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On the impact of tool material and lubrication in ball end milling of ceramic foams

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Abstract. High porosity materials, such as ceramic foams, can be used for several applications spanning from thermal insulators, biomedical implants, molten metal filters, and others. The general practice is to adjust the shape of those ceramic foams in a pre-sintering stage to obtain complex shapes. This work aims to investigate the workability of ceramic foams in a post-sintering condition as an alternative way to overcome premature product failure during production and inhomogeneous shrinkage during sintering. An experimental campaign of ball end milling of alumina-based ceramic foams in a sintered state was carried out herein. Two different tool materials (aluminum oxide-based, diamond-coated) have been tested using two levels of spindle speed under minimum quantity lubrication (MQL) and flood lubrication regimes. The most important findings are: (i) the influence of lubricant is more pronounced analyzing the tool wear, but it has a smaller effect on surface characteristics of the workpiece, (ii) higher spindle speed improves workpiece surface quality (ii) diamond coated tools are the best available choice in terms of both tool wear and surface quality.

Introduction

Porous ceramics are classified as advanced materials which, in general, are capable to supply additional functionalities compared to conventionally used ones; these materials include a wide range of structures based on several morphologies and compositions. High porosity materials can be used for different applications embracing thermal insulators [1], biomedical implants [2], molten metal and other fluids filters [3-7], gases porous burners [6], monolithic catalyst supports [7-9] because of their elevated surface-volume ratio, coatings to enhance lubrication during mechanical processing [10]; some of these applications may require a high level of refractoriness, creep and corrosion endurance, as properties belonging to ceramic materials.

To manufacture ceramic foams several processes are available, some of them involve other materials like polymers as precursors, to provide the lattice shape after sintering [11]. Usually, to change the structure of the obtained ceramic foams, it is possible to modify the precursor shape or work the material ahead of sintering [12]. Nowadays, many studies are being carried out about new sustainable production processes and complex shape development [13], also involving extrusion [14] and additive manufacturing [15], to avoid premature product failure during the production process and inhomogeneous shrinkage in the sintering phase [16,17]. However,

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additive manufacturing still shows limitations (e.g. thermal shrinkage, surface quality, resolution), thus it is increasing the use of additive processes in combination with subtractive ones [18]. Processing is often supported by sustainable techniques, such as cryogenic and minimum quantity of lubricant (MQL), allowing to perform machining using a lower amount of cutting fluids to reduce waste and the spread of hazardous substances [19]. Concerning conventional and non-conventional machining methods of bulk ceramic materials [18] many studies were carried out while there is still poor knowledge about the machinability of porous ceramic materials. These latter are considered difficult to machine, since they lead to accelerated tool wear [19], together with poor final surface quality. In fact, they are characterized by a high brittleness combined with the complex lattice shape and porosity, that impact on workability.

Ceramic foam components are mainly used as molten metal filters due to their specific properties in terms of creep and thermal-shock resistance, high functional porosity, low molten metal wetting and specific heat capacity, erosion and corrosion resistance, chemical affinity with inclusions to be removed. Thus, the microstructure and the associated mechanical and thermal properties have a critical influence on the suitability of materials for these types of filters [20]. Many studies demonstrated that the performance of porous ceramics depends on pore size and shape, matrix grain size, intergrain bonding, and pore volume fraction [21-23]. Further analysis has shown that geometric parameters and roughness affect the performance of the ceramic foam in the molten metal filtering process [24], as a result of different inclusion filtering mechanisms such as direct particle impact to the filter, adhesion, and entrapment into recirculation areas [25].

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

This paper aims to assess the machinability of alumina based ceramic foams for molten metal filter applications. In fact, it is worth noting that the effective machining of ceramic foams has not been yet comprehensively assessed. Most commonly used machining techniques for bulk ceramics involve conventional methods (e.g. abrasive wheel cutting, diamond or wire saw cutting), non-conventional machining (e.g. wire electrical discharge machining WEDM, laser beam machining LBM, abrasive water jet machining AWJM) and hybrid machining (e.g. hybrid laser waterjet machining, electrochemical discharge assisted wire machining) and the most commonly used tools are diamond-based ones, for their durability [26]. However, studies based on these techniques [20] demonstrated that the machinability of bulk ceramics still represents an issue for both tool wear and surface integrity of the obtained components.

Thus, this paper presents the evaluation of the machinability of alumina based ceramic foams by spherical end milling process using different lubrication methods and tools materials.

Materials and Methods

The samples under investigation are cylindrical alumina-based ceramic foams, with a diameter of 30 mm, the height of 30 mm, and pore density of 30 pores per inch (ppi). The foams, produced via the replica process [16,27], consist of a network of randomly-oriented dodecahedral-shaped cells interconnected through struts.

Two different tool materials (Fig. 1) were chosen for the experimental campaign on spherical end milling process: vitrified hard bond pink aluminum oxide and electroplated diamonds on a metal substrate with an average grit size of around 120 μm. The reason of these choices lies within to the common use of diamond-coated tools to process ceramics, as explained in the review of the state of the art, and the opportunity to differentiate material removal mechanisms by comparison with abrasive tools. Aluminum oxide tools were provided by Meusburger Georg GmbH & Co KG while diamond coated ones were provided by SICUTOOL S.p.A.

A full factorial experimental campaign, as a complement to a preliminary campaign performed under the same conditions [28] was carried out at fixed axial depth of cut, feed rate, and number of passes and varying tool material, lubrication conditions (flood and minimum quantity of lubricant - MQL) and spindle speed. The parameters of the experimental campaign were recommended by the tool manufacturer since a comprehensive literature on the machining of porous ceramics does not exist.

The setup for milling tests is shown in Fig. 2 while the factors considered for the experimental campaign and their levels are reported in Table 1.

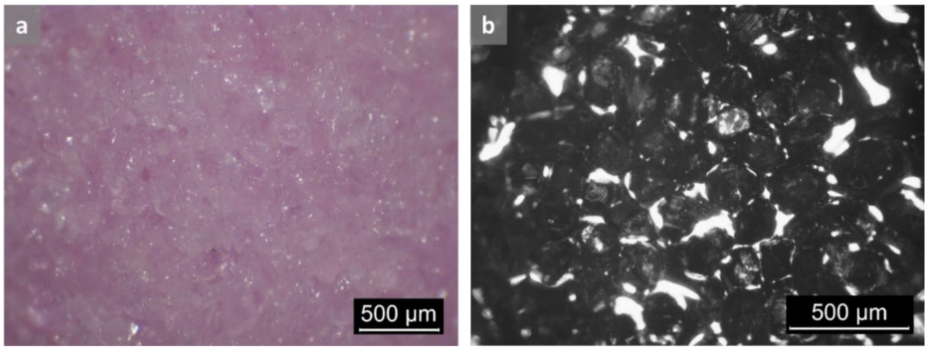

Fig. 1. Micrographs of as received pink aluminum oxide (a) and diamond coated (b) tools.

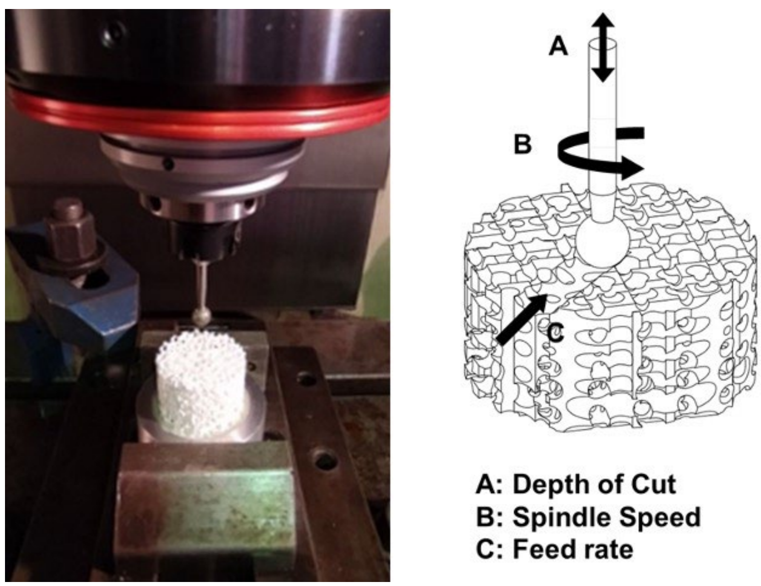

Fig. 2. Schematic of the experimental setup and spherical end milling process.

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Table 1. Design of experiments for the full factorial experimental campaign.

Factor	Level 1	Level 2
Tool material	Aluminum oxide	Diamond coated
Lubrication conditions	MQL	Flood
Spindle speed [RPM]	10000	40000
Number of Passes	2	
Depth of Cut [mm]	0.5	
Feed Rate [mm/min]	50	

After processing, samples and tools were inspected through a Scanning Electron Microscope to assess the surface characteristics before and after milling, and the tool wear mechanisms.

Results and Discussion

Tool wear is a direct expression of tool life, and it is strictly related to machined surface and subsurface quality. Fig. 3 shows the surfaces of aluminum oxide tools, and the damage is immediately recognizable. For the test at 40000 RPM and using MQL, the tool surface appears flattened (Fig. 3d), the same phenomenon appears to be attenuated for the remaining tests. Also, adhesive wear takes place during the process since a certain amount of adhered foam material was found on the tool surface.

Tool surface flattening and materials mixing can be explained by tool and sample material affinity in terms of composition and mechanical properties. Fig. 4 shows the aluminum oxide worn tools at varying spindle speed, highlighting how different parameters can affect the tool life. Lower spindle speed (Fig. 4a) shows a more marked wearing effect in terms of build-up edge and plastic deformation while rising the speed (Fig. 4b) leads to a lower content of workpiece material adhering to the tool, even though brittle cracks are detectable. Also, adhesion is reduced in the case of flood lubrication which results, by nature, in a more efficient lubrication effect.

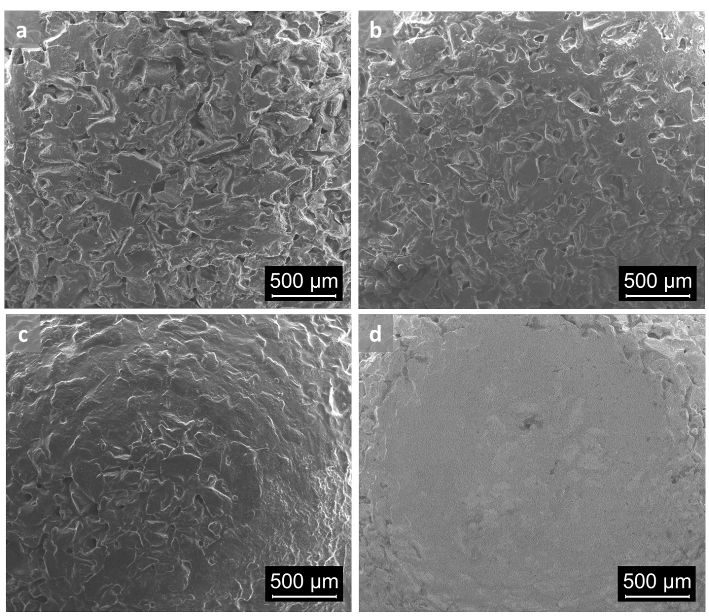

Fig. 3. Aluminum oxide tools after milling at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

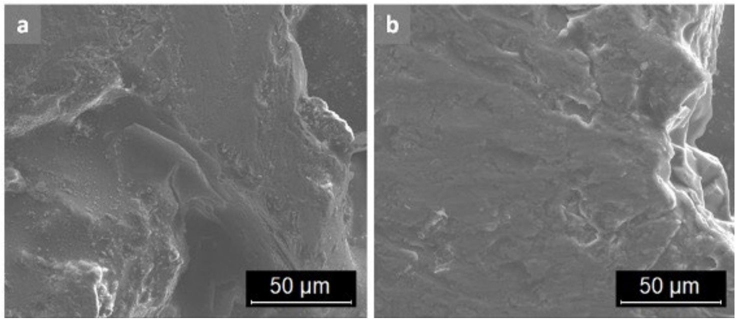

Fig. 4. Details of aluminum oxide tools after milling at different spindle speeds (a) 10000 rpm, (b) 40000 rpm.

As regards diamond coated tools, the damage is not easily recognizable at low magnification, as shown in Fig. 5. A low amount of residual adhered foam material can be seen (Fig. 5d), greater in the case of tests involving MQL. Furthermore, Fig. 6a shows a void left by a diamond being pulled out while Fig. 6b the adhesion phenomenon [28].

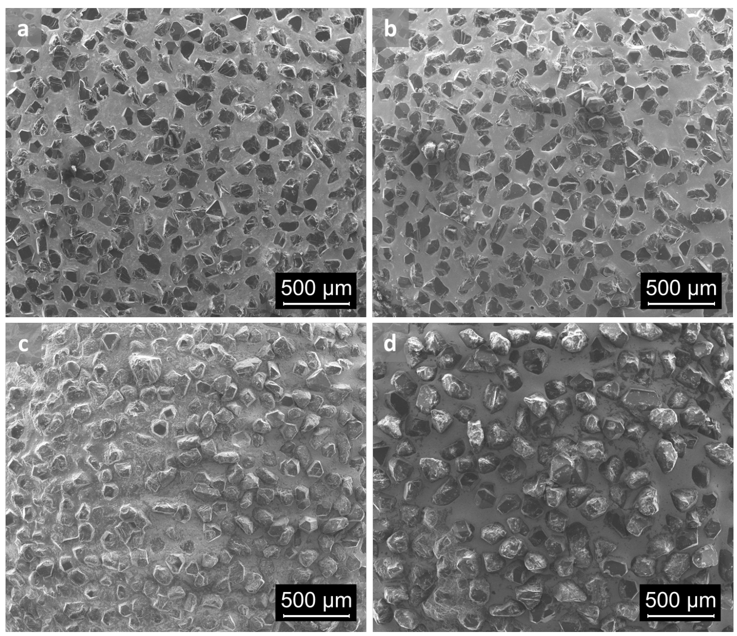

Fig. 5. Diamond coated tools after milling at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

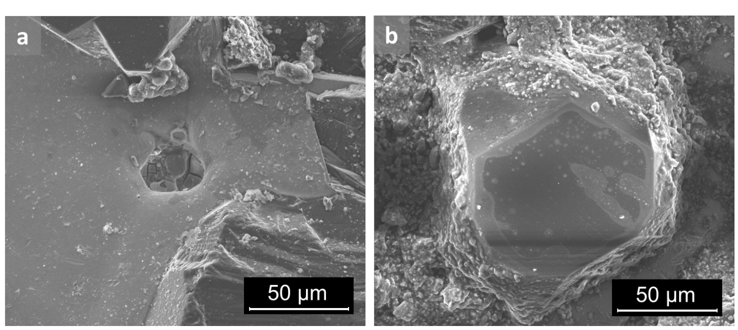

Fig. 6. Details of diamond coated tools after milling (a) diamond pull out, (b) adhesion phenomenon [28].

The process described, inevitably brings both brittle and ductile fractures in workpieces 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 also take place, like adhesion between tool/workpiece surfaces, as reported above. Furthermore, excessive local forces can generate different defects like chips, fissures, and cracks. The above issues are worsened by the geometric characteristics of the investigated workpieces.

When aluminum oxide tools are used, the adhesion effect evidently affects the fracture mechanism, as shown in Fig. 7. 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 here reported also confirms adhesive wear on the tool.

The effect of lubrication methods can also be evaluated by analyzing Fig. 7 and 8, where no appreciable difference in the final quality of the ceramic surface can be detected. This finding suggests the possibility of effectively machining the samples by avoiding the massive use of lubricants.

On the other hand, the spindle speed influences the machined surface quality as shown by Fig. 7. However, such difference cannot be appreciated at higher magnifications, as Fig. 8 highlights.

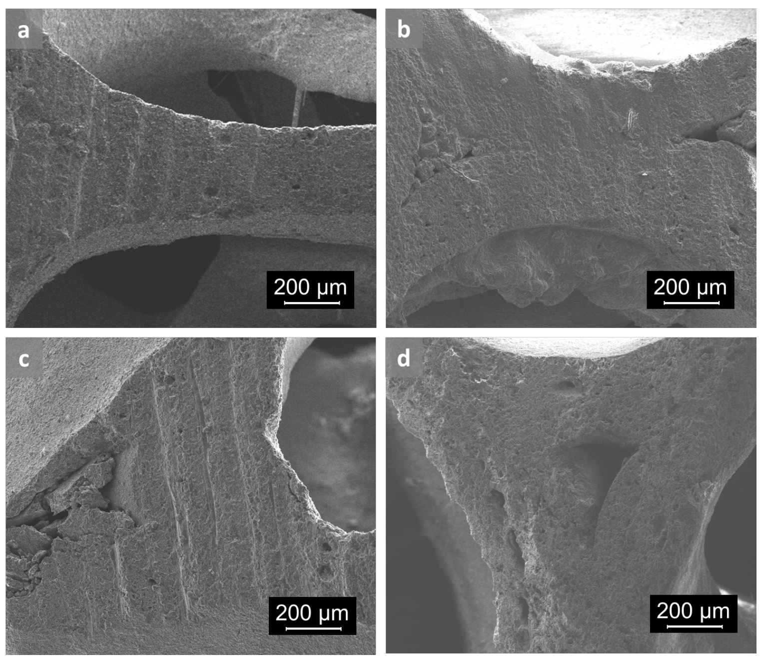

Fig. 7. Ceramic foam surface after milling with aluminum oxide tools at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

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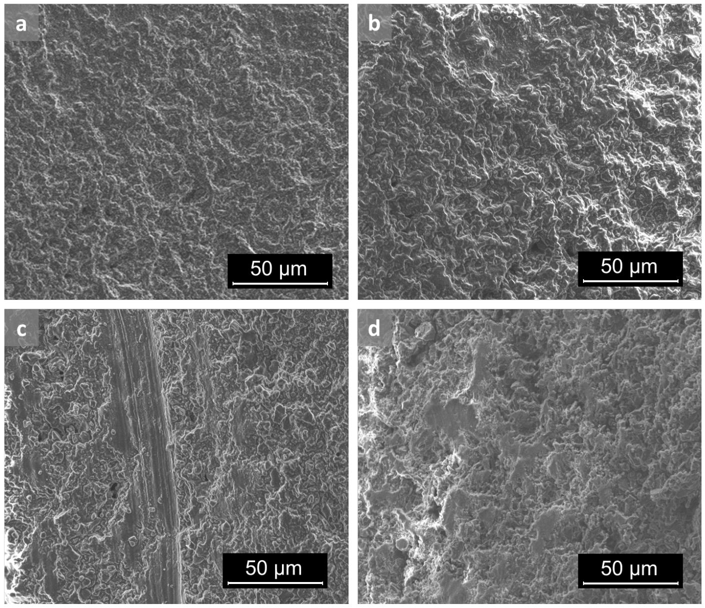

Fig. 8. Details of ceramic foam surface after milling with aluminum oxide tools at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

Diamond coated tools result in a more efficient cutting process since less adhesion effect is present. Fig. 9 and 10 show both ductile and brittle fracture areas, which are typical of the process. The diamond abrasive grains exposed on 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 of as several micro-cutting edges with locally different depths of cut, causing areas of both ductile and brittle fracture when machining ceramics. Furthermore, it is possible to state that the effect of lubricant is minimum and that the spindle speed has the same effects as those reported for the aluminum oxide tool.

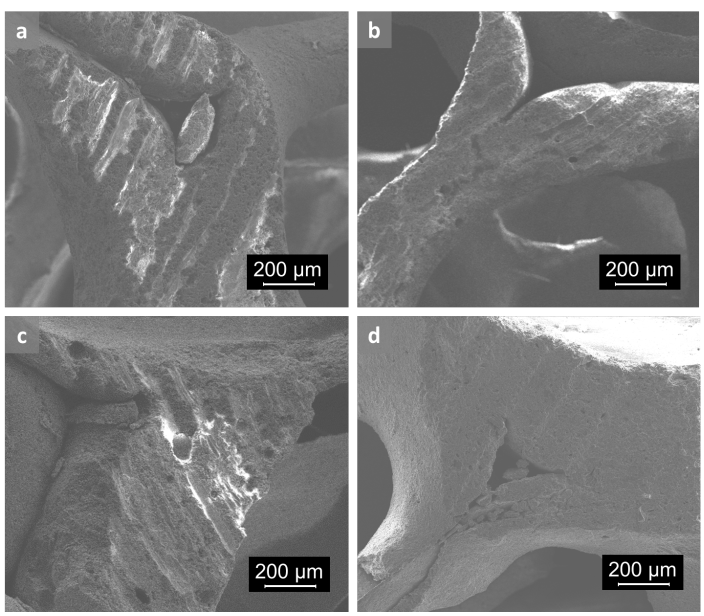

Fig. 9. Ceramic foam surface after milling with diamond coated tools at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

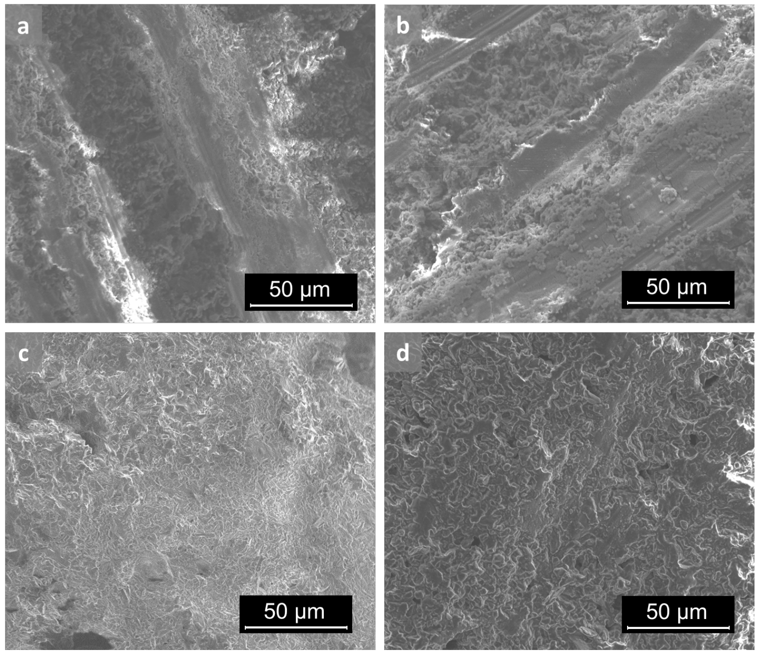

Fig. 10. Details of ceramic foam surface after milling with diamond coated tools at (a) spindle speed 10000 rpm, flood lubrication [28], (b) spindle speed 40000 rpm, flood lubrication, (c) spindle speed 10000 rpm, MQL, (d) spindle speed 40000 rpm, MQL.

Summary

This paper presents an analysis of the workability of alumina based ceramic foam. Such materials combine the issues of machining conventional ceramics with those related to the machinability of geometrically complex parts. The experimental campaign involved the spherical end milling of the workpieces at varying cutting tools, lubricant conditions, and spindle speed.

The results highlighted the tendency of such a process to fast wearing the tools and the combination of ductile and brittle deformation modes on the machined surfaces. The influence of lubricant is more pronounced analyzing the tool wear, where the flood lubrication ensures a longer tool life. Concerning the surface characteristics, lubrication has a smaller effect. On the other hand, the spindle speed plays instead a key role in the deformation mechanism showing a better surface quality when higher speeds are employed.

The results obtained allow the authors to state that ceramic foams can be machined by spherical end milling to obtain a variety of complex shapes and that diamond coated tools are, up to now, the best available choice. In future works, a more comprehensive study of the involved phenomena will be investigated, involving the transition from ductile to brittle material removal, related to locally different depths of cut.

It should be noted that the overall process needs to be optimized to define a workability window able to minimize the tool wear and maximize the surface quality.

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