# Cutting force effects modelling and spindle load prediction for milling technology

Ing. Jaroslav Kovalčík

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

***Abstract***

*The machining process is quite complicated and it is influenced by many different parameters and some of them are often not univocally defined. Therefore it is quite intricate to carry out the machining process modelling, or more precisely, it is difficult to carry out the exact prediction of the main parameters, such as cutting forces, temperature, chip shape, durability of the cutting tool, etc. In order to reach the maximum concordance of the modelling parameters with the experimentally evaluated values, it would be necessary to catch all the aspects of the mutual interaction of the cutting tool, workpiece, machine tool and cutting fluid. That is, however, not practically possible even because we usually do not know any details of the individual aspects in the instant moment, such as, for example, the real shape and state of the cutting tool edge, mechanical properties of the workpiece material, etc. Therefore, the modelling methods will always be just a simplification of the real machining process. The usability of a specific modelling method will primarily depend on the accuracy of the applicable results with the combination of the calculation speed. In order to evaluate cutting force effects and spindle load prediction, I have decided to create a software, which will help technologists in practice to choose appropriate types of machine tools, cutting tools, operations and also quickly determinate the main parameters of the cutting process.*

***Keywords***

*modelling, cutting forces, machining, specific cutting force, spindle load*

## 1. Introduction

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 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 is the speed of calculation for the output parameters, and also universality, simplicity and perhaps most importantly, without costly and time-consuming experiments. In this article, I exclusively focus on the perspective of the cutting force effects. The main output is the cutting force, which is the reason why it is necessary to focus on its prediction.

## 2. Cutting force effects modelling based on the specific cutting force

There is a various number of modelling methods to predict the machining process from the cutting force effects point of view, such as: FEM modelling and material modelling, modelling the geometric ratios of the engagement of the cutting tool, modelling based on empirical data and modelling based on a specific cutting force, see references [1] - [23].

With regard to the fact that I want to create the software application and the requirements mentioned above, I have decided to choose the modelling method based on a specific cutting force $k_c$.

This modelling method is described and/or applied in the references [8] - [19]. 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.). Among the main advantages is also the fact that this method is applicable on more technologies (milling, drilling, turning, boring) by using the same empirical coefficients.

The cutting force $F_c$ is calculated by the multiplication of the specific cutting force $k_c$ and the cross-section area $A$, see equation (1). If we want to know the specific cutting force $k_c$, we have to use the same equation and get them from the experimental values of the mean cutting forces.

The workability of the cross-section area depends on the cutting technology (milling, drilling, turning), on the geometry of the cutting tool (lead angle, rake angle, nose radius, helix angle), and on the shape of the cutting tool insert (square, round, triangle).

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

The basic equations of the specific forces for all types of forces ($F_c$, $F_f$, $F_p$) is a dependency of the specific force on an unreformed chip thickness, see equations (2), (3), and (4).

$$k_c = k_{c1.1} \cdot h^{-m_c} \cdot K \tag{2}$$

$$k_f = k_{f1.1} \cdot h^{-m_f} \cdot K \tag{3}$$

$$k_p = k_{p1.1} \cdot h^{-m_p} \cdot K \tag{4}$$

There is also a correction factor $K$, which is a function of variety of factors which have the influence on the specific cutting process, such as: the correction factor of the rake angle - $K_\gamma$, correction factor of the cutting speed – $K_{Vc}$, correction factor of the tool wear – $K_{TW}$, correction factor of the cutting tool material – $K_{CTM}$, 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 (5), references [8] – [12].

$$k_c = k_{c1.1} \cdot h^{-m_c} \cdot K_\gamma \cdot K_{v_c} \cdot K_{TW} \cdot K_{CTM} \cdot K_{WM} \cdot K_{CEn} \tag{5}$$

It is practically impossible to cover all the factors for the software application. Therefore, I have to focus on the parameters which have really huge impact on the specific cutting force. Also, when using the parameters $k_{c1.1}$, $m_c$ from catalogues of the manufactures of cutting tools, we do not have enough information to cover all the correction factors. However, from the practical point of view, it is really sufficient method and therefore it is good for using it in the software application.

## 3. Cutting force effects modelling for milling technology

To calculate the values of cutting forces (and also power, torque) in the milling technology is more complicated than to calculate these values in other technologies (turning, drilling, boring). There are many factors which we have to consider when calculating these parameters in milling, such as:

- type of the cutting tool (face milling cutter, shell-end cutter, cylindrical cutter, groove cutter, etc.),
- type of strategy depending on the cutter and its immersion into the workpiece material (fmilling head: full immersion, face milling, side milling; grooving: direct grooving, T-grooving)
- type of strategy depending on workpiece material removal – removing from the maximum value of the chip thickness to the minimum value (climb milling) and the second case, removing from the minimum value of the chip thickness to the maximum value (conventional milling),
- type of the cutting tool insert (square, triangle, round),
- geometry of the cutting tool (rake angle, helix angle, etc.),
- working conditions (depth of cut, feed per tooth, cutting speed, width of cut, etc.)
- workpiece material (its parameters of specific cutting force, hardness, tensile strength).

In this article I focus on milling by milling head. As it was mentioned above, there are three types of milling strategy depending on the immersion of the cutting tool into the workpiece material (full immersion, face milling and side milling), see Fig. 1.

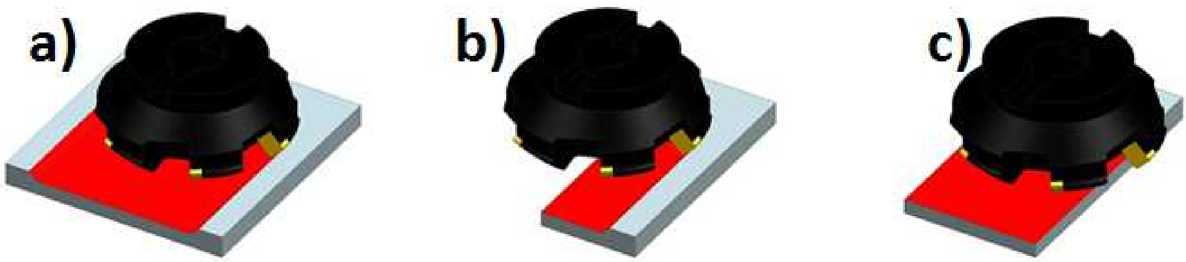


***Fig. 1*** *Milling by milling head: a) full immersion, b) side milling, c) face milling.*

To calculate the cutting force in each of the mentioned case, we use the equation (1). If we want to calculate the mean value, we can either use the equation with the mean values of the chip thickness and cross-section area of the chip or we can calculate the actual values of the cutting force in the range of one revolution and calculate the mean value on this interval by using the same equation with the actual values of the chip thickness and cross-section area. It is better to use the second case, because we can consider many different things, such as: shimmy of the cutting edges, actual values of the cutting tool geometry which are changeable during the cutting process (rake angle).

### Chip thickness

As we can see, the first value which we have to calculate is the specific cutting force $k_c$. To calculate the actual value of the specific cutting force $k_{Ci}$, we have to use the equation (2) with the actual value of the chip thickness. This value is calculated by using the equation (6) for square, triangle inserts and by the equation (7) for round inserts [15] - [18].

$$h_i = f_Z \cdot \sin\varphi_i \cdot \sin\kappa_r \tag{6}$$

$$h_i = f_Z \cdot \int_{\varphi_{KDst}}^{\varphi_{KDex}} (\sin\varphi) d\varphi = -f_Z \cdot \sin\varphi_i \cdot \frac{\cos\varphi_{KDex} - \cos\varphi_{KDst}}{\varphi_{KDex} - \varphi_{KDst}} \tag{7}$$

The actual values of the chip thickness are calculated in the range from the starting engagement angle $\varphi_{st}$ to the ending engagement angle $\varphi_{ex}$ of the cutting process, because it is obvious that the chip thickness is zero when not cutting the workpiece material – see Fig. 2.

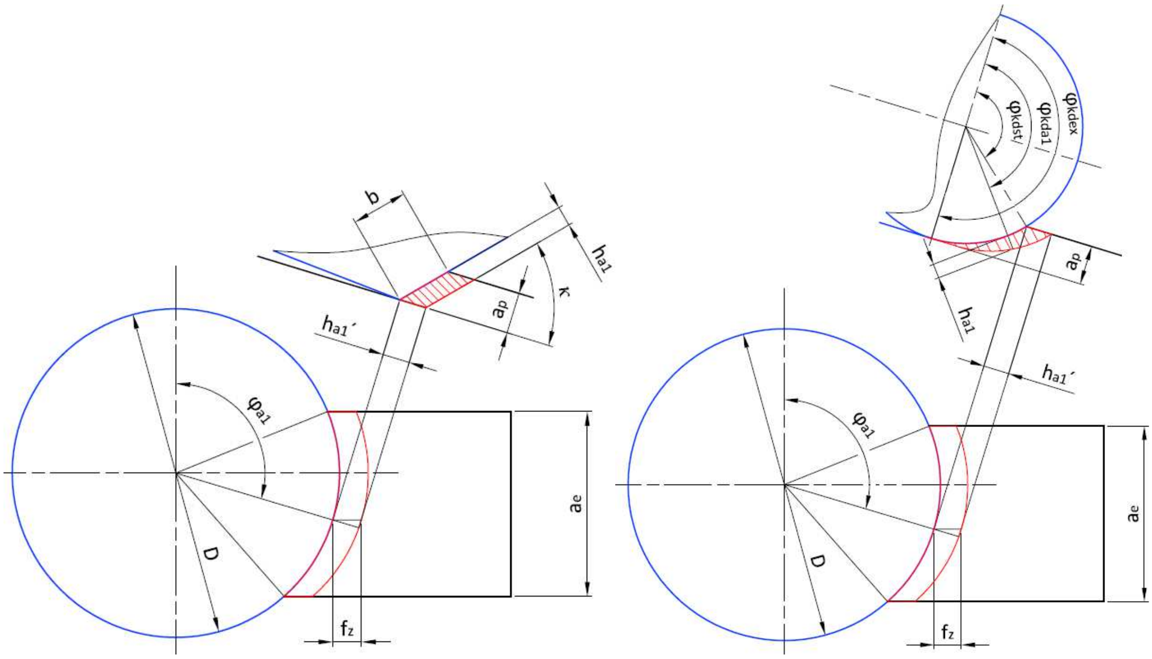


***Fig. 2*** *Face milling by milling head: a) square insert, b) round insert [18].*

As it was mentioned above, there are 3 types of strategies depending on the cutter and its immersion into the workpiece material. For each of these strategies we have to calculate the starting and ending engagement angles in order to calculate the chip thickness in this range. Also, in face milling and side milling we have to consider the climb milling and conventional milling, because the engagement angles varies depending on it. As for the full immersion (see Fig.1a), the starting engagement angle is 0° and the ending engagement angle is 180°. For the face milling (see Fig. 1c, Fig. 2), we have to calculate these angles with consideration of eccentricity for the climb milling – equation (8) and conventional milling – equation (9). In the case that the eccentricity is equal to 0 mm, it is the symmetrical face milling, in other case, it is the non-symmetrical milling.

$$\varphi_{ST-CLIMB} = a\cos\frac{\frac{a_e}{2}+e}{\frac{D}{2}} \qquad \varphi_{EX-CLIMB} = 180 - a\cos\frac{\frac{a_e}{2}-e}{\frac{D}{2}} \tag{8}$$

$$\varphi_{ST-CONV} = a\cos\frac{\frac{a_e}{2}-e}{\frac{D}{2}} \qquad \varphi_{EX-CONV} = 180 - a\cos\frac{\frac{a_e}{2}+e}{\frac{D}{2}} \tag{9}$$

For the side milling (see Fig.1b), it is also necessary to calculate these angles for the case of the climb milling – equation (10) and conventional milling – equation (11).

$$\varphi_{ST-CLIMB} = a\cos\frac{a_e-\frac{D}{2}}{\frac{D}{2}} \qquad \varphi_{EX-CLIMB} = 180^{\circ} \tag{10}$$

$$\varphi_{ST-CONV} = 0° \qquad \varphi_{EX-CONV} = 180 - a\cos\frac{a_e - \frac{D}{2}}{\frac{D}{2}} \tag{11}$$

**Chip width**

In order to calculate the cutting force $F_c$, we need to calculate the cross-section area $A$. As it is seen in the equation (12), the actual value of the cross-section area $A_i$ is a multiplication of the actual value of the chip thickness $h_i$ and the value of the chip width $b$.

$$A_i = h_i \cdot b \tag{12}$$

The chip width $b$ is not the actual value as the chip thickness $h_i$ is. To calculate this value, we can have a look at the Fig. 3.

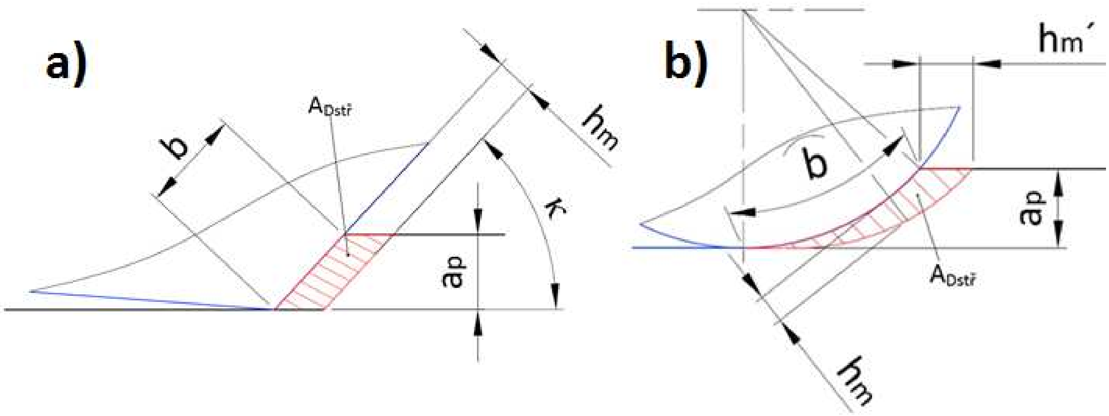


***Fig. 3*** *Chip width, mean chip thickness: a) square insert, b) round insert [18].*

The calculation of the chip width $b$ for the case of the square insert is depended on the depth of cut $a_p$ and the lead angle $\kappa_r$, see equation (13) and Fig. 3a. The chip width $b$ for the case of the round insert is calculated according to the equation (14).

$$b = \frac{a_P}{\sin \kappa_r} \tag{13}$$

$$b = \frac{\pi \cdot D_d \cdot (\varphi_{KDex} - \varphi_{KDst})}{360} \tag{14}$$

**Cutting force**

When having the actual values of chip thickness $h_i$ and the chip width $b$, we can calculate the actual value of the cutting force per one tooth $F_{C1Ti}$ in the interval of one revolution, see equation (15). Finally we can calculate the actual value of the total cutting force for all the cutting edges in the engagement $F_{Ci}$ in the range of one revolution, see equation (16).

$$F_{C1Ti} = k_{Ci} \cdot A_i \tag{15}$$

$$F_{Ci} = \sum_{i=1}^{Ze} F_{C1Ti} \tag{16}$$

The mean value of the total cutting force can be calculated by the mean value of all the actual values of the cutting forces in the range of one revolution.

In Fig. 4 you can see all three cutting forces: the actual values of the cutting force per one tooth, the actual values of the total cutting force and the mean value of the cutting force.

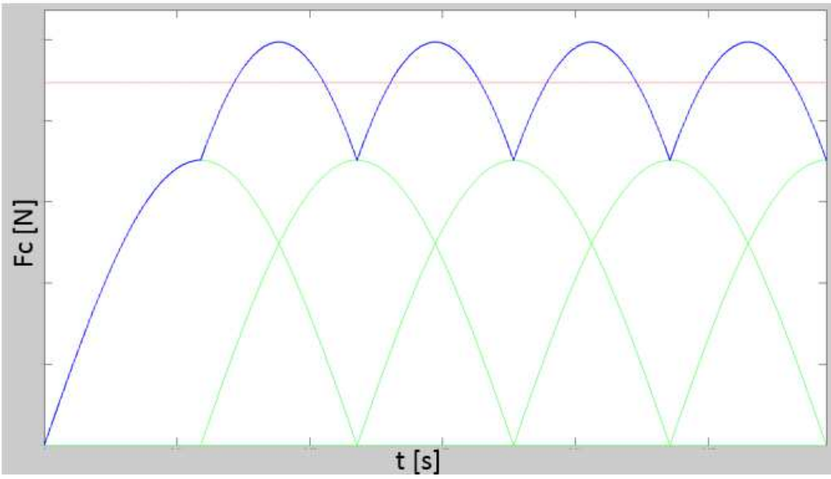


***Fig. 4*** *Cutting force in time.*

## 4. Method for the prediction of spindle load for milling technology

The dependence of the allowed torque and power of a specific spindle is possible to demonstrate by using the power and torque characteristics in the whole range of the revolutions of the specific spindle, see the Fig. 5.

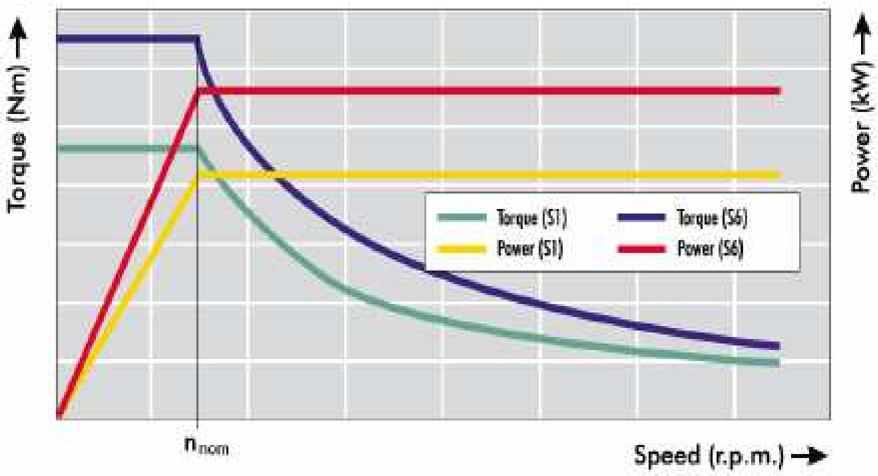


***Fig. 5*** *Power and torque characteristic of a spindle [24].*

In order to predict the spindle load, we need to calculate the torque and power for the specific conditions (workpiece material, cutting conditions, cutting tool, and cutting environment) and put it into the torque and/or power characteristic. The manufactures of the spindles use the standard ČSN EN 60034-1 according to which there are 10 types of the load [25]. In order to calculate the torque and/or the power, we need to predict the cutting force $F_c$, which is, as it has been proven, the only one force of the machining process which has the impact on the spindle load.

From the point of view of the contact of the cutting tool with the workpiece, there are two types of milling process – continuous and discontinuous, see the Fig. 6.

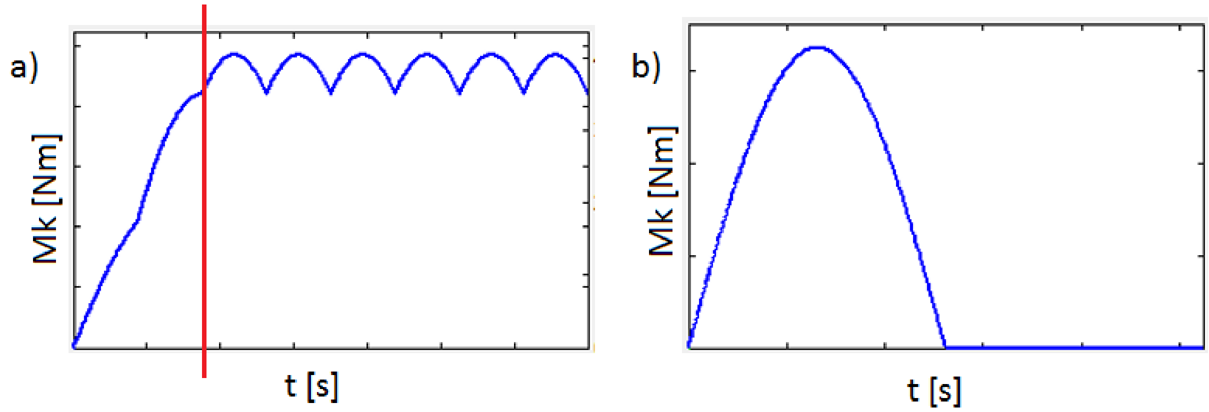


***Fig. 6*** *Dependence of the torque on the time: a) continuous cutting, b) discontinuous cutting [16].*

**4.1 Continuous cutting**

As it is seen in Fig. 6a, the cutting tool gradually runs from the zero value to the full engagement, in which all the teeth cut the workpiece material. Then the torque starts to vary between the maximum and minimum values and it does not fall to the zero value. Therefore, it is a case of the continuous cutting process with the periodical variable values and the required torque, which we want to know, is called the effective torque $M_{Keff}$ (or effective power $P_{eff}$). The approach is therefore that the continuous cutting is converted to the permanent load with the constant value of the torque – $M_{Keff}$. This type of the load is therefore the S1 load which is mentioned in the standard ČSN EN 60034-1. On the Fig. 7 you can see an example of the substitution of the variable torque by its effective value $M_{Keff}$ [16][24].

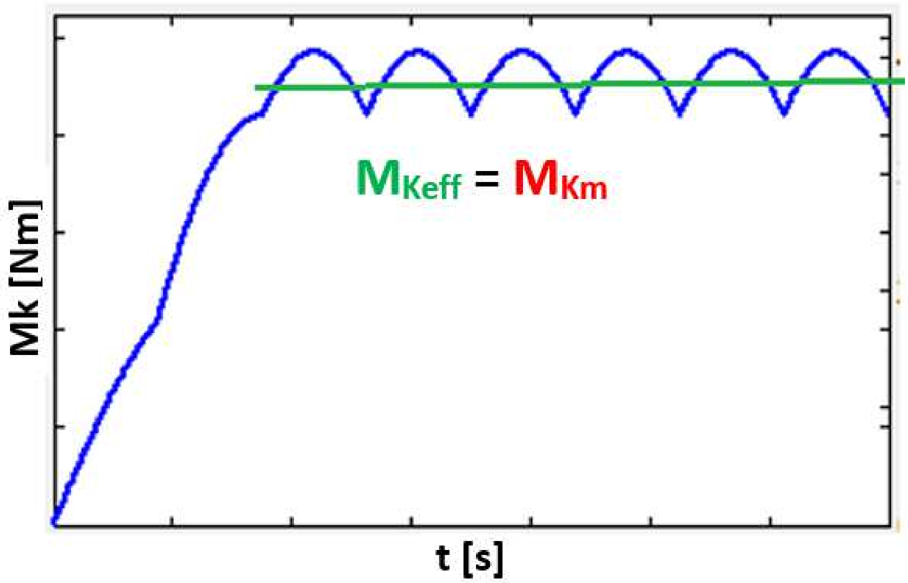


***Fig. 7*** *Effective torque for the continuous cutting [16].*

If we want to calculate the value of the effective torque $M_{Keff}$ for the case of the permanent load, we have to calculate the mean value of torque $M_{Km}$ which is, in this case, equal to the effective torque $M_{Keff}$. This torque can be can put into the torque characteristic of the selected spindle. In Fig. 8 you can see an example of the calculated value of the effective torque and power in the characteristics of the machine tool MCFV 5050 LN (spindles values: nominal revolutions 3000 rev/min, maximum revolution 15000 rev/min, maximum torque 57,3 Nm).

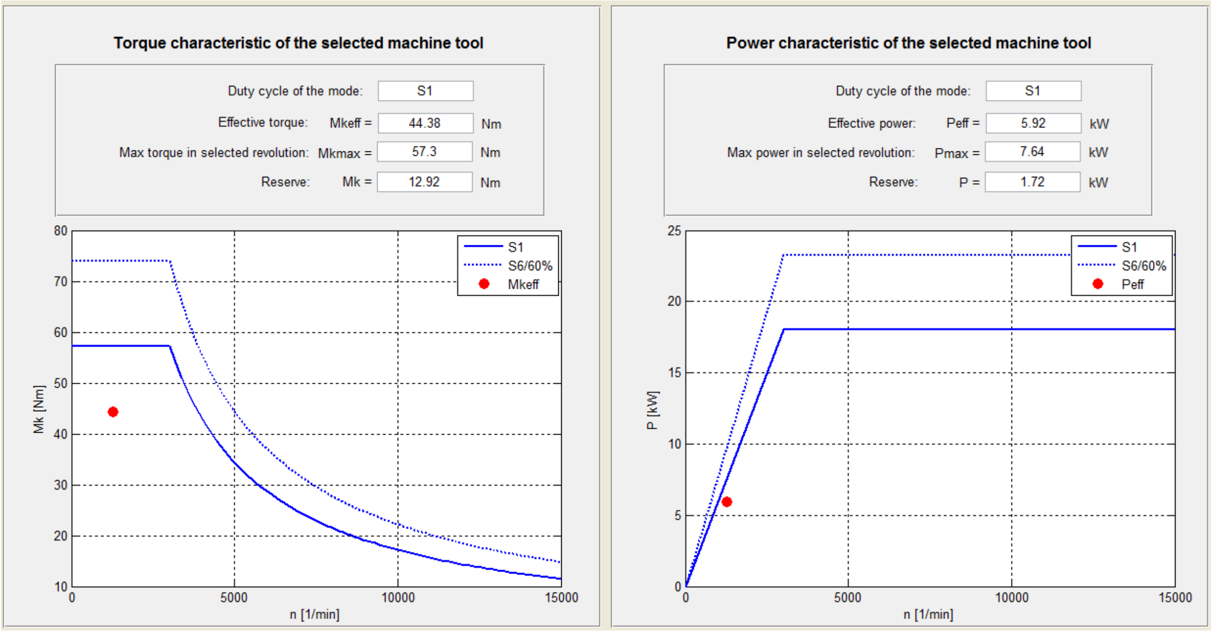


***Fig.8*** *Effective torque and power in the characteristics of the machine tool MCFV 5050 LN.*

As you can see, there might be a case where the effective torque is under the torque characteristic and the case in which the effective torque is below the torque characteristic. It is necessary to reach the case that the effective torque is below the torque characteristic. We can do that, for example, by changing some of the cutting condition parameters.

### 4.2 Discontinuous cutting

The second type of cutting process in the milling technology is the discontinuous cutting. It is the case when the cutting tool is in the engagement and cuts the workpiece material (it has non-zeros values of torque) and when it is out of the engagement, it does not cut anything and therefore it has zeros values of the torque. This process is continuously the same. This type of the load is therefore the S6 load which is mentioned in the standard ČSN EN 60034-1. In Fig. 9 you can see an example of full immersion milling (the engagement angle is 180°) in the range of one revolution.

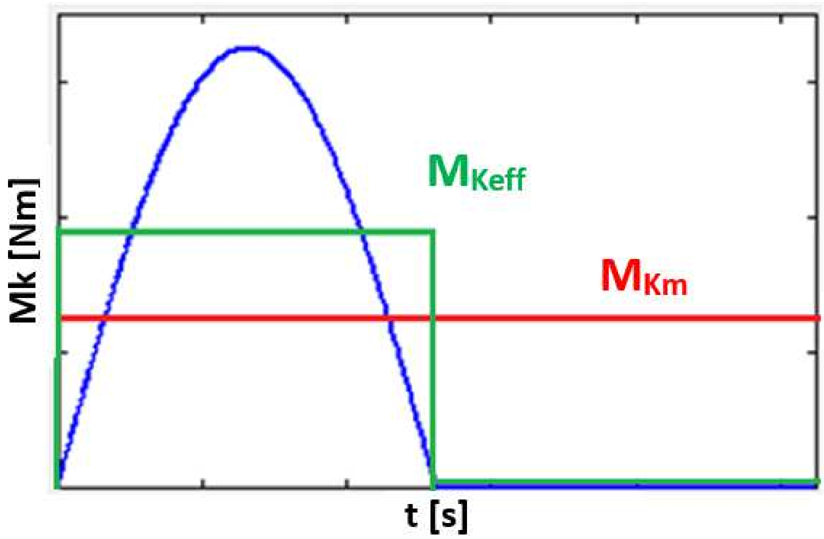


***Fig. 9*** *Effective and mean torque for the discontinuous cutting in the range of one revolution [16].*

In this case, the effective torque $M_{Keff}$ is different than the mean torque $M_{Km}$. As you can see in Fig. 5, there are the both types of torques – the mean torque $M_{Km}$ which is the mean value in the range of one revolution, and secondly, there is the effective torque $M_{Keff}$, which we need for the spindle characteristics. The effective torque, in this case, is the mean value of the area where the cutting tool cuts the material.

## 5. Summary and conclusion

The aim of this article was to introduce a theoretical model which predicts the cutting force effects and spindle load for milling technology. This model was made for the purpose of creating a software application which would be used by technologist. The requirements for the software application is the speed of calculation of the output parameters, universality and simplicity. In order to fulfil the requirements I have decided to choose the modelling method based on a specific cutting force which is described in the chapter 2. This method is quite universal because it is possible to use the same empirical coefficients for different technologies with defined geometry of the cutting tool (milling, drilling, turning, boring).

In the chapter 3 I focus on the cutting force modelling method based on the specific cutting force for the milling technology. The basic equation for the cutting force prediction is based on a multiplication of the cross-section area and the specific cutting force. Step by step I introduce this method for different strategies of milling. The strategies varies depending on the cutter's immersion into the workpiece material (full immersion, face milling, side milling). From the point of view of the workpiece material removal, there might be a climb milling and conventional milling.

In the chapter 4 I focus on the prediction of a spindle load. For the prediction of the spindle load it is important to know the cutting force which is, as it has been proven, the only one force of the machining process, which has the impact on the spindle load. By modelling the actual values of the cutting force we can calculate the actual values of the torque and power which are used in the spindle load prediction in a way that from them we obtain the effective torque or/and power which are afterwards put into the torque or/and power characteristics. The calculation of the effective torque or/and power depends on the milling process from the point of view of the contact of the cutting tool with the workpiece (continuous and discontinuous cutting). For the continuous cutting, there is used the S1 load and for the discontinuous cutting, the S6 load. The both loads are mentioned in the standard ČSN EN 60034-1.

There are many different ways how to improve the modelling method. The first way is to improve the calculation of the specific cutting force by implementing correction factors, such as correction factor for rake angle, cutting environment, workpiece material, cutting speed, cutting tool edge's durability, etc. Secondly, the improvements can be made by the calculation of the cross-section area with consideration of the shimmy of the cutting edges, actual values of cutting tool geometry (rake angle which is changeable during the cutting process) and also consideration of the helix angle.

### *Terminology*

| | | |
|---|---|---|
| $A$ | cross-section area | $(mm^2)$ |
| $A_i$ | actual value of the cross-section area | $(mm^2)$ |
| $a_e$ | depth of cut | (mm) |
| $a_p$ | width of cut | (mm) |
| $b$ | chip width | (mm) |
| $D$ | cutting tool diameter | (mm) |
| $D_d$ | cutting tool insert diameter | (mm) |
| $f_Z$ | feed per tooth | (mm) |

| | | |
|---|---|---|
| $h$ | chip thickness | (mm) |
| $h_i$ | actual value of the chip thickness | (mm) |
| $F_c$ | cutting force | (N) |
| $F_{Ci}$ | actual value of the cutting force | (N) |
| $F_{C1Ti}$ | actual value of the cutting force per one tooth | (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 | ($N.mm^{-2}$) |
| $K$ | total correction factor | (1) |
| $K_\gamma$ | 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) |
| $\kappa_r$ | lead angle | (°) |
| $\varphi_i$ | actual value of the engagement angle | (°) |
| $\varphi_{ST}$ | starting engagement angle | (°) |
| $\varphi_{EX}$ | ending engagement angle | (°) |

***References***


[1] 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.

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

[3] 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.

[4] 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.

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

[6] 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.

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

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

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

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

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

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

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

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

[15] 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.

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

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

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

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

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

[21] 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.

[22] 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.

[23] 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.

[24] KUBEČEK, P. *Vývoj a verifikace části aplikace pro určování silového zatížení stroje při obrábění*. Diplomová práce. ČVUT Praha, 2013.

[25] ČSN EN 60034-1. Točivé elektrické stroje – Část 1: Jmenovité údaje a vlastnosti. ICS 29.160. Ed. 2. Praha: ÚNMZ, září 2011.