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The mystery of missing feed force — The effect of friction models, flank wear and ploughing on feed force in metal cutting simulations

Sampsa V.A. Laakso[a,b,*], Mathias Agmell[a], Jan-Eric Ståhl[a]

[a] Lund University, Production and Materials Engineering, Ole Römers Väg 1, Lund, 223 63, Sweden
[b] Aalto University, School of Engineering, Puumiehenkuja 3, Espoo, 02150, Finland

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ABSTRACT

Underestimated feed force is a known systematic error in cutting simulations. It is considered a consequence of inaccurate friction models, but there are indicators that friction is not the only reason for the error. In some cases, the value of Coulomb friction must be over 1.0 to compensate for the feed force and such values cause over-estimated chip thickness for example. In turning, the ploughing force of the tool is affected by the feed velocity, which changes with the work diameter when cutting speed is constant. In addition, the edge geometry of the tool affect the ploughing force. In this paper, friction, edge geometry and the plough force are investigated with experiments and simulations to identify their effect on feed force.

1. Introduction

Feed force is typically underestimated in cutting simulations when compared to experiments. The error is considered an effect of defective friction models. Metal cutting simulations are complex thermo-mechanical problems where the coupled nature of the governing equations makes it difficult to identify the effect of a single parameter. Laakso & Niemi presents an inverse methodology to acquire material model parameters for cutting simulations from cutting tests using extended Oxley's analytic cutting model. The results show multiple local minima when fitting the material model to the data. Therefore, in addition to cutting tests, actual material properties from tensile testing are required to identify the physically valid minimum [1,2]. Agmell et al. discusses similar method using an inverse analysis with FEM analysis and a Kalman filter and the method shows a good correlation with the experiments [3]. The material properties in terms of flow stress can be trusted to a good degree, but the feed force error is still present. If the error of feed force is solely caused by friction, the problem should be easy to solve. However, when friction is increased to compensate the missing feed force, the Coulomb friction or shear friction coefficient must often be over 1.0, and that causes unrealistically high chip thickness and tool temperature, and the cutting force is also affected. Changing one parameter to fix one output value completely impairs the rest of the simulation. This paper investigates three aspects of cutting that have effects on feed force: the tool ploughing effect, the edge geometry and the friction model.

2. Materials and methods

The effect of friction models and ploughing is investigated using simulations and cutting experiments. This paper investigates only AISI 304 stainless steel for work material and tungsten carbide for tool material to give a direction to further research with a wider coverage of materials. The effect of ploughing is evaluated against cutting experiments done with Ø50 mm workpiece and semi-orthogonal longitudinal turning with a high cutting depth and a cutting edge angle of 90 °s. These experiments were done in author previous research [4]. The experiments were done with VDF-research lathe with 100 kW spindle power. The setup is shown in Fig. 1. The forces were measured with Kistler Kiag swiss type 9263 3-axis piezosensor and the temperature with FLIR SC660 infrared camera. The workpiece was painted with matte black for good emissivity and the whole lathe was covered with cardboard to prevent any additional outside thermal signals. More details about the thermal imaging done in this work can be found in Laakso [5].

The simulation procedure is done by running full factorial analysis of the variables. The 2D simulations are run with feed velocity and without with flank wear and without and with five different friction models/value sets. This leads to a total of $2 \times 2 \times 5 = 20$ simulations. The simulations are done with DEFORM finite element software. Cutting parameters for the simulations are 0.4 mm/r feed (uncut chip thickness), 140 m/min cutting speed and 4 mm cutting depth. The feed velocity is either 29.7 mm/s or zero, which translates to 10 mm or infinite workpiece diameter, as explained in Fig. 4. The top surface of the

* Corresponding author at: Lund University, Production and Materials Engineering, Ole Römers Väg 1, Lund, 223 63, Sweden.
E-mail address: sampsa.laakso@aalto.fi (S.V.A. Laakso).

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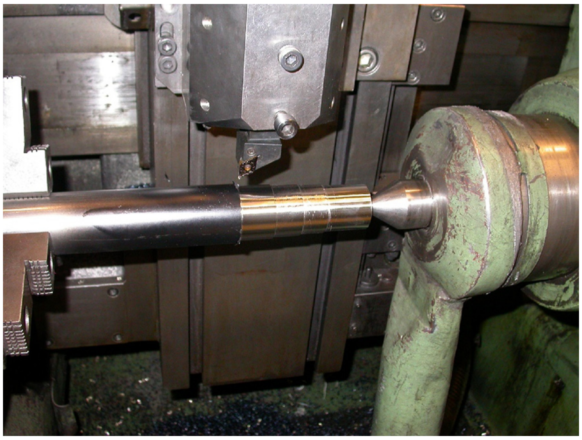

Fig. 1. Semi-orthogonal longitudinal turning setup.

workpiece is inclined so that the inclination angle matches the feed velocity in order to keep the uncut chip thickness constant. The inclination angle δ_f of the work surface can be calculated with Eq. (1), where f is the feed and D is the workpiece diameter.

$$\delta_f = \tan^{-1} f/_{\pi D} \tag{1}$$

The effect of tool edge geometry and friction models are further evaluated with fully orthogonal cutting by using radial feed to cut flanges on Ø90 mm cylindrical workpiece, shown in Fig. 2. The orthogonal cutting experiments were done using five different cutting parameters, in Table 1. The corresponding simulations were done with five different setups using either idealized tool geometry or measured tool geometry and four different frictions. Total number of the simulations for this phase is 5 × 5 = 25. The experiments were done with an SMT 500 Swedturn NC-lathe. The tools were measured with an Alicona InfiniteFocus 3D optical tool microscope. The tool was custom made for the experiments in Lund University, shown in Fig. 3. The tool material is WC-10%Co with 1 μm grain size.

2.1. Friction models

Four different friction models are used presented in Table 2: Coulomb friction, shear friction, hybrid friction or Childs' model [6] and simulations without friction. The Childs' model combines Coulomb friction and shear friction in piecewise defined function, where inequality defines the friction mechanism, i.e. if Coulomb friction is used until it is greater than the shear strength of the work material. Coulomb friction is proportional to the normal pressure at tool-chip interface. Shear friction is proportional to the shear strength of the material. Hybrid model uses Coulomb friction in tool-chip contact where the friction stress is less than the shear strength of the material and shear

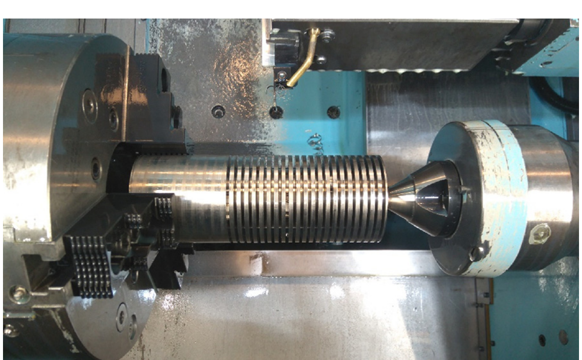

Fig. 2. Orthogonal cutting setup.

Table 1
Cutting parameters for orthogonal experiments.

nr.	v_c [m/min]	f [mm/r]
1	70	0.4
2	140	0.05
3	140	0.2
4	140	0.4
5	280	0.4

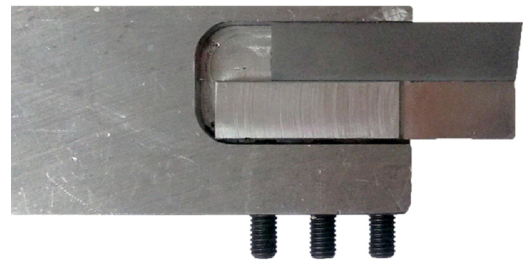

Fig. 3. Custom tool for orthogonal cutting experiments.

Table 2
Friction models and coefficient values.

Friction model	Equation	Value
Coulomb	$\tau_f = \mu P$	$\mu = 0.3$
Shear	$\tau_f = m_s k$	$m_s = 0.4$
Hybrid	$\tau_f = min(\mu P,\ m_s k)$	$\mu = 0.3$ / (0.85), $m_s = 0.4$
No Friction	$\tau_f = 0$	

stress elsewhere. Models without friction are defined with zero friction stress. The values for the friction models are taken from Agmell et al. regarding the shear friction value 0.4, the Coulomb friction value 0.3 is the generally used friction coefficient for steel-carbide contact and hybrid friction value for Coulomb friction 0.85 is taken from Yang et al. [7,8]. Hybrid friction with 0.3 value for Coulomb and 0.4 for shear is used by many authors, Childs among others.

2.2. Ploughing

Ploughing is a combination of two factors, the feed velocity and tool edge geometry. Feed velocity is a function of the workpiece diameter and cutting speed in turning that is often used in cutting experiments. In turning operations with radial feed, the cutting is nearly orthogonal if the cutting depth is considered negligible in respect to the diameter of the workpiece. However, when it can be considered so, is an excellent question. Fig. 4 presents an illustration of the feed velocity v_f as a function of the feed f and the rotation speed n_r or the feed and the work diameter D and the cutting speed v_c.

In analytical modelling, cutting tool edge geometry is traditionally considered perfectly sharp. Recent advances in the field have enabled researchers to implement round cutting edge in slipline field models developed in Fang, Ozturk et al. and Uysal et al. [9–11]. Round tool is typically used also in FEM simulations. The tool cutting edge roundness is typically between 10–100 μm and a typical value for finishing operations is 20 μm, found in several publications. Tool wear is often considered negligible in FEM simulations, which is surprising, since there are multiple publications that state that the initial wear of the tool takes place in the first 10100 seconds of cutting. Initial wear has been shown to be 50,100 μm of magnitude. Albrecht, investigated the effect of ploughing in orthogonal cutting using analytical expressions and cutting experiments and devised a new force diagram, where the effects of the tool edge radius and flank face plateau are included. This new force diagram shown in Fig. 5 solved the problem of friction coefficient