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Experimental characterization of friction coefficient at the tool–chip–workpiece interface during dry cutting of AISI 1045

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ABSTRACT

This paper presents the application of an experimental set-up able to simulate similar tribological phenomena as the ones occurring at the tool–chip–workpiece interface in metal cutting. Especially, this system enables to reach contact pressures up to 3 GPa and sliding velocities between 0 and 300 m/min. In addition to classical measurements of friction coefficients, the system provides information about the heat flux transmitted to pins, which enables to estimate the heat partition coefficient along the interface. This system has been applied to the characterization of the tool–chip–workpiece interface during dry cutting of an AISI 1045 steel with TiN coated carbide tools. It has been shown that the sliding velocity is the most influential parameter whereas contact pressure has only a limited influence. However, three friction regimes can be distinguished. In the first regime (low sliding velocity), friction coefficient is almost constant whereas heat flux transmitted to cutting tools is proportional to sliding velocity. In the second regime (intermediate sliding velocity), friction coefficient decreases very significantly with sliding velocity whereas heat flux remains almost constant. In the third regime (high sliding velocity), friction coefficient is not affected by sliding velocity whereas heat flux transmitted to the cutting tools increases again.

1. Introduction

In the context of global competition, companies from all countries are compelled to improve their productivity. As a consequence, they must optimize their production processes including metal cutting operations. In order to achieve this aim, industry adopts very high cutting regimes (high cutting speeds and feed rates). Under severe conditions, caused by a high cutting regime, the mechanical stresses and temperatures at the tool–chip interface and near the cutting edge can be critically high, resulting in excessive tool wear or even premature tool failure. Therefore, it is necessary to develop accurate cutting process simulations to identify optimum cutting conditions in terms of tool materials, tool geometries and coatings in order to sustain the productivity improvement in machining operations.

The 'cutting' scientific community aims at improving the fundamental understanding of frictional phenomena occurring at the tool–chip interface ('secondary shear zone') and at the tool–workpiece interface ('rubbing zone') in order to achieve an accurate modeling by means of finite element methods (Fig. 1) [1]. So far, the Coulomb model with a constant friction coefficient, irrespective of the temperature and the pressure, is usually used to describe the friction phenomena at these interfaces. However, in metal cutting, a wide range of cutting speeds is used (60–600 m/min) [2]. The temperature at interfaces is directly influenced by the friction velocity. Moreover, the sliding velocities in the rubbing zone and in the secondary shear zone are very much different. As a consequence, the range of temperature is very large as shown by infrared measurements at the tool–chip–workpiece interface by Rech [3]. The pressure along the interface is also very different as reported by Trent [4], values up to 2 GPa are mentioned [2]. Both temperature and pressure are well known to have a great influence on the frictional behaviour. Thus, the assumption of a constant friction coefficient along the interface is not appropriate.

In order to investigate the tribological phenomena at these interfaces, scientists consider two approaches. The first approach consists of using the cutting process itself [5–7]. The second one consists in using laboratory tests [8–12].

The first approach has been used by several researchers. The investigations are usually based on turning tests of a tube made of

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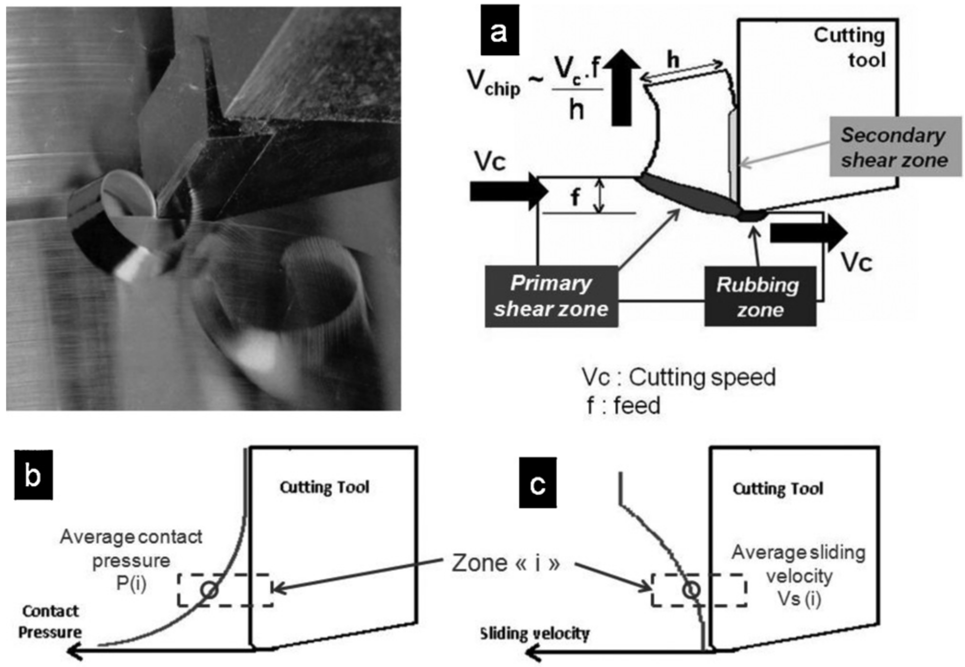

Fig. 1. Chip formation mechanisms (a), typical shape of normal stress distribution (b) and sliding velocity distribution on the tool rake face (c) [1].

the investigated material, with a cutting tool made of the relevant substrate and coating. During tests, cutting forces and temperatures are measured. After testing, the geometry and microstructure of the chips are analyzed, in parallel with the tracks left by the tool/chip/workpiece interfaces remaining on cutting tools. In general, this type of test is the best way to uncover relevant friction conditions. However, it is impossible to have directly detailed information about the local contact pressure or temperature or about the local sliding velocity. In order to overcome this problem, authors use analytical models enabling to make a link between some experimental measurements, local shear strength, temperature, local sliding velocity, etc. The problem of this approach comes, on the one hand, from the large uncertainty during the measurements of some parameters and, on the other hand, from the limitation of analytical models, of which the validity has to be questioned due to the fact that they are applied in a very different context than the one of their identification.

The second approach consists of using bench-type tribological tests. These laboratory tests enable the control of the contact conditions and the ability to modify these conditions as desired. Several test configurations already exist. The most common test is the pin-on-disc system, which is unable to simulate the contact conditions in cutting, since the conditions (temperature, pressure) are not similar to those observed in reality as shown by Grzesik et al. [8]. The contact pressures reached using this system rarely reaches 1 GPa. Moreover, during a cutting operation, the chip flows on the rake face and exits the contact (Fig. 1). In parallel, the cut surface rubs the flank face and is no more in contact with the tool. On the contrary, in pin-on-disc systems, the pin always rubs on the same track. Both configurations lead to different tribological results.

Recently, another experimental set-up based on the principle of Hedenqvist's system has been used successfully by Bonnet et al. [13] (316L machining) and Rech et al. [14] (AISI 1045 machining) in order to investigate the friction coefficient occurring at tool–chip–workpiece interfaces during the high speed dry cutting. This system aims to reach contact pressures up to 3 GPa and sliding velocities up to 400 m/min. However, this tribometer has some limitation, as it does not enable more to reach low sliding velocities more to vary contact pressure.

It is commonly accepted by the scientific community that friction depends on temperature, pressure and sliding velocity. The main problem is that these parameters are linked together. Thus, it does not make sense to identify a friction model including these three parameters. As a consequence, two strategies are proposed by the literature. The first method consists in identifying the evolution of the adhesive friction coefficient versus pressure [15] and/or temperature [16], without proposing a heat partition model. The second method, developed by Bonnet et al. [13], Rech et al. [14] and Zemzemi et al. [17], consists of identifying a friction model and a heat partition model depending on local sliding velocity, but these friction models cannot simulate all the contact zones at the tool–chip–workpiece interface [13,17].

In this paper, a new tribometer has been developed in order to reach a larger range of sliding velocities. The objective of this work is to present the improvement of this tribometer and its application to the characterization of the frictional properties during the dry machining of an AISI 1045 steel with TiN coated carbide tools in order to improve results obtained by Rech et al. [14].

2. Experimental approach

2.1. Set-up

A new tribometer has been developed in order to reach contact conditions coherent with those occurring in cutting. The principle of this experimental set-up is illustrated in Figs. 2 and 3. This device is installed on a CNC lathe with a higher rigidity structure compared to the conventional manual lathe involved in the first version of the tribometer [13]. A cylindrical workpiece, made of the work material, is fixed onto a lathe's chuck. A cutting tool refreshes the surface before each friction test. The normal force on the pin is applied by means of a hydraulic jack, instead of a pneumatic jack used in the previous version [13]. Pins have a cylindrical shape with various spherical tip radii. This contact (small sphere diameter against a large cylinder) has been chosen in order to reach a high contact pressure simulating cutting applications, yet avoiding the risk of chip formation. Various diameters of spherical extremity (9, 13 and 17 mm) can be used in order to reach a range of contact pressures.