Precision Engineering 36 (2012) 546–553

Contents lists available at SciVerse ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Application of atmospheric plasma jet machining (PJM) for effective surface figuring of SiC

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ARTICLE INFO

Article history:
Received 29 August 2011
Received in revised form 21 March 2012
Accepted 2 April 2012
Available online 7 April 2012

Keywords:
Ultra-precision machining
Plasma jet machining
Silicon carbide
Surface figuring
Asphere

ABSTRACT

Optical and mechanical components made of SiC are widely used in ground and space based astronomical instruments and other scientific instrumentation. Although the manufacturing steps for SiC have been improved and optimized during the last decade, in some cases conventional abrasive shaping and finishing techniques are not applicable, e.g. because of complex surface shapes like free forms or aspheres with strong curvatures, or very small sized components. As an alternative contactless plasma jet based techniques can be applied for surface shaping or figure error correction on SiC surfaces. In this paper some aspects of plasma jet interaction with the surface are discussed. Furthermore, we demonstrate the capability of atmospheric plasma jet machining technology to process optical and mechanical components made of SiC in an effective way.

1. Introduction

Sintered silicon carbide (SiC) ceramic provides excellent physical and chemical properties like high specific stiffness, high hardness, low thermal susceptibility, and chemical inertness, which makes it a material preferably used for structural and optical elements to construct lightweight and athermal ground and space-based astronomical instrumentation or other scientific instruments. SiC mirror production comprises several manufacturing steps including conventional abrasive optical finishing processes, i.e. diamond tooling, lapping and polishing [1,2]. Since SiC is an extremely hard and strong material, material removal rates of conventional shaping and finishing techniques are very time consuming compared to the processing of other optical materials [2].

Although in the past 10 years much effort has been made to develop effective processing chains for the manufacturing of large high quality SiC mirrors, difficulties still exist in the fabrication of small and medium sized mirrors (10–300 mm diameter) with complex surface shapes like off-axis aspheres or freeforms. These elements often exhibit large departures from flats or spheres and have steep surface gradients. With conventional diamond tooling the accessible surface shape accuracy is limited to PV values of several microns, and subsequent polishing processes require multiple iterations to achieve high quality optical surface profiles ($<\lambda/10$). Even if the surface form (long spatial wavelength range) and the micro roughness (high spatial frequency range) can be brought into the respective specifications, midspatial frequency errors cannot be addressed by the conventional abrasive techniques. On contrary, those structures are often introduced by diamond tooling or small tool polishing during finishing. In order to speed up the optics manufacturing and to increase the process convergence, an additional process is required that

(i) provides sufficiently high material removal rates,
(ii) gives deterministic results based on metrology data,
(iii) interacts locally with the substrate (subaperture tool),
(iv) provides flexible adjustment of tool size,
(v) is insensitive to substrate geometry and mechanical loading effects [2].

To cope with the challenges and to meet the requirements, several non-conventional technologies have been developed in the past or are still under development. On the one hand, magnetorheological finishing (MRF) as a non-conventional deterministic polishing method [3,4], and ion beam figuring (IBF) as a well established technology for surface figure error correction on high-end optics [5,6], both provide excellent process stability and yield highly deterministic results, however at the expense of material removal rate. On the other hand, plasma assisted techniques have been developed for a deterministic high rate material removal, e.g. chemical vaporization machining (CVM) [7,8], reactive atom plasma (RAP) [9], plasma jet machining (PJM) [10], and other techniques based on similar principles.

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http://dx.doi.org/10.1016/j.precisioneng.2012.04.001

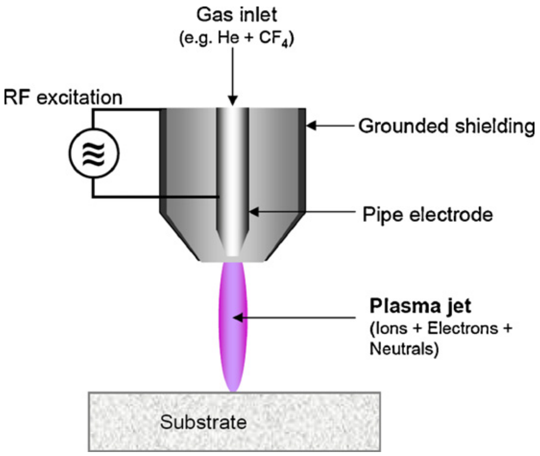

Fig. 1. Experimental setup for plasma jet machining.

Atmospheric plasma jet machining (PJM) presents a non-conventional surface figuring technology that has been under steady development for about 15 years. This technology is dedicated for effective generation of surface shapes (aspheres or freeforms) and for surface error correction on optical elements. It has been successfully applied for figuring and error correction on optical elements made of fused silica [11]. In this paper the application of PJM to silicon carbide is presented. We focus on the interaction of the plasma jet with different types of SiC substrates regarding etching rate and surface roughness evolution, figuring of aspherical test structure and the midspatial frequency error correction on small SiC optics and precision-mechanical components.

2. Experimental details

The plasma jet machining system comprises a CNC machine equipped with 5 axes, a plasma jet source mounted as the tool and power and gas supply for the plasma generation. The plasma source is a capacitively coupled RF plasma torch made up of a conductive coaxial system where the inner conductor forms a coaxial tubing system for a multi-channel gas supply. A schematic drawing of the setup is shown in Fig. 1. The coaxial system ends in a gas nozzle. By applying RF power (13.56 MHz) to the inner conductor a stable plasma jet discharge can be generated at the nozzle. The central gas channel is fed by inert gas helium ([He] = 0.5–2.0 slm). A mixture of the fluorine containing precursor gas CF_4 and O_2 is supplied either through the peripheral gas channel or the central channel as well. Typical CF_4 gas flow rates range from 0.5 to 2 sccm when using the central channel or 5–50 sccm for the peripheral gas feed. RF power has been adjusted between 60 and 150 W.

PJM is a contactless material removal process based on chemical etching reactions between the surface atoms of the substrate and reactive radicals in the plasma jet. The plasma jet does not exert any significant mechanical forces onto the surface. Material removal is accomplished by the simplified reaction scheme

$$\mathrm{SiC} + \mathrm{O}^* \rightarrow \mathrm{SiO_2} + \mathrm{CO}_x \tag{1}$$

$$\mathrm{SiO_2} + 4\mathrm{F}^* \rightarrow \mathrm{SiF_4} \tag{2}$$

$$\mathrm{SiC} + \mathrm{F}^* \rightarrow \mathrm{SiF_4} + \mathrm{CF}_x \tag{3}$$

where O^* and F^* are radicals formed in the plasma and SiF_4 and CO_x are volatile compounds desorbing from the substrate surface. The actual mechanisms that are taking place on the surface are much more complex [12] and still not fully understood.

The process is applied under normal environmental conditions, which makes this technology cost effective. Plasma jet surface figuring is accomplished using the dwell time method. This technique and all necessary mathematical algorithms are far developed [13] and widely used for the different subaperture figuring methods like ion beam figuring, corrective polishing or MRF. The plasma jet source moves relative to the surface on a raster or spiral path with a certain line spacing and a given local velocity that is proportional to the local dwell time. Etching experiments have been performed on different types of sintered SiC:

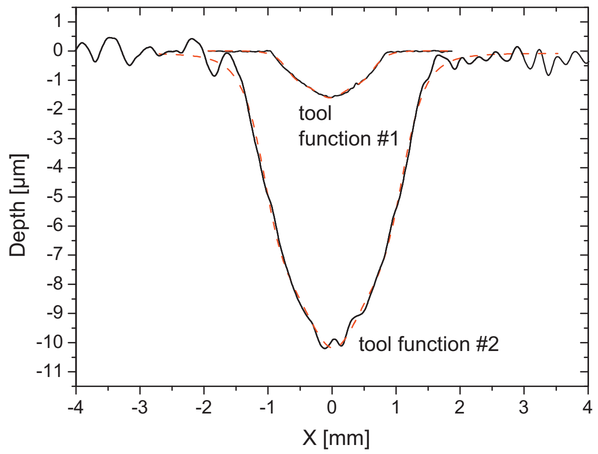

Fig. 2. Example of two different plasma jet tool functions (groove etchings): Tool function #1: $V_R = 0.654\,\mathrm{mm^3/h}$, FWHM: 1.2 mm, Tool function #2: $V_R = 7.34\,\mathrm{mm^3/h}$, FWHM: 2.02 mm, red dotted lines: Fit using inverse polynomial peak function. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Substrate #1: round disc, no CVD coating, ground surface (supplied by Boostec, originating from year 1999).
- Substrate #2: round disc, with SiC-CVD coating, ground surface (Boostec, 1999).
- Substrate #3: plate, with CVD coating, mechanically polished surface (Boostec, 2010).

Since the production date of substrate #3 differs significantly from the others, a better quality, especially that of the CVD coating is expected. Surface roughness and etching rates have been determined using a laser autofocus surface profiler (µscan) from groove-like test etchings or homogeneous etchings on small areas. Rq values have been obtained from a 0.5 mm profile length measured with a lateral resolution of 2 µm and applying an 80 µm cut-off filter to the measured profile. In some cases, roughness has also been evaluated using a white light interferometer (MicroMap) equipped with a 50× objective.

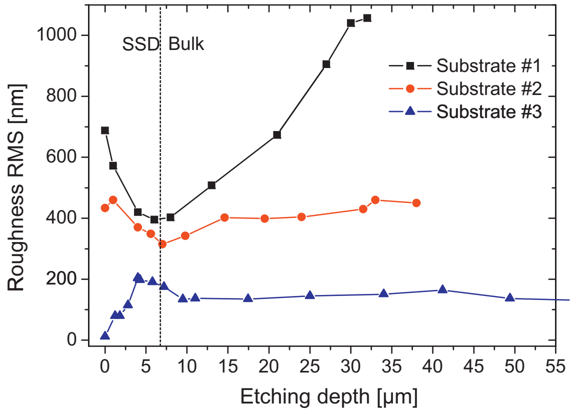

Fig. 3. Surface roughness (Rq) on SiC samples depending on the final etching depth, measured with laser profiler.