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Full Length Article

Selective removal of metallic layers from sintered ceramic and metallic plates using abrasive slurry-jet micro-machining

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ABSTRACT

Abrasive slurry-jet micro-machining (ASJM) is a low-cost and relatively quick alternative for the selective removal of metallic layers compared to conventional processes such as chemical-mechanical planarization (CMP). The present study used a computational fluid dynamics (CFD)-aided methodology with over-lapping ASJM channel machining to predict the thickness of copper and nickel-phosphorous layers that could be removed without eroding the underlying ceramic or metallic substrate.

High-viscosity soybean oil was used instead of water to eliminate undesirable erosion caused by the secondary slurry flow adjacent to the primary footprint, thereby providing better control of the areas being eroded. Experiments and CFD models showed that the much larger boundary layer thickness of soybean oil reduced the particle velocities near the surface and modified particle trajectories so that erosion was minimized beyond the primary jet footprint where the flow moved mostly parallel to the target surface. CFD models were used to explain measured variations in the specific erosion rates found in single-pass channels of varying depths, brought about by the geometry of the machining front. It was found that the greater ability of viscous soybean oil to deflect the particles prior to impact caused the machining of relatively deep channels to be uneconomical, while the opposite trend was found using water. The generalized functions for the dependence of erosion on particle impact velocity and angle were measured experimentally for electrodeposited copper and nickel-phosphorous, and then used as inputs in CFD models to obtain erosion patterns. These were then calibrated and used in an existing superposition model for the prediction of the profile of channels machined using ASJM. In summary, the present work demonstrated that ASJM can be used to selectively remove metal layers deposited on both ceramic and metal substrates by controlling the process conditions.

1. Introduction

Abrasive slurry jet micro-machining (ASJM) can machine micro-features such as pockets, channels and holes in brittle and ductile materials using a high-speed, narrow slurry jet containing fine abrasives. A useful feature of the process is its capability to erode brittle and ductile materials at different rates by controlling the process parameters. The selective removal of metallic layers is of industrial interest in many applications. For example, Kowsari et al. [1] demonstrated that ASJM can be used to selectively erode and flatten individual copper pillars protruding from the surface of a sintered ceramic wafer used as a heat sink in a microelectronics device.

Existing studies related to the abrasive erosion of coatings have been designed to assess the wear resistance of the coatings using slurry or air jets. For example, Iwai et al. [2] eroded approximately 2 μm thick titanium nitride coatings on high speed steel (HSS) substrates using a slurry jet with 1.2 μm alumina from a 3 × 3 mm square nozzle at about 100 m/s. They found that the erosion behavior changed with the coating ductility. In a similar study, Hawthorne et al. [3] subjected high velocity oxy-fuel (HVOF) sprayed ceramic and metallic coatings to 35–200 μm diameter alumina abrasives carried by either a 15 m/s slurry jet or an 84 m/s air jet. They found the specific erosion rate using the air jet was three orders of magnitude greater than using the slurry jet because of the much higher particle impact velocities in the air jet. Other related

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studies include those of Wood [4], Santa et al. [5], and Sugiyama et al. [6], but none considered the controlled removal of metallic layers from a substrate.

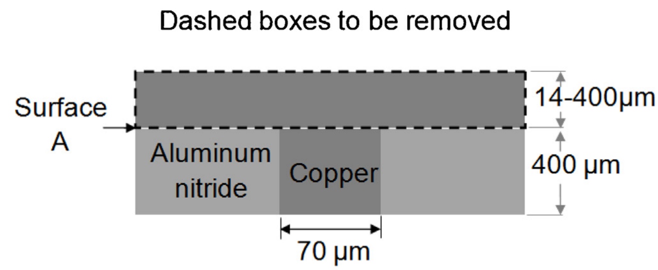
Tamannaee et al. [7] and Kowsari et al. [1] used repeated adjacent passes of the ASJM jet to mill planar areas (pockets) in talc-filled thermoplastic olefin (TPO) and sintered alumina, respectively. Billingham et al. [8] used a high-pressure (414 MPa) abrasive water jet machine (AWJM) with a 1 mm diameter nozzle and 180–300 μm garnet particles to machine pockets into a titanium-based alloy (Ti_6Al_4V) using over-lapping channels. All of these authors predicted the shape of the machined pockets using a superposition model in which the cross-sectional profile of a single-pass channel, obtained experimentally, was summed, taking into account the overlap of adjacent passes of the scanning jet. These studies limited the material removal per pass so that the shape of the single-pass channel continued to be representative of the erosion pattern for each pass of the nozzle. Prediction of the single-pass erosion pattern from first principles (e.g. computational fluid dynamics (CFD)) for use in the superposition model has not yet been attempted.

In the above-mentioned work with sintered ceramics containing copper-filled through-holes, Kowsari et al. [1] distinguished the slurry erosion in the direct footprint of a 150 μm diameter, 89 m/s ASJM aqueous jet, blasted at perpendicular incidence, from the predominately ductile erosion that occurred in the secondary slurry flow over the target surface at shallow particle incidence. The latter preferentially eroded the ductile copper-filled holes within the ceramic substrate producing unwanted dimples in the finished surface.

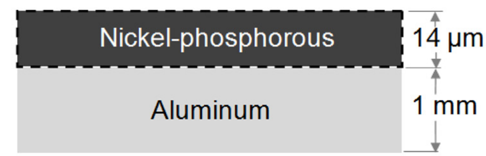
Kowsari et al. [9] found that the use of viscous fluids such as soybean oil could enlarge the boundary layer thickness of the jet over the target causing a reduced flow velocity near the opening of holes made with ASJM. This decreased the pressure drop at the hole edge thereby reducing the generation of cavitation bubbles. The authors also found that particles deflected to a much higher degree within the stagnation zone of the relatively viscous soybean oil slurry jet while machining holes, but the effect of fluid viscosities much greater than that of water on the erosion rate in ASJM channel machining remains unexplored.

Nouraei et al. [10] machined channels in brittle and ductile materials using ASJM, and found that the slope of the leading edge during channel machining decreased the effective erosion rate in glass while increasing it in PMMA. They hypothesized that a steeper leading edge decreased the local impact angles thereby reducing the erosion rate in brittle glass (maximum erosion at perpendicular incidence) and increasing it in ductile PMMA (maximum erosion at approximately 45°). However, Nouraei et al. [10] did not examine this hypothesis with CFD, and did not study the role of fluid viscosity in controlling this leading-edge effect on erosion rate.

The present objective was to explore the use of ASJM to selectively remove uniform copper or nickel-phosphorous layers and copper protrusions from sintered ceramic and metallic substrates without eroding the underlying material. Experiments were complemented by extensive computational slurry-flow modeling to understand the effects of the ASJM process parameters on the particle trajectories, the boundary layer thickness and the resulting erosion.



(a)



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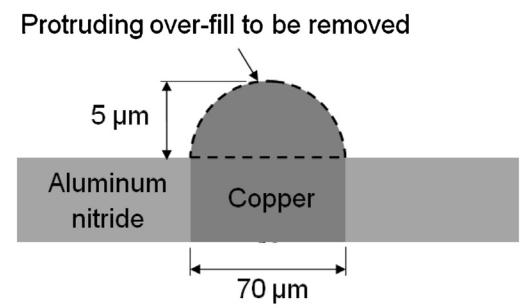

(c)

Fig. 1. Schematic section views through the 3 test specimens. (a) copper-plated aluminum nitride containing copper-filled through-holes. (b) nickel-phosphorous-plated aluminum. (c) protrusion formed due to over-filling of through-hole in aluminum nitride wafer. The dashed regions are those to be removed using ASJM.

2. Experiments and flow modeling

2.1. Target materials

The experiments involved 3 configurations of 4 materials as described in Table 1: (i) copper-plated aluminum nitride wafers containing copper-filled through-holes (Fig. 1a); (ii) nickel-phosphorous-plated aluminum substrates (Fig. 1b); and (iii) aluminum nitride containing copper pillars protruding from over-filled through-holes (Fig. 1c). The objective was to use ASJM to remove the copper or the nickel-phosphorus material within the regions indicated by the dashed lines, while leaving the substrates intact. Upon selective removal of these regions, specimens such as those in Fig. 1a and c find application as heat sinks for electronic

Table 1
Properties of the target materials, obtained from the manufacturer of aluminum nitride, from ASM [11] for aluminum, and from Zhaojiang [12] for copper and nickel-phosphorous.

Composition	Supplier	Dimensions (mm)	Grain size (μm)	Density (g/cm^3)	Vickers hardness (kgf/mm^2)
Aluminum nitride (AlN)	K170, Toshiba Corp., Minato, Tokyo, Japan	50 × 50 × 0.375	<1	3.26	1100
Electrodeposited copper (Cu)	–	50 × 50 × 0.014 50 × 50 × 0.400	–	8.96	83
6061-T6 aluminum (Al)	–	85 × 25 × 1	–	2.71	112
Electrodeposited nickel-phosphorous (Ni-P)	–	85 × 25 × 0.014	–	8.00	255