euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Development of the hybrid sequential machining: laser machining and milling.

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Abstract
The demand of micro products has increased significantly in recent years. The traditional stand-alone machine tools were optimized to market demands. These processes still remains a big issue in the repeatability, predictability and the productivity of manufacturing. Today, the machine tools are combined to increase the productivity of manufacturing. These hybrid processes are decomposed in three domains: the assisted hybrid, the mixed hybrid and the sequential hybrid. The sequential hybrid is the combination of the minimum of two technologies in the same structure. The different processes must be mastered before the combination.
The aims of this paper is to study the advantages and disadvantages of laser micro-machining and the micro-milling. The final goal is to couple these processes in the same structure. The sequential hybrid process is subtractive-subtractive it combines the laser μ-machining and the μ-milling. The samples are machined with the two processes to compare the dimensional tolerance and the geometrical tolerance of fundamental geometries.

Hybrid machining, laser machining, milling, ceramics

1. Introduction

In recent years, the demand of micro products has increased gradually in various areas: bio-medical devices, aerospace, electronics. Micro manufacturing is characterized by the size of functional features, the high precision, the good surface finish, the complexity parts in a wide variety of materials. The traditional stand-alone machine tools were intensively used to produce micro-components. These processes may still lack performance in the repeatability, predictability and the productivity of manufacturing [1]. More and more the machine tools combine several production techniques in order to increase the productivity without changing the desired tolerances. The multifunctional machine tools are decomposed in three domains: the assisted hybrid, the mixed hybrid and the sequential hybrid [2, 3]. The assisted hybrid machining is a traditional machine tools is superimposed with one or several types of energy processes to improve the micro-machining process. The mixed hybrid machining is the simultaneous combination of two different processes using their respective advantages. Finally, the hybrid sequential is the sequential combination of the two different processes which combines the advantages of the two technologies. Each processes must be mastered individually before the processes combination [4]. Table 1 shows some characteristic of some micro-manufacturing processes [1, 5, 6]. The material removal rate (MRR) is higher in micro-milling than in laser micro-machining. However, the minimum of feature size is smaller in laser machining.
The aims of this paper is compare two technologies to micro-machining ceramic: the laser machining and the milling. The comparison allows to highlight some advantages and disadvantages of the each process.

Table 1: Capabilities and performance specifications of micro-manufacturing processes (adapted from [1, 5 6])

Process	Minimum Feature Size	Tolerance	MRR
Micro machining by mechanical	10 μm	1 μm	High MRR
Excimer laser	6 μm	0.1 – 1 μm	Low MRR
Short pulse laser	1 μm	0.5 μm	Low MRR

The machining of hard ceramic is complicated because its a brittle behaviour. Alternative solutions can be used such as the green machining, the pre-sintered machining and the sintered machining [7, 8].

2. The experimental setup

Experimental tests were carried out on rectangular blanks where cylindrical and conical holes were machined with a cutting tool and a laser beam. Then, the samples are compared dimensionally and geometrically using a coordinate measuring machine (Wenzel LH54).
The depth is 3 mm for each hole. The first samples are two cylindrical holes of 10 mm diameter and eight holes of 5 mm machined with laser machining. The next samples are conical holes with two 10 mm diameters and eight 5 mm diameters on the upper face of the blanks. The taper angle of the conical holes is 10°.
Laser machining is performed in green ceramic whereas milling is carried out in pre-sintered ceramic. The machined ceramic is the Y-TZP which is a ceramic commonly used in the dental restoration such as bridges, implants, etc [9]. The machining operations are carried out on 3-axis machines. The bank preparation is different for each process.

Table 2: Machining parameters

Parameters of the µ-laser machining	
Laser Intensity	23 A
Spot speed	800 mm/s
Spot diameter	40 µm
Repetition Frequency	30 kHz
Parameters of the µ-milling operation	
Tool diameter	3 mm
Cutting speed	175 m/min
Feed per tooth	0.048 mm/tooth (2 teeth)
Axial depth of cut	0.7 mm

2.1. Green laser machining

The powders are pressed uniaxially at 33 MPa, followed by an isostatic compaction at 195 MPa during 5 minutes. The green ceramic is machined with the machining parameters in Table 2. Then, the machined product undergoes several heat treatments. The temperature increases between 20°C and 700°C at a heating rate of 3°C/min. The block remains during 1 hour after the threshold to increase again the temperature with the heating rate of 5°C/min until 1500°C. The level temperature at 1500°C is maintained during 2 hours. Finally, the temperatures is decreased at the speed of 5°C/min to 20°C.

2.2. Milling in the pre-sintered block

The preparation of the green block is the same as the previous one. The block is pre-sintered before being machined, the heat treatment is a temperature increase between 20°C and 900°C at a heating rate of 3°C/min. Then, the block remains at constant temperature during 2 hours. The treatment allows to give intermediate properties. The pre-sintered block is machined by cutting tools with the parameters in Table 2. Then, the machined product undergoes a thermal treatment of 1500°C during 2 hours at a heating rate of 5°C/min. Finally, the temperature decreases at the speed of 5°C/min to 20°C.

3. Results

Figure 1 shows a machined sample in the Y-TZP ceramic.

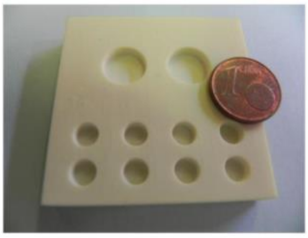

Figure 1. Machined sample

3.1. Cylindrical holes machined by laser

The first sample examined are the cylindrical holes manufactured by laser machining. The metrology control is firstly carried out on the geometrical tolerance. The circularity tolerance is inferior to 50 µm excepted for one hole with a deviation larger than 70 µm. By contrast, the cylindrical deviation is very high with a minimum deviation of 124 µm. The average depth deviation is larger than 200 µm.

The deviation is very high in cylindricity control. The cylindrical tolerance is the accepted distance between two coaxial cylinders containing the profile measure. Figure 3 allows to explain the high deviation in the laser machining during the measuring process of cylindrical tolerance.

The deviation was amplified at the three different depths. The circle radius decreases when the depht rises. Indeed, the cone is the result of the laser beam which is not a rectilinear beam [10]. The taper angle depends of the beam quality and the focal distance. Moreover, the material removal in laser machining is very complex. The planarity must be assured to control the material removal. This phenomenon is particularly sensitive in the laser machining [11].

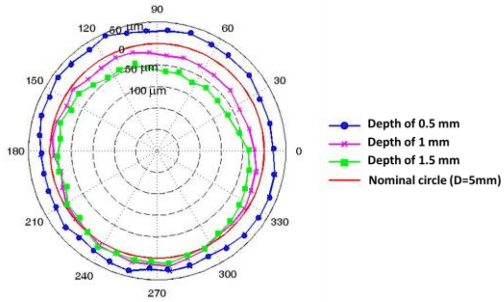

Figure 2. Amplification of the circularity deviation at three different depths for one cylindrical hole

3.2. Conical holes machined by each process

The sample faces are rectified before machining of the cone holes. The samples examined are the conical holes machined with the two processes. The diameters of the upper face are measured. The deviation measured is larger than 80 µm in laser machining while the deviation is always smaller in micro-milling. By contrast, the deviation between the centres of holes is similar for the two technologies: generally smaller than 100 µm. The deviation of depth average is around 70 µm. The holes circularity is controlled on the upper face. The deviations are inferior 10 µm for laser machining and a slightly larger in the milling. The two processes are close except for the dimensional control on the diameters. The circularity with the laser machining is more accurate than the milling. Milling in the pre-sintered is difficult. An adapted tooling is using because of the pre-sintered weakness. Indeed, the beginning of the interaction between the cutting tool and material may produce damages.

4. Conclusion

Laser machining is a good alternative as compared milling because of the absence of contact between the tool and the material. But the process have some disadvantages such as the taper angle and a difficult control of the material removal depth. The tolerance in laser machining is slightly smaller than milling when the blank is rectified before machining. Moreover, the material removal rate is lower than for milling [4].

The combination of the two technologies may allow to remove a high material rate by milling before using the laser machining. The laser machining would then carry out the finish operation.

The future of the work is to deepen the combination of the two technologies in one machine. A methodology to determine an optimum sequence should be carried out.

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