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ScienceDirect

Procedia CIRP 58 (2017) 251 – 256

www.elsevier.com/locate/procedia

16th CIRP Conference on Modelling of Machining Operations

A coupled Eulerian Lagrangian model to predict fundamental process variables and wear rate on ferrite-pearlite steels

M. Saez-de-Buruaga[a,*], J.A. Esnaola[a], P. Aristimuno[a], D. Soler[a], T. Björk[b], P.J. Arrazola[a]

[a]Mondragon University, Loramendi kalea 4,20500 Mondragon, Spain
[b]Swerea KIMAB AB,Box 7047, 16407 Kista, Sweden

* Corresponding author. Tel.: +34 943 79 47 00; fax: +34 943 79 15 36. *E-mail address:* msaez@mondragon.edu

Abstract

A coupled Eulerian-Lagrangian Finite Element model of the orthogonal cutting process was developed to predict the influence that ferrite-pearlite steel variants have on fundamental process variables and tool wear. As a case study, this paper is focused on two different ferrite-pearlite inclusion free alloys, where mainly the influence of ferrite-pearlite ratio was tested. Flow stress behavior based on dynamic compression tests and thermal properties function of temperature were characterized for model input parameters. The numerical model is compared with orthogonal cutting tests where the cutting and feed forces, tool temperature, chip morphology and tool wear related variables were measured. Globally, predicted tendencies match with experiments in forces and temperatures. Widest differences on predictions were found for chip thickness and tool-chip contact length. Predicted wear rates are in accordance to experimentally measured values.

Keywords: Finite element method (FEM); Micro structure; Wear

1. Introduction

Tool wear is of great importance in machining processes and has significant impact on process cost and the quality of machined components. Tool wear depends mainly on thermo-mechanical loads and chemical effects generated at the tool chip contact area. These physical effects may become in various types of wear (adhesion, abrasion, diffusion) generating different geometrical wear regions on the tool [1]. Specifically, the wear situated on the rake face (crater wear, KT) and flank wear (VB) are linked to tool life. Therefore, several studies are found in literature on relating material properties with tool wear [2, 3].

The influence that workpiece material has on tool wear has been widely analyzed. Issues such as material composition, heat treatment and the processing method affect physical and thermomechanical properties of materials and their microstructure. These factors in turn affect wear behavior during subsequent processing by machining [2, 3].

The evolution of tool wear related to workpiece material has been tried to be characterized during the last decade. Phenomenological wear rate laws based on experiments or inverse analysis studies taking into account workpiece and tool interface phenomena have been developed [4].

With the aim to reduce the costs of empirical tests to determine machinability, finite element based numerical modelling could become an important tool for wear predictions. In the beginnings of the last decade, previously developed wear rate models such as the ones developed by Usui *et al.* [5] or Takeyama *et al.* [6] started to be implemented in 2D specific purpose codes [7]. These ones were mostly focused on flank wear prediction, simulating the tool wear by nodal displacement. Furtherly, several authors improved the algorithm for crater and flank wear [8]. 3D tool wear models of nose turning have also been published [9] or

doi:10.1016/j.procir.2017.03.194

even coupled tool wear models, where adhesive or diffusive wear models depending on tool temperature could be distinguished [10].

Numerous machining models have been developed in last decades [4]. As mentioned in the previous paragraph, most of the tool wear related modelling is focused on added subroutines in specific purpose codes. These codes are mostly based on lagrangian formulations where the chip formation is obtained by element remeshing or element deletion routines, being a widely-accepted methodology for machining modelling. As alternative to this numerical costly models, authors as Ducobú *et al.* [11] have developed Coupled Eulerian Lagrangian (CEL) models of the chip formation process. These models avoid the need of workpiece remeshing or even element deletion to make possible the chip to be generated.

This paper, sets out a comparison between numerical and experimental framework to validate a CEL technique for modelling machinability effects, focused on ferrite-pearlite steels. In the first step, fundamental variables such as cutting force, feed force, tool temperature, contact length and chip thickness are studied numerically and experimentally.

As a second step, comparison of wear rate between experiments and model is carried out.

Nomenclature

V_s	sliding velocity
σ_n	contact pressure
T	local temperature
S	cutting speed
F	feed
VB	flank wear land (based on ISO3685)
KT	crater ear depth (based on ISO3685)
A_{JC}	elastic limit (Johnson Cook law)
B_{JC}	work hardening modulus (Johnson Cook law)
C_{JC}	strain hardening coefficient (Johnson Cook law)
m	thermal softening coefficient (Johnson Cook law)
n	work hardening coefficient (Johnson Cook law)
A	contact coefficient (Usui wear rate law)
E	activation energy (75.35 KJ/mol·K) [6]
R	gas constant coefficient (8.314 KJ/mol·K) [6]

2. Material selection and characterization

As a case study, two free alloyed ferritic-pearlitic steels were selected: C45 and C60 grades. The C45 grade was selected as a widely-employed material in metal machining. With the aim of validating the model in a wider material range, C60 grade was selected due to the higher pearlite content. Higher pearlite is well known to increase tool wear, aspect that was wanted to be reflected in numerical and experimental framework [2]. In the Table 1 measured grain size and ferrite-pearlite ratio are shown.

For modelling purposes, thermal and mechanical characterization of the selected steels is necessary [4]. Plastic behavior of the material was characterized based on dynamic compression tests. The resultant regression to Johnson-Cook flow stress law coefficients for the numerical model are given in the Table 2. Specific heat, conductivity, thermal expansion and density were characterized in function of temperature, detailed in Table 2. Contact and tool material properties were taken from literature [12].

Table 1. Microstructure properties of C45 and C60 steel grades.

	%F	%P	Grain size F	Grain size P
C45	36	64	22-27	22-27
C60	22	78	22-31	31

3. Coupled Eulerian Lagrangian FE Model

An orthogonal cutting Coupled Eulerian Lagrangian (CEL) model was developed under Abaqus 6.14/Explicit platform. The model was composed by two parts: tool and workpiece. The tool was discretized under a lagrangian frame. A lagrangian domain implies that material deformation is linked to a mesh deformation. For the case of the workpiece, an eulerian domain was selected. In this case, the mesh is static and the material flows through the elements while is being deformed.

The eulerian region was divided into two sections. One of them was composed by “filled” elements, modelling the workpiece, and the other was set with “void” elements. Once the chip is generated, the material flows filling the void elements based on a Eulerian Volume Fraction (EVF) without mesh deformation. This EVF represents the ratio of material fraction that the element has, ranging values between 0-1 for totally void or filled elements [13].

As CEL model in Abaqus is only available for 3D cases, taking as an example the work developed by [11], the workpiece was modelled with one element width, trying to make it as closer as possible to a plane strain 2D model. The eulerian region was meshed with 4 µm elements of 10 µm width. As shown in Fig. 1, the workpiece was fixed on the bottom nodes. To ensure that material could not flow outside the eulerian boundary, symmetry constrain was set to the out of plane walls.

The tool was defined as a lagrangian component. The boundary of the tool was taken as a kinematic constraint in the eulerian calculation and the stress from the eulerian cell was used to calculate the resulting surface stress [13]. The tool was modelled with 6 elements width and wider than the workpiece, in order to ensure eulerian material not to flow outside the corners of the tool. The element size on the tool edge was set to 2 µm and 4 µm in the contact faces of the rake and flank faces. The relative movement of the cutting speed was set to the tool as a kinematic constraint.

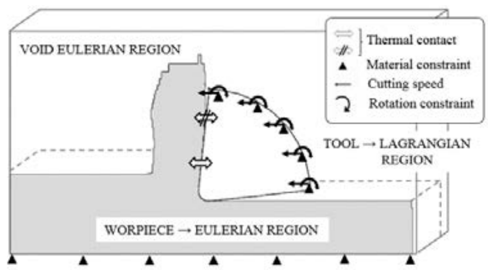

Fig.1. Coupled Eulerian Lagrangian (CEL) model.