C. R. Mecanique ••• (••••) •••–•••

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Computational simulation of manufacturing processes

Some insights on the modelling of chip formation and its morphology during metal cutting operations

Tarek Mabrouki [a,∗], Cédric Courbon [b], Yancheng Zhang [c], Joël Rech [b], Daniel Nélias [c], Muhammad Asad [d], Hédi Hamdi [b], Salim Belhadi [e], Ferdinando Salvatore [b]

[a] Université de Tunis El Manar, École nationale d'ingénieurs de Tunis (ENIT), 1002 Tunis, Tunisia
[b] Université de Lyon, CNRS, École nationale d'ingénieurs de Saint-Étienne, LTDS UMR5513, 42023 Saint-Étienne cedex 2, France
[c] Université de Lyon, CNRS, INSA-Lyon, LaMCoS UMR5259, 69621 Villeurbanne cedex, France
[d] Department of Industrial & Mechanical Engineering, School of Engineering, University of Management & Technology, 54770 Lahore, Pakistan
[e] Mechanics and Structures Research Laboratory (LMS), 8 May 1945 University of Guelma, P.O. Box 401, 24000, Algeria

A R T I C L E I N F O

Article history:
Received 10 May 2015
Accepted 22 August 2015
Available online xxxx

Keywords:
Cutting simulation
Plasticity
Damage
Chip formation
Size effect

A B S T R A C T

The present paper deals with the mechanisms of chip formation during cutting operations. It deals with some experiments characterising the chip morphologies and microstructure chip investigations under high loadings. In this contribution, mechanisms of chip segmentation are presented. The effect of cutting conditions on cutting forces is treated. Consequently, the chip segmentation phenomenon was correlated to cutting forces evolutions. Also, an investigation on chip strain localisation is carried out. Numerical simulations dealing with chip formation and considering thermomechanical phenomena are also presented. Some numerical results related to chip formation based on the theory of strain gradient plasticity are also discussed. Moreover, the effect of machining system stiffness on chip segmentation is analysed.

1. Introduction

In the framework of machining, it is essential to have predictive approaches helping to complement the knowledge necessary for a comprehensive and industrial understanding of the process. There are various experimental methods dedicated to cutting studies in terms of tool wear investigation [1,2], evolution of cutting forces, etc. In particular the investigation of chip formation such as the quick-stop testing, temperature measurement systems or methods of chip visualisation were proposed, etc. However, these methods have limitations because of their costs and also because of difficulties in providing a comprehensive and relevant understanding.

It is important to note that analytical cutting models are still essentially driving from experimentation. Some parameters and coefficients of these experimental models are obtained with tests codified both by the scientific community and the industrial sector concerned. Measurement methods are standardised to allow their transmission and their interchangeability. Analytical cutting models of a two-dimensional representation (orthogonal case) are elaborated for these experimental scientific approaches. These empirical analytical models are usually defined for a given Couple Workpiece/Tool

∗ Corresponding author.
E-mail address: tarek.mabrouki@enit.rnu.tn (T. Mabrouki).

http://dx.doi.org/10.1016/j.crme.2016.02.003

Nomenclature

List of symbols

A	Initial yield stress (MPa)
a_p	Cutting depth or axial depth of cut (mm)
B	Hardening modulus (MPa)
b	Burgers vector (nm)
C	Strain rate dependency coefficient
C_{eq}	Equivalent linear damping of machining system ($kg\,s^{-1}$)
C_p	Specific heat ($J\,kg^{-1}\,K^{-1}$)
D	Overall damage variable
$D_1 \ldots D_5$	Coefficients of Johnson–Cook material shear failure initiation criterion
D_T	Tool diameter in milling (mm)
E	Young's modulus (MPa)
f	Feed rate (mm/rev)
F_i	Cutting force (N) along various axis ($i =$ axial, radial, tangential)
G	Shear modulus (MPa)
G_f	Fracture energy (N/m)
K_C	Fracture toughness ($MPa\sqrt{m}$)
K_r	Insert attack angle or entering angle (deg)
k_{eq}	Equivalent linear stiffness of machining system (N/m)
l	Intrinsic characteristic length of the cut material
L_C	Tool rake face-chip contact length (μm)
m	Thermal softening coefficient
m_{eq}	Equivalent moving mass (kg)
N	Spindle rotation frequency (rev/min)
n	Work-hardening exponent
P	Hydrostatic pressure (MPa)
r_β	Tool hone edge radius (μm)
T	Temperature at a given calculation instant (°C)
T_m	Melting temperature (°C)
T_0	Room temperature (°C)
$\bar{u}$	Equivalent plastic displacement (mm)
$\bar{u}_f$	Equivalent plastic displacement at failure (mm)
Δu	Relative displacement of spring element (mm)
V_C	Cutting speed (m/min)
$P/\bar{\sigma}_{JC}$	Stress triaxiality
$\bar{\varepsilon}^p$	Equivalent plastic strain
$\bar{\varepsilon}_f$	Equivalent plastic strain at failure
$\Delta\bar{\varepsilon}^p$	Equivalent plastic strain increment
σ_n	Normal stress (MPa)
$\bar{\varepsilon}_{0i}$	Plastic strain at damage initiation
$\dot{\bar{\varepsilon}}^p$	Plastic strain rate (s^{-1})
$\dot{\bar{\varepsilon}}^p_0$	Reference strain rate ($10^{-3}\ s^{-1}$)
$\bar{\sigma}$	von Mises plastic equivalent stress (MPa)
σ_y	Yield stress (MPa)
τ_f	Friction shear stress (MPa)
$\bar{\sigma}_{JC}$	Johnson–Cook equivalent stress (MPa)
τ_Y	Yield shear stress (MPa)
λ	Edge inclination angle (deg)
α_t	Taylor's constant
α_o	Flank/clearance angle (deg)
γ_o	Rake/cutting angle (deg)
χ_r	Edge entering angle (deg)
μ	Friction coefficient
ω	Damage initiation criterion
r_ϵ	Insert radius (mm)
ζ_{eq}	Equivalent damping ratio of the machining system
η	Strain gradient coefficient
λ	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	Density of the material ($kg\,m^{-3}$)
χ	Geometric factor defining the density of GND
ν	Poisson's ratio

List of abbreviations

ALE	Arbitrary Lagrangian–Eulerian formulation
CWT	Couple Workpiece/Tool
FE	Finite Element
$F_{Seg\text{-}signal}$	Chip segmentation measured by gathering signal (Hz)
$F_{Seg\text{-}geo}$	Chip segmentation measured on chip morphology (Hz)
GND	Geometrically Necessary Dislocation
HDC	Hybrid Dynamic Cutting model
JC	Johnson–Cook
rpm	Revolution per minute
SG	Strain Gradient
UCT	Uncut Chip Thickness
w/o	Without
2D	Two dimensional model
PSZ	Chip Primary Shear Zone
SSZ	Chip Secondary Shear Zone

(*CWT*) methodology [3] and are exploited to obtain a range of optimal cutting parameters with a minimum of experiments. Nevertheless, it is underlined that cutting experimentation is always costly, due to the need for specialised equipment such as dynamometers, accelerometers, and data acquisition systems. Generally, a complete *CWT* is accomplished when it is necessary to determine ranges of cutting parameters for achieving a given quality criteria or a production cost function.

In this context, the simulation of machining processes appears to be an important approach to control and monitor operating cutting parameters. Developing a machining numerical model for predictive purposes, based on a physical understanding, is possible only through proper comprehension of thermomechanical phenomena occurring during the tool–workpiece interaction [4]. Imperfect knowledge of certain physical effects on this interaction constitutes a real obstacle to the development of a robust numerical simulation of processes. From a numerical point of view, the modelling of machining is referring to the theory of finite transformation considering both thermomechanical coupling and also tribological phenomena during the dynamic cutting process. According to the literature, three approaches can be adopted in machining modelling. Definitions and boundaries of these approaches are not always in agreement within the scientific community: