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Finite Element Analysis Of Influence Of Flank Wear Evolution On Forces In Orthogonal Cutting Of 42CrMo4 Steel

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ABSTRACT

This paper presents analysis of flank wear influence on forces in orthogonal turning of 42CrMo4 steel and evaluates capacity of finite element model to provide such force values. Data about magnitude of feed and cutting force were obtained from measurements with force tensiometer in experimental test as well as from finite element analysis of chip formation process in ABAQUS/Explicit software. For studies an insert with complex rake face was selected and flank wear was simulated by grinding operation on its flank face. The aim of grinding inset surface was to obtain even flat wear along cutting edge, which after the measurement could be modeled with CAD program and applied in FE analysis for selected range of wear width. By comparing both sets of force values as function of flank wear in given cutting conditions FEA model was validated and it was established that it can be applied to analyze other physical aspects of machining. Force analysis found that progression of wear causes increase in cutting force magnitude and steep boost to feed force magnitude. Analysis of F_c/F_f force ratio revealed that flank wear has significant impact on resultant force in orthogonal cutting and magnitude of this force components in cutting and feed direction. Surge in force values can result in transfer of substantial loads to machine-tool interface.

1. INTRODUCTION

Evolution of tool wear is observed by gradual increase of forces in machining, chatter and temperature in cutting area. These physical symptoms of wear are known to adversely affect surface finish (surface roughness, and waviness) or shape and dimensional accuracy of a machined part. Furthermore, tool wear has considerable influence over energy requirements for machining process, tool life and overall cost of machining operations. Failure of meeting standards for quality control is prevented by proper tool management where worn tool is withdrawn before it could affect part-forming process. Since the tool wear affects directly economics of machining, wear evolution function is being used as a basic optimization function. For better understanding of machining process and influence of wear on its physical aspects, first a fundamental model of mechanics of metal cutting must be introduced. Such a model is a mechanism of chip formation which provides thermo-mechanical data at tool-chip interface.

Analytical models reduced to orthogonal cutting were developed by renown researchers like Merchant [1] or Oxley [2] but with substantial progress in computing hardware of last three decades, finite element method can be applied to numerically solve problems regarding chip formation process. This type of analysis must consider impact of multiple non-linear physical aspect of tool-chip interaction that takes place in highly dynamic and high temperature fields with highest strain rate (range of $10^3 \div 10^6$ s^{-1}) associated with convention metal forming techniques. Research of chip formation using explicit finite element analysis (FEA) is usually done by deploying one of two primary types of technique. In both types of models usually Johnson-Cook constitutive model is applied to calculate flow stress. The first one relies on fracture mechanism to simulate transformation of uncut chip layer into chip separated form

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workpiece and the other method is a model of wedge indentation into workpiece due to the plastic flow. In the first model the workpiece mesh domain is defined as classical Lagrangian body which is divided into three layers: uncut chip section (no damage criteria is applied here), sacrificial layer (with ductile damage criteria) and undeformed workpiece layer (no damage criteria). Tool progressing movement initiates with energy or geometrical criteria a ductile damage in sacrificial later resulting in deletion of elements in this layer thus separating uncut chip layer from the workpiece. It is relatively popular model among researchers and it was applied in works of [3-6]. In the second model characteristic chip is formed by plastic flow of deformed material which is achieved by implementing robust remeshing algorithm countering large deformations of mesh element cell. The workpiece can be modeled either as a body with classical Lagrangian surfaces or domain with Eulerian one. In Lagrangian approach chip is formed due to workpiece-tool kinematics and friction. Eulerian approach requires that initial chip geometry must be predefined and the final shape of chip would adjust during analysis. The model utilizing flow stress with Lagrangian surfaces was presented in works [6-10] and analysis of chip formation with Eulerian boundaries was carried out in works of [11-13].

In terms of modeling wear researchers focus mainly on two aspects: estimating wear and effects of wear on mechanics of metal cutting. For wear estimation Taylor's tool life expectancy equations are commonly applied to manage tool wear problem in industrial and scientific practice. Taylor's model estimations are based on empirical trials for given set of cutting conditions. The application of FEA model in estimating flank and rake wear was first introduced by Usui [14] and continued in works of [15-17]. In their research wear was modeled as modification of tools geometry due to displacement of tool's nodes. The displacement of nodes at tool surface was calculated by taking into account both contact pressure and temperature value at tool surface. Looped thousands of consequent simulations allowed estimation of wear evolution. Analysis of impact of wear on physical aspect of machining was first carried out by combining analytical and empirical approach as in comprehensive model introduced by Koren-Ko. [18]. This model allowed to estimate wear on the basis of online measurement of forces during machining. So contrary to Taylor's model wear was estimated on the basis of registered load acting on tool. FE method also was applied to determine physical aspects of machining by predefining wear on tool geometry as in works of [19-21]. The presented paper utilizes stress flow model of chip formation with Lagrangian boundaries to investigate influence of flank wear on forces in orthogonal turning of 42CrMo4 steel. The premise of modeling flank wear in orthogonal cutting is presented on Fig. 1.

2. FEA MODEL OF CHIP FORMATION

Model for analysis was prepared in ABAQUS/CEA commercial software which utilize finite element method. This simulation software is commonly applied for solving problems in structural mechanics, electrical engineering, acoustics, fluid dynamics, soil mechanics and more. Since ABAQUS is a robust environment for solving multiphysical problems, every new analysis requires definition of fundamental set of mechanical properties and physical principles of each phenomenon taken in account for a given model. In this paper chip formation is modeled as coupled temperature-displacement problem, and therefore definition of it in ABAQUS involves specifying properties like thermal conductivity, specific heat, mass densities, friction mechanism and most importantly constitutive model for stress-strain relation.

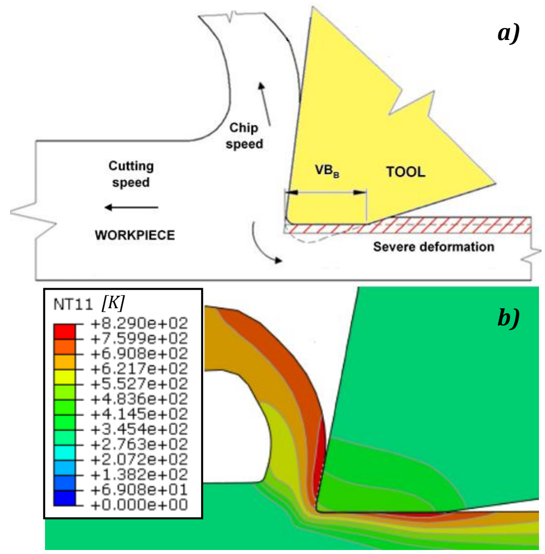

Fig. 1. Basic model of flank wear in orthogonal cutting [22] (a) and thermalanalysis of chip formation with predefined wear geometry using FEA model (b)

Fig. 2 presents 2D FEA model of chip formation process in orthogonal cutting. Relative motion of tool-workpiece pair is achieved by prescribing velocity type boundary conditions to nodes at tool surface. This type of boundary conditions defines displacement of nodes in X and Y direction which will occur only with specified velocity. Each node at selected tool surface will move in X direction with velocity equal to cutting speed and in Y direction the movement will occur with velocity equal to feed speed. Whole tool geometry is defined as a rigid body which significantly reduces calculation cost. Rigid body constrain means that motion of every node in tool's domain is governed by the motion of one arbitrary chosen reference node. This node is designated as reference point (RP). Throughout a simulation relative position of nodes within rigid body is constant. As a result the tool will not undergo any deformation but the movement of the tool will be possible as all of its nodes will move simultaneously. However rigid body constrain will exclude stress and strain analysis from tool domain.

Onset of chip formation in this model is caused by gradual indentation of tool's wedge into workpiece. Since relative motion of tool-workpiece pair is already specified thus wedge indentation would occur regardless of amount of work needed to begin plastic deformation of the workpiece. Cutting forces are obtained as reaction force due to contact pressure acting on all tool surfaces and are probed in the rigid body reference node (RP) where tool mass is reduced to a single point in space. Therefore reaction forces in FEA model are results of force needed to onset wedge indentation and friction of tool-workpiece interface in given cutting condition. Force values are collected from *RF1* and *RF2* variables in ABAQUS software that represent consecutively cutting force F_c (X direction) and feed force F_f (Y direction).

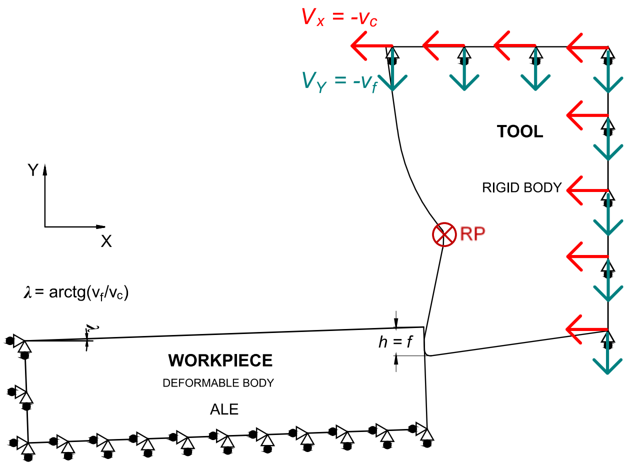

Fig. 2. FEA model of chip formation process

In 2D analysis a workpiece can be modeled as a rectangle which length is equal to 3 mm and height equal to 0.4 mm. The size of this workpiece section is sufficient to a model chip formation process in given cutting conditions for duration of 1.2 ms. Displacement boundary conditions are set to rectangle's bottom and far left edge. These BCs prescribe displacement and rotation equal to 0 in all directions for selected surfaces. The workpiece mesh domain is tilted at angle λ to account for resultant tool trajectory which is a combination of movement in X and Y direction. Consequently, tilted workpiece geometry coupled with tool trajectory would maintain constant value of uncut chip thickness.

For Explicit dynamic analysis Arbitrary Lagrangian-Eulerian (ALE) description is applied throughout the workpiece mesh domain. ALE description is an adaptive meshing algorithm that governs node and material movement during analysis. It combines classical Lagrangian approach (material and node grid movement is identical) with Eulerian representation (material moves through node grid which movement is constricted during analysis). In result of adaptive meshing, the movement of material points and nodes is independent from one another, not constricted which contributes to maintaining initial mesh topology. Hence, ALE description is proven to handle large plastic deformation by minimizing mesh distortion. ALE description does not allow element deletion form mesh domain therefore is applicable for analysis of continuous chip [23].

Coupled temperature-displacement analysis requires implementing CPE4RT element type for both bodies. CPE4RT is a 4-node plane strain element type of quadrilateral shape suitable for 2D analysis. Workpiece domain was discretized evenly into rectangular shaped elements. By trial and error method it was established that with mesh side ratio 3:1 remeshing algorithm is robust enough to counter large deformation and allows completion of analysis. For tool body mesh discretization was increased in the area near cutting edge to ensure finer distribution of temperature field. Adopted mesh element refinement for tool and workpiece is presented on Fig. 3.

For 2D plain strain analysis section thickness must be defined to account for heat capacity of each body.

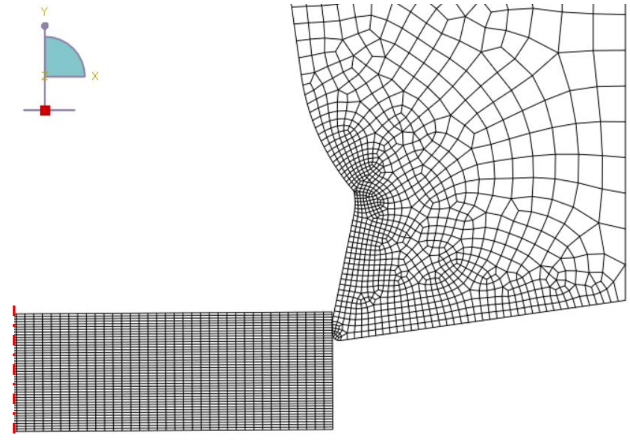

Fig. 3. Adopted mesh element refinement for FE analysis

The workpiece mesh domain is modeled with section thickness equal to depth of cut a_p (3 mm) and tool section is set to 12 mm corresponding to insert size. In orthogonal cutting feed value is equal to uncut chip thickness. Throughout both bodies predefined temperature field was set with initial temperature of 300 K degrees.

Throughout chip-tool and workpiece-tool interface a modified Coulomb friction model is deployed. The application of this model in mechanics of chip formation was proposed by Zorev (Fig. 4 [24]).

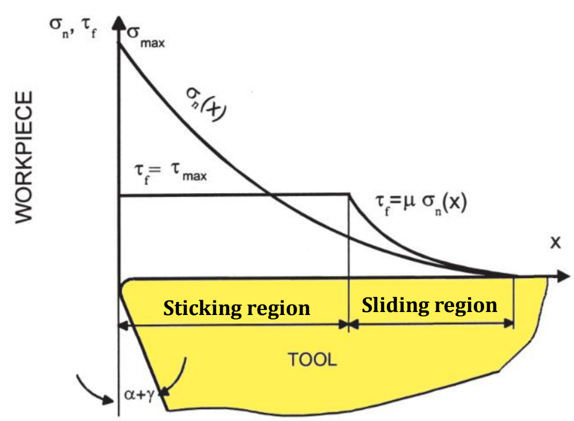

Fig. 4. Application of Coulomb's friction model in chip-tool interface [24]

The model takes into account nonlinear value of shear stress along tool surface as a function of normal stress. In sliding region shear stress depends on multiplication of normal stress magnitude by friction coefficient. The friction coefficient may or may not be defined as constant. Coulomb friction model sets certain limit value to shear stress (sticking region). This model is described by set of equations [25]:

$$\begin{cases} \tau_f = \mu\sigma_n \quad if \quad \mu\sigma_n < \tau_{\max} \quad (sliding\ region) \\ \tau_f = \tau_y \quad if \quad \mu\sigma_n \geq \tau_{\max} \quad (sticking\ region) \end{cases} \tag{1}$$

The limit value to shear stress is known as material yield shear stress. Its value can be estimated from uniaxial yield stress [26]:

$$\tau_{\max} = \tau_y = \frac{\sigma_y}{\sqrt{3}} \tag{2}$$

3. MATERIAL MODEL

Stress-strain relation characteristic for chip formation process seemingly surpass applicability of Hook's elastic model. The calculation off low stress value in material subjected to large deformations with high strain rate and temperature requires introducing proper constitutive model. Hence new model for von Mises flow stress was introduced by G.R. Johnson and W.H. Cook [27]. This material law in frequently applied in finite element analysis for such problems where large and abrupt deformations occurs. For instance, this model is successfully adopted to solve problems occurring in explosions, impacts or metal forming. The constitutive model is given by formula:

$$\sigma_y = (\mathrm{A} + \mathrm{B}\varepsilon_p^{\mathrm{n}})\left(1 + \mathrm{C}\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{\mathrm{p}}^0}\right)\right)\left(1 - \left(\frac{T - \mathrm{T_o}}{\mathrm{T_t} - \mathrm{T_o}}\right)^{\mathrm{m}}\right) \tag{3}$$

Where in formula (3) independent variables are equivalent plastic strain ε_p, equivalent plastic strain rate $\dot{\varepsilon}_p$ and workpiece nodal temperature T. The definition of remaining constants is presented in table 1 with parameters for equations (3) specific for 42CrMo4 workpiece adopted from [13]. Brief analysis of eq. 3 revels that three subsequent parenthesis account for strain, strain rate and temperature impact on stress value.

Table 1. Johnson-Cook model parameters for 42CrMo4 steel [13]

Yield stress coefficient	**A**	[MPa]	595
Strain hardening coefficient	**B**	[MPa]	580
Strain rate sensitivity coefficient	**C**	[-]	0.023
Strain hardening exponent coeff.	**n**	[-]	0.133
Thermal softening coefficient	**m**	[-]	1.03
Reference strain rate	$\bar{\varepsilon}_0$	[s^{-1}]	1000
Room temperature	T_o	[K]	300
Material melting temperature	T_t	[K]	1793

Complete thermo-mechanical analysis of tool-workpiece interface using FE simulations require to specify other properties. All remaining proprieties necessary for this analysis were shown in table 2.

Table 2. Material proprieties for 42CrMo4 steel and carbide insert [7, 13]

	42CrMo4 steel	Carbide insert
Density ρ [kg/m³]	7850	15000
Young's modulus E [GPa]	210	800
Poisson's ratio ν [-]	0.3	0.2
Conductivity λ [W/m·K]	38	80
Specific heat C_p [J/kg·K]	358	203

4. CUTTING CONDITIONS

For experimental test carried out on TUR-560E lathe a SNMG 12 04 04 – VF Korloy insert was selected. It is a carbide insert with CVD coating (Al_2O_3-TiC-TiCN) and is characterized by complex geometry of rake face designed for chip breakage. Modeling of orthogonal cutting process requires measurement of only insert's cross-section in the middle of the cutting edge. Insert geometry was established by contact profilometery techniques using HOMMEL T8000 instrument. On Fig. 5 insert's CAD geometry is presented in tool-in-hand system. The same geometry is used in FE analysis. By mounting insert in a tool holder clearance angle is set to α_o = 8° and rake face can be characterized by two rake angles: first very short face is inclined at negative rake angle γ_{o1} = -1.5° and second face is inclined at positive rake angle γ_{o2} = 11.5°. For selected feed values chip-tool contact was observed only on the first and the fraction of the second rake face of new tool geometry which proves that range of modeled geometry is more than sufficient. The average value of edge radius was determined to be equal to r_n = 23 µm. To observe influence of flank wear on cutting force and to include effect of wear evolution, a broad scope of VB_B instances was selected. Mesh model was modified accordingly to Fig. 6.a through setting flank clearance to 0° angle at length VB_B to mimic flank wear. Similar tool geometry subjected to flank wear was investigated in [19].

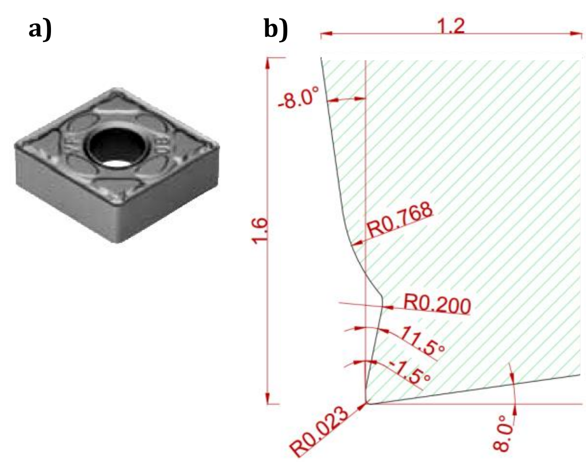

Fig. 5. Korloy SNMG 12 04 04 – VF insert (a) and it's CAD geometry at midpoint of cutting edge (b)

In order to provide necessary data for experimental validation of FEA model the same geometry had to be modeled on inserts. Therefore four cutting edges were selected and insert geometry was modified on surface grinder. Insert was clamped at specific angle so it would be possible to obtain even flat wear along cutting edge in tool-in-hand system. VB_B width were verified under microscope (Fig. 4.b) and attained values in range of 0.15 ÷ 0.42 mm. Excessive wear at VB_B = 0.3 mm eroded completely the first rake face with negative rake angle γ_{o1} = -1.5°. Experimental test was conducted with cutting conditions presented in table 3. Orthogonal turning was carried out for each cutting edge with modeled wear for three takes during which cutting force F_c and feed force F_f were measured. Each take took about 3 seconds which was enough to provide steady-state force measurement signal.

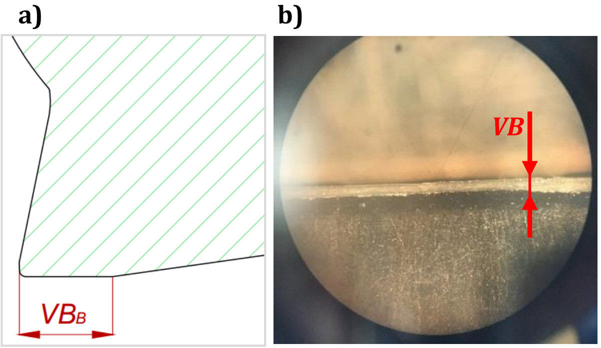

Fig. 6. Modification of insert geometry to include effects of flank wear (a) and wear observed under microscope (b)

Table 3. Cutting conditions

Parameter	Designation	Unit	Value
Spindle speed	n	min^{-1}	710
Cutting speed	v_c	m/min	114
Depth of cut	a_p	mm	3
Feed rate	f	mm/rev	0,097
Tube outer diameter	D_Z	mm	51
Tube inner diameter	D_O	mm	45

5. RESULTS AND DISSCUSION

Simulation of chip formation process from computational standpoint is genuinely expensive analysis. Explicit nature of this kind of problem makes it even harder and sometimes impossible in most commercial FEA software to enable parallel computation to cut on required calculation time. Surprisingly even 1 second of FE analysis of 2D cutting process would consume days to compute with top grade PC. Therefore it is very common in FE analysis of chip formation process to reduce time of simulation to magnitude of couple of milliseconds.

Fig. 7 presents evolution of forces during FEA in one selected case of tool wear. Analysis time was reduced to merely 1.2 ms and provided satisfactory information about average force value for given VB_B. The calculation time for one simulation in this study ranged from 20 to 60 minutes using Intel i7 processor. For both cutting and feed force a peak value can be observed at 0.1 ms of analysis time. This peak is associated with initial wedge indentation into workpiece. Data collected after 0.3 ms of simulation time were used to obtain average force value. It is also noted that simulation didn't record force evolution up to intended 1.2 ms of analysis time. Failure to record force values was due to abrupt error linked to overlapping of mesh cells caused by large deformation. Deployed ALE remeshing algorithm is not always capable to counter large deformation and in some cases, changing mesh cell ratio is enough to mend this issue. Hence extending analysis time beyond scope of few milliseconds will increase the peril of encountering this error since ALE is unable to retain original mesh topology for such deformed geometry.

For orthogonal turning with new insert's geometry cutting and feed force were measured to be 658 N and 411 N respectively in given cutting conditions. In FEA model average force was recorded at F_c = 497 N and F_f= 172 N, so comparing to experimental values cutting force was underestimated by 24.5% and feed force by 58.2%. The value of both forces as a function of flank wear is presented on fig. 8. Additionally exponential regression functions are used to model data points for each force where full lines indicate data from experimental test and dashed lines refers to FEA model. With progression of flank wear both cutting and feed force values increased and FEA simulations were able to account for this phenomenon. Feed force value increase notably with progression of wear and around VB_B = 0.16÷0.19 mm its value is equal to cutting force. Intensive gain of F_f must be associated with resulting friction of flank wear onto machined surface. Magnitude of contact pressure acting in vertical direction is proportional to length of contact in this interaction. Vertical direction (refer to Fig. 2) of resulting contact pressure is the direction of the feed force.

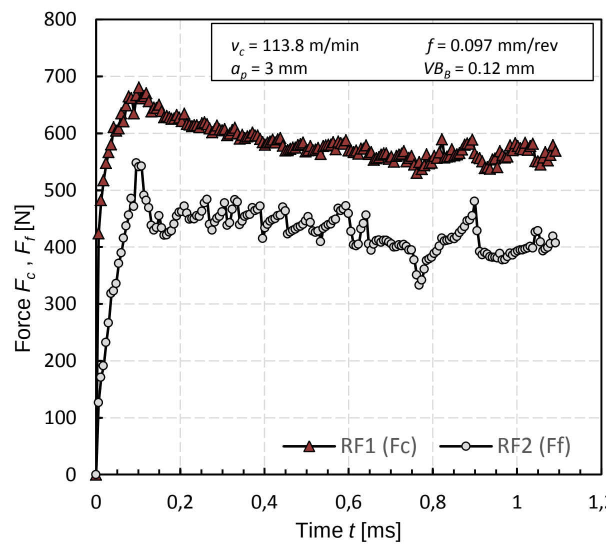

Fig. 7. Registered tool reaction force RF1 and RF2 in FEA model for tool with VB_B = 0.12 mm

However for both experimental and FEA measurements a substantial drop of F_f value is observed at transition from VB_B = 0.28 mm to VB_B = 0.29 mm data points. Sudden drop can be partially linked to progression of wear to threshold of compete erosion of first rake face. This resulted in a shift from negative to positive rake angle, which is known to affect forces in machining. To evaluate validity of FEA model a chart on Fig. 9 is used to show relative error as a function of flank wear. It is apparent that with growth of VB_B a magnitude of relative error of this model decreases. The greatest error is recorded for feed force of new tool's geometry.

All simulations in this study were carried out with constant value of friction coefficient when due to abrasive wear a different tribological condition should be applied for flank wear surface, which is pure carbide when the rest of tool's surfaces are coated. Other researchers [28-29] indicate a need for differentiating friction coefficient for every cutting condition using F_c and F_f values from experimental tests. However, it was not an intention of this paper to build FEA models based on *a priori* knowledge of force values.

FEA model can also be validated by comparing experimental and numerical values of F_c/F_f force ratio. The chart of this ratio as a function of flank wear is presented on Fig. 10.

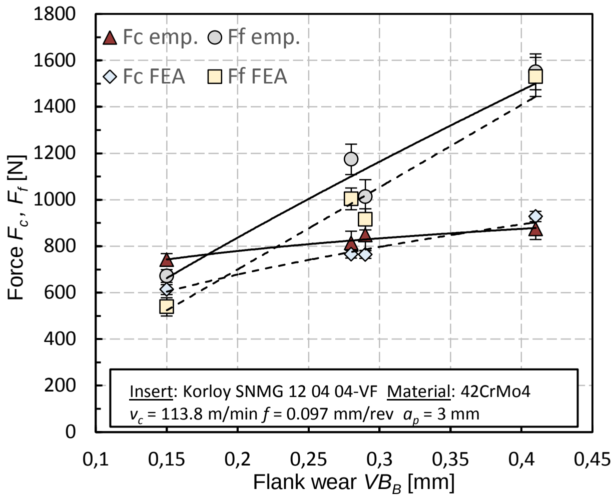

Fig. 8. Comparison of forces in orthogonal turning of 42CrMo4 steel tube obtained from FEA model and empirical trial

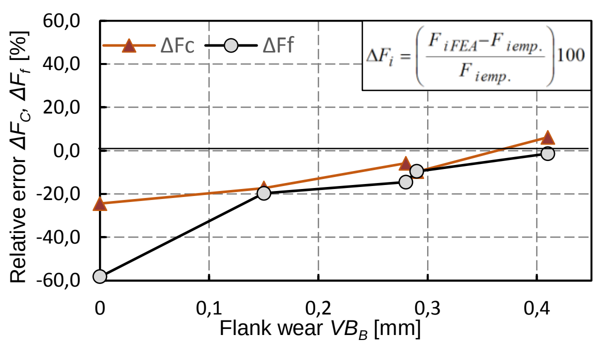

Fig. 9. Relative error of Finite Element Analysis

It is apparent that proper but slightly elevated force ratio was retained throughout investigated scope of flank wear. With exception of VB_B = 0.28÷0.29 mm threshold, force ratio decreases for both empirical and FEA model as wear progress. Some minor discrepancies are observed for VB_B = 0.28 mm. Model validation through comparison of force ratio is especially justified for finite element analysis of chip formation process since parameters for Johnson-Cook equation and other constants were determined by other institutes for their locally acquired 42CrMo4 designated steel. Material acquired in other part of Europe could differ in quality, chemical composition, structure or applied heat treatment, which all could affect specific cutting force. Thus, it is correct to assume that some minor deviation in force value could occur. Therefore relying on force ratio to evaluate FEA model's capacity to provide qualitative data about metal cutting process is justified.

FEA model based on J-C equation provides great deal of data about strain and stress magnitude and distribution within a workpiece. Fig. 11 presents stress contour plot from selected frames at 1 ms of analysis time for different stages of tool wear. In both severely different stages of wear a characteristic primary deformation zone is present and maximum stress values are quite similar. Constant value of Misses stress and its distribution within this zone indicates that flank wear does not affect shearing process in uncut chip layer. Nonetheless, associated with flank wear increasing contact of workpiece-tool interface results in friction accompanied by immense contact pressure acting on the machined surface. It is apparent from presented frames that due to this interaction a much greater stress occurs deeper into the machined surface. Stress legend in these two cases points out that minimal stress recorded in the workpiece domain is 2.8 times greater for the workpiece machined with worn tool.

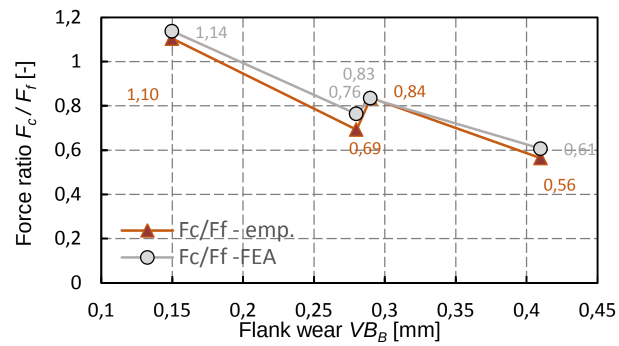

Fig. 10. Comparison of F_c/F_f force ratio of empirical trial and FEA model

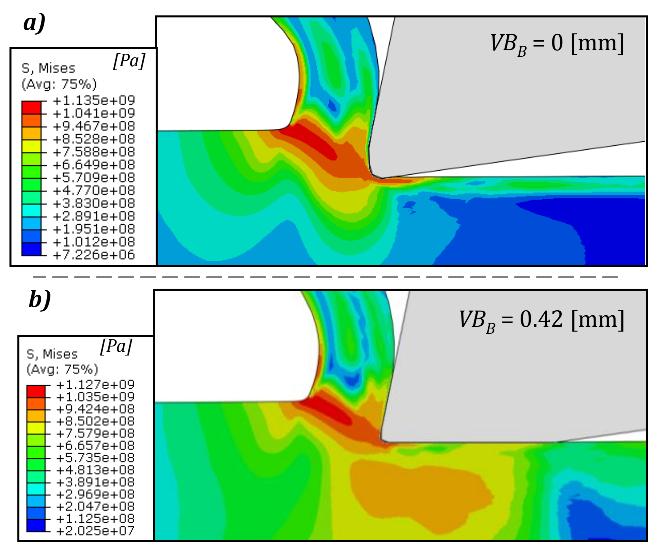

Fig. 11. Misses stress contour plot in worpiece and chip layer for new (a) and worn tool (b)

6. CONCLUSIONS

- Evolution of flank wear contributes to increase of magnitude for both cutting and feed force in orthogonal turning. This same phenomenon was observed in empirical trials and with finite element analysis.
- FEA model was capable of adequately estimating forces in orthogonal cutting within scope of investigated wear with relative error ranging from -19% to 6%. However for new tool geometry both forces were greatly underestimated with relative error for F_f at-59% and -24% for F_c.

- With constant value of friction coefficient at μ = 0.3 for FE model a good convergence of F_c/F_f force ratio with experimental trials was observed. Force ratio decreases with the increasing width of flank wear, which indicates greater sensitivity of feed force to VB_B evolution.
- Evolution of flank wear does not have significant effect on maximum stress in primary deformation zone. However, due to rubbing of wear land on machined surface a greater residual stress is observed for the part machined with worn tool.
- Both experimental trial and numerical analysis were susceptible to changes in rake surface geometry. Wear at VB_B = 0.28÷0.29 mm corresponding with erosion of first rake face caused a shift from negative to positive rake angle. In result of this shift forces as functions of wear are non-monotonic.
- Reducing analysis time to 1.2 ms and introducing rigid body constraint to tool mesh domain contributed to shorter computation time. Time of analysis was sufficient to generate steady-state force signal in ABAQUS software.

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