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EXPERIMENTAL AND SIMULATION INVESTIGATIONS OF FACE MILLING PROCESS OF Ti-6Al-4V TITANIUM ALLOY

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S u m m a r y

This paper is focused on the finite element analysis of machining of Ti6Al4V titanium alloy in a non-orthogonal (3D) face milling process. The study was conducted for face milling with the cutting speed of 80 m/min, depth of cut of 1 mm, cutting width of 10 mm and different feed rates. The FEM simulations include the cutting force components and average maximum cutting temperatures. The simulation results were compared with experimental data obtained for similar milling process configuration. It was found that the kind of FEM constitutive model influences the force and temperature values. In this case the cutting force has a better match with experimental data when using the JC model. On the other hand, a good fitting for both feed and passive forces was achieved for the PL model. Additionally, a very good fitting for the cutting temperature using PL FEM model was obtained. It was also found that the feed rate has a significant effect on the average interface temperature and can be modelled by using FEM material models presented in the article.

Keywords: 3D FEM simulation, milling process, titanium alloy

Symulacja numeryczna i badania eksperymentalne procesu frezowania stopu tytanu Ti6Al4V

S t r e s z c z e n i e

W pracy prowadzono analizę wyników symulacji procesu frezowania walcowo-czołowego stopu tytanu Ti6Al4V, w układzie nieortogonalnym (3D) z zastosowaniem metody elementów skończonych. W procesie frezowania płaskiego stosowano prędkość skrawania 80 m/min, głębokość skrawania 1 mm, szerokość skrawania 10 mm, dla różnych wartości posuwów. Przy użyciu MES określono wartości składowych sił skrawania oraz maksymalną wartość temperatury skrawania. Walidację wyników symulacyjnych i badań eksperymentalnych prowadzono dla takich samych wartości warunków obróbki. Stwierdzono, że rodzaj konstytutywnego modelu MES ma wpływ na wartości siły i temperatury skrawania. W tym ujęciu dobrą zgodność danych symulacji normalnych i eksperymentalnych, dla przypadku składowej głównej siły skrawania, uzyskano przy zastosowaniu modelu JC. Natomiast lepsze dopasowanie dla składowej posuwowej i odporowej (pasywnej) uzyskano dla modelu PL. Dodatkowo dobre dopasowanie wyniku symulacji i eksperymentu, dla temperatury skrawania, uzyskano także dla modelu MES typu PL. Stwierdzono, że posuw ma znaczny wpływ na wartość średniej temperatury skrawania. Modelowanie tych oddziaływań można realizować, stosując modele materiałowe MES przedstawione w pracy.

Słowa kluczowe: 3D symulacja MES, frezowanie, stop tytanu Ti6Al4V

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1. Constitutive material models for FEM simulations

Rationalization of technological processes is an important step required in the implementation phase of manufacturing process. There are many methods of technological process optimization. For example, engineers use the modification of tool paths with fitting the technological parameters and changing the cutting tool configuration. All of these methods need expensive experiments and technological tests in production environment.

The FEM based simulation is a basic engineering tool to solve this problem successfully. However, a universal FEM model which will cover a wide spectrum of both the workpiece and cutting tool materials should be developed [1, 2]. In particular, more accurate and complete constitutive material models which consider the appropriate mechanical thermophysical properties of both the workpiece and tool materials are needed [3]. This mainly concerns the modelling of modern construction materials, which include a group of titanium and nickel-based alloys [1, 2, 4, 5]. The success in developing the constitutive models depends on solving the following important problems:

- definition of mechanical properties of the workpiece material under real cutting conditions [6, 7],
- specification of the thermophysical properties of the workpiece and cutting tool materials also those with thin layered coatings deposited [8, 9],
- quantification of friction in the cutting zone [10, 11],
- chip segmentation in machining [4].

The determination of the appropriate parameters of the constitutive material model requires numerous experimental tests and analyses. Recently, reverse solutions have also been proposed [1, 12]. Moreover, the FEM constitutive model should meet the High Speed Cutting (HSC) and High Performance Cutting (HPC) demands which requires the implementation of high strain rate tests. In addition, it should cover a wide spectrum of cutting tool materials including multilayer coated and composite tools.

Taking into consideration all these facts, the paper is, in general, focused on the influence of the two basic constitutive models of the workpiece material, Power Law (PL) and Johnson-Cook (JC), on the results and simulation accuracy when performing 3D flat milling operations using carbide tools with grooved rake faces to machine a Ti-6Al-4V titanium alloy. An important aspect of the generation of material constitutive models is to determine accurately their parameters based on the experimental data.

2. Methodology of investigations

The tests were carried out for a flat milling with six-flute cutter-head type H490 F90AX D050-6-22-09 with carbon groove indexable insert type ANCX090416PDR from Iscar. The 3D CAD model of the grooved cutting insert

(a) and the model of the tool edge used in FEM simulation (b) are presented in Fig. 1. The defined tool insert model with appropriate settings resulting from its location in the cutter head were imported correctly to the FEM simulation system. The CAD model of the cutter head is shown in Fig. 2. The experimental and simulation conditions are specified in Table 1. Additionally, it was necessary, looking at FEM simulation method, to convert the cutting force components from FEM to the tool coordinate system. Figure 3 visualizes technological parameters introduced in FEM package along with the coordinate system and cutting force components.

a) b)

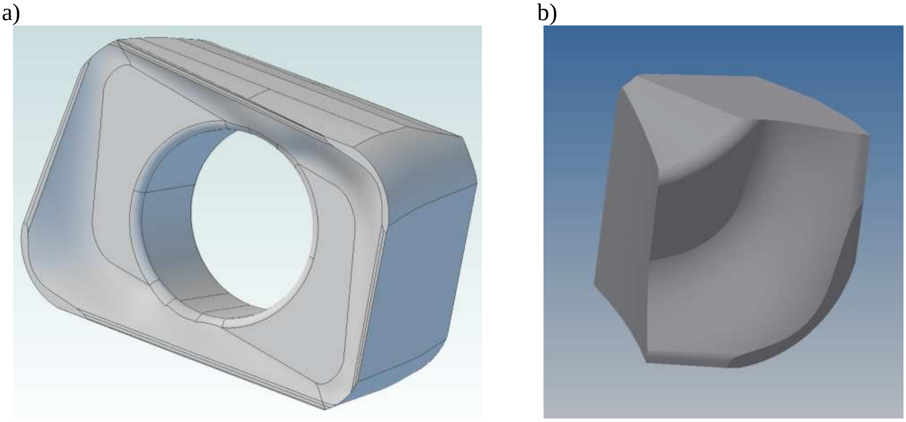


Fig. 1. Computer CAD model of the Iscar's tool insert ANCX090416PDR (a) and prepared tool model used in the FEM simulation (b)

Fig. 2. CAD computer model of a milling cutter head denoted by symbol H490 F90AX D050-6-22-09

The objective of this study is to compare the experimental results with simulation data obtained for two basic constitutive material models. This concerns the Power Law model (PL), available in the AdvantEdge software [13] and the Johnson-Cook model (JC). The JC model is predominantly used for modeling of machining processes of metallic alloys [4]. The mathematical equations for constitutive models used in this investigation were presented in Refs. [5] and [8]. The constitutive model parameters for both models are specified in Table 2.

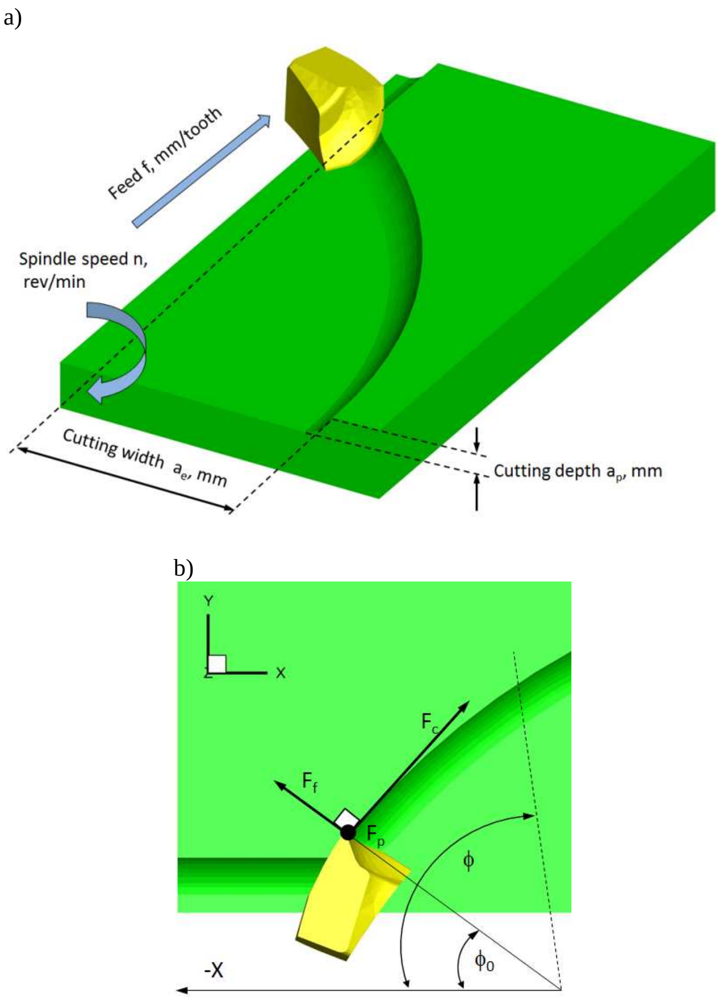


Fig. 3. Technological parameters (a) and axis configuration with defined vectors of cutting force components in the FEM system (b). Fixed initial angle of head rotation $\phi_0 = 37°$

Experimental research was carried out on CNC DMU 80P duoBLOCK milling machine equipped with plate piezoelectric dynamometer Kistler 9257B with a charge amplifier module 5019B and a digital analog converter NI 6062E from National Instruments. Visualization and signal processing takes place using the CutPro system. Measurements of the temperature in milling process were realized using HD infrared camera X6540sc. Emissivity coefficient for Ti-6Al-4V alloy was determined at the value of 0.48. During the tests, maximum temperatures in cutting zone were recorded. The values of the maximum temperature were calculated as an average of obtained maximum values for every contact of cutting edge with workpiece during machining.

Table 1. Conditions of numerical and experimental tests

Workpiece	**Ti-6Al-4V**
Technological parameters	v_c = 80 m/min, a_p = 1.0, a_e = 10 mm f_z = 0.1 and 0.15 mm/tooth
Tool	Cutting tool insert: ANCX090416PDR Material: cemented carbide H10 with TiAlN layer 3 µm thick Nous radius r_ε = 1.758 mm
Constitutive models	Power Law (PL) Johnson-Cook (J-C) with defined thermohysical parameters
Friction coefficient	0.5 (in FEM simulations)
Type of FEM simulation	Three-dimensional (3D)

The AdvantEdge (AE) package was used for the FEM modeling of the face milling process. Some examples of visualizations of FEM meshes generated during chip formation are shown in Fig. 4.

Table 2. Power Law PL and Johnson – Cook JC constitutive model parameters

Parameter	A, MPa	B, MPa	n	C	m	ε_p^0, 1/s
J-C	500	864	0.196	0.01594	0.605	0.0026
Parameter	σ_o. MPa	n	ε_p^0	ε_{cut}^0	$\Theta(T)$	
PL	952	22.19	0.035	0.12	c_0 = 1.822 c_1 = –0.00571 c_2 = 1.7 10^{-5}	c_3 = –2.164 10^{-8} c_4 = 6.48 10^{-12}
Melting temperature					1655 °C	
Young module					110 GPa	
Poisson's rate					0.3	
Thermal expansion coefficient					9.4 10^{-6} 1/K	
Density					4.430 kg/cm^3	

In order to obtain the increase of the nodal mesh density, at the junction between the cutting edge and the workpiece material, the settings of AE were modified (Fig. 4 – C). This also results in increasing of the mesh density in the cutting zone (Fig. 4 – B) and allows to achieving a significant increase in the number of nodes in the area of workpiece material after machining (Fig. 4 – A).

3. Experimental results

Experimental and simulation studies of flat milling using a six tooth milling cutter were carefully planned. It should be noted that the so-called fly milling in which only one cutting tooth is in the contact with the workpiece was carried out. In this case, the resultant cutting force is relatively easy to resolve. As a result, it is possible to generate simple waveforms of the cutting force components as a function of the rotation angle ϕ of the milling cutter head. Their graphical visualizations for two feed values of are shown in Fig. 5 and 6. It was observed that for both feed rates tested that the application of the Johnson-Cook (JC) model results in a reduction of the componential force values. In the case of the cutting force *Fc* (the tangent component) this is a good trend. As shown in Figs. 5a and 6a FEM simulation with the JC model results in a reduction of the differences of force values obtained from measurements and FEM simulations. The average difference for the JC model was calculated based on the polynomial equations listed in Table 3. In this case, for the feed of f = 0.1 mm/tooth it is about 20%, and for f = 0.15 mm/tooth about 44%. In relation to the PL model these differences are higher and equal to 60 and 75% respectively.

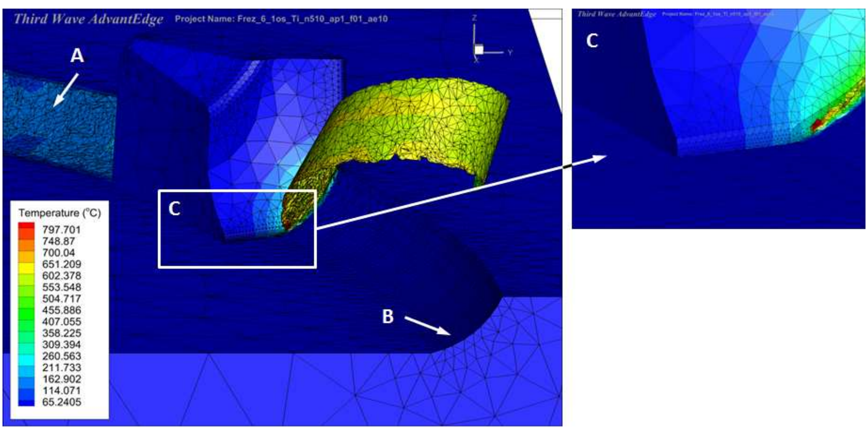


Fig. 4. Visualization of the FEM meshing strategy under modeling of shoulder milling. Areas after (A) and before (B) machining. C – zoomed area in the cutting zone

Table 3. Parameters of polynomial approximating function of the force data obtained in experiment and simulations tests

Feed	Parameters	Approximating function $f(\phi)=a+b\cdot\phi+c\cdot\phi^2+d\cdot\phi^3$, ϕ – angle of head rotation								
		Experiment			Johnson-Cook			Power Law		
		Fc	Ff	Fp	Fc	Ff	Fp	Fc	Ff	Fp
0.1 mm/tooth	*a*	375.87	228.68	999.2	354.36	109.06	99.62	1029.32	183.67	281.43
	b	-3.79	0.318	-36.73	0.828	2.6	1.688	-32.271	0.368	-6.591
	c	0.04775	0.00064	0.61	-0.0514	-0.06	-0.0451	0.55563	-0.0201	0.09058
	d	-0.0005	-0.0002	-0.0034	0.00015	0.00026	0.00022	-0.0036	0.00001	-0.0005
0.15 mm/tooth	*a*	-284.86	87.81	732.25	635.15	190.19	197.27	1869.77	62.49	-135.93
	b	28.78	3.878	-28.237	-5.954	0.2055	-1.718	-66.181	9.735	17.323
	c	-0.456	-0.0537	0.4874	0.04684	-0.0109	0.01711	1.0966	-0.1813	-0.3115
	d	0.002	0.00009	-0.0028	-0.0005	-0.0001	-0.0002	-0.0066	0.00085	0.00164

A completely different force distribution was obtained for other components of the resultant cutting force. In this case, the experimental values were visibly higher than the simulation data. This fact was observed for both feed force F_f (radial component – Fig. 5b and 6b) and for passive force F_p – Fig. 5c i 6c. For these cases, the PL model gives a better fit. A higher difference between the FEM simulation and the experiment was obtained for the feed rate of 0.1 mm/tooth. The values of this difference come, in extreme cases, up to 44% for F_f, and up to 60% for F_p. For a higher feed rate the simulation results match the predictions better. A very good agreement was obtained for the feed force as shown in Fig. 6b. Experimental values are arranged between the JC and PL model simulation results. Also in this case, the differences for the F_p component are lower and reach, for the PL model up to 15% and up to 30% for the JC model.

It can be reasoned based on the simulated data that both constitutive models and simulation procedure used give quite realistic predictions for higher feed values. This fact can be verified in Fig. 7 when comparing the predicted and experimental results. The dotted line inclined at the angle of 45° is the reference line for an ideal agreement between them. The changes of force components are presented in the form of polynomial functions of the 3rd order as specified in Table 3. As shown in Figs. 7b and 7c the percentage agreement between measurements and FEM predictions increases to 70-80% for the F_f and F_p forces. In the contrary, as shown in Fig. 7a, this effect for the Fc force is about 30% worse. In addition, also generated force spectra obtained for the feed of f = 0.15 mm/tooth are more stable and force fluctuations are visibly smaller as shown in Fig. 6.

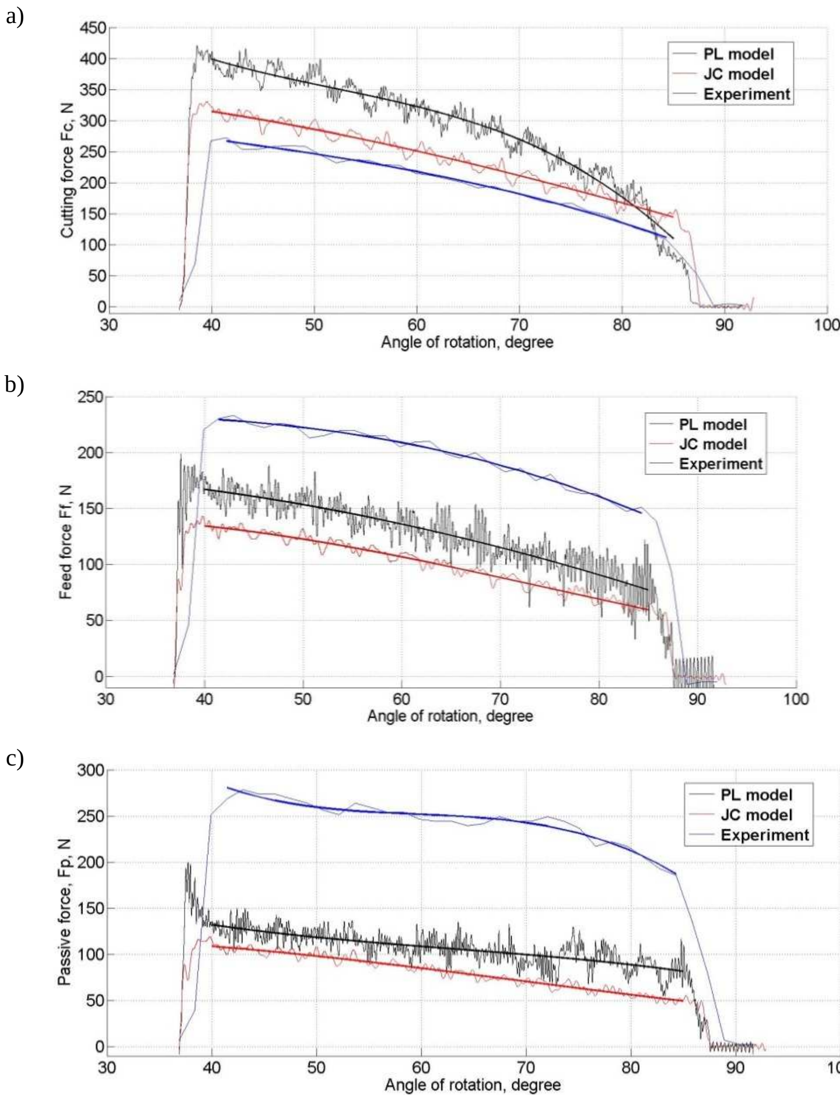


Fig. 5. Changes of the force components as functions of the rotation angle of milling cutter head: a) cutting force, b) feed force, c) passive force. Machining parameters: v_c = 80 m/min, a_p = 1 mm, f = 0.1 mm/tooth

It was observed when comparing force records in Figs. 5 and 6 that the PL seems to be more sensitive to the changes of milling feed. A smother spectrum was obtained for a higher feed for which higher forces are exerted on the milling cutter. This effect is more pronounced for the highest F_c force and it implies the conclusion that FEM simulations are less sensitive to process disturbances when mechanical loads are higher. This fact is also confirmed in Fig. 9, which shows the changes of the cutting temperature recorded successively during cutter rotation obtained for both constitutive models applied.

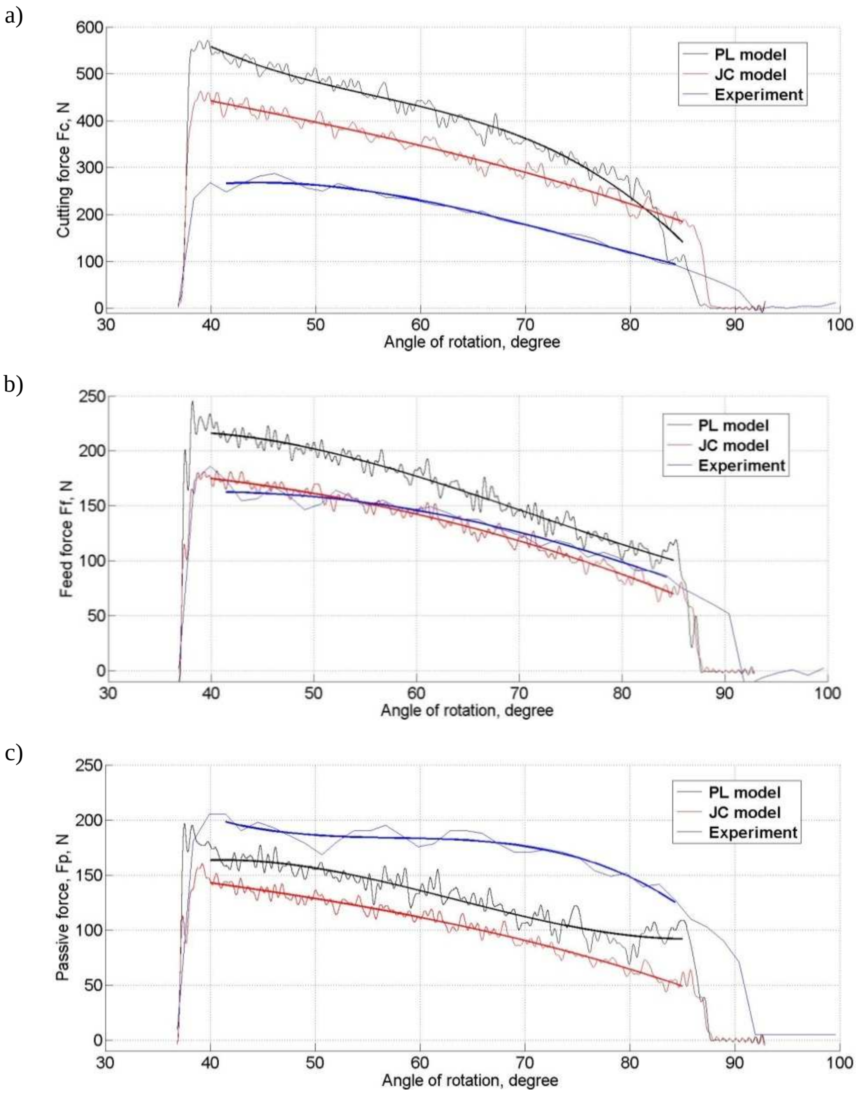


Fig. 6. Change of the force components as a function of the rotation angle of cutter head: a) cutting force, b) feed force, c) passive force. Machining parameters: $v_c = 80$ m/min, $a_p = 1$ mm, $f = 0.15$ mm/tooth

The temperature spectrum recorded in the function of the rotation angle of a milling cutter is show in Fig. 9. In this case, the predicted values were validated using the average temperature values recorded by a high resolution IR camera. A representative temperature spectrum recorded with the average values determined are shown in Fig. 8. The calculated values of the cutting temperature and relevant parameters in polynomial models are specified in Table 4. It is observed that average values of temperature are lower for the JC than for the PL model. This difference can result from precision definition of the thermophysical properties, in general, the specific heat and thermal diffusivity [5, 10].

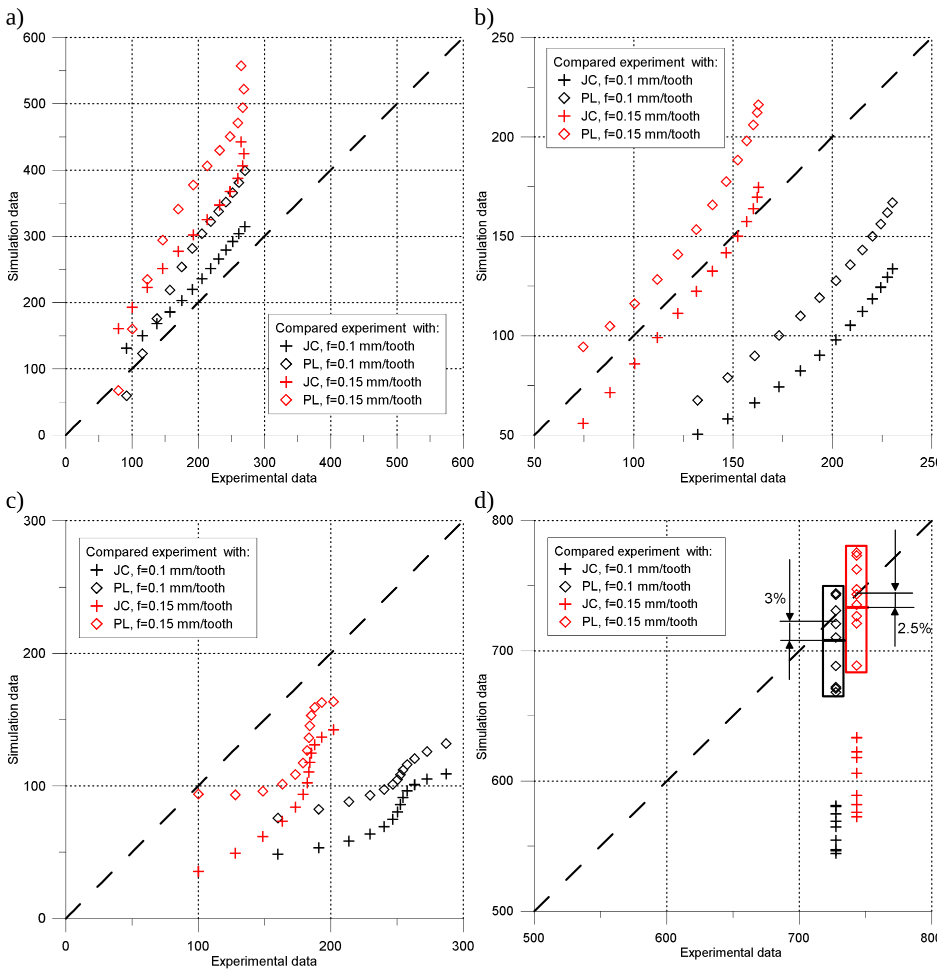


Fig.7. Comparison of experimental and FEM simulation data for: a) cutting force, b) feed force, c) passive force, d) cutting temperature

An exceptionally good agreement was documented for the PL model which is recommended by the Advant Edge FEM package. This model overestimates the cutting F_c force which results in a higher mechanical energy produced, which, in turn, is exchanged into heat. This contributes to the prediction of a higher temperature. Similar thermal effects are also obtained when increasing the feed. Moreover, the recorded temperature signal is more dynamic (especially if the feed is equal to *f* = 0.1 mm/tooth) when the milling process was simulated using the PL model.

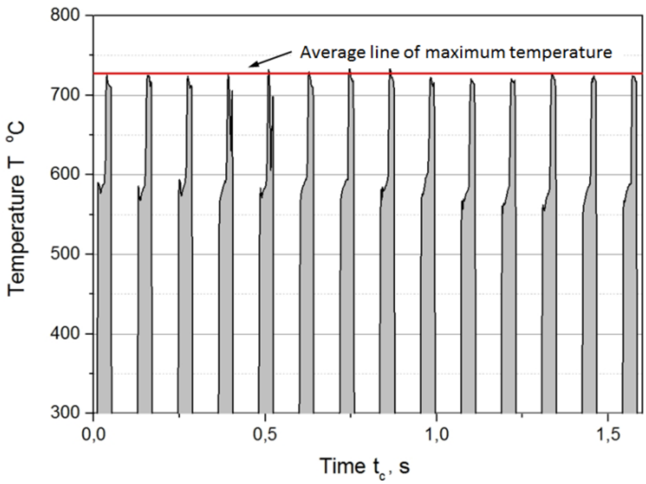


Fig. 8. Recorded temperature signal (by HD infrared camera) measured in the cutting zone with calculated average values of maximum temperature for 14 contacts areas of the cutting edge with the workpiece

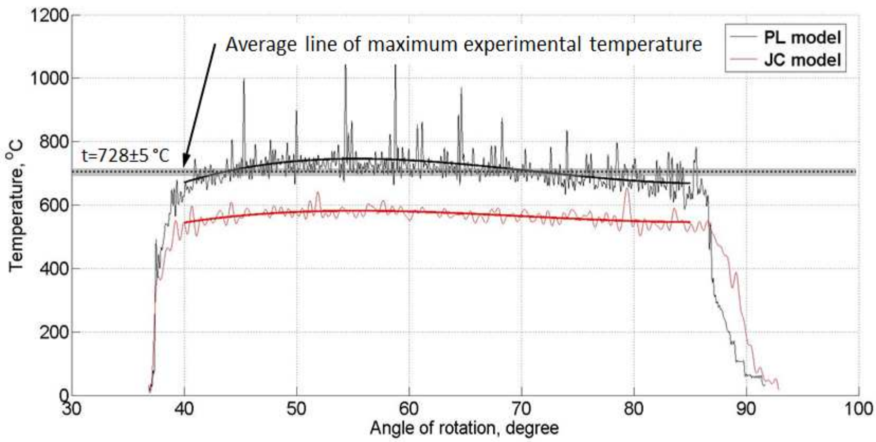
Table 4. Experimental results of average maximum temperature for different feed rates with parameters of polynomial approximating functions for maximum cutting temperature determined for both simulation tests

Feed mm/tooth	Experiment temperature, °C		Parameters	Johnson-Cook	Power Law
	Average value	Standard deviation			
0.1	727.7	5.0 (±2.5)	*a*	-220.34	-857.71
			b	36.91	73.66
			c	-0.5486	-1.091
			d	0.00259	0.00513
0.15	743.4	6.3 (±3.15)	*a*	-550.39	-1181.87
			b	54.75	91.36
			c	-0.8144	-1.385
			d	0.00383	0.00676

A good agreement between measured and simulated values of the cutting temperature is confirmed in Fig. 7d. In this graph the data were determined from the 3rd polynomial models. As a result, the difference for temperatures determined for two feeds of f = 0.1 and mm/tooth does not exceed 3%. It can then be concluded that the field of isotherms shown in Fig. 10 is close to a real one.

Two examples of the temperature distribution in the cutting zone obtained for the PL and JC models are shown in Fig. 10. It is roughly visible that the temperatures in the vicinity of the cutting edge for the case presented in Fig. 10b are lower than for competitive example shown in Fig. 10a.

a)



b)

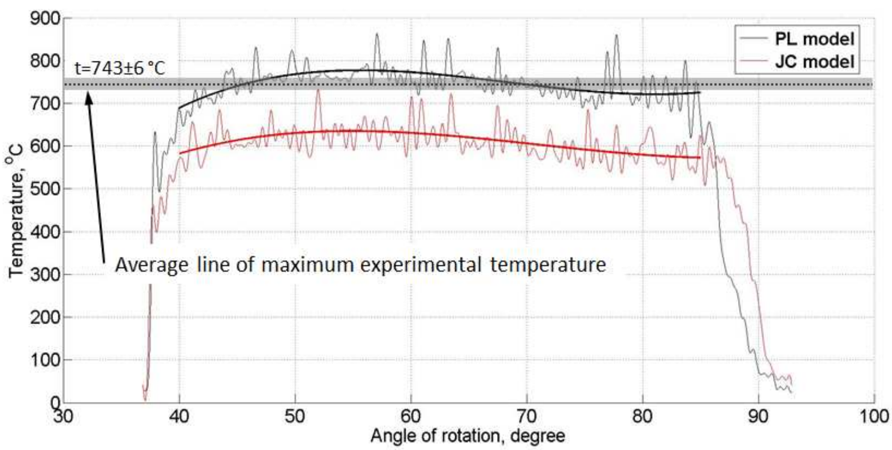


Fig. 9. Spectra of FEM temperature signal as a function of the rotation angle of a cutter head for PL and JC models compared with average maximum of measured temperature. Machining parameters: a) v_c = 80 m/min, a_p = 1 mm, f = 0.1 mm/tooth, b) f = 0.15 mm/tooth

a) b)

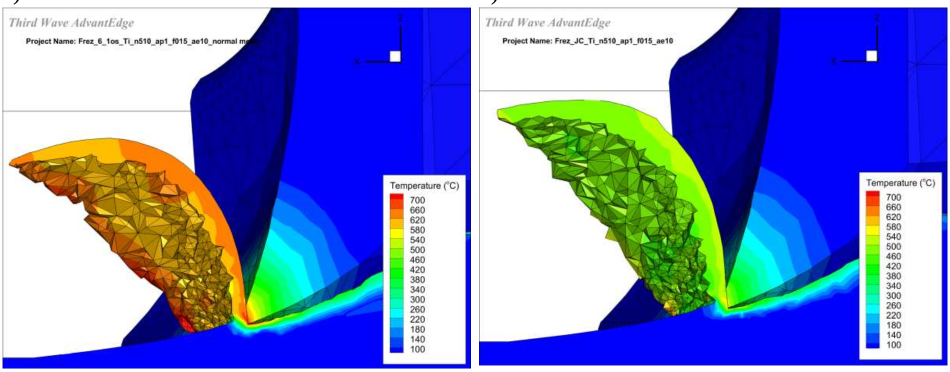


Fig. 10. Differences in the temperature distribution in the cutting zone for PL (a) and JC (b) simulation models. Machining parameters: $v_c = 80$ m/min, $a_p = 1$ mm, $f = 0.15$ mm/tooth

Conclusions

Constitutive model of workpiece material has a significant impact on the results of FEM simulation, especially in the area of mechanical and thermal influences [14]. Based on the experimental results and FEM predictions the conclusions are as follows:

- The J-C constitutive law results in the prediction of lower values of force components in relation to the PL model.
- The J-C model results in a better compatibility of experiment and FEM simulation data in relation to the cutting force component. In this case the revaluation, depending on the value of feed rate, is at the level of 40%.
- It was documented that the PL model causes that the predicted results are more sensitive to changes of the feed rate. Both force and temperature spectra obtained by means of the J-C model are less stable for a lower feed rate.
- A good thermal comparison was obtained for FEM simulation using the PL model. In these cases higher predicted cutting forces result in more heat generated and, as a result, in a higher cutting temperature.

It is finally concluded, based on experiences resulting from this study, that the practical implementation of the most accurate constitutive model is extremely difficult and needs a number of advanced experiments for their validation.

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References

[1] T.H.C. CHILDS, K. MAEKAWA et al.: Metal cutting. Theory and applications. Arnold, London 2000.

[2] F. KLOCKE, T. KRIEG: Coated tools for metal cutting-features and applications. *Ann. CIRP*, **48**(1999)2, 515-525.

[3] F. DUCOBU, E. RIVIÈRE-LORPHÈVRE, E. FILIPPI: Influence of the material behavior law and damage value on the results of an orthogonal cutting finite element model of Ti6Al4V. *Procedia CIRP*, (2013), 378-383.

[4] P.J. ARRAZOLA, T. OZEL, D. UMBRELLO, M. DAVIES, I.S. JAWAHIR: Recent advances in modelling of metal machining processes. *CIRP Annals - Manufacturing Technology*, **62**(2013) 695-718.

[5] P. NIESŁONY, W. GRZESIK, R. CHUDY, P. LASKOWSKI, W. HABRAT: 3D FEM simulation of titanium machining. Proc. Int. Conference on Advanced Manufacturing Engineering and Technologies – NEWTECH 2013, **31**(2013).

[6] F. KLOCKE, D. LUNG, S. BUCHKREMER: Inverse identification of the Constitutive Equation of Inconel 718 and AISI 1045 from FE Machining Simulations. *Procedia CIRP*, **8**(2013), 212-217.

[7] Y. CHEN, C. BUNGET, L. MEARS, T. R. KURFESS: An Improved Empirical Constitutive Model for γ'-Strengthened Nickel-Based Superalloys. *Proceedings of NAMRI/SME*, **41**(2013).

[8] P. NIESŁONY, W. GRZESIK, P. LASKOWSKI, W. HABRAT: FEM-based modelling of the influence of thermophysical properties of work and cutting tool materials on the process performance. *Procedia CIRP*, **8**(2013), 3-8.

[9] P. NIESŁONY, W. GRZESIK, P. LASKOWSKI, J. SIENIAWSKI: Numerical and experimental analysis of residual stresses generated in the machining of Ti6Al4V titanium alloy. *Procedia CIRP*, **13**(2014), 78-83

[10] F. ZEMZEMI, J. RECH, W. BEN SALEM, A. DOGUI, PH. KAPSA: Identification of friction and heat partition model at the tool-chip-workpiece interfaces in dry cutting of an Inconel 718 alloy with CBN and coated carbide tools. *Advances in Manufacturing Science and Technology*, **38**(2014)1, 5-22.

[11] T. ÖZEL, Y. KARPAT: Identification of constitutive material model parameters for high-strain rate metal cutting conditions using evolutionary computational algorithms. *Int. J. Materials and Manufacturing Processes*, **22**(2007)5, 659-667.

[12] J. PUJANA, P.J. ARRAZOLA, R.M. M'SAOUBI et al.: Analysis of the inverse identification of constitutive equations applied in orthogonal cutting process. *Int. J. Mach. Tools Manuf.*, **47**(2007), 2153-2161.

[13] Third Wave AdvantEdge User's Manual, 2014, Version 6.1, Minneapolis, USA.

[14] P. NIESLONY, W. GRZESIK: Sensitivity analysis of the constitutive models in fem-based simulation of the cutting process. *J. Machine Engineering*, **13**(2013)1, 106-116.

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