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FEM THERMO-MECHANICAL SIMULATION OF CUTTING FORCE, TORQUE AND TEMPERATURES IN HIGH-SPEED DRILLING PROCESS OF AISI 4140

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Abstract: *This paper presents finite element simulations of cutting force, torque, chip formation and temperature in high-speed drilling of AISI 4140 alloy. The FEM simulations were conducted at a cutting speed of 200 m/min and a feed rate of 0.2 mm/rev., using a TiAlN multilayer coated solid carbide drill. The temperature field in a tool and the forces that appear in the cutting process have an essential effect on the tool wear mechanism and life. Experimental findings confirmed the predicted cutting forces, torques, and chips shape. It was observed that the predicted and measured values were found to be in good agreement.*

Key words: *Cutting tool, High Speed Drilling, FEM simulation, Cutting parameter, Cutting Forces.*

1. INTRODUCTION

Drilling is one of the most widespread manufacturing processes that offers geometric precision. It is mainly used in the production of machine parts, as well as for installation processes. It is the most commonly used metal cutting process, as well the most significant step in the whole machining process and has a share of ca. 33% of all metal cutting processes. Despite the importance of drilling, there are several considerable process characteristics, such as machining parameters, the properties of drill and workpiece materials, or the drill macro- and microgeometry. The points mentioned have a direct influence on the machining process due to the effect on the chip morphology, cutting forces, tool life and quality as well as the dimensional accuracy of the final product [1,2]

Due to the geometry of the cutting edge, the drilling operation involves very complex cutting dynamics. The twist drill bit cutting process is divided into multiple stages. [3]

Orthogonal cutting with a negative rake angle occurs away from the center at the chisel edge [4]. Nevertheless, the obliquely cutting lip cuts the material, and as the radius of the cutting lip increases outward, so do the machining parameters [5,6].

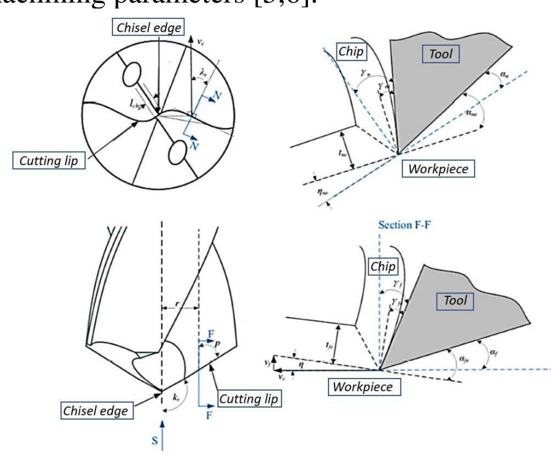

Fig. 1. Schematic view of cutting geometry [8]

Figure 1 shows the interaction of cutting lip and chisel edge during a typical drilling operation. In order to analyze the thrust force and torque, produced during the drilling operation of unidirectional CFRP, Yan et al. [7] devised a method. A finite element model was also employed in the study to calculate the force coefficient for an accurate result prediction. The anticipated findings were found to be in good agreement with the experimental data after performing an experimental validation.

The principal issues that influence tool life in metal cutting are relative vibrations between the tool and the workpiece, chip or tool temperature, machining parameters like feed rate (f), spindle rotation speed (n), cutting depth (d), etc. Heat generation is always a key subject to research in metal cutting [9]. Proactive quality monitoring during the machining process, rather than after the product is finished is beneficial for process improvement as it reduces or even eliminates the possibility of producing defective components [10]. Modeling the interactions between the cutting tool, workpiece, and chip is essential for an improved cutting tool performance. Various methods are suggested for better cutting performance such as mechanical, empirical, numerical, or analytical. [11] However, tool wear might result in tool failure during drilling operations. Therefore, it is important to investigate in-process tool wear forecasts in drilling operations. [12].

While drilling Inconel 718 with uncoated and coated twist drill bits, Kivak et al. [13] investigated the impact of cutting parameters on tool wear and the quality of the hole, namely the circularity of the hole diameter. It was observed that at higher rotational speeds and feed rates, the quality of the hole and the twist drill bit's performance are quite low and there is a noticeable increase in tool wear.

Tool wear has a significant influence on both tool life and final product quality in terms of dimensional accuracy and surface quality.

More so than cutting speed, feed rate is a factor in determining the qualitative attributes of drilling operations and impacting the drilling forces since it impacts thrust force. [14]

Modern industrial engineering is very interested in the process of high-speed cutting, considering the production costs and times. Understanding the material and structural behavior in addition to technical circumstances are necessary to fully exhaust its potential. Research based on the modeling and simulation of the process are required to accomplish this. These studies were initially analytical in nature and focused on the machining process [15,16].

For today's ever more complex processes and geometries, numerical simulation-based methods, in particular finite-element methods, represent the state of the art. [17-21]. Most of these methods are based on thermo-visco-plastic material modeling, which takes into consideration how high strain rates and temperature affect material behavior.

Due to the increased computing power of current computers, modeling and simulation of metal cutting processes are now more often used to reduce the number of design iterations and the need for cost and time-consuming experimental research. Compared to analytical models, they offer more thorough and precise predictions regarding cutting factors affecting machining performance, such as cutting forces, temperatures, hardness, microstructural changes, residual stress, tool-wear, part distortion, surface quality, chip serration and form, process dynamics, stability of machining operations, etc. Additionally, finite element analysis facilitates to anticipate some important data which are challenging to measure experimentally [22,23].

Large stresses and angular distortions, many contacts and self-contact, the formation of new boundaries, fracture with numerous fractures, and defragmentation are all involved factors in the numerical simulation of machining operations. The aforementioned problems are all challenging to solve with conventional finite-element techniques (FEM) [24].

Numerous studies are now being conducted to find solutions to these problems in the numerical simulation of cutting operations. Although there are several research in the literature [25-29] that have been done on the use of FEM to forecast the performance characteristics in the machining of a variety of workpiece materials.

Determining the oscillatory temperature distribution in the tool, workpiece and chip is of the greatest priority [30-32].

Temperature distribution and heat flux have a major importance in machining processes; the temperature field in the tool plays an important role in wear and tool life, and at the same time, the temperature of the workpiece has an impact on the part's quality, the workpiece's dimensional accuracy, surface damage, oxidation, quick corrosion, burning, etc.[33-35,40,41] As the degree of deformation in the flow zone on the underside of the chip is significantly higher than in the shear zone, the maximum temperatures may be anticipated between the chip and the tool. During metal drilling, around 85% of the heat generated in the process is carried away from the system by chips. [33] The machining process, the workpiece material and the tools, the cutting conditions, tool wear, and cutting fluids all have an impact on temperature development and heat dispersion.

Measurement of the tool temperature and the heat flux density demands significant efforts and are not quite often suitable in manufacturing conditions, to find out these variables are used different inverse solution methods [38]. However, although analytical techniques are hampered by the incredibly broad assumptions [36], the numerical ones and FEM have been used successfully, with sufficient accuracy [37]. The FEM-based model was shown to have a higher interface temperature than the experimental results. [40]

This work is focused on the numerical simulation of tool behavior in high-speed drilling of AISI 4140, focusing on the temperature distributed in the tool associated with the wear evolution, the release of the chips, the forces and the torque appeared in the cutting process. Experimental data on drilling AISI 4140 with the same cutting parameters as those used in the finite element analysis were used to validate the numerical simulation.

2. EXPERIMENTAL SETUP AND PARAMETERS¶

Drilling experiments were conducted in a three-axes vertical CNC machining center made by HAAS, model VF3-YT. These tests were carried out utilizing coated cemented carbide (TiAlN coating) twist drills on heat-treatable alloy work material, AISI 4140, with a hardness equivalent to 35 HRC.

The CAD model of the drill for the numerical simulations (see Fig. 2) was generated using Siemens NX. The tool is a twist drill made of cemented carbide with a high cobalt concentration ratio, a multilayer coating, and following geometric parameters: drill diameter of 6.8 mm, helix angle of 15°, four margins, point angle of 135°, drill run-out of 0.004 mm, flute length of 52.2 mm, increasing core diameter from 2.05 to 1.84 mm, clearance angle varying from 8° to 25° and an average cutting-edge radius of 35 μm.

Fig. 2. Tested twist drill

The drilling tests were performed with a cutting speed (vc) of 200 m/min, the feed (f) of 0.2 mm/rev., and a machining depth of 5x nominal diameter. The parameters were chosen based on multiple manufacturers' catalogs regarding high-speed drilling. The metal working fluids (MWF) were composed of 90% of water and 10% synthetic cutting fluid (emulsion concentrate) at 40 bar pressure.

During the drill tests, axial force and drilling torque were measured using a piezoelectric dynamometer from KISTLER, model 9129AA. It has a measuring range of ±10 kN and measurement precision of 0.1 kN.

Fig. 3. Experimental setup

The dynamometer's signal was amplified using a multichannel charge amplifier type

LabAmp 5167A, equipped with a 50 Hz low-pass filter to help reducing the noise and vibrations that occur. The frequency of the data samples was set at 25000 Hz. For each measurement, the arithmetic mean values were noted. The complete experimental setup is illustrated in Fig. 4. Using the program DynoWare, dynamometer data were converted into numerical values.

The tested drills were examined using a scanning electron microscope (SEM) type Zeiss Sigma 300 before and during the tests. It was also used an opto-digital microscope to follow the evolution of wear. A Keyence VHX 5000 microscope was used to investigate and measure the shape and dimensions of the chips.

The drill was examined under a microscope during the experiments at 25%, 50%, 75%, and 100% of its predicted durability, as well as at 40%, 60%, and 80% of the durability to better comprehend the occurrences that had developed. The tests stop when the wear limit of 200μ is reached, a point considered 100% of the tool's life.

3. MODELLING AND SIMULATION

The simulation was done in the advantEdge software. To get good results from a metal cutting simulation, flow stress modeling of the workpiece's material is essential.

For finite element modeling, a plastic deformable box-shaped workpiece with more than 45000 tetrahedral components was used. The mesh is unconsistent for better results prediction. The largest element size for the workpiece is 0.3, while the minimum element has 0.03 mm.

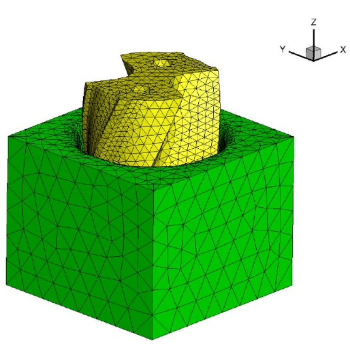

Fig. 4. Geometrically rendered pattern

The cutting parameters were set as cutting speed of 200 m/s, feed 0.2 mm/rev., and cutting depth 1 mm.

Coated cemented carbide was selected as tool material and its thermal properties were taken from advantEdge material database.

Since the feed of f = 0.2 mm/rev only equates to a feed per tooth of fz = 0.1 mm/rev, there are extra high demands placed on the FEM modeling and meshing of the already extremely complicated micro-tool design. For the chip formation simulation, the minimum element size (MES) must be at least three times smaller than the chip thickness, which in this case translates to an extremely thin local mesh of MES = 0.0229–0.03 mm.

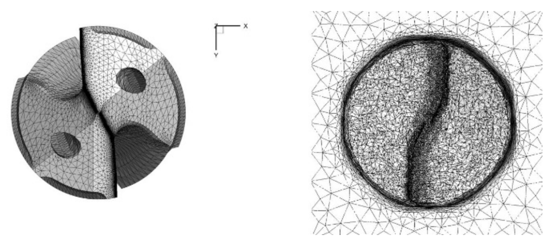

Fig. 5. Meshed tool

Reduced size finite elements were used to mesh the cutting edge, whereas coarse completed elements were used for the body of the tool in general. The maximum element size is 1.5 mm and the smallest element size is 0.0229 mm, on the cutting-edge area of the tool.

It is important to remember that the study aim justifies the variation in mesh precision between the workpiece and the tool. The simulation focuses on the tool because it wants to investigate how tool wear develops. In keeping with this concept, the workpiece was represented with a few components to decrease the calculation time.

4. RESULTS AND DISCUSSIONS

4.1 The drilling force and torque

Fig. 6 shows the FEM prediction for a 180° rotation of the tool, regarding force and torque.

The maximum predicted value for the force is approximately 840 N, while for the torque a maximum of almost 3 Nm is predicted.

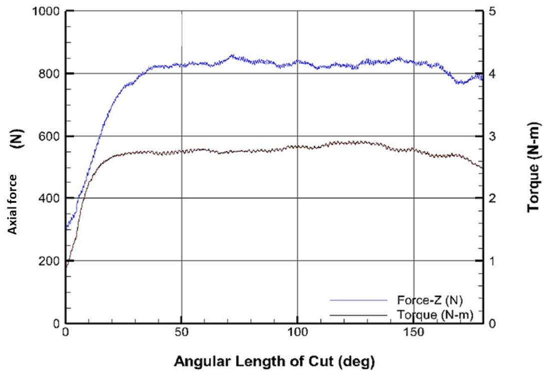

Fig. 6. Force Z and torque predicted with FEM

The force and torque were measured in the tests at the very first hole of the tested drill, throughout the drilling cycle.

The drilling force is illustrated in Fig.7, taking a maximal value of 1166 N and having a constant evolution during the drilling operation, with a minimum value of 1107 N. The mean value is 1107 N.

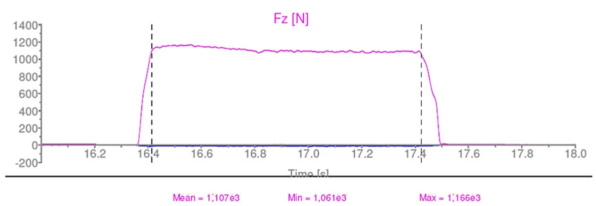

Fig. 7. Axial force measured in tests

The torque evolution graph in tests is represented in Fig. 8. It takes constant values through the drilling process, with a maximum point of 2.777 Nm and a minimum of 2.487 Nm. The mean value is 2.661 Nm.

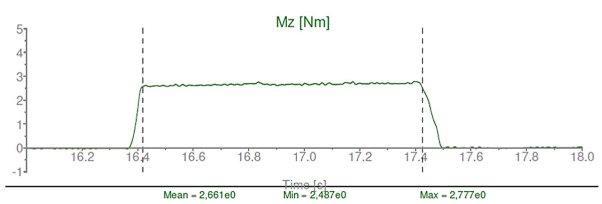

Fig. 8. Torque measured in tests

Between the FEM simulation and the physical tests, there are differences in the axial force of approximately 25%, while for the torque the differences are about 10%.

4.2 Temperature distribution and wear

The maximum temperature of the cutting edge reaches a maximum of 550°C, the maximum values being registered in the corner area and in the transition radius, as can be seen in Fig. 9.

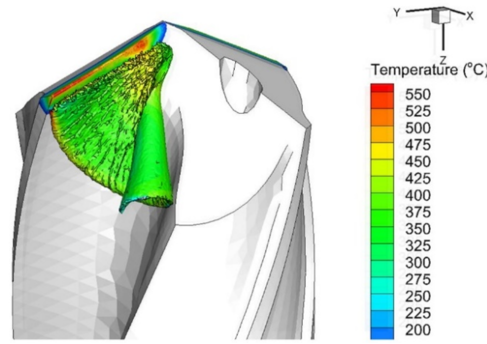

Fig. 9. Temperature distribution after FEM simulation

The comparison of the temperature distribution on the cutting edge in the FEM analysis with the development of wear in the performed tests can be seen in Fig. 10.

At 40% of tool life there is wear in the corner area visible. The wear becomes evident at 80% of tool life and is located exactly in the regions with very high FEM predicted temperatures.

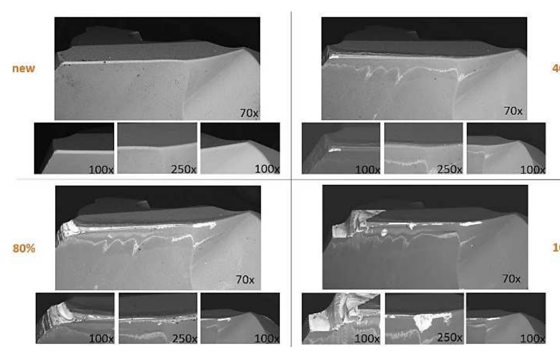

Fig. 10. SEM analyses

At the end of the test, the wear remains accentuated in the same areas and suggests an obvious link between the maximum temperature zones predicted by FEM simulations and the wear evolution on the tool, as in Fig. 10.

The tool’s corner is most exposed to wear, immediately followed by the transition radius.

4.3 Chip serration and form

According to the FEM simulation, the formation of chips is done after a radius of 1.8 mm, like in Fig. 12.

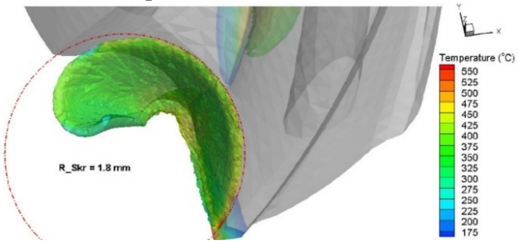

Fig. 11. FEM predicted chips shape

The chips are collected after producing the first hole in the test and are displayed in Fig.12. Shear planes can be easily observed on the surface of the chips.

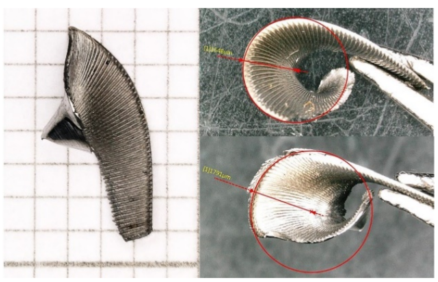

Fig. 12. Chips resulting from the tests

The measurements made on the chips, indicate a bending radius with values between 1.54 and 1.79 mm. These values are very close to the one predicted by FEM analysis, having a maximum dimensional difference of 15%.

5. CONCLUSIONS

A similar pattern can be seen when comparing experimental results to numerical simulations based on FEM. The rake face, which has a high-temperature point in the corner, is the tool's hotter area. The wear appearance in the test is related to the highest temperature zones. Both the axial force and the torque have quite close predicted and measured values. In the case of continuous chip simulation, a coupled thermo-mechanical FEM model can eliminate the requirement for expensive experimental measurements. The FEM simulation results in terms of force, torque and temperature are confirmed by the behavior of the drill in the experimental tests.

6. ACKNOWLEDGEMENTS

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SIMULAREA TERMO-MECANICĂ CU ELEMENTE FINITE A FORȚEI DE AȘCHIERE, A MOMENTULUI DE TORSIUNE ȘI A TEMPERATURILOR APĂRUTE ÎN PROCESUL DE GĂURIRE DE MARE VITEZĂ ÎN AISI4140

Această lucrare prezintă simularea cu elemente finite a forței de așchiere, momentului de torsiune, mecanismului de formare a așchiilor și temperaturilor aparute în găurirea de mare viteză a aliajului AISI 4140. Simulările FEM au fost efectuate la o viteză de așchiere de 200 m/min și avans de 0,2 mm/rot., folosind un burghiu din carbură metalică cu acoperire multistrat TiAlN. Temperatură din sculă și forțele care apar în procesul de așchiere au un efect esențial asupra evoluției uzurii și a duratei de viață a sculei. Experimentele desfășurate au confirmat forțele de așchiere, momentul de torsiune și forma așchiilor prezise. S-a observat că valorile prezise și măsurate s-au dovedit a fi în bună concordanță.

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