NUMERICAL SIMULATION OF DUCTILE MACHINING OF SILICON NITRIDE

Thimmaiah G.Kumbera, John A.Patten*, Harish P. Cherukuri
University Of North Carolina at Charlotte
Charlotte NC 28223 USA

Christopher J.Brand, Troy D.Marusich
Third Wave Systems
Minneapolis, MN 55439 USA

Abstract: Recent experiments into the ductile-regime machining of Silicon Nitride have confirmed that Silicon Nitride behaves in a ductile manner under high pressure and micrometer depths of cut. This paper reports results from a series of numerical simulations carried out to model and understand the ductile machining of Silicon Nitride. The cutting process is modeled using the commercial software package ADVANTEDGE. Effects of various parameters like cutting speed, feed, rake angles and tool tip radius that favor brittle-to-ductile transitions are the focus of the parametric study. Feed, tool tip radius and depth of cut are in the range of tens of microns while speeds are in the range of 1m/min to 300m/min. Results from this study indicate that ductile cutting may be possible at high speeds, small tool tip radii, high negative rake angles and small depths of cut.

Keywords: Silicon Nitride, High pressure phase transformation, Diamond turning, Simulation, Brittle to ductile transition.

1. Introduction

Brittle materials, by their inherent properties, are difficult to machine while maintaining the desired surface roughness. Recently, single point machining techniques such as laser assisted machining and diamond turning of brittle materials like Silicon Nitride (Si_3N_4) have been reported as an alternative to finishing processes such as grinding and polishing [2,3]. Ductile machining of brittle materials, where material removal is by plastic deformation is possible at very low material removal rates, usually in the micrometer range [7,8]. The ductile behavior of nominally brittle materials is due to high-pressure phase transformations at the tool-chip interface and is metallic in nature [6]. For the Silicon Nitride samples reported in this paper, phase transformation occurs under hydrostatic stress state conditions at approximately the hardness value of 22GPa. In addition, brittle fracture can also occur during machining. Such fractures can occur at two zones relative to the tool – in front of the tool, where chip formation occurs due to a compressive stress field and in the wake of the tool due to a trailing tensile stress field [4]. Brittle behavior in front of the tool is governed by rake angle and the uncut chip thickness and may not cause surface cracks as the fracture is sometimes constrained inside the chip. Brittle behavior behind the tool typically occurs at a threshold value of depth of cut and causes extensive surface and subsurface damage.

This paper reports a series of numerical results from a parametric study carried out to model the ductile regime machining of Silicon Nitride. The commercial general purpose machining software ADVANTEDGE [1,5,9] is used to model the process. The constitutive model assumes ductile material behavior and does not include phase transformation or brittle fracture models. However, it is expected that the numerical results will provide information on the threshold values for ductile to brittle transition as a function of various parameters like rake angle, tool tip radii, cutting speeds and feed.

2. Finite Element Model

The machining of silicon nitride is modeled as an orthogonal cutting process assuming plane strain conditions. A schematic of the tool-workpiece configuration is as shown in Figure 1, where the v is the cutting velocity, r the tool tip radius, f is the feed, α and β the rake and clearance angles respectively. The length of the workpiece is l and the height is h.

* Corresponding author. Email: patten@uncc.edu

The commercial finite element package ADVANTEDGE from Third Wave Systems is used for the numerical simulations. ADVANTEDGE is a Lagrangian finite element package used for two-dimensional modeling of orthogonal cutting. The element topology used is a six-noded quadratic triangle element with three corner and three midsize nodes. Continuous adaptive remeshing is used to correct the problem of element distortion due to high deformations. The larger elements are refined and smaller elements coarsened at regular intervals.

For the model, Si_3N_4 is assumed to behave in a ductile manner. The material behavior is modeled by using the constitutive equation,

$$\left(1+\frac{\dot{\varepsilon}^{p}}{\dot{\varepsilon}^{p}_{o}}\right)=\left[\frac{\bar{\sigma}}{g\left(\varepsilon^{p}\right)}\right]^{m_1} \quad \text{for } \dot{\varepsilon}^{p} \le \dot{\varepsilon}^{p}_{t}$$

$$\left(1+\frac{\dot{\varepsilon}^{p}}{\dot{\varepsilon}^{p}_{o}}\right)\left[1+\frac{\dot{\varepsilon}^{p}_{t}}{\dot{\varepsilon}^{p}_{o}}\right]^{\frac{m_2}{m_1}}=\left[\frac{\bar{\sigma}}{g\left(\varepsilon^{p}\right)}\right]^{m_2} \quad \text{for } \dot{\varepsilon}^{p} > \dot{\varepsilon}^{p}_{t} \qquad (1)$$

where the function g (ε^p) accounts for the thermal softening and strain-hardening effects and the function $\theta(T)$ is the thermal softening function.

Only strain hardening effects are considered in this paper. Thus the strain rate sensitivity exponent's m_1 and m_2 are set to large values in equation (1). Thermal softening effects are neglected until the temperature reaches the cutoff temperature.

The material model for Si_3N_4 is as given by Table 1. Cutting tool material is single point diamond which is assumed to be elastic and the material properties are E = 1.2E+12 Pa, $\nu = 0.2$, $\kappa = 1500$ W/m-^{0}C, c = 471.5 J/Kg-^{0}C, ρ=3520 Kg/m^3. The work tool friction coefficient value is 0.4 and is modeled as per Coulomb friction law.

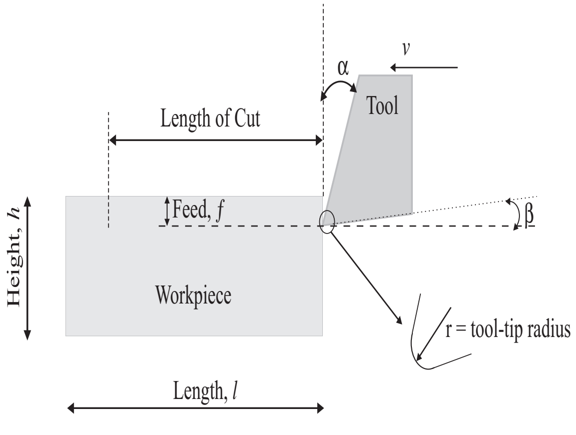

Figure 1. Schematic orthogonal cutting model used for numerical simulations.

E	3.1E+11Pa
ν	0.27
κ	26 W/m-^{0}C
c	800 J/Kg-^{0}C
ρ	3210 Kg/m^3

$\dot{\varepsilon}^{p}_{0}$	1 /s
$\dot{\varepsilon}^{p}_{t}$	1E+7 /s
m_1,m_2	300
ε^{p}_{0}	0.006
n	5
σ_0	1E+10

C_0	1.0
C_i, $1 \leqslant i \leqslant 5$	0
T_{cut}	1800^{0}C
T_{melt}	2500^{0}C
T_{ref}	0^{0}C

Table 1. Material Properties of Si_3N_4 used in numerical model.

3. Numerical Results

3.1 Effect of Cutting Speed

The parameters for the study of effects of cutting speed are: feed=20μm, rake angle=0^0 and tooltip radius=10μm. Figure 2 shows the corresponding maximum temperatures and pressures. Temperatures increase as the cutting speed increases. The maximum temperature distribution is along the shear plane and varies from 300^{0}C at low speeds to melting temperatures at high speeds. Pressure plots indicate that phase transformation pressures of 20GPa are possible at higher speeds. Hydrostatic pressure distribution into the workpiece as a percentage of feed increases with increase in cutting speeds, i.e., the zone of high pressure increases in extent. The fluctuation of temperature and pressure between the speed ranges of 5m/min to 15m/min is possibly due to mesh density. This is currently being studied. Figure 3 shows the plot of machining forces as a function of cutting speed. Cutting forces decrease with decrease in cutting speeds. Thrust forces increase marginally as speed is increased.

3.2 Effect of Feed

The effect of feed was studied setting the parameters as: cutting speed=6m/min, tooltip radius=10μm, Rake angle= 0^0. Maximum temperatures and pressures are plotted as a function of feed in Figure 4. As the feed increases, maximum temperatures increase while maximum pressure values do not change significantly. This marginal change in pressure values is possibly due to numerical approximation. The machining forces are plotted as a function of feed in Figure 5. Cutting forces increase with the increase in feed due to an increase in chip load. Thrust forces follow a minimally increasing trend.

3.3 Effect of Rake Angle

The effects of rake angle are studied at speed=300m/min, tooltip radius=1μm, feed=10μm. Figure 6 shows a plot of maximum temperature and pressure. Maximum temperatures are along the shear plane and are close to melting temperature. This may be due to the high speed at which the simulation was run. Temperatures decrease with high negative rake angles. The fluctuation of temperature is possibly due to numerical approximation. Pressures show a gradual increase as rake angle is decreased from 15^0 to -45^0. Values for pressure at -45^0 approach the phase transformation pressure of 20GPa indicating more efficient machining at high negative rake angles. Machining forces as a function of rake angles are shown in Figure 7. Cutting and thrust forces increase with decrease of rake angle with a crossover at -45^0.

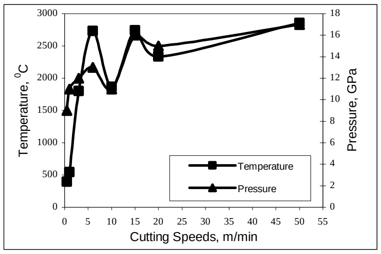

Figure 2. Maximum temperature and pressure plot for varying cutting speeds.

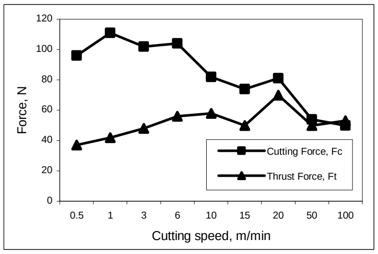

Figure 3. Maximum cutting and thrust force plot for varying cutting speeds.

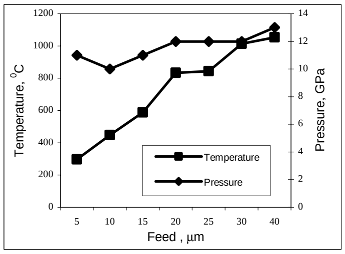

Figure 4. Maximum temperature and pressure plot for varying feeds.

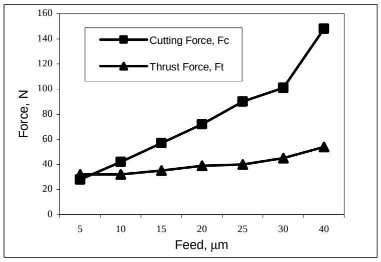

Figure 5. Maximum cutting and thrust force plot for varying feeds.

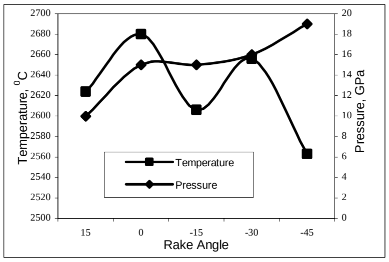

Figure 6. Maximum temperature and pressure plot for varying rake angles.

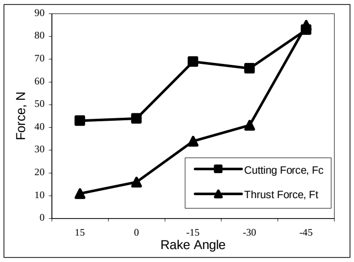

Figure 7. Maximum cutting and thrust force plot for varying rake angles.

3.3 Effect of Tooltip Radius

The effect of tooltip radius are studied by setting speed=1m/min, feed=70μm, Rake angle= -45^0. Figure 8 shows the maximum temperature and pressure values as a function of increasing tool tip radius. Temperatures in general decrease with the increase in tooltip radius. Pressures increase with decrease in tooltip radius indicating that brittle-ductile transition due to high-pressure phase transformation is possible at small tooltip radii. This decrease in pressure for larger tooltip radius is expected since this is analogous to cutting with a blunt tool. Figure 9 shows the plot of machining forces. While the cutting forces show a marginal change in values, thrust forces increase slightly with increasing tooltip radius.

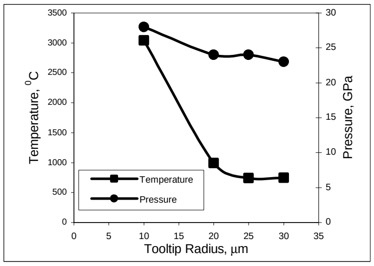

Figure 8. Maximum temperature and pressure plot for varying tooltip radius.

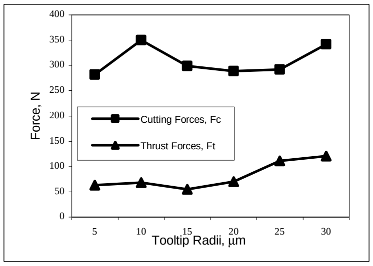

Figure 9. Maximum cutting and thrust force plot for varying tooltip radius.

4. Discussion

Ductile-regime orthogonal cutting (single point diamond turning) of Silicon Nitride is modeled parametrically to study the effects of various machining parameters such as cutting speed, feed, rake angles and tooltip radius on the process. Results indicate that for small values of feed, small tooltip radius and at high speeds, conditions of pressure and temperature exist that facilitate ductile behavior during machining. Negative rake angles are more likely to cause a brittle to ductile transition when compared with the positive or zero degree rakes.

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