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A laser assisted hybrid process chain for high removal rate machining of sintered silicon nitride

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ABSTRACT

This paper presents a hybrid process chain for efficiently machining hard silicon nitride. The process includes a laser treatment phase to weaken the material, followed by diamond grinding. Optimized laser parameters have been identified to control the generation of a network of cracks that weakens the volume of material to be ground. Comparison of data between traditional and hybrid process chain shows a reduction in grinding force of about thirty per cent in the latter case. A finite element model has been developed for the analysis of thermal stresses generated by laser exposure and the prediction of crack formation.

1. Introduction

In recent years, silicon nitride ceramics (Si_3N_4) have found increasing use in several industries, ranging from aerospace to automotive, thanks to the unique properties of Si_3N_4: high temperature wear resistance, chemical inertness and high strength-to-weight ratio [1].

Unfortunately, the preservation of high hardness at elevated temperatures makes Si_3N_4 very difficult to machine and, for this reason, silicon nitride components are usually sintered to near net shape and successively ground to achieve the required dimensional accuracy. This last process, performed by diamond grinding, makes machining very expensive and time consuming.

In order to increase productivity and reduce cost, hybrid manufacturing that combines chip removal machining and thermal treatment has been proposed [2,3]. Usually, an external thermal source such as a laser provides the energy/power to soften the ceramic, making the subsequent material removal process easier as it is completed while the material is still at high temperature [4]. Modification of the mechanical and thermal properties of Si_3N_4 with temperature, as well as the type of laser source and the interaction between material and laser, play a fundamental role in the laser assisted hybrid process.

Several investigations, carried out using different laser sources, propose models to predict the absorbed energy, thermal field and constitutive equation to describe the mechanical behaviour of Si_3N_4 cut at high temperature [5,6]. Laser irradiation is done by using CO_2, solid state fibre, Nd:YAG, and diode lasers [7,8]. Although these studies provide very interesting data and results on the softening induced by means of laser heating, none of them address crack propagation with the exception of Ref. [5] that focuses on micromachining.

The present paper extends the results presented in Ref. [5] for Si_3N_4 micromachining to the fabrication of macro components. The proposed process is based on an initial phase in which surface layer cracks are generated by means of thermal shock induced by exposure to a high intensity continuous wave diode laser, followed by removal of the cracked layer by diamond grinding. The process yields a final surface that provides the required accuracy and surface quality.

In contrast to Ref. [5], this paper presents a laser-material interaction model developed in order to correlate the laser parameters including power, intensity distribution, wavelength and scanning speed, to the thermo-mechanical properties of the target material. This model permits the prediction of crack depth due to laser exposure and estimation of the number of grinding passes per laser pass to remove macro quantities of Si_3N_4.

2. Process model

Sintered Reaction Bonded Silicon Nitride (SRBSN) ceramics have properties that depend on the sintering process, the quality of the powder and the additives employed during sintering.

Due to the presence of oxide additives to promote densification at the sintering temperature, SRBSN has an intergranular glassy phase that surrounds the β-Si_3N_4 grains. The glassy phase plays a fundamental role in conventional laser assisted machining since its yield strength drops rapidly at temperatures greater than 900 °C and vanishes at the decomposition temperature of 1400 °C. In this temperature range the β-Si_3N_4 phase is solid, although strength, thermal conductivity and emissivity change.

Decomposition of the solid β-Si_3N_4 phase happens at temperatures above 1900 °C [9]. The proposed hybrid process seeks to

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first mechanically weaken a specified volume of the ceramic by subjecting it to controlled thermal stress cycling via laser heating, which introduces thermal cracks in the material, followed by easy mechanical removal of the cracked volume. This requires a detailed understanding of the effect of severe thermal stress cycling on the thermo-mechanical response of the ceramic.

2.1. Modelling of transient laser-material interaction

In order to predict the thermal field and subsequent thermal stress in the workpiece, a model of the laser beam and its absorption into the material have been developed.

When using a continuous-wave low intensity laser, the interaction with matter is governed by the Beer–Lambert law:

$$I_{abs} = I_0 \cdot e^{-\beta \cdot z} \cdot A_c$$

where

- I_{abs} is the absorbed intensity at distance z from the irradiated surface;
- β is the radiation absorption coefficient into the bulk;
- I_0 is the incoming laser intensity;
- A_c is the surface absorption coefficient.

The energy transferred into the workpiece and the resulting temperature distribution can be calculated in two steps: first, by determining the exact energy absorbed via the Beer–Lambert law, and second, by computing the heat flux into the bulk material by means of the Fourier equation.

Since the diode laser used in this work is a low intensity laser source, non-linear effects in laser absorption can be neglected and consequently the absorption coefficient β does not depend on the intensity I_0, but just on the interacting medium and the radiation wavelength.

In order to take into account the correct spatial interaction between the laser beam and workpiece surface, a flat top laser intensity distribution has been modelled considering the intensity shape distribution of the diode laser used in the experiments.

2.2. Thermo-mechanical behaviour of Si_3N_4

The laser-material interaction model yields the temperature distribution and the corresponding thermal stress produced in the irradiated volume of the ceramic. In order to use this model to establish the laser parameters required to generate cracks in the ceramic, knowledge of the thermal fracture stress of the ceramic is required. In this paper, a thermal fracture stress value of 350 MPa, which was determined through laser shock tests on a Si_3N_4 specimen with mechanical properties similar to those of the SRB Si_3N_4 material used in the current experiments [10], is used. Cracks are produced when the maximum tensile stress produced in the irradiated ceramic exceeds the thermal fracture stress. By comparing the thermal stress magnitude predicted by the model (for given laser parameters) to the thermal fracture stress for Si_3N_4, the depth of the cracked region in the Si_3N_4 can be determined.

3. Experimental setup

3.1. Laser setup

A continuous wave IR diode laser (NUVONYX ISL-1000 M) with a maximum power of 1000 W and wavelength of 808 nm was used. The complete experimental campaign is summarized in Table 1. The laser head was mounted on two linear stages that enabled the positioning of the laser and variation of the spot dimensions (Fig. 1). Two other stages were mounted in front of the laser head (perpendicular to one another) to enable the positioning of the laser on the plate surface and movement of the sample during laser treatment.

Table 1
Experimental process parameters.

Spot (mm)	Power (W)	Scan speed (mm/min)	Power density (W/mm^2)	Overlap (%)
1	20–560	5–1100	25–715	
1.5	50–300	80–200	28–170	
2	100–350	100	32–111	
2.5	100–400	100	20–81	
3	150–450	100	21–64	
3.5	200–500	100	20–52	10–50
4	250–500	100	19–40	10–50
4.5	350–560	50–150	22–35	10–50

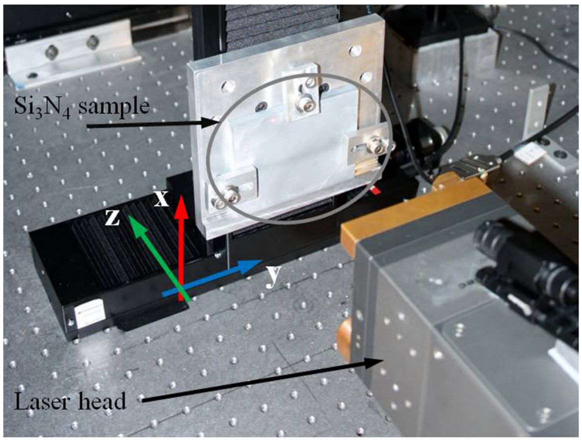

Fig. 1. Experimental setup.

3.2. Grinding setup and test procedure

A grinding wheel with diamond abrasive (ASD150-R75B99-1/4) 304.8 mm diameter × 6.35 mm width was used. The wheel was mounted on a 3-axis automatic surface grinding machine (CHEVALIER 1224-AD). The grinding forces were measured with a 3 axis dynamometer (Kistler 9256C2) connected to a data acquisition unit. All grinding tests were performed with a wheel speed of 1800 rpm, a feed rate of 130 mm/s and a cut depth of 0.0127 mm in a concordance set up.

The forces were acquired during grinding passes with a sampling frequency of 5000 Hz.

3.3. Material and test procedure

The samples used to test the hybrid process were SRBSN (Ceralloy® 147–31 N) plates with dimensions 100 mm × 80 mm × 9 mm. Physical properties and their variation with temperature are given in Refs. [8,11]. Preliminary tests, carried out with the parameters reported in Table 1, permitted evaluation of the effect of laser parameters including power (P), scanning speed (v_s), spot size (s), power density (d) and overlap (o) on the Si_3N_4 surface and subsequently the correct choice of laser parameters to be used in the grinding phase. The laser parameters used for the samples undergoing successive grinding passes were $P = 560$ W, $v_s = 100$ mm/min, $s = 4.5$ mm and $o = 25\%$.

4. Results and discussion

4.1. Numerical modelling results

The simulation model, developed in COMSOL according to the theoretical models described in Section 2, considers all laser parameters involved in the process: power, intensity distribution, wavelength, physical and optical properties of the target material, scanning speed and overlap. In particular, the model is able to predict the temperature and stress evolution in the Si_3N_4 workpiece during laser treatment.

The severity of the thermal cycle was estimated for the laser parameters adopted in the hybrid process ($P = 560$ W, $v_s = 100$ mm/

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