Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 101 (2021) 118–121

www.elsevier.com/locate/procedia

9th CIRP Conference on High Performance Cutting (HPC 2020)

Comparative study of stability predictions in micro-milling by using cutting force models and direct cutting force measurements

Shukri Afazov*

Department of Engineering, Nottingham Trent University, Nottingham, NG11 8NF, UK

* Corresponding author. Tel.: +441158483212; *E-mail address: shukri.afazov@ntu.ac.uk*

Abstract

Chatter vibration in micro-milling is critical for the breakage of the cutting tools. Therefore, the dynamic stability is important and chatter vibration should be avoided. This paper presents a comparative study between two models for prediction of chatter. The difference between the two models is in the source of cutting forces. The first chatter model uses a mathematical cutting force model while the second chatter model uses direct measured cutting forces. Both chatter models are solved in the time domain and the same criteria for chatter is applied. The results showed that the chatter model using direct measured cutting forces was in better agreement with fast Fourier transform analyses.

Keywords: micro-milling; chatter; cutting forces; process stability

1. Introduction

Chatter is a self-excited vibration between the cutting tool and the workpiece in conventional and micro-milling. It is characterised by poor surface finish and fast tool wear. Cutting tool damage and reduced material removal rate can also be observed. A number of chatter models have been developed and applied in micro-milling to obtain the process stability [1, 2]. Generally, the chatter is modelled by solving the equation of motion in frequency or time domain followed by a certain criterion for chatter detection. For both time and frequency domain solutions, the modal dynamic parameters obtained at the cutting tool tip and the micro-milling cutting forces must be determined. Several analytical, mechanistic empirical and finite element models have been developed to predict the micro-milling cutting forces [3-6].

Another phenomenon observed in micro-milling is the presence of size-effect or dependence on material strength as observed in [7]. The size-effect can be described as a non-linear increase of the specific cutting energy at different micro-milling cutting conditions. Afazov et al. [3] researched the size-effect in micro-milling of Ti6Al4V. They found that the cutting forces up to 6μm/tooth were better predicted using a material model that includes the size-effect, however, for feed rates greater than 6 μm/tooth, the inclusion of size-effect has led to over-prediction of the cutting forces.

The aim of this paper is to compare the chatter stability using published cutting force models for Ti6Al4V [3] against the use of direct measured cutting forces, which is a new approach explored in this paper.

The paper first presents two cutting force models and comparison between predicted and measured cutting forces. A chatter model with a time domain solution is then presented. Predicted stable depths of cut and stable depths of cut based on fast Fourier transforms (FFT) are compared and discussed.

10.1016/j.procir.2021.02.015

2. Cutting force models

The micro-milling cutting forces of Ti6Al4V were measured using a Kistler dynamometer 9258C2 mounted on a 5-axis KERN Evo [3]. Two-flute TiN coated end-milling carbide cutting tool with diameter of 500µm was utilised.

Afazov et al. [3] used the finite element method to simulate the tool workpiece interaction represented in orthogonal cutting. The key component of the finite element model was the modelling of the material behavior in order to predict the cutting forces. Two constitutive isotropic thermal-elastic-plastic material models were used, including the classical Johnson Cook and a size-effect (SE) model based on the strain gradient plasticity theory. The strain-rate and temperature dependent visco-plastic JC material model is given by:

$$\sigma_y = \left(A + B\bar{\varepsilon}^n\right)\left(1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_{melt} - T_r}\right)^m\right) \quad (1)$$

where $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ is the plastic strain rate, $\dot{\bar{\varepsilon}}_0$ is the reference strain rate ($\dot{\bar{\varepsilon}}_0 = 1$ s^{-1}), T is the reference temperature, T_r is the room temperature, T_{melt} is the melt temperature, A is the initial yield stress, B is the hardening modulus, n is the hardening exponent, C is the strain rate dependency coefficient and m is the thermal softening coefficient. The material constants for the JC material model for Ti6Al4V can be found in [3].

The size-effect material model is formulated based on the strain gradient plasticity theory. Unlike the conventional plasticity theory where the strength of the material is considered as a function of the strain, in the strain gradient plasticity theory, the strength is considered as a function of the strain gradient as well. The SE material model is given by:

$$\sigma_y = \sigma_{ref}\left(1 + \left(\frac{b(M\alpha G)^2}{\sigma_{ref}^2 L_{shear}}\right)^{\mu}\right)^{\frac{1}{2\mu}} \quad (2)$$

where M = 3.06 is the Taylor's factor, L_{shear} is the shear length, G is the shear modulus, μ is a constant which gives the lower limit of the density of the geometrically necessary dislocation found to be 0.25, b = 0.3nm is the magnitude of Burgers vector, α is a constant and a value of 0.5 was used. The JC material model from Eq.1 is used as a reference stress σ_{ref} in order to account for the plastic strain, strain rate and temperature effects. The size-effect (SE) material model was implemented in ABAQUS/Explicit using the VUMAT subroutine. The shear length (L_{shear}) of the primary deformation zone was defined within the VUMAT subroutine after implementing an algorithm for determining the shear length using FE variables supplied by the VUMAT subroutine.

The developed models were run and the forces in the cutting direction (F_c) and the tangential direction (F_t) were obtained. The relationship between cutting forces, uncut chip thickness (h) and cutting velocity (v) was then described by:

$$F_{c,t} = (p_1 v^{p_2} + p_3)\left[1 - \exp(p_4 h)\right] + (p_5 v^{p_6} + p_7)\left[1 - \exp(p_8 h)\right] \quad (3)$$

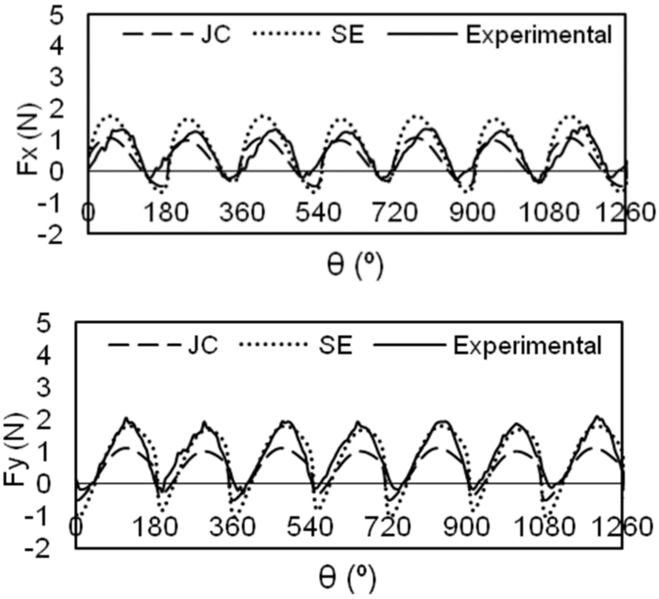

Fig. 1 Forces at w = 25,000 rpm *and feed/tooth of* 2.4µm [3]

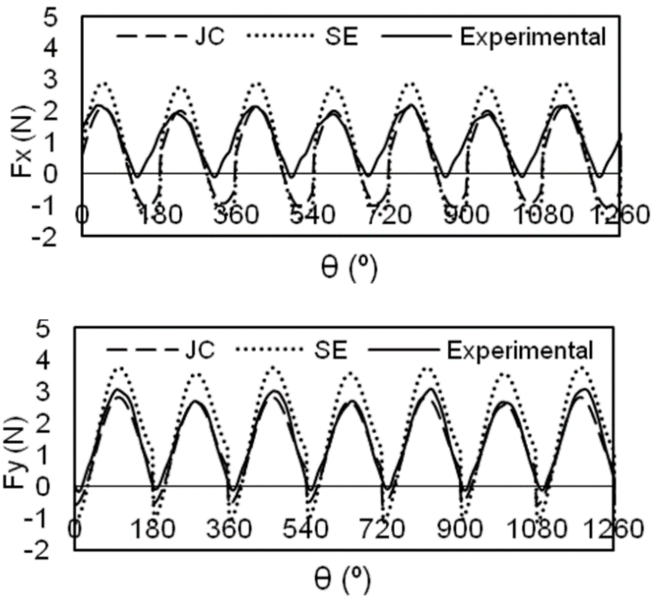

Fig. 2 Forces at w = 25,000 rpm *and feed/tooth of* 12µm [3]

The cutting force constants were obtained by fitting and the results are given in Table 1. Equation 3 was coupled with a kinematic model of the cutting tool considering the run-out effect and the uncut chip thickness [3]. Comparison between predicted and measured cutting forces are shown in Figures 1 and 2.

Table 1: Cutting force constants for Ti6Al4V [3]

Constants	JC material model		SE material model	
	F_c	F_t	F_c	F_t
p_1	295.9	0	-53.77×10^{5}	0
p_2	-6.67×10^{-2}	0	98.64×10^{-4}	0
p_3	0	710	64.6×10^{5}	-0.2
p_4	-1×10^{-2}	-5×10^{-4}	-3×10^{-6}	0.18
p_5	-20.4×10^{-2}	0	-88.43×10^{-2}	0
p_6	30.71×10^{-2}	0	24.24×10^{-2}	0
p_7	6.225	5.7	13.1	11.5
p_8	-5	-7	-2.3	-6

3. Modelling of chatter

Two chatter models are applied in this study. The first model is based on the cutting force models presented in Section 2 using the JC and SE material models. The second chatter model is based on the use of direct measured cutting forces instead of a cutting force model. The two chatter models are solved in the time domain. The modal dynamic parameters are adopted from [3] (w_n = 4035 Hz, ζ = 0.016 and k = 2.1425 MN/m). By assuming that the helix angle of the micro-milling tool is negligible at small axial depths of cut, the micro-milling system can be reduced to two degrees of freedom as shown in Fig. 3.

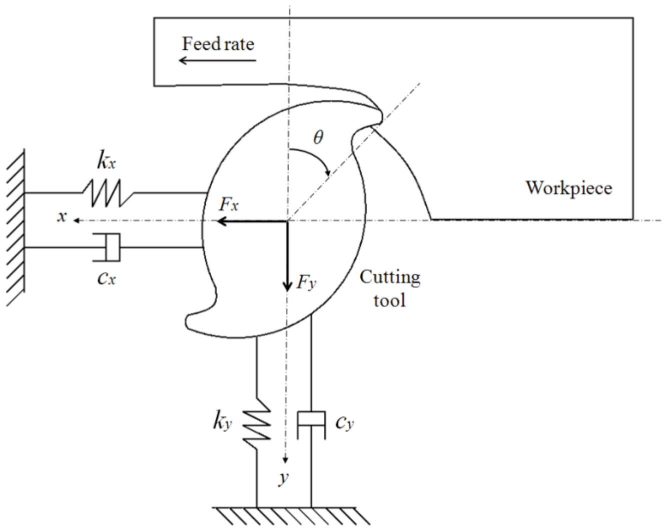

Fig. 3 Two degrees of freedom micro-milling system

The dynamics of the micro-milling system can be described by two second order ordinary deferential equations for each degrees of freedom. Considering the relationships $c/m=2\zeta w_n$ and $k/m=w_n^2$, the micro-milling system can be given by:

$$\ddot{x}(t) = \frac{w_{n,x}^2 F_x(t)}{k_x} - 2\zeta_x w_{n,x}\dot{x}(t) - w_{n,x}^2 x(t) \qquad (4)$$

$$\ddot{y}(t) = \frac{w_{n,y}^2 F_y(t)}{k_y} - 2\zeta_y w_{n,y}\dot{y}(t) - w_{n,y}^2 y(t) \qquad (5)$$

Equations (4) and (5) are solved in the time domain using the fourth order of precision Runge-Kutta numerical integration method. After solving equations (4) and (5) and computing the displacements in the x and y directions for the corresponding time, a chatter detection criterion is employed based on statistical variances. The statistical variances are given by:

$$s_x^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}; s_y^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1} \qquad (6)$$

where s_x^2 and s_y^2 are statistical variances in the x and y directions, x_i and y_i are the displacements at the corresponding computed time, n is the number of time increments, $\bar{x}$ and $\bar{y}$ are the averaged displacements in the x and y directions. The micro-milling cutting is considered unstable when the statistical variances are higher than the value of 1 μm^2. A minimum stability limit is determined when one of the statistical variances in the x or y directions reaches 1 μm^2 ($s_x^2 > 1$ μm^2 or $s_y^2 > 1$ μm^2).

4. Results and discussion

Fast Fourie transform (FFT) analyses were first performed on the micro-milling conditions used in this comparative study. Measured cutting forces for Ti6Al4V were used for the FFT analyses. The results from the FFT and the micro-milling cutting are shown in Table 2. No chatter was detected for all experimented micro-milling conditions using the FFT method.

Table 2: Micro-milling conditions and FFT analyses

Cutting trial	Spindle speed, rpm	Feed, μ m/ tooth	Applied depth of cut, μm	FFT Analyses, chatter?
1	5000	3	100	no
2	5000	6	100	no
3	5000	12	100	no
4	5000	30	100	no
5	25000	0.6	100	no
6	25000	1.2	100	no
7	25000	2.4	100	no
8	25000	6	100	no
9	25000	12	100	no
10	25000	24	100	no
11	50000	0.6	100	no
12	50000	1.2	100	no
13	50000	3	100	no
14	50000	6	100	no
15	50000	12	100	no
16	50000	24	100	no

The two chatter models were employed to predict the stability limits. In the chatter model using the cutting force model, a feed rate and a spindle speed were applied to predict the stable depth of cut, which is the conventional way. The chatter model using the direct measured forces predicted the stable depths of cut by applying measured cutting force signals for five revolutions obtained for applied process parameters (feed, spindle speed, depth of cut). In the cases when no chatter was predicted, the cutting forces were linearly increased based on the assumption that the cutting forces linearly increase by increasing the depth of cut. The increase of force was carried out until a chatter was detected. This is how the stable depths of cut were obtained.

Fig. 4 shows the predicted stable depths of cut for different feeds and spindle speeds. The predicted trends are similar, but the magnitudes are different for the three sets of results. The chatter model using both cutting force models (JC and SE) predicted unstable cutting at 5000rpm and 50000rpm while the FFT analyses do not show a sign of chatter. The chatter model using the direct measured forces is in better agreement with the FFT analyses. This might be because the measured cutting forces are actual while the cutting force models do not represent the cutting forces with enough accuracy.

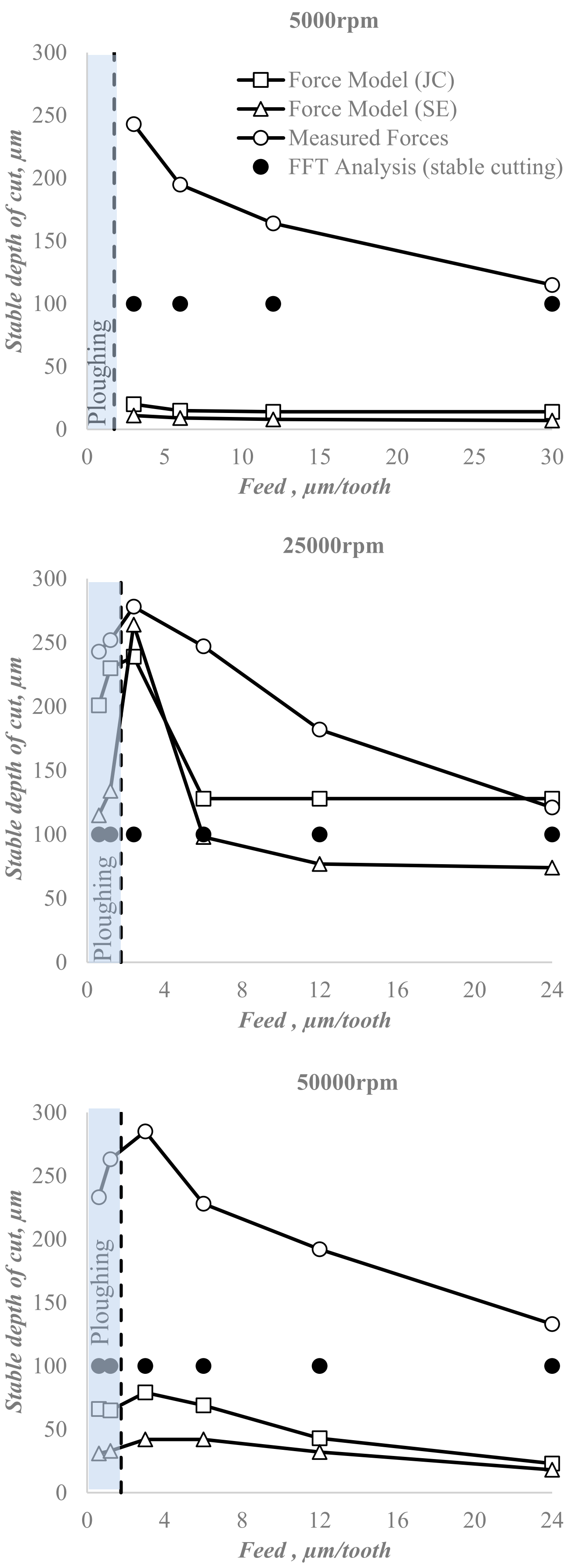

Fig. 4 Comparison of predicted stable depths of cut

An interesting observation is that the stable depths of cut are lower in the ploughing regime. The ploughing regime is assumed at a feed of 1.5μm/tooth considering that the cutting tool edge radius of the tool has been measured to be 3.5μm [3]. The results suggest that the chatter is more likely in the regime dominated by ploughing. However, this needs to be further investigated and verified.

The use of the proposed cutting force models in [3] seems to be conservative in predicting stable depths of cut, comparing to the FFT analyses. The new approach of using direct cutting forces is in better agreement with the FFT results. This approach has the potential to be used in process monitoring and control. Its advantage is that it can capture all physics, including the dynamic run-out, actual geometry of the tool, and friction conditions. However, more research needs to be conducted in this area.

5. Conclusions

The following conclusions were obtained from this research:

- the proposed cutting force models by Afazov et al. [3] demonstrated a conservatism in predicting stable depths of cut in micro-milling;
- the use of measured cutting forces for prediction of stable depths of cut showed agreement with FFT analyses.
- the use of direct measurement forces for prediction of stable cutting should be further researched to understand its potential and limitations.

References

[1] Wang, J.; Uhlmann, E.; Oberschmidt, D.; Sung, C.; Perfilov, I. Critical depth of cut and asymptotic spindle speed for chatter in micro milling with process damping. *CIRP Ann. – Manuf. Technol.*, 2016, *65*, 113–116

[2] Afazov, S.M.; Ratchev, S.M.; Segal, J.; Popov, A.A. Chatter modelling in micro-milling by considering the process nonlinearities. *Int. J. of Machine Tools and Manufacture, 2012, 56, 28-38*

[3] Afazov, S.; Segal, J.; Ratchev, S. Determination of cutting forces and process stability in micro-milling of Ti6Al4V alloy by considering the size-effect phenomenon. *Micro and Nanosystems*, 2011, *3*, 199-209

[4] Altintas, Y.; Jin, X. Mechanics of micro-milling with round edge tools. *CIRP Ann. – Manuf. Technol.*, 2011, *60*, 77–80

[5] Baburaj, M.; Ghosh, A.; Shunmugam, S. Experimental and theoretical investigation on cutting forces in off-centre micro ball end milling. *CIRP J. Manuf. Sci. Technol., 2018, 23, 108-117*

[6] Attanasio, a.; Abeni, A.; Ozel, T.; Ceretti, E. Finite element simulation of high speed micro milling in the presence of tool run-out with experimental validations. *Int. J. of Adv. Manuf. Technol.*, 2019, *100*, 25–35

[7] Bissacco, G.; Hansen, H.; Slunsky, J. Modelling the cutting edge radius size effect for force prediction in micro milling. *CIRP Ann. – Manuf. Technol.*, 2008, *57*, 113–116