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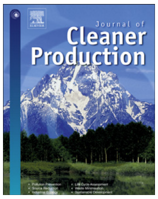

Allowance removal from green pieces as a method for improvement surface quality of advanced ceramics

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ABSTRACT

Advanced ceramics are usually machined after sintering in order to produce details and/or achieve the dimensional and geometric tolerances specified by project. However, this operation is neither cheap nor easy since it requires diamond tools, machine tools of high stiffness, and very low removal rates, even so, the finished parts might invariably contain critical defects. Machining of compacted ceramic powder before sintering, named green machining, is an alternative. This method does not require cutting fluid, presents great machinability, low energy consumption and few or no introduction of damages in the sintered workpiece. The single-action uniaxial pressing is the most used method for obtaining green ceramic pieces. Nevertheless it produces significant density variations in the outer regions of the piece, mainly located around the top and bottom edges, while the variation inside is smaller. The non-uniformity of density is considered responsible for distortion of the ceramic part during sintering. In this study, the distortion of the sintered workpieces was evaluated after green ceramic workpieces were machined using five different allowance values (1, 2, 3, 4, and 5 mm) in order to progressively remove the greatest density gradients. The distortion analysis was made on the top and bottom regions of the workpiece, where each upper and lower punch.

operates, respectively. It was found that the distortion of the top region of the sintered workpieces was reduced about 97% when there was 5 mm of allowance removal and 82% for 1 mm of allowance. In the bottom region, the reduction was about 91% for removal of 5 mm of allowance and 48% for 1 mm. Cutting tool wear, cutting force, and surface roughness of green and sintered workpieces were also analyzed. In general, the influence of tool wear on surface roughness of sintered pieces and the correlation between surface roughness of the sintered pieces and the corresponding green ones were observed.

1. Introduction

Although advanced ceramics have several favorable properties, such as high resistance to wear and temperature, chemical stability, and low density, these materials also have characteristics that limit their applications, especially regarding low fracture toughness, responsible for low impact resistance and reduced plastic deformation.

Machining using diamond tool is the main technique to achieve specified dimensions and surface finishing of ceramic parts. Depending on the workpiece size, material, shape, and surface quality, the machining of the sintered ceramic can amount to more than 50% of the production costs (Strakna et al., 1996). Among the machining processes, grinding represents more than 80% of all advanced ceramic machining. However, due to high degree of brittleness, mechanical components invariably suffer surface/sub-surface damages such as cracks during conventional material removal processes, compromising mechanical strength (Marinescu et al., 2007). Furthermore, hard ceramic machining demands for high stiffness machine-tools as well as diamond cutting tools, becoming the material removal process expensive.

According to experimental results from Xu and Jahanmir (1995) associated with study by Swain (1979), in machining of sintered polycrystalline ceramic different types of damages are verified as consequence of three different material removal mechanisms: (1)

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intergranular fracture and dislodgment of grains; (2) microcracks and formation of grain fragments through intragranular cracks; (3) and removal of large portions of grains by chipping due to the propagation of nanogranular cracks. Depending on highly controlled machining conditions, brittle removal mechanisms that involve the formation of cracks can be minimized, or even ductile machining can be achieved, in which removal mechanisms are characterized by plastic deformation, like in metals (Zhong, 2003; Ajjarupu et al., 2004). The two material removal modes, ductile or brittle, are associated with a critical depth of cut, which if exceeded, may result in damages. In order to reduce them, some works (Marshall et al., 1983; Malkin and Ritter, 1989; Blackley and Scattergood, 1991, 1994) recommend the use of much lower material removal rates than those used in finishing of metal components. Nevertheless, this procedure does not guarantee that ceramic components will be microcrack-free.

In order to improve the machinability and minimize ceramic material damages, some non-conventional machining processes have been studied. Electrodischarge machining process (EDM) is one of them, since it can produce variable shapes and it is not dependent on the hardness or abrasiveness of the material itself. However, the ceramic electrical conductivity must be higher than 0.01 cm^{-1} such as boron carbide (B_4C) and silicon infiltred silicon carbide (SiSiC), which were machined successfully by Sánchez et al. (2001). The fact of the most of the ceramics, for instance Al_2O_3, ZrO_2, Si_3N_4 and SiC, are electrically nonconductive can be minimized adding some doping to improve their conductivity, so that them become susceptible to the EDM. This is the case of studies carried out by Lee and Lau (1991), wherein up to 40% of TiC was included in an Al_2O_3 to improve its conductivity. Another well-established technique, since Mohri et al. (1996), is based on application of a metallic layer of high conductivity on the workpiece surface. But, in relation to the workpiece surface integrity of ceramic machined by EDM, Sánchez et al. (2001) state that surface and subsurface damages may be induced due to the thermal fatigue or to the material recast on the surface after removal.

Among the non-conventional machining processes, laser assisted machining (LAM) possibly is the most promising technique applied on the removal of difficult-to-machine materials. In this technique, the material is locally heated by an intense laser source prior to material removal, without melting or sublimation of the ceramic (Samant and Dahotre, 2009). As a result of the material heating, its yield strength decreases promoting lower both machining forces and cutting tool wear, besides improving the surface finishing (Chang and Kuo, 2007). Previously to the laser use, the plasma was the heating source used for softening the material, which it achieved success in many metallic materials, such as Inconel 718 in study conducted by López de Lacalle et al. (2004), but the plasma was not effective in ceramic materials according to Kitagawa and Maekawa (1990).

An alternative to avoid the damages in ceramic machining is the use of green machining technique, which removes material from compacted pieces before their sintering (i.e. in the green state). This process consumes few cutting energy, at least 50 times lower than in steel cutting for a same removed material volume, and is cheaper than removing material of a sintered ceramic, since green ceramic presents good machinability (Su et al., 2008; Ekabaram, 2008).

Green machining is carried out without cutting fluid, being this fact highly beneficial since if it is used makes the workpiece manufacturing more expensive, causing environmental problems and health risks. Even so, according to Debnath et al. (2014), approximately 85% of the cutting fluids used around the world are mineral-based cutting fluids. The cutting fluids require systems for storage, treatment, and recycling when they are discarded. Previous studies, such as Wichmann et al. (2013) and Zhao et al. (2012), have demonstrated that the highest consumption of tap water in machining processes is related with the use of cutting fluids, mainly for cleaning machined workpieces. Cutting fluids also contain biocidal compounds to prevent the growth of fungi and bacteria. However, these compounds are harmful to the health of operators because they release formaldehydes. Operators exposed to cutting fluid and its fumes may develop allergic dermatitis and respiratory diseases as reported by Burton et al. (2012). A study presented by Trafny (2013) revealed the presence of biofilms in cutting fluids, formed by fungi and nontuberculous mycobacteria that cause hypersensitivity pneumonitis and are not eliminated by conventional biocides, and that, moreover, may be stored in the system's metal components. Minimum quantity lubrication (MQL) technology is presented as an alternative to reduce fluid consumption in machining. MQL consists in spraying micro-oil particles to be used as cutting fluid. The flow rate used with this technique is established between 10 ml/h and 100 ml/h. Using several types of vegetable oils, Pereira et al. (2017) found satisfactory results in milling of Inconel 718 applying high sun flower oil. According to authors, the use of biodegradable/vegetable oils is required to achieve a full environmental process optimization. Besides, the use of biodegradable/vegetable oils prevents not only environmental issues but also health diseases. However, the MQL technique cannot be used in green machining since the workpiece is impregnate by lubricant, which it is capable to modify the sintering mechanisms and preclude the powder recycling, besides that the spraying causes workpiece erosion and spreads the powder.

Goindi and Sarkar (2017) state that researchers have tried to machine components without using any cutting fluids. Machining carried out without the assistance of cutting fluids is also termed as “dry machining”, which green machining also makes part of it. Gouveia et al. (2017) studied green machining in dental prostheses composed by zirconia stabilized with 3 mol% of yttria (3Y-TSZ), whose wasted powder was recycled. As result, they concluded that the wasted powder after treatment can be used in other applications, mainly in jewelry, without loss of mechanical resistance in relation to the original powder. In this case, the use of any fluid would become the machining process impracticable.

According to Klock et al. (2001), the primary objective of the machining sequence, prior to ceramic sintering, is usually to produce a contour similar to the finished component and a surface rim zone free from damage. In this way, complex shapes and details can be manufactured. In industrial practice, machining of green oxide ceramics with a defined cutting edge tool is an efficient shaping method as a step process of ceramic production. Nevertheless, as green machining was mostly considered a subordinate step on the way towards the ceramic component, there was a considerable deficit in fundamental process knowledge in the past (Klock et al., 2001).

Maier and Michaeli (1997) machined green ceramic workpieces (99.7% pure alumina) and observed a positive relationship between surface quality and mechanical strength after sintering. In both states, green or sintered, the machining under severe conditions is accompanied by chippings and invariably brings on microcracks on the surface of the piece, whereas mild machining conditions are capable of producing damage free pieces and surfaces with visible marks only left by cutting tool tip. These two mechanisms were called “chipping mode” and “cutting mode”, respectively. The authors found that green workpieces have very similar mechanical strength regardless of their surface finishing. However, the surface finishing produced by each one of these two modes affects the bending strength of sintered workpieces. As a result, the machined green ceramics with the best surface finishing presented greater mechanical strength (around 8%) when compared to the non-