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FEM method in chip shape and cutting force prediction when drilling difficult to cut materials

Abstract: This paper is focused on using finite element method (FEM) in process of cutting tool design. This method has been successively used in many branches of industry. Mainly in automotive, aerospace and power industry. In this paper the FEM method is employed on solid twist drill design. Especially on selection of point angle. Therefore two models of solid twist drill with different point angles were created using CAD software CATIA V5. These models were analyzed using commercially available FEM code AdvantEdge FEM. The main observed parameters were chip shape, magnitude of cutting forces, temperature field distribution on rake face and on flank face of the solid twist drill. Based upon results from analysis the one geometry of solid twist drill has been selected and manufactured. In order to evaluate performance of real solid twist drill prototype experimental measurement has been conducted. The chips produced by real twist drill prototype were collected and cutting forces were measured by 4-component piezoelectric dynamometer KISTLER type 9272. These data were compared with results from numerical analysis in order to evaluate the accuracy of numerical analysis.

Keywords: FEM, twist drill

1. INTRODUCTION

The technological and economical pressure in production engineering requires an optimization of existing processes [1]. In order to satisfy this requirement on development level it is necessary to obtain information about product performance before it's produced. For this purpose the finite element method (FEM) can be used. This method has been successively used in automotive, aerospace and power industry, where the many types of analysis are required. Mainly structural analysis, thermo analysis, CFD analysis or more complex types of analysis like thermo-mechanical analysis.

The cutting process involves large strains, large strain rates and high temperature gradients between cutting tool face and its free surface. Therefore the analysis of cutting processes is one of the most difficult from numerical point of view. The FEM was firstly used on cutting process analysis using custom FEM code for the 2D simulation. Lately the commercial FEM codes focused on machining application were used. The advantages of these types of software among custom FEM codes are that the user's intervention is considerably lower and therefore it is possible to obtain results faster, which is important reason for cutting tool companies. The source [2] a [4] used Deform 2D for analysis of orthogonal cutting. The main analyzed parameters were chip formation, temperature field distribution and wear of cutting tool. However the source [2] reported difference between predicted and real value of wear. This was caused by inaccurate values of parameters used in the wear model. This implies to another important requirement for practical application of cutting tool analysis – the knowledge of correct values of parameters used in numerical models to satisfy the credibility of results obtained from simulation. It must be noted that due to the nature of cutting process it is necessary to use advanced material testing methods, which is very time and thus financial consuming. This is another advantage of commercial FEM codes focused on machining used nowdays. They commonly have implemented databases which describes the behavior of machined material.

Today's cutting tools have complex geometries and therefore it is necessary to use 3D simulation to provide proper analysis of cutting tool. The source [17] used commercial FEM code AdvantEdge FEM for numerical analysis of drilling titanium alloy Ti6Al4V with solid carbide twist drill. The predicted values of thrust force were different in 10-25% with comparison to experimental measured data especially at higher cutting speeds.

The same FEM code will be used in this study, which is focused on analysis of solid twist drill for drilling into AISI D3 tool steel, used for dies and molds. The structure of this paper is as follows. In the second section the brief description of solid twist drill is presented. In order to select appropriate point angle of solid twist drill, two models have been created using CAD software CATIA V5. In this section the model preparation for the purpose of analysis is also presented with boundary conditions description. The third section presents the results obtained from analysis. The main observed parameters were chip formation, cutting forces – torque T_c, thrust force F_T and temperature field distribution on the rake face and on flank face of twist drill. The fourth section presents the comparison between results from analysis and experimentally measured data. The result discussion is proposed also in this section. The conclusion of the paper are presented in the last section.

2. DESCRIPTION OF SOLID TWIST DRILL GEOMETRY AND BOUNDARY CONDITIONS OF NUMERICAL ANALYSIS

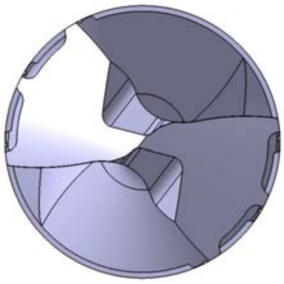

Fig. 1:Model of solid twist drill

The twist drill geometry is presented in the Fig. 1. The authors are not allowed to present the exact values of all parameters of twist drill geometry, because of manufacturer of twist drill prototype. Therefore only the intervals of most geometrical parameters will be presented. The twist drill has standard single point tip. The chisel edge is thinned on <0,5-1mm> in order to decrease the rubbing action of drill due very low cutting speed and highly negative rake angle in this area. The drill is designed for operating at dry cutting conditions. This type of cutting condition is favorable because of lower costs of the process. The nature of drill's flute secures chip removing from the hole, which is essential in drilling mainly due to resulting constant cutting forces during the process, which helps to overcome premature drill wear or decreasing the hole accuracy. It must noted that this property goes in conjunction with appropriate chip formation. The helix angle of the flute ranges from <5-15°>. For better support when the tool moves within the hole it has six facets. The diameter of the twist drill is 12mm.

In order to select appropriate twist drill geometry, two types of models have been created using CAD software CATIA V5. These models have same helix angle but differs in point angle. The parameters of both models are presented in Table 1.

Table 1:

Geometrical parameters of analyzed models

Parameters	Geometry A	Geometry B
Helix angle[°]	Same	Same
Point angle [°]	130	140

2.1 CAD model preparation

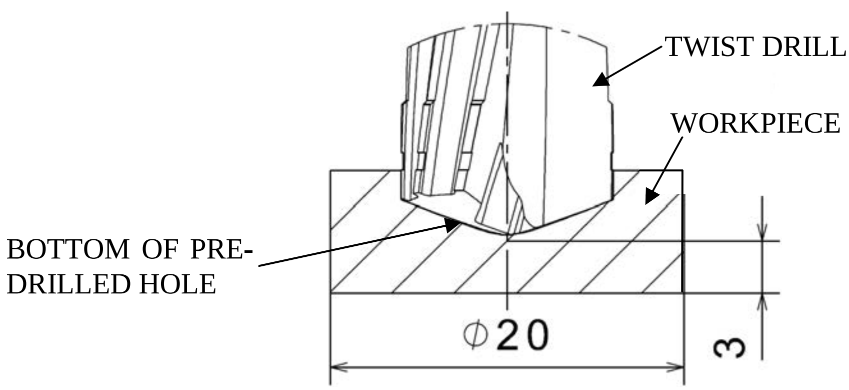

Fig. 2: Computational model of the twist drill and the workpiece

In order to decrease the computational resources required for numerical analysis, the entire model of the twist drill were cleaned up from unnecessary features. In other words the length of the twist drill was decreased from 100mm to 10mm. The computational model of the twist drill is shown in fig.2. In order to satisfy maximum correlation between results from analysis and experiments the custom model of the workpiece was created also. It was cylinder with diameter of 20mm to suppress the edge effect. The thickness of remained material under the tip was 3mm to achieve appropriate stiffness. The bottom of predrilled hole consists of two opposite helical surfaces. This shape of bottom was created using advanced modeling techniques. This set up were imported in to AdvantEdge FEM v 5.4 environment for further analysis.

2.2 Set up of boundary condition

In the AdvantEdge FEM v 5.4 environment were set up the boundary conditions for analysis. The boundary conditions are summarized in Table 3. It must be noted that mesh setting were redefined only for the workpiece, other parameters remained unchanged. The meshed FEM model is shown in Fig. 3.

Table 3

Boundary conditions for analysis

Workpiece material	AISI D3 (53HRC)
Twist drill material	Sintered carbide
Cutting speed v_c [m/min]	25
Feed[mm/rev]	0.08
Cutting environment	Dry

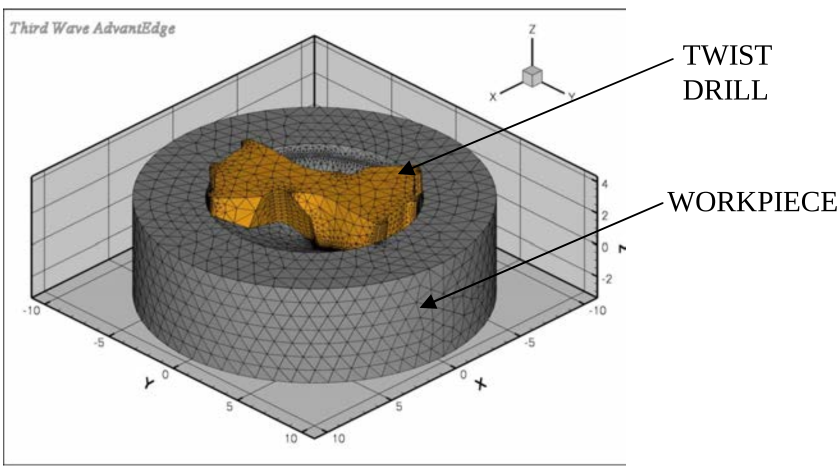

Fig. 3: Meshed twist drill and workpiece

3. **RESULTS FROM NUMERICAL ANALYSIS**

3.1 Chip shape comparison

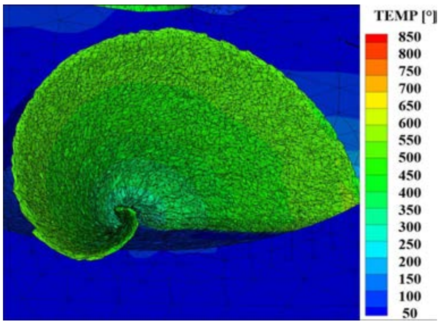

Fig. 4 Chip produced by geometry A

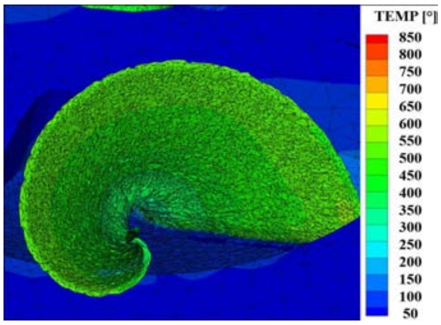

Fig. 5 Chip produced by geometry B

In the Fig.4 ,Fig. 5 the temperature field distribution of both chips produced by geometry A , geometry B respectively are shown. The temperature over the chips varies from 300° to 500° C and are the same for both geometries. This is with agreement with theory and can be explained by the same value of helix angle of both geometries, because the helix angle determines the face angle of drill.

The difference in point angle influenced the inclination angle α between chip and drill's axis see fig.6. This is not clearly visible from fig. 4 and fig. 5 respectively. This situation is better shown in detailed views in fig 8. and fig.10. This observation is also with agreement with theory, because larger point angle makes the inclination angle to rise and therefore the chips are better directed in to the flute and more uniform chip removing can be achieved, which helps in stabilization of cutting forces.

However what is more surprising is that the difference of 10° in point angle between geometry A and B didn't change the shape of produced chip significantly. The only difference is visible in change of inclination angle α stated above. The explanation of this observation can be found in mechanical properties of workpiece material. In the fig. 11 is shown the graph, where the influence of temperature on hardness of workpiece material for different tempering temperatures is shown. From the graph is obvious that until 500°C the hardness of material decreases continuously. In the same manner the strength

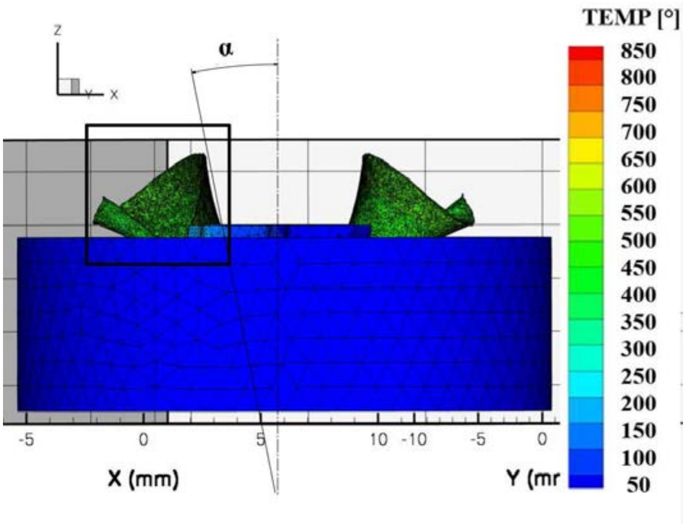

Fig. 6 Inclination angle α between drill's axis and chip

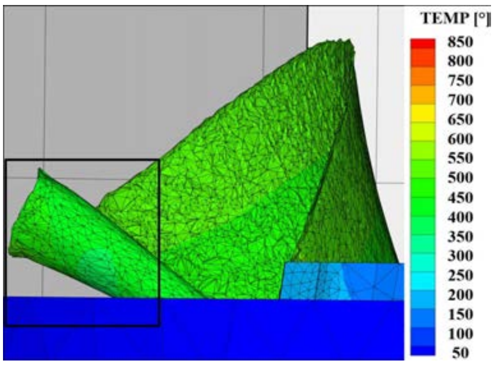

Fig. 7 Detailed view from rectangular area in fig. 6 – Geometry A

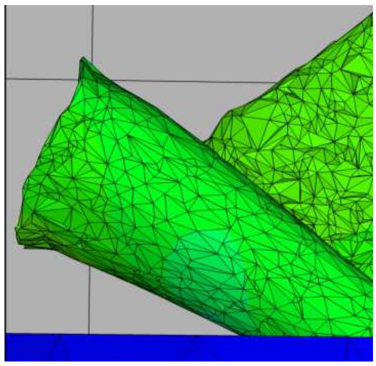

Fig. 8 Detailed view from rectangular are in fig. 7 - Geometry A

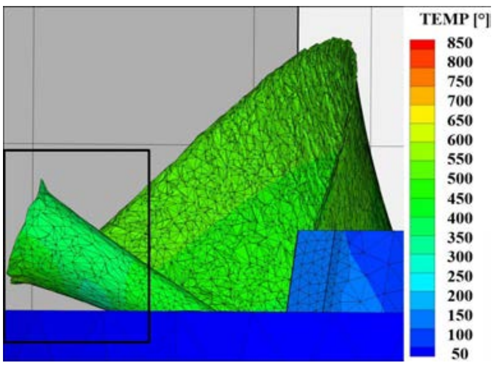

Fig. 9 Detailed view from rectangular area in fig. 6 – Geometry B

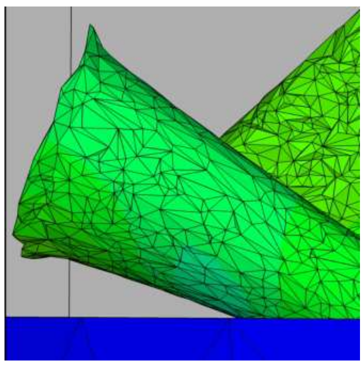

Fig. 10 Detailed view from rectangular area in fig. 9 – Geometry B

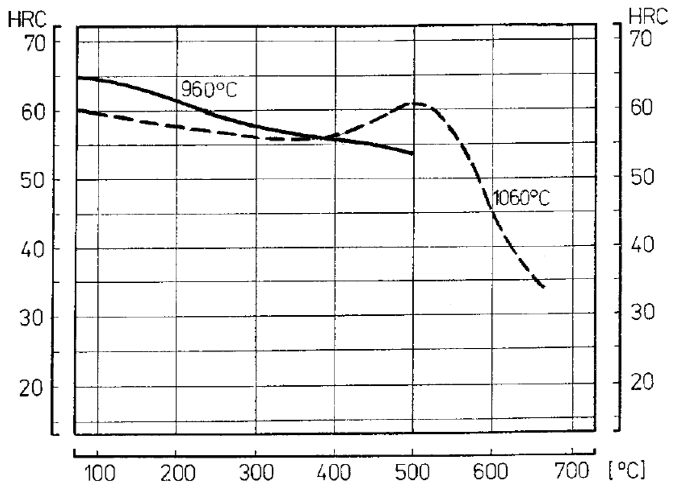

Fig. 11 Influence of temperature on hardness of workpiece material with respect to different tempering temperatures

of material will decreased also. In other words the mechanical properties of material doesn't change significantly. If we take into account the temperatures in chip from Fig. 4 and 5 respectively we can make a conclusion that AISI D3 tool steel is less sensitive for appropriate point angle selection. Or in other words, the difference of 10° in point angle didn't change the chip shape significantly.

3.2 Temperature field distribution on rake face and flank face of twist drill

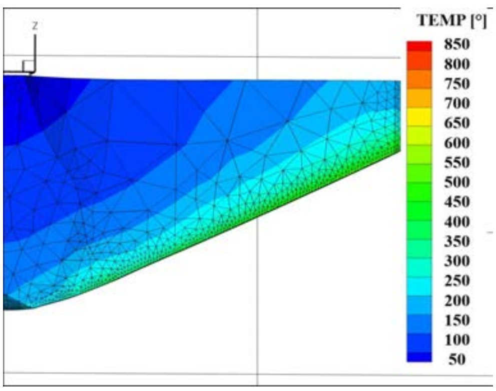

Fig 12 Temperature field distribution on twist drill's rake face

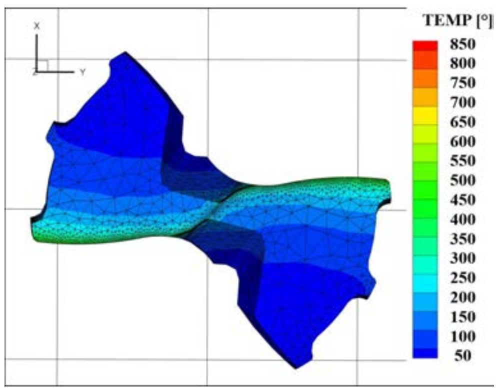

Fig 13: Temperature field distribution on twist drill's flank face

In the fig. 12 is shown the temperature field distribution on twist drill's rake face. From the figure is obvious that the temperatures rise from center to outer diameter of the twist drill. This is with agreement with theory, because cutting speed increases with distance from center of twist drill and it mainly influences the heat generation in cutting zone and consequently temperatures. The temperature field distribution on flank face can be used for determination of proper shape of chisel edge thinning within the flute. If there was temperature peaks it implies that the chip locks in chisel edge thinning area and therefore the appropriate chip removing cannot be satisfied. In other words if there was found temperature peaks the chisel edge thinning should be redesigned.

The temperature field distribution can be used also for the analysis of drill's flank face as it is shown in fig. 13. As it was in the case of rake face of the twist drill, the temperature field on the flank face has also no temperature peaks with continuous increase of temperature from center of the drill to outer diameter.

3.3 Cutting forces comparison

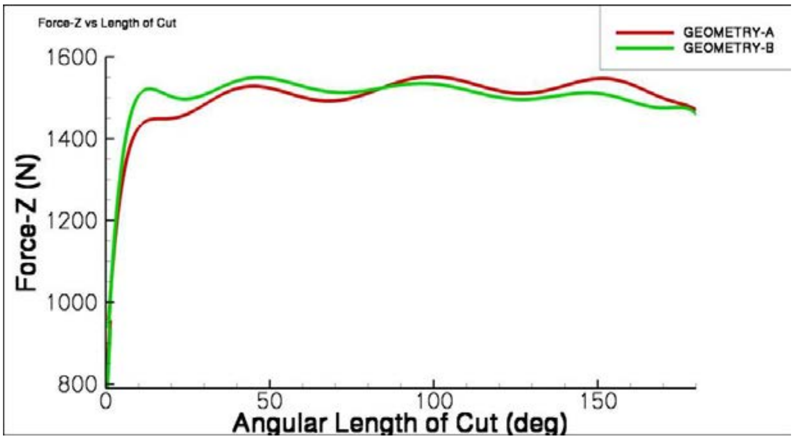

Fig 14: Thrust force comparison

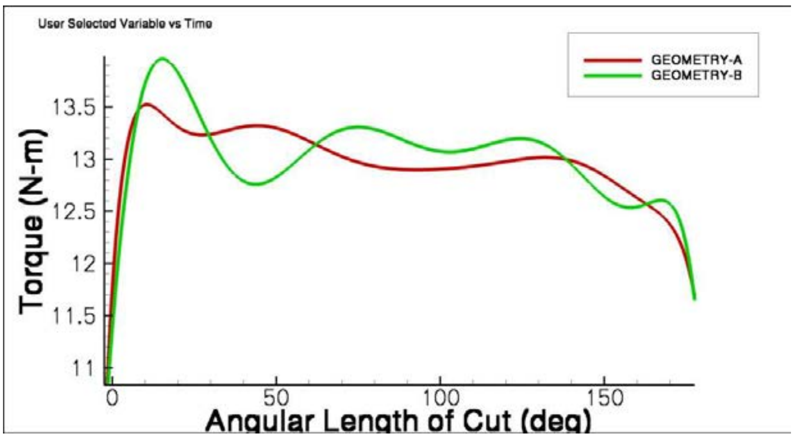

Fig 15 Torque comparison

In the fig. 14 the comparison of thrust force between geometry A and geometry B is provided. It is obvious that both geometries generated the same magnitude of thrust force. This is also surprising if we take in to account that difference in point angle between geometry A and geometry B is 10°. This can be explained by the same helix angle and it leads to conclusion that in this type of workpiece material the helix angle has influence on magnitude of thrust force while the difference of 10° in point angle has no significant influence on the magnitude of thrust force.

The same magnitude of torque is with agreement with theory because of same value of helix angle.

The same magnitudes of thrust force and torque provide also support to the results obtained by analysis of chip shape and temperature field distribution presented in the section 3.1.

Based upon results from numerical analysis the geometry B was selected because of better direction of chip in to the flute of solid twist drill. This type of geometry has been manufactured in the company HOFMEISTER s.r.o.

4. COMPARISON BETWEEN RESULTS FROM NUMERICAL ANALYSIS AND EXPERIMENTAL MEASURED DATA

In order to evaluate the accuracy of predicted parameters described in previous section the experimental measurement were conducted. The test were carried out on vertical milling center MCV 750 A with continuous variation of spindle speed. The workpiece material was cylinder with diameter of 20mm and length of 36mm. The shape of produced chip was compared by visual observation while the torque and thrust force were measured using 4 component dynamometer KISTLER type 9272. The data were post processed using LabView 8.1 and Matlab software. The twist drill were clamped in hydroplastic tool holder Güehring see fig. 16. The cutting conditions were the same as in numerical analysis.

Fig 16: Clamped twist drill

4.1 Chip shape comparison

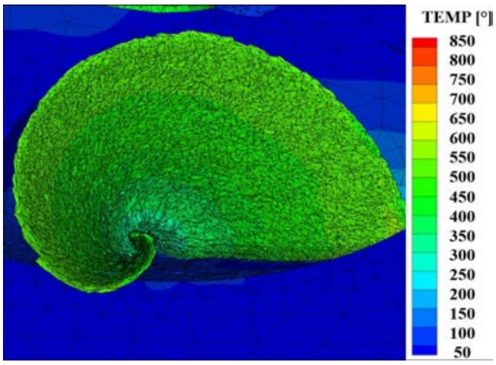

Fig 17:Chip shape predicted by numerical analysis

Fig 18 Chip shape produced by real prototype

In the fig. 17 and fig.18 respectively the comparison between predicted and real chip shape is provided. It is obvious that both chips are almost identical. The difference was found in curls on outer part of chip produced by real prototype. However from the cutting tool design point of view can be this inaccuracy overlooked, because more important is segmented shape of chip. This can lead to conclusion that AdvantEdge FEM software can be used for the prediction of chip formation.

4.2 Cutting force comparison

In the fig. 19 and fig. 20 the comparison between predicted magnitudes of both thrust force and torque are presented. The predicted value of thrust force was $F_{T\text{-}PRED}$ = 1600 N, while the measured one was about $F_{T\text{-}MEAS}$ = 2600N.
This is means the software underestimates the value of predicted thrust force and the difference is almost 40%. When we compared the values of torque we figured out that the software overestimates the value of torque. The predicted value was $T_{C\text{-}PRED}$ = 14 Nm and the measured one was $T_{C\text{-}MEAS}$ = 11 Nm which is the difference of 22%.
The reason in difference of errors between thrust force and torque can be explained by two factors. The first factor is difference in hardness between workpiece material in numerical simulation (53HRC) and real workpiece material (56±2HRC) caused by the nature of heat treatment process.

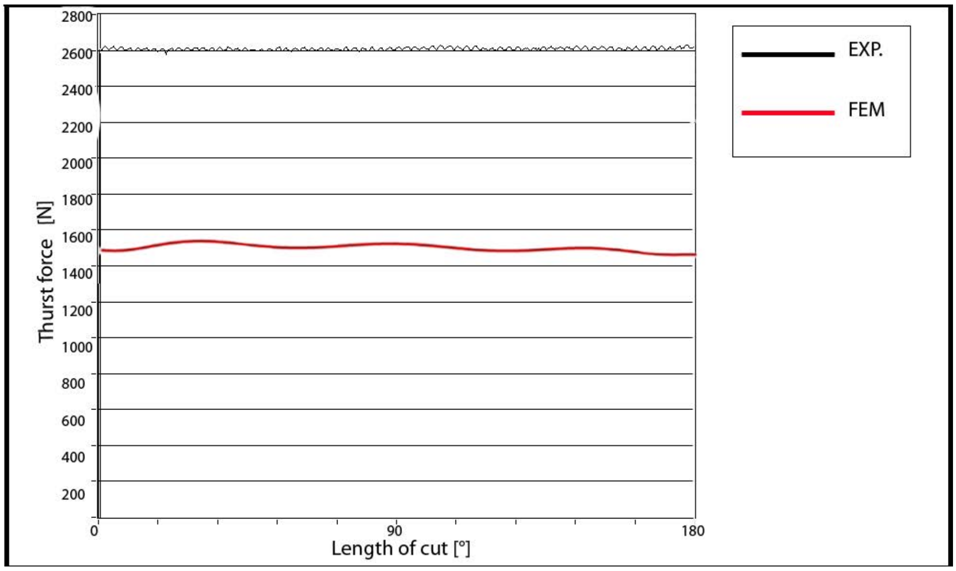

Fig 19: Thrust force comparison

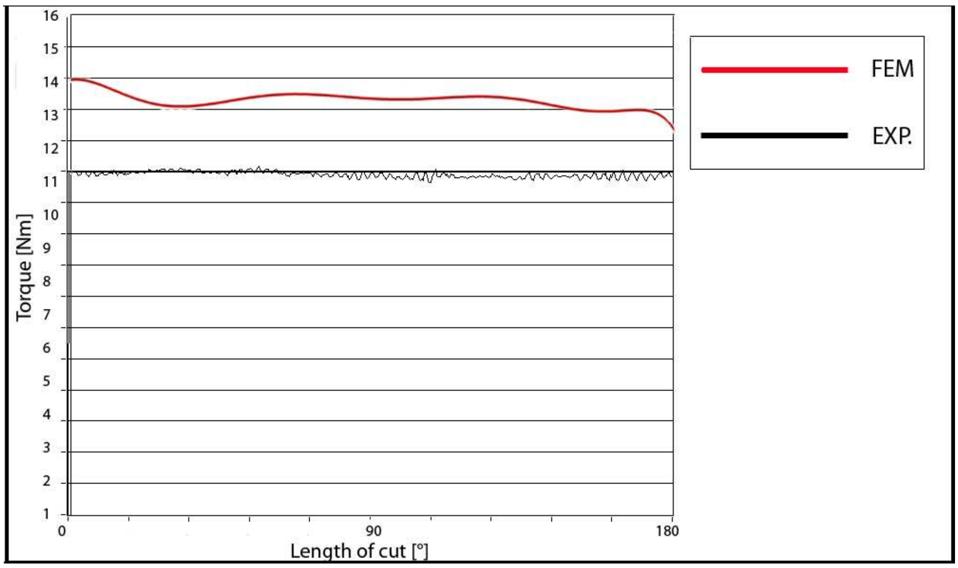

Fig 20: Torque comparison

Therefore the real workpiece material exhibits higher resistance against drill engagement, which tends the thrust force to increase. The second factor is different temperatures in primary cutting zone and tertiary cutting zone see fig.21.

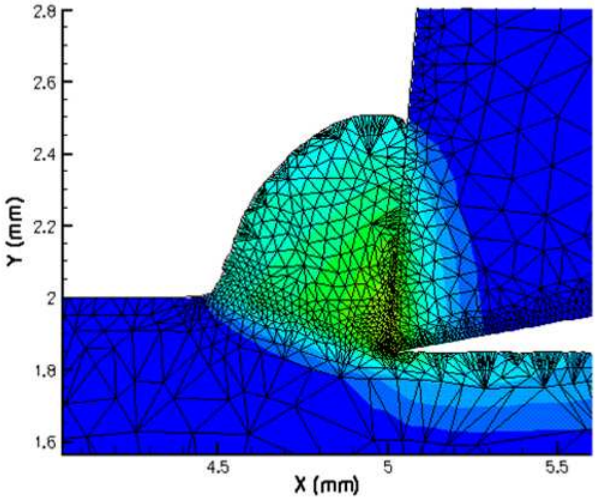

Fig 21 Temperature field distribution in cutting zones

In primary cutting zone, where is the tangential component of cutting force which generates the torque are generally higher temperatures than in tertiary cutting zone. Due to higher temperatures, the material of the workpiece tends to softening more rapidly. As a consequence the difference in hardness between real workpiece and the one in numerical analysis can be reduced.

5. **CONCLUSION**

This paper presents the using of FEM element method in design of solid twist drill geometry. In order to select appropriate twist drill geometry the two models of solid twist drill were created. These models were different in point angle while the helix angle was the same. For the analysis of twist drill geometry the commercially available FEM code AdvantEdge FEM was used. Based upon results from analysis the geometry with larger point angle was manufactured and experimentally tested in order to evaluate the accuracy of numerical analysis. The main observed parameters were chip shape and cutting forces. The main conclusion of this paper can be summarized as follows:

- The difference in point angle of 10° doesn’t influence the chip shape and magnitude of cutting forces when drilling AISI D3 tool steel

- The difference in point angle of 10° influences the inclination angle α between drill's axis and the chip which affect the directing of chips in to the flute when drilling AISI D3 tool steel
- The AdvantEdge FEM software can be used for chip shape prediction because the differences between real and predicted chip are insignificant
- The difference between magnitudes of predicted thrust force and experimentally measured one was 40% and the software underestimates the magnitude of predicted thrust forces
- The difference between magnitudes of predicted torque and experimentally measured one was 22% and the software overestimates the magnitude of predicted thrust forces
- The difference in errors of predicted values can be explained by the higher temperatures in primary cutting zone which reduce the difference in hardness between real workpiece and the one used in numerical analysis

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