PREDICTIVE MATERIALS-INFLUENCED FORCE MODEL IN THE DUCTILE-REGIME MACHINING OF POLYCRYSTALLINE BRITTLE MATERIALS

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ABSTRACT

A new modeling approach has been introduced in this paper to predict the forces in the ductile-regime machining of the polycrystalline brittle materials. The materials-influenced force model did incorporate, for the first time, material microstructural attributes in a tentative to increase the accuracy of the predictions and to allow the resulting material bulk properties to be computed based upon process mechanics. The influences of the average grain size prior to machining and the initial crystallographic orientation have been incorporated into the physics-based model prediction of flow stress of the materials, thus affecting the machining stress distributions and the machining forces. Experiments have been executed to validate the model results. This model presented a case study to evaluate the importance of the influence of microstructural attributes on the modeling in the field of manufacturing.

KEYWORDS

Microstructure, forces, modeling, grain size, brittle, ductile

1. INTRODUCTION

In the precision micromachining applications the process parameters such as feed, depth of cut, etc. are of the same order of magnitude as the microstructure attributes such as grain size as shown in Figure 1. Hence, establishing a prediction model for forces where the microstructure is incorporated is therefore important. The brittle materials are used more and more in specific application such as semiconductor and the microelectronic area. The plastic deformation of these materials have been studied and reported recently by [1]. No exciting model was able to capture the physics of this industrial problem accurately. The materials-influence manufacturing is here introduced as a technique that is integrating the materials behavior in the manufacturing process modeling. In most of micromachining processes, the amount of forces and temperature generated are not enough to reach an energy threshold to activate material evolution. In this study, the microstructure is therefore captured statically. This means that the initial bulk material microstructure state is investigated experimentally and used as an input to evaluate the flow stress. The obtained flow stress is therefore used in the prediction of the cutting forces.

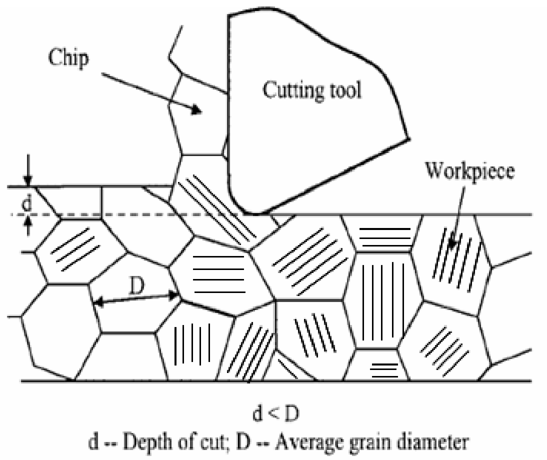

Figure 1. Configuration of micromachining operation

In this paper, a materials-influenced force model to predict the cutting force has been developed to predict the force in the ductile-regime cutting of brittle materials. The model was based on initial grain size, initial grain orientation and the grain boundaries. The efficiency of the materials-influenced methodology is validated experimentally appropriate.

2. INFLUENCE OF MICROSTRUCTURE ON PROCESS MODELING

An analytical force model for the micromachining situation is proposed by Liu et al [2] to predict the cutting and thrust forces by integrating the force of each infinitesimally segment along at the tool edge.

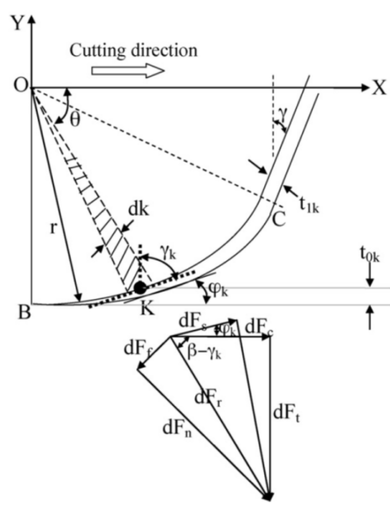

Figure 2. Force configuration in the orthogonal micromachining process

The schematic of the machining mechanics is shown in Figure 2. The tool has a nominal rake angle of γ and cutting edge radius of r. The expressions for cutting and thrust per unit width are given in equation (1) and (2) respectively:

$$\begin{cases} F_c = \int_{-\pi/2}^{\gamma} \frac{k_s \cdot \cos(\beta_k - \gamma_k) \cdot r\cos(\gamma_k)}{\sin(\varphi_k) \cdot \cos(\varphi_k + \beta_k - \gamma_k)} d\gamma_k + \frac{k_s \cdot \cos(\beta - \gamma) \cdot (t_0 - r(1+\sin\gamma))}{\sin(\varphi) \cdot \cos(\varphi + \beta - \gamma)}, & t_0 > r(1+\sin\gamma) \\ F_c = \int_{-\pi/2}^{\sin^{-1}\left(\frac{t_0}{r} - 1\right)} \frac{k_s \cdot \cos(\beta_k - \gamma_k) \cdot r\cos(\gamma_k)}{\sin(\varphi_k) \cdot \cos(\varphi_k + \beta_k - \gamma_k)} d\gamma_k & , t_0 \le r(1+\sin\gamma) \end{cases} \quad (1)$$

$$\begin{cases} F_t = \int_{-\pi/2}^{\gamma} \frac{k_s \cdot \sin(\beta_k - \gamma_k) \cdot r\cos(\gamma_k)}{\sin(\varphi_k) \cdot \cos(\varphi_k + \beta_k - \gamma_k)} d\gamma_k + \frac{k_s \cdot \sin(\beta - \gamma) \cdot (t_0 - r(1+\sin\gamma))}{\sin(\varphi) \cdot \cos(\varphi + \beta - \gamma)}, & t_0 > r(1+\sin\gamma) \\ F_t = \int_{-\pi/2}^{\sin^{-1}\left(\frac{t_0}{r} - 1\right)} \frac{k_s \cdot \sin(\beta_k - \gamma_k) \cdot r\cos(\gamma_k)}{\sin(\varphi_k) \cdot \cos(\varphi_k + \beta_k - \gamma_k)} d\gamma_k & , t_0 \le r(1+\sin\gamma) \end{cases} \quad (2)$$

where γ_k is the instantaneous rake angle and φ_k is the instantaneous shear angle related to γ_k through the relation shown in equation (3). Here r_c is the chip ratio or cutting ratio.

$$\tan\varphi_k = \frac{r_c \cos\gamma_k}{1 - r_c \sin\gamma_k} \quad (3)$$

The flow stress used in this study was able to capture different microstructural attributes such as the grain size, the crystallographic orientations and finally the grain boundaries. The model here used is proposed by Hughes et al [3] According to their work, the dislocation boundaries are classified into geometrically necessary boundaries (GNB) and incidental dislocation boundaries (IDB). The GNBs are extended cell block boundaries which separate regions that deform by different slip system combinations, strain amplitudes and strain. The IDBs are ordinary cell boundaries that formed by trapping of glide dislocations.

The strength contribution of IDBs is accounted via their contribution to the total dislocation density ρ_t which is given as:

$$\rho_t = \rho_0 + \rho_b \quad (4)$$

where ρ_0 is the dislocation density in the volume between the boundaries; ρ_b is the dislocation density per unit volume and is given as:

$$\rho_b = k\theta_{av} / D_{avg} b \quad (5)$$

If ρ_0 is small, its contribution to the flow stress may be neglected. For the IDBs, it is reasonable to consider the dislocations in those boundaries as if they were randomly distributed and thus the flow stress due to IDB can be expressed as:

$$\sigma_{IDB} = M\alpha Gb\sqrt{\rho_t} = M\alpha Gb\sqrt{\frac{k\theta_{av}}{D_{avg} b}} \quad (6)$$

where M is the Taylor factor; α and k are constants; θ_{av} is the average misorientation, b is the Burgers vector; and D_{avg} is the average grain boundary spacing.

However, for the case of GNBs, it is unrealistic to consider the flow stress contribution based on the dislocation density. Instead, the Hall-Petch equation is introduced here since this equation defines the strength of the average (high angle) grain boundary. It is given as:

$$\sigma_{GNB} = K_{HP} / \sqrt{D} \tag{7}$$

where D is the grain size, K_{HP} is the Hall-Petch coefficient.

The overall flow stress taking into account of contributions of both IDBs and GNBs are thus given by:

$$\sigma = \sigma_o(\varepsilon, \dot{\varepsilon}, T) + M\alpha Gb\sqrt{\frac{k\theta_{av}}{D_{avg}b}} + K_{HP}(\varepsilon, \dot{\varepsilon}, T)D^{-1/2} \tag{8}$$

where σ_o is substituted by the Johnson-Cook material constitutive model which describes flow stress as a function of strain, strain-rate, and temperature.

$$\sigma = [A + B \cdot \varepsilon^n][1 + C \cdot \ln\dot{\varepsilon}^*][1 - T^{*m}] \tag{9}$$

The Hall-Petch coefficient is based on the material properties of SiC and is computed using the following relationship from the work of Nes et al [4]:

$$K_{HP} = M\sqrt{\frac{\tau_b 4Gb}{(1-\upsilon)\pi}} \tag{10}$$

where M is the Taylor factor, τ_b is the critical grain boundary stress, G is the shear modulus and υ is the poisson ratio. The critical grain boundary shear stress is given by von Blackenhagen et al [5]

$$\tau_b = 0.057 \cdot G \tag{11}$$

The flow stress obtained in (8) can be related to shear flow stress (plane strain condition) as given by

$$k = \frac{\sigma}{\sqrt{3}} \tag{12}$$

3. COMPREHENSIVE MODEL

The introduction of a microstructure influenced model to predict important process parameters such as the cutting forces is an innovation that opens many opportunities to enhance and optimize better the processes in the future. The influence of the microstructure has in important role and the implementation was made following the approach described in Figure 3.

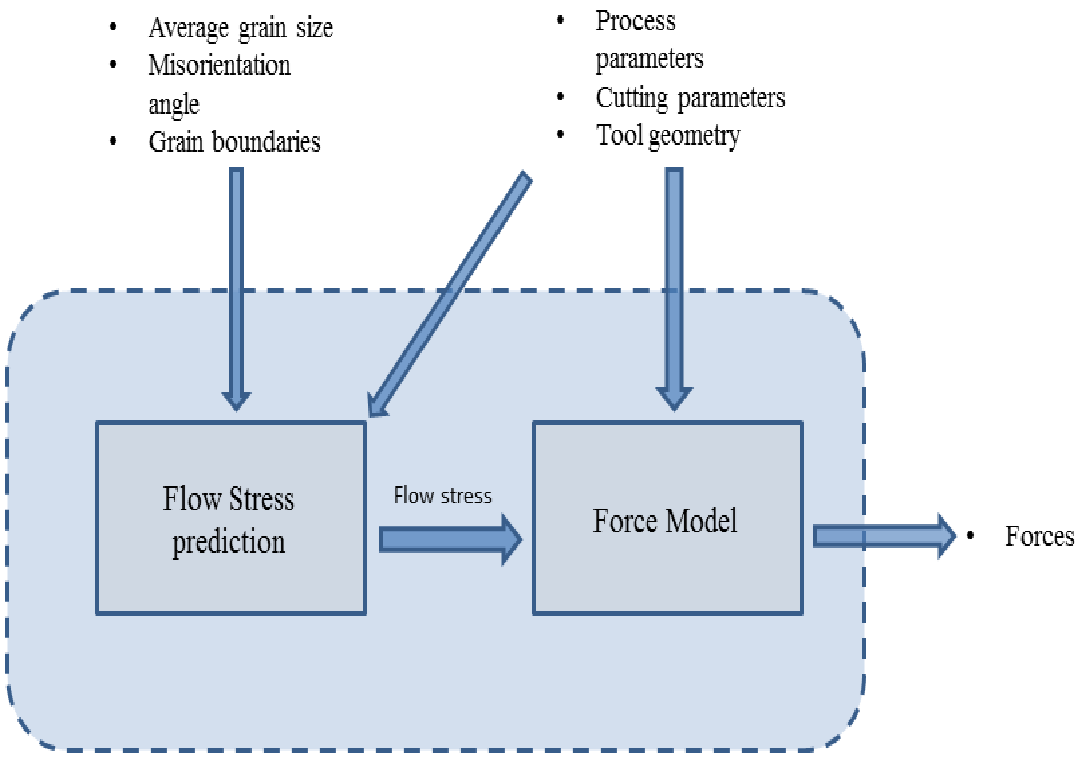

Figure 3. Schematic of the modeling approach

4. Simulation and Experiment Results

The experiments were performed on polycrystalline silicon carbide (p-SiC) using an ultra-precision lathe and a round nosed single crystal diamond tool. The experimental plan for validating the model is set at depth of cut ranging from 0.5 to 300 µm. The feed and the cutting velocity were held constant at 0.25 µm/rev and 1m/s. The nominal rake angle and relief angle is 0° and 7°. The tool nose radius is 0.5mm. The cutting forces were measured using a Kistler 9256A1 dynamometer. The sampling frequency of recording is 24KHz. The undeformed chip thickness is related to the feed, tool nose radius and the depth of cut.

To analyse the contribution of microstructure effects, the cutting force and thrust force excluding and including the microstructure effects are compared with the experimental results in Figure 4 and Figure 5

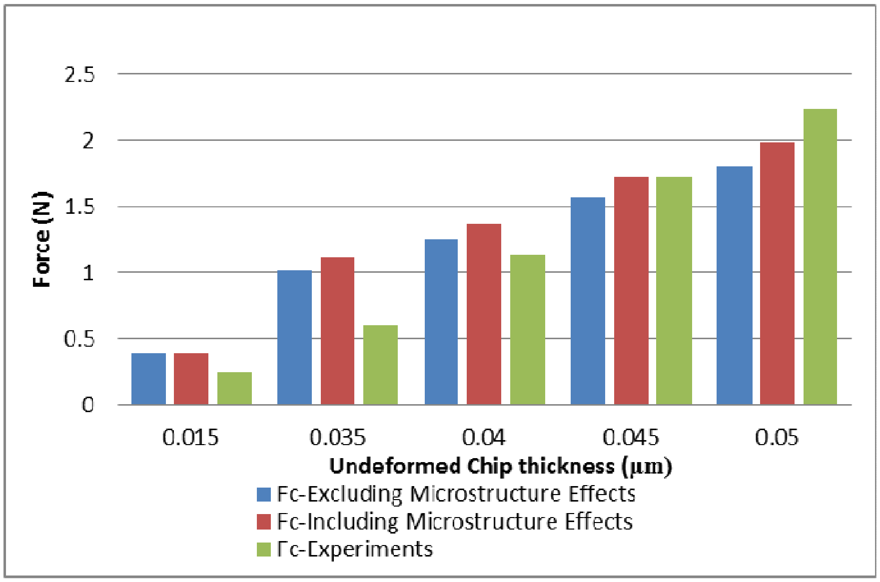

Figure 4. Comparison of the cutting forces

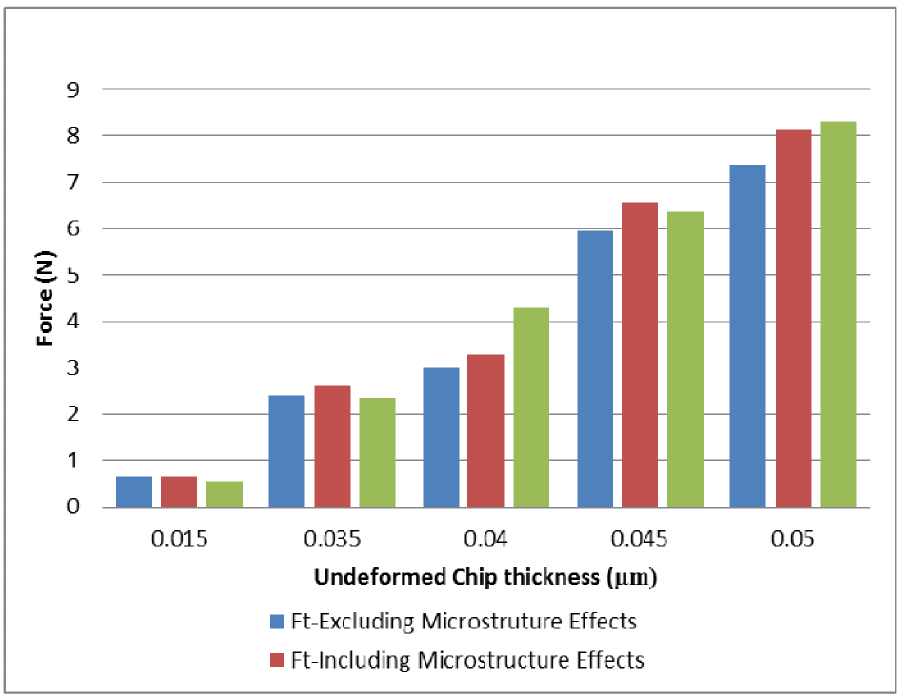

Figure 5. Comparison of the thrust forces

The plots show that predicted values agree with the experiments. Better predictions are achieved when microstructure effects are included, especially at higher undeformed chip thickness. The force variation of two predictions is around 10%. We must note that the model is only capable of calculating the force under ductile-regime machining since it is totally different mechanism in brittle fracture material removal. The highest undeformed chip thickness must be under the critical undeformed chip thickness of the specific material.

5. CONCLUSIONS

This paper focuses on introducing a material influenced cutting force model to predict the cutting forces. The concept of dislocation is introduced and then followed by details of physics based model adopted to relate the flow stress of a material to its microstructural characteristics. The model is validated by experiment of polycrystalline silicon carbide. This model contributed to the introduction of the microstructure attributes as important parameter in the understanding of the manufacturing process. Future research will be focusing on an iterative approach for the microstructure blending process.

REFERENCES

[1] Toh, S. B. & McPherson, R., (1986) “Fine Scale Abrasive Wear of Ceramics by a Plastic Cutting Process”, *Science of Hard Materials*, Bristol and Boston: Adam Hilger Ltd., pp856-871.

[2] Liu, K. & Li, X. P., (2001) “Modeling of Ductile Cutting of Tungsten Carbide”, *Transactions of NAMRI/SME*, Vol. 29, pp120-122.

[3] Hughes, D. A. & Hansen, N., (2008) “Microstructure and Strength of Nickel at Large Strains”, *Acta Materialia*, Vol. 48, No. 11, pp2985-3004.

[4] Nes, E., Holmedal, B., Evangelista, E. & Marthinsen, K., (2005) “Modeling Grain Boundary Strengthening in Ultra-Fine Grained Aluminium Alloys”, *Materials science and Engineering: A*, Vol. 410-411, pp178-182.

[5] von Blackenhagen, B., Gumbsch, P. & Arzt, E., (2001) “Dislocation Sources in Discrete Dislocation Simulations of Thin-Film Plasticity and the Hall-Petch”, *Modelling and Simulation in Materials Science and Engineering*, Vol. 9, No. 3, pp157-169.

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