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Process Modeling and Simulation of Abrasive Jet Machine-A Review

KEYWORDS: Abrasive jet machining, finite element modeling, particle impact, erosion mechanism

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ABSTRACT *The demand for macro and micro products and component is rapidly increasing in industries of automotive parts, aerospace component, electronics devices, medical instruments and communications. These industries require materials such as tool steel, carbides, super alloys and titanium alloys which are difficult to machine materials. Due to the machining challenges these materials seem to have limited applications. Abrasive jet micromachining (AJM) is one of the most appropriate micromachining technologies for hard and brittle materials. This paper presents a brief review of research and developments in modeling in AJM, surface roughness and effect of material properties on erosion rate. Recent development in finite element modeling of abrasive jet machining is also reviewed.*

INTRODUCTION

Abrasive jet micromachining (AJMM) is a non-traditional machining technology that can effectively remove hard and brittle materials at high quality. In which material removal occurs as the result of a large number of impacts of either.

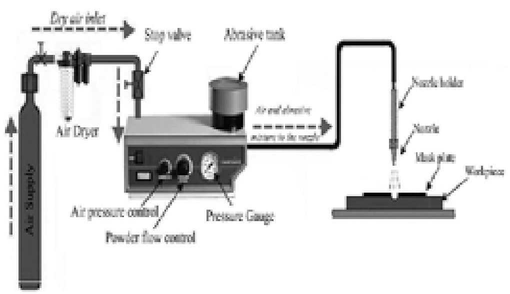

Fig. 1. Typical AJM process.[1]

Spherical or irregular angular particles, as the particles are usually carried in pressurized fluid streams.

AJM is different from shot or sand blasting, as in AJM, finer abrasive grits are used and parameters can be controlled more effectively providing better control over product quality. The kinetic energy of the abrasive particles would be sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives. The material removal mechanism in AJM process is achieved by means micro plastic deformation in ductile materials and by means of crack propagation in case of brittle or ceramic material. A modeling of AJM process is necessary to determine the velocity of abrasive particles.

Abrasive jet Machining consists of

1. Air supply system
2. Abrasive tank
3. Control unit
4. AJM Nozzle
5. Abrasives

Air supply system supplies clean and dry air. Air, Nitrogen and carbon dioxide to propel the abrasive particles. Gas may be supplied either from a compressor or a cylinder. In case of a compressor, air filter cum drier should be used to avoid water or oil contamination of abrasive powder. Gas should be non-toxic, cheap, and easily available. It should not excessively spread when discharged from nozzle into atmosphere.

Required quantity of abrasive is supplied by abrasive tank. Control unit is used to control the feed rate of abrasive powder and the air pressure. AJM nozzle is usually made of tungsten carbide or sapphire which has resistance to wear. The nozzle is made of either circular or rectangular cross section and head can be straight, or at a right angle. It is so designed that loss of pressure due to the bends, friction etc is minimum. With increase in wear of a nozzle, the divergence of jet stream increases resulting in more stray cutting and high inaccuracy.

For successful utilization of AJM process, it is necessary to analyze the different process criteria like material removal rate ,geometry, surface finish and material property of workpiece, wear rate of the nozzle etc.

AJM PROCESS MODELING AND SIMULATION

In AJM process estimation of erosion rate is essential and erosion rate depend on process parameters such as stand-off distance between nozzle-tip and target surface, particle velocity, particle shape and size, mass flow rate of particle. Therefore AJM modeling involves set of pressure, velocity and inertial mass equations.

S. Dhar et al.[2] has performed an experiments to approximate the erosion rate of aluminum alloy by impacts of well-defined hardened steel angular particles on it. Fundamental mechanisms of material removal are identified, and measurements of incident and angular velocity of single hardened steel particles are captured by a high speed digital camera setup. Result has a good agreement with a rigid-plastic theory based computer simulation.

The theoretical model for impact of rigid angular particles with fully-plastic targets has presented by M. Papini et al. [3] with the purpose of estimating crater size, shape, and rebound parameters as a function of incident particle velocity, angle, orientation, and shape. They predicted the effect of varying input parameters on the amount of target material removed.

Crater volume per unit width is also examined as a function of particle side length, angularity, initial particle orientation, initial velocity, target dynamic hardness and friction coefficient by earlier authors [3, 4]. And the predicted result shows that very low coefficients of friction produce negligible changes in crater volume as compared to the frictionless case at all angles of attack as well as highly angular particles will create the largest craters on the target surface.

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Effect of work piece properties on machinability in abrasive jet machining of ceramic materials has been studied by M. Wakuda et al.[5] A micro-blaster was used for the machining experiments. This machine is capable of shooting fine, hard abrasives along with a pressurized nitrogen gas stream and result shows that the radial cracks did not propagate downwards by particle impacts during the machining process. AJM process exhibits high potential of a damage-free micromachining method for ceramic materials.

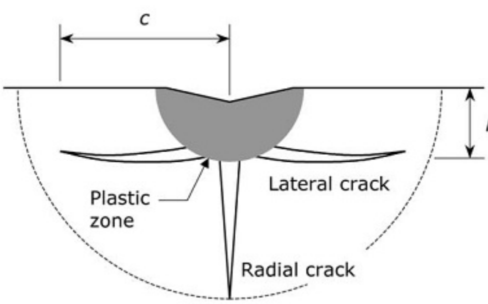

Fig. 2. Crack system when subjected to the indentation with a sharp indenter. [5]

Simulation of interference effects in particle streams following impact with a flat surface presented by D. Ciampini et al.[6] deals with the interference between an incident stream of spheres and those rebounding from a flat surface is described using a

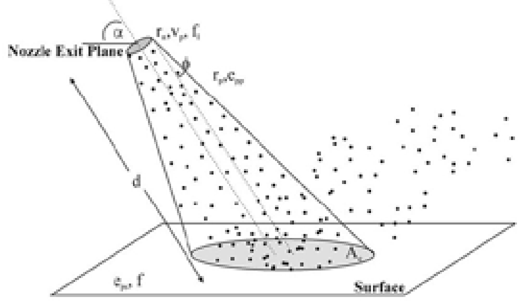

Fig. 3. Definitions of parameters modelled in simulation. [6]

computer model. The model was capable of examining the effect of stream angle of incidence, nozzle divergence angle, incident particle velocity, flux, particle size, particle–particle and particle–surface impact parameters, and stand-off distance. they found that over 90% of the damage occurred in the region directly below the nozzle.

The computer model described for parametric study of effect of varying inputs on availability of power at the surface, and implicit conclusion drawn by D. Ciampini et al. [7] and the friction coefficient for particle–surface collisions, was found to have a negligible effect. It is applicable in shot peening and blast cleaning application.

In modeling of AJM process determination of abrasive particle velocities is essential. H.Z. Li et al. [8] has done theoretical analysis for particle velocities in micro- abrasive air jet. The particle velocities at the nozzle exit are determined based on the nozzle length, particle mean diameter, particle density, air density and air flow velocity. The velocities of particle in the centerline of stream after leaving the nozzle is modelled based on surrounding air and particle interaction numerical solution for same is also developed.

In the abrasive jet machining process the surface roughness is also important criteria in micro fluidic channels. A implementation of narrow band level set methods was presented by T. Burzynski et al. [9] for the surface evolution of masked micro-channels made by glass and poly-methyl-methacrylate (PMMA) using abrasive jet micro-machining (AJM) at inclined impact angle of particle. A level set method is a sturdy numerical technique used to calculate the gradual development of dynamic surfaces.

Dependency of erosion rate on abrasive jet inclination angle for aluminum alloys and stainless steel materials at specific velocities are measured by S. Ally et al. [10] where the model used is originally developed for glass and polymers. A surface evolution model for estimate erosion rate has developed for brittle and ductile materials by introducing relationship between the erosion rate and angle of attack. Since the erosion rate is dependent on both the normal and tangential incident velocity components. Erosion testing is a function of impacting particle and jet nozzle parameters. The model for interference effects of particle and target plate has developed by M. Papini et al. [11]. The model was capable to simulate the wide variety of blasting parameters. They found that erosion of brittle materials by hard, solid micro-particles is a consisting of many different and connected process in which material is erode from the target surface by brittle fractures. A key function of particle impact parameters, target material properties, and the major process parameter are used by J.M. Fan et al.[12] to develop a model to predict the erosion rate.

FINITE ELEMENT ANALYSIS OF AJM

Advantage of the finite element (FE) model of abrasive jet machining is that it is easy to measure the residual stress and the depth of penetration which are quite difficult in experimental procedure. Yu-Fei Wang et al. [13] has developed a 3D computational model of erosive wear. The model is capable to find the erosive wear at variety of inclination angle and velocity of the abrasive particle. The explicit dynamic finite element method is used in the erosion model, in which material has been divided in many small finite elements and through the dynamic calculations the failure element is removed from the model immediately.

An improved computer simulation model of particle second strike has been introduced by A. Ghobeity et al.[14] in abrasive jet machining. The effect of second strike of the particle on the surface is become insignificant in case of large thickness of mask. This is due to the very large quantity of particles that strike against a mask edge, rebound on the thick mask wall on the opposite side and cannot reach the exposed surface. Sometimes its happen due to the inter collision of particle in the stream leaving the jet nozzle.

A 2D finite element model for single impact study of angular particle on ductile target has been developed by M. Takaffoli et al. [15]. The experimental and simulated result shows that the material pileup and chip separation for impacts of rhomboidal particle on copper target can be predicted by presented finite element model. The explicit finite element code LS-DYNA 971 was used in order to preserve solution stability model require very small time step size.

As a function of process parameters such as: abrasive nozzle size, inclination, standoff distance, particle velocity a computer simulation model was developed by N. Shafiei et al.[16]. The model is used to predict the time evolution of eroded profiles of abrasive jet machined surfaces. The model was tested through experiments on brittle erosive system and ductile erosive system by making holes and channels on brittle and ductile materials.

M. Takaffoli et al. [17, 18] has model highly irregular realistic particle geometries based on measurement of the particle surface area, circular diameter, sphericity and thickness of aluminum oxide powder. The multiple particle impacts on target material with non-overlapping and overlapping simulations was presented. The simulation has been done with smooth particle hydrodynamics (SPH) model at oblique and

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normal incidence of particles.

Abrasive jet micro-machining (AJM) is used to machine micro-features such as: holes and channels in brittle and ductile materials. However, the roughness of machined surface using AJM is generally more than other non-conventional techniques of micro-machining such as wet etching. R. Haj Mohammad Jafar et al. [19, 20] has attempted experiments to get smooth machined surface on unmasked borosilicate glass in AJM by varying shapes and size of abrasive particles at different angle of attack.

CONCLUSIONS

The conclusions reached in this study can be summarized as follows:

1. The effect of varying input parameters on amount of target material removed can be examines by analyzing collision between arbitrarily shaped rigid particles and flat target material.
2. An upper limit to crater volume is independent of particle angularity in the frictionless case, and dependent on initial particle orientation and angularity in constant friction case.
3. The maximum erosion rate occurred between impact angles of 20°-30° on aluminum, stainless steel and titanium alloy using abrasive jet machining.
4. The fracture toughness and hardness of the target materials are critical parameters affecting the material removal rate in AJM.
5. When the jet nozzle radius is greater than 15 times the particle radius, the most important parameters affecting interference between a stream of incident and rebounding spheres were angle of attack, stream density, and coefficient of restitution for particle surface collisions. The friction coefficient for particle–surface collisions was found to have a negligible effect.
6. The finite element methods for the modeling of solid particle erosion in ductile materials can model using material pile up and chip formation techniques.
7. Particle tracking and collision kinematics can be used to predict the abrasive jet machined profile in abrasive jet operations.

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