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The mechanics of cutting: In-situ measurement and modelling

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Abstract

This work presents a new constitutive modelling approach to describe the operating friction mechanisms in material cutting. The modelling approach is based on an advanced experimental set-up with high speed filming and thermography of the orthogonal cutting process as well as the Merchant’s circle force diagram. Finite element cutting simulations on carbon steel AISI 1045 with different uncut chip thicknesses were conducted to validate the developed friction modelling approach. A realistic analytical and numerical prediction of chip formation, local thermo-mechanical load and cutting force could be achieved.

Keywords: Metal cutting; Friction mechanics; Oxley model; In-situ measurement; FEM

1. Introduction

Being an integral factor in metal cutting operations, contact friction between the tool and the workpiece is one of the key topics in machining research. This is primarily due to the fact that friction controls the quality of the material removal in cutting processes and directly influences the deformations in the primary shear zone, the chip thickness, the chip flow direction, the required cutting force, the temperature rise in the cutting tool, the tool wear rate, and the workpiece final surface finish. In addition, the friction is a complicated function of several interrelated variables. So, it is influenced by contact pressure and temperature, surface properties, cutting conditions, lubrication, tool material and geometry, workpiece material, and process kinematic. For a better understanding of friction control mechanisms, machining researchers have developed a large number of experimental setups [1-5] and empirical describing models [6-11]. The developed pin-on-disc tribometers measure the normal and tangential forces acting on a pin rubbing over rotating disc to determine the friction coefficient. The main test parameters are sliding velocity, contact temperature and contact pressure. However, a pin-on-disc system cannot reproduce the operating contact conditions of the cutting process. Recently, Puls [12] developed a new experimental friction test providing contact conditions comparable to real cutting operations. His test concept can be considered as orthogonal cutting with an extreme negative rake angle and very high feed, so severe plastic deformation and friction take place in the tool-workpiece interface.

Finite element technique is established as an efficient tool to investigate cutting operations. The friction model is its second most important and critical input after the material law. The most published works for FE cutting simulation ignored the governing contact friction mechanisms and used Coulomb or shear friction model with a constant friction coefficient. The Result is an inappropriate prediction of the cutting process. Adequate friction modelling approaches [9] combine Coulomb and shear friction by considering two friction zones sliding and sticking. The friction coefficients are estimated from normal pressure in the tool-chip interface. These models require high experimental efforts to identify the boundaries of the friction zones. This paper presents a quantitative and direct analysis and modelling of the friction behavior in metal cutting. The proposed model can directly link the friction mechanics to the cutting parameters.
2. Advanced experimental setup for cutting operation

Due to the high complexity of the metal cutting processes, sophisticated observation and measurement equipment is required for better understanding and quantitative characterizing of the mechanisms involved during cutting operation. In this regard, WZL developed an advanced fundamental test-bench based on a vertical broaching machine tool (max. cutting speed: 150 m/min, max. force: 80 kN, max. power: 40 kW), see Fig. 1.

The used broaching machine tool allows a very good accessibility to the cutting zone and thus the optimal use of different measurement and video recording methods (high-speed filming, thermography, thermocouple, two-color pyrometer, cutting force measurement). Because of the fixed tool, the chip formation process can be recorded by means of a high speed camera of type Vision Research Phantom v7.3 (frame rate: 6,688 fps at a resolution of 800 x 600 pixels and 500,000 fps at 32 x 16 pixels). The translational motion of the workpiece (3.5 mm x 40 mm x 200 mm) makes it possible to directly realize the engagement condition in the contact zone and keep it constant during the cut. To measure temperature changes in the tool-workpiece system, a high speed infrared (IR) camera type FLIR SC7600 (frame rate: 100 fps at 640 x 512 pixels or 800 fps at 160 x 128 pixels, measuring range: -20 - 3000 °C, accuracy: ± 1°C) is used. The recorded sides of the tool and the workpiece with the IR camera were painted with black lacquer in order to predefine an emissivity coefficient of about 90% for the hot surfaces. The cutting tool is mounted on a three-component piezoelectric force platform from the company Kistler. This force dynamometer is specially designed for the measurement of the machining force in high speed broaching. Within the framework of the present investigation, dry orthogonal cutting tests are carried out on carbon steel AISI 1045 (normalized) with different cutting speed (v_c = 50, 100, 150 m/min and uncut chip thickness h = 0.01 - 0.50 mm). As cutting material, an uncoated cemented cut-off insert (Sandvik H13A, rake angle: γ = 6°, clearance angle: α = 3°, sharp r_ε ≤ 5 μm) was employed. Fig. 2 shows exemplarily (a) chip formation (chip form, primary shear zone, chip thickness, contact length on the rake face) and (b) the measured temperature distribution on the cutting zones and on the deformed chip.

Fig. 1. Fundamental test-bench for orthogonal cutting

Fig. 2. (a) High speed filming; (b) High speed IR thermography (v_c = 150 m/min, h = 0.20 mm, dry cut)

Fig. 3. Cutting force, feed force and the measured temperature
As expected the maximum temperature is detected on the bottom side of the chip by contacting the rake face of the tool. The measured machining forces and the mean temperature at the primary shear zone are shown in Fig. 3 for the cutting speed \( v_C = 150 \text{ m/min} \) and various uncut chip thicknesses.

3. Analytical prediction of the cutting process response

After the experimental characterization of the present cutting process (continuous chip form, thinner primary shear zone, plane strain ductile deformation, sharp cutting edge), the classical Oxley’s parallel shear zone theory \[13\] can be used to predict the cutting process response. The Oxley model is based on the Merchant’s shear plane model (see Fig. 4) and slip-line field theory and is the unique predictive cutting approach considering the strain hardening, strain rate sensitivity and thermal softening of the machined material.

Oxley assumed that the primary shear zone thickness is about one tenth of the primary shear zone length. Then friction coefficient \( \mu = \tan(\rho) \) Eq. 1, shear angle \( \phi \) Eq. 2, strain and strain rate in the primary shear zone Eq. 3 and 4 respectively, as well as cutting force Eq. 7, feed force Eq. 8 can be calculated. The known inputs for the Oxley’s parallel shear zone model are (i) tool geometry (rake angle \( J \)), (ii) chip thickness compression ratio \( O_h \) (determined from test), (iii) cutting parameters \( v_C, h, b = 3.5 \text{ mm} \) and (iv) constitutive workpiece material law. A modified Johnson-Cook model Eq. 5 is proposed to obtain the adiabatic shear flow stress Eq. 6 in closed-form, and thus the temperature Eq. 9 by adiabatic deformation, considering the Taylor-Quinney relation \( U_d c dT = \beta \cdot V d \varepsilon \) \[14\] to describe the fraction of the plastic energy transferred to heat (\( U_d \): density, \( c \): specific heat capacity, \( T \): temperature, \( \beta = 90\% \), \( V \): effective stress, \( \varepsilon \): plastic effective strain).

\[
\mu = \frac{F_y \cos(\gamma) + F_x \sin(\gamma)}{F_y \sin(\gamma) - F_x \cos(\gamma)} \\
\phi = \arctan \left( \frac{\cos(\gamma)}{\lambda_h - \sin(\gamma)} \right) \\
\varepsilon = \frac{\cos(\gamma)}{\sqrt{3 \cos^2(\phi - \gamma) \lambda_h}} \\
\dot{\varepsilon} = \frac{10 \cos(\gamma) \sin(\phi) \cdot v_c}{\sqrt{3 \cos(\phi - \gamma) h}} \\
\tau_y = \frac{(A + B \cdot \varepsilon^m) \cdot [1 + C \cdot \ln(\varepsilon / \varepsilon_o)] \cdot \exp[-\beta \cdot (T - T_m) / T_m]}{\sqrt{3 \cdot [1 + a \cdot (A + B \cdot \varepsilon^m) / (n + 1)] \cdot [1 + C \cdot \ln(\varepsilon / \varepsilon_o)]}} \\
a = (0.9 \beta) / (\rho_c \cdot c \cdot T_m) = 0.0003 \text{MPa}^{-1} \\
F_c = \frac{\cos(\rho - \gamma) \cdot \tau_y}{\sin(\phi) \cdot \cos(\phi + \rho - \gamma)} \cdot b \cdot h \\
F_f = \frac{\sin(\rho - \gamma) \cdot \tau_y}{\sin(\phi) \cdot \cos(\phi + \rho - \gamma)} \cdot b \cdot h \\
T = \frac{0.9 \cdot \tau_y \cdot \cos(\gamma) \cdot \lambda_h + T_o}{\rho_d \cdot c \cdot \cos^2(\phi - \gamma) \lambda_h + T_o}
\]

Table 1 shows first the estimated cutting process reactions by means of the analytical Oxley’s parallel shear zone model for orthogonal cutting AISI 1045 with \( v_C = 150 \text{ m/min} \). The estimated values of the temperature, cutting force and feed force agree well with the measured results (deviation < 10%). With decreasing uncut chip thickness \( h \), chip compression, strain, strain rate and temperature increase, however shear angle, shear flow stress and machining forces decrease.

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<th>( f )</th>
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<th>( \varepsilon )</th>
<th>( \dot{\varepsilon} / \varepsilon )</th>
<th>( \tau_y )</th>
<th>( T / \text{MPa} )</th>
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4. Characterisation and modelling of friction behaviour

To characterize the contact friction behavior in the performed orthogonal cutting tests, the apparent friction coefficient $\mu$ is first calculated by means of the rake angle and the measured cutting and feed force using Eq. 1, see Fig. 5. For selected cutting parameters, the apparent friction coefficient shows minor change during the cutting operation. With decreasing uncut chip thickness $h$, the friction increases and will tend to converge to a definite limit. The obtained friction curves for smaller uncut chip thickness $h \leq 0.1$ mm are not smooth indicating a change in the friction behavior compared to $h > 0.1$ mm.

Fig. 6 shows the influence of the cutting parameters $h$ and $v_C$ on friction. To check the operating friction mechanism during cutting, the bottom side of the deformed chip has been photographed and represented in Fig. 6. By material cutting with $v_C = 150$ m/min and chip thickness compression ratio $\lambda_0 \leq 2$, sliding friction dominates (see Fig. 6 a, b, c). On the contrary, the governing friction mechanism by $\lambda_0 > 3$ is sticking (see Fig. 6 d, e, f). The Beginning of sticking friction can be calculated using the von Mises yield criterion to $\mu_s = 0.577$, which is the maximum possible value of sliding friction. The material thermal softening due to the rise of the cutting speed leads to a decrease of friction by sliding (at higher values of the uncut chip thickness) and an increase by sticking (more adhesion at lower $h$ values). Fig. 7 illustrates the temperature generation and distribution at tool-chip interface by (a) sliding and (b) sticking friction. By sliding friction, the temperature is uniformly distributed on the bottom side of the chip. On the contrary by sticking, the temperature distribution is concentrated on the tip of the cutting edge and the entire chip will be heated. At the end of the cut, the sliding chip leaves the rake face and the sticking one remains adhered.

To describe the discussed friction behavior in this work, a double exponential function $\mu = f(h,v_C)$ is proposed, see Fig. 6. The friction model parameters $C_1$, $C_2$ and $C_3$ depend on the used cutting speed and are listed in Fig. 6.

Fig. 5. Calculated apparent friction coefficient $\mu$ over cutting length.

Fig. 6. Influence of the cutting parameters $h$ and $v_C$ on friction.

Fig. 7. HS temperature recording by (a) sliding (b) sticking ($v_C = 150$ m/min).
5. FE validation of the friction modelling approach

In order to validate the developed friction modelling approach, 2D thermo-mechanical coupled FE cutting simulations are performed with different uncut chip thicknesses \( v_C = 150 \text{ m/min} \) by using the commercial implicit FE code DEFORM-2D\textsuperscript{TM}, see Fig. 8. The tool (rigid body with mesh) is constrained in x and y directions and the movement of the workpiece (deformable mesh) is specified by its translation only in x direction. For the discretization of the tool and workpiece, the Lagrangian approach was applied.

![Fig. 8. 2D FE model for orthogonal cutting AISI 1045.](image)

In the performed simulations, a gradient continuous auto-remeshing is used for generating the mesh of the workpiece. To minimize the interpolation error and to improve the convergence of the solution, the mesh density in areas with high gradients of plastic strain has to be increased. The cutting process in the simulation is modeled as forming operation and the chip formation is simulated by continuous remeshing without using any material fracture criteria. The workpiece is selected as a deformable body with thermo-visco-plastic and isotropic material behavior. The thermo-mechanical material flow behavior in the simulation was described with the modified Johnson-Cook model according to Eq. 5. The tool is modeled as rigid and has a constant mesh to calculate the temperature distribution within the tool. The cutting material data used in the simulation was obtained from the literature [16]. Friction at the tool-chip interface is described by the friction model discussed in section 4 and is implemented in the FE pre-processing as follows:

\[
\mu < 0.577 \rightarrow \text{only sliding friction (Coulomb friction)} \\
\mu \geq 0.577 \rightarrow \text{sliding + sticking friction (hybrid friction)}
\]

For the thermal boundary conditions, conduction and convection of the generated heat were applied. The gap conductance and the thermal convection coefficient between two contacting surfaces were assumed to be equal to \( 10^3 \text{ W/m}^2\text{K} \) and \( 20 \text{ W/m}^2\text{K} \), respectively. The thermal properties of the workpiece material (thermal expansion, thermal conductance, heat capacity) are given as a function of the temperature. The workpiece and tool temperatures were initially set at room temperature \( T = 20^\circ\text{C} \). In order to adapt the energy balance in the modeled workpiece to the experiment, the nodes temperature at the bottom side of the workpiece and at the fixed edge of the tool was kept constant at a value of \( T = 20^\circ\text{C} \).

Fig. 9 shows a comparison between the measurement and FE prediction of chip form and shear angle for different cutting conditions, a) only sliding friction \( h = 0.5 \text{ mm} \), b) sliding and sticking friction \( h = 0.2 \text{ mm} \), and c) only sticking friction \( h = 0.04 \text{ mm} \), whereby a good prediction could be obtained. The computed cutting and feed force agree also with the measured values (deviation \(< 10\%\)).

![Fig. 9. FE model validation, chip form and shear angle \( v_C = 150 \text{ m/min} \).](image)

The distribution of the computed effective plastic strain, stress, strain rate as well as the temperature in the tool-workpiece system are presented exemplarily for \( h = 0.5 \text{ mm} \) and \( v_C = 150 \text{ m/min} \) in Fig. 10. Here too, a realistic prediction of the local state could be reached. This computed thermo-mechanical load and the characterized friction mode are necessary to determine the wear mechanism. Special investigations in this context will be treated separately in further papers.
6. Conclusions

In this research work, a new constitutive friction model is developed and successfully validated by means of FE simulation of cutting AISI 1045 with different cutting parameters. This friction model describes the operating friction mechanisms during metal cutting and is based on orthogonal cutting tests and the Merchant’s circle force diagram. The main results achieved in this investigation can be summarized as follows:

- Advanced fundamental test-bench with high speed filming and thermography was presented for a deep analysis of the mechanics of the cutting process.
- The classical Oxley’s parallel shear zone theory was successfully applied to estimate cutting process reactions.
- Quantitative direct analysis of the friction behavior in metal cutting was performed.
- A friction model was proposed to directly link the friction mechanics to the cutting parameters.
- The developed friction model is successfully validated by means of FE simulation of orthogonal cutting AISI 1045.

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