Modeling and simulation of tool wear during the cutting process

F. Salvatorea*, S. Saad1, H. Hamdi1*

Université de Lyon, ENISE, LTDS, UMR CNRS 5513, 58 Rue Jean Parot, 42023 Saint Etienne, France

* Corresponding author. E-mail address: ferd3@free.fr.

Abstract

Experimental and analytic methods are still the main ways to investigate different cutting tool wear types. Numerous developments of numerical methods and simulations, associated to the existence of more and more powerful computer make possible tool wear studies using FEM. The main purpose of this work is to present a new approach to predict tool wear progression during cutting operation. In particular, an energy approach, linking the tool wear volume with the energy dissipated by friction is used. In addition, the interaction between residual stresses induced by cutting and the variation of tool geometry due to wear's mechanisms is investigated.

In order to carry out this study, it is presented the experimental measurements of the wear of the tool, in particular the lost volume during the cut. Numerical simulation of orthogonal cutting operation using the commercial FEM code ABAQUS/Explicit is employed.

© 2013 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of The International Scientific Committee of the “14th CIRP Conference on Modeling of Machining Operations” in the person of the Conference Chair Prof. Luca Settineri

Keywords: tool wear; numerical simulations; cutting; chip formation;

1. Introduction

The tool wear has a large influence on the economics of machining operation and the influence in the surface integrity. In fact, tool wear affect the tool life and the quality of the final product in terms of residual stress. For these reasons many investigations on tool wear are found in the literature [1-2-3]. The simulation of wear of the cutting tool in orthogonal cutting is developed to either validate a mechanism of wear. Either in these simulations, researchers tend to better understand the influence of tool wear in the impact of the residual stress in the final product [4]. In some investigations [5-6] the tool wear model implemented in a subroutine, is relative to a specific wear mechanism like abrasion and diffusive wear. So in this investigation, a specific mechanism is considered as largely influencing the wear phenomena.

In fact, tool wear is affected by several and different mechanisms like material adhesion, erosion, corrosion, abrasive, and fracture. During cutting, tool geometry is changing due the tool wear effect. This updating in the tool geometry is largely modeled, in numerical simulation, by a movement of the tool face node [7]. This method is used with a specific subroutine which evaluates the cutting variables like, temperature, normal pressure and sliding distance from every tool nodes that exist in the simulation of orthogonal cutting. After that, other subroutine is launched to impose node movement.

The existing wear model can be classified into two types: the first one is cutting parameter-tool life type, such Taylor’s equation, the second one is cutting process variable often based on one or several wear mechanisms [8]. This modeling is weak because, on one hand, the wear phenomena are modeled as discontinuous phenomena in time which is not the case in reality. On the other hand, it is limited in terms of the implemented wear mechanism, i.e. the problem of wear is reduced to one or two wear mechanism.

The phenomenon of wear in contact is illustrated in fretting system by a relationship between the formation of debris and the energy dissipated by friction in the contact. This dissipated energy is the more controllable in terms of quantity used in the contact zone [9]. This method is experimental, a tribometer is used to quantify the value of efforts in the contact and then the energy...
dissipated by friction and links it with the lost volume in this zone [10].

For these reasons, it is presented in this paper a new approach, which provides not only a global modeling of the wear phenomena but also the combination of two aspects, the progression of tool wear and his impact on the residual stress of the final product in the orthogonal cutting configuration.

In order to lead this study, the methodology proposed has three different parts. In the first part, a tool wear measurements are presented. Afterwards, the energy approach is presented and modified for the application in the orthogonal cutting. A numerical simulation of the orthogonal cutting operation is developed, using the commercial FEM code ABAQUS/Explicit. The last part includes the numerical results of the tool wear evolution during simulation and the conclusion.

2. Experimental tests

The experimental tests, conducted to validate the FEM model and measure the progressive tool wear, consisted of turning operation discs made of 42CD4 with an initial diameter of 70 mm. the used tool is uncoated with a tungsten carbide (WC) referenced as TPKN 1603 PPR. (Fig. 1).

Wear measurements are done using microscope and there are presented in table 1, according to figure 2. \( V_c \) is the cutting speed, \( f \) the feed rate.

| Cutting conditions | Time (s) | KM (mm) | Kt (mm) | VB (mm) |
|--------------------|----------|---------|---------|---------|
| Vc=120 m/min       | 10       | 0.03    | -       | 0.029   |
| f=0.1 mm/rev       | 20       | 0.05    | 0.001   | 0.038   |
|                    | 30       | 0.06    | 0.003   | 0.040   |
|                    | 40       | 0.074   | 0.006   | 0.042   |
|                    | 60       | 0.084   | 0.007   | 0.06    |
|                    | 80       | 0.09    | 0.008   | 0.065   |
| Vc=260 m/min       | 20       | 0.06    | 0.001   | 0.029   |
| f=0.1 mm/rev       | 40       | 0.077   | 0.005   | 0.043   |
|                    | 60       | 0.087   | 0.007   | 0.066   |
|                    | 80       | 0.094   | 0.008   | 0.074   |
|                    | 100      | 0.096   | 0.010   | 0.112   |
|                    | 120      | 0.107   | 0.011   | 0.116   |
|                    | 140      | 0.114   | 0.013   | 0.119   |

Fig. 2. Location of measured geometries of the tool

3. Numerical model

3.1. Tool modeling

The material used for the cutting tool is tungsten carbide. This choice is influenced by the type of tool used in experimental tests, which are tools made of tungsten carbide. So, to compare the results issued by the experience and those issued by the numerical simulation, the choice of using the same type of materials is required. In regard to the law used to model
the flow of material was chosen to use the curve constraints functions of plastic strain. Therefore, the material used to model the tool has an elastic-plastic behavior like it is acted in table 2 [11].

Table 2. Carbide tungsten material model

| Effective plane strain | Yield stress (KPa) |
|------------------------|-------------------|
| 0.00000E+00           | 4.19530E+5        |
| 2.63000E-04           | 1.69690E+6        |
| 9.73640E-04           | 2.67550E+6        |
| 2.10700E-03           | 3.37650E+6        |
| 3.57400E-03           | 3.85820E+6        |
| 5.28700E-03           | 4.17800E+6        |
| 7.17600E-03           | 4.38220E+6        |
| 9.19000E-03           | 4.50480E+6        |
| 1.12900E-02           | 4.57010E+6        |
| 1.34520E-02           | 4.59550E+6        |
| 1.42790E-02           | 4.59730E+6        |
| 1.00000E-01           | 4.59730E+6        |

The damage model implemented on the calculation software ABAQUS/Explicit to model the damage of the tool is the model of Johnson and Cook [12-13]. The parameters used are given in the following table 3 [9].

Table 3. Carbide tungsten material model

| D1  | D2   | D3   | D4   | D5   |
|-----|------|------|------|------|
| 0   | 0.01072 | -1.669 | 0    | 0    |

The cutting tool is defined as deformable and damageable. The cutting speed is rather imposed a rigid body. This idea comes from the fact that we must avoid applying a velocity or displacement on a deformable body. So to avoid all purely numerical problems, we chose to use a rigid body that supports the deformable tool. The connection between the two is done with the function Tie.

The tool has a cutting edge radius of 10 µ, and a flank angle of 11°. The geometric modeling is on the cutting insert used in experimental tests. Because of contact problems, it is ensured that a portion of the tool cutting edge radius is without damage (Zone D) like it is showed in figure 3. This solution is necessary to maintain contact between all nodes in the separation zone and the outer surface of the D zone.

Fracture energy $E_{\text{max}}$ (in ABAQUS) was implemented in the tool quite low in order to found a fast tool wear in numerical simulations of orthogonal cutting that lasts a few ms.

3.2. Work piece modeling

Very high strain, strain rate and temperature in metal cutting process, have strong influence on materiel’s flow. To get better chip formation analysis results, a material model that combines all these aspects is necessary. In this simulation, it is opted for the Johnson and Cook behaviour and constitutive law [14-15-16].

3.3. Contact problem

The most important problem faced in the development of a numerical model of orthogonal cutting that takes into account the tool wear is contact management. Already, this aspect is very sensitive in the classical simulation and it grows in the case where the contact is dynamic, i.e. between two sets of nodes, respectively node of work piece and tool node. Note that the ABAQUS software, on how the numerical model is developed, cannot handle the contact regions between two nodes. So, it just allows a contact between a surface and a set of nodes. The commercial software is limited in terms of contact management regarding 2D modelling. (Fig. 4).
This solution can manage the contact between all nodes of the tool and the inner surface of the chip that will be generated. This method is possible through the use of a model of orthogonal cutting with a separation line defined fields and three areas of separation, where the ability to select the inner surface of the chip (Fig. 5).

Fig. 5. Contact problem between the tool and the chip

The contact and friction at tool/chip and tool/work determines the cutting power and the tool wear. In this paper a Coulomb’s friction model is used with a constant frictional coefficient of 0.2.

4. Numerical simulations

4.1. Development of a simulation lasting several seconds

Numerical simulations of orthogonal cutting last in most cases a few milliseconds. These simulations greatly reduced in terms of simulation time have a fairly large computational time and can take several days. So, regarding the numerical simulations where the simulation time is in order of one minute, it is expected that a fairly high computational time which may meet several weeks. In order to develop a numerical simulation which takes several seconds, we must find solutions to reduce the computation time. In the following, it is presented the developed model which provides innovative solutions to address this problem.

The computation time in a numerical simulation is mainly divided between the need to calculate the deformations within the material and the need to manage the contact. This time is variable depending on the formulation used. It is known that the computation time is even less important in the order of the following formulations, Lagrangian, Eulerian and ALE.

It can be concluded that the choice of the Lagrangian formulation is already done and we cannot change it, because of contact constraints imposed from the beginning. This goes back to investigate the second channel which is responsible for increasing the computing relative to management of the contact. So it is possible to deduce that the contact time is more important than the number of nodes in contact is high. The following figure, (Fig. 6), shows the case of numerical simulation of relatively long pieces of about 50 mm, the calculation time is increasingly important given the increase of nodes in contact. These nodes are related to chips. In some cases, there were excessive distortions that create a stop calculation. The distorted meshes are particularly located in the chip. This is due to the winding of chip on itself.

Fig. 6. Increase in computation time caused by the nodes in contact

It is now focused on the problem created by the gradually chip generated as the simulation evolves. The solution is in place from the fact that the chip generates significant computational time for the management of nodes in contact. This solution also relies on the fact that the chip is something of a waste, even if it allows us to have a wealth of information concerning the conduct of the cut operation. Consequently it is opted for the elimination of this chip. So that it does not cause complications in the simulation which would be reflected in the computation time implemented to manage the contact between the chip itself and the raw surface. The following figure 7 presents the model developed with the discontinuous chip. After a period of time the chip is ejected from the cutting area. The ejection of the cutting area saves time thanks to the sizable reduction of the contact surfaces and then the resulting equations.

Fig. 7. Solution to reduce the calculation time, e=80 μm
4.2. Numerical wear simulations

The developed model delivers first fairly satisfactory results. It shows that the crater wear develops gradually as the simulation advances. From the following figure 9, it is shown that the solutions chosen to manage the contact between the chip and all nodes of the tool work well. These give satisfying results, where we see that the inside of the chip follows the tool wear and keeps a contact surface between the crater and all nodes of the formed chip.

It is observed that this approach gives rather poor results in terms of flank wear because of the neglected spring back phenomenon that happens in front of the flank tool. This contact effect as raising the coefficient of friction that causes high temperatures in this area [17]. But in the presented study the ratio between feed rate and cutting edge radius \(f/R\) is high and it is possible to neglect flank wear.

Conclusion

In the presented paper, tool wear modeling has developed as a result from the energy dissipation on the contact zone. This approach leads to implementing a damage law in the tool material. The method of elimination of nodes of the tool is used when the latter reaches the value of a defined maximum energy fields.

The first results of the tool wear delivered by FEM energetic approach seems interesting. For sure, it is necessary to complete the study with the setting of the tool wear using fracture energy.

Afterwards, a section is devoted to the development of a new method that allows us to significantly reduce the computation time required to complete the simulation. The approach highlights the fact that the computation time is generated by the complexity of managing the contact between the chip and work piece.

This method presented in this paper keeps the history of machining in the finished part and as a result, it is possible to derive the residual stresses induced in the part. This last aspect will be presented in a future paper.
References

[1] Kgnay, Tchadj M., 2009, Contribution à l’identification des mécanismes d’usure en usinage d’un WC-6%Co par une approche tribologique et thermique. ENSMP 2009. Thèse de doctorat. ED n°.432.
[2] Nouari M., Molinari A. 2002, Modeling of tool wear by diffusion in metal cutting, Wear 252-1, p. 135–149.
[3] Poulachon G., Moisan A. et Jawahir I. S. 2001, Tool-wear mechanisms in hard turning with polycrystalline cubic boron nitride tools, Wear, 250(1-12) p. 576–586.
[4] Muñoz-Sánchez A., Canteli J.A., Cantero J.L., Miguélez M.H. 2011, Numerical analysis of the tool wear effect in the machining induced residual stresses, 19-2 p. 872–886.
[5] Yen Y. C., Söhner J., Lilly B., and Altan T., 2004, Estimation of tool wear in orthogonal cutting using the finite element analysis. Journal of Materials Processing Technology, 262 p. 82-91.
[6] Filice L., Micari F., Settineri L., Umbrello D. 2007, Wear modelling in mild steel orthogonal cutting when using uncoated carbide tools, Wear, 262, p. 545–554.
[7] Attanasio A., Ceretti E., Fiorentino A., Cappellini C., Giardini C. 2010, Investigation and FEM-based simulation of tool wear in turning operations with uncoated carbide tools, Simulation Modelling Practice and Theory, 269, p. 344-350.
[8] Xie L.-J., Schmidt, Schmidt C., Biesinger F. 2004, 2D FEM estimate of tool wear in turning operation, Wear, 258-10, p. 1479-1490.
[9] Ramalho A., Miranda J.C. 2006, The relationship between wear and dissipated energy in sliding systems, Wear 260, p. 361-376.
[10] Huq M.Z., Celis J.-P ., 2002 Expressing wear rate in sliding contacts based on dissipated energy, Wear 252, p. 375–383.
[11] Moxnes J. F., Teland J. A., Skriudalen S., Bergrud S. M., Sundem-Eriksen L. and Fykse H. 2010, Development of material models for semi-brittle materials like, Norwegian Defence Research Establishment (FFI), ISBN 978-82-464-1830-8.
[12] Johnson R. and Cook W.K., 1983, A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, 7th International Symposium on Balistics p. 541-547.
[13] Johnson W.H. and Cook G.R. 1985, Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperature and Pressures, 21 p. 31-48.
[14] Barge M., Hamdi H., Rech J. and Bergheau J. M., 2005, Numerical modelling of orthogonal cutting: influence of numerical parameters, Journal of Materials Processing Technology, 164-165, p. 1148-1153.
[15] Mabrouki T., Girardin F., Asad M., and Rigal J.-F. 2008, Numerical and experimental study of dry cutting for an aluminium alloy 48, p. 1187 - 1197.
[16] Salvatore F., Mabrouki T., Hamdi H., 2012, Numerical and experimental study of residual stresses induced by machining processes, Int. Journal of Surface Science and Engineering, 6-1/2, p. 136-147.
[17] Salvatore F., Mabrouki T., Hamdi H., 2011, Numerical simulation and analytical model-ling of ploughing and elastic phenomena during machining processes, Int. Journal of Surface Science and Engineering, 6-3, p. 185-200.