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The Hybrid Machining of Ceramic: The choice of production stage

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Abstract
The demand for micro products has increased gradually since last decades in various areas, requiring the development of micro manufacturing processes. Micro manufacturing is characterized by the size of functional features (smaller than 10 µm), a high precision, a good surface finishing and complex parts in a wide variety of materials. The Traditional Machining Processes (TMPs) are intensively used to produce micro-components, but the minimum feature size they can produce is limited. In parallel, the Nontraditional Machining Processes (NMPs) were developed to manufacture micro components of a few microns, but the processing times are slower. Hybrid Machining Processes (HMPs) was introduced to address the demand to increase production with an enhanced quality for difficult-to-machine materials such as ceramics.
In this paper, the HMP considered, a combination of micro-milling and laser machining, is developed to machine ceramic materials. This HMP may be carried out at different stages in the ceramic production. The goal of this paper is to determine the most attractive production stage in ceramic machining with this HMP.

Hybrid machining, Micro milling, Laser machining, Ceramic machining

1. Introduction

The miniaturization appears as being one of the most important challenges of the last decades. The demand for micro-products requires the development of new micro-manufacturing processes with high performance in the repeatability and the productivity of manufacturing. The Traditional Machining Processes (TMPs) and the Nontraditional Machining processes (NMPs) have been developed to manufacture micro components, but these processes are limited. Consequently, Hybrid Machining Processes (HMPs) have been introduced to get around the limitations [1-3]. The HMP combines a minimum of two machining processes in a single machine centre. In this paper, the two technologies are the micro milling and the laser machining. Actually, these two technologies are complementary because it is possible to combine the high material removal rate of the milling and the precision of the laser machining (See Figure 1).

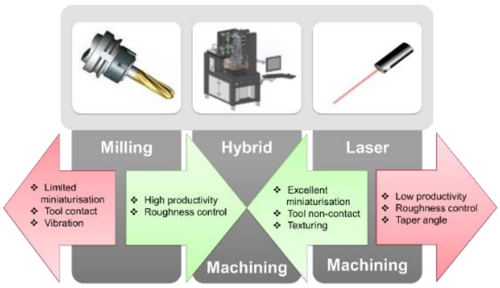


Figure 1. Complimentary of milling and laser machining

The studied material is an All-Ceramic material which is a competitive alternative to metal-ceramic materials for manufacturing crowns and fixed partial dentures (FDP). The aesthetical properties and biocompatibility are important advantages in the medical field. Zirconia are ceramics which plays an important role due to their mechanical properties and their biocompatibility (See Table 1).

Table 1: Typical mechanical properties of representative dental ceramic materials [4]

Ceramic Material	Flexural Strength (MPa)	Fracture Toughness ($MPa\sqrt{m}$)
Y-TZP	1200	9.00
Zirconia (3% Y2O3 stabilized)	900	9.00
Alumina industrial	547	3.55
Alumina slip cast	419	2.48

Y-TZP properties are the result of the mechanism of transformation toughening. Indeed, quadratic lattices substitute monoclinic lattices at ambient temperature. The transformation from tetragonal phase to monoclinic phase achieves during energy input, such as the crack. (Energy input like a crack allows transformation from tetragonal to monoclinic phase.) The monoclinic phase is thermodynamically stable in the stress field around the crack. The stress-induced transformation of metastable tetragonal zirconia particles generates a compressive stress around any crack. The mechanism causes the spread of these cracks to be hampered [4,5].

2. Methodology

The HMP may be carried out at different stages in the ceramic production (See Figure 2). The different production stages can be used in the ceramic machining. For each technology of the HMP, each production stage is investigated, by experiments or by a literature analysis to select the most appropriate choice.

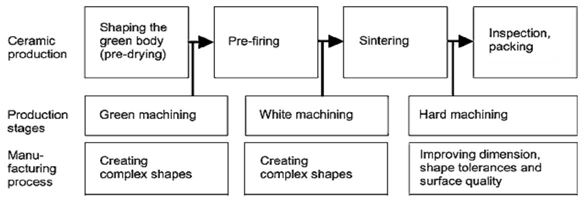


Figure 2. Classification of green, white and hard machining in the production process [6]

The experiments are carried out with a hybrid centre (see the characteristics of the tools in Table 2). The hard machining is a machining which is carried out after the ceramic sintering. The white machining is used in the dental restoration field. Indeed, the mechanical properties are intermediate and the milling is very easy [7]. The green machining is carried out after the isostatic pressing. The added binder influences the mechanical properties.

Table 2. The characteristic tools in the hybrid centre

Laser		
Source	Nanosecond	Femtosecond
Spot Size (μm)	20	
Average power (W)	100	10
Pulse energy (μJ)	1000	20
Pulse duration	100 ns	400 fs
Spindle		
Tool diameter (mm)	3	
Spindle speed (min^{-1})	1,000 – 50,000	
Max. Torque (N.cm)	6	
Pmax (W)	300	
Feed rate (mm/min)	2100	

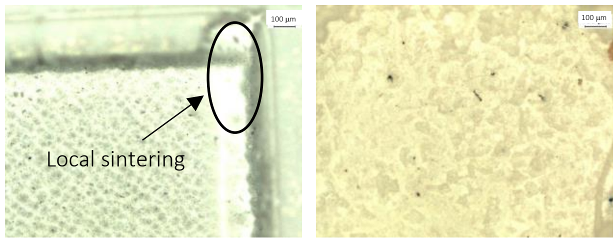
3. Results

3.1. Hard machining

The hard machining is a mastered process in laser machining and milling but the machining time is very slow, due to the material weakness. Actually, precautions must be taken to machine sintered ceramic. During the laser machining, a heat-affected zone (HAZ) is produced and could induce cracks into the ceramic microstructure. Despite the mechanism of transformation toughening, these cracks could themselves lead to the failure of the ceramic part. The milling in the ceramic is achieved with an adapted tool because of the material hardness, and so the machining parameters are also adapted. Indeed, the machine power is very important to machine the ceramic, and the tools are expensive. The machining time is very long and the contact tool-material raises crack propagation [8].

3.2. White machining

The white machining is very popular in the dental restoration field. Indeed, the pre-sintering ceramic is machined with a mill to undergo a post-treatment after the machining. The machining quality depends upon the uniaxial pressing, the heat treatment and the size of the grains. The material is brittle and the contact with the tool can cause defaults. These defaults could be diminishing due to the shrinkage during the sintering. The material removal rate (MRR) is approximately 4.41 cm^3/min. By contrast, the withe machining with the laser source is very complex. The pulse duration is too long with the nanosecond source which leads to local sintering (See Figure 3). The depth of desired target is not reached because of the sintered surface. The other parameters do not eliminate the risk of local sintering. The femtosecond source does not result in the local sintering but the machining time is very important. Actually, the MRR is nearly 0.0001 cm^3/min.



(a) (b)

Figure 3. Results of the laser machining by (a) nanosecond source and (b) femtosecond source

3.3. Green machining

The green machining is similar to the white machining but the binder plays an important role. *Indeed*, the green ceramic is more hardness as the pre-sintered ceramic. The binder could have an influence in the exchange between source and material. The MRR is around 0.233 cm^3/min. The laser source could cause a re-solidified layer by sintering. By contrast, the sharp edge of the tool could lead to defaults in the machining quality. The green machining is a potential alternative for the rapid fabrication. The processing routes to make green ceramic, influences the green ceramic strength and toughness, and so machinability and surface finishing [9,10].

4. Conclusion

The machining analysis in the different stages of ceramic production shows that the laser machining is a very slow process and it is difficult to set up. The caused defaults during the hard machining do not diminish because the shrinkage sintering. By contrast, the defaults could be diminishing in the other stages. But the laser machining in the white stage and the green stage lead to a re-solidified layer by local sintering. The hybrid machining of ceramic is more interesting in the green stage because of the influence of binder which could play an important role during the exchange between laser source and material. The ideal sequence is a roughing by a cutting tool and a finishing by laser to avoid damages by contact or re-solidified layer by several passages of the laser.

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