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High throughput hybrid laser assisted machining of sintered reaction bonded silicon nitride

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ABSTRACT

Silicon nitride is a high-performance ceramic reserved for the most demanding high-temperature structural applications due to its elevated strength, fracture toughness, corrosion resistance and hardness. These aspects also make it extremely difficult to machine, leading to component costs that are prohibitive in many fields where its physical properties could nonetheless provide improvements in performance, efficiency and lifespan. In the present work, precision two-step laser assisted machining of sintered reaction bonded silicon nitride is performed to reduce grinding forces and improve tool service life. Laser surface treatment is first undertaken at 15 mm/s with a 980 nm wavelength 3.3 kW diode laser focused to a 32 mm × 2 mm rectangular spot, inducing thermal cracks to a depth of approximately 615 μm with 2.5–3 kW laser power, corresponding to an energy dose of 4.7–5.6 J/mm^2. Grinding tests are then performed on the treated areas, confirming a reduction in peak and average machining forces of approximately 26–27% where thermal cracks are present. A numerical simulation is developed to provide insight into the failure mechanisms leading to thermal cracking and afford a relatively simple method of selecting laser parameters for real mechanical components.

1. Introduction

The high temperature mechanical and chemical properties of silicon nitride have led to its uptake in the most demanding high-temperature structural applications. With very high hardness, fracture toughness, high-temperature strength and corrosion resistance (Ziegler et al., 1987), this material is reserved for applications such as automotive glow plugs, turbochargers, bearings, machine tool inserts (Diniz and Ferrer, 2008), gas turbines and rockets. Sintered reaction bonded silicon nitride, in particular, is utilized for vehicle and aircraft armor plating. Complete reviews of applications, structure, properties and production methods are provided by Riley (2000) and Hampshire (2007). Though silicon nitride is attractive for production of high temperature, wear resistant components, it presents a number of obstacles for traditional manufacturing processes. A typical production chain currently consists of sintering semi-finished components that must then be machined to their final geometry and surface roughness via diamond grinding. Samant and Dahotre (2009) noted that the cost of grinding typically exceeds that of the material itself, impeding uptake in potential applications where its characteristics would provide benefits in terms of performance, efficiency and lifespan. To offset these issues, a number of authors such as Kumar et al. (2011) have proposed hybrid laser assisted machining as a possible solution for shaping high performance ceramics, reducing grinding costs by inducing thermal cracks to facilitate brittle fracture and reduce grinding forces and tool wear.

Hybrid machining processes involving laser technology exploit localized heating to achieve softening or weakening that facilitates material removal. Lauwers et al. (2014) provide a review of state-of-the-art assisted, mixed and combined hybrid manufacturing processes. Anderson et al. (2006) showed that the cost effectiveness of processing difficult-to-machine alloys can be enhanced by utilizing a laser beam to improve machinability by increasing the temperature and therefore decreasing the yield strength at which cutting takes place. Westkämper (1995) showed that laser assisted grinding of high performance ceramics can achieve stock removal rates some six times greater than conventional grinding. Rozzi et al. (1999) performed laser assisted machining of silicon nitride, demonstrating that semi-continuous or continuous chips can be produced where temperatures near the cutting tool are above the glass transition temperature. Lei et al. (2000) developed a constitutive equation for silicon nitride under the same processing conditions, demonstrating that material removal is due to

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both plastic deformation in the shear zone and segmentation of chips due to intergranular microcracks. Yang et al. (2009) investigated edge chipping of silicon nitride, finding that temperatures in the range 1300–1400 °C during laser assisted machining yield optimum results. Dandekar and Shin (2013) then developed a multi-scale model for subsurface damage in silicon carbide reinforced matrices following laser-assisted machining. They found that an increase in temperature due to laser exposure led to a reduction in sub-surface damage.

Two-step laser assisted machining of ceramics instead exploits thermal cracking to weaken a surface layer that is then ground after a minimum cooling period. This procedure reduces grinding forces without subjecting the tool to excessive temperatures that are ultimately counter-productive to improving service life. Laser heating is flexible, efficient and capable of dealing with complex components, as demonstrated by Skvarenina and Shin (2006) for laser surface hardening. Laser heating is well-suited to silicon nitride due to its high optical absorptivity (Palik, 1998) and low thermal conductivity (Wachtmen, 1989) compared to most metals, allowing the generation of a thin cracked surface layer with relatively little energy input. Kumar et al. (2011) showed that limiting crack depth and subsurface damage is important for ensuring long-term resistance of silicon nitride during cyclic thermal and mechanical loading. Fortunato et al. (2015) achieved grinding force reductions of 30–50% and tool wear improvements following laser heating of silicon nitride. Studies to date, however, have dealt with relatively small surface areas with limited control over crack depth. Due to both productivity and quality requirements in silicon nitride manufacturing settings, there is scope for development of a process that exploits the high output power of modern industrial laser sources while controlling the resulting thermal crack depth in components with complex geometry.

With the feasibility of two-step laser assisted machining of silicon nitride established, the present work seeks to address some of the issues surrounding real manufacturing settings, including throughput, precision and parameter selection for components with arbitrary geometry. A 3.3 kW diode laser with 32 mm wide rectangular spot has been utilized to induce cracking in silicon nitride samples at a velocity of 15 mm/s, corresponding to a throughput of 480 mm^2/s. A precise energy density threshold has been established for crack formation, with subsequent grinding experiments confirming a corresponding reduction in cutting forces. A numerical simulation has then been developed to determine thermal stresses during laser exposure with the scope of providing a relatively simple tool with which laser parameters can be selected for components prior to manufacturing. Such a tool provides a framework with which designers can assess the feasibility of hybrid laser assisted machining and, more generally, the introduction of silicon nitride over a range of new applications.

2. Experimental setup

2.1. Samples

Sintered reaction bonded Ceradyne Ceralloy 147-31N silicon nitride plates of dimensions 100 mm × 80 mm × 9 mm were used for all experiments. The physical properties of this material are provided in Table 1 (Matweb, 2012). Published values for compressive strength of silicon nitride range from more than 3 GPa at room temperature to approximately 1.5 GPa at 1000 °C (Lankford, 1983), while the flexural strength ranges from 800 MPa at room temperature to approximately 500 MPa at 1000 °C (Wachtmen, 1989).

Table 1
Physical properties of Ceradyne Ceralloy 147-31N sintered reaction bonded silicon nitride (Matweb, 2012).

Density	3200 kg/m^3
Thermal conductivity	16–26 W/mK[a]
Coefficient of thermal expansion	3.3×10^{-6} 1/K
Specific heat capacity	683–1200 J/kgK[a]
Compressive strength	1.5–3 GPa[a]
Flexural strength	500–800 MPa[a]
Young's modulus	310 GPa
Poisson's ratio	0.27
Optical absorptivity @ 980 nm	89%[b]

[a] Vary with temperature up to 1000 °C (de Faoite et al., 2012; Wachtmen, 1989; Lankford, 1983).

[b] Calculated based on a refractive index of 2 at a wavelength of 980 nm (Palik, 1998).

2.2. Laser treatment

Laser exposures were performed on the silicon nitride samples with a 980 nm wavelength diode laser with maximum output power of 3.3 kW. The laser was equipped with a 150 mm focal length focusing lens that produced a 32 mm × 2 mm rectangular spot with top-hat intensity distribution. The focusing lens was mounted on an anthropomorphic robot and connected to the laser via an optical fiber, allowing arbitrary motion between the laser spot and workpiece. Linear exposures were performed along the center of each silicon nitride plate, with laser motion parallel to the 80 mm edge and the laser spot orientated such that the exposed track was as wide as possible (32 mm). Separate treatments were performed at 2 kW, 2.5 kW, 3 kW and 3.3 kW laser power, with two samples prepared at 3 kW to allow grinding tests to be performed both parallel and normal to the direction of laser motion. A scanning velocity of 15 mm/s was chosen for all experiments so as to maximize throughput (480 mm^2/s) and minimize thermal penetration while still providing sufficient incident energy to achieve thermal cracking. Laser treatment of the entire 80 mm length of each sample took 5.3 s. The energy dose administered during laser treatment was 3.8–6.2 J/mm^2, taking into account 10% losses from the laser optics, according to the following relationship:

$$E = \frac{\eta P}{wv} \tag{1}$$

where E is the energy dose (J/mm^2), P the laser power (W), $w = 32$ mm the laser spot width, $v = 15$ mm/s the scanning velocity and $\eta = 90\%$ the optical efficiency of the beam delivery system. With visible thermal cracks evident at 3 kW and not at 2.5 kW, subsequent analyses and grinding tests were performed on samples treated at 2.5 kW and 3 kW. Where thermal cracking was present, crack formation was parallel to the direction of laser motion. A schematic and photograph of the laser setup and treatment is presented in Fig. 1.

2.3. Grinding tests

Grinding tests were performed on untreated and treated samples at room temperature with a Norton ASD150-R75B99-1/4 grinding wheel. This particular grinding wheel is commonly employed for both roughing and finishing of hard-to-machine ceramic materials. Single-pass surface dry grinding tests were performed on all samples with concordance kinematics. Feed direction was parallel to laser motion for samples not exhibiting evidence of thermal cracking, while tests were performed both parallel and perpendicular to cracking where this was present. Typical values of cutting speed and feed rate for very hard materials were employed, while the depth of cut was maintained as small as possible (5 μm) so as to detect the thermal crack depth with the highest possible sensitivity. Grinding fluid was not employed during the tests to avoid possible interference with force measurements and crack depth detection. This choice was justified by the grinding wheel specifications, very low depth of cut and high resistance of silicon nitride to elevated grinding temperatures. Wheel sharpening was performed with a Norton 38A220-HVBE aluminum oxide dressing stick every 10 grinding passes. Grinding forces were measured during each grinding pass with a Kistler 9257B dynamometer equipped with triaxial load cell. The latter was characterized by a 10 kHz sample frequency to