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Experimental investigation on friction under metal cutting conditions

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ABSTRACT

This paper presents an experimental test to analyze friction phenomena within the tool–chip interface in metal cutting. Therefore, it is designed to obtain experimental data under conditions that are characterized by high contact temperatures, pressures and sliding velocities. The experimental approach is derived from an orthogonal cutting process, modified to a high speed forming and friction process by using an extremely negative rake angle. Such an angle suppresses the formation of chips and results in a smooth plastic flow of metal over the tool surface which generates very high contact temperatures and therefore approaches the conditions of metal cutting. Investigations were conducted for three workpiece materials AISI 1045, AISI 4140 and Inconel 718 in combination with uncoated WC-6Co cemented carbide tools. For these materials, the experimental analysis shows significant thermal softening within the contact interface caused by frictional heat generation and plastic deformation. To account for the observed phenomena, a temperature dependent friction model is proposed and evaluated by a finite element model.

1. Introduction and State of the Art

The thermo-mechanical load in the tool–chip interface is vitally important for the design of metal cutting processes. It is basically determined by the mechanical stresses of the plastic deformation and friction in the so-called primary and secondary shear zones. In combination with the sliding velocities in the tool–chip interface, these stresses generate very high temperatures up to the melting temperature of the workpiece material [1]. Consequently, this load affects the whole process performance because of the direct correlation between the thermo-mechanical load and the tool wear, cutting forces, energy consumption and chip formation. Nevertheless, the friction in the tool–chip interface is still a challenging research topic and not fully understood [2]. Up to now, there is no existing friction model, to generally describe the contact between tool, workpiece and chip under the conditions of metal cutting [3]. The tool–chip interface in metal cutting involves several complex physical phenomena. In general, metal is flowing along the interface and the material is continuously changing its mechanical and thermal state due to the plastic deformation and generated heat. Hence, the contact behavior will be locally different. This local behavior complicates the analysis to great extent. The external measured forces, which are often used to analyze the friction behavior, are involved with a loss of information about the local state of the material. To analyze the local contact behavior there are two common approaches: tribometer experiments and a direct analysis of the metal cutting process. In the following sections these methods are briefly discussed.

1.1. Analysis of tool–chip interface friction by tribometer tests

For different engineering applications tribometers are utilized to analyze wear and friction phenomena between different contact partners with controlled parameters like specimen temperatures, different sliding velocities and varied normal forces. The most challenging task in this context is to ensure that the controlled parameters are not influenced by the process itself. For example, the temperatures of both contact partners are controlled but nevertheless the friction in combination with high sliding velocities can raise the preset temperature significantly. In this case, the real contact temperature differs from the specified value. Due to high local temperature gradients this increase is also very difficult to measure. However, a lot of different methods have been developed to reproduce and analyze the contact conditions of metal cutting. Olsson, for example, modified a pin-on-disc system with a refreshing cutting tool to ensure a fresh tribochemical state of the workpiece material surface [4]. The test is able to generate high sliding velocities and contact temperatures, but is limited to low contact pressures of around 15 MPa [4]. Other approaches from Zemzemi (Pin-on-Cylinder), Grzesik (Cylinder-on-Disc), Hedenqvist (Cylinder-on-Cylinder), Brocail (Cylinder on Cylinder) or Rech (Pin-on-Cylinder) can exemplarily be found in [5–9]. In principle, these systems have the disadvantage that the contact surface is not fully geometrically defined due to point, line

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or spherical contact in combination with plastic deformation of the softer material. Subsequently, the direction of the tangential and normal forces cannot be determined precisely to calculate normal and tangential contact forces. To overcome this issue, numerical post-processing can be used to determine the friction coefficient as for instance done by Zemzemi et al. [5] and Bonnet et al. [10].

1.2. *Analysis of tool–chip-interface friction by metal cutting tests*

Another opportunity to analyze contact phenomena in metal cutting is the direct investigation of the cutting process itself. The simplest method is the analysis of the cutting force components, as suggested by Merchant [11]. He analyzed the coefficient of friction by measuring the normal and tangential force acting on the rake face of the tool. However, the assumptions that the ploughing force acting on the cutting edge radius and initial flank wear can be neglected do not match with further investigations [12]. In addition, this approach assumes the coefficient of friction to be constant regardless of local differences in the thermal and mechanical state of the material. On the other hand, different authors showed that the friction coefficient can be considered as non-constant [13,14,9]. To further analyze contact and friction behavior on a more local scale, other methods have been developed like the split-tool technique (e.g. [15]) or the observation of photoelastic tools (e.g. [16]). Astakhov discussed and summarized these methods in [17]. Without a discussion of the advantages and disadvantages of these methods all have an important drawback in the context of friction modeling. These approaches cannot link the contact stress distributions to the local strain and temperatures of the material, which greatly influence the plastic material behavior.

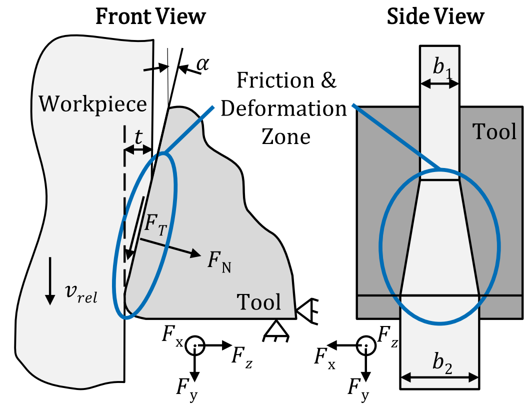
2. Concept of a friction test

In order to resolve some problems of the previously mentioned methods a new friction test was designed to obtain contact forces for different temperature levels and sliding velocities in the contact zone. Fig. 1 shows the kinematic concept. The test was derived from the orthogonal cutting process. In contrast to cutting, an extremely negative rake angle is utilized to suppress chip formation which results in a simple high speed forming process and plastic metal flow over the inclined plane of the tool.

Thus, the normal contact force F_N and tangential contact force F_T can easily be calculated by geometrical transformation of the measured forces F_z and F_y. The negative rake angle in this case is defined as the tool inclination angle α. In contrast to a previously published paper [13], the test was enhanced by using linear moving thin sheet metals as workpieces instead of rotating thin discs. The undeformed width of the workpieces b_1 is significantly smaller than the tool width. The friction and deformation zone has approximately a trapezium shape and results in a deformed workpiece width b_2. In summary, the temperature, strain, and strain rate levels can be primarily controlled by the process parameters t, α, v_{rel}:

(a) The depth of engagement between tool and workpiece t characterizes the strain distribution within the contact zone and resulting surface layer of the workpiece.
(b) In addition with the tool inclination angle α the depth of engagement t also defines the contact length and both are affecting the contact temperature.
(c) Furthermore the relative velocity v_{rel} between the fixed tool and the moving workpiece affects the strain rate and interface sliding velocity and therefore the resulting contact temperature.

A further explanation is given in Fig. 2. It shows the relationship between α, the depth of engagement t and the contact length *CL*.



α: Tool inclination angle
t: Depth of engagement
F_N: Normal contact force
F_T: Tangential contact force
F_x: Measured force x-direction
F_y: Measured force y-direction
F_z: Measured force z-direction
b_1: Undeformed workpiece width
b_2: Deformed workpiece width
v_{rel}: Relative velocity between tool and workpiece

Fig. 1. Kinematic concept of the friction test.

The contact length primarily effects the temperature in the contact zone. A material particle that passes the contact zone is heated up to higher temperatures because the plastic deformation is larger and the friction length is also increased. Therefore, it can be assumed that the mean contact temperature is also raised by an increased contact length. In comparison to other tribometers the approach provides the following advantages.

(a) Metal is severely deformed under high strain rates which directly results in very high temperatures similar to metal cutting. A heating device is not necessary.
(b) The contact forces can be calculated easily due to the geometrically well-defined tool inclination plane.
(c) The chemical purity inside the contact zone is directly realized by the significant enlargement of the workpiece contact surface during the deformation. Thus, a large proportion of the workpiece material was not in contact with the atmospheric environment prior to the process.
(d) Standard cutting tools and simple metal sheets are used as specimens which result in low testing expenditures.

In summary, the test concept is a promising approach to realize the metal cutting conditions and to investigate different parameters separately by a variation in the process parameters. For instance, different temperature levels can be realized for the same sliding velocity by using a larger contact length. In conventional pin-on-disc tests these two variables are connected to a greater extent.

3. Experimental procedure

3.1. *Test bench design*

An experimental setup has been designed on a vertical broaching machine tool with a maximum cutting velocity of 100 m/min to investigate the concept in addition to already published investigations that were conducted on a lathe [13]. Fig. 3 shows