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Hybrid erosive jet micro-milling of sintered ceramic wafers with and without copper-filled through-holes

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ABSTRACT

Abrasive slurry jet micro-machining (ASJM) in combination with abrasive air jet micro-machining (AJM) was used to mill micro-pockets in three different ceramic wafers: sintered alumina, aluminum nitride, and zirconium tin titanate. A composite substrate of aluminum nitride with an array of copper-filled through-holes was also machined using a hybrid process of AJM and ASJM that capitalized on the significant differences in the erosive characteristics of each method. The objective was to investigate an alternative to laser micro-milling. The sintered ceramics were found to erode in a brittle manner by the dislodgment of grains upon abrasive particle impact. The eroded profiles produced by ASJM and AJM were modeled analytically.

ASJM could make 100 μm deep flat pockets, 500 μm wide with 60° sidewall angles in the sintered ceramics using overlapping parallel channels. The shapes of the pockets could be predicted accurately as long as the depth of each machined pass was less than 50 μm. Pockets of the same size and roughness ($R_a = 0.4$ μm) could also be machined and modeled accurately using masked AJM. The surface roughness of the sintered ceramics was found to be insensitive to particle size, being controlled by the size of the sintered grains.

Similar pockets could be machined in the aluminum nitride containing 180 μm diameter copper through-holes using ASJM provided that the maximum depth was about 25 μm. Beyond that, the secondary slurry flow away from the jet footprint created unwanted etching of the copper-filled through-holes leading to a lack of flatness. Deeper pockets in these substrates were machined using a hybrid AJM–ASJM methodology, in which AJM was used to selectively erode the brittle sintered ceramic without etching the ductile copper, followed by the leveling of the protruding copper pillars to the depth of the ceramic using ASJM. Computational fluid dynamics models were used to explain the results in terms of the large differences in the local particle impact angles and velocities in ASJM and AJM.

1. Introduction

The increasing use of micro-electromechanical and micro-fluidic devices of complex geometries made from difficult-to-machine materials has required the development of non-conventional machining processes. For instance, abrasive slurry-jet micro-machining (ASJM) can erode a wide range of materials without thermal damage and without the use of patterned masks. The high repeatability of low-pressure ASJM was demonstrated by Nouraei et al. (2012), who machined micro-channels and micro-holes in glass with a maximum variation in the depth and width along a single channel of less than 3%. Kowsari et al. (2014) demonstrated the feasibility of ASJM to machine micro-channels and micro-holes in sintered alumina, and used a basic surface evolution model to predict the shapes of the profiles. However, that study was limited to feature depths smaller than 50 μm so that the near-flat target geometry had no effect on the slurry flow field. The modeling of deeper features must account for changes in the erosive flow.

Machining of micro-pockets in ceramics containing metallic through-holes (Fig. 1) is of interest in industrial applications such as the packaging of hybrid microwave integrated circuits (HMIC) involving high-power, low-noise amplifiers operating at high frequencies; i.e., 3–30 MHz, as explained by Khalil et al. (2009). The use of relatively thick (i.e., 375–675 μm) sintered ceramic wafers such as alumina, aluminum nitride, and zirconium tin titanate as

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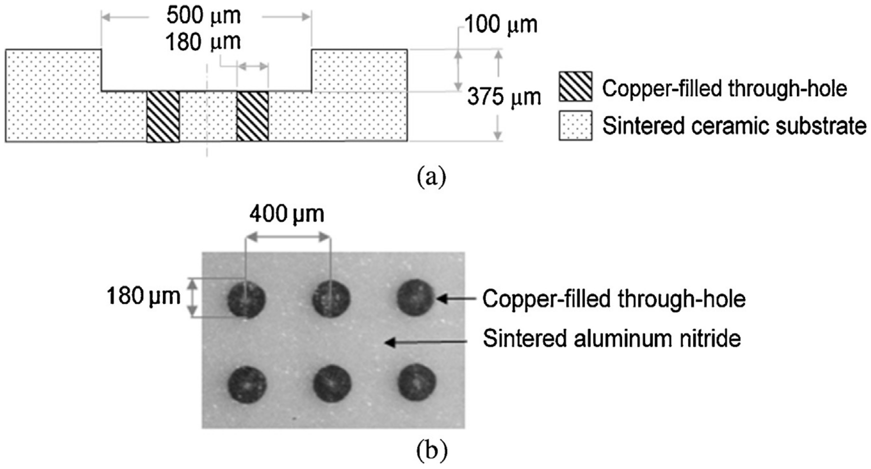

Fig. 1. Schematic of (a) cross-sectional profile and (b) plan view of a pocket in an aluminum nitride wafer containing copper-filled through-holes (vias).

substrates can result in an electronically optimal circuit. However, the relatively low thermal conductivity of alumina for instance (26.9 W/m k) can cause an active device such as a field effect transistor to overheat if placed on such a substrate. Temperatures can be reduced using copper-filled through-holes (vias) to conduct heat through a wafer to an attached heat sink as illustrated in Fig. 1.

The devices are soldered to the bottom of the pockets, making thermal and electrical connection with the copper-filled through-holes or vias. Laser micro-milling is commonly used for such applications, but, as explained by Jandeleit et al. (1998), avoiding thermal damage and micro-cracking require the use of relatively expensive, high-frequency lasers. The aim of the present work was to investigate the feasibility of ASJM as a low-cost alternative to micro-mill pockets into composite substrates of sintered ceramic wafers containing metallic-filled through holes.

The only existing investigation of the ASJM of pockets was conducted by Tamannaee et al., 2016 who used overlapping adjacent nozzle passes to create 800 μm wide flat-bottomed pockets in ductile polymers. The effect of overlapping eroded footprints was also considered in the fluid jet shaping and polishing of optical glass (e.g., Fähnle et al. (1998), Booij et al. (2002, 2004), and Fang et al. (2006)), and the ion beam milling of optical glass by Shanbhag et al. (2000); however, these applications considered only the removal of a few microns from rotating glass targets. Of related interest is the work of Ghobeity et al. (2008a) who used abrasive air jet micro-machining (AJM) to machine flat pockets in brittle glass using over-lapping machined channels; however, the minimum pocket width was about 10 mm because of the relatively large air jet footprint. The much larger divergence of the AJM jet relative to an ASJM jet usually requires the use of patterned masks to reduce the size of the blast zone to the micron range. For example, Park et al. (2005) used an ultraviolet (UV) hardening polyurethane mask to produce pockets as small as 50 μm wide in metals. More recently, Billingham et al. (2013) used a high-pressure (413.7 MPa) abrasive water jet machine (AWJM) with a 1 mm diameter nozzle and 180–300 μm garnet particles to machine pockets into a titanium-based alloy (Ti_6Al_4V) using over-lapping channels. They developed a model to predict the pocket profiles, but its applicability was limited to very shallow pockets because of non-linearities in the local erosion rate and fluid flow field brought about by the steepening sidewalls.

Existing models of the erosive flows produced by ASJM have overlooked the effects of the shape of the surface profile on the flow field. For example, Fan et al. (2011) and Gnanavelu et al. (2011) used computational fluid dynamics (CFD) to simulate the impingement of a jet on a flat plate, but did not investigate flows within the machined features. Liu (2007) attempted to model the flow within a hole by approximating the cross-sectional shape as a rectangular cavity, but this simplification prevented the model from capturing a critical high velocity (low pressure) zone in the rounded region near the hole opening that was reported by Nguyen et al. (2014) who utilized more accurate hole profiles. However, Nguyen et al. (2014) considered a much lower Reynolds number and their system was on a much larger scale than ASJM; i.e. they utilized a 6.4 mm orifice compared to the 180 μm used in the present ASJM. In addition, all of these studies contained simplifications that strongly affected the predicted shapes of ASJM features; e.g., insufficient mesh density to capture velocity gradients within the boundary layer, treatment of particles as points rather than volumes, neglect of secondary particle impacts, neglect of abrasive particle size distribution, and the assumption of spherical rather than angular abrasive particles.

In summary, although ASJM has the potential to be a relatively inexpensive technology for milling flat pockets into sintered ceramics, little is known about the associated material removal mechanisms in such materials. Relevant milling studies of the past are limited to high-pressure AWJM and AJM of glass and metal targets. This paper presents an experimental study of the effects of process parameters on the shape and roughness of micro-pockets machined in sintered ceramics with and without copper-filled through-holes using, for the first time, a hybrid AJM and ASJM methodology. The observed trends were explained using CFD modeling of the slurry flow fields.

2. Experiments and flow modeling

2.1. ASJM and AJM apparatus

The ASJM apparatus used in the present work, described fully in Nouraei et al. (2014), consisted of an abrasive slurry pump (LCA/M9/11-DC, LEWA Inc., Leonberg, Germany) with a pulsation damper (FG 44969/01-9, Flowguard Ltd., Houston, TX, USA) connected to an open, stirred slurry reservoir tank.

A sharp sapphire orifice with a diameter of 180 μm having a length-to-diameter ratio of 1.67 (KMT Waterjet, KS, USA) produced a jet with a diameter of 150 μm (measured using a microscope attached to a digital camera with a field of view of 3 × 2 mm) and a free jet velocity of about 126 m/s for a typical back-pressure of 8 MPa. The jet diameter was approximately constant over the 20 mm standoff distance (i.e., the distance between the orifice and target) which was below the theoretical breakup length of 36 mm as explained in Kowsari et al. (2013). The aqueous slurry used in all