Powder Technology 268 (2014) 150–157

Contents lists available at ScienceDirect

Powder Technology

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

A study on the vibration induced transport of nanoabrasives in liquid medium

Sagil James, Murali M. Sundaram *

Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221, USA

ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 14 August 2014
Accepted 14 August 2014
Available online 23 August 2014

Keywords:
Abrasive machining
Acoustic streaming
Cavitation
Nanopowder

ABSTRACT

Vibration Assisted Nano-Impact-machining by Loose Abrasives (VANILA) is an emerging process suitable for the target specific nanomachining of hard and brittle materials. Understanding the transport of nanodiamond powders in fluid is essential to determine the effective gap between the tool and the work surface in VANILA process. In this paper, various forces acting on the abrasive nanoparticle in aqueous slurry are analyzed. It is understood that transient cavitation force and acoustic streaming forces have the most dominating effects in causing the nanoparticle impact on the workpiece surface. A model to predict the impact velocity of the nanoabrasive grain on the workpiece surface is developed and it is found that during the machining process, an impact velocity in the order of 10^2 m/s is achieved. molecular dynamics simulation (MDS) is used to simulate the nanoparticle transportation during the process. The MDS study reveals that the machining gap during the VANILA process needs to be maintained at less than 200 nm for an abrasive grain size range of 5–20 nm. The MDS results are in conformance with the theoretical modeling results.

1. Introduction

Machining using abrasive powders is a time tested material removal method applicable for a wide range of materials, especially hard and brittle advanced engineering materials. Addition of vibration to the tool or workpiece is found to be very effective in performance enhancement of abrasive machining processes. Recently, a novel nanomachining process "Vibration Assisted Nano-Impact-machining by Loose Abrasives (VANILA)" has been developed which exploits the potential of loose nanopowders suspended within a fluid for target-specific material removal of hard and brittle materials [1]. The VANILA process is conducted on an atomic force microscope (AFM) as the platform and a slurry of nanodiamond powders smaller than 10 nm which is introduced between the tool and the workpiece. The tool used is a tapping mode AFM tip and it is vibrated constantly while maintaining a constant distance from the workpiece as shown in Fig. 1a. This results in continuous hammering of suspended nanodiamond powders which in turn impact the workpiece surface repeatedly resulting in nanoscale material removal (Fig. 1b and c). The feasibility of nanoscale machining using the VANILA process was successfully demonstrated on hard and brittle materials such as borosilicate glass and silicon. Patterns of nanocavities were successfully machined to demonstrate the controllability and repeatability of the process as shown in Fig. 2 [1].

The material removal during the VANILA process is happening due to the impacts of the sharp nanoabrasive particles on the workpiece surface [2]. This paper investigates the *forces involved* in the transport of nanoabrasive powder in liquid to estimate the velocity of impact of the nanopowder on the workpiece surface and determine the effective gap between the tool and the work surface for the given machining conditions. A theoretical approach is used to model the nanoscale forces and predict the velocity and penetration depth of the abrasive powder within the liquid medium and the model is verified using a 3-D molecular dynamics simulation (MDS).

2. Prediction of nanopowder velocity and penetration depth in liquid medium

During the VANILA process, nanodiamond powder is dispersed in the liquid and the vibration of the tool at resonance introduces an acoustic field into the slurry medium [3,4] which leads to movement of the nanoparticles. The combination of various forces experienced by the abrasive nanoparticle determines its motion towards the workpiece surface. Therefore, in order to predict the behavior of the nanoparticle in suspension passing through an acoustic field, the forces experienced by the particle need to be quantified. The following section describes the main forces influencing the nanoparticle dynamics within the nanofluid. Since the derivation of exact expressions for the forces acting on the nanoabrasive particle during the machining process is too difficult and beyond the scope of this study, order-of-magnitude estimates

* Corresponding author. Tel.: +1 513 556 2791; fax: +1 513 556 3390.
E-mail address: murali.sundaram@uc.edu (M.M. Sundaram).

http://dx.doi.org/10.1016/j.powtec.2014.08.032
0032-5910/

Nomenclature

Tool variables

f_t	frequency of vibration of tool (kHz)
A_t	amplitude of vibration of tool (nm)
V_t	velocity of tool tip (m/s)
E_t	elastic modulus of tool material (GPa)
ν_t	Poisson's ratio of tool
a_t	maximum acceleration at tool tip (m/s^2)
k_t	spring constant of tool (N/m)
Q_t	quality factor of tool
R_t	radius of tool tip (nm)

Process parameters/ operating variables

t	time (s)
T	bulk temperature (K)
F_{impact}	tool impact force (pN)
F_{drag}	viscous drag force (pN)
F_{grav}	gravitational force (pN)
I	ultrasonic energy flux (J·m^{-2}·s^{-1})
V_{Th}	thermophoretic velocity (m/s)
$\dot{\gamma}$	shear rate (s^{-1})
∇T	temperature gradient (K/m)
k_{El}	equivalent elasticity constant
$damp$	damping factor (fs)
γ	proportionality constant

Abrasive grain variables

E_a	elastic modulus of abrasives (GPa)
R_a	radius of abrasive grain (nm)
ρ_a	density of abrasive grain (kg/m^3)
ν_a	Poisson's ratio of abrasive grain
V_a	velocity of abrasive grain (m/s)
Ω_a	Ang. velocity of abrasive grain (rad/s)
k_a	thermal conductivity of grain (W/mK)
ϕ	volume fraction of abrasive grains
m_a	mass of abrasive grain (g)

Fluid variables

μ_{fl}	dynamic viscosity of fluid (kg/(m.s)
ν_{fl}	kinematic viscosity of fluid (m^2/s)
ρ_{fl}	density of fluid (kg/m^3)
K_n	Knudsen number
V_{fl}	velocity of fluid (m/s)
k_{fl}	thermal conductivity of fluid (W/mK)
P_c	cavitation shockwave pressure (MPa)

Constants

g	acceleration due to gravity (m/s^2)
k_B	Boltzmann constant (J/K)
c	speed of sound (m/s)

of the individual forces acting on the nanoabrasive grains are considered to determine their degree of influence.

2.1. Analysis of forces on the nanopowder in liquid medium

Several nanoscale forces could arise due to the relative motion and also the size effect of the nanodiamond abrasive grains moving within the liquid medium. The forces that could influence the motion of the abrasive nanopowder have been identified as: tool impact force, acoustic radiation force, acoustic streaming forces, gravity force and Brownian force [5,6]. Several other nanoscale forces such as inertial forces, thermophoresis, hydrophobic effects, Van der Waals force, electrostatic force, Casimir force and molecular surface forces are not considered in this study as they are less significant. The modeling of individual forces is described below.

2.1.1. Tool impact force

The tool used in the VANILA process is a tapping mode AFM probe which consists of a cantilever with a conical tip having a nanoscale radius. The tool is acoustically driven by a piezoelectric element at the fundamental resonant frequency of the tip. The oscillatory motion of tool tip used in the VANILA process can be expressed as $A_t e^{i(\omega t+\pi/2)}$ as shown in Fig. 3. The phase associated with the total force is considered as π/2 due to the fact that machining is conducted at resonance frequency and since on resonance the oscillations of the cantilever follow the total force with a phase delay of π/2 [7]. The drive force will generate acceleration (a_t) at the tool tip perpendicular to the workpiece surface, resulting in impact onto particles coming into contact with the tool tip. This tool impact force (F_T) can be estimated as [8]

$$F_T = m_a a_t. \tag{2.1.1a}$$

As a general rule, nanoparticles having very small aspect ratio (<2) can be considered as spherical for nanoscale force calculations. Thus, for a single particle having radius R_a, the mass of the abrasive particle m_a can be written as

$$m_a = \frac{4}{3}\pi R_a^3 \rho_a. \tag{2.1.1b}$$

The maximum acceleration (a_t) at the tool tip can be expressed as

$$a_t = 4\pi^2 f_t{}^2 A_t. \tag{2.1.1c}$$

The acoustic power generated at the tip which is excited at its resonant frequency can be found as [9]

$$P_t = \frac{\pi k_t A_t^2 f_t}{Q_t}. \tag{2.1.1d}$$

The vibration intensity of the acoustic waves generated at the tool tip can be calculated by dividing the acoustic power by the area of the radiating surface which is the tool tip surface area [10].

$$I_t = {}^{P_t}\!\big/_{(\pi R_t^2)} \tag{2.1.1e}$$

2.1.2. Acoustic radiation force

The mechanical vibration of the tool in the vicinity of the slurry could generate acoustic waves in the bulk of the nanofluid slurry, thus transmitting acoustic radiation through the slurry. The acoustic radiation leads to momentum transfer between the neighboring particles and consequently, every single nanoabrasive grain starts to oscillate about its mean position at driving frequency. These acoustic radiation forces (F_R) affect the motion of the nanoparticles in the vicinity of the tool. The acoustic radiation force instantaneously drives the nanoabrasive particles near its vicinity towards the workpiece surface with a unidirectional displacement [11]. For particles much smaller than the wavelength of acoustic waves as in the case here, the acoustic radiation