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Milling of alumina-based ceramic foams: tool material effects

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Abstract. Porous ceramics are recognized to have the potential to be used for a wide variety of industrial applications, such as catalyst support and molten metal filter. It is a common practice to adjust the shape of ceramics in a pre-sintering stage in order to obtain various configurations but some limitations due to premature failure of the product, marked tool wear or inhomogeneous shrinkage during processing stages may arise, whenever a complex shape is requested. Almost the same happens in the case of post-sintering stage ceramics machining leading, in most cases, to an inefficient process characterized by a severe tool wear and poor final product quality. Such problems, related to tool material, material removal modes and hence process parameters represent a huge limitation for many industrial applications of the above materials. Milling of alumina-based ceramic foams in a sintered state is the focus of the present work. An experimental campaign has been carried out at fixed axial depth of cut, feed rate, number of passes, spindle speed and under flood lubrication regime varying tool material (aluminum oxide-based, diamond-coated). Tool wear mechanisms and final product quality have been investigated through surface analysis in order to verify the workability of alumina based ceramic foams and the related tool wear.

Introduction

Porous ceramics are classified as advanced materials, able to supply additional functionalities with respect to conventionally used ones; these materials cover a wide range of structures based on different morphologies and composition [1, 2]. High porosity materials can be used for several applications due to their elevated surface-volume ratio; some applications may require high level of refractoriness, creep and corrosion resistance, as properties belonging to ceramic materials.

For the ceramic foams production several processes are available, some of them involve other materials (such as polymer) as precursor, in order to provide the lattice shape after sintering [3]. Usually, to change the structure of the obtained ceramic foams, it is possible to take action on precursor shape or working on material ahead of sintering [4]. Nowadays, many studies are being carried out about new sustainable production processes detection and on complex shape development [5], also involving additive manufacturing [6], to avoid premature product failure during the production process and inhomogeneous shrinkage in sintering phase [7, 8]. Several studies are referred to conventional and non-conventional machining methods of bulk ceramic materials [9] while there is still a lack of knowledge concerning the machinability of porous ceramic materials. These latter are considered difficult to machine, since they lead to an accelerated tool wear [10], together with a poor final surface quality.

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It is extremely important to find innovative, cheap and easy to perform production methods in order to guarantee high performance, reliable, long lifetime ceramic filters. At the same time, it is necessary to optimize resources minimizing the maintenance costs and downtime arising from failure of a filter element ensuring, at the same time, the compliance with the environmental constraints.

It is worth noting that effective machining of ceramic foams has not been yet assessed. Most commonly used machining techniques for bulk ceramics involve conventional methods (e.g. abrasive wheel cutting), non-conventional machining (e.g. wire electrical discharge machining) and hybrid machining (e.g. hybrid laser waterjet machining) and the most commonly used tools are diamond based ones. However, studies based on these techniques [9] demonstrated that the machinability of bulk ceramics still represents an issue for both tool wear and surface integrity of the obtained components.

This paper presents the evaluation of the machinability of alumina based ceramic foams by means of spherical end milling process using different tools materials and under flood lubrication method.

Materials and Methods

The samples under investigation are cylindrical alumina-based ceramic foams, with a diameter of 30 mm, height of 30 mm and pore density of 30 pores per inch (ppi). They have been provided by Lanik s.r.o. and have the following chemical composition: Al_2O_3 84.0%, SiO_2 14.0%, MgO 0.8%, Other 1.2%. The foams, produced via the replica process [8, 11], consist of a network of randomly-oriented dodecahedral-shaped cells interconnected through struts (Fig. 1).

Two different tool materials (Fig. 2) have been selected for the experimental campaign on spherical end milling process: vitrified hard bond pink aluminum oxide (average grit size 120 μm) and electroplated diamonds on a metal substrate (average grit size 118 μm). Tool shank and head diameter were respectively 3 mm and 6 mm for both tools. The experimental campaign has been carried out varying tool material and at fixed axial depth of cut, feed rate, number of passes, spindle speed and under flood lubrication regime.

Preliminary milling tests have been performed in order to choose the set of parameters for the experimental tests, starting from values recommended by the manufacturers for similar bulk materials. However, it is worth noting that there are no available recommendations for milling ceramic foams. The factors considered for experimental campaign are reported in Table 1. After machining, samples and tools have been inspected under a Scanning Electron Microscope in order to analyze the surface characteristics prior and after processing and the tool wear mechanisms.

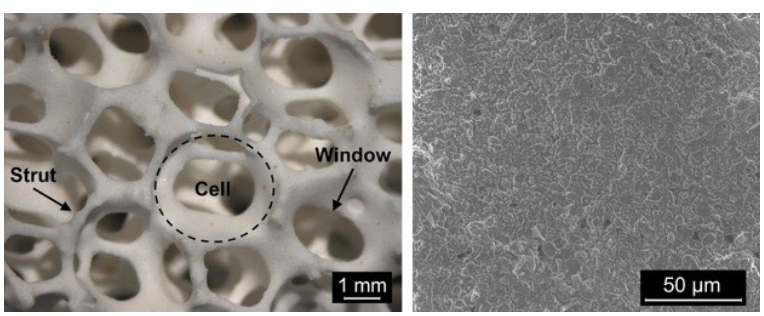

Fig. 1 – As received alumina based ceramic foam (a) foam structure, (b) SEM image of the as received surface.

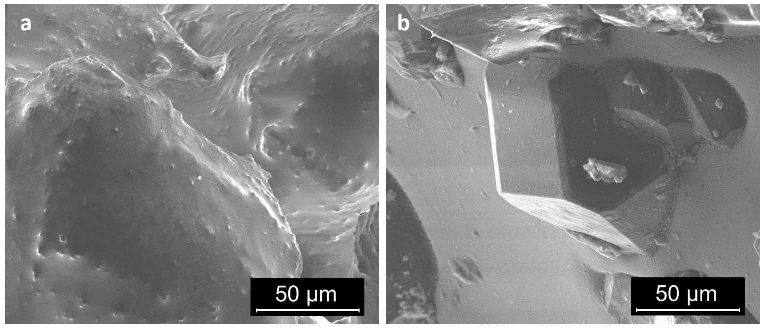

Fig. 2 – SEM images of as received pink aluminum oxide (a) and diamond coated (b) tools.

Table 1. Design of experiments for the experimental campaign.

Factors	
Tool material	Aluminum oxide, Diamond coated
Lubrication conditions	Flood
Spindle speed [RPM]	10000
Number of Passes	2
Depth of Cut [mm]	0.5
Feed Rate [mm/min]	50

Results and Discussion

Tool wear mechanisms

Tool wear is a direct expression of tool life and it is strictly related to machined surface and subsurface quality. Fig. 3a shows the low magnified (100x) surfaces of aluminum oxide tools in which the damage is immediately recognizable. Also, adhesive wear takes place during the process since a certain amount of adhered foam material can be easily found on tool surface.

The phenomena of flattening and materials mixing can be attributed to tool and sample material affinity in terms of composition and mechanical properties. In particular, adhesion is generally reduced by flood lubrication which results, by nature, into an efficient lubrication effect.

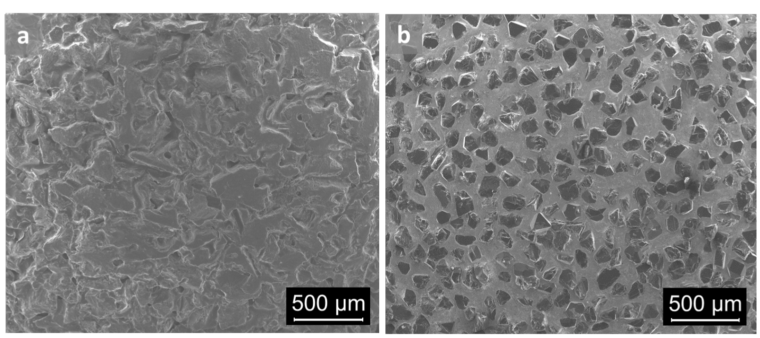

Fig. 3 – Aluminum oxide (a) and diamond coated (b) tools after milling at different magnification.

Concerning diamond coated tools, damage is not easily recognizable at 100x magnification, as shown in Fig. 3b.

Fig. 4 shows a detailed view of tool surfaces after milling process. Fig. 4a has been taken using Backscattered Electrons (BSE) mode in order to highlight the presence of different materials, Fig. 4c shows a void left by a diamond being pulled out while Figure 4d displays a damaged diamond.

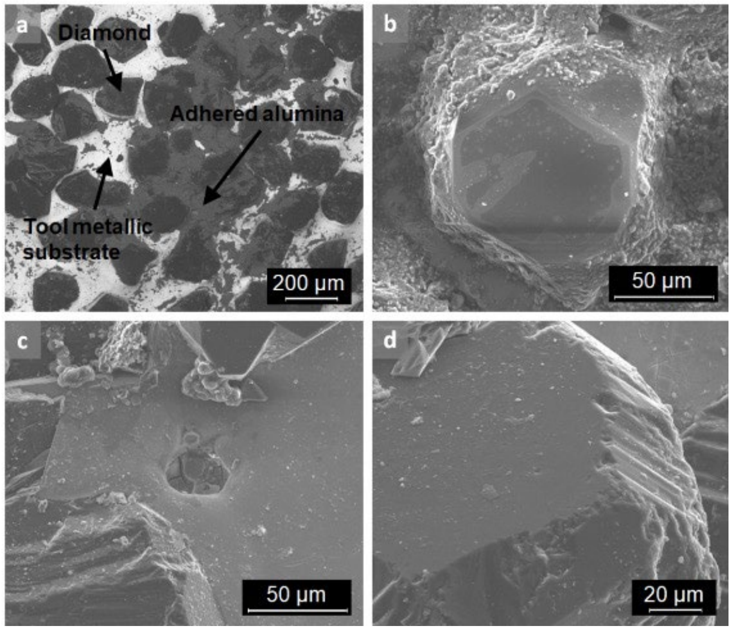

Fig. 4 – Details of diamond coated tools after milling (a) adhesion phenomenon, BSE image, (b) adhesion phenomenon, (c) diamond pull out, (d) diamond fracture.

Machined surface analysis

The presented process inevitably involves both brittle and ductile fractures due to the multitude of scratches and their relative interactions when abrasive grains cut into ceramic specimens. The machined surface results ideally deformed similarly to that left by an indentation process but other mechanisms can also take place, such as adhesion between tool/workpiece surfaces, mainly due to chemical affinity. Also, excessive local forces can generate different defects like chips, fissures, cracks or flaws. The above issues result exacerbated by the geometric characteristics of the workpiece under investigation.

When aluminum oxide tools are employed, the adhesion effect evidently influences the fracture mechanism, as shown in Fig. 5. In fact, the chemical affinity between the foam and the tool brings to machined surfaces characterized by a higher content of brittle fractures. The analysis reported herein also confirms the presence of adhesive wear on the tool, as presented in the previous section.

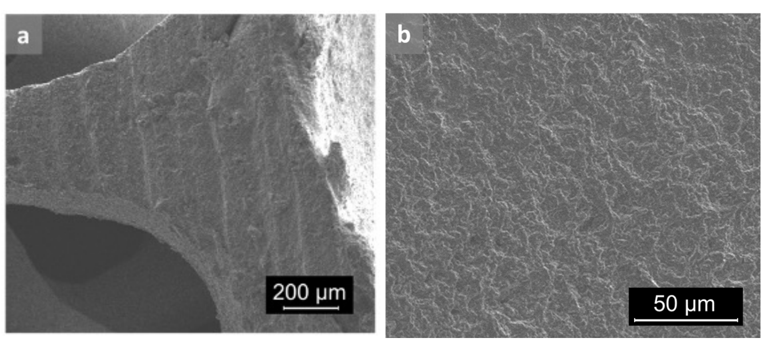

Fig. 5 – Details of ceramic foam surface after milling with aluminum oxide tools.

Diamond coated tools result into a more efficient cutting process since less adhesion effect is present. Fig. 6 clearly show both ductile and brittle fracture areas, which are typical of the process. The diamond abrasive grains exposed on the lip of the milling tool are of random distribution, with a consequent difference in the exposure highness of each diamond.

The overall machining is achieved by the combined actions of what can be thought as numerous micro-cutting edges with locally different depths of cut, causing areas of both ductile and brittle fracture when machining ceramics.

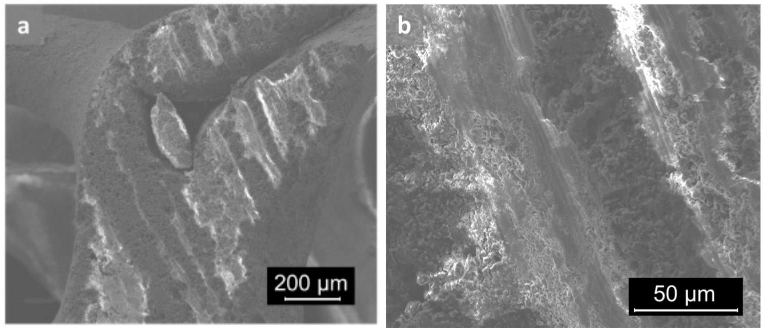

Fig. 6 – Details of ceramic foam surface after milling with diamond coated.

Conclusions

This paper presents an analysis of workability of alumina based ceramic foams. In particular, such materials combine the issues of machining conventional ceramics with those related to machinability of geometrically complex workpieces. The experimental campaign involved the spherical end milling of the workpieces at varying cutting tool materials.

The overall results highlighted the tendency of such process to fast wearing the tools and the combination of ductile and brittle deformation mode on the machined surfaces.

The results obtained allow to state that ceramic foams can be machined by spherical end milling in order to try to obtain a variety of complex shapes and that diamond coated tools are, up to now, the best available choice. It should be noted that the overall process needs to be optimized in order to define a workability window able to minimize the tool wear and maximize the surface quality.

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