Contact and friction analysis at tool-chip interface to high-speed machining

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ABSTRACT: Numerical approaches to high-speed machining are necessary to increase productivity and to optimise tool wear and residual stresses. In order to apply such approaches, the rheological behaviour and the friction model have to be correctly determined. The existing numerical approaches that are used with current friction models do not generate good correlations of the process variables, such as the cutting forces or tool-chip contact length. This paper proposes a new approach for characterizing the friction behaviour at the tool-chip interface in the zone near the cutting edge. An experimental device was designed to simulate the friction behaviour at the tool-chip interface. During the upsetting-sliding test conducted on this devise, the indenter rubs the specimen with a constant velocity, generating a residual friction track. The contact pressure and friction coefficient are determined from the test's numerical model and are then used to identify the friction data according to the interface temperature and the sliding velocity. These initial findings can be further developed for implementation in FEA machining models in order to increase productivity.

Key words: Orthogonal cutting, friction model, tool-chip interface

1 INTRODUCTION

Numerical approaches to high-speed machining are necessary to increase productivity and to optimise tool wear and residual stresses. In order to apply such approaches, the rheological behaviour and the friction model have to be correctly determined. The linear friction models such as the models of Coulomb, Coulomb-Orowan and Tresca are used to describe contact at the tool-chip interface. Other nonlinear relations take into account of the shear flow stress k in order to correlate the experimental profiles [1-3]. Recent studies [4-6] show the influence of friction model on the numerical results. The existing numerical approaches that are used with current friction models do not generate good correlations of the process variables, such as the cutting forces or tool-chip contact length.

This paper proposes a new approach to characterize the friction behaviour at the tool-chip interface. The extreme contact conditions of process require a mechanical analysis of the high speed machining. Contact pressure, plastic strain, sliding velocity and temperatures at tool-chip interface have to be determined. The first part of this study deals with the upsetting-sliding test and the methodology for friction analysis. In the second part, the stainless steel AISI 304L is tested. A numerical model of the upsetting-sliding test is used to determine two radius of contactor. The tests can be conducted for a range of pressures between 600 MPa and 1.2 GPa. An accommodation phase is necessary because intense adhesion phenomena are observed during initial tests.

2 EXPERIMENTAL STRATEGY

2.1 Upsetting-sliding test

An Upsetting Sliding Test (UST) is used to simulate the specific contact conditions of the interface zone near the cutting edge (zone 1, figure 2). The contactor contacts the specimen and rubs against it with a constant velocity and generates a residual friction track (figure 1). The UST parameters are the geometry of the contactor, the value of its penetration within the specimen, its sliding velocity and the contactor and specimen temperatures. This friction test involves the specimen and the contactor, which respectively represent the chip and the tool. The contactor and the specimen are respectively machined in the tool material and in the workpiece. The mechanical parameters of the contact (mainly contact pressure, and sliding velocity) are adjusted using the test parameters (penetration (p), geometry of the contactor).

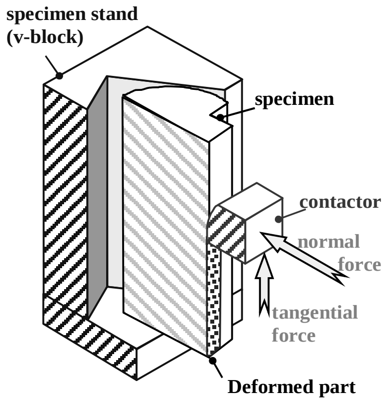


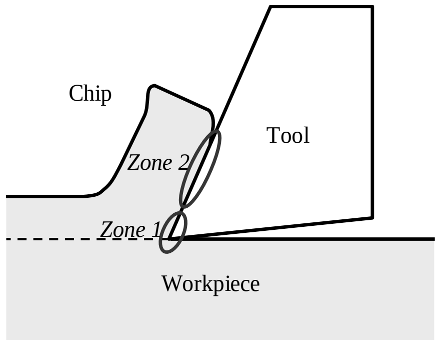
Fig. 1. Design of upsetting sliding test

2.2 *Methodology for friction analysis*

The methodology for friction analysis has been led in four steps: process mechanical analysis, identification of optimum UST parameters, test performance, and identification of friction coefficient.

The aim of the process mechanical analysis is the identification of the mechanical properties to be reproduced on the testing stand UST. The contact pressure and the plastic strains are estimated with the finite element simulation of high speed machining. According to numerical approaches of orthogonal cutting [7-10], very intense plastic strains (from 1 to 5) and high strain rates (until 10^5 s^{-1}) are representative of high speed machining process. Experimental results obtained by the split tool method [11] show a pressure on the tool tip higher than 1 GPa. This contact pressure value has been recently confirmed by a thermomechanical model [12] and numerical approaches [6,10]. The interfacial temperature is mainly generated by the plastic strains undergone in the primary shearing zone and by the friction at the tool-chip interface [13]. A temperature of 800 °C is observed in the tool tip against 1100 °C in a hot zone located at some tenth of millimetres from the tool tip [14]. The contact conditions in the tool-chip interface are characterized by seizure and/or sliding phenomena [15-19] and a sliding velocity reduced in the tool tip. The tool-chip interface can be divided into two zones (figure 2). A low sliding velocity combined with a contact pressure higher than 1 GPa are characteristic of the interface zone 1 near the cutting edge. The zone 2 is subject to contact pressures less important, and a sliding velocity up to the speed of the chip.

This study deals with the zone near the cutting edge.



Zone 1 :

- Low sliding velocity
- σ_n on the tool tip > 1 Gpa
- T° of 800 °C

Zone 2 :

- High sliding velocity (v_{chip})
- Lower contact pressure
- T° up to 1100 °C

Fig. 2. Description of two zones of tool-chip interface

Contactor penetration and geometry are the parameters to identify in order to reproduce the contact pressure at the tool-chip interface.

A numerical model of the upsetting sliding test allows estimating the contact pressure and the plastic strains produced by the test.

Heating of the specimen is performed via a heating inductor. Temperature is controlled by three thermocouples. The contactor is then heated by a regulated heating cartridge. Finally, the penetration of the contactor is adjusted within the specimen. The contactor can now slide along the specimen. A sliding residual friction track is present on the specimen. The sliding velocity is regulated by an hydraulic jack up to 0.5 m.s^{-1}. Normal and tangential forces on the contactor are recorded during the test.

3D optical surface profile measurements are carried out on the specimen to determine the penetration p. Then the penetration is introduced into the numerical model of the upsetting sliding test. The Coulomb's friction coefficient is optimized to allow the numerical efforts to correlate the experimental efforts.

3 TEST AISI 304L

3.1 Numerical model

A finite elements model of the upsetting sliding test (figure 3) is used to determine the test parameters (penetration (p), geometry of the contactor (R_0)). Only the prismatic zone of the specimen is meshed with specific element on the Abaqus software (CPE4). Rigid surface is used for the contactor meshing.

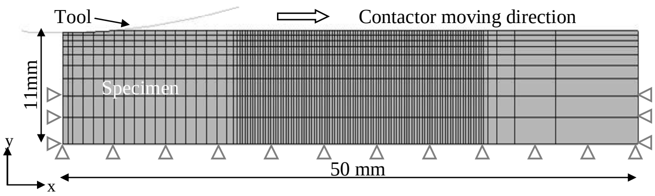


Fig. 3. Numerical model of the upsetting sliding test

Simulations are carried out with different penetrations (p) and different radius (R_0) to analyse the influence of these parameters on the contact pressure. This study is carried out with a Coulomb’s friction coefficient equal to 0.10. To increase the penetration or to decrease the radius generates a rising in contact pressure (figure 4). A maximum contact pressure about 1 GPa is obtained with a contactor radius of 5 mm and a penetration of 0.1 mm.

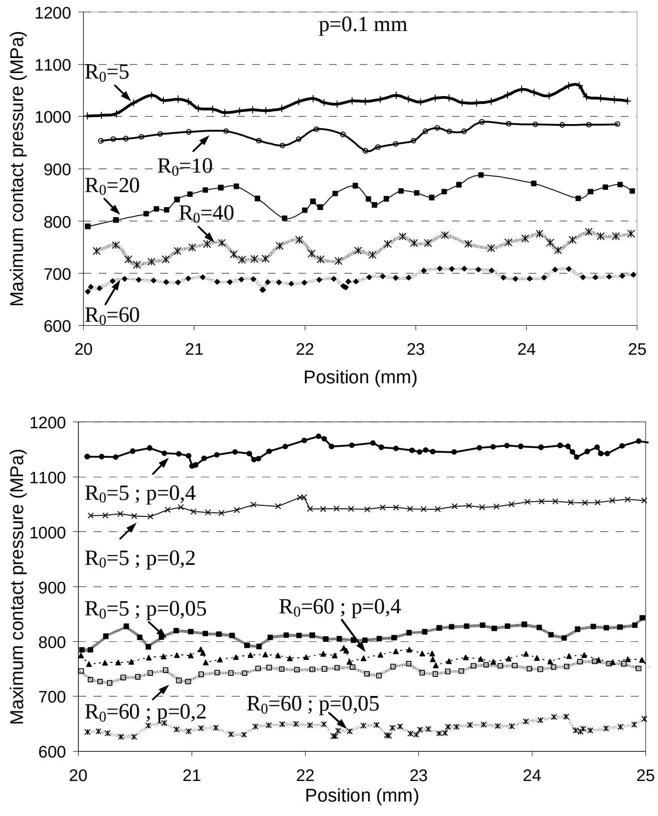


Fig. 4. Influence of parameters (p and R_0) on the maximum contact pressure

3.2 Experiments

The experiments are carried out with an AISI 304L specimen stainless steel and an uncoated carbide contactor (ISO K20). The contactor has a radius of 60 mm and a seating of 3 mm. The contactor and the specimen are respectively heated at 200 °C and 900 °C. The penetration of the contactor is adjusted at 0.2 mm within the specimen to obtain a contact pressure about 700 MPa. The contactor moves up with a constant velocity equal to 200 $mm.s^{-1}$. A tangential force higher than normal force is observed during the initial tests. Analyse of contactor with a scanning electron microscopy (SEM) show adhesive phenomena (figure5).

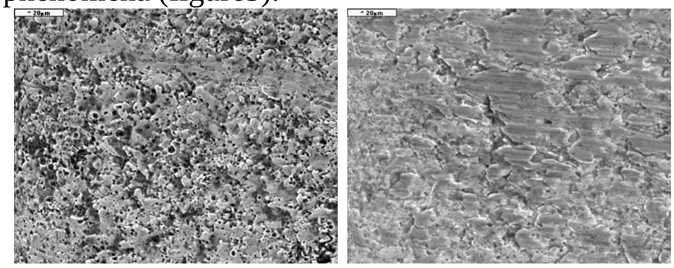


Fig.5. Analyse SEM of contactor:
virgin (left), after six tests (right)

Forces in both normal and tangential directions are measured during the test. After a fast rising in efforts, a stationary zone is observed. Then the efforts decrease when the contactor reaches the end of the specimen (figure6).

The mean Coulomb’s friction coefficient is evaluated with the numerical model of the upsetting sliding test. The depth of trace is measured by profilometry. The Coulomb’s friction coefficient is optimized with the parameters p and R_0 respectively equal to 0.2 mm and 60 mm. Numerical forces are obtained for a unitary width. The numerical efforts are multiplied by an equivalent width equal to 2.36 mm. The equivalent width is determined by comparing the contact surface to a semi-ellipse. An error of -1.73% and -2.35% is respectively obtained for the normal force and the tangential force. These results are obtained with a Coulomb’s friction coefficient equal to 0.54.

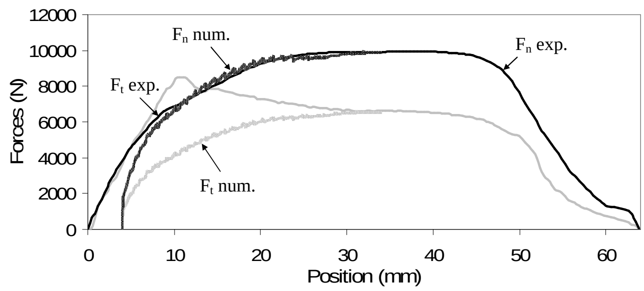


Fig. 6. Numerical and experimental efforts

4 CONCLUSIONS

The contact at the tool-chip interface has to be master in order to accurate numerical approaches of high-speed machining process. This new approach to friction analysis at tool-chip interface enables to define the contact near the cutting edge. This methodology conducted on stainless steel AISI 304L showed intense adhesive phenomena. An accommodation phase of contactor is necessary. A specific study will be conducted in order to optimize this accommodation phase and to understand the adhesive phenomena.

For the second zone an experimental device is actually designed. This specific device would be set on a milling machine in order to study higher sliding velocity.

The contact at the tool-chip interface will be defined by these two studies. The friction data will be identified according to the interface temperature and the sliding velocity in order to be implemented in FEA machining models. An orthogonal cutting model will be developed to validate this local approach.

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