Journal of Materials Processing Technology 209 (2009) 4366–4378

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Computer simulation of developing abrasive jet machined profiles including particle interference

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ARTICLE INFO

Article history:
Received 28 June 2008
Received in revised form 29 October 2008
Accepted 15 November 2008

Keywords:
Cellular automaton
Surface advancement
Particle collisions
Abrasive jet machining

ABSTRACT

A novel and generally applicable computer simulation was developed to predict the time evolution of the eroded profiles of air abrasive jet machined surfaces, as a function of process parameters such as: abrasive nozzle size, inclination and distance to target surface, abrasive jet particle velocity, size and flux distribution. The effect of collisions between incoming and rebounding particles was included by the tracking of individual particles, performing inter-particle and particle to surface collision detection, and implementing collision kinematics. The target surface advancement was determined by representing the surface by a grid of cubic cells, each of which was assigned a damage parameter based on the number of particles impacting it. The predictions of eroded profiles of the simulation were tested against those that are experimentally measured for a typical microabrasive blasting setup, with good agreement at low particle flux, and reasonable agreement at high particle flux.

1. Introduction

In abrasive jet machining (AJM) processes, microscopic abrasive particles are accelerated in a compressed carrier gas, and fed through a nozzle to produce a jet of high velocity particles. The impact of the particle jet results in target material removal due to mechanical processes such as cutting, ploughing, and fracture. AJM has found application for etching, polishing, cutting and deburring operations. One of AJMs most important applications is the machining of micro-sized features (e.g., microchannels, microholes, etc.) in ceramics (e.g., glass, Si) and polymers for the fabrication of devices used in the microelectronic, microfluidic, and optoelectronic industries. For example, Belloy et al. (2002) have used AJM to micromachine inertial sensors, and Solignac et al. (2001) to fabricate microfluidic devices in glass. Kruusing et al. (1999) have demonstrated that AJM can also be used to rapid prototype microfluidic devices in silicon. Moreover, Black (1950) has also introduced the use of abrasive jets in dental operations, where their use instead of dental drills may make local anesthesia unnecessary.

In most applications of AJM, the depth and shape of the machined surface are of importance. Highly accurate AJM processes can be achieved by controlling various parameters such as the stand-off distance between the nozzle tip and surface, particle size, particle velocity, nozzle diameter, etc. Much attention in the literature has been focused on experimental investigation of the effects of these machining parameters on the shape and size of the erosion profile resulting from AJM. For example, Verma and Lal (1984) and Venkatesh et al. (1984) studied the effects that changes in the process parameters (e.g., stand-off distance, air/abrasive mixture ratio, particle size, etc.) have on the material removal rate. Balasubramaniam et al. (2000) performed similar empirical studies, with the aim of determining how changes in process parameters affect the radius of deburred edges. A number of analytical models have also been proposed for the prediction of the shape and size of abrasive jet machined features. For example, the model of Balasubramaniam et al. (2002) showed the effects that changes in particle size, stand-off distance and jet center line and peripheral velocity had on the resulting eroded profile. Achtsnick et al. (2005) have proposed an analytical model for the AJM process, using experimental data to characterize particle spatial distribution within the jet, compressible flow theory to model particle velocities, and indentation fracture mechanics to predict the resulting eroded profile. The model demonstrated that the nozzle configuration can affect the erosion and thus the resulting eroded surface profile. The predicted shape of the eroded profiles qualitatively matched experimentally measured ones, but the erosion rate was overestimated. In both of these models, the collisions between reflected and incoming particles (i.e., particle interference effects), and the impact angle dependency of the erosion rate, were neglected.

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doi:10.1016/j.jmatprotec.2008.11.020

Nomenclature

A_t	unit area of the target material
D	erosion rate constant
d	nozzle to surface stand-off distance
d_p	eroded depth of surface cells
d_c	distance to surface cell from initial uneroded surface
d_s	target thickness
E	erosion rate
e_{pp}	coefficient of restitution for particle–particle collisions
e_{ps}	coefficient of restitution for particle–surface collisions
f	friction coefficient
f_n	particle launch frequency; i.e., the number of particles per unit time launched from the nozzle
$f(\Theta)$	function describing the dependence of erosion rate on incident angle
$G(\varphi)d\varphi$	probability of a particle being launched in the plane of the nozzle at an angle between φ and $\varphi+d\varphi$
$H(r_p)$	particle distribution function for radii of the blasted powder
h	thickness of a surface cell
Hv	ductile target surface hardness in GPa
k	erosion rate velocity exponent
m_1, m_2	masses of impacting spherical particles
n	number of surface cell impacting particles
n_1, n_2	ductile target erosion rate constants
N_c	number of target cells removed in a given time period
$P(r)dr$	probability that particles arrive to the target surface between r and $r+dr$
r	radial coordinate on the target surface from the nozzle centerline
r_c	cutoff radius at which the majority of particle arrive to surface
r_l	radial location on nozzle cross section at which a particle is launched
r_n	nozzle radius
r_p	particle radius
$v_p(r)$	particle velocity at a given r
v_s	scan velocity of target relative to stationary nozzle
Vol_p	volume of particles hitting the surface
Vol_s	volume of target material removed
α	nozzle orientation angle
β	nozzle focus coefficient
Δt	time period
Δl	depth to which surface area A_t is eroded in time Δt
ρ_p	particle density
ρ_s	target density
θ	angle between particle trajectory and nozzle centerline
η	angle between the resultant impulse ratio and the axis in the tangent plane
μ	impulse ratio for particle–surface collisions
Θ	angle between particle incident velocity vector and local normal to surface
σ, ζ	parameters used in the log normal distribution of the particle size

In the context of abrasive jet micromachining operations, Slikkerveer and in't Veld (1999) and ten Thije Boonkkamp and Jansen (2002) have proposed more generally applicable analytical models which consider the impact angle dependency of erosion rate, and allow for variations in particle flux and velocity distribution. These surface evolution models, valid for systems which erode in a 'brittle' manner, reflect the fact that for such systems, the local erosion rate depends on only the component of the particle flux and velocity that is locally perpendicular to the surface. The time dependent eroded surface profile, i.e., the eroded surface advancement, can be obtained by solution of a partial differential equation. When implemented for a system in which an abrasive jet was blasted through a small linear or circular opening in an erosion resistant mask, the models gave eroded channel and hole profile shapes that initially agreed reasonably well with those measured experimentally, under very low particle flux conditions. For deeper profiles, the models deviated significantly from experimental results in both depth and shape. An improvement in the estimation of the variation of flux as the mask edges were approached was implemented into the model of ten Thije Boonkkamp and Jansen (2002) by Ghobeity et al. (2008a), yielding somewhat better results. Recently, Getu et al. (2007) have extended this model to systems eroding in a ductile manner (i.e., with an erosion rate that depends on both the normal and tangential components of particle flux), also with reasonable results. Ghobeity et al. (2007) also implemented the model with computer particle tracking techniques in order to study the effect of particle ricochet from the edges of non-eroding masks in abrasive jet micromachining applications. None of these models, however, considered inter-particle interference effects; i.e., the change in surface particle flux due to collisions between incoming and rebounding particles.

Very recently, Yagyu and Tabata (2008) have implemented a cellular automata technique to predict the shape of an abrasive jet micromachined microchannel and the surrounding polymeric mask. The technique demonstrated a good qualitative agreement of eroded mask and machined channel shape with experiments; however, a direct quantitative comparison with experimentally obtained channel profiles was not made. Moreover, the algorithm does not allow for non-uniform particle spatial distribution, non-perpendicular jet orientation, and does not take into account particle scattering, second strike, and interference effects.

Since all existing surface evolution models do not consider particle interference effects, their application has been limited to extremely low incident particle fluxes, where these effects are negligible. Analytical solutions are intractable in the high flux case, because particle interference effects are instantaneously coupled to the surface profile; i.e., the direction of particle ricochet from the surface depends on the instantaneous shape of the surface, which, in turn, depends on the trajectories of previously scattered particles. Despite the possible benefit of a more rapid machining rate, there is presently no technique available for the prediction of the eroded surface profile for the high flux case, described, for example, by Papini et al. (2003). Moreover, none of the models present in the literature allow the prediction of the abrasive jet machined surface shape for the case where a nozzle is oriented obliquely to the surface, despite the demonstrated (Belloy et al., 2001) promise of this oblique incidence technique for machining complex 3D structures.

Abrasive jet micromachining without the use of masks is of importance when fabricating relatively large features. For example, Ghobeity et al. (2008b) showed that multiple, staggered nozzle passes can be superimposed to produce planar areas, or V shaped features, without using a mask. This paper describes a novel and generally applicable computer simulation which can be used to predict the time dependent eroded profile resulting from unmasked abrasive jet machining operations at normal or oblique incidence on both ductile and brittle erosive systems, including the effect of particle interference under high incident particle flux conditions.