euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Multiphysics based modelling and analysis of micro milling metal matrix composites (MMCs) against the effects of key process variables

Zhichao Niu [1], Kai Cheng [1]

[1] *Institute of Materials and Manufacturing, College of Engineering, Design and Physical Sciences, Brunel University, Uxbridge, UB8 3PH, UK*

Emails: zhichao.niu@brunel.ac.uk; kai.cheng@brunel.ac.uk

Abstract
Metal matrix composites (MMCs) are increasingly applied in high value engineering industries. Machining of MMC is scientifically less understood in micro milling in particular. The key process variables, including cutting edge radius, grain size of SiC particles, depth of cut, cutting speed and feed rate, significantly affect the resultant cutting performance but need to be quantitatively analysed. This paper presents a multiscale multiphysics modelling and analysis approach to investigating the effects of key process variables and their intrinsic relationships in micro milling MMC. Multiphysics based modelling and analyses are developed to simulate the effects of key process variables identified against the cutting performance, i.e. surface roughness, material removal rate (MRR) and form and dimensional accuracy. Micro milling trials using PCD micro cutters are carried out to evaluate and validate the modelling and simulation. Metrology assessment on the surface topography, texture and defects/features machined is further undertaken by using the benchtop SEM JCM-6000 and Zygo 3D surface profiler.

Keywords: Multiscale modelling, micro milling, MMC machining, process optimization, multiphysics analysis

1. Introduction

Metal matrix composites (MMCs) having excellent mechanical and chemical properties such as light weight, specific high strength and stiffness, high wear resistance, excellent corrosion and heat resistance have been rapidly developed over the last 1-2 decades. These MMCs have started to be increasingly applied in engineering industries such as aerospace, energy, optics, automotive and medical engineering, etc. However, as a kind of hard-to-machine material, the discontinuity, inhomogeneity and anisotropic nature of MMCs make the high precision machining particularly on micro milling difficult due to the excessive tool wear and poor surface quality. Great efforts on maintaining the tool wear and surface performance have been made by controlling the process conditions and improving the precision of milling cutters and machine tools. While, the cutting mechanics of particle reinforced MMCs are currently less understand. In addition, only limit research focus on comprehensive thermo-mechanical analysis of micro milling MMCs processes. In this paper, the effects of process parameters on the tool wear and resultant surface quality are investigated with multiphysics based analysis. Micro milling experiments are also conducted to evaluate and validate the intrinsic relationship between cutting performance and process variables.

2. Multiphysics based analysis of micro milling MMCs

2.1 Integrated approach to micro milling MMCs and the process optimization

The integrated approach for the analysis of micro milling processes is schematically illustrated in Figure 1. Cutting tool geometries and cutting parameters are the critical factors that influence the cutting force, cutting temperature and tool-workpiece interfacing conditions such as lubrication and friction. These basic micro cutting physics contribute to the tool wear and resultant surface roughness, material removal rate (MRR) and form accuracy[1]. In addition, the interrelationship of these physics and also the reaction of cutting performance on the following cutting conditions make the micro milling processes more complex. Thus, multipysics based modelling and simulations are developed to analyze the tooling performance and the cutting process optimization. The theoretical and fundamental aspects of the analysis are presented below.

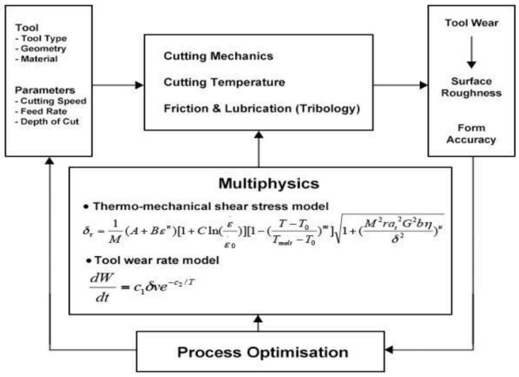

Figure 1. Theoretical approach to the micro milling of MMCs.

Johnson-Cook constitutive model[2] as shown in Equation (1) is employed to estimate the von mises flow stress:

$$\delta = (A + B\varepsilon^n)[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})][1 - (\frac{T - T_0}{T_{melt} - T_0})^m] \tag{1}$$

Considering the size effect, fully coupled thermo-mechanical multiphysics model is introduced to demonstrate the cutting shear stress with a modified Johnson-Cook model[3] as:

$$\delta_\tau = \frac{1}{M}(A + B\varepsilon^n)[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})][1 - (\frac{T - T_0}{T_{melt} - T_0})^m]\sqrt{1 + (\frac{M^2 r a_t^2 G^2 b\eta}{\delta^2})^u} \tag{2}$$

Where, ε is plastic strain, έ is plastic strain rate, έ0 is reference stain rate, A is yield stress, B is hardening modulus, n is hardening exponent, C is strain rate coefficient, A,B,C,m,n are

Johnson-Cook constants, T is current temperature, T_{melt} is material melting temperature, T_0 is reference temperature, M is Taylor factor, r is Nye factor, at is an empirical coefficient, G is the shear modulus, b is the magnitude of the Burgers vector, η is the plastic strain gradient and u is the exponential factor.

As illustrated in Figure1, micro milling tool wear significantly affect the resultant surface roughness. With the minimum tool wear conditions, surface roughness will be lower and surface integrity will be higher. Thus, tool wear is the obvious factor to form the relationship between cutting parameters and surface roughness in micro milling processes. The tool wear model performed by tool wear rate is illustrated as:

$$\frac{dW}{dt} = c_1 \delta v e^{-c_2/T} \tag{3}$$

where c_1 and c_2 are the constants in equation. Thus, generating the Johnson-Cook shear stress model, the tool wear rate model can be then modified as follows:

$$W_t = \frac{1}{M} c_1 v e^{-c_2/T} (A + B\varepsilon^n)[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})][1 - (\frac{T - T_0}{T_{melt} - T_0})^m]\sqrt{1 + (\frac{M^2 r a_t^2 G^2 b \eta}{\delta^2})^u} \tag{4}$$

2.2 Multiphysics coupling and analysis on tool wear in micro milling MMCs

The micro milling simulations are performed in COMSOL Multiphysics environment. In this model, Silicon carbide particles with average size of 5μm are debonded on the aluminum matrix and the MMC workpiece is milling with a PCD tool. The micro milling simulation is performed with the spindle speed of 6,000/9,000/12,000/15,000/18,000/21,000 RPM and the feed rate of 2/3/4/5/6/7 μm/rev. The solution of this multiphysics model is performed with fully coupled solid mechanics module and heat transfer module regarding to the cutting shear stress and tool wear rate models.

The simulation results are obtained with the distribution of various process parameters as shown in Figure 2. From the simulation results, it can be significantly observed that tool wear rate gradually increase with the increase of spindle speed. The tool wear rate then significantly rise to a high value after a short stable between 12,000RPM and 15,000RPM. In term of feed rate, tool wear rate keep increasing due to the significant increase of cutting force in large feed rate. While for the total tool wear, the contact time is much longer in lower feed rate. Thus, considering the cutting conditions, 6,000RPM in spindle speed and 5um/rev are selected as the optimal parameters for the optimization of total tool wear, material removal rate and resultant surface roughness.

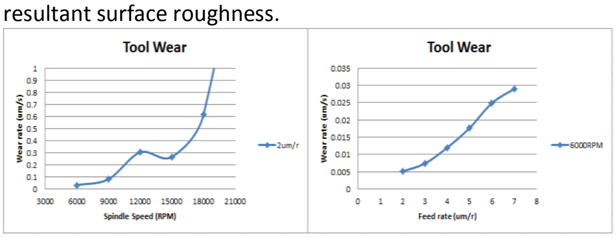

Figure 2. Micro milling tool wear vis spindle speed and feed rate.

3. Micro milling set-up and cutting trails

Figure 3 shows the micro milling experimental set-up and cutting parameters according to the simulation results respectively. Micro milling of 42% SiC/Al MMC with 1mm singe blade PCD tool is conducted on CREN milling machine. The data acquisition system is based on a Kistler 9256C dynamometer connected to PC via an A/D card.

4. Results and discussion

The machined surface roughness was measured with a Zygo 3D surface profiler. Surface profile and tool wear were further analysed by image processing at the JCM-6000 Benchtop SEM. Figure 4 shows the side surface roughness profile. From the comparison of side surface roughness against various radial depth of cut shown in Figure 5, it can be observed that with the increase of radial depth of cut (DOC), side surface roughness slightly increase at the beginning and then significantly rise with the continue increase of radial DOC. In addition, side surface roughness keep in a constant level after the the radial DOC reach to 20μm. Thus, better side surface performance can be achieved with a lower radial depth of cut in micro milling MMC.

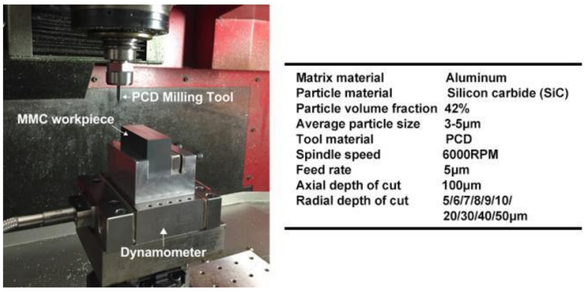

Figure 3. Micro milling set-up and cutting parameters.

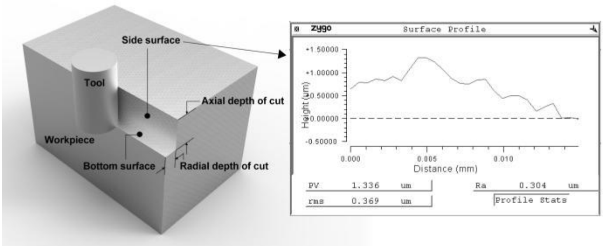

Figure 4. Surface roughness profile micro milled at the MMC.

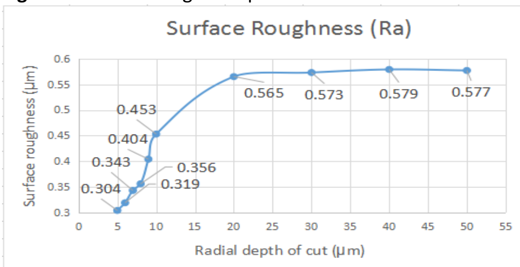

Figure 5. Side surface roughness against the radial DOC.

5. Conclusions

Micro milling tool wear and resultant surface integrity are affected by the key process variables as identified. Multiphysics based simulations are developed and well-designed experiments carried out to analyze those process variables and their intrinsic effects on the tool wear and surface roughness in micro milling particles reinforced metal matrix composites. A better tooling performance and resultant surface generation can be obtained particularly on the side surface under the optimal process variables and cutting conditions (6,000RPM spindle speed, 30mm/min feed rate and 5μm radial DOC) in micro milling SiC/Al MMCs with PCD tools.

References

[1] K. Cheng, D. Huo, 2013, Micro Cutting: Fundamentals and Applications (Editors), John Wiley & Sons Ltd, Chichester.

[2] G.R. Johnson, W.H. Cook, 1983, A constitutive model and data for metals subjected to large strain, high strain rates and high temperatures, Proc. 7th Int. Symposium on Ballistics, April, The Hague, Netherlands, pp.541–547.

[3] L. Zhou, F.Y. Peng, et al, 2015, Analytical modeling and experimental validation of micro end-milling cutting forces considering edge radius and material strengthening effects, International Journal of Machine Tools & Manufacture, 97, pp.29–41.