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CUTTING FORCES, CHIP FORMATION AND TEMPERATURE FOR TWO-DIMENSIONAL FINITE ELEMENT SIMULATION OF MILLING PROCESS

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Abstract: *Milling is a key machining technology for manufacturing. The correct design of the cutting conditions, together with the appropriate geometry of the cutting tool, can contribute to greater productivity in the milling process. In this study, a two-dimensional finite element (FEM) simulation of the milling process was used to compare the cutting forces obtained by simulation with milling experiments and dynamometer measurements. The results showed that the FEM simulation was able to provide a simplified representation of the complex three-dimensional process, but it provides a clear picture of key phenomena such as stress distribution, temperature evolution, chip formation, and cutting forces. The STFC company DEFORM software is used for the FEM simulation model.*

Key words: *Milling operation, FEM, cutting forces, cutting simulation, cutting tool.*

1. INTRODUCTION

Cutting processes play an essential role in numerous manufacturing industries, including aerospace, automotive, precision engineering, etc. Achieving optimal cutting conditions is crucial to enhance productivity, ensuring high-quality production, and reducing costs. Accurate prediction and analysing the complex interactions between the cutting tool, the workpiece and machining environment presents a challenge of experiences, knowledge, and skills. FEM simulation appears as a powerful tool for understanding and optimising cutting processes. By using the partial differential equations, initial and boundary conditions, FEM provides insight into the cutting process into various physical phenomena, such as stress distribution, temperature flow, forces, deformation, etc. Although the computational power of current computers is strong, the prevailing tendency is to simplify and generalise the cutting problem. One possibility of simplification is the use of 2D orthogonal cutting modelling. Kyratsis at al. [1] performed a comparative study between 2D and 3D Finite Element Methods in machining. In this study, efforts were made to capture the effectiveness of each method when studying standard machining results such as cutting forces and torque, the temperatures, residual stresses, and the tool wear. Several studies have been conducted in which a physical experiment has been validated with a simulation model, such as [2] in which experimental validation of Tool Wear with FEM simulation. The finite element model is developed to perform conventional turning, ultrasonic assisted turning, and hot ultrasonic-assisted turning at 200 ° C. The results were examined in terms of tool flank and crater wear, tool–chip contact length, cutting force, and feed forces. As can be shown, FEM simulation can also be used for specific machining technologies, e.g. ultrasonic-assisted turning. Hussain at al. [3]**,** describes another special technology, hard turning. In the case of FEM hard-cutting technology, importance is given to the correct use of the material model. Since 2D simulation [4] has its justification due to the lower demand for computer hardware performance, the study described in this paper is focused on 2D milling simulation. Although it is not possible or very difficult to observe the orthogonal cutting conditions such as inclination angle 0, setting angle 90, and open ends at the cutting edge in the case of milling, the 2D simulation provides basic information about the root of the cut and chip formation. In this study, an attempt is made to compare the experimental measurement of cutting forces in the milling process with the 2D FEM simulation.

2. EXPERIMENT SETUP

The monolithic milling tool used in the experiment was manufactured in CE5AM (Centre of excellence of 5-axis machining) laboratory on a grinding machine.

2. 1. Milling tool

The design of the tool was derived from the commercial SECO Tools JS754 100E2C.0Z4-HXT. The tools were manufactured from cemented carbide grade CTS20D that is equivalent to the ISO K20-K40 code. The basic parameters of the toll are summarised in Table 1.

Table 1

Milling tool parameters.

Tool parameters	value
Cutting diameter	10 mm
Maximum shank diameter	10 mm
Count of cutting edges	4
Flute helix angle	48°
Main cutting edge setting angle κ_r	89°
Secondary cutting edge setting angle κ_r‘	4,15°
Corner chamber length/radius size	0,125x45° mm

The geometry of the tool was designed using NUMROTOPLUS software. This tool was manufactured using a multi-axis tool grinder. The tool model can also be used to prepare FEM simulation models. Fig. 1 shows the use of cutter geometry to create a 2D FEM model of the milling operation based on the specified machining conditions.

2.2. Workpiece material

Austenitic stainless steel STN 17349/DIN X2CrNiMo17-12-2(AISI 316L) was used as experimental machined material. This type of steel contains austenitic structures, present as a result of the alloying elements such as nickel, manganese, carbon, and nitrogen. It has low yield strength of 230 to 300 MPa, but high toughness of up to 240 J.cm^2.

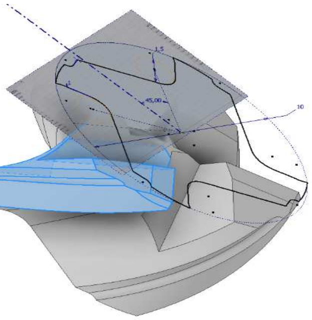

Fig. 1. Geometry preparation for the FEM model.

Thermal conductivity is relatively low with a value of 16.9 Wm^{-1}K^{-1} but in higher temperature more as 500 ° C is thermal conductivity higher, a value of 21.9 Wm^{-1}K^{-1}. The thermal conductivity is temperature dependent, and this property must be included in the FEM material properties simulation. The chemical composition as well as mechanical properties are listed in Tables 2 and table 3.

Table 2

Chemical composition of AISI 316L.

C	Si	Mn	P	S
0.019	0.64	1.48	0.025	0.016
Cr	**Ni**	**Mo**	**Ti**	**Co**
16.56	10.62	2.00	0.012	0.12

Table 3

Mechanical properties of AISI 316L.

Mech. property	Designator	Value
Yield strength	Rp 0.2% [MPa]	265
Yield strength	Rp 1.0% [MPa]	308
Tensile strength	Rm [Mpa]	568
Elongation	A [%]	56.8

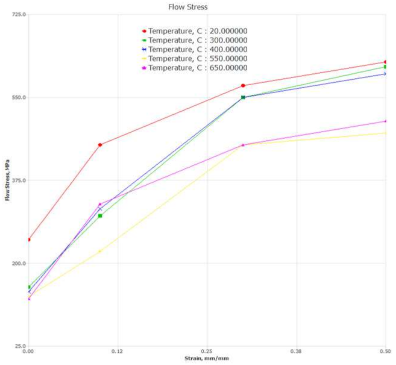

Fig. 2. Flow-stress of machined material.

The machined material model for simulation is an ideal plastic thermodynamic model which describes the flow stress by physical quantities such as temperature, strain, and strain rate. The material model is represented in tabular data form. The flow stress graph is shown in Fig. 2.

2.3. Experiment machining condition

The experiments were carried out at a CNC machining centre with cutting parameters of radial depth 3 mm feed per tooth 0.09 mm and cutting speed 190 m.min^{-1}. In machining experiment is about side-down milling operation. Based on the parameters of the machining process, the boundary conditions of the simulation FEM model are set. Cutting forces were measured with a Kistler 5070A dynamometer during milling.

3. FEM SETTING AND BOUNDARY CONDITIONS

The commercial DEFORM 2D in V12 was used for the FEM simulation. The implicit solver uses Lagrangian formulation of the nonlinear time incremental problem, which allows the cutting process to be analysed from the start of the cut, to the few μs when the chip begins to separate. Software DEFORM provides chip separation methods by re-mesh functionality which can be specified as increment depth between object, maximum stroke increment, maximum time increment or maximum step increment. Remeshing also occurs automatically if the Jacobi determinant of any of the resulting elements is less than 0. In this case of milling operation, the re-mesh criterion was set as interference depth 0.01 mm. The parallel solver can use the Newton-Raphson or direct iteration method. Implicit setting of iteration is Newton-Raphson method, because provide low computation times, however, if the increment does not converge, the iteration method is switched automatically to direct method. This combination provides low computation times when providing an automatic solution. However, the calculation time is also influenced by other factors, such as the amount of elements, friction model, as well as the material model etc. In terms of the number of elements, a 2D simulation is much less demanding than a 3D complex simulation. However, even in the case of 2D simulation, we try to reduce the number of elements so that dimensionally small elements remain only in the zones of interest of the solution to the problem, and in the zones of no interest the elements are as large as possible. Fig. 3 shows the setting of cutting model in 2D DEFORM software.

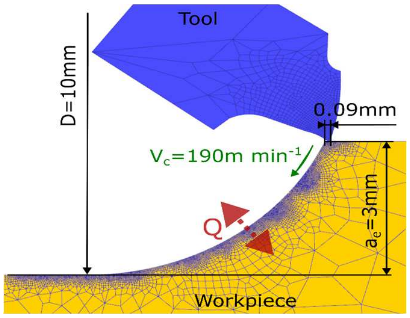

Fig. 3. Setting of the FEM orthogonal cutting model in 2D FEM DEFORM software

In the cutting zone, near the cutting edge of the side sizes of the tool, the elements are 0.018 mm. In the cutting zone, close to the cutting edge of the tool, the size of the elements faces is approximately 0.018 mm. If the feed per tooth is 0.09 mm, this element size results in 5 elements per chip thickness, which is satisfactory in this case. Since it is a step-by-step milling process, the chip thickness becomes thinner, causing complications in the simulation. The simulation had to be restarted several times during tool rotation, and at the end when the cutting edge comes out of the material being machined, the simulation results can no longer be considered to be significant.

The tool model is defined as a rigid (nondeformable object), but since the thermo-mechanical properties of the machined material are used, it is necessary to define the thermal properties of the tool and consequently to mesh the geometry.

The size of the mesh depends mainly on the geometric properties of the tool (radius of the cutting edge); Fig. 3. The thermal conductivity of the tool has been set to 59 Wm^{-1}K^{-1}.

The contact properties of the objects are: friction is set as a constant shear coefficient vale 0.25 and the heat transfer coefficient between objects is set to 5 NS^{-1}mm^{-1}°C.

4. RESULT

Fig. 4 shows the cutting forces measured by the Kisler dynamometer during experimental milling. Forces were measured in all axes of the Cartesian coordinate system of the workpiece.

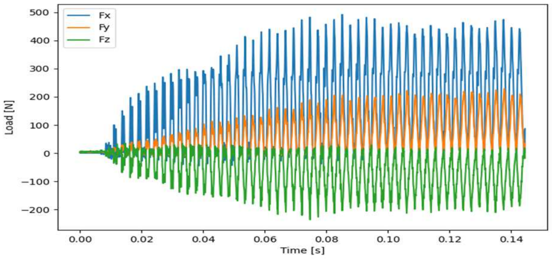

Fig. 4. Diagram of the obtained cutting forces by the dynamometer

When the tool enters the workpiece, the cutting forces increase uniformly; then, the cutting forces are stabilised. At the same time, it is evident how the cutting forces are acting on the cutting edge in the picture. Since the radial depth and the depth of cut is 3mm, with the helix of the monolithic milling tool of 30°, there are more cutting edges in the cut, the study **[5]** discusses the prediction of the milling forces.

4.1. Post-processing forces from FEM software

The FEM DEFORM software allows visualisation and export of the forces acting on the tool during the formation of the chip in the cutting process. Compared to measurement of the dynamometer, the force time history are only a few milliseconds, and also the amplitude of the forces is considerably unstable. Fig. 5 shows the tool load (cutting forces) in the X, Y direction. The dotted lines are the data exported from the DEFORM software.

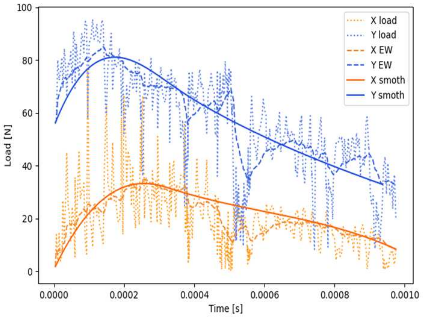

Fig. 5. Cutting forces acting on the tool from the FEM DEFORM software

As can be seen from the graph of the forces exported by DEFORM, it is not possible to determine the values or the shape. The exported data provided exponentially weighted (EW) calculations with 20 of specify delay in terms of centre of mass. These data are represented by dashed lines in the graph. Therefore, from these data it is possible to estimate both the path and the magnitude of the forces acting on the cutting tool. For an even clearer expression of the magnitude and path of cutting forces, the spline curve fitting has been applied for the data. This relation is expressed by the solid line in Fig. 5.

4.2. Comparison of measured cutting forces with FEM simulation

Fig. 6 shows a plot of the measured cutting forces using the dynamometer (dotted line) and the cutting forces obtained by simulation (solid line).

The simulation of the movement of the tool runs only for approximately 1 ms. This time was selected throughout the dynamometer measurement. As can be seen from Fig. 6 the rise of the cutting force in the case of the simulation is far steeper than in the case of the dynamometer measurement.

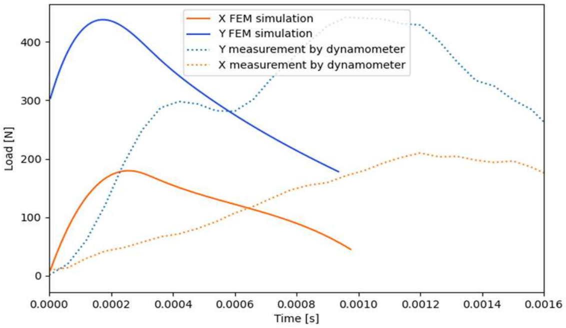

Fig. 6. Plots of the cutting forces

Also, since this is a 2D fem simulation, the amplitude of the cutting forces cannot be taken into account accurately. It can be assumed that if the depth of cut is 3mm, then the correct value is three times the exported data from the simulation. In this case, it comes out to 5.4 times. The accuracy of the dynamometer depends on the sampling and measurement frequency. The sampling measure frequency of the used Kistler dynamometer has been set of 16,66 KHz, which means that the measurement took place approximately 17 times in 1ms. Also in the case of 2D simulation it is not possible to take into account multiple cutting edges in the milling process.

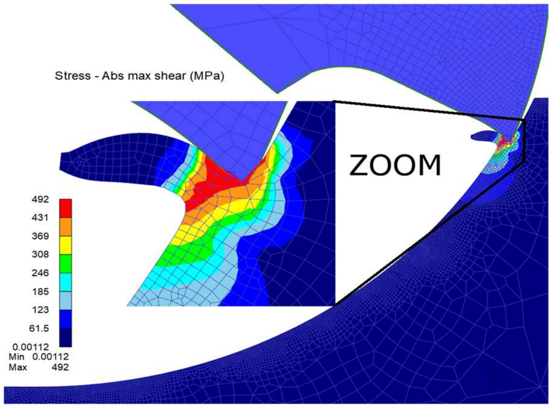

Fig. 7. Shear stress in the cutting zone

4.3 Stress distribution in cutting zone

FEM modelling enables visualization and quantification of stress concentration points, allowing researchers and engineers to identify potential weak points in the tool, workpiece, or interface. Fig. 7. show shear stress in the cutting zone of the milling operation. Based on the representation of the shear stress, it is possible to analyse the evolution of the primary, secondary, and tertiary regions of the cut zone.

Mohammadpour at al. [6] developed a nonlinear code for investigating the effect of cutting speed and feed rate on residual stresses induced after orthogonal cutting. Fig. 8 show residual stress of the workpiece after chip removal.

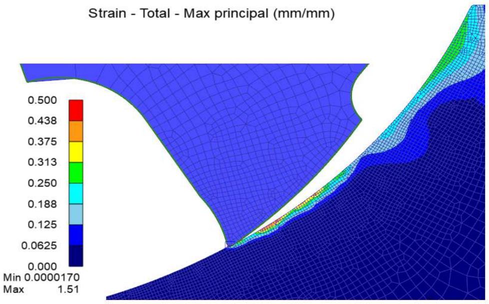

Fig. 8. Residual stress of the workpiece after chip removal by the tool

4.4. Temperature distribution in cutting zone

One of the key advantages of FEM analyses in cutting is the ability to identify localised high temperature zones. Fig. 9 visualises the critical temperature in chip. By zooming and changing the temperature scale it is possible to visualise the critical temperature on the cutting edge as show in Fig. 10. It should be noted that the simulation length is only a few milliseconds, so the maximum temperature on the instrument is quite small. To find the maximum temperature on the tool, additional thermal analysis would be required. In the case of thermal dependencies, it is not only necessary to work with the distribution of the thermal areas of the object under study, but it is also necessary to know the evolution of the temperature over time.

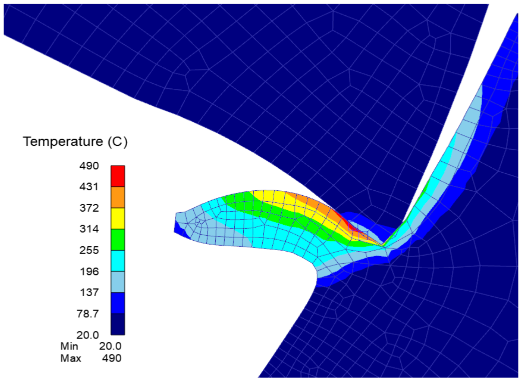

Fig. 9. Temperature distribution in cutting zoone

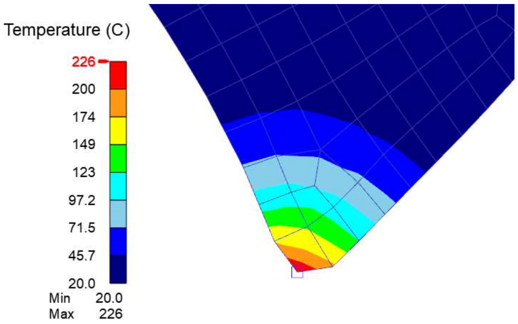

Fig. 10. Temperature distribution on the cutting tool

5. CONCLUSION

The presented work describes the use of 2D FEM analysis of the milling process. The main objective was to be able to compare the cutting forces obtained by simulation with the milling experiment and the cutting forces obtained by dynamometer measurements. Although the trend is to produce comprehensive multiphysics analyses, 2D FEM simulations have provided a comprehensive understanding of critical aspects within the cutting zone. The advantage of 2D

FEM lies in its ability to rapidly assess fundamental cutting behaviours while maintaining a balance between accuracy and computational demands. This approach offers a simplified representation of the complex three-dimensional process but provides a clear picture of key phenomena such as stress distribution, temperature evolution, chip formation, and cutting forces.

6. ACKNOWLEDGEMENT

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FORȚELE DE TĂIERE, FORMAREA AȘCHIILOR ȘI TEMPERATURA PENTRU SIMULAREA BIDIMENSIONALĂ CU ELEMENTE FINITE A PROCESULUI DE FREZARE.

Rezumat: Frezarea este o tehnologie de prelucrare cheie pentru producție. Proiectarea corectă a condițiilor de tăiere, împreună cu geometria adecvată a sculei de tăiere, poate contribui la o productivitate mai mare în procesul de frezare. În acest studiu, a fost utilizată o simulare cu elemente finite (FEM) bidimensională a procesului de frezare pentru a compara forțele de tăiere obținute prin simulare cu experimentele de frezare și măsurătorile dinamometrice. Rezultatele au arătat că simularea FEM a fost capabilă să ofere o reprezentare simplificată a procesului tridimensional complex, dar oferă o imagine clară a unor fenomene cheie, cum ar fi distribuția tensiunilor, evoluția temperaturii, formarea așchiilor și forțele de tăiere. Pentru modelul de simulare FEM este utilizat software-ul DEFORM al companiei STFC.

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