Software application proposal for predictability of cutting force effects based on a specific cutting force

Ing. Jaroslav Kovalčík

Supervisor: doc. Ing. Martin Vrabec, CSc.
Supervisor specialist: Ing. Pavel Zeman, Ph.D.

Abstract

In the fierce competition amongst users and suppliers of manufacturing technologies, cutting tools, machine tools and components, it is necessary to improve the exploitation of the potential of the individual elements of the cutting process, such as cutting tool, machine tool, clamping, and working conditions. For the manufacturer, it is important to know the specifications of the machining process, the anticipated productivity and efficiency as well as their partial aspects, such as the required power and torque, material removal rate, energy efficiency, machining time and estimated cost of operation. In order to predict these parameters without lengthy calculation and/or costly and time-consuming experiments, I have decided to create a software application. This application will help technologists in practice to choose the appropriate types of machine tools, cutting tools, operations and also quickly determine the main parameters of the cutting process. The first step was to choose the most suitable modelling method, so that the application would work with technologies, such as milling, drilling and turning and with a variety of workpiece materials. For this purpose I have chosen a modelling method based on a specific cutting force.

Keywords

cutting process, modelling, cutting forces, specific cutting force, productivity

1. Introduction

There is currently an increased demand to improve the efficiency of the machining process. The efficiency of the machining process can be observed from two basic perspectives:

- enhancing the cost-effectiveness of the process (decreasing production costs),
- increasing production in time.

Via these two approaches alone, manufacturers of parts, and suppliers of machine tools and cutting tools, constantly strive to improve their market position in a highly competitive and international market. One of the approaches to increase efficiency is via the correct choice and optimal exploitation of the potential of cutting tools and machine tools as well as a reduction in the intensity of the energy that is required for the cutting process of a particular component. This is what led to the idea of creating an analytical-material model to determine the force interaction between the cutting tool and workpiece, energy intensity and machining process efficiency. The result will be a software application that will help technologists in practice to choose correctly the appropriate types of cutting tools, operations, machine tools and also quickly determine the main parameters of the cutting process so that there is the possibility of comparing their results with other variants.

In order to acquire the main parameters of the cutting process, there are various modelling methods. The basic output of the methods is a value of cutting forces or cutting process temperature. According to the reference [1], knowledge of the cutting forces can be indirectly used for assessing the following phenomena:

- power and torque of the machine tool,
- thermal effects of the cutting process,
- energy efficiency
- durability of the cutting tool,
- total economic balance of cutting.

The first step was to choose the most suitable modelling method for the software application. As per the reference [2], I have created an overview of the cutting process modelling methods, along with descriptions and comparisons of their advantages and disadvantages. The most well-known and employed methods of cutting process modelling are:

- FEM modelling and material modelling – references [3] – [11],
- modelling the geometric ratios of cutting tool engagement – references [12] – [16],
- cutting process modelling based on empirical data – references [16] – [21],
- cutting process modelling based on a specific cutting force – references [21] – [44].

For the purpose of creating the software application, I decided to choose the method based on a specific cutting force, for the following reasons:

- it is a universal method which may be used for milling, turning, drilling, pre-drilling,
- in the catalogues provided by manufactures of cutting tools, there are parameters for a variety of workpiece materials,
- using this method is quick and flexible.

2. The predictability of force effects based on a specific cutting force

2.1 Introduction to the method

This method of the force effects modelling is a method that is based on a calculation of a cutting force via multiplication of a specific cutting force (k_c, k_f, k_p) and the cross-section area of a chip (A), see equations (1), (2), (3).

$$F_c = k_c \cdot A = k_c \cdot h \cdot b \tag{1}$$

$$F_f = k_f \cdot A = k_f \cdot h \cdot b \tag{2}$$

$$F_p = k_p \cdot A = k_p \cdot h \cdot b \tag{3}$$

The specific cutting force is the resistance that is experienced by the workpiece material, when the workpiece material is in direct contact with the cutting edge of the cutting tool. When this resistance has been overcome, the workpiece material is cut by the cutting tool [16].

The workability of the cross-section of the chip (A) depends on:

- the cutting technology (milling, drilling, turning),
- the geometry of the cutting tool (lead angle, rake angle, nose radius),
- the shape of the cutting tool insert (square, round, triangle).

2.2 Basic equation of the calculation of the specific cutting force

The basic equation of the specific cutting force is a dependency of the specific cutting force on an undeformed chip thickness, see equations (4), (5), and (6).

$$k_c = k_{c1.1} \cdot h^{-m_c} \tag{4}$$

$$k_f = k_{f1.1} \cdot h^{-m_f} \tag{5}$$

$$k_p = k_{p1.1} \cdot h^{-m_p} \tag{6}$$

In Fig. 1 there is an example of a dependency of a specific cutting force on an undeformed chip thickness when turning C45 steel (W.Nr. 1.0503) by a cutting tool of parameters: r_ε=0.8mm, κ=70°, γ=5° for the cutting conditions: v_c=135m/min, a_p=2mm and a_p=3mm.

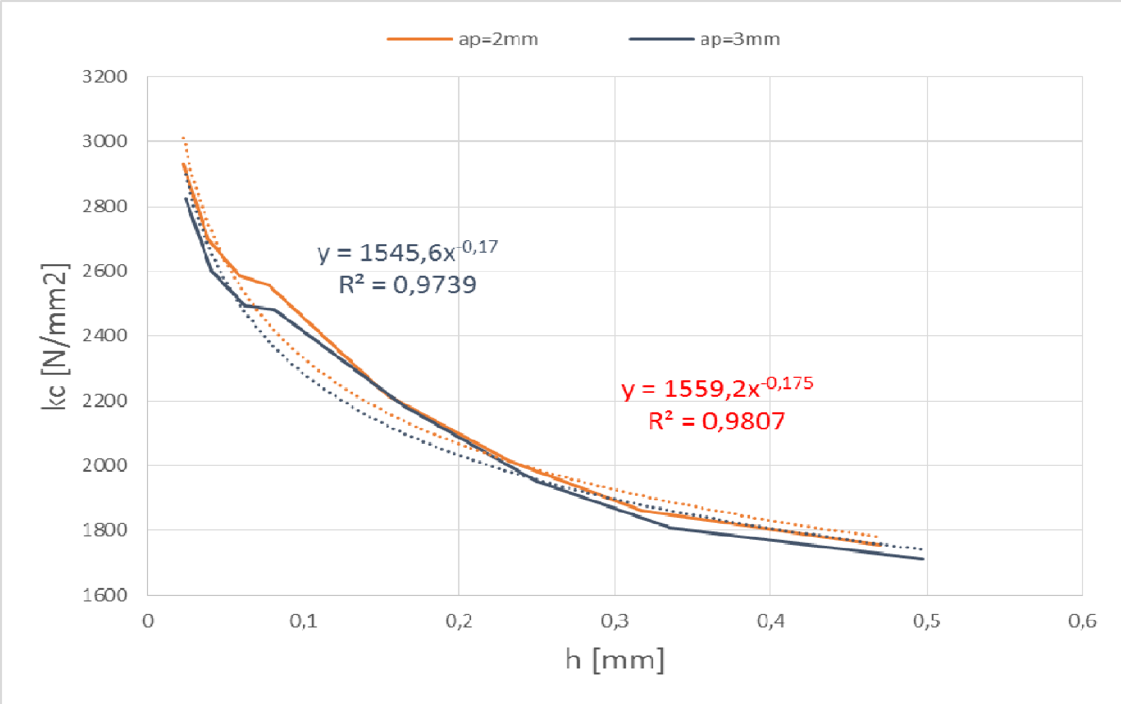

Fig. 1 *Specific cutting force as a function of undeformed chip thickness when turning C45 steel*

As it is seen in Fig. 1, the higher the value of the underformed chip thickness, the lower the value of the specific cutting force. Technologies of metal machining with low values of undeformed chip thickness, such as lapping or grinding, have quite high values of specific cutting forces, see Fig. 2.

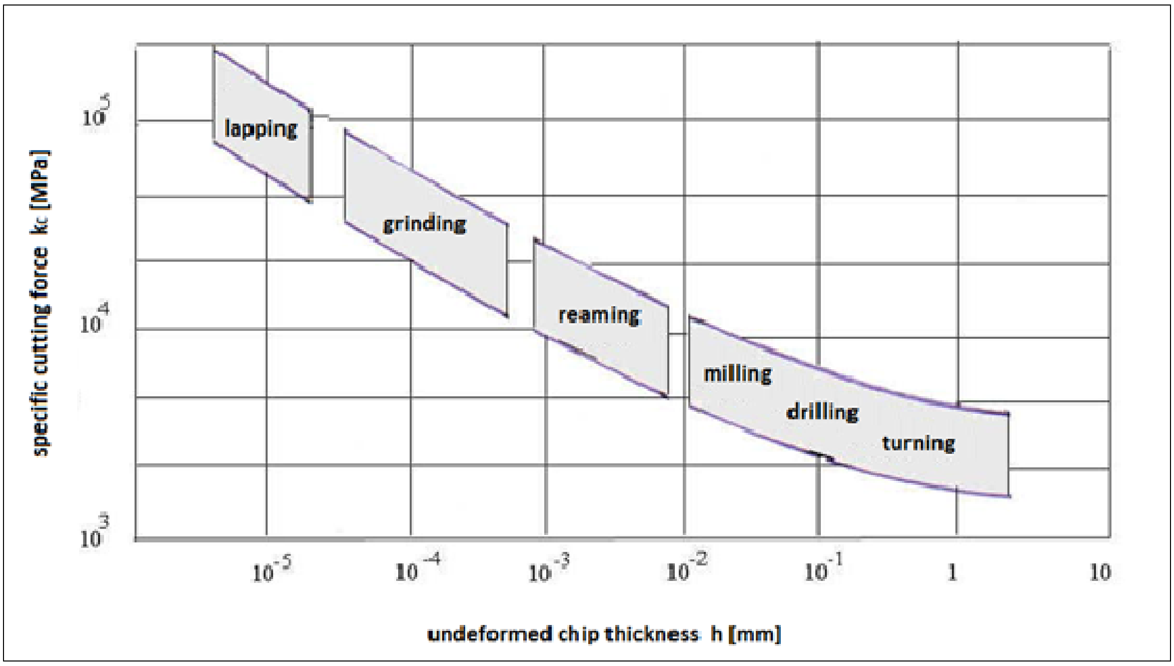

Fig. 2 *Specific cutting force for different methods of metal machining [22]*

A major advantage of this modelling approach is the speed of calculation that has universal applicability in practice. This is due to a wealth of existing and detailed databases of the $k_{c1.1}$ and m_c (and other) parameters for a considerable variety of materials, which may be found in catalogues provided by the manufacturers of cutting tools [32][33], as well as in a variety of technical literature [14][24][25], see example in Fig. 3.

Cutting conditions								
Cutting speed		$v_c = 100$ m/min						
Depth of cut		$a_p = 3.0$ mm						
Cutting material		Cemented carbide P10						
Cutting edge geometry								
			α	γ	λ	ε	κ	r_ε
		Steel	5°	6°	0°	90°	70°	0.8 mm
		Cast iron	5°	2°	0°	90°	70°	0.8 mm
Material	**Material number**	**R_m (N/mm²)**	**Specific machining forces $k_{i1.1}$**					
			$k_{c1.1}$	**$1-m_c$**	**$k_{f1.1}$**	**$1-m_f$**	**$k_{p1.1}$**	**$1-m_p$**
St 50-2	1.0050	559	1499	0.71	351	0.30	274	0.51
St 70-2	1.0070	824	1595	0.68	228	−0.07	152	0.10
Ck45N	1.1191 N	657	1659	0.79	521	0.51	309	0.60
Ck45V	1.1191 V	765	1584	0.74	364	0.27	282	0.57
40Mn4V	1.1157 V	755	1691	0.78	350	0.31	244	0.55
37MnSi5V	1.5122 V	892	1656	0.79	239	0.31	249	0.67
18CrNi8BG	1.5920 BG	618	1511	0.80	318	0.27	242	0.46
34CrNiMo6V	1.6582 V	1010	1686	0.82	291	0.37	284	0.72
41Cr4V	1.7035 V	961	1596	0.77	291	0.27	215	0.52
16MnCr5N	1.7131 N	500	1411	0.70	406	0.37	312	0.50
20MnCr5N	1.7147 N	588	1464	0.74	356	0.24	300	0.58
42CrMo4V	1.7225 V	1138	1773	0.83	354	0.43	252	0.49
55NiCrMoV6V	1.2713 V	1141	1595	0.71	269	0.21	198	0.34
100Cr6	1.2067	624	1726	0.72	318	0.14	362	0.47
GG30	JL1050	HB = 206	899	0.59	170	0.09	164	0.30

Fig. 3 *Values of the $k_{c1.1}$, $k_{f1.1}$, $k_{p1.1}$, m_c, m_p, m_f parameters for some materials [24]*

2.3 Improvement to the accuracy of the calculation of the basic equation of the specific cutting force

It is accepted that the specific cutting force is not only a function of an undeformed chip thickness, but it is a function of a variety of parameters (workpiece properties, cutting speed, rake angle, cutting environment, cutting tool wear, etc.) [14][16][24][25]. If only the basic formulas of the specific cutting forces are applied to the calculation of cutting forces, it is expected that there will be a poor concordance of the predicted values with real values. As per the mentioned references, it is possible to improve the accuracy of the calculation of the basic equation of the specific cutting force via the implementation of a variety of correction factors, see equation (7).

$$k_c = k_{c1.1} \cdot h^{-m_c} \cdot K_\gamma \cdot K_{v_c} \cdot K_{TW} \cdot K_{CTM} \cdot K_{WM} \cdot K_{CEn} \tag{7}$$

In the catalogues provided by the manufacturers of cutting tools [32][33] as well as in the technical literature [14][24][25] we can find the $k_{c1.1}$, m_c parameters. These parameters were acquired via the process of longitudinal turning, with a new cutting tool insert with a specified rake angle, without the use of cutting fluid, on a workpiece material with a specified hardness HB or a specified tensile strength (see Fig. 3). In most cases, there are no values for the cutting speeds, nor a definition for the material of the cutting tool insert used for the experiments. Thus it follows that, when using the parameters from the catalogues, we can work with the basic equation of the specific cutting force improved by the correction factor of the rake angle - K_γ, correction factor of the tool wear – K_{TW}, correction factor of the workpiece material – K_{WM}, and correction factor of the cutting environment (using a specific type of a cutting fluid or dry machining) - K_{CEn}, see equation (8).

$$k_c = k_{c1.1} \cdot h^{-m_c} \cdot K_\gamma \cdot K_{TW} \cdot K_{WM} \cdot K_{CEn} \tag{8}$$

Correction factor of the rake angle

The rake angle has the greatest impact on the specific cutting force from the geometric characteristics. The impact of the rake angle is related to the primary deformation zone of the cutting process. The more positive the rake angle, the smaller the primary deformation zone. Thus the lower the specific cutting force, see Fig. 4 [16].

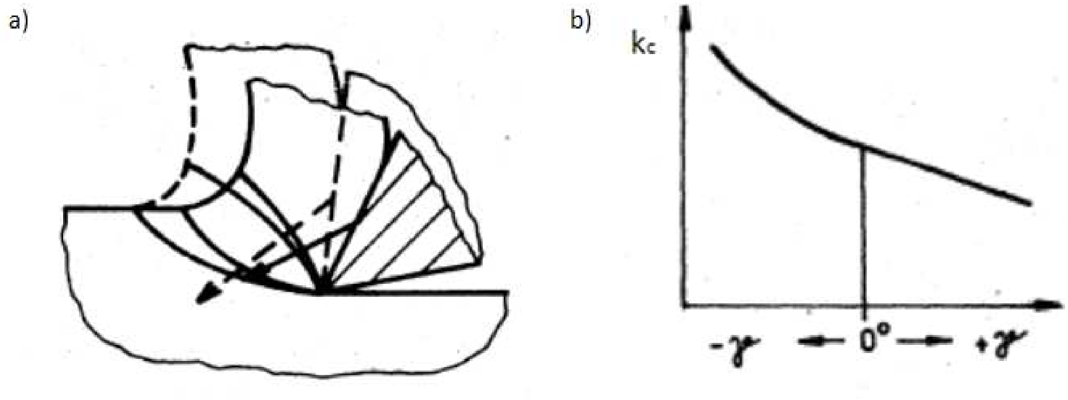

Fig. 4 *Dependency of the rake angle on: a) the change of the primary deformation zone; b) the change of the specific cutting force [XX]*

As per the references [14][18][32], the equation for the correction factor of the rake angle is based on the fact that a change of the rake angle of 1°, changes the specific cutting force by 1.5%, see equation (9).

$$K_\gamma = 1 - \frac{\gamma_0 - \gamma_{act}}{66.7} = 1 - 0.015 \cdot (\gamma_0 - \gamma_{act}) \tag{9}$$

In the previous equation there are two rake angles:

- the rake angle γ_0: the rake angle of the cutting tool which was employed for the experiment from which the $k_{c1.1}$ and m_c parameters were acquired,
- the actual rake angle γ_{act}: the rake angle of the cutting tool for which the cutting force is calculated.

As it follows from the equation (9) as well as from the Fig. 4, the more positive the rake angle, the lower the specific cutting force.

As a matter of an additional information, if we want to calculate cutting forces for drilling with a twist drill, we need to calculate the rake angle of the twist drill at the point of application of the force. This is because the rake angle changes along the cutting edge, see Fig. 5.

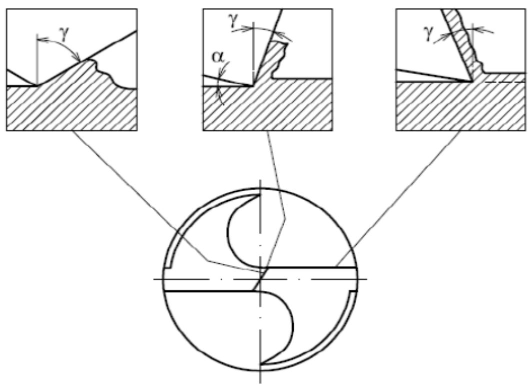

Fig. 5 *Rake angle in different positions of the cutting edge of a twist drill [31]*

Correction factor of the tool wear

It has been proven that tool wear has a considerable impact on the power or cutting force [14][16][24][25]. The impact of tool wear is also related to the primary deformation zone of the cutting process. The greater the tool wear, the higher the value of the cutting edge radius. Thus the greater the primary deformation zone, and the need for a higher specific cutting force.

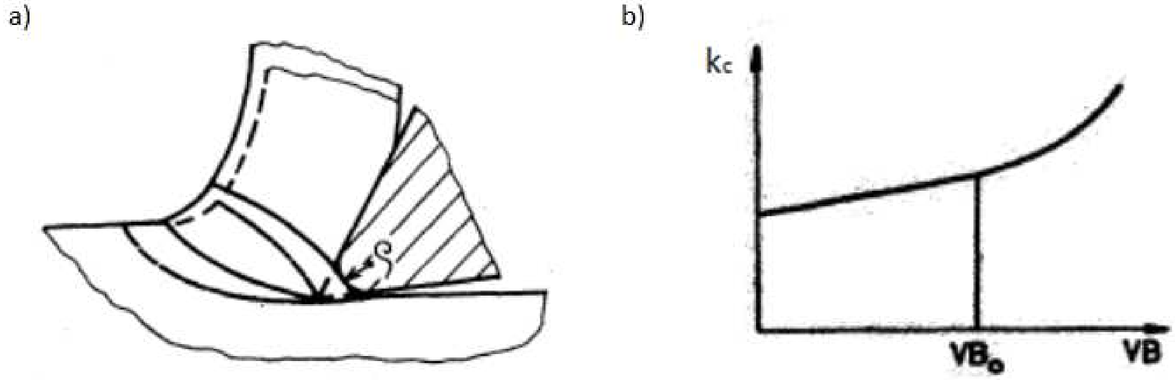

Fig. 6 a) *Dependency of the cutting edge radius on the primary deformation zone, b) Dependency of the specific cutting force on tool wear [16]*

The $k_{c1.1}$, m_c parameters are acquired by using a cutting tool with a new cutting tool insert. Thus the correction factor for the tool wear, of K_{TW}=1. As per the references [14][23][24], the correction factors for the tool wear range from 1.3 to 1.5. This means that if the cutting tool insert is worn, the specific cutting force can be of a range that is 30% to 50% higher, than the cutting force acquired for a new cutting insert.

Correction factor of the workpiece material

The $k_{c1.1}$, m_c parameters are acquired for a workpiece material with a specified hardness HB or a specified tensile strength. For each workpiece material, in addition to the $k_{c1.1}$, m_c parameters, a value of hardness and/or tensile strength is usually available from catalogues or technical literature. If we want to calculate cutting forces for the same type of workpiece material, as it is specified in a catalogue, but for different hardness or tensile strength than in the catalogue, it is necessary to use the correction factor for the workpiece material - K_{WM}.

As per the references [16][18][22], the correction factor of the workpiece material for steels is defined by the ratio between the tensile strength specified in the catalogue and tensile strength for which we calculate the specific cutting force, see equation (10). The exponent n, located in the same equation, is in a range of 0.4 to 0.7. The correction factor of the workpiece material for cast irons is defined by the ratio between the hardness specified in the catalogue and hardness for which we calculate the specific cutting force, see equation (11). The exponent r, located in the same equation, is in a range of 0.3 to 0.7.

$$K_{WM} = \left(\frac{R_{m1}}{R_{m2}} \right)^n \tag{10}$$

$$K_{WM} = \left(\frac{HB_1}{HB_2} \right)^r \tag{11}$$

Correction factor of the cutting environment

The use of a coolant also has an appreciable impact on the specific cutting force. As per the references [16][24], the specific cutting force may be 5 – 15 % lower, when using a coolant in comparison to cutting without a coolant (dry machining). The magnitude of the impact depends on the composition and the properties of the coolant. Because the kc1.1, mc parameters were acquired from dry machining, the correction factor for dry machining is K_{CEn}=1. When using a coolant, we can use the correction factor K_{CEn}=0.9.

3. Software application proposal

The primary aim of this article is to propose a software application that will be able to predict the cutting force effects. Thus the reason that I analysed the modelling method for the cutting force effects, described in chapter 2. However, this is only the first step. The final version of the application will be able to evaluate the cutting process from three perspectives, and not exclusively from the perspective of the cutting force effects. The three perspectives are:

- cutting force effects,
- economic,
- productivity.

From the perspective of the cutting force effects, from knowing the cutting force Fc, we can also predict a specific cutting energy and cutting power/torque. The specific cutting energy is an important parameter for companies due to its effect on the final price for a product. The cutting power/torque is important to know in order to predict the spindle load. These calculated parameters can be shown in characteristics of the selected machine tool, see Fig. 7.

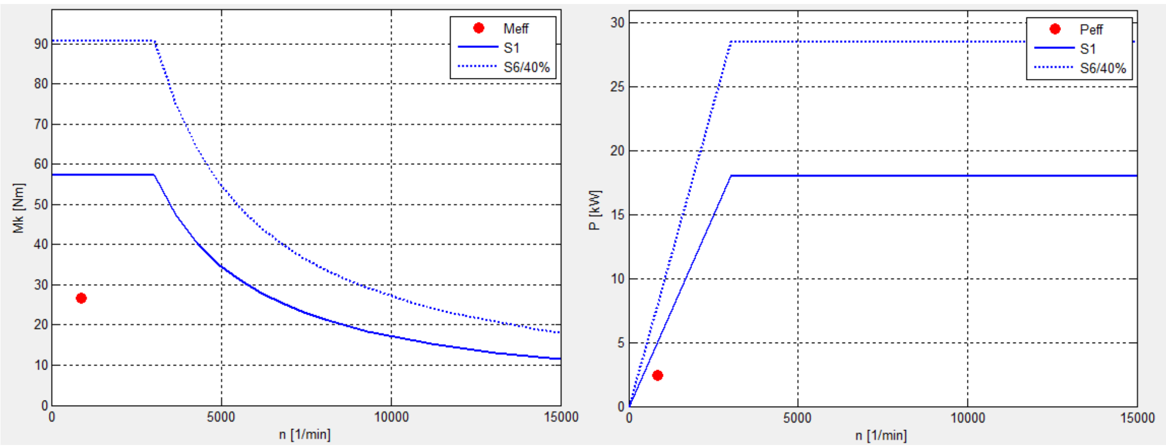

Fig. 7 *Characteristics of a selected machine tool: a) torque characteristic, b) power characteristic*

From the perspective of productivity, it is important to remove the greatest amount of material in the shortest period of time, yet achieve the same or better quality of surface for the workpiece. Thus the parameters that will be calculated by the application are:

- material removal rate (MRR) – the volume of material removed per minute,
- machine time – the time that a machine is actually processing an item,
- secondary machine times.

The final perspective is an evaluation of how economic the cutting process will be. The parameters that will be calculated by the software application from this perspective are:

- price per operation,
- price per hour.

In Fig. 8 you can see a basic scheme of the proposed application.

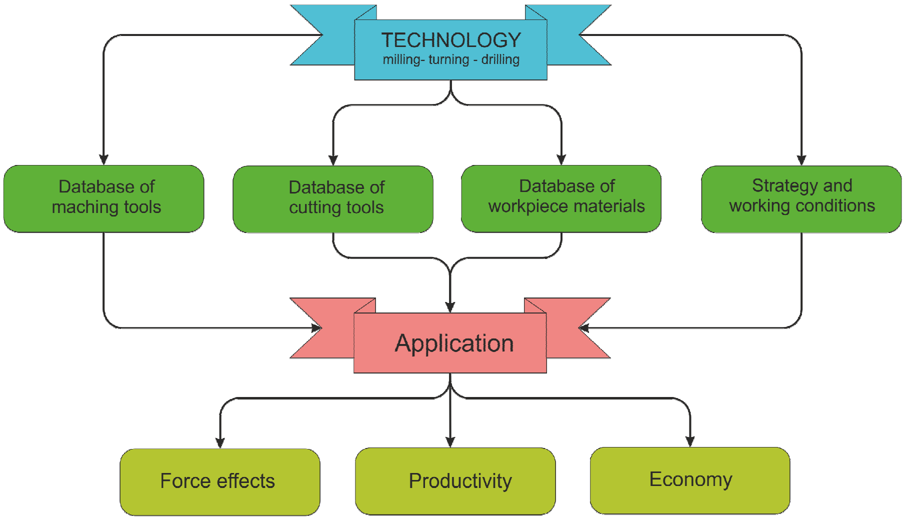

Fig. 8 *Basic scheme for the proposed software application [2]*

As per the figure above, the input parameters of the software applications are:

- a machine tool characterised by its parameters (it is selected from database of machine tools),
- a cutting tool characterised by its parameters (it is selected from database of cutting tools),
- a workpiece material characterised by its hardness or tensile strength (it is selected from database of workpiece materials),
- strategy and working conditions.

For now, with regard to the strategy for milling, there are three strategies from which to choose: full immersion, face milling (symmetrical, asymmetrical) and shouldering, see Fig. 9.

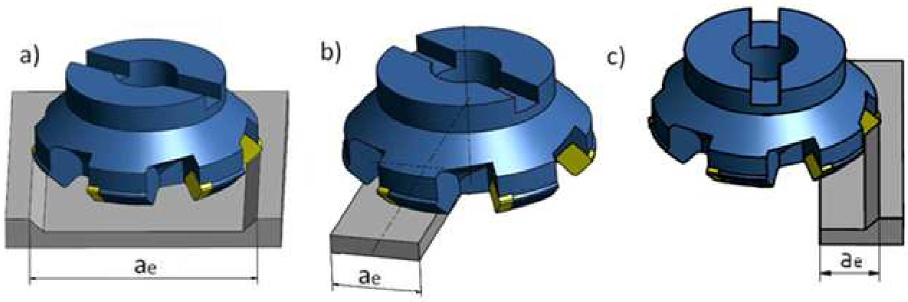

Fig. 9 *Milling by milling heads: a) full immersion, b) face milling, c) shouldering [27]*

With regard to the strategy for turning and again for now, there are two strategies from which to choose: longitudinal turning, grooving/parting off, see Fig. 10.

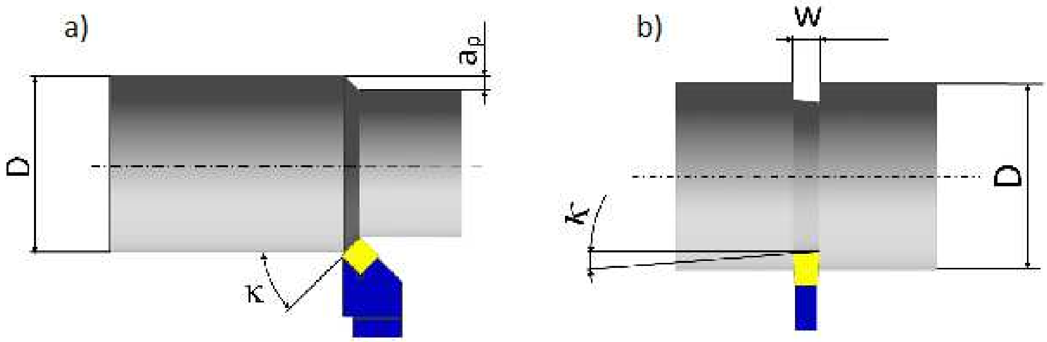

Fig. 10 *a) Longitudinal turning, b) Grooving/Parting off [28]*

In the Fig. 11 you can see a main window of the proposed software application for milling created in Matlab.

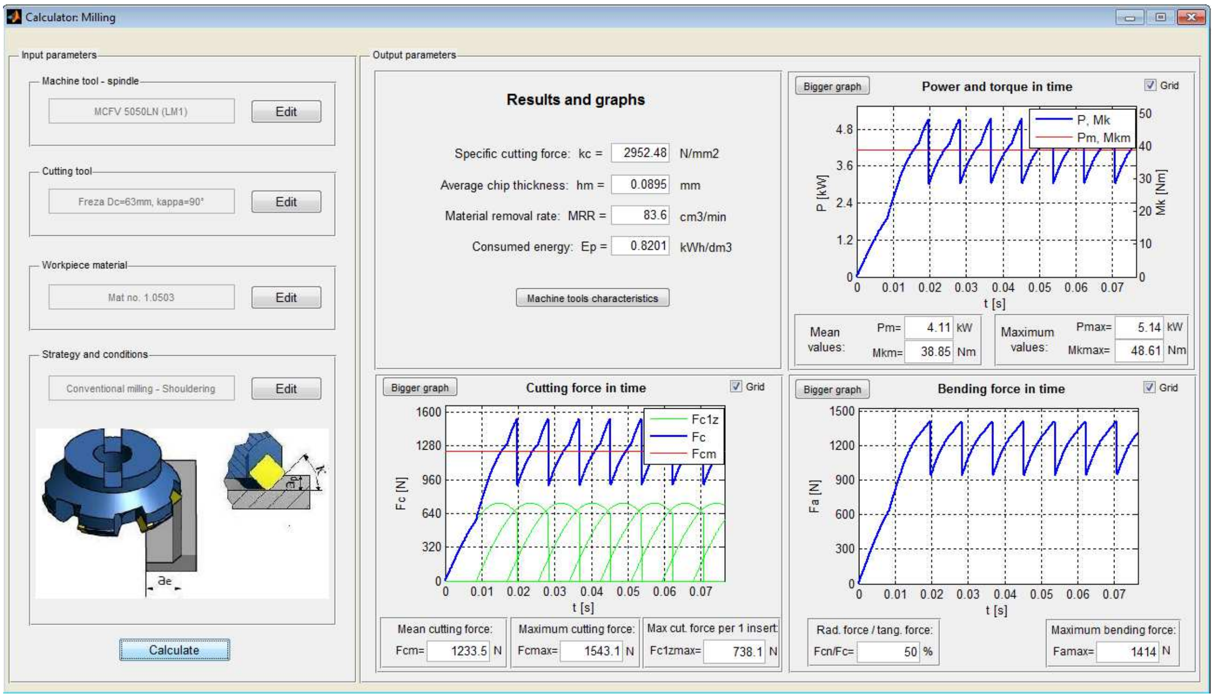

Fig. 11 *Main window of the proposed software application for milling*

In Fig. 12 you can see a main window of the proposed software application for drilling created in Matlab.

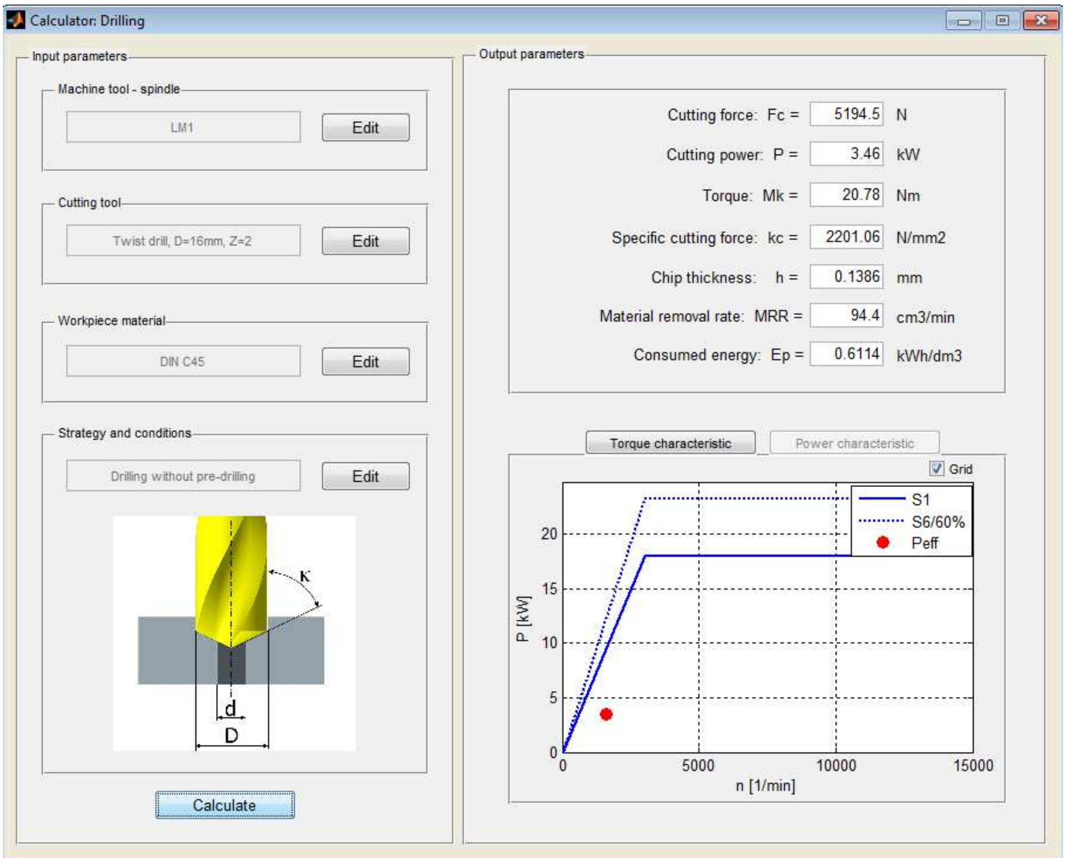

Fig. 12 *Main window of the proposed software application for drilling*

4. Summary and conclusion

In order to evaluate the cutting process from the perspective of cutting force effects, productivity and economics, I have decided to create a software application. The essential requirements for the software application are the speed of calculation for the output parameters, universality and simplicity. In this article, I exclusively focus on the perspective of the cutting force effects. The main output is the cutting force, which is why it is necessary to focus on its prediction.

In order to fulfil the requirements mentioned above, I chose a modelling method of cutting force effects based on a specific cutting force. This method is described in chapter 2. The main advantage of this method is the fact that the specific cutting force is calculated by using the workpiece parameters ($k_{c1.1}$, m_c) which are specified in catalogues provided by manufacturers of cutting tools, as well as in a variety of technical literature. Thus it is not necessary to perform a variety of expensive experiments, in order to discover the workpiece constants, as it is for alternative methods (modelling the geometric ratios of cutting tool engagement, cutting process modelling based on empirical data, etc.).

The basic formula for a specific cutting force is defined as a function of an undeformed chip thickness, see equations (4), (5), (6). This basic formula may be improved by implementing correction factors. The workpiece parameters were acquired via the process of longitudinal turning, with a new cutting tool insert with a specified rake angle, without the use of cutting fluid, on a workpiece material with a specified hardness (or a specified tensile strength). Thus it is possible to improve the basic formula by implementing the correction factors for the workpiece material, rake angle, tool wear and cutting environment.

As per the software application proposal, three technologies will be implemented: milling, turning and drilling. The calculation of the cutting force effects will be based on the already described method. As for the input parameters, there will be databases of machine tools, cutting tools and workpiece materials from which it will be possible to select the required items, for the proposed machining operation. As for the output parameters, there are three types of outputs: cutting force effects, productivity and economy. From knowing the cutting force Fc, we can predict the specific cutting energy and power/torque. The specific cutting energy is an important parameter, since it has an impact on the final price for a product. The cutting power/torque is the parameter via which the spindle load may be predicted. From the perspective of productivity, it is important to know the material removal rate, machine time and secondary machine times. This is because there is a demand to remove the greatest amount of material in the shortest period of time, yet achieve the same or better quality of surface finish, for the workpiece. As for the final perspective, the economic perspective, there will be two prices: a price for an operation and a price per hour.

Terminology

b	width of cut	(mm)
h	chip thickness	(mm)
HB_1	hardness of the cast iron for which the cutting force is calculated	(HB)
HB_2	hardness of the cast iron of the workpiece material from the catalogue	(HB)
F_c	cutting force	(N)
F_f	feed force	(N)
F_p	passive force	(N)
k_c	specific cutting force	($N.mm^{-2}$)
k_f	specific feed force	($N.mm^{-2}$)
k_p	specific passive force	($N.mm^{-2}$)
$k_{c1.1}$	specific cutting force, b=h=1mm	($N.mm^{-2}$)

$k_{f1.1}$	specific feed force, b=h=1mm	(N.mm^{-2})
$k_{p1.1}$	specific passive force, b=h=1mm	(N.mm^{-2})
K_{γ}	correction factor of the rake angle	(1)
K_{vc}	correction factor of the cutting speed	(1)
K_{TW}	correction factor of the tool wear	(1)
K_{CTM}	correction factor of the cutting tool material	(1)
K_{WM}	correction factor of the workpiece material	(1)
K_{CEn}	correction factor of the cutting environment	(1)
m_c	exponent of the specific cutting force	(1)
m_f	exponent of the specific feed force	(1)
m_p	exponent of the passive force	(1)
R_{m1}	tensile strength of the steel for which the cutting force is calculated	(MPa)
R_{m2}	tensile strength of the steel of the workpiece material from the catalogue	(MPa)
γ_0	rake angle of the cutting tool which was employed for the experiment from which the $k_{c1.1}$ and m_c parameters were acquired	(°)
γ_{act}	rake angle of the cutting tool for which the cutting force is calculated	(°)

References

[1] BRYCHTA, J. *Nové směry v progresivním obrábění*. Ostrava: Ediční středisko VŠB – TUO, 2007. ISBN 978-80-248-1505-3.

[2] KOVALČÍK, J. *Modelování řezného procesu*. Kritická rešerše. ČVUT Praha. 2014.

[3] ZEMAN, P., MÁDL, J.: *The Effect of High Cutting Speed on the Chip Formation Process*. 8th CIRP International Workshop on Modeling of Machining Operations, The University of Warwick, 2005, ISBN 3-937524-24-X.

[4] ZEMAN, P.: *The Effect of Cutting Speed on the Chip Formation Process*. 17th CFM Conference 2005, Université de Technologie de Troyes, 2005.

[5] ZEMAN, P., MÁDL, J.: *Experimental and Simulation Study of Cutting Speed Effect on the Chip Formation Process with a view to the Plastic Flow*. MATAR PRAHA 2004 - Proceedings of Sections 2,3,4: Forming machines and forming production systems Industrial robots and automation Machining and forming processes, Společnost pro obráběcí stroje, 2004, ISBN 80-903421-4-0.

[6] ZEMAN, P. *Experimentální a simulační výzkum vlivu řezné rychlosti na proces tvorby třísky se zaměřením na plastické deformace obráběcího materiálu*. Dissertation. Praha: ČVUT Praha, 2005.

[7] ZEMAN, P.; MÁDL, J. *Simulace deformací v obrobku softwarem AdvantEdge 3.6*. Strojírenská technologie. Ročník VII, prosinec 2002, č. 4. ISSN 1211-4162.

[8] ROUD, P. *Metody zefektivnění konstrukce řezných nástrojů*. Dissertation. Plzeň: ZČU Plzeň, 2013, 81 s.

[9] ZEMAN, P. *Experimentální a simulační výzkum vlivu řezných podmínek na silové jevy při HSC obrábění*. ČVUT Praha. 2007. 36 s. Výzkumná zpráva V-07-001.

[10] CHILDS, T.; MAEKAWA, K.; OBIKAWA, T.; YAMANE, Y. Metal Machining – Theory and Applications. ISBN 0-340-69159-X.

[11] Third Wave Systems. Webpage: www.thirdwavesys.com

[12] ALTINTAS, Y. *Manufacturing automation: metal cutting mechanics, machine tools vibrations, and CNC design*. New York: Cambridge University Press, 2000, 286 s. ISBN 05-216-5973-6.

[13] MUZIKA, Č. *Modelování řezných sil při soustružení*. Diplomová práce. Praha: ČVUT, 2013.

[14] DEGNER, Werner; LUTZE, Hans; SMEJKAL, Erhard. *Spanende Formung: Theorie – Berechnung – Richtwerte. 16. Aktualisierte Auflage*. ISBN 978-3-446-41713-7. Germany 2009.

[15] VÁŇA, J; ZEMAN, P. *Model pro výpočet velikosti silových parametrů řezného procesu*. ČVUT Praha. 2011. 66 s. Výzkumná zpráva V11-080.

[16] MÁDL, J. *Teorie obrábění*. Praha: ČVUT Praha, 1989. 156 s.

[17] ZEMAN, P.; FOJTŮ, P. *Výzkum řezného procesu*. ČVUT Praha. 2010. 68s. Výzkumná zpráva V10-083.

[18] GAZDA, J. Teorie obrábění. Řezné síly při obrábění. Liberec: VŠST Liberec, 1993.

[19] VASILKO, K; MÁDL, J. *Teorie obrábění – 1. díl*. Univerzita J. E. Purkyně v Ústí nad Labem. 298 s. ISBN 978-80-7414-459-2.

[20] ČEP, P; PETRŮ, J. *Experimentální metody v obrábění – učební texty*. Technická Univerzita Ostrava, 2011. 143 s.

[21] KOCMAN, K.; PROKOP, J. Speciální technologie obrábění – řešené příklady. VUT Brno 2003.

[22] VASILKO, K. *Analytická teória trieskového obrábania*. ISBN 978-80-8073-759-7. 2007. Prešov.

[23] KOCMAN, K. Technologické procesy obrábění. Univerzita Tomáše Bati, Brno 2011. ISBN 978-80-7204-722-2. 330 s.

[24] GROTE, H.; ANTONSSON, ERIK K. Springer Handbook of Mechanical engineering. ISBN 978-3-540-49131-6. 1576 s.

[25] TSCHATSCH Heinz. *Applied Machining Technology*. Springer. 2009. ISBN 978-3-642-01006-4.

[26] Production Technology, 1000 s, Publisher: McGraw-Hill Education, ISBN-10: 0070964432, ISBN-13: 978-0070964433.

[27] BRAJER, J.; KOVALČÍK, J.; MÁCA, O.; MALÝ, J.; MAŠEK, P.; ZEMAN, P. Problemabika obrábění těžkoobrobitelných, kompozitních, případně dalších materiálů a návrh způsobu hodnocení produktivity a hospodárnosti obrábění. ČVUT Praha. 2012. Výzkumná zpráva V-12-037.

[28] KOVALČÍK, J. ZEMAN, P. *Vývoj software pro podporu návrhu technologie obrábění a jejího hodnocení*. ČVUT Praha. 107 s. Výzkumná zpráva V13-048.

[29] KOVALČÍK, J; HOLKUP, T.; VYROUBAL, J.; SMOLÍK, J. *Ecodesign OS – predikce obráběcích sil a výkonů*. ČVUT Praha. 2011. 44 s. Výzkumná zpráva V13-049.

[30] KUBERA, T. *Modelování energetické náročnosti řezného procesu*. Diplomová práce. ČVUT Praha, 2012.

[31] HON, P. *Analýza řezných sil při vrtání šroubovitým vrtákem*. Bakalářská práce. VUT Brno 2009.

[32] Complete machining solutions: rotating tools. ISCAR. 2008.

[33] *Technická příručka*. Sandvik Coromant. 2010. Dostupné z http://www.sandvik.coromant.com

[34] HUMÁR, A. *Technologie obrábění - 2. část: Studijní opory pro magisterskou formu studia*, Brno: VUT v Brně, 2004.

[35] PETROPOULOS, G.; NTZIANTZIAS, I.; ANGHEL, C. *A predictive model of cutting force in turning using Taguchi and response surface techniques*. 1st International Conference on Experiments/Process/System Modelling/Simulation/Optimization. Athens, 6-9 July, 2005.

[36] MEYER, R.; KOHLER, J.; DENKENA, B. *Influence of the tool corner radius on the tool wear and process forces during hard turning*. Springer, 2011. International Journal of Advanced Manufacturing Technology. ISSN: 1433-3015.

[37] VELCHEV, S.; KOLEV, I.; IVANOV, K. *Empirical mathematical models of the dependence of the specific cutting force on thickness of cut in turning*. Annals of Faculty of Engineering Hunedoara – International Journal of Engineering Tome IX, 2011. Fascicule 3. ISSN 1584-2673.

[38] SAGLAM, H.; SULEYMAN, Y.; UNSACAR, F. *The effect of tool geometry and cutting speed on main cutting force and tool tip temperature*. Materials and design 28, 2007. Dostupné na www.sciencedirect.com.

[39] DENKENA, B; TRACHT, K; CLAUSEN, M. *Predictability of milling forces based on specific cutting forces*. 8th CIRP International Workshop on Modeling of Machining Operations. May 10-11, 2005. Chemnitz, Germany. ISBN 3-937524-24-X.

[40] SANDVIK COROMANT. *Příručka obrábění – kniha pro praktiky*. Nakladatelství Scentia 1997. ISBN 91-97 22 99-4-6.

[41] SANDVIK COROMANT. Technická příručka. 2012. Dostupné z: http://www.rpb.cz/katalog_sandvik_coromant

[42] STAHL, J-E. Metal Cutting – Theories and models. Seco tools, 2012. 580 s.

[43] Iscar. Machining Power Aplikace [Online]. Dostupné z http://mpwr.iscar.com/machiningpwr/machiningpower.wgx

[44] Sandvik Coromant. „Calculator for power and torque“ aplikace [Online]. Dostupné z http://www2.coromant.sandvik.com/coromant/calculators/aero/power_torque/index.htm