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Experimental and numerical analyses of the tool wear in rough turning of large dimensions components of nuclear power plants

B. Haddag [a,*], M. Nouari [a,*], C. Barlier [b], J. Dhers [c]

[a] University of Lorraine, Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, LEMTA CNRS-UMR 7563, Mines Albi, GIP-InSIC, 27 rue d'Hellieule, 88100 Saint-Dié-des-Vosges, France
[b] CIRTES, Centre Européen de Prototypage et Outillage Rapide, 29 bis rue d'Hellieule, 88100 Saint-Dié-des-Vosges, France
[c] AREVA NP, Usine de Chalon Saint Marcel, 71380 Saint-Marcel, France

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ABSTRACT

This paper deals with experimental investigation and numerical modelling of the tool wear in rough turning of large dimensions components of nuclear power plants made of 18MND5 steel. The tool wear has been characterised experimentally at microscopic scale using SEM observations of different zones of the engaged cutting part at the tool rake face. A FE model has been developed to predict the tool wear as observed on SEM images. The major finding of the paper concerns the prediction of contact discontinuities at the microscopic scale on the tool rake face and where the wear process is highly localized. These discontinuities are attributed to the complex geometry of the rake face of the grooved cutting insert, designed especially to reduce the tool–chip contact area and to promote the chip breakage. The cutting force, specific cutting force and chip morphology parameters are also predicted and compared to experimental trends. This research work is a contribution for the tool wear prediction in rough turning to improve the tool life of complex cutting inserts at high material removal rate.

1. Introduction

For the construction of nuclear power plants, several machining processes such as turning, deep drilling and broaching are used to realize large dimension components (of the order of a few meters). After forging components, they are machined following several steps to obtain specified dimensions and forms. For instance, for shells composing steam generators of nuclear power plants, the rough turning process is the first step machining operation, on the forged component, used to remove a maximum of the workmaterial. High material flow rate is required to obtain a good productivity. Vertical turning machines are usually used to support huge workpieces (e.g. shells of more than 5 m of diameter and 6 m of height). Cutting inserts used for the rough turning undergo a strong thermomechanical loading causing an excessive tool wear, which has a consequence on the tool life. This leads to change several times cutting inserts, which necessitates stopping the cutting operation every times. The manufacturing delay is therefore slowed.

The analysis of the cutting process in rough turning including tool wear prediction is therefore justified to understand physical mechanisms of tool wear and further to improve the cutting operation. There is no criterion on the cutting conditions to qualify the rough turning operation, since it depends on global dimensions of the workpiece, but it can be defined as first cutting steps where the objective is to remove the maximum of the workmaterial before finishing steps. In the case of rough turning of large dimensions components (about several meters), studied here, it corresponds to depth-of-cut of at lest 10 mm and feed rate of about 1 mm. However the cutting speed is very low on the vertical lathe (less than 100 m/min) to reduce inertia and vibration effects due to the size of the workpiece. This allows obtaining an acceptable material flow rate. The cutting operation can take several hours.

The turning process has been widely studied in the literature. However few research works are dedicated exclusively to the rough turning operation. For instance, Diniz and Oliveira [1] have performed rough turning tests under dry and wet conditions. Their work aims to seek conditions in which dry cutting is satisfactory compared with the flood of fluid (called wet cutting) usually used. They conclude that if the tool material has a good wear resistance, dry cutting can be used with similar cutting conditions to those used with a flood of fluid. Kee [2] has developed constrained optimisation analyses and strategies for selecting the optimum

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* Corresponding authors. Tel.: +33 3 29 42 18 21; fax: +33 3 29 42 18 25.
E-mail addresses: badis.haddag@univ-lorraine.fr (B. Haddag), mohammed.nouari@univ-lorraine.fr (M. Nouari).

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Nomenclature

V_c	cutting speed [m/min]
f	feed [mm]
ap	depth of cut [mm]
Kr	approach angle [°]
λs	inclination angle [°]
γo	normal rake angle [°]
F_c	cutting force [N]
F_f	feed force [N]
F_p	depth of cut force [N]
K_c	specific cutting force [N/m^2]
t_1	uncut chip thickness [mm]
t_2	chip thickness [mm]
ccr	chip compression ratio
σ	true or Cauchy stress tensor [MPa]
f_v	body force density [N/m^3]
$\ddot{u}$	acceleration [m/s^2]
ρ	material density [kg/m^3]
E	Young modulus [GPa]
ν	Poisson's ratio
A	initial uniaxial tension stress of the workmaterial [MPa]
B	strain hardening parameter of the workmaterial [MPa]
n	strain hardening exponent parameter of the workmaterial
C	strain-rate sensitivity parameter of the workmaterial
m	temperature sensitivity parameter of the workmaterial
$\bar{\varepsilon}^p$	von Mises equivalent plastic strain
$\dot{\bar{\varepsilon}}^p$	von Mises equivalent plastic strain-rate
$\dot{\bar{\varepsilon}}_0$	reference equivalent plastic strain-rate
$\bar{\sigma}$	von Mises equivalent stress [MPa]
σ_n	normal friction stress [MPa]
τ_f	shear friction stress [MPa]
μ	friction coefficient
$\tau_{\max}$	shear stress limit [MPa]
V_s	sliding velocity at the tool–workpiece interface [m/s]
T	temperature [°C]
T_0	reference ambient temperature [°C]
T_m	melting temperature [°C]
T_t	tool temperature at the tool–workpiece interface [°C]
T_w	workpiece temperature at the tool–workpiece interface [°C]
λ	thermal conductivity [W/m/°C]
c_p	specific heat capacity [J/kg/°C]
α	thermal expansion [μm/m/°C]
η_p	plastic work conversion factor (Taylor–Quinney factor)
η_f	frictional work conversion factor
f_f	heat partition coefficient of the frictional heat
h	heat transfer coefficient for the tool–workpiece interface [kW/m^2/°C]
$\dot{q}_v$	volumetric heat generation in the workmaterial [W/m^3]
$\dot{q}_p$	volumetric heat generation due to plastic work [W/m^3]
$\dot{q}_c$	heat conduction flux at the tool–workpiece interface [W/m^2]
$\dot{q}_{\to t}$	heat flux going into the tool at the tool–workpiece interface [W/m^2]
$\dot{q}_{\to w}$	heat flux going into the workpiece at the tool–workpiece interface [W/m^2]

cutting conditions for multi-pass rough turning operations on CNC and conventional lathes. The analysis is based on the criterion typified by the maximum production rate and incorporates various relevant technological constraints. Ratava et al. [3] have proposed a new method to improve cutting efficiency for steel rough turning. The approach is based on the control of feed rate to raise machine power to a maximum safe level while avoiding the onset of cutting instability in rough turning operation.

Since in rough tuning the cutting tool undergoes strong thermomechanical loading involving excessive tool wear, particularly when machining hard materials, the choose of adequate inserts for this operation is primordial. So Serdyuk et al. [4] have analysed the influence of heat treatment parameters on characteristics and wear mechanisms of T5K10 coated carbide insert (square form insert very similar to that analysed in this paper) used for rough turning operations. These authors stated that the tool life is altered by the presence of residual microporosity on cemented carbide structure. So reducing the microporosity in fabrication process improves the tool life in rough turning. Globally the tool wear in turning process is widely investigated by experimental means. The main observed types of tool wear are abrasion, adhesion, diffusion, attrition and chipping. Apparition of each type of wear depends on several parameters such as the workmaterial behaviour (hardness, ductility…), the cutting insert (uncoated or coated), cutting conditions (cutting speed, feed rate and depth of cut), the lubrication (dry or wet machining), and the vibration process (rigidity of machine tool components) and the workpiece size (inertia effects). For rough turning operation, depending on the workmaterial, the cutting insert may present any of these wear types. For instance, in hard turning abrasive tool wear is the dominant mechanism, while when machining ductile material, adhesion and diffusion might be the dominant wear types.

In conjunction with experiential investigations, tool wear prediction in machining has been constantly a preoccupation of researchers. Both analytical and numerical analyses are proposed. For example, Usui et al. [5,6] have proposed a phenomenological model to predict tool wear. They proposed a tool wear law as function of the tool–chip interface parameters, such as pressure, temperature and sliding velocity. Calibration parameters are introduced to better fit experimental measurements of the formed crater wear. The main advantage of such laws is the implantation ease. Later more physical models have been proposed. For instance, Molinari and Nouari [7] and Nouari and Molinari [8] have proposed a physical model to predict diffusive tool wear and applied it for high speed cutting under orthogonal cutting configuration. With advances in the development of the finite element method and associated softwares dedicated to the simulation of large deformation in metal machining, wear evolution laws are implemented to predict the worn geometry and wear rate on the cutting tool. These laws are assessed thanks to calculated thermomechanical fields (contact pressure, temperature and sliding velocity) at the tool–workpiece interface. In some research works, the evolution of the tool geometry during machining is taken into account, as done by Yen et al. [9], Xie et al. [10], Filice et al. [11], and Lorentzon and Järvstrat [12] for a 2D cutting configuration, and Attanasio et al. [13,14] for a 3D cutting configuration. But all these approaches are marginal, since they necessitate advanced and particular numerical developments to performs, particularly that related to remeshing the cutting tool, thermomechanical field transfer and contact control when the tool rake face geometry evolves. Thus Haddag and Nouari [15] developed recently a multi-steps 3D finite element modelling of the turning process to predict the tool wear as well as the heat diffusion in the cutting tool;