Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is a promising material for dental restoratives. Although grinding or polishing with diamond tools is widely used to machine Y-TZP, the processing efficiency and cost of the process are problematic. In this study, we applied laser-assisted machining (LAM) to Y-TZP, in which non-diamond tools were used. Unlike LAM applied to other materials, decrease of the fracture toughness at elevated temperatures which is a unique feature of the Y-TZP was adopted as a key mechanism for machinability enhancement. In addition, a systematic method to determine the LAM conditions was proposed. In this study, we explain the LAM condition-determining method, which is based on numerical simulations of the temperature distribution. Secondly, the determining method was evaluated through a series of LAM experiments to obtain the appropriate LAM conditions. Using the determined conditions, LAM of Y-TZP was demonstrated to be effective; the thrust force was reduced by 51.3% and the tool wear was significantly reduced, while no cracks formed on the Y-TZP.

Keywords: laser-assisted machining, Y-TZP finite element method, genetic algorithm, machinability

1. Introduction

In the biomedical field, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is considered the most suitable material for implants. It is mainly used in dental crowns and fixed partial dentures [1] because of its superior material properties, such as high hardness, high fracture toughness, chemical inertness, and human tooth-like white color.

Y-TZP possesses high mechanical strength, which impedes machining at room temperature. It is common to use very expensive tools, such as single-crystalline diamond tools, to machine such difficult-to-cut materials [2]. Two main machining methods are used. The first comprises three steps: hot pressing, machining of the green part, and a final sintering. The second utilizes diamond grinding and polishing following the sintering process [1]. Both methods have disadvantages in geometric accuracy, efficiency, or cost, requiring improvement; thus, a new machining method for Y-TZP is highly desired.

The material cools after the sintering process. The change of the crystal structure during cooling induces volume change and crack generation in pure zirconium oxide. The crystal structure of pure zirconium oxide is monoclinic, while the tetragonal structure of Y-TZP is maintained even at room temperature; Y-TZP includes additives of 3 mol% yttria (Y₂O₃) [3]. The tetragonal structure is crucial for the high fracture toughness of Y-TZP in a mechanism called stress-induced transformation toughening, which prevents crack propagation and increases the fracture toughness [4], as found by Garvie et al. in 1975 [5]. The details are as follows. The tetragonal structure of Y-TZP is metastable at room temperature; therefore, it transforms into the monoclinic structure under high-pressure conditions, such as at a crack tip when the grain size is larger than approximately 0.4 μm [6]. The transformation from tetragonal to monoclinic structure induces a volumetric change and the subsequent compressive dilatational stress prevents cracking. However, the tetragonal structure becomes stable at temperatures above approximately 400°C. This means that the toughening mechanism does not work at elevated temperatures; the fracture toughness is expected to decrease under these conditions. Although the grain size of the Y-TZP blocks used in this study is approximately 0.4 μm, both the fracture toughness and the bending strength of Y-TZP measured in our former work [7] were shown to decrease at elevated temperatures.

We focus on the unique characteristics of Y-TZP at elevated temperatures, namely the decreases in bending and fracture toughness. Improved machinability can be expected at elevated temperature; thus, we propose the thermally assisted machining of Y-TZP. Various methods can be used to heat the material. The heating process in the thermally assisted machining process must not harm fabricated parts, and neither heat-affected nor degraded zones should remain in the part. The crystal structure of Y-TZP transforms depending on time and temperature, as described in the time-temperature transformation (TTT) diagram [8]. The diagram suggests that the crystal structure may degrade to monoclinic by maintaining Y-TZP at approximately 400°C for a certain period of time. A slow
heating or cooling process may cause the degradation of the crystal structure; thus, rapid temperature changes are appropriate for this process. We apply the laser-assisted machining (LAM) method to Y-TZP, because it can realize rapid heating and cooling. The machinability is expected to be enhanced by laser irradiation and the subsequent decrease of the mechanical strength and fracture toughness. LAM utilizing decreased fracture toughness in the workpiece has not yet been reported.

The authors previously reported the validity of the LAM process for Y-TZP [7, 9–10]. However, a systematic method to determine the appropriate machining conditions in the laser-assisted process has not been presented.

2. LAM of Y-TZP

LAM is a process in which a workpiece is locally heated before material removal by a cutting tool. The assistance of the laser beam reduces the mechanical strength of the workpiece and enhances its machinability. LAM of various materials has been reported, including silicon nitride [11], magnesia-partially-stabilized zirconia [12], Inconel 718 [13], austenitic stainless steel [14], tool steel [15], aluminum oxide [16], titanium alloy (Ti-6Al-4V) [17], and white cast iron [18]. The laser system was implemented on a five-axis machine tool to conduct laser-assisted milling [19, 20]. A preheating tactic was applied for the LAM of Inconel 718 and AISI 1045 steel [21]. The machinability is typically improved by LAM through the enhanced ductile-mode removal mechanism induced by the increased temperature. We, however, focus on the decrease in fracture toughness at high temperature, which is a unique characteristic of Y-TZP. Enhanced process efficiency and reduced cost are expected by utilizing the decreased fracture toughness. The geometrical accuracy and the surface roughness must be kept within certain tolerances, despite the reduced fracture resistance in the process, as is discussed later.

The LAM process intrinsically possesses a larger number of conditions that must be appropriately determined, compared to non-assisted cutting processes. Although previous works investigated the machinability with various LAM conditions, a method for determining the LAM conditions has not yet been established. It is essential to establish a method that allows operators to determine the appropriate LAM conditions before processing to allow industrial use of the technology in the future; thus, we propose such a method in this study.

In this work, we show the effectiveness of LAM on Y-TZP, utilizing the decreased fracture toughness for efficient and cost-economic processing of the material. First, we propose a method for determining the LAM; it utilizes the results of a developed simulation of the temperature distribution near a laser spot. The appropriate LAM conditions are determined by this method. Finally, the effectiveness of the LAM process on Y-TZP is demonstrated in Section 4.

3. Method of Determining LAM Conditions

3.1. Development of Method

We assumed a milling process utilizing a square endmill throughout this study. In the milling process, the LAM conditions are as defined in Table 1 and Fig. 1. The conditions involve seven different variables where four are categorized as cutting conditions and the others are categorized as laser conditions. Both the cutting tool and laser spot have the condition of feed speed. We must distinguish these speeds if both are independently controlled in the LAM process. Since the laser device used in this study was fixed on the spindle of a machine tool, both feed speeds were assumed equal, and the feed speed was categorized only as a cutting condition, not a laser condition, as shown in Table 1.

Every LAM condition affects the machinability in a complex manner. The workpiece temperature near the cutting edge, for instance, is important for the machinability. The machinability varies depending on the laser conditions and some cutting conditions, where each affects the temperature in different ways. It is beyond an operator’s capability to determine the appropriate set of LAM conditions by trial and error. Thus, a system that determines the appropriate conditions for the process is necessary for LAM.

The structure of the method for determining the LAM conditions is shown in Fig. 2. In this method, the appropriate workpiece temperature for the process, feed speed, depth of cut, and tool diameter are taken as a set of inputs. The laser conditions are determined so that the process fulfills three conditions regarding the temperature distribution over the cutting area and in the laser spot, as defined in Fig. 1. The three conditions are as follows:

<table>
<thead>
<tr>
<th>Cutting conditions</th>
<th>Laser conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed speed: ( f ) [mm/min]</td>
<td>Power: ( p ) [W]</td>
</tr>
<tr>
<td>Depth of cut: ( h ) [mm]</td>
<td>Spot diameter: ( d_o ) [( \mu )m]</td>
</tr>
<tr>
<td>Tool diameter: ( d_t ) [mm]</td>
<td>Spot-tool distance: ( d ) [mm]</td>
</tr>
<tr>
<td>Rotational speed of a tool: ( s ) [rpm]</td>
<td></td>
</tr>
</tbody>
</table>
1) The mean temperature on the cutting area should be equal to the desired workpiece temperature, as defined in the input.

2) The temperature should be uniformly distributed over the cutting area, and the temperature variance in the area should be minimized.

3) The maximum temperature in the laser spot should be lower than a certain limit to avoid workpiece damage.

In order to search for a set of LAM conditions that satisfies the three conditions above, it is necessary to estimate a temperature distribution in the workpiece around the laser spot. We developed a numerical simulation to obtain this temperature distribution using the finite element method, where the laser spot is modeled as an elliptically shaped heat source moving on the workpiece surface, as explained in Section 3.2.

3.2. Laser Simulation

3.2.1. Simulation Methods

The temperature distribution in a workpiece upon laser irradiation must be discussed with respect to LAM machinability. We developed a simulation to obtain the temperature distribution in the workpiece when the laser beam hits the surface with a defined set of conditions. We chose the finite element method as the simulation manner and utilized the Dassault Systems integrated platform of ABAQUS 6.13. The Y-TZP properties used in the simulation are shown in Table 2[22]. The environmental conditions and mesh conditions are shown in Table 3.

The laser spot is modeled as an elliptically shaped moving heat source whose energy distribution within the spot is Gaussian. The laser device used in this study is a continuous-fiber laser with a wavelength of 1070 nm and maximum power of 200 W. In the LAM process, the laser beam axis is not vertical to the workpiece surface to avoid interference between the laser beam and spindle; thus, the spot shape is elliptical. The intensity distribution within the laser spot is obtained as follows when the laser beam hits the workpiece surface vertically:

\[ q(r) = q_0 \exp\left( -\frac{2r^2}{r_0^2} \right) \]  \hspace{1cm} (1)

where \( q(r) \) is the intensity [W/cm²] of a point whose radial distance from the spot center is \( r \), \( q_0 \) is the peak intensity [W/cm²], and \( r_0 \) is the spot radius. The spot radius is defined as the distance from the spot center where the intensity becomes \( 1/e^2 \) of the peak intensity. The following integrating operation derives the relationship between the peak intensity and the total laser power:

\[ q_{all} = \int_0^\infty 2\pi r \cdot q_0 \exp\left( -\frac{2r^2}{r_0^2} \right) dr = \frac{\pi r_0^2}{2} q_0 \]  \hspace{1cm} (2)

where \( q_{all} \) is the laser power [W]. When the tilt angle of the beam axis against the workpiece surface is \( \theta \), the major axis and the minor axis of the laser spot, represented by \( a_0 \) and \( b_0 \), can be calculated as \( a_0 = \frac{r_0}{\cos(\theta)} \) and \( b_0 = r_0 \), respectively. The Gaussian distribution in an elliptical shape is complex, so we approximated the distribution as follows with reference to [23]:

\[ q(x_i, y_i) = \frac{2q_{all}}{\pi r_0^2 \cos(\theta)} \exp\left( -\left( \sqrt{2n} \right)^2 \right) \exp\left( -\left( \frac{\sqrt{2m}}{\sqrt{1-n^2}} \right)^2 \right) \]  \hspace{1cm} (3)

where \( q(x_i, y_i) \) is the intensity [W/cm²] at a point described by the coordinates of \( x_i \) and \( y_i \), whose axes originate at the ellipse center, while \( m \) and \( n \) are obtained as \( m = \frac{b}{a_0} \) and \( n = \frac{b'}{a_0} \), respectively. Although Eq. (3) describes the approximated distribution of the intensity in an elliptical laser spot, some beam intensity contacts the workpiece outside of the spot, because the spot edge is defined by the positions where the beam intensity becomes \( 1/e^2 \approx 13.5\% \) of the peak intensity. We modified Eq. (3) to enable the calculation of the intensity at a position whose distance from the center is up to \( \sqrt{2} \) times as large as that of the original spot edge. The equation is as follows:

\[ q_0 = \frac{2q_{all}}{\pi r_0^2 \cos(\theta)} \exp\left( -\left( 2n' \right)^2 \right) \exp\left( -\left( \frac{2m'}{\sqrt{1-n'^2}} \right)^2 \right) \]  \hspace{1cm} (4)
where \( m' = \frac{y}{\sqrt{2} a_0} \) and \( n' = \frac{y}{\sqrt{2} b_0} \). Eq. (4) is used as a model describing the distribution of the laser intensity in the simulation.

### 3.2.2. Evaluation of the Simulation Results

The comparison between the simulated temperature distributions and the experimentally measured results under the laser conditions used in the simulations is necessary to ensure the validity of the simulation results. We conducted three experiments to measure the temperature distribution around the laser spot. The dimensions of the Y-TZP workpieces used in the experiments were 20 mm \( \times \) 20 mm \( \times \) 4 mm. The black material THI-1B (Tascojapan Co., Ltd.) was sprayed over the surface of the workpiece to avoid reflection of the laser beam from the surface; the emissivity of the surface was fixed at 0.94. The beam was tilted by 30° and the temperature was measured using thermography. A schematic of the experiment and a view of the setup are shown in Figs. 3(a) and (b), respectively. As described in Figs. 3(a) and (b), a view of the workpiece through the thermographic device causes geometric distortion of the workpiece surface in captured images, because the thermographic camera is inclined. The projective transformation method is applied to correct this distortion of the measured temperature distribution and to compare the experimental results with the simulations.

The laser device comprises two parts. First is the beam generator (Jenoptik AG, JenLas® fiber cw 200), and second is the irradiator, which includes focusing optics. A detailed image of the laser irradiator is given in Fig. 3(c). The spot diameter was measured prior to the experiments. A beam profiler (Ophir Optronics Solutions Ltd., BGP-USB-SP620) was used to measure the beam diameter. The comparison between the experimentally measured results and the simulated results is shown in Fig. 4. The laser power and spot diameter were varied and so were the feed speeds. The maximum measurable temperature of the thermographic camera is 500°C, so the temperature distribution below 500°C was compared. The results show that the simulation results match well with the measured distributions. Although the temperature distribution inside the material cannot be directly compared because of the lack of direct measurement methods, it can be considered that the good match between the surface temperature distributions and the actual measurements validates the calculated temperature distribution inside.

The temperature distributions on the cutting area defined in Fig. 1 were calculated using the simulation results. Examples of the calculated results are shown in Figs. 5(a) and (b). Figs. 5(c) and (d) also show the mean and variance of the temperature on the area as a function of the cutting distance in the LAM process.

### 3.3. Determination of LAM Conditions

The determination of the LAM conditions was summarized as the solution to the following optimization problem:

\[
\begin{align*}
\min f(x), & \quad x = \begin{pmatrix} p \\ d_0 \\ d \end{pmatrix} \quad \ldots \quad (5) \\
\text{s.t.} & \quad ax \leq b, \quad x_{\min} \leq x \leq x_{\max}, \quad T_{\text{max}}(x) \leq T_{\text{lim}} \\
& \quad f(x) = (T_{\text{mean}}(x) - T_{\text{opt}})^2 + T_{\text{var}}(x) \quad \ldots \quad (6)
\end{align*}
\]

The first constraint, \( ax \leq b \), means that the laser spot and tool must not overlap where \( a = \begin{pmatrix} 0 & 1/2 & -1 \end{pmatrix} \) and \( b = -d_1/2 \). \( T_{\text{mean}}(x) \) and \( T_{\text{var}}(x) \) are the mean and variance, respectively, of the temperature on the cutting area. They are calculated using the developed simulation, as mentioned in Section 3.2. \( f(x) \) cannot be expressed as any particular equation form, since it relies on the numerically calculated results. A genetic algorithm was adopted to solve this optimization problem; such algorithms can be applied to non-linear optimization problems. The to-be-determined laser conditions have tolerance ranges restricted by the device configurations. The device used in this study determined the ranges of the values as follows:

\[
\begin{align*}
5 < p < 200 \\
1 < d_0 < 4 \\
1 < d < 4
\end{align*}
\]

The range of each variable is evenly divided into eight
Fig. 4. Results of the comparison between the simulation and the measured temperature on the surface of the workpiece. (a) $p = 4.42$ W, $d_0 = 3.56$ mm, $f = 20$ mm/min, (b) $p = 13.35$ W, $d_0 = 3.56$ mm, $f = 10$ mm/min, (c) $p = 13.35$ W, $d_0 = 2.16$ mm, $f = 5$ mm/min.

Fig. 5. A set of examples of the simulation. (a) Simulation results on the surface and the cross-sectional view, (b) temperature distribution on the cutting area, (c) mean temperature on the cutting area over the cutting distance, (d) temperature variance on the cutting area over the cutting distance.
sections, so that a set of nine different values is obtained for each variable. The simulations were conducted with sets of conditions designed in a full-factorial way; therefore, simulations were conducted $9^3 = 729$ times. The mean temperature of the cutting area, variance of the temperature on the cutting area, and maximum temperature in the laser spot were calculated in each simulation. The calculated results were stored in tables and a linear interpolation was conducted for each of them. The interpolated functions estimate the mean, variance, and maximum temperature corresponding to any set of laser conditions that remain within the tolerance ranges, which are therefore $T_{\text{mean}}(x)$, $T_{\text{var}}(x)$, and $T_{\text{max}}(x)$. Examples of the behaviors of $T_{\text{mean}}(x)$ and $T_{\text{var}}(x)$ depending on the laser power and spot diameter under a fixed spot-tool distance of 4 mm are shown in Fig. 6.

Through optimization, a set of LAM conditions were obtained as summarized in Table 4. The input conditions given in the first three rows of Table 4 are the inputs for the method of determining the LAM conditions; subsequently, the outputs shown in the last three rows of Table 4 are obtained. Here, the appropriate workpiece temperature $T_{\text{opt}}$, which is one of the inputs shown in Fig. 1, was set to 400°C. This was selected as the appropriate workpiece temperature because the fracture toughness of Y-TZP is known to decrease at this temperature, as mentioned in Section 1. The determined set of conditions is denoted LAM condition A in the following sections.

### Table 4. LAM condition A.

<table>
<thead>
<tr>
<th>Feed speed [mm/min]</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of cut [mm]</td>
<td>0.3</td>
</tr>
<tr>
<td>Tool diameter [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Rotational speed of a tool [rpm]</td>
<td>2500</td>
</tr>
<tr>
<td>Laser power [W]</td>
<td>23.08</td>
</tr>
<tr>
<td>Spot diameter [mm]</td>
<td>3.63</td>
</tr>
<tr>
<td>Spot-tool distance [mm]</td>
<td>4.00</td>
</tr>
</tbody>
</table>

4. Evaluation of the Method for Determining LAM Conditions

#### 4.1. Methods

The optimization problem shown in Eq. (3) assumes that three conditions must be fulfilled to obtain an appropriate set of laser conditions. The three conditions are the value of the mean temperature on the cutting area, minimized temperature variance on the area, and the maximum temperature tolerance on the temperature in the laser spot. We deliberately searched for sets of laser conditions such that each had one condition out of the three that was not fulfilled in the optimization procedure. The machinability of each LAM condition with a single unfulfilled condition was compared with that of LAM condition A.

In the case of LAM condition A, the calculated mean temperature on the cutting area is 390.5°C, the temperature variance on the area is 1726.1°C², and the maximum temperature tolerance in the laser spot is 1500°C. For condition B listed in Table 5, the mean temperature on the cutting area is 199.8°C, while the others are equal to those of condition A. For condition C listed in Table 5, the temperature variance on the cutting area is 20000°C² while the other two are equal to those of condition A. Condition D was determined under the constraint that the maximum temperature tolerance in the laser spot is 5000°C, while that in condition A is 1500°C. LAM experiments were conducted using LAM conditions A, B, C, and D. The machinability of conditions B, C, and D were compared with that of condition A, respectively. If the machinability under condition A is improved relative to those of conditions B, C, and D, the validity of the three conditions in this proposed method is supported.

#### 4.2. Experimental Setup of the LAM

The view of the experimental setup is shown in Fig. 7. The setup consists of the focusing optics fixed on the spindle, the tube leading the assisting air, and the high-speed camera with an IR filter. The tools were two flute square
endmills with diameters of 2 mm (MS2MSD0200, Mitsubishi materials corporation, Tokyo, Japan). The workpiece was a Y-TZP block (NPZ-10, Nippon tungsten Co., Ltd., Fukuoka, Japan) fixed to a force sensor by clamping at the four corners. The black material was sprayed on the surface in order to enhance laser absorption.

4.3. Results

4.3.1. Mean Temperature of Cutting Area

The comparison of the machinability between conditions $A$ and $B$ was conducted. Condition $B$ has a lower temperature on the cutting area, as mentioned in Section 4.1. In condition $B$, the laser power, spot diameter, and spot-tool distance are smaller than those in condition $A$, realizing one-half of the mean temperature and equivalent values for the other two parameters. A view of the process is shown in Fig. 8(a). Although the maximum temperature tolerance in the laser spot was equal to that of condition $A$, the determined laser condition induced a much lower maximum temperature in condition $B$, which resulted in the darker spot. The cutting force comparison is shown in Fig. 8(b). In the thrust force, the maximum value is 137.0 N for condition $A$ and 196.7 N for condition $B$, which shows better performance under condition $A$. Images of the tool tips are shown in Fig. 8(c). Here, the angle $\alpha$ described in Fig. 9 is used to quantify the amount of tool wear. According to Fig. 8(c), the angle $\alpha$ is $33^\circ$ in condition $A$ and $42^\circ$ in condition $B$, which also reveals suppressed tool wear under condition $A$. The stipulation that the mean temperature of the cutting area should match the determined appropriate workpiece temperature was, thereby, shown to be necessary in determining the appropriate laser conditions.

4.3.2. Temperature Variance on the Cutting Area

The machinability was compared between the conditions $A$ and $C$. Condition $C$ causes a higher temperature variance on the cutting area, while the mean and maximum temperatures in the laser spot are equal to those in condition $A$. The laser power is nearly doubled, while the spot diameter and the spot-tool distance are smaller in condition $C$ compared to that in condition $A$. The captured view of the process is shown in Fig. 8(a). The spot distance is obviously smaller in condition $C$ than in condition $A$. The measured thrust force in condition $C$ is shown in Fig. 8(b). The maximum value is 150.5 N in condition $C$, which is larger than that of condition $A$ at 137.0 N. The tool tip image in condition $C$ is shown in Fig. 8(c). The angle representing the tool wear amount is $36^\circ$ in condition $C$, which is larger than that in condition $A$. Condition $A$ demonstrates better machinability compared to condition $C$, although the difference between the two is smaller than that described in Section 4.3.1. The results support the necessity of the condition that the temperature variance on the cutting area should be minimized in this proposed method.

4.3.3. Maximum Temperature Tolerance in a Laser Spot

In conditions $A$–$C$, the maximum temperature tolerance was set to 1500°C to reflect the sintering temperature of Y-TZP. The tolerance was increased on purpose to 5000°C for laser condition $D$. The laser power is 37.05 W, which is much higher, and the spot diameter is 1.25 mm, which is smaller, compared to those in condition $A$, so we expect a much higher temperature in the laser spot. The laser irradiation test was conducted with the same LAM conditions without engagement of the cutting tool during the process. The much denser energy in the laser spot resulted in the emittance of intense light from the spot, and the workpiece was severely fractured as shown in Fig. 10, with cracks propagating outward from the heated region. Although the optimality of the maximum temperature tolerance of 1500°C, set in the search for condition $A$, requires further discussion, we can conclude that excessive temperature in the laser spot is not appropriate for the LAM of Y-TZP.

4.4. Discussion of the Validity of the Method for Determining LAM Conditions

In this study, we proposed a method to systematically determine the LAM conditions appropriate for the processing of Y-TZP. The method was evaluated in Section 4.3, where the necessity of the three conditions used

### Table 5. LAM conditions $B$, $C$, and $D$.  

<table>
<thead>
<tr>
<th></th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed speed [mm/min]</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Depth of cut [mm]</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Tool diameter [mm]</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rotational speed [rpm]</td>
<td>2500</td>
<td>2500</td>
<td>20</td>
</tr>
<tr>
<td>Laser power [W]</td>
<td>5.94</td>
<td>11.01</td>
<td>37.05</td>
</tr>
<tr>
<td>Spot diameter [mm]</td>
<td>2.19</td>
<td>2.49</td>
<td>1.25</td>
</tr>
<tr>
<td>Spot-tool distance [mm]</td>
<td>2.64</td>
<td>3.80</td>
<td>3.80</td>
</tr>
</tbody>
</table>

Fig. 7. LAM setup.

$\alpha$ is $33^\circ$ in condition $A$ and $42^\circ$ in condition $B$, which also reveals suppressed tool wear under condition $A$. The stipulation that the mean temperature of the cutting area should match the determined appropriate workpiece temperature was, thereby, shown to be necessary in determining the appropriate laser conditions.

4.3.2. Temperature Variance on the Cutting Area

The machinability was compared between the conditions $A$ and $C$. Condition $C$ causes a higher temperature variance on the cutting area, while the mean and maximum temperatures in the laser spot are equal to those in condition $A$. The laser power is nearly doubled, while the spot diameter and the spot-tool distance are smaller in condition $C$ compared to that in condition $A$. The captured view of the process is shown in Fig. 8(a). The spot distance is obviously smaller in condition $C$ than in condition $A$. The measured thrust force in condition $C$ is shown in Fig. 8(b). The maximum value is 150.5 N in condition $C$, which is larger than that of condition $A$ at 137.0 N. The tool tip image in condition $C$ is shown in Fig. 8(c). The angle representing the tool wear amount is $36^\circ$ in condition $C$, which is larger than that in condition $A$. Condition $A$ demonstrates better machinability compared to condition $C$, although the difference between the two is smaller than that described in Section 4.3.1. The results support the necessity of the condition that the temperature variance on the cutting area should be minimized in this proposed method.
Laser-Assisted Milling of Zirconia with Systematically Determined Machining Conditions

Fig. 8. Results of the LAM experiments. (a) View of the LAM processes, (b) thrust force, (c) tool wear.

Fig. 9. The angle representing the amount of the tool wear.

in the optimization procedure were tested. The results showed that the three conditions are all necessary to obtain the appropriate laser conditions.

However, in this study, the laser beam made contact with a flat surface, which simplified the simulation procedure because the laser spot could be modeled as an elliptical planar heat source. The simulation must be able to accommodate more complex workpiece geometries than that of a flat surface.

5. Machinability of Y-TZP in LAM Compared to Non-Assisted Process

5.1. Compared Results

The proposed LAM method of Y-TZP itself, utilizing the decreased fracture toughness, must be evaluated. A comparison between the LAM machinability under condition A determined in Section 3.3 and that of the non-assisted process is described in this section. The results of the LAM process with condition A are shown in Fig. 8. Machining under the same cutting conditions as those in condition A was then conducted without laser assistance.

The results of the non-assisted process are given in Fig. 11. In comparison with the condition A, the maximum thrust force value is reduced from 250.9 N in the non-assisted process to 137.0 N in condition A. The tool wear is much worse in the non-assisted process, where the angle representing tool wear measured 98°. This value actually means that wear occurred across the en-
tire outer edge of the bottom face of the tool. The results demonstrate a significant machinability improvement under the LAM process with condition A compared to the non-assisted process.

Although a clear machinability improvement is observed in the LAM of Y-TZP, a crack propagated during LAM under condition A that finally separated the workpiece block into two pieces. The generated crack is shown in Fig. 12. The crack propagation mechanism is as follows. Firstly, a crack is generated from the top to the bottom surface of the block, by thermal shock or shock from tool contact. Secondly, the crack propagates horizontally through the region where the fracture toughness is significantly reduced by the elevated temperature; therefore, it intersects the spot center, which finally separates the workpiece. The crack runs on the center line of the generated groove that represents the trajectory of the spot center. Several methods to solve the generation of surface cracks can be proposed. Further decreasing the temperature in the spot center or using a laser beam with uniform energy distribution in the laser spot would significantly contribute to solving the problem.

5.2. Laser Control to Prevent the Crack Generation During the LAM

We constructed a machining procedure to conduct the LAM process with crack generation avoidance, as shown in Fig. 12. The procedure is shown in Fig. 13(a). The concept of the procedure is to avoid crack generation near the edge of the workpiece by stopping the laser emission in this region. Using a single tool from the beginning of the LAM process during the procedure makes the tool wear incomparable, because the machining during the non-laser-assisted time near the edge of the workpiece significantly enhances the wear.

The LAM experiment was conducted following the procedure explained below and shown in Fig. 13(a). Firstly, a groove was generated with a length of approximately 3 mm from the edge of the workpiece without laser assistance (Step 1). Secondly, LAM was conducted following the pre-generated groove after changing to a new tool (Step 2). During the second step, the laser was not turned on from the beginning, as shown in Fig. 13(a). A non-assisted process with the same cutting distance was also conducted to compare the amount of tool wear.

The resulting grooves are shown in Fig. 13(b). The LAM process with no cracks remaining on the machined surface is demonstrated to be feasible. The thrust force comparison is shown in Fig. 13(c). The maximum value is 221.7 N in the non-assisted process and 108.0 N in LAM under condition A, representing a 51.3% decrease. The tool tip images are shown in Fig. 13(d). The tool wear with the angular representation is 98° in the non-assisted process while the other is 37°, showing significant decrease in the tool wear. The tool wear amount of 98° from the non-assisted process means that the entire outer edge of the tool’s bottom face was worn.

5.3. Discussion of LAM of Y-TZP

The LAM of Y-TZP using a non-diamond cutting tool was proved to be feasible under an appropriate set of LAM conditions, such as condition A, which was obtained in advance. Although the proposed LAM positively utilizes the fracture toughness decrease at elevated temperature, which is a unique characteristic of Y-TZP, the excessive temperature increase can induce crack propagation, as explained in Section 5.2. This propagation was suppressed by switching the control of the laser at the edge of the workpiece in the process described in Section 5.2. The switching control of the laser tested in this study involved only the on-off control. Future systems should use gradual control tactics for the laser power near the edges. The laser power could be held below the threshold to suppress cracking at the workpiece edge and gradually increased as the cutting area moves toward the inside of the workpiece. In addition, a method for determining LAM condi-
Fig. 13. Successful LAM results with the laser control to suppress cracks in comparison with the non-assisted process. (a) Schematic diagram of the steps of the process, (b) generated grooves, (c) thrust force, (d) tool wear.
lations was proposed, considering the temperature distribution on the cutting area, although the cracking probability is not considered. Future improvements to the method must include a function to suppress cracking.

We utilized milling tools made of tungsten carbide, which is not sufficiently hard for machining Y-TZP at room temperature. Although the enhanced fracture at elevated temperatures improved the machinability, further improvement of the LAM is necessary for actual use in industrial situations. Further investigations will include the use of other tool materials. Regarding the economical aspects of the LAM, the investment necessary for the laser device is negligible. The fiber laser device adopted in this study is not completely suitable, despite its low cost compared to other laser devices, such as YAG lasers. The use of the diode laser would fit the problem better.

6. Conclusions

The LAM of Y-TZP was proposed, in which the decrease of the fracture toughness at elevated temperatures was positively utilized. A method for determining LAM conditions was also proposed to obtain appropriate sets of LAM parameters. The method is based on the simulation of the temperature distribution caused by laser irradiation. The determination procedure for the laser conditions was consequently summarized into an optimization problem to optimize the temperature distribution on the cutting area. The validity of the method was shown through experiments, which verified that the obtained LAM conditions were appropriate.

The machinability improvement with LAM under the determined conditions was significant; the thrust force was decreased by 51.3%, tool wear amount was reduced to an angle of 37° from the wear observed on the entire outer edge of the bottom face of the milling tool in the non-assisted process. The force decrease enhances the processing efficiency and the decrease of the tool wear decreases the processing cost.

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