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Binder influence on green ceramic machining by means of milling and laser machining

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Abstract

The micro manufacturing of ceramic components is technologically challenging especially when complex shapes and micro features are required. A hybrid manufacturing chain is developed for non-sintered (green) blanks machined using sequentially a cutting tool and a laser source. During the preparation of the green blank, a binder is added to the powder to improve compaction. The amount of binder can affect the quality of the machining. The goal of this paper is to study its influence on the material removal rate and the surface quality with both technologies and to determine the optimal proportion for using this hybrid machining.

Keywords: Ceramic; Miniaturization; Laser micro machining; Milling

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1. Introduction

Advanced ceramics have become increasingly attractive over the last 30 years. This growing market is due to their mechanical, electrical and chemical properties as well as their biocompatibility. The ceramic machining is complex due to the brittle behavior of the material [1]. This complexity is reinforced as a result of the demand for miniaturization, which is constantly increasing [2]. Non-traditional machining processes such as laser machining are an alternative for machining in dense ceramics, but the thermal properties of the material do not allow a high material removal rate (MRR) as opposed to traditional. Unfortunately, machining with a cutting tool usually leads to the generation of cracks that weaken the final part. To reduce this risk, modern industry machines the material in an intermediate stage of production in which the material is not sintered (green state). Afterwards, a sintering cycle, that is a heat treatment, gives the final properties of the part. For Y-TZP ceramic, the final properties are a flexural strength of 900-1200 MPa and a fracture toughness of 6-9 MPa.m$^{1/2}$ [3]. Fig. 1 shows the traditional chain (A) in which the green machining is carried out with a cutting tool. The literature review shows that the preparation of green compact has an influence on the surface quality in machining [4,5]. The choice of technology and the percentage by weight of to produce a green compact directly influence the surface quality obtained by milling.

Despite the heat exchange during laser machining, A patent has been developed to favor laser ablation by modification of the powders composition [6]. This patent by the Belgian Ceramic Research Centre (BCRC) shows that the addition of a particle increases the MRR. That makes it possible to define a new manufacturing chain (M in Fig. 1) in which the hybridization of the two processes is carried out in order to

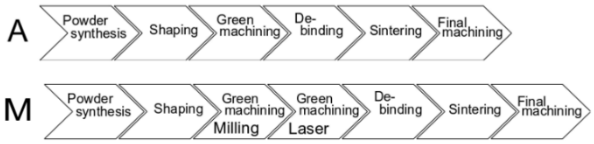

Fig. 1. Manufacturing chain for ceramic (A) traditional chain (M) new chain (inspired of [1])

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machine a green ceramic. This manufacturing chain allows to increase miniaturization by reducing the overall machining time thanks to sequential hybridization [7-9].

The quality of laser machining is influenced by initial surface roughness of the part. Indeed, Mustafa et al. [10] show the surface roughness has an effect on the ablation fluence threshold of zinc and steel with ultrashort pulsed source. An increasing surface roughness leads to an increased absorptivity, but the ablation threshold also increases with the rise of the roughness. The initial surface roughness should be low to have a high ablation efficiency [10].

The goal of this paper is to determine optimal percentage of binder in green ceramic. A repeatable surface quality in milling and the highest MRR in laser machining are expected. To achieve this, a study on the binder influence in the mechanisms of material removal specific to each process is carried out.

2. Material and methods

The BCRC manufactured three green blanks of black Y-TZP following the patent [6]. These blanks are from the same batch, but the percentage of binder varies for each blank (1 wt%, 2 wt% and 3 wt%).

Grooves are carried out for each technology with constant machining parameters, except one: the cutting speed for milling and the fluence for laser machining. For milling, the experimental plan is based on the Couple tool-material standard [11] for ductile material which is applied to a green ceramic [3] with two repetitions for each groove. The cylindrical cutting tool of 3 mm diameter has 2 flutes and is made of carbide. The constant parameters are the axial depth of cut (0.7 mm) and the feed per tooth (0.048 mm/tooth). The groves of 66 mm long are carried out with a single pass of the tool. By contrast, the experimental plan for laser is carried out with the SPI redEnergy G4 which is a nanosecond source (pulse duration of 26 ns) of 20 W, the constant parameters for laser process are the spot diameter (50 µm), the repetition rate (47 kHz) and the scanning speed (1000 mm/s). The micro-grooves of 2 mm long are carried out with a single pass of the laser spot without repetition. Table 1 shows the variable parameters values for each process: the cutting speed in milling and the fluence in laser machining.

Table 1: Experimental plan

Variable parameters		
Milling	Laser Machining	
V_c (m/min)	Fluence (J/cm²)	
98	0.40	2.49
124	0.57	3.19
139	0.75	4.98
152	0.92	5.36
179	1.10	5.75
193	1.27	6.13
208	1.45	6.51
221	1.62	
236	1.79	

Measurements of surface roughness and ablated depth are carried out with a VK-X-Series Keyence (a 3D Laser Scanning Confocal Microscope). The surface roughness is measured from 5 distinct areas on the groove bottom.

2.1. Analysis of milled quality

Standard ISO 25178 defines 3D analysis of the surface condition that allows to characterize an anisotropic surface. That anisotropic surface can be characterized with the help of spatial parameters. All spacing information are contained in the autocorrelation function (ACF) [12].

This function allows to evaluate the correlation of part of an image with respect to the whole image. The ACF is defined as a convolution of the surface with itself, shifted by (τ_x,τ_y) which are relative lateral displacements [12]

$$ACF\left(\tau_x,\tau_y\right)=\frac{\iint z\,(x,y)z\left(x-\tau_x,y-\tau_y\right)dxdy}{\iint z(x,y)^2dxdy} \tag{1}$$

The texture aspect ratio parameter, Str is one of the most important parameters to characterize the isotropy of the surface. This parameter is calculated from ACF by applying a threshold of 0.2 [13]. This parameter is dimensionless between 0 and 1. A value below 0.3 indicates the presence of a directional texture while a value above 0.5 indicates that the surface has a rather uniform texture.

2.2. Analysis of laser ablation

The material removal with the laser is determined with the primary profile which is perpendicular to the groove obtained by laser machining. This profile is used to determine the maximal depth and ablated section.

The evolution of depth in relation to fluence can be expressed on the logarithmic graph. In fact, the depth ablation, Z_a, for nanosecond laser source can be modelled by Jackson [14]

$$Z_a\approx\sqrt{at}\ln\left(\frac{F_a}{F_{th}}\right) \tag{2}$$

Where F_a is the absorbed fluence, F_{th} is the threshold fluence, and (at) is the thermal diffusion depth. This equation follows a logarithmic evolution. This equation can be rewritten as follows

$$Z_a\approx\sqrt{at}\ln(F_a)-\sqrt{at}\ln(F_{th}) \tag{3}$$

The gradient of this linearized equation is therefore proportional to the thermal diffusion depth.

3. Results

The results are divided into two main parts according to the manufacturing process.

3.1. Milling

Fig. 2 shows the evolution of the spatial parameter Str in relation to cutting speed for each blank. The texture aspect ratio parameter (Str) is relatively constant for the blank with 2 wt% binder surrounding 0.07. At the beginning, the curve of 3 wt% decreases sharply from 0.2 to 0.07. Then it varies around 0.07. The Str parameter is higher for 3 wt% and 1 wt% blanks than 2 wt% at the lowest cutting speed. Moreover, the curves of 1 wt% binder and 2 wt% binder are similar in the range of cutting speed between 152 and 193 m/min.

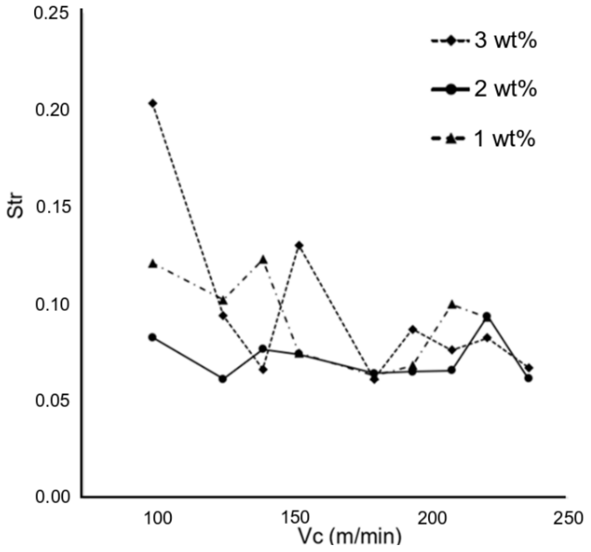

Fig. 2. Evolution of Str spatial parameter in relation to cutting speed for different wt% in the blank preparation (1 wt% binder, 2 wt% binder and 3 wt% binder)

Table 2 shows the Str deviation between two grooves in which the Str is a mean on 5 distinct areas of the bottom of the groove. The deviation is greater at low cutting speeds. It is significantly lower than the mean value. The grooves machined on the 2 wt% blank have a more stable deviation than the two other wt% values.

Table 2: Str deviation between two grooves with the same parameters

	S_{tr} deviation		
V_c(m/min)	3 wt%	2 wt%	1 wt%
98	0.105	0.033	0.023
124	0.033	0.011	0.009
139	0.009	0.008	0.062
152	0.057	0.017	0.028
179	0.008	0.015	0.005
193	0.011	0.014	0.006
208	0.025	0.008	0.014
221	0.011	0.022	0.021
236	0.010	0.010	/

Above a cutting speed of 152 m/min, the deviations is globally similar whatever the binder percentage in the green ceramic.

3.2. Laser Machining

A difference is made between the maximum ablated depth and the total ablated results. It is important to note that the cross-section of the micro-grooves is constant over the machined length.

3.2.1. Ablation depth

Fig. 3 shows the evolution of ablated depth for the different preparation of blanks. The evolution follows the theoretical law (see equation 3) with a gradient that increases when the wt% binder decreases. The ablated depth of 1 wt% is higher than the two others. The coefficient correlation for 2 wt% of linear regression is 98% and the detected fluence threshold is at 0.73 J/cm².

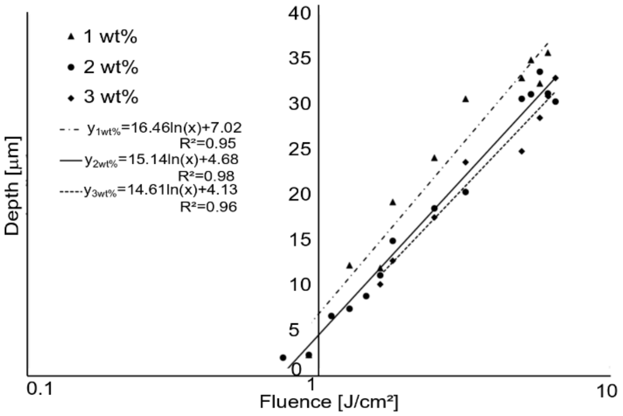

Fig. 3. Evolution of the ablation depth in relation to the fluence for different wt% in the blank preparation (1 wt% binder, 2 wt% binder and 3 wt% binder)

3.2.2. Ablation section

Fig. 4 shows the section of grooves in relation to fluence. The three evolutions are similar but a higher gradient is noted for the 3 wt% binder. The combination of the two graphs can also give an indication on the conicity.

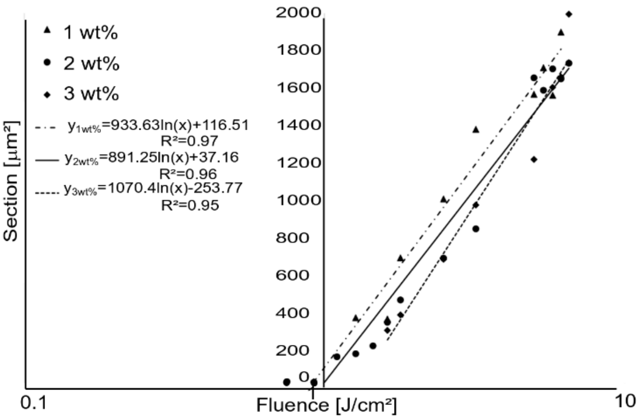

Fig. 4. Evolution of the total ablated section in relation to fluence for different wt% in the blank preparation (1 wt% binder, 2 wt% binder and 3 wt% binder)

4. Discussion

The Str shows that the machined surface by milling is anisotropic because its value is lower than 0.3. In fact, the bottom of the grooves shows the machining traces that are due to the teeth passage. Fig. 5. shows these traces which lead to an anisotropic surface due to the principal direction that is the machining direction. Nevertheless, this parameter is not constant for all blanks. When the percentage of binder is too low, the amount of binder does not ensure a uniform matrix to hold the ceramic powders. On the other hand, when the percentage is too high, material is pulled off at low cutting speeds, resulting in poor surface quality with material particles that have agglomerated on the machined surface. Indeed, the material is pulled off because the polymer matrix is over-compacted.

Laser machining is also impacted by binder addition and more particularly on the thermal diffusion depth in the material. By adding polymer as binder, the thermal diffusivity coefficient of ceramic composite decreases and leads to a reduction of the ablation depth.

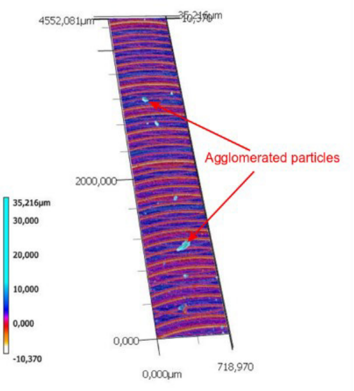

Fig. 5. Agglomerated particles caused by the material pullout

As the intensity increases, the machined section increases faster for this percentage of binder while still maintaining a lower depth than the two others. The grooves have a homogeneous V-shaped cross section. Those ablated sections show the impact of the heat affected zone. In fact, the decrease of thermal diffusivity depth directly impacts the mechanism of ablation. An important addition of binder leads to a rapid rise of the ablated section. The heat exchange with the binder more rapidly generates the mechanism of ablation because the fusion temperature of polymer is lower than the composite without binder. Finally, the lowest possible percentage of binder allows for a higher rate of material removal by avoiding increasing the conicity phenomenon.

In the case of hybridization, the optimal binder percentage is therefore a compromise for both technologies. For our case study, the optimal of binder percentage is 2 wt%. This compromise makes it possible to ensure a constant Str over a wide working range and thus allow the most uniform laser machining possible while ensuring the highest MRR in laser machining.

5. Conclusion

In this paper, the study of the influence of the binder of a green ceramic material (Y-TZP) is carried out in order to determine the adequate percentage for a new production line combining milling and laser machining.

Since laser machining is affected by the initial surface condition, milling was characterized using spatial surface roughness (Str) indicator. This indicator shows the anisotropy of the machined surface caused by the trace of the milling tool.

The study shows that a minimum percentage of binder must make up the raw ceramic block to guarantee a repeatable surface quality whatever the chosen cutting speed. On the other hand, the addition of binder has a negative impact on laser machining. Indeed, the MRR decreases when binder is added.

In the case of the new production line for Y-TZP, the optimum binder percentage is 2 wt%, allowing milling with optimum surface quality while minimizing the impact of binder addition during laser machining.

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