ABSTRACT

Milling is among machining processes one of the most frequently used, but although milling processes operations are very used in mechanical engineering industries and as a lot of experimental results are available, some essential physical phenomena present difficulties of understanding. Indeed milling is a very complex process with physical interactions between shearing, compression, ploughing, friction, very high strain rate, thermal effects and failure. Actually the machining industry needs to use new methodologies to optimise milling operations. In this context, a three dimensional finite element model of milling process, using an explicit commercial code, was developed in the proposed works. The workpiece material behaviour is in a first approach described using a Johnson-Cook constitutive law. In the same time, milling tests have been conducted to furnish cutting forces data in a shoulder milling configuration. In this way, a measuring methodology for cutting forces is presented to introduce the comparison step and the difficulties to reach experimental conditions in milling simulations through finite elements method. To improve the predictive capacity of these modelling approaches, the main difficulty is to characterise the workpiece material behaviour.

Keywords: milling, stainless steel, finite element method

1. INTRODUCTION

The understanding of the physical phenomena and the identification of material behaviour in machining are the main issue for the manufacturing processes understanding. Some analytical models were previously proposed by Merchant [1], developed by Oxley [2] and Molinari & Dudzinski [3], and more recently they were adapted to milling [4]. Nevertheless, these models give only a partial interpretation of the cutting process mechanisms and numerical methods should be used to provide powerful modelling solutions. The Finite Element Method can give useful results but it needs rigor and analysis in construction, calibration and optimisation procedures to obtain relevant results in a reasonable time. Some calibrated and optimised models exist for elementary cutting processes as related in the works of Pantalé [5]. These analyses have now to progress in the way of the real machining process simulation and in particular for milling operations. In the present paper, a 3D FEM model of shoulder milling is presented. It has been developed with the LS-Dyna® commercial software and provides numerical cutting forces values that can be compared with experimental data. A measuring methodology for cutting forces is presented to introduce the comparison step and the difficulties to reach experimental conditions in milling simulations through finite elements method. To improve the predictive capacity of these modelling approaches, the main difficulty is to characterise the workpiece material behaviour.
Table 1. Tools characteristics corresponding to the milling experiments.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Diameter</th>
<th>Number of teeth</th>
<th>Coating</th>
<th>Helix angle</th>
<th>Rake angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool 1</td>
<td>6 mm</td>
<td>2</td>
<td>No</td>
<td>40°</td>
<td>8°</td>
</tr>
<tr>
<td>Tool 2</td>
<td>6 mm</td>
<td>2</td>
<td>TiCN</td>
<td>40°</td>
<td>8°</td>
</tr>
<tr>
<td>Tool 3</td>
<td>6 mm</td>
<td>4</td>
<td>No</td>
<td>40°</td>
<td>0°</td>
</tr>
<tr>
<td>Tool 4</td>
<td>6 mm</td>
<td>4</td>
<td>TiCN</td>
<td>40°</td>
<td>5°</td>
</tr>
<tr>
<td>Tool 5</td>
<td>4 mm</td>
<td>2</td>
<td>No</td>
<td>30°</td>
<td>≈0°</td>
</tr>
</tbody>
</table>

The presented approach is the first step for setting an inverse method [6] [7] [8] for the identification of model parameters directly from machining experiments. [10] [11]

2. MILLING TESTS

In this section is related a complete instrumentation including sensors and on line measuring system set up to obtain the cutting forces of milling operation on a 304L stainless steel. The results of the experiments are firstly presented.

2.1 Experimental protocol

The experimental setup is based on a Kistler® dynamometer using the piezoelectric accelerometers technology. The experiments were carried out on a Kern® micro milling machine, which has been chosen for its high precision and rigidity. The dynamometer was fixed on the table of the 3 axes CNC machine, and then was connected to a PC through a charge amplifier and an input/output acquisition card as shown in Figures 1 & 2. Real-time data checking and force determination in milling were allowed by a specific software. For instance, the acquisition frequency can be compared to the dynamometer’s limit in order to validate the test. Finally, the signals were checked through a spectral analysis to verify their stability and their relevance. The selected tools are mainly uncoated tungsten carbide two teeth end mills from the manufacturers Dixi Tools® and Diager Industrie®. The different tested tools are related in Table 1. All the experiments were realised in shoulder milling and the conditions are summarised in Figure 3. All the test specimens have been machined in the same 304L austenitic stainless steel bar and in the same dimensions: 80 mm x 40 mm x 10 mm. The milling experiments are mainly carried out without lubrication. Before the experiments, the tool run out of each tool has been measured with an accuracy less than one micrometer. The tool run-out is an offset of position and/or angle between the cutter axis and the spindle axis. This offset creates a gap in the cutting forces between the two teeth of the mill.

Figure 1. Micro milling machine KERN and milling test set-up.

Figure 2. Experimental data acquisition chain used in milling experiments.

Figure 3. Milling configuration.
2.2 Experimental results

For all the tests, the cutting forces on three axes have been measured with the data acquisition system. Figure 4 relates a zoom of the cutting forces stabilized signals in milling with the tool number 1 as related in Table 1. The cutting conditions and machining parameters correspond to a spindle speed $\Omega = 3715$ rpm, a feed $f_t = 0.045$ mm.tooth$^{-1}$ and a cutting speed $V_c = 70$ m.min$^{-1}$. These cutting forces curves show that it is possible to get a good and accurate variation of the milling forces in the 3 directions. The curves show cyclic and sinusoidal shape, where each cycle corresponds to a milling cutter revolution and, each cycle peak corresponds to a tooth path. A discrepancy in the forces level appears between the two peaks, which is mainly due to the tool run-out, corresponding in that case to 5 µm.

2.3 Summarise

These milling experiments above described allowed us to analyze accurately the measured cutting forces curves and to obtain reliable and useful measured data. The average amplitude of the cutting forces $F_x$, $F_y$ and $F_z$ have been measured on Tool 1 tests for different feed values as related in Figure 5. From these results, it is possible to conclude that the high speed machining zone for the 304L stainless steel begins around 450 m.min$^{-1}$. And its machinability is summarized in Figure 7.
3. MILLING SIMULATIONS

In order to perform numerical simulations of milling, a finite element model was implemented in LS-Dyna© FEM code. As machining is an high speed metal forming process characterized by large dynamic stresses and localized high strains, an explicit code solution scheme was adopted through the LS-Dyna© FEM code. The final aim consists to prove the feasibility of a reliable simulation of milling, able to give accurate estimated values for the cutting forces.

3.1 Model parameters

At the beginning, a 4 mm diameter end mill is used and a 304L stainless steel rectangular specimen has been designed. The test specimen is meshed with 260,000 elements and the end mill is meshed with about 100,000 elements. The material mesh need to be optimised in order to decrease the number of elements, to obtain a correct chip formation. The meshes are illustrated in Figure 8 & 9. The material behaviour has been firstly modelled using classical Johnson-Cook constitutive model \[ \sigma = \left[ A + B\varepsilon^p \right] \left[ 1 + \ln \left( \frac{\varepsilon}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T - T_{ref}}{T_{melt} - T_{ref}} \right)^n \right] \] (1)

The material parameters were provided through a research project supported by the CETIM foundation and are related in Table 2. For the simulation the end mill is considered as a rigid body. This model uses here, an element failure criterion based on a limiting plastic strain critical value \( \varepsilon_r = 48 \% \) and a static friction Coulomb law \( \mu = 0.7 \). The cutting conditions used in the simulation correspond to a cutting speed: \( V_c = 250 \text{ m.min}^{-1} \) and a feed: \( f_t = 0.2 \text{ mm.tooth}^{-1} \). The calculation time is about 20 days on a bi-processor Xeon 3.2 GHz for two end mill rotations.

\[
\begin{array}{|l|l|}
\hline
\text{Parameters} & \text{Value} \\
\hline
A & 253.32 \text{ Mpa} \\
B & 685.1 \text{ Mpa} \\
n & 0.3128 \\
C & 0.097 \\
m & 2.044 \\
T_{melt} & 1698 ^\circ \text{K} \\
T_{ref} & 296 ^\circ \text{K} \\
\hline
\end{array}
\]

Table 2. 304L stainless steel material parameters.

The material parameters were provided through a research project supported by the CETIM foundation and are related in Table 2. For the simulation the end mill is considered as a rigid body. This model uses here, an element failure criterion based on a limiting plastic strain critical value \( \varepsilon_r = 48 \% \) and a static friction Coulomb law \( \mu = 0.7 \). The cutting conditions used in the simulation correspond to a cutting speed: \( V_c = 250 \text{ m.min}^{-1} \) and a feed: \( f_t = 0.2 \text{ mm.tooth}^{-1} \). The calculation time is about 20 days on a bi-processor Xeon 3.2 GHz for two end mill rotations.

Figure 8. End mill mesh.

Figure 9. Machined material mesh.
3.2 Simulation results

Figure 10 shows different steps during the simulation, it is possible to observe the chip formation during a tooth path, and the final machined surface. In this model, the choice has been made to keep around 10 elements in the thicker part of the chip to limit the effect of elements size on cutting forces level and obtain a reasonable computing time. It corresponds here to an average element size of 0.02 mm with cubic type elements.

Figure 11 (a) gives the cutting forces obtained at the end of the simulation for three tooth paths. The numerical response is cyclic and sinusoidal. A small difference between the first $F_x$ peak and the others appears. This discrepancy is due to an error of the end mill initial position in the finite element mesh. When the starting position is passed, the following peaks are similar.

3.3 Comparison with experiments

The Figure 11 presents the numerical results (a) and the experimental curves obtained for the same conditions (b), (c) and (d). The same shape of cutting forces curves is reproduced as the curves related on Figure 4.

For the experimental tests in the same cutting conditions, as related in Figure 11, the measure of the $F_x$ and $F_z$ cutting forces is damaged by the critical value of the feed (0.2 mm/tooth) for a Ø4mm end mill. But in order to show the feasibility to obtain numerical cutting forces, the choice of a high feed speed decreases the element size and in the same way the calculation time. Figure 11 shows that the material removal is not very stable, and the $F_x$ cutting force is more perturbed because of quick change of chip thickness in this direction.
Moreover $F_z$ become positive with the tool wear, indeed an observation after the test shows that the end mill changes quickly its geometry in a bull-nose one. A bull-nose end mill provides positive cutting force on $z$ axis for a straight cut test as shown by Fontaine [12]. Moreover, for all cutting forces, the zone between the peaks presents some discrepancies mainly due to the effect of dynamic tool motion and sensors response. In the same way, the simulation does not reproduce the tool run-out, the average curve of the experimental forces has been added on each plot of Figure 11. With these averaged curves, errors of 320% and 300% have been found respectively for $F_x$ and $F_y$ cutting forces. As described previously no conclusion are now possible for the $F_z$ cutting forces. The errors on the cutting forces curves can be explain with the choice of the element failure criterion value ($\varepsilon_r = 48\%$). In fact this value is very hard to identify experimentally in the same mechanical solicitations involved during machining. An inverse identification procedure needs to be conducted on this criterion. But also other parameters need to be considered, in particular the tool geometry used in the simulation doesn’t reproduce perfectly the real helix and rake angles, and many analytical works have shown the importance of these angles on the cutting mechanism.

3.4 Summarise
These first works have shown the feasibility to simulate a milling operation in 3D with a commercial code and to obtain numerical cutting forces. Some parameters need to be identified with inverse method to have a better approximation of the cutting forces values.
But one of the main difficulties in milling simulation is the meshing of the machined material. In fact in industrial milling conditions, the feed per tooth is very small in front of the global geometrical size of the finite element model. A very small feed involve a very small element size, and in an explicit scheme the calculation time increase very quickly.

The difficulties to optimise the mesh and the computation time seem to be the main obstacle for the simulation of the milling process. Another difficulty appears in the tool numerical modelling and meshing, because the simulation needs to respect with accuracy the location of cutting edge and local angles but real tool geometry is difficult to mesh efficiently.

4. IDENTIFICATION PROCEDURE

The last part of this work consists to carry out an inverse identification procedure on the numerical and experimental cutting force results for the determination of 304L stainless steel parameters or interface parameters (friction, chip separation...).

The identification methodology needs an objective function to minimize, a set of parameters to analyze, a finite elements method solver and a procedure for updating the targeted parameters. For the milling experiments identification, the parameters system $p$ can be chosen in the Johnson-Cook constitutive law (1) or in the numerical model interface parameters.

Then an objective function dependent of the measured experimental criteria (here the cutting forces) has been defined in equation (2). The previous function measures difference between the cutting forces curves obtained with the numerical simulation software and with the experimental set-up.

$$R(p) = \frac{1}{2} \left( \sum_{i=1}^{N_p} [F_{x}^{\text{exp}} - F_{x}^{\text{num}}(p)]^2 + ... ight)$$

$$... \sum [F_{y}^{\text{exp}} - F_{y}^{\text{num}}(p)]^2 + ...$$

$$... \sum [F_{z}^{\text{exp}} - F_{z}^{\text{num}}(p)]^2$$

Figure 12 schematically relates the identification loop, the procedure is based on a set of parameters obtain through simulation and then compared with experimental results. After this estimate, whether the objective function is equal to zero and the optimised solution appeared, or the function is different to zero and the set of parameters has to be modified and the loop begin one more time. Several methods exist for the identification strategy, but in this
work the Moving Least Square Approximation (MLSA) method has been used.

5. CONCLUSION
Milling experiments allow to analysing with accuracy the cutting forces curves and permit to obtain reliable and useful measured data for the finite elements model validation. Then, a first 3D simulation of milling process has been set up but few more investigations seem necessary to reach industrial cutting conditions. A good modelling of the geometrical cutting conditions in using a CAD model of the experimental tools need to be used to improve the numerical cutting forces prediction. The identification procedure seems necessary to find the value of semi-numerical and experimental parameters as the element failure criterion. Moreover, further developments are in progress concerning the numerical model improvements and the choice of a new material behaviour model more adapted to a high speed machining process in order to test the method in High Speed Milling conditions.

ACKNOWLEDGEMENTS
This work has been carried out with the financial support of the CETIM Foundation in the frame of a national project on High Speed Processes (PGV). Thanks to F. Gaillard from DIAGER Industrie® for his help in choosing and obtaining tools.

LIST OF REFERENCES