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PRODUCTION PROCESS

A new experimental methodology to analyse the friction behaviour at the tool-chip interface in metal cutting

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Abstract This paper investigates a new test to analyse the friction behaviour of the tool-chip interface under conditions that usually appear in metal cutting. The developed test is basically an orthogonal cutting process, that was modified to a high speed forming and friction process by using an extreme negative rake angle and a very high feed. The negative rake angle suppresses chip formation and results in plastic metal flow on the tool rake face. Through the modified kinematics and in combination with a feed velocity that is five to ten times higher than in conventional metal cutting, the shear and normal stresses are only acting in a simple inclined plane, allowing to calculate the mean friction coefficient analytically. In addition, the test setup allows to obtain the coefficient of friction for different temperatures, forces and sliding velocities. Experiments showed, that the coefficient of friction is strongly dependent on the sliding velocity for the example workpiece/tool material combination of C45E+N (AISI 1045) and uncoated cemented carbide.

Keywords Friction · Metal cutting · Machining

1 Introduction

Tribological processes at the tool-chip interface are vitally important for the metal cutting process. In particular the friction between the tool, chip and workpiece directly affects the chip formation and therefore the tool life, surface quality and the energy consumption of the process respectively. In consequence, detailed knowledge about friction in metal cutting is crucial for further developments and especially for modelling of the metal cutting process [1]. State of the art chip formation models are mainly based on the finite element method. The finite element method allows to conduct coupled analyses, that include structural mechanics, heat transfer and their related boundary conditions. According to that, different submodels such as material models, interface heat transfer models and interface friction models have to be implemented. In the context of modelling metal cutting or forming processes the friction model is essential because it has a high impact on the structural mechanics as well as the resulting generation of heat.

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2 Background

Due to its high relevance, friction in metal cutting has been subject to many research activities and studies in the past. A number of shear and normal stress distributions were proposed for a local description of friction along the tool-chip interface. For instance, Zorev proposed an exponentially decreasing normal stress along the tool-chip contact length [2]. For the shear stress distribution he proposed a model that divides the tool-chip contact into two zones: The sticking and the sliding friction zone. For the sliding zone he proposed the friction stress τ to be proportional to the normal stress σ_N. In the sticking zone near the cutting edge, the friction stress is limited to a constant shear flow stress k of the chip material. Investigations by Takayema and Usui [3] and Childs [4] support the plateau shear stress level in the sticking zone. Zorev's assumptions, that are used by a number of authors, can be summarised in Eqs. 1 and 2.

$$\tau = \mu \cdot \sigma_N \quad \text{for } \mu \cdot \sigma_N < k \tag{1}$$

$$\tau = k \quad \text{for } \mu \cdot \sigma_N \geq k \tag{2}$$

To use the relationship in Eqs. 1 and 2 in a chip formation model, the local coefficient of friction μ must be determined under the specific local conditions in the tool-chip interface. This local measurement or analysis is the challenge in this context, because local temperatures, stresses and sliding velocities can be very different over the tool-chip contact length. One basic approach to obtain the coefficient of friction in metal cutting is the model by Merchant [5], which calculates the average coefficient of friction according to Eq. 3.

$$\mu = \frac{F_c + F_t \cdot \tan\gamma}{F_t - F_c \cdot \tan\gamma} \tag{3}$$

In consideration of the rake angle γ the equation transforms the cutting F_c and feed force F_t into a tangential and normal force on the rake face. This concept assumes a constant friction coefficient over the whole tool-chip contact length. Based on the stress distributions measured by different authors [2–4, 6] the friction coefficient can be considered as non constant. Furthermore the model cannot account for seizure conditions like the one proposed by Zorev. In addition, it considers the tool to be ideally sharp, to neglect elasto-plastic stresses acting on the cutting edge radius.

Friction processes in machining are characterised by wide ranges of temperatures, very high contact pressures and different sliding velocities [7]. These parameters are on the one hand variable along the tool-chip contact length and on the other hand they vary for different process parameters like the cutting velocity. Therefore, other approaches use analogy experiments to determine friction data with controlled parameters like specimen temperatures, different sliding velocities and varied normal forces. The objective of these tests is to identify relationships between the coefficient of friction and controlled parameters. Nevertheless, the contact conditions of the analogy experiments have to be comparable to the metal cutting conditions in order to obtain valid data. Furthermore the tribochemical state of the contact partners have to be equal to the chip formation process [8].

The first tribometers were pin-on-disc systems, originally designed for sliding wear testing, where a pin rubs over a rotating disc surface to record forces normal and tangential to the pin to obtain the coefficient of friction. In first designs, the pin rubs more than once over the same friction track and did neither fulfill the required contact conditions nor the refreshed surface of the metal cutting process. Thus new tribometers had to be developed. Olsson modified the pin-on-disc system with a refreshing tool and was able to reach relevant sliding velocity and contact temperatures, but low contact pressures of around 15 MPa [9]. Grzesik and Zemzemi also used modified pin-on-disc system, while Grzesik focused on the tool wear and rubbed more than once on the same friction track [10]. Zemzemi worked with a refreshed surface and was also able to reach the required contact conditions [11, 12]. Nevertheless, this experiment does not ensure chemical purity of the contact surface because the machined surface is still able to react with the environment before the friction pin contacts the surface. In addition, the spherical shape of the friction pin arises elasto-plastic stresses which are not separable from the friction stresses without numerical postprocessing. Finally the test is extensive because of the necessary special devices, specimens and the mandatory postprocessing.

Another approaches are modified pin-on-ring systems by Hedenqvist [13] and Bonnet [14], where a pin rubs over a cylindric surface in a helical movement. While both designs cannot completely avoid oxidized surfaces, the design of Bonnet is able to create the required contact pressures. However, because of the spherical shape of the pin and the relative axial movement of the workpiece, the frictional and normal force are not completely geometrically defined. Brocail developed a tribometer on a new principle, in which two cylinders represent the tool and the workpiece [15]. Although Brocail's tribometer provides the required contact pressure and temperature, the tribometer cannot develop high sliding velocities and ensure an unoxidized surface. In summary, no tribometer exists according to the state of the art, which is able to provide the required contact conditions, a refreshed unoxidized surface with reasonable experimental or numerical efforts.

3 Concept and theory of a new friction test

A new friction test was designed to determine and analyse the normal and shear forces under the conditions of metal cutting. To create the contact conditions, the orthogonal cutting process has been modified in order to achieve a more uniform distribution of stresses, sliding velocities and temperatures along the tool-chip contact length compared to the real cutting process. Figure 1 shows the concept for this approach, which can be considered as a metal cutting process with an extreme negative rake angle. The negative rake angle can be realised by rotating the workpiece in opposite direction and by using a very high feed.

This kinematic approach turns the clearance angle α_o into an extreme negative rake angle γ_o. Compared to the real metal cutting process, the chip formation is avoided and results in severe plastic deformation and metal flow on the clearance face of the tool, similar to plastic deformation on the rake face in the real metal cutting process. The difference to the metal cutting process is, that the total resultant force is only acting on a simple inclined plane.

The cutting edge radius is not or negligible in contact with the workpiece. In consideration of this fact, the ratio between friction force F_f and normal force F_N can be calculated by measurement of the forces F_y and F_z and geometrical transformation. The direction of the normal and the friction force is defined by the inclined plane, see Fig. 1. Therefore the ratio μ of the friction and normal force can be calculated by Eq. 3 analogous to Merchant's model. In addition, the chemical purity of the contact interface is an important boundary condition. In common friction tests, this condition is not always fulfilled because heating of the contact specimens can result in oxidation or unintentional heat treatment processes, which results in modified tribological conditions. The proposed test does not need heating of the contact partners because high temperatures are directly generated by the friction and plastic work similar to the real metal cutting process. Analogous to the cutting process the temperature can be modified by the cutting speed / sliding velocity and contact length of the deformation zone. To ensure a refreshed surface the cutting insert can be used to machine the surface with an orthogonal cutting process, just seconds before the subsequent friction process. However this does not guarantee the absence of chemical reactions, but an adequate chemical purity is further given by the tool-chip interface itself. Similar to real cutting processes the interface directly enlarges the workpiece surface. Through the forming process, the disc width b is enlarged approximately by factor two in the workpiece / tool interface, depending on the feed. That means that a major fraction of the generated surface was not in contact with the environment before the process. Furthermore the duration of the friction test is less that one rotation of the workpiece to avoid rubbing against the already deformed workpiece surface. The test also involves high contact pressures, which can be calculated by the relationship force measurements and surface area of the friction and deformation zone.

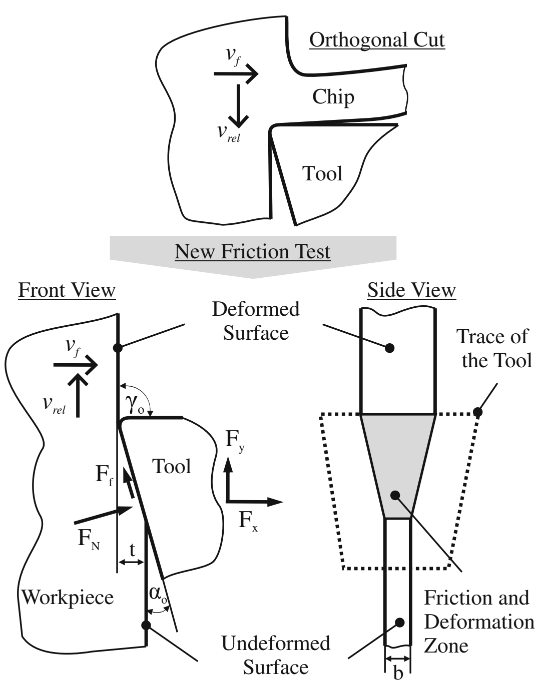

Fig. 1 Concept of the new friction test

4 Experimental setup

Figure 2 shows the experimental setup, that has been used to realise the concept shown in Fig. 1. A grooving tool and a workpiece rotating in opposite direction compared to the conventional turning process has been used. In this case, the clearance angle of 10° turns into a rake angle of $-80°$ and the chip formation is suppressed in order to realise the friction and forming process.

A Kistler dynamometer is used to obtain forces during the process. In addition, temperatures are measured with a fibre-optic two-color pyrometer. The width of the disc b is limited to approximately 1 mm to avoid breakage of the cutting insert due to overload. The feed was 1.5 mm/rev and the programmed target diameter was 1 mm less than the starting diameter d_{start}. In this case the maximum deformed layer thickness (see t in Fig. 1) of 0.5 mm was reached after a workpiece rotation angle of 120° after the first contact of tool and workpiece. After the maximum force and deformed layer thickness has been established, the tool is pulled back with the same feed of 1.5 mm/rev. In this study an uncoated cemented carbide insert *Sandvik N151.2-540-40-3B H13A* has been utilised. The blank inserts were grinded to a surface roughness of $R_a = 0.1$ µm (according to standard DIN EN ISO 4287:2010-07) and had a cutting edge roundness of 60 µm to stabilise the

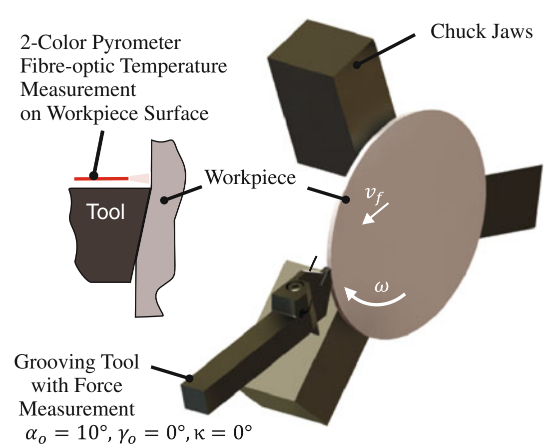

Fig. 2 Experimental concept

cutting edge. The workpiece material was C45E+N (AISI 1045) in normalised state.

5 Experimental results

The test has been carried out for different sliding velocities to account for the assumption, that the sliding velocity on the tool-chip interface is a local variable. Apart from that, the average sliding velocity is linked to the cutting velocity. Therefore it is necessary and reasonable to analyse the frictional behaviour for different sliding velocities. In this study velocities of 20, 50, 100, 150, 200 m/min were tested. A plot for two example experiments shows Fig. 3 for a sliding velocity of 200 m/min (a) and 20 m/min (b).

In Fig. 3a, the surface temperature, measured above the contact zone, is increasing from room temperature to about 1,000 °C, while the normal force is increasing from zero to approximately 1700 N and afterwards decreasing again. The increase and decrease of the forces is related to the increasing and decreasing deformed layer thickness within the feed movement (see *t* in Fig. 1). After the first contact between the workpiece and tool, it takes a workpiece rotation angle of 120° to establish the maximum deformed layer thickness and peak forces. Afterwards, a feed movement in the opposite direction is conducted, resulting in a decreasing deformed layer thickness. The process ends after a rotation angle of 240°. The feed used in this case is an empirical value. On the one hand, it should be as high as possible in order to form a large inclined plane compared to the cutting edge radius. On the other hand, the feed is limited to avoid tool breakage. At the beginning and end of the process, a slightly higher friction coefficient is calculated. A possible explanation is the entrance and exit of the tool. During these periods the cutting edge radius influences the deformation and therefore the deformation does not take place in the geometrically defined inclined plane. In addition there might be elastic effects that have to be considered as well.

After a certain force and subsequently a certain deformation has been reached, the coefficient of friction is nearly constant. A temperature-induced influence on the coefficient of friction cannot be observed in the single measurement plot. If there is any temperature influence this would mean that the proposed experimental setup is not suitable to detect this relationship. On the other hand a temperature increase is measured before the peak force has been reached and a temperature decrease after the force starts to decrease again. This means that the average temperature in the contact zone must be linked to the forces within the friction process. Therefore it is concluded that the temperature is not constant during the process, even though the measured temperature might not be equal to the contact zone temperature. Nevertheless, the measurement shows constant friction coefficients over a wide range of temperatures and forces.

Figure 3b shows a measurement graph for a sliding velocity of 20 m/min. In this case, the process shows oscillations in the force and temperature plot. The surface of the workpiece shows smeared material on the generated surface instead of a smooth surface for the high velocity of 200 m/min. It is concluded that this smearing and sticking effect, comparable to the built-up edge formation in metal cutting, is responsible for the force oscillations and the high values for the coefficient of friction. In addition, it is concluded that smeared material extends the process duration during the backward movement in the period between 600 and 800 ms, because the smeared material extends the cutting edge similar to a built-up edge in machining. Due to the process kinematics, the time period of the forward and backward movement should be equal but in this case the backward movement takes approximately twice as long as the forward movement. This can also explain the drop in the coefficient of friction at 600 ms. However this has not an influence on the obtained coefficients of friction. The coefficients for each experiment were obtained during the first period, when the forces

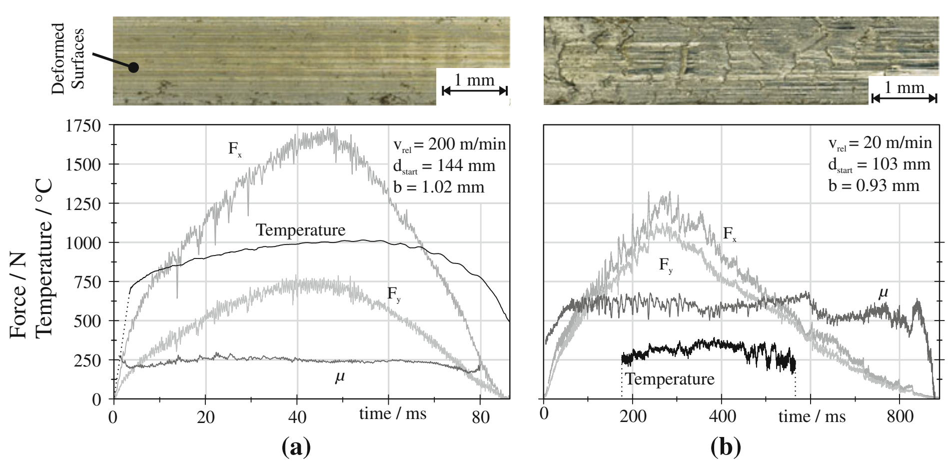

Fig. 3 Combined force and temperature measurement for a sliding velocity v_{rel} of **a** 200 m/min and **b** 20 m/min

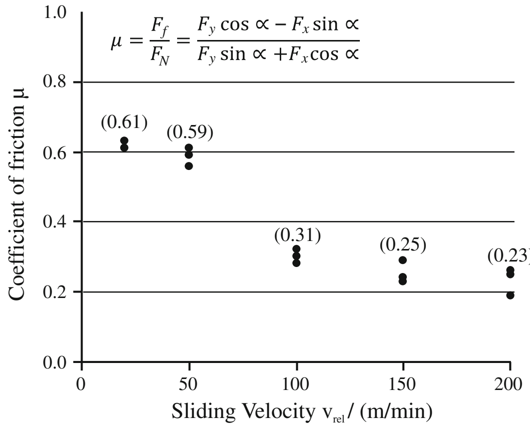

Fig. 4 Coefficient of friction for different sliding velocities v_{rel} for the material combination C45E+N (AISI 1045) and uncoated cemented carbide. Average values in *brackets*

are increasing. The results of the temperature measurement also show a higher uncertainty at lower temperatures. The temperature signal (sample rate 20 kHz) was filtered with a moving average filter (ten values) and has been cut off for periods of high noise (dotted line), while the force signals are unfiltered.

Finally, Fig. 4 shows the friction coefficient for different sliding velocities which have been repeated twice. At low sliding velocities the friction coefficient is very high and strongly decreases between 50 and 100 m/min. At velocities between 100 and 200 m/min the coefficient of friction slightly decreases, but the difference is comparable to the measurement uncertainty. A decreasing coefficient of friction with increasing sliding velocities has also been observed by other authors [15–17]. The sliding velocity has a direct influence on other factors like the temperature and normal pressure. Therefore, further experimental investigations, combined with FEM models of the friction process, are necessary in order to calculate and separate dependent factors in the friction and deformation zone. Apart from that, the obtained values in Fig. 4 can be utilised to create a velocity dependent friction model as a submodel for chip formation or forming models for this specific combination of tool and workpiece material.

6 Conclusions and future work

A new friction test for metal cutting has been developed which uses a conventional lathe and tool without special devices and specimen preparation. The process can be considered as the orthogonal cutting process while the workpiece is rotating in the opposite direction. This turns the clearance angle of the tool into an extreme negative rake angle. In combination with a very high feed, severe plastic deformation and friction takes place in the tool/workpiece interface. Due to the inclined deformation plane, the ratio of normal and tangential force can be calculated from the measured forces. The test provides interface temperatures, heating rates, pressures and sliding velocities comparable to real cutting processes.

Investigations have been conducted for the material combination C45E+N (AISI 1045) and uncoated cemented carbide (Sandvik H13A). In modern high speed cutting processes, high sliding velocities occur in the interface between tool and chip. For these cases the proposed friction process shows excellent stability and almost constant ratios of the forces, acting on the tool. The results for this material combination show a strong relationship between the friction coefficient and the sliding velocity. However, a clear temperature relation to the friction coefficient is not observed during the process. It is concluded that other complex material aspects are responsible for the modified ratio of normal and tangential forces at low sliding velocities.

In future work further experiments are going to be conducted to analyse the velocity effects of the friction process for different material combinations. Furthermore the test will be modified for a better separation of the process variables. In order to separate the relationship between the sliding velocity and temperature, a heated workpiece, modified kinematics and variable contact lengths will be used. However, a temperature modification will also modify temperature dependent material properties like the flow stress of the material. Therefore, additional metallographic and FEM analyses will support the investigations to provide a better understanding of the complex friction processes in metal cutting.

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