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Analytical and experimental investigation of rake contact and friction behavior in metal cutting

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ABSTRACT

In this study, the friction behavior in metal cutting operations is analyzed using a thermomechanical cutting process model that represents the contact on the rake face by sticking and sliding regions. The relationship between the sliding and the overall, i.e. apparent, friction coefficients are analyzed quantitatively, and verified experimentally. The sliding friction coefficient is identified for different workpiece–tool couples using cutting and non-cutting tests. In addition, the effect of the total, sticking and sliding contact lengths on the cutting mechanics is investigated. The effects of cutting conditions on the friction coefficients and contact lengths are analyzed. It is shown that the total contact length on the rake face is 3–5 times the feed rate. It is observed that the length of the sliding contact strongly depends on the cutting speed. For high cutting speeds the contact is mainly sliding whereas the sticking zone can be up to 30% of the total contact at low speeds. From the model predictions and measurements it can be concluded that the sticking contact length is less than 15% for most practical operations. Furthermore, it is also demonstrated that the true representation of the friction behavior in metal cutting operations should involve both sticking and sliding regions on the rake face for accurate predictions. Although the main findings of this study have been observed before, the main contribution of the current work is the quantitative analysis using an analytical model. Therefore, the results presented in this study can help to understand and model the friction in metal cutting.

1. Introduction

The friction due to the contact between the workpiece and the cutting tool is one of the key subjects in machining research. It is well known that cutting involves three deformation zones. The primary shear zone, i.e. the shear plane, is responsible for the chip formation whereas in the secondary shear zone on the rake face the workpiece and tool are in a complex state of contact. The third region, on the other hand, is responsible for ploughing and flank contact. Numerous models have been proposed involving, analytical with thin [1] and thick [2] shear zone approaches, semi-analytical [3,4], and numerical (mostly FEM based) [5,6] methods. Two important inputs for these models are the material model parameters and the friction coefficient between the tool and the workpiece material. These two inputs can be considered to be independent of the cutting mechanics as they are related to the mechanical and physical properties of the materials. Identification of both properties is very critical for accurate modeling of the machining processes. The focus of this paper is on the friction characteristics in metal cutting operations.

Being a common topic in mechanics, friction has been extensively studied in basic sciences. However, machining researchers have also paid special attention to friction due to its importance in cutting processes. The early studies on the subject concluded that there is a direct relationship between the shear angle and the friction. Using minimum energy principle for the continuous type chips, Merchant [1] concluded a relationship between the shear angle and the rake face friction. Oxley, [2] on the other hand, included the strain hardening effect in the slip-line model. As another approach, the semi-analytical method known as the mechanics of cutting [3,4] relates the apparent friction coefficient to the rake angle, feed rate and the cutting speed, and uses them in force predictions. However, this approach may take longer testing time since high number of tests must be carried out depending on the ranges. Similar mechanistic models do not provide much insight about the friction behavior of the workpiece and tool couples. In FEM modeling [5,6] the researchers mostly focused on the material behavior and chip formation and lacks the importance of the friction conditions on the rake face. Lee and Shaffer [7] obtained a similar relationship by applying slip-line field theory to the orthogonal cutting. The solutions presented in

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these studies have assumptions which do not accurately represent the friction behavior of the process. Based on the experimental observations, however, it has been well accepted that the overall (apparent) friction coefficient on the rake face decreases with the increasing rake angle. On the other hand, the effects of other parameters such as cutting speed or feed rate were not known that well. Eventually, Zorev [8] approached the problem by observing the normal pressure and shear stress distributions on the rake face, and proposed distribution forms for them. Basically, Zorev [8] proposed that the material exiting the primary shear zone reaches the rake face with such a high normal pressure that there is a sticking contact zone close to the tool tip. Due to the drop in the normal pressure, the contact state changes to the sliding (Coulomb) friction away from the tool tip on the rake face. This behavior is also verified by numerous researches in later studies [9–12] mostly by split-tool experiments measuring the normal pressure and shear stress distributions on the rake face. In a later study, Fang [13] concludes that the tool–chip friction decreases with increasing absolute value of negative rake angle and with increasing cutting speed, by applying slip-line field analysis.

Friction between two contacting bodies has several dependencies such as the material pair, temperature, pressure, and speed depending on the application ranges [14–17]. For instance, in a recent study, Philippon et al. [18] conducted several experiments in an original test setup in order to investigate the sliding friction behavior at high sliding velocities, and concluded that the sliding coefficient of friction strongly depends on the speed and the pressure. In a different study Moufki et al. [14] proposed an orthogonal cutting model which relates the sliding friction coefficient to the mean temperature on the rake face.

A recent study [17] proposed an analytical orthogonal cutting model, which considers the sticking and sliding friction regions on the rake face and uses Johnson-Cook (JC) constitutive model. The JC constitutive relation is relatively simple, one dimensional model that accounts for the effects of strain, strain rate, and thermal softening on flow stress utilizing von Mises yield criterion. It describes the material hardening behavior based on the well-known power-law function. Also, this empirical relation is relatively simple to calibrate for a given material. It is relatively easy to implement into computer codes, inexpensive to use, and produces reasonably accurate predictions for a range of materials if the loading conditions do not exceed those used during the parameter identification tests. In the model [17], the sliding friction coefficient is related to the friction speed, and calibrated using a small number of orthogonal cutting tests, where the JC parameters are also calibrated for the given cutting speed range. The proposed model has both calibration and prediction capabilities.

Accurate representation of contact behavior on the rake face is critical for the thorough understanding and modeling of the metal cutting operations. In this regard, quantitative analysis of the friction behavior in metal cutting is important for better understanding of the nature of the process. The identification of the sliding friction coefficient between the workpiece–tool couple and the relation of the sliding friction coefficient to the apparent one is critical for process modeling. The contact lengths which are basically the physical representations of the friction behavior on the rake face, must also be modeled and analyzed. Based on these, the objective of this study is to further investigate the friction behavior in metal cutting operations. The focus of the study in this paper is on the mechanical behavior rather than micro-structural investigation. For this purpose, the rake contact model presented in [17,19] is used throughout this paper.

2. Thermomechanical dual-zone model

In this section, the cutting model which is used in this study is briefly presented. Although the dual-zone model detailed formulation applied to the orthogonal cutting conditions can be found in the Appendix, the detailed formulation for the oblique cutting conditions can be found in [19]. In this model, the contact between the chip and the tool on the rake face is represented by a dual-zone approach. Basically, the contact is divided into the sticking and a sliding friction region, which was originally proposed by Zorev [8] (see Fig. 1). In the first region, the contact condition is plastic due to the high normal pressure exerted on the tool, whereas in the second region the contact is elastic which can be represented by the sliding friction. There are two different friction coefficients that are defined on the rake contact. The apparent friction coefficient μ_a is due to the total cutting forces acting on the rake face. The sliding friction coefficient μ, on the other hand, is only due to the forces acting on the sliding region on the rake face.

The normal pressure distribution on the rake face is needed for the formulation of forces. The following distribution is selected as it is used and verified by several studies [10,11,14]

$$P(x) = P_0\left(1 - \frac{x}{\ell_c}\right)^{\zeta} \tag{1}$$

where ℓ_c is the total contact length, x the distance on the rake face from the tool tip, and ζ an exponential constant which represents the distribution of the pressure, and is selected as 3 in the current study based on the analysis of the split-tool test results [10,11]. It can be observed from Fig. 1, that the shear stress on the rake face is equal to the shear yield stress of the material (τ_1) along the sticking region with length ℓ_p. In addition, the shear stress in the sliding region is equal to the product of the sliding friction coefficient (μ) and the normal stress (P), according to the Coulomb friction law. Therefore, the mathematical representation of the shear stress distribution on the rake face can be defined as follows:

$$\tau = \begin{cases} \tau_1 & x \le \ell_p \\ \mu P & \ell_p \le x \le \ell_c \end{cases} \tag{2}$$

The three important outputs of the model is the total contact length ℓ_c, the sticking length ℓ_p, and the relationship between the sliding and sticking friction coefficients [19]

$$\ell_c = f\,\frac{\zeta + 2}{2}\,\frac{\sin(\phi_n + \lambda_a - \alpha_n)}{\sin\phi_n \cos\lambda_a \cos\eta_c} \tag{3}$$

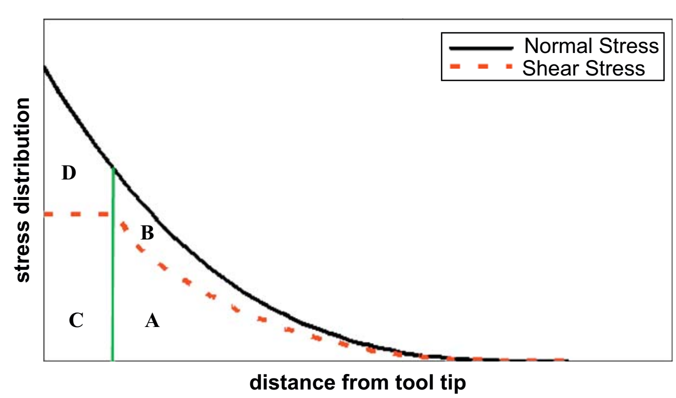

Fig. 1. Stress distributions on the rake face.