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Effect of Process Parameters to the Main Cutting Force in Milling

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There are many approaches to predict the average pressure acting in the cutting zone, and these are usually based on specific cutting force and the cutting resistance. Common theme for these modelling approaches is to use chip thickness to describe the uncut chip. These models are usually based on process parameters such as the depth of cut a_p, radial engagement a_e and feed per tooth f_z. The purpose of this paper is to investigate the underlying process parameters affecting the main cutting force in milling operations using the Full Factorial Design model. For this study, single-tooth climb milling with indexable carbide inserts in medium carbon steel C45E, were selected. The design, and experiment, and analysis were performed using Modde Pro. During the test, the main cutting force was measured with a dynamometer and compared with the results from the FFD model. These results revealed that the inclusion of the interaction of parameters in the model was important for the model accuracy. As expected, it also shows that any increase of a_e, a_p, and f_z will increase the main cutting force and therefore all three parameters should be included in a DoE, when modelling main cutting force in milling. In conclusion, a statistical approach can be used to calculate the main cutting force, complementing the traditional models that are based on cutting resistance and chip thickness.

Keywords: cutting forces, radial depth of cut, tool engagement, cutting force modelling.

1. INTRODUCTION

The main goal of today's manufacturing industry is to use time and resources effectively in the production of a large variety of products. Machining is a fundamental manufacturing process that involves the removal of material from a workpiece using a cutting tool [1]. The main cutting force is a critical parameter in machining, which affects the tool wear, the surface quality of the machined part, risk of vibrations and the overall machining efficiency. It is also essential to predict the machining forces when selecting a machine tool to ensure that the applicable power and torque are enough for the cutting process. Therefore, understanding and predicting force, with the factors that influence the main cutting force, is essential for optimizing any machining process [2].

Milling operations are known to be challenging due to the engagement of multiple cutting edges and varying chip thickness over the rotation of the tool, resulting in varying loads acting in the process. There are several types of milling operations, including climb milling, conventional milling, slotting and side milling, each with specific challenges [3]. Climb milling involves the rotation of the tool against the feed direction, while conventional milling involves the rotation of the tool with the feed direction. Side milling is a variation of milling used to create narrow slots or shapes in the workpiece [4]. A descriptive picture of a) climb milling and b) conventional milling is in Fig. 1. Several approaches can be used to predict the average pressure acting in the cutting zone, expressed in units of N/mm². The most commonly used models are based on the specific cutting force introduced by Kienzle [2] and the cutting resistance as defined by Hök [3] and Ståhl [4].

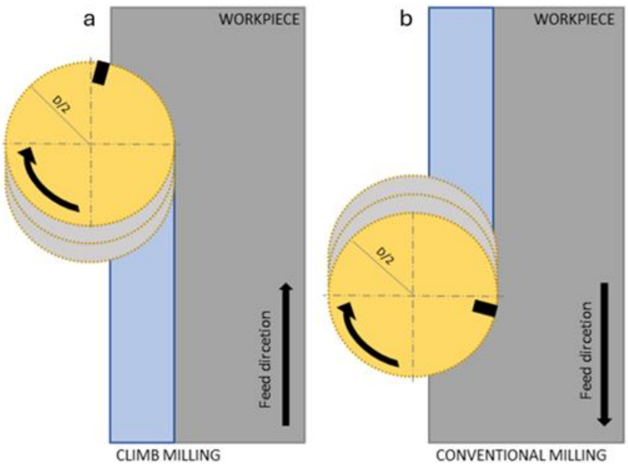

Fig. 1. Direction of the cut when using: a – climb milling; b – conventional milling

Both the cutting resistance (C_r) and specific cutting force (k_c) are defined as the force required per unit area of the chip. The two most widely used models for describing or calculating the cutting pressure are those formulated by Kienzle [2] and Woxén-Johansson [1], [5] as presented in Eq. 1 and Eq. 2, respectively. More recently, Hägglund [6] proposed an expanded version of the Woxén-Johansson model as shown in Eq. 3, referred to herein as the extended Woxén-Johansson model.

$$k_c = k_{c1.1} \cdot h_1^{-m_c}; \quad (1)$$

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$$C_r = \frac{F}{h_1 \cdot b_1} = C_{r_1} + \frac{C_{r_2}}{h_1}; \tag{2}$$

$$h_e = \begin{cases} \dfrac{a_p f}{r_\varepsilon \arccos\left(\frac{r_\varepsilon - a_p}{r_\varepsilon}\right) + \frac{f}{2}} & \text{for pointed inserts if } a_p \le r_\varepsilon(1 - \cos\kappa_r) \\ \dfrac{a_p f}{\frac{a_p - r_\varepsilon(1-\cos\kappa_r)}{\sin\kappa_{re}} + r_\varepsilon \kappa_r + \frac{f}{2}} & \text{for pointed inserts otherwise} \end{cases} . \tag{3}$$

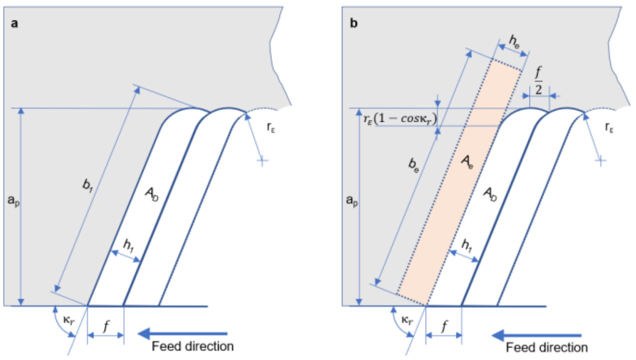


Fig. 2. a – Woxén-Johansson model for calculating cutting pressure; b – extended Woxén-Johansson h_e- model

A common theme for these modeling approaches is using the chip thickness to describe the uncut chip, such as the average chip thickness h_m, equivalent chip thickness h_e [5] or maximum chip thickness h_{ex} [7]. All these models are based on the depth of cut a_p, radial engagement a_e, feed per tooth f_z, major cutting angle κ_r, and may also include the nose radius of the tool r_ε [8]. The majority of experimental work done in this area is based on testing in turning, avoiding the challenges of intermittent cutting, varying thermal loads, and varying chip thickness present in milling [9, 10]. The work that has been done is mainly using average or equivalent chip thickness to calculate cutting forces [11], [12] or using experimental data to calculate coefficients used to calculate chip thickness[13, 14].

The objective of this study is not to investigate different force models or models to represent the chip thickness, but rather to investigate the underlying process parameters affecting the main cutting force in milling operations. To provide a comprehensive understanding, the effect on the main cutting force was assessed by varying radial engagement, cutting depth and feed. Fort this, single-tooth climb milling with indexable carbide inserts in medium carbon steel C45E, were selected. The design of experiments and statistical analysis were performed using program Modde Pro [15].

Industrial machining usually includes a milling cutter with multiple teeth. Therefore, the forces are distributed between all teeth in the milling cutter, making the force analysis complicated. In order to study the parameter's influence on the cutting force, to simplify calculations a single tooth was used in the cutter.

2. MATERIALS AND METHODS

The aim of the experiment is to investigate cutting forces in milling and measure the effect of a_e, a_p and f_z whilst keeping v_c and D_c constant. The experiment was performed in a milling machine Okuma MB-46VAE (Machine 1). The workpiece used was normalized steel C45E with size of 100 × 100 × 40 mm described in Fig. 3.

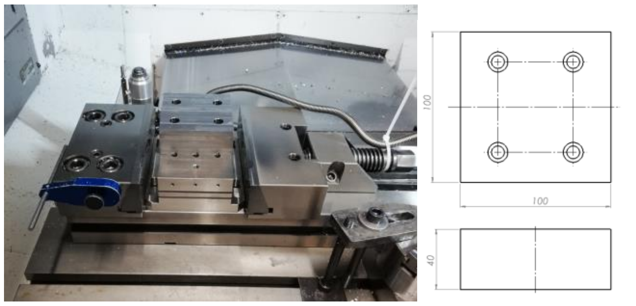


Fig. 3. Mounted table dynamometer with a sample of size 100 × 100 × 40 mm in the milling Machine 1

Single tooth climb milling was chosen as the cutting method, an indexable shoulder mill with diameter (D_c) of 32 mm and widely used insert XOMX10T308TR, were used. All the material, tooling and inserts were provided by SECO Tools.

2.1. Independent and dependent variables

Design of experiment and data analysis were done with program Modde Pro. In this research, underlying cutting process parameters a_e, a_p and f_z were investigated. Therefore, these parameters are considered as factors in this experimental setup, as stated in Table 1. All other parameters used in the study are interpreted as constants as given in Table 2.

Table 1. Dependent factors

Factor name	Factor symbol	Min value	Max value
Engagement of the tool	a_e	20 %	50 %
Cutting depth	a_p	2 mm	4 mm
Cutting feed	f_z	0.095 mm/rev	0.2 mm/rev

Table 2. Independent factors

Constant name	Constant symbol	Constant value
Cutting speed	v_c	230 m/mm
Tool diameter	D_c	32/40 mm

Full Factorial Design (FFD) was used to study the effects of the factors, as this model allows us to analyse the parameters' effect separately and jointly. In this case, FFD model outputs a total of 11 test runs, where 8 were individual runs and 3 were repetitions* of the same run. The ranges of the given parameters are shown in Table 3. The calculated main cutting force values for each run were added to the worksheet, after which it was possible to complete a model fit analysis and use multiple linear regression (MLR) to model the results. For the model analysis, it was necessary to assess which combinations of different factors have significant effect on the model. Thereafter, the power of the model was described by four different parameters: model fit (R2), future prediction precision (Q2), model validity (MV) and reproducibility (Rep). These results are described between range 0 to 1 (0 to 100 %).

Table 3. FFD model outputs for a total of 11 test runs 8 singles and 3 repetitions*

Test run no.	1	2	3	4	5	6	7	8	9*	10*	11*
Cutting speed v_c, m/min	230	230	230	230	230	230	230	230	230	230	230
Eng. of tool a_e, %	20	50	20	50	20	50	20	50	35	35	35
Depth of cut a_p, mm	2	2	4	4	2	2	4	4	3	3	3
Feed rate f_z, mm/tooth	0.095	0.095	0.095	0.095	0.2	0.2	0.2	0.2	0.1475	0.1475	0.1475

With these values, it is possible to indicate the reliability of the constructed model. Usually, when the R2 and Q2 values are higher than 0.5 it is possible to estimate the effect of the factors. If the repeatability of the test is high (higher than 0.9), then Rep values are considered almost identical, and the pure error of the model is small. Also, this indicates that the Modde Pro could miscalculate the MV value and MV could be less than 0.5 [15].

2.2. Methods of measurements

Cutting forces, measured with Kistler table dynamometer type 9257B and processed with DAQ system type 5070A, are analyzed using Kistler Group universal software Dynoware [16]. For the test with the table dynamometer the sampling frequency (SF) is set to 30 000 Hz. The fundamental connection of increasing the frequency is that by increasing the SF, it is possible to increase the number of measurement points and thus also the measurement accuracy. Such settings also mean that there is a high possibility of having a high degree of background noise in the results. Therefore, based on previous studies [17, 18], to reduce the amount of unwanted noise during test runs, the collected data is filtered with a low pass filter of 800 Hz.

The experiment was repeated in the milling machine MORI SEIKI SV-500 (Machine 2), with a shoulder milling cutter of diameter 40 mm and using the same inserts (XOMX10T308TR) as in the experiment described above. The change in cutter diameter was made due to limitations of fixing the tool and charge amplifier together into the tool holder in Machine 2. Another change included the different method of cutting force measurements and the value of SF. For that, Kistler rotating dynamometer 9124A, with included charge amplifier and DAQ system, is used and SF is lowered to 8000 Hz. In this experiment, it allows us to assess the possibility of using lower frequencies and still have enough accuracy for future calculations and modelling. Later, the collected data is filtered with low pass filter of 300 Hz to reduce background noise.

2.3. Calculation of main cutting force

All the data, cleaned from background noise, was processed in the software Matlab. In Matlab the mean maximum values of the forces were calculated out of 20 cycles in the area of stable cutting [19]. To calculate the main cutting force, the measured force values F_x and F_y, are recalculated to match the workbench coordinate system. The engagement angle $\theta\,(0-90^\circ)$ for the table dynamometer was calculated, whereas with the rotating dynamometer it was measured to 3.5 degrees.

After locating the engagement angles, the resulting local cutting forces in the machine coordinates F_{xL} and F_{yL} were calculated by using Eq. 4 (the table dynamometer) and Eq. 5 (rotating dynamometer). The calculated main cutting force was added to the worksheet of the Modde Pro.

$$F_{xL}\,(\theta) = F_x \cdot \sin\theta + F_y \cdot \cos\theta;$$

$$F_{yL}(\theta) = F_x \cdot \cos\theta + F_y \cdot \sin\theta, \tag{4}$$

where force values F_x and F_y are measured parameters of main cutting force and θ angle of engagement in radians collected with the table dynamometer.

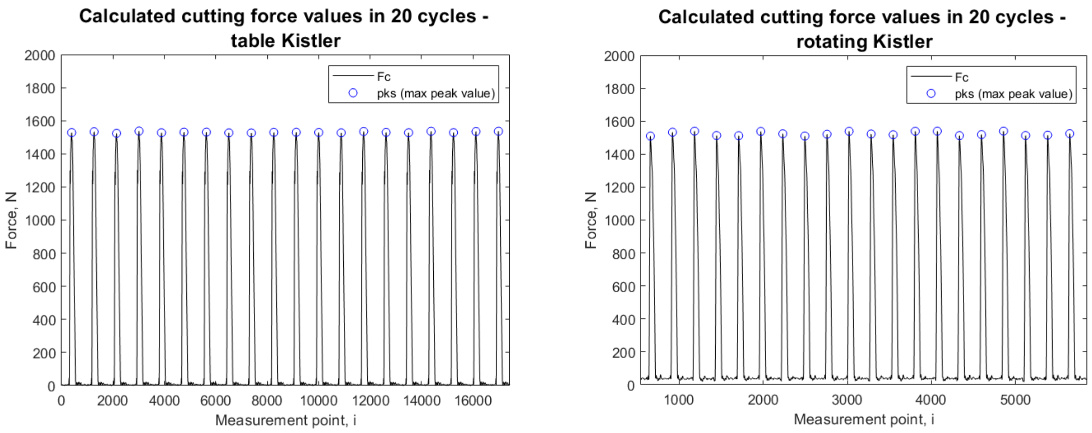
$$\begin{bmatrix} F_{xL} \\ F_{yL} \\ F_{zL} \\ T_L \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\,\varphi & sin\,\varphi & 0 \\ 0 & -sin\,\varphi & cos\,\varphi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ T \end{bmatrix}, \tag{5}$$

where force values F_x, F_y and F_z are measured parameters of main cutting force collected with rotating dynamometer and T_L is torque. Angle φ shows an angle of engagement in degrees and was measured to 3.5 degrees.

3. RESULTS AND DISCUSSIONS

The main experiment was performed with Machine 1 and the control experiment was performed in Machine 2. The purpose of the test in Machine 2 is a repetition of the main the experiment, by using different equipment and settings described in section 2.2. Due to changes in the control test, it is not possible to compare the results from the two experiments with each other. However, these results can be used to evaluate the merit of the main experiment and therefore are shown together in the figures stated below.

Fig. 4 shows the filtered average main cutting force of one test, run no. 8. This data is from stable cutting area throughout 20 cycles from both experiments in machines 1 and 2. The same data is used to describe average main cutting force deviation over 20 cycles and is shown in Fig. 5. In both tests, the average deviation of the forces acting on a fully loaded tool is less than 2 % and therefore is concluded to be stable cutting. From the start of the rotation, the force increases greatly, thereby indicating the starting point of cutting into the workpiece. After that, forces stabilize and finally almost fade out at the end of the cut. In machine 1 there is a slight fluctuation (blue rectangle) with negative growth of forces, which likely can be attributed to the lack of stiffness of the machine. This phenomenon is not present when using rotating Kistler. The average maximum force of 20 cycles, as presented in Fig. 4, is included in the calculations. Fig. 6 shows the results of the calculations for all 11 test runs of the average max cutting force. These values are later used to carry out model fit analysis. Due to the difference of experimental setup, the levels of measured forces are not comparable, but the trends are. Having established the similarities between the two experiments, four different model fit analysis were carried out as stated in Table 4.



a b

Fig. 4. Calculated cutting force values in 20 cycles in test run no. 8 with: a – table Kistler; b – rotating Kistler

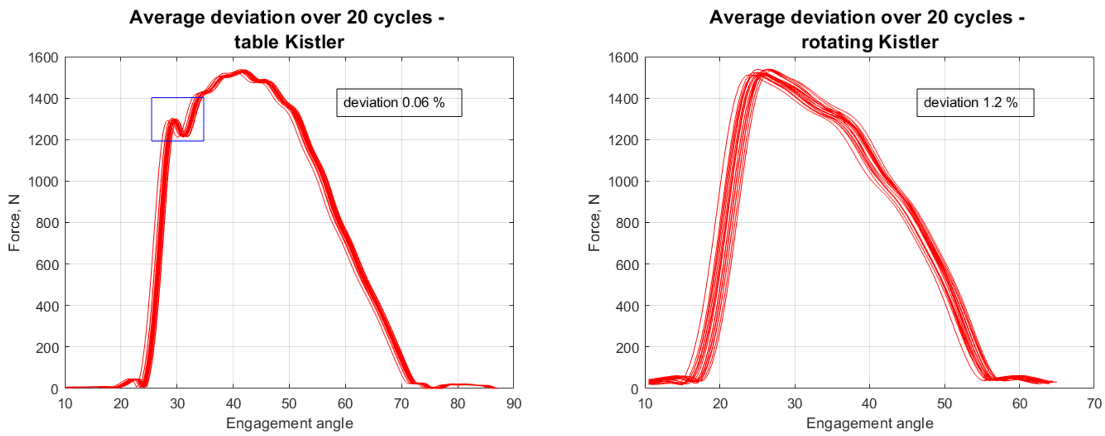


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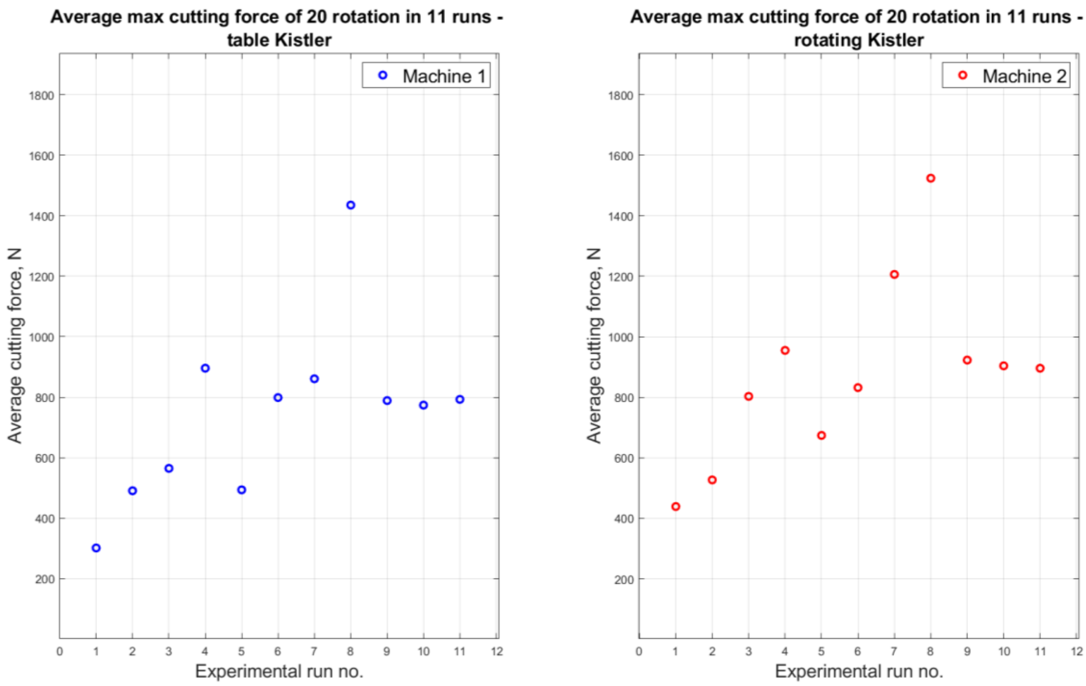
Fig. 5. Average cutting force deviation over 20 cycles in machines 1 and 2: a – table Kistler; b – rotating Kistler



a b

Fig. 6. Average max cutting force for setup: a – table Kistler; b – rotating Kistler

Table 4. Force prediction models with different effects, with table Kistler

Model 1 (square and interaction effect Δ) → confidence 95 %	Model 2 (interaction effect +) → confidence 95 %	Model 3 (main effect ◊) → confidence 95 %	Model 4 (square effect •) → confidence 95 %
Model fit R2 = 99.7 % Q2 = 85.2 % Model validity = 23 % Reproducipility = 99.9 %	Model fit R2 = 99.0 % Q2 = 82.0 % Model validity = 0.05 % Reproducipility = 99.9 %	Model fit R2 = 93.0 % Q2 = 77.2 % Model validity = -20 % Reproducipility = 99.9 %	Model fit R2 = 93.0 % Q2 = 77.2 % Model validity = -20 % Reproducipility = 99.9 %

The outcome, described with a summary of model fit, is represented with four different parameters R2, Q2, Model validity and Reproducibility. For both machines, the values of R2 and Q2 are higher than 0.5, meaning that the models are considered to be significant. Even though the Model validity value is less than 0.5, the high Reproducibility of 0.95 balances the model and pure error is small. In conclusion, this shows that the model fit was successful regardless of tool diameter, measuring equipment, or measuring frequency.

In order to choose the most accurate model for predicting cutting force, it is necessary to compare the models given in Table 4 with the experimental results. For this, the desired outcome would be the experimental vs. model differences fluctuate as little as possible. In the first run, the a_e value is 20 %, a_p is 2 mm and f_z is 0.095 mm/tooth. Models 2 – 4 show a large fluctuation between the test run no. 1 and the experimental run no. 1. However, in the case of Model 1 vs. the run no. 1, the fluctuation remains below 5 %, as shown in Fig. 7.

The significance of the coefficient is visualized with the whiskers which are positioned in the bars. Usually, when both ends of significance interval are outside of the parameter value (green bars), it has no significant effect and should be excluded from the model. However, in this case, the value of a_e^2 is important for a functional model and must be shown in Fig. 8. Factors a_e, a_p and f_z all increase the value of cutting force.

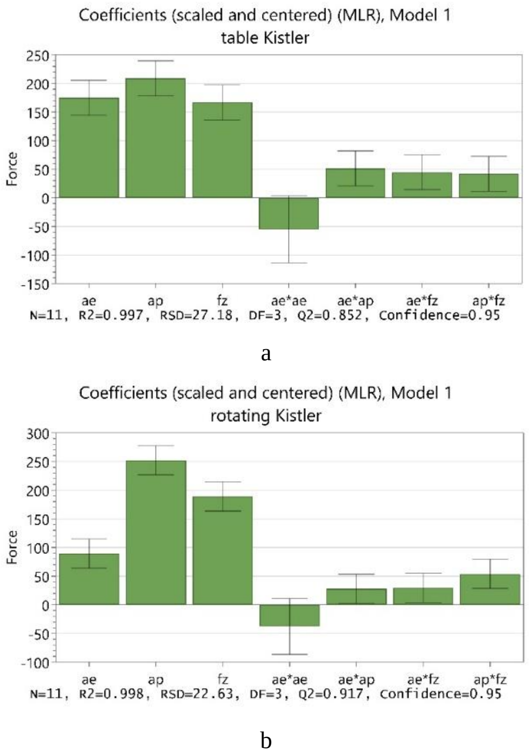


Fig. 8. Model 1 coefficients effect to model validity: a – table Kistler; b – rotating Kistler

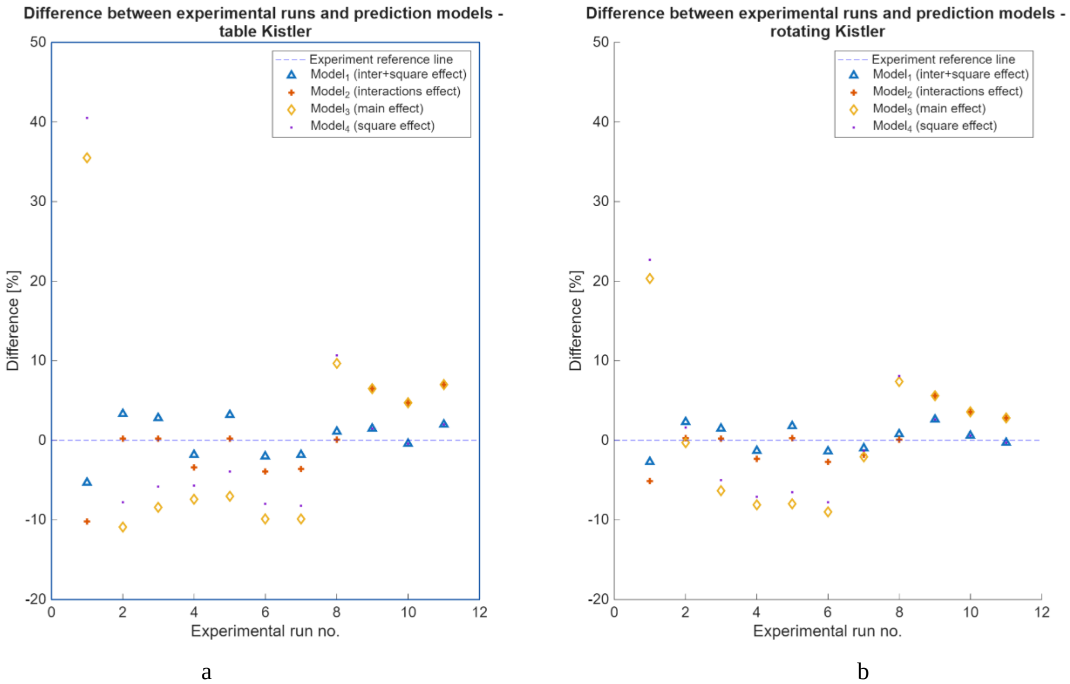


Fig. 7. Force prediction models (with different effects) comparison to experimental results: a – table Kistler; b – rotating Kistler

Same effect is when a_e interacts with a_p, f_z and a_p with f_z. But when a_e value is squared, it has a decreasing effect on the cutting force value. This indicates that if engagement of the tool is increasing, the cutting force normalizes or even decreases to some extent.

Fig. 9 – Fig. 11 show the interaction between factors a_e and a_p during the cutting process.

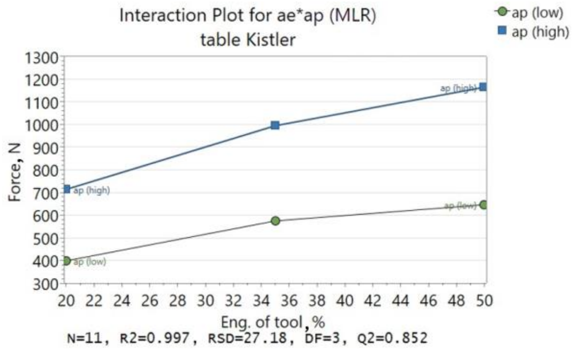


Fig. 9. The effect of interaction between factors a_e and a_p with table Kistler

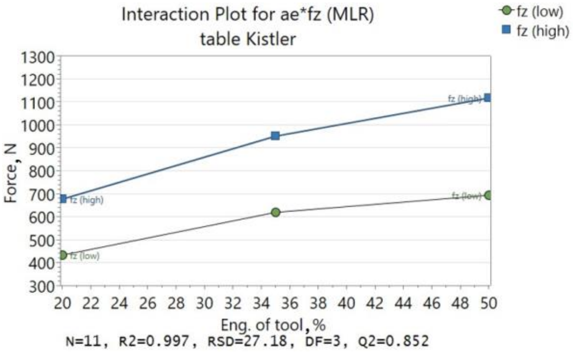


Fig. 10. The effect of the interaction between factors a_e and f_z with table Kistler

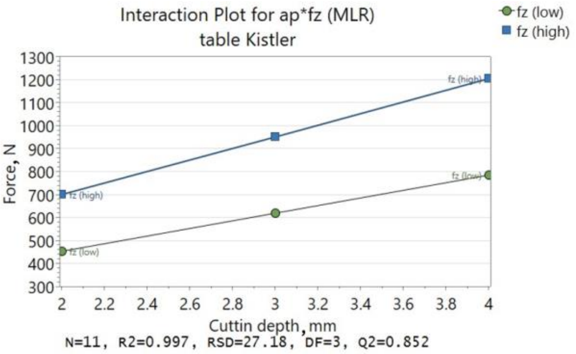


Fig. 11. The effect of the interaction between factors a_p and f_z with table Kistler

In both ways, when the a_p is low or high, increasing the engagement of the tool also increases overall cutting force value. When the tool is engaged more than 35 %, the increasing effect of the factor a_p to the cutting force slows down and normalizes. Similar behavior occurs when parameters a_e and f_z interact with each other as shown in Fig. 10. However, when looking at factors a_p and f_z interaction in Fig. 11, there is only an increasing effect to the cutting force value. Based on this analysis, it can be concluded that although factor a_e has significant influence on the formation of the cutting force, this importance decreases when more than 35 – 50 % of the tool is engaged. This also shows that increasing a_e helps to reduce the influence of factors a_p and f_z to the cutting force.

3.1. Model-based force prediction

Determined with the results of the experiment, it was possible to create a model-based force prediction equation, and it is shown as Eq. 6. This model contains all the factors presented in this study and their interactions between one and other. Each factor has its own coefficient value and is shown in Table 5. With this model, it is possible to calculate the predicted force value.

$$F_{predicted} = Const + a_e\mathrm{B} + a_p\mathrm{C} + f_z\mathrm{D} + a_e^2\mathrm{E} +$$
$$+ a_e a_p\mathrm{F} + a_e f_z\mathrm{G} + a_p f_z\mathrm{H}, \quad (6)$$

where a_e, a_p and f_z are factors and $a_e\mathrm{B}$, $a_p\mathrm{C}$, $f_z\mathrm{D}$, $a_e^2\mathrm{E}$, $a_e a_p\mathrm{F}$, $a_e f_z a\mathrm{G}$ and $a_p f_z\mathrm{H}$ are coefficients given in the model. *Const* is a constant value got from the model.

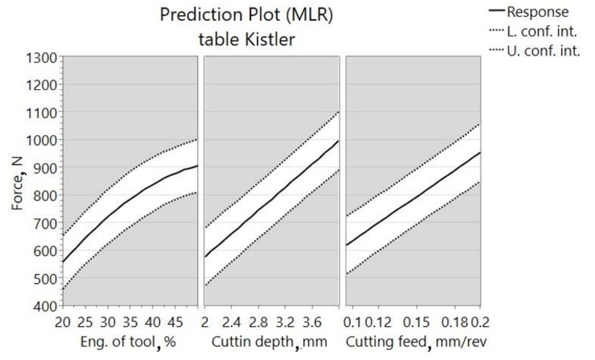
Table 5. Coefficient values in model-based force prediction formula with table Kistler

Coefficient name	Coefficient Value
Constant	-10.640
B	10.076
C	-28.649
D	-1208.7
E	-0.2442
F	3.4250
G	56.984
H	797.62

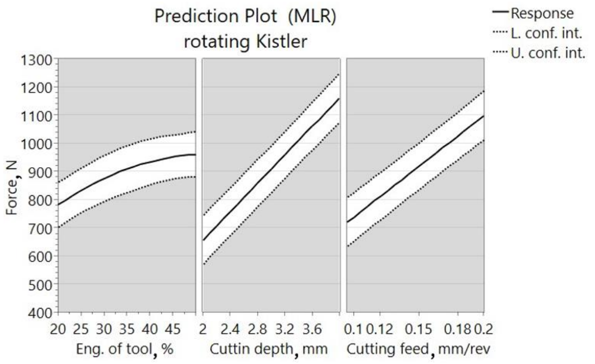
Three factors a_e, a_p and f_z all have significant effect on the value of the cutting force based on the analysis stated in section 3. The increase or decrease in the force value is controlled by factors values during cutting. Therefore, this type of model-based force prediction can be used to predict what will happen with the force, when factors have specific values. In Fig. 12 the prediction performance of individual factors a_e, a_p and f_z is shown, with a confidence of 95 %. It shows that with the given response value of the factor, the magnitude of the cutting force stays within the range in the white area. When fixing some of the factors, the prediction of the force value will become more precise. For example, in Fig. 13, the contour plot shows possible responses to the cutting force value, when f_z is set to 0.1475 mm/rev and v_c is 230 m/mm, and varying factors are a_p and a_e.

Force prediction in milling is difficult due to many variables during the cutting process. Some of these variables are cutting parameters, background noise of the machine, vibrations, effect of the tooling, etc. Simplifying some parts of the process such as using only a single tooth or making the cutting parameter constant gives the possibility to use different kinds of approaches to calculate forces. Also, rather than using chip thickness to calculate and predict cutting force value, it is possible to use only cutting parameters as factors like in this experiment.

Even though the accuracy of the prediction model is high, it must be recognized that the experiment based on which the model was built does not imitate the everyday working environment. Usually, in normal circumstances, more than one cutting edge is used at the same time, when machining is done with a face mill used in this work.

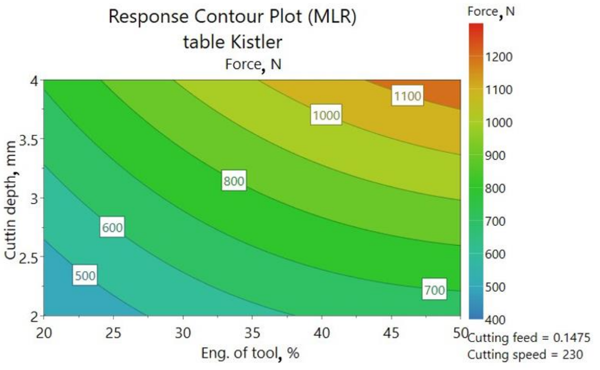


a



b

Fig. 12. Prediction of the factor's performance increases or decreases their value: a – table Kistler; b – rotating Kistler



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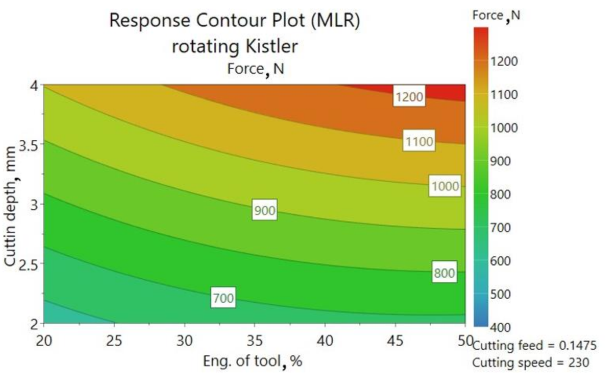

b

Fig. 13. The response to cutting force values, when varying factors a_p and a_e, $f_z = 0.1475$ mm/rev and $v_c = 230$ m/mm: a – table Kistler; b – rotating Kistler

In addition, the machines were chosen for their accuracy and stability during cutting process rather than like the average machine used in a normal working environment. Although these simplifications are not real life, the model is still viable to use as a basis for further experiments.

4. CONCLUSIONS

It is a common practise that chip thickness is used to calculate cutting forces. In this paper, the authors have investigated alternative route using statistical modelling for cutting force estimation.

The purpose of this experiment-based study was to investigate the influence of process parameters on the development of cutting force using MLR. The statistical data processing program Modde Pro was used for this inevestigation. The cutting force data collected from the dynamometer was cleaned and aligned with the machine coordinate system to obtain the correct values of the force components for the calculation of the cutting force. Thereafter, results were added to the data sheet in Modde Pro and a base model was created to evaluate the outcome of the test results. The following conclusions could be drawn from the test results.

1. The results of the experiment were not affected by the differences between the two experiments, which were the use of tools with different diameters, different types of milling machines, or the use of different types of measuring machines.
2. Lower SF is justified by significantly reducing noise from the background system. Therefore, the value of SF should be based on the rule that SF is at least 2 to 3 times higher than the tooth passing frequency.
3. When looking at the individual effect of process parameters on cutting force value, all parameters a_e, a_p and f_z influence the development of the cutting force by increasing it.
4. Although a_e increases the cutting force, the effect of this parameter decreases when more than 35% of the tool is engaged.
5. Parameter a_e helps to reduce the effect of parameters a_p and f_z on the cutting force.
6. Based on the results obtained, a model-based cutting force prediction equation was created.

As part of this work, a cutting force model was created, but the cutting forces calculated with the model were not verified with an experiment. Therefore, for further work, it is possible to compare the obtained model with previously created models.

This experiment showed that there is a possibility to use statistical modelling approach to calculate cutting forces during milling rather than calculating chip thickness and then calculate forces. But it also showed that in order to get conclusive results with statistical modelling in the future, more comprehensive work should be done.

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