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Procedia CIRP 31 (2015) 293 – 298

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15th CIRP Conference on Modelling of Machining Operations

Characterization and modelling of the rough turning process of large-scale parts: tribological behaviour and tool wear analyses

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Abstract

Machining large-scale parts in several industries (nuclear, naval, energy…) is a challenge for machine tools operators. Various problems are encountered, like respecting specified dimensions, deformation of the workpiece during machining, limit of the cutting speed, excessive tool wear, etc. All these difficulties are related to the large size of the machined part, which may have several meters and weigh several hundred kilograms. This study focuses on analysis of the rough turning process of a shell component, having few meters, as a part of steam generators of nuclear power plants. During the rough turning step, a high material removal rate (moderate cutting speed, but high depth-of-cut and feed rate) is necessary to achieve the workpiece in reasonable time. Experimental and theoretical analyses are conducted to highlight the intense thermomechanical loading at the tool–workmaterial interface. Revealed physical phenomena at the tool rake face, like adhesion and abrasive wear types, using various characterization techniques, are reproduced by a numerical model developed to simulate the cutting process. As an interest result, contact discontinuities at the tool–chip interface as well as where the wear is highly localized are well predicted as observed on scanning electron microscope. These contact discontinuities are attributed to the grooved rake face of the insert, designed with a chip breaker to reduce the tool–chip contact area and to promote the chip fragmentation. This study can be helpful for the design of rough turning inserts, by analysing the effectiveness of the rake face geometry (contact area, chip breaker…).

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations
Keywords:

1. Introduction

Various machining processes are used to realize large scale parts, having few meters, in heavy industry (naval, nuclear, etc.). For instance, for shells composing steam generators of nuclear power plants, the rough turning process is the first machining operation, on the forged component, to remove a maximum of the workmaterial. High material flow rate is required to optimize the productivity. Vertical turning machines are usually used to support huge workpieces. The cutting inserts used in the rough turning operation undergo a strong thermomechanical loading, which generates an excessive tool wear and therefore reducing drastically the tool life. This leads to change several times cutting inserts, which necessarily needs stopping the cutting operation and hence affects the productivity. The analysis of the cutting process in rough turning, including the tool wear, is therefore justified to understand mechanisms of tool wear and further to improve the cutting operation. The rough turning of a large scale part, studied here, corresponds to depth of cut of at least 10 mm and feed rate of about 1 mm. However the cutting speed is very limited on the vertical lathe (less than 100 m/min) to reduce inertia effects and vibration due to the size of the workpiece. This allows obtaining an acceptable material flow rate, since the cutting operation takes several hours.

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

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations
doi:10.1016/j.procir.2015.03.046

has a good wear resistance, dry cutting can be used with similar cutting conditions to those used with a flood of fluid. Recently, Stephenson et al. [2] studied the impact of lubrication in rough turning Inconel 750. They stated that CO2-based minimum quantity lubrication gives better tool life compared to using water-based flood coolant. Tirelli et al. [3] conducted similar study by comparing between traditional and cryogenic cooling conditions in rough turning of Ti-6Al-4V. Kee [4] has developed constrained optimisation analyses and strategies for selecting the optimum cutting conditions for multi-pass rough turning operations on CNC and conventional lathes.

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 is important. So Serdyuk et al. [5] have analysed the influence of heat treatment parameters on wear mechanisms of T5K10 coated carbide insert, similar to that analysed in this paper, used for rough turning. The authors have stated that the tool life is altered by the presence of residual microporosity on cemented carbide structure.

Globally, the tool wear in turning process is widely investigated by experimental means. Readers can find an abundant literature in scientific databases. Modelling the tool wear in machining was also a concern of the scientific community. Both analytical and numerical analyses are proposed. Usui et al. [6]-[7] have proposed a phenomenological model to predict tool wear. The wear law is function of the tool–chip interface parameters (contact pressure, temperature and sliding velocity). Later, more physical models have been proposed. For instance, Molinari and Nouari [8] have proposed a physical model to predict diffusive tool wear. The model has been applied for high cutting speed under orthogonal cutting configuration. With the development of finite element codes and their ability to simulate metal machining processes, wear evolution laws are implemented to predict the wear rate and hence the worn tool geometry. The laws are assessed with predicted quantities at the contact interface. The evolution of the tool geometry during machining is taken into account, as done by e.g. Yen et al. [9] and Xie et al.[10] for a 2D cutting configuration, and Attanasio et al. [11]-[12] for a 3D cutting configuration. Haddag and Nouari [13] recently developed a multi-steps 3D FE modelling of the turning process to predict the tool wear as well as the heat diffusion in the cutting tool using interface thermomechanical fields. In Haddag et al. [14] uniform and non-uniform heat fluxes applied at the tool rake face are assessed to analyse the tool heating.

This paper summarizes research works published recently by Haddag et al. [15]-[16] about the rough turning of large-scale parts. It aims to analyse the tribological behaviour and tool wear in rough turning of a large-scale part of nuclear power plants using grooved coated insert. Experimental and theoretical analyses are performed. An experimental work has been performed to highlights the intense thermomechanical loading on the cutting insert. The tool wear has been characterized using optical microscope, scanning election microscope and profilometer observations. A finite element modelling has been developed to predict the intense thermomechanical loading at the tool–workpiece interface, including tool wear prediction. Comparisons have been performed between experimental observations and numerical predictions of tool wear zones as well as the chip formation. The nature of the tool–workmaterial contact has been discussed.

Nomenclature

v_c	cutting speed [m/min]
f	feed rate [mm/rev]
a_p	depth of cut
κ_r	approach angle [°]
λ_s	inclination angle [°]
γ_o	orthogonal rake angle [°]
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
$\bar{\tau}$	von Mises equivalent shear flow stress [MPa]
β	shear limit factor [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]
h	heat transfer coefficient for the tool–workpiece interface [$kW/m^2/°C$]
$\dot{q}_c$	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]
$\dot{w}$	wear rate [mm/s]
a , b	wear law coefficients

2. Description of the rough turning on a large-scale part

A rough turning operation on a large-scale part has been performed in an industrial site of AREVA NP Company. It consists on the machining a cylinder shell part, as a component of steam generators of nuclear power plants. Fig. 1 shows the experimental setup of the rough turning operation.

The cutting test has been performed on a vertical lathe supporting large workpieces, where the cutting speed is limited to reduce inertia and vibration effects due to the size of the workpiece. However the depth of cut and feed rate are high enough to obtain an optimal material removal rate. The cutting configuration is defined by three angles (κ_r = 75°, λ_s = –6°, and γ_o = –6°. The cutting condition corresponds to v_c = 100 m/min, f = 1 mm/rev and a_p = 10 mm.

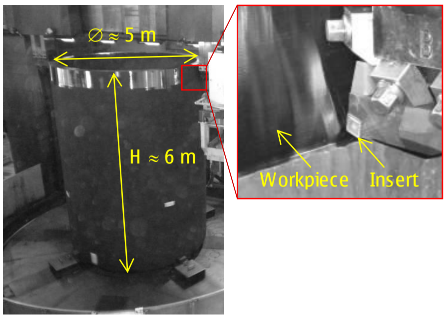

Fig. 1. Rough turning operation on vertical lathe of a large-scale part made of 18MND5 steel using SNMM250924RH coated insert.

The cutting insert has a square form, shown in Fig. 2(a), designated by SNMM250924RH. Its dimension characteristics are D = L10 = 25.4 mm, S = 9.53 mm, Rε = 2.4 mm and D1 = 9.12 mm. The insert is made of cemented tungsten carbide with cobalt as binder phase (WC–Co), and coated with KC8050 coating type (TiN–AL_2O_3–TiCN layers with TiN as the extern layer). The tool rake face geometry is shown in Fig. 2(b).

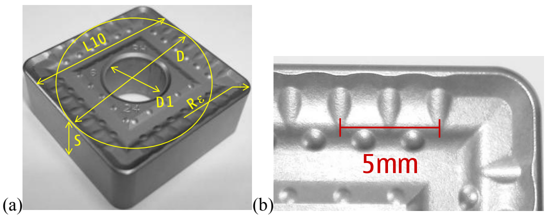

Fig. 2. Rough turning operation on vertical lathe of a large-scale part made of 18MND5 steel using SNMM250924RH coated insert.

The machined part is a component of a steam generator in nuclear power plants having a cylindrical shape, with more than 5 m of extern diameter and about 6 m of height. The workpiece is made of low alloy steel 18MND5.

3. Characterisation of the tool wear

The tool wear has been characterized using Scanning Electon Microscopy (SEM) and Optical Profilometry (OP). The global view of the insert after machining, highlighting the engaged cutting face, is shown in Fig. 3(a). The SEM micrograph of the engaged cutting face (see Fig. 3(b)) reveals several localized wear zones, where adhesion of the workmaterial or abrasive wear occurs, noted Z1, Z2 and Z3.

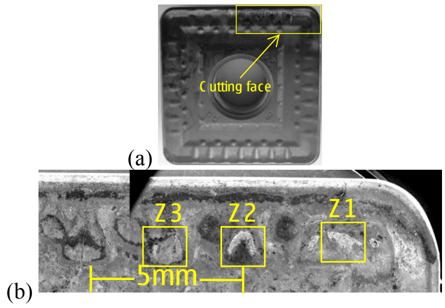

Fig. 3. (a) SNMM250924RH insert after machining and (b) SEM micrograph of the engaged cutting face, highlighting several localized wear zones.

Using the OP device, the crater depth as well as the thickness of the adhered workmaterial layer are estimated. As shown in Fig. 4, in Z1 and Z2, which are close to the rounded cutting edge, OP images indicate clearly the amount of adhered workmaterial layers and their form. The concave shape in these zones combined with high contact pressure and temperature lead to the adhesion of the workmaterial in the form of a thin tribolayer. The thickness of the adhered layer in Z1 is about 30 µm, and in Z2 is about 10 µm. In Z3, where the chip leaves the rake face, there is combined wear mechanisms, i.e. a low adhesion but more abrasion wear, which is the consequence of chip sliding under low contact pressure in this zone.

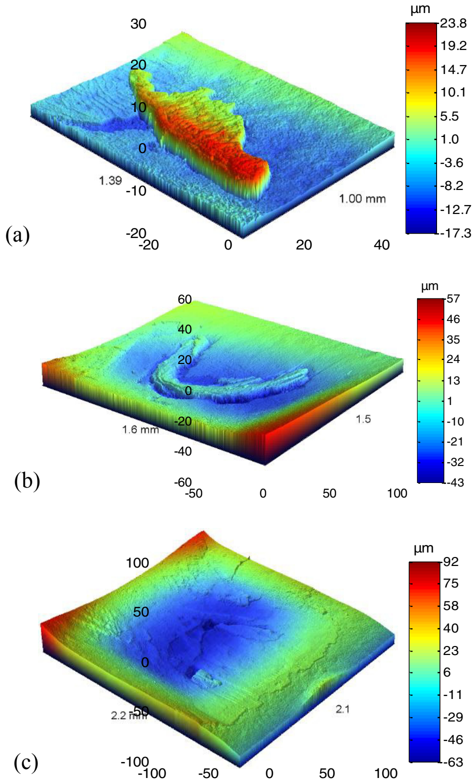

Fig. 4. 3D profiles of the three localized wear zones, revealing adhesion of the workmaterial at (a) Z1 and (b) Z2, and dominant abrasion wear at (c) Z3.

4. Numerical modelling

A 3D FE model has been developed in Deform FE software [17] to analyse finely the tribological behaviour and tool wear in the rough turning test. The software is commonly used these last years to simulate various cutting processes, since it integrates a dedicated cutting module to develop easily the cutting problem. For instance, recently, Buchkremer et al. [18] developed a 3D-FE modelling of the longitudinal turning with grooved coated inserts in this software. They analysed the capability of a new thermo-viscoplastic model to predict cutting forces and chip morphology in finishing, semi-roughing and roughing steps. However, the tribological behaviour is not analysed, e.g. estimating the effective tool-chip contact area in different cutting steps. In the present study, the developed model aims predicting the local thermomechanical loading occurring at the contact interface during the cutting process.

Fig. 5 shows the cutting configuration. The cutting tool is considered thermo-rigid, while the workmaterial is represented by the Johnson-Cook (JC) thermo-viscoplastic law. The workpiece and tool are meshed with tetrahedron FE of Deform library, a coupled linear displacement–temperature four nodes element, with about 240 000 for the insert and 100 000 for the workpiece at the initial configuration. As the insert penetrates in the workmaterial, the workpiece is remeshed to form de chip and the FE number increases to capture geometrical non-linearities. A minimum FE size of about 100 µm is taken in the insert (at the engaged part of the rake face), and about 400 µm in the chip.

Note that the tool coating is taken into account implicitly through parameters involved in the contact interface equations (3)-(4). As reported by Koné et al. [19], since the simulated cutting time is very short (few milliseconds), predicted contact interface fields (e.g. pressure, temperature, sliding velocity) is less affected by the coatings due to their small thickness (few micrometres).

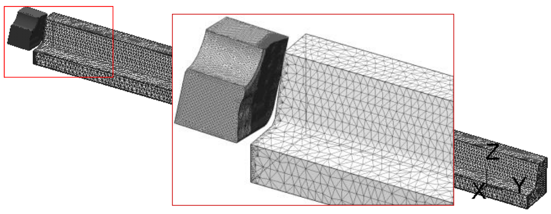

Fig. 5. FE model of the rough turning test.

The workmaterial behaviour is represented by the classical JC flow stress:

$$\bar{\sigma} = g\left(\bar{\varepsilon}^{p}\right) h\left(\dot{\bar{\varepsilon}}^{p}\right) k\left(T\right) \tag{1}$$

with

$$g\left(\bar{\varepsilon}^{vp}\right) = A + B\left(\bar{\varepsilon}^{p}\right)^{n}$$

$$h\left(\dot{\bar{\varepsilon}}^{p}\right) = \begin{cases} 1 + C\ln\left(\dfrac{\dot{\bar{\varepsilon}}^{p}}{\dot{\bar{\varepsilon}}_0}\right) & \text{if } \dot{\bar{\varepsilon}}^{p} > \dot{\bar{\varepsilon}}_0 \\ 1 & \text{if } \dot{\bar{\varepsilon}}^{p} \le \dot{\bar{\varepsilon}}_0 \end{cases} \tag{2}$$

$$k\left(T\right) = 1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}$$

The contact behaviour at the tool-workpiece interface is defined by the relationship:

$$\tau_f = \min\left(\mu\sigma_n, \beta\bar{\tau}\right) \tag{3}$$

The heat exchange at the contact interface is expressed as follows:

$$\begin{aligned} \dot{q}_{\to t} &= \tfrac{1}{2}\dot{q}_f + h\Delta T \\ \dot{q}_{\to w} &= \tfrac{1}{2}\dot{q}_f - h\Delta T \end{aligned} \tag{4}$$

where the frictional heat ($\dot{q}_f = \tau_f v_s$) is assumed going equally into the tool and workmaterial, and the temperature gap at the interface induces a heat conduction flux taken as $\dot{q}_c = h\Delta T$.

To estimate the tool wear for the considered tool–workmaterial couple, the phenomenological Usui wear law [6]-[7] expressed as follows is used:

$$\dot{w} = a\sigma_n v_s \exp\left(-b/T\right) \tag{5}$$

Parameters of the proposed FE model are reported in Haddag et al. [15]-[16].

5. Results and discussion

The developed finite element modelling is used hereafter, in comparison with experimental observations, to analyse finely the cutting process and the tribological behaviour and tool wear in the rough turning operation.

5.1. Analysis of the cutting process

The formed chips in the rough turning operation is quasi-continuous with small amount of segmentation. During the turning test, the chips fragmentation occurs when chips reach a certain cutting length (few centimetres), due to the increase of their curvature during cutting. Since the workmaterial is represented with the classical JC flow stress, the simulated chip is continuous. To reproduce the chip segmentation, the flow stress should be softened as the strain in the primary shear zone increases. One possible method is to couple the classical JC model with a damage model, as performed by Atlati et al. [20] and Kouadri et al. [21]. Note that various flow stress laws are proposed in the literature to reproduce correctly the softening effect as the workmaterial deform. Fig. 6 shows different views of the cutting process, where continuous chip is formed and the contact at the tool–chip interfaces is clearly discontinuous.

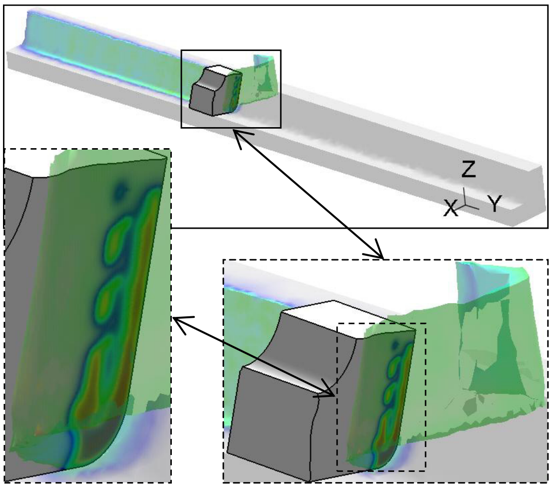

Fig. 6. Tribological behaviour during the chip formation process; prediction of contact discontinuities.

5.2. Analysis of the tool wear

The tool wear characterisation shows that the contact at the tool–chip interface is discontinuous and the wear is highly localized at particular zones on the cutting face. This is due mainly to the geometry of the rake face (grooved face), which presents concave zones, and also to the intense thermomechanical loading at the tool–chip interface (combined high contact pressure and temperature, due to the high engaged uncut area). The contact discontinuity induces a stress concentration in small zones (Z1, Z2 and Z3 in Fig. 3(b)), which support the major loading, leading naturally to the wear localization.

The developed FE-based model allowed prediction of the interface thermomechanical quantities, which are not accessible to direct measure using experimental means, like distribution of the contact pressure, the sliding velocity and the interface temperature. Predicted thermomechanical fields at a certain cutting time, when the chip formation is stabilized, are shown in Fig. 7. All quantities are highly localized at observed zones by SEM technique (see Fig. 3(b)). At contact zones the temperature is high enough to cause the adhesion of the workmaterial on the rake face, particularly in Z1 and Z2 of Fig. 3(b), although the insert is coated and has a good wear resistance.

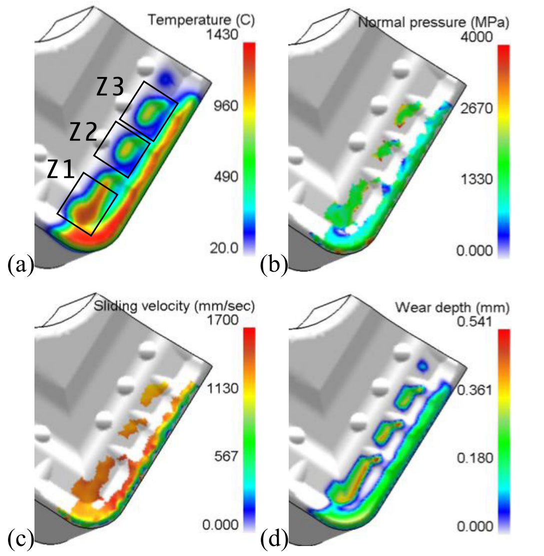

Fig. 7. Predicted (a) temperature, (b) contact pressure, (c) sliding velocity and (d) wear depth fields at the tool rake face.

To confirm thermomechanical conditions leading to the workmaterial adhesion on the rake face, Fig. 8 shows the temperature field evolution beyond half the absolute melting temperature of the workmaterial. As stated e.g. by Qi and Mills [22], beyond about half of the melting temperature conditions of adhesion wear may occur. In addition, as reported early by Saka et al. [23], it is emphasized that beyond about half the absolute melting temperature of materials thermal aspects at the contact interface in sliding systems become important particularly at high sliding speed. Fig. 8 shows that the first zone where the cutting temperature exceeds half of the melting temperature is Z1, which is close to the rounded cutting edge, followed by Z2 and then Z3. Indeed, as highlighted with OP technique (see Fig. 4), the amount of adhesion wear is higher in Z1, then in Z2 and lastly in Z3.

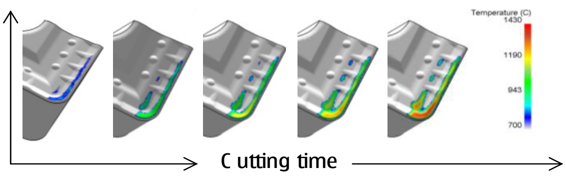

Fig. 8. Evolution of the temperature field beyond half the melting temperature at the tool rake face.

Although the simulated cutting time is very short (few milliseconds), this is sufficient to highlight wear localization zones and the intense thermomechanical loading at the contact interface leading to observed wear types. The qualitative prediction of the tool wear corresponds closely to that observed by SEM technique, as shown in Fig. 9. There is a close correspondence between FE prediction and SEM observation of the tool wear at the rake face.

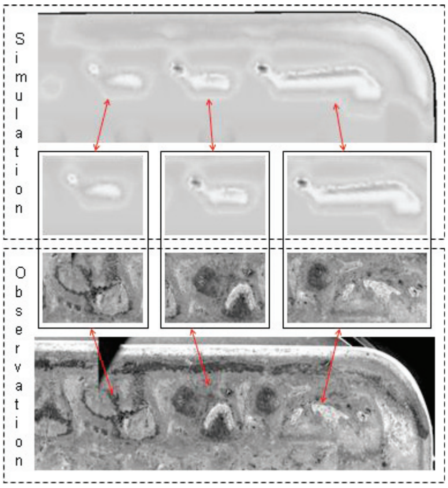

Fig. 9. Close correspondence between FE prediction and SEM observation of localized wear zones on the rake face.

6. Conclusion

Analyses of the tribological behaviour of the tool–workmaterial interface and associated tool wear mechanisms in rough turning of a large-scale part, made of 18MND5 mild steel, with SNMM250924RH grooved coated insert have been performed. Literature review shows that there is little research works dedicated to the analysis of the rough turning operation on large-scale parts. Using different characterisation techniques, it is revealed that the tool–chip interface presents contact discontinuities. This is due to the particular tool rake face geometry, designed especially to reduce the contact area and hence to facilitate the chip flow. In some contact zones, adhesion of the workmaterial is occurred, due to the combined effect of a high contact pressure and a low sliding velocity.

Analysis of the cutting process shows that the chip morphology is well reproduced by the FE model. To highlight the origin of the particular tribological behaviour at the contact interface and wear localization on the rake face, the developed FE model has allowed the prediction of thermomechanical fields, not accessible by direct measurements, which confirm the intense loading and wear localisation on small contact zones. The contact features are well reproduced as observed in SEM images. The FE-based approach can be used for the design of cutting tools, by studying the tribological behaviour at the tool–chip interface.

Acknowledgement

The authors wish to acknowledge the direction of AREVA Company for their acceptance to perform experimental tests in their manufacture site of Le Creusot (France).

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