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Microfabrication of green ceramics: Contact vs. non-contact machining

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ABSTRACT

Micromilling of ceramics is challenging due to its high hardness and low fracture toughness. Manufacturing of small components by non-contact micromachining of green ceramics could be a viable approach to overcome limitation associated with sintered state machining. In the present study, micromachining of green ceramics was carried out by contact (milling) and non-contact (laser ablation) methods and processibility was compared as well. Machining parameters such as machinability of micro-scale features, relative machining time and reproducibility were studied. Depth of machining, surface roughness, surface morphology, and changes in edge of machined features were analyzed.

1. Introduction

In miniaturization of devices, microfabrication-using top down approach is one of the most successful techniques in last decade to develop smart tools for diagnostics, minimally invasive therapies, microfluidics, and electronics [1–4]. Owing to high melting point, high thermal, corrosion resistance, ceramic components are preferable for strategic applications [5]. Ceramic microfabrication techniques are being used for transducers, MEMs devices, craniomaxillofacial reconstruction surgeries, bone screws, and microfluidic channels for micro-reactors [3–6]. However, machining of sintered ceramics is a time consuming and expensive technique due to high hardness, low fracture toughness, and high wear resistance properties. Direct manufacturing using soft-molding, micromachining via tooling are very sensitive and limited to size of the mold and tool diameter, respectively. However, high rejection rate is unavoidable associated with manufacturing defects during casting, demolding, and tool movement [7].

In last decade, machining through radiation (electron beam, laser, and plasma arc) has gained most attention due to its abrasionless, non-contact processes [8]. These modalities are free from limitations of the contact based techniques, such as tool wear, tool vibration and deflection, sub-surface damage, heat conductivity. Sharpening and depth of design can be controlled with power of radiation and exposure time. In this process, a beam of light is focused on the desired area of the sample and materials are removed through melting or vaporizing [9]. Machining of sintered materials requires high power, which makes the process time consuming as well as expensive. On the other hand, melting/vaporizing actions raise caution toward complete damage-free, precise machining. Even though, due to its non-contact procedure, reduced processing costs and scalability, radiation machining is a method of choice for micromachining [10].

Among different radiation machining, laser (Light Amplification by Stimulated Emission of Radiation) is recognized as rapid, effective, and economical process for most advanced applications. Besides micromachining, laser is used in different applications, such as re-melting, sealing, alloying, drilling, cutting, shaping, scribing. It is also revealed that laser machining offers improvement in tribological properties. Lee et al. reported that the grain growth could not be eluded completely, but proclivity toward crack propagation was decreased efficiently with laser surface treatment [11]. Zawrah et al. reported that laser treated alumina alloy surfaces had less tendency of crack formation and grain growth [12]. Using similar process, porous alumina surface was sealed effectively for strategic application. Recently, Krishnan et al. have revealed transformation of metastable γ- alumina into α-phase in a single step during laser machining and final component was free from internal micro-defects with reduced porosity [13]. Laser re-melted alumina coating was found less corrosive than plasma-deposited coating [14]. Laser machining offers rapid fabrication of symmetrical or

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arbitrary shapes with lateral resolution down to 50 μm and depth resolution comparable to the grain size of the work piece [15].

Machining of sintered ceramics by laser ablation encounters problem associated with poor thermal shock resistance leading to initiation and propagation of crack [16]. Interaction of laser radiation with work piece causes rapid rise in temperature. During this period, a sharp thermal gradient was formed in between exposed layer and intact substrate that leads to unequal expansion causing tension within the substrate and successive crack formation [4,17,18]. This effect is relatively less pronounced in case of powder compact as compared to dense sintered ceramics. Powder compaction is the primary step toward near net shape forming of ceramics which subsequently sintered to the final product. Due to larger pore volume in the powder compact (green ceramics), the damage associated with thermal gradient could be less pronounced during laser ablation.

The green state machining is an emerging area owing to invention of green body forming techniques [19] in recent time. There are several reports for fabrication of near net shape via computer numerical controlled (CNC) machining of green ceramics wherein green body strength is an important mechanical property. Green state machining has advantages including less energy consumption and cost effective tooling [20]. Further, notches created via green state machining could be healed or rounded off during shrinkage associated with sintering. Laser ablation machining could also provide similar benefits. Interestingly, materials removal rate of green ceramics by laser ablation may not be affected by green body strength [10]. The noncontact machining may offer relatively easy removal of materials, where firm attachment of sample is not essential.

Most of the earlier work was carried out on low temperature co-fired ceramics (LTCC), bisque-fired ceramics. Li et al. recently reported drilling of green ceramics using laser [4,5,8]. In this report, laser beam was also used for cutting of ceramic components. However, there was no significant reference on comparative study between contact and non-contact machining for green ceramics in terms of quality of machined surface. Further, machinability of green ceramics using both laser and milling could also be compared for efficacy of micro-scale patterning using a CAD model. The green gel cast samples with organic binder could also be studied and compared for both the modalities.

In the present study, we propose laser micromachining of green ceramics as an alternative to conventional CNC milling. Different micro-scale features like gears, grooves and pillars were designed using SolidWorks, and soft models were used for green machining. Outcomes of the laser-machined samples were compared with milled green ceramic compacts. The machining time, depth of machining, surface roughness, surface morphology, and edge of machined surface were compared for two different processes.

2. Experimental procedures

2.1. Fabrication of green ceramics

Green ceramic objects were prepared using slurry casting method as described previously [21]. Briefly, Alumina powder (RG 4000, Almatis, Germany) of average particle size and surface area 0.7 μm and 7 m^2/g, respectively, was used for preparation of green compacts by protein coagulation casting (PCC) [20,21]. Prior to the preparation of 55 vol% alumina slurry, a premix was prepared through optimization study using 27 ml distilled water and 3 ml of polymaleic acid (Aquapharm, Pune, India) as dispersant along with 20 vol% egg albumin (premix volume basis) with 3 wt% sucrose (on alumina powder weight basis) as binders. The prepared slurry was milled for 24 h to break-down agglomerates and homogenization. Prior to milling, 200 μl 1-octanol (Merck, India) was added (per 100 ml of slurry) as antifoaming agent to minimize entrapped air bubbles. The resultant alumina slurry was cast into rectangular polypropylene mold and was dried under controlled humidity cabinet. The dried samples were stored under vacuum for machining.

2.2. Designing of macro/micro pattern architecture

Prior to machining, the CAD (Computer Aided Design) model of macro/micro patterns were designed using SolidWorks (Dassault Systèmes SOLIDWORKS Corp., USA) and converted into ‘stl’ format (as shown in Fig. 1). A gear with 12 teeth, 3 mm diameter, depth 0.5 mm, and a micro pattern (array of pillars of dimension 0.5 mm × 0.5 mm × 0.5 mm) were designed.

2.3. Milling of green ceramics

A bench-top 4-axis CNC milling machine (MDX 540, Roland DG Ltd., Japan) was used for machining of green ceramic controlled by software (MODELA 4, Japan). The vacuum dried samples were placed on a sample holder and mechanically mounted on the base of CNC machine. The ‘stl’ file was used for generation of tool path and machining parameters, which were subsequently saved in ‘MPVJ’ format. Different tools were explored for machining of green alumina samples. Based on previous studies, diamond impregnated conical pointed end was used for milling of alumina owing to its high wear resistance property. Different machining parameters like rpm of the spindle, lateral movement, and depth of cut were optimized for machining. However, spindle rotation of 10,000 rpm along with linear axis movement of 2 mm/s (x, y, and z-axis), depth of cut 0.5 mm and 0.2 mm path interval were optimized for efficient machining of green alumina compact. These parameters were used for surfacing, roughing and finishing.

2.4. Laser machining of green ceramics

A tabletop computer controlled laser machine (VLS 2.30, Universal Laser System, UK) was used for non-contact machining. It was CO_2 gas based laser with high power density focusing optics (HPDFO), which could be operated with varying power, speed, and resolution with vector and raster settings. Green ceramic compacts were placed on the platform without mechanical fixation and laser beam was focused over the desired area of work piece. Software controlled laser machining was carried out by varying power, exposure time and resolution. During machining, air suction was applied to remove fragmented chips and smoke. The machining parameters and rate of machining were optimized according to size and shape of object to be machined. Optical and digital magnifications of lenses were kept constant during machining. For each design, the power, pulse per inch (PPI) and linear speed were set at 40 W, 600 and 50 mm/s, respectively.

2.5. Characterisation of machined ceramics

The milled and laser machined surfaces were examined under the optical microscope (Stereozoom Leica DFC 295, Germany) and scanning electron microscope (ZEISS EVO 60 Scanning Electron Microscope, Germany) for topography. Further, the machined samples were sintered in a muffle furnace (Bysakh, Kolkata, India) in air with holding time of 2 h at 1550 °C to achieve 99.9% density. The surface texture of the as-machined surface and sintered machined surfaces were assessed using surface profilometer (Talysurf i60/i120/i200-Inductive Systems, Taylor Hobson Limited, Leicester, England).