were inspected using inspection software. (c) Measurement points in the height and width directions.

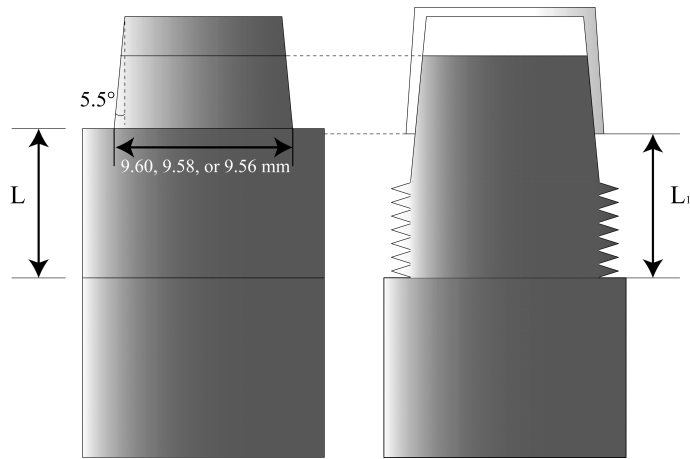


Fig. 5 Schematic diagrams of a metal die having a taper of 11° used to evaluate machining accuracy.

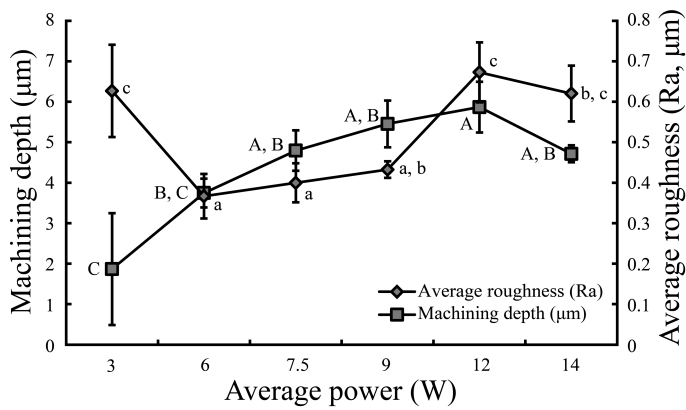


Fig. 6 Means and standard deviations of calculated average roughnesses (Ra) and machining depths of irradiated Y-TZP surfaces for different average power levels. The six average power levels were statistically divided into three subgroups (a, b, and c) with respect to average roughness and three subgroups (A, B, and C) with respect to machining depth. Means with different letters are significantly different ($p < 0.05$).

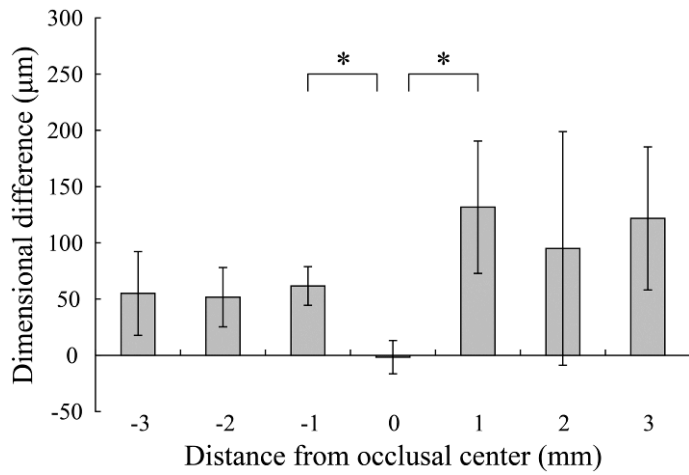


Fig. 7 Means and standard deviations of dimensional differences in the height direction. The asterisk (*) indicates a significant difference at $p < 0.05$.

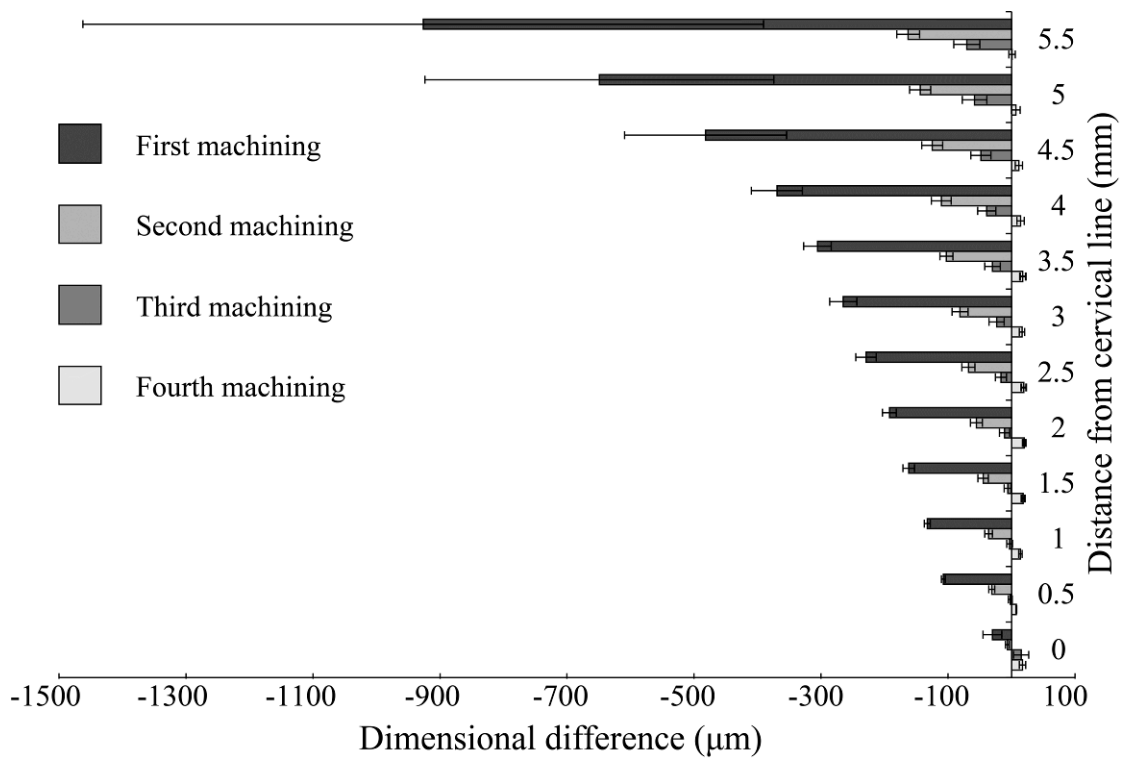


Fig. 8 Means and standard deviations of dimensional differences in the width direction.

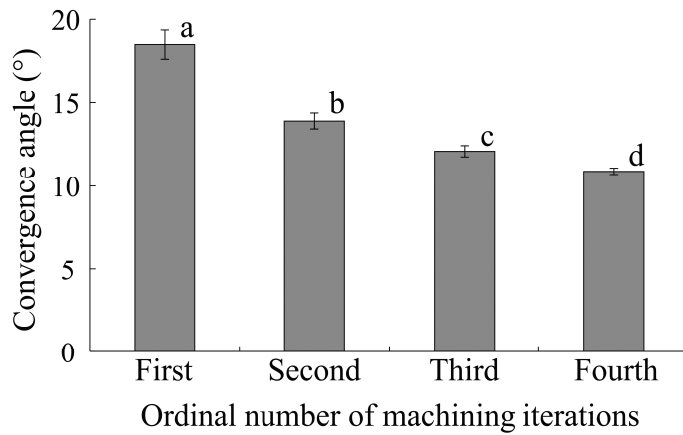


Fig. 9 Means and standard deviations of convergence angles of inner machined copings. Means labeled with different letters (a, b, c, and d) are statistically different from each other ($p < 0.01$).

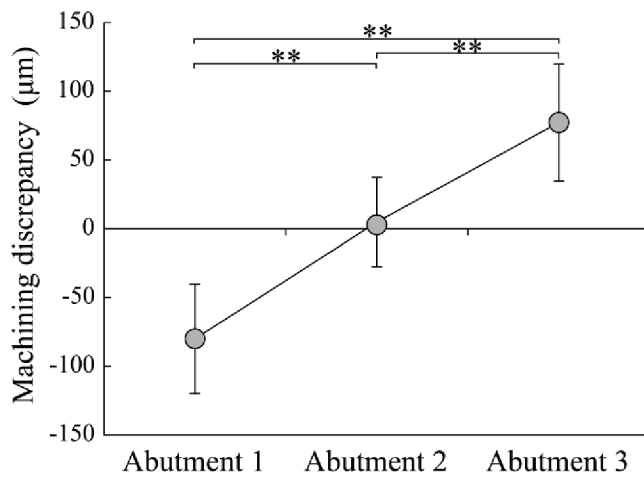


Fig. 10 Machining accuracy using three metal dies having convergence angles of 11° and different cervical widths; Abutment 1: 9.60 mm, Abutment 2: 9.58 mm, and Abutment 3: 9.56 mm. Significant differences are indicated by asterisks ‘**’ ($p < 0.01$).

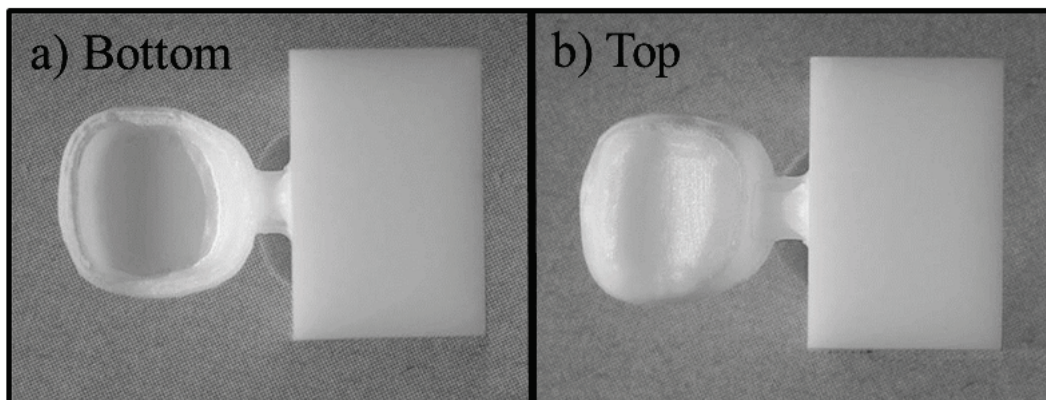


Fig. 11 A crown coping machined at an average power of 7.5 W. The crown coping was successfully fabricated in a clinical form.

Table 1 Specifications of the laser machine

Specification	Description
Laser type	Nd:YVO ₄ crystal
Wave length	1,064 nm
Pulse width	18 ns
Operation mode	Q switched pulse
Scan speed	500 mm/s
Peak power	16 kW
Pulse frequency	50 kHz
Focus diameter	30 μm
Track distance	10 μm

Table 2 Average roughness and machining depth per pulse after nanosecond laser irradiation of fully sintered Y-TZP

Average power (W)	Average roughness (Ra, μm)	Machining depth (μm)
	Mean (SD)	Mean (SD)
3	0.63 (0.11)	1.9 (1.4)
6	0.37 (0.06)	3.7 (0.4)
7.5	0.40 (0.05)	4.8 (0.5)
9	0.43 (0.02)	5.5 (0.6)
12	0.67 (0.07)	5.9 (0.6)
14	0.62 (0.07)	4.7 (0.2)

Table 3 Dimensional difference in the height direction at each measurement point

Distance from occlusal center (mm)	Dimensional difference (μm)	
	Mean	(SD)
-3.0	55.0	(37.3)
-2.0	51.7	(26.4)
-1.0	61.7	(17.2)
0.0	-1.7	(14.7)
1.0	131.7	(58.8)
2.0	95.0	(130.9)
3.0	121.7	(63.7)

Table 4 Dimensional difference in the width direction at each measurement point

Distance from cervical line (mm)	Dimensional difference (μm)							
	First machining		Second machining		Third machining		Fourth machining	
0.0	-30.1	(14.8)	-6.5	(3.0)	15.1	(12.0)	17.2	(5.0)
0.5	-107.5	(2.9)	-31.0	(4.7)	-1.9	(3.0)	7.6	(0.6)
1.0	-132.6	(4.6)	-36.3	(6.1)	-3.1	(4.4)	14.0	(2.8)
1.5	-161.9	(9.0)	-44.7	(8.3)	-6.0	(5.5)	18.2	(2.7)
2.0	-192.2	(10.9)	-55.3	(9.3)	-10.8	(8.0)	20.0	(2.4)
2.5	-229.2	(16.3)	-68.0	(10.4)	-16.7	(8.7)	19.1	(3.9)
3.0	-265.0	(21.4)	-81.1	(12.7)	-23.5	(12.0)	16.5	(4.2)
3.5	-305.6	(21.8)	-102.6	(10.3)	-30.0	(12.2)	17.8	(4.5)
4.0	-369.4	(40.1)	-110.6	(15.7)	-39.0	(14.1)	14.3	(5.8)
4.5	-481.8	(127.6)	-125.0	(16.4)	-48.2	(15.8)	11.5	(5.7)
5.0	-649.0	(274.6)	-143.9	(16.8)	-58.2	(19.4)	6.8	(6.9)
5.5	-926.4	(536.0)	-162.8	(17.9)	-70.6	(20.5)	1.8	(5.1)