CORRELATION BETWEEN COMPONENTS OF CUTTING FORCE BY TURNING

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Abstract: The paper give a summary of the experimental research of the dependence between cutting force components by longitudinal turning of the mild steel by coated cutting tool. The effects of cutting conditions on the cutting force components were experimentally investigated. During experiments, three components of cutting force were measured, the main cutting force, the feed force and the passive force. The main cutting force is the largest, the feed force is the middle and the passive force is the smallest. Dependence between cutting force components is approximately linear.

1 INTRODUCTION

The need for improving the technological performance of machining operations as assessed by the forces, power, tool-life and surface finish has long been recognized to increase the economic performance of the machining operations. Metal cutting process is a complicated process where the performance depends upon a number of cutting and tooling conditions. Cutting force has a significant influence on cutting process. Information about the expected cutting force components is significant for the following reasons: the forces occurring in the metal cutting process provide information about the power requirements of the machine, choosing the right cutting process and the optimum technological parameters results in significant savings of energy during machining. For developments in the filed of adaptive control of the cutting process, knowledge of the cutting force is of major importance in defining the performance limit confining the range of optimization. Of the factors influencing the cutting force, the following are very important: cutting method (constant or varying cross-sectional area of cut), cutting conditions (cutting speed, feed, and depth of cut), the material of workpiece (chemical composition, heat treatment), the cutting tool (tool material, cutting edge geometry, chip breaker, coating, tool wear), and cutting fluid.

The cutting force components in lathe turning can be measured in three directions, figure 1. The component of the force acting on the rake face of the tool, normal to cutting edge, in the direction of motion of the workpiece is called the main cutting force (tangential force) F_c. This is usually the largest force component, and acts in the direction of the cutting speed. The force component acting on the tool in the direction parallel with the direction of feed, is called the feed force (axial force) F_f. The third component, push the cutting tool away from the work in radial direction, is called the passive force (radial force) F_p. If we know the components of cutting force we can determine cutting force by equation:

$$F = \sqrt{F_c^2 + F_f^2 + F_p^2} \quad (1)$$

The cutting force components present the basic category of the cutting process mechanics.

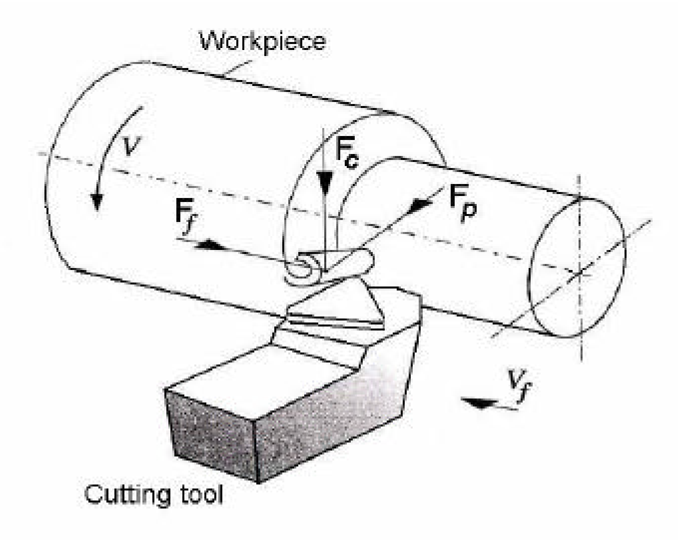

Figure 1. Components of cutting force

Main cutting force (tangential force) acts in direction tangential to the revolving workpiece and represents the resistance to the rotation of the workpiece. Kienzle has suggest the equation for determine the main cutting force in form:

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

Where is $k_{c1.1}$ - specific main cutting force unit, b - width of cut, h - thickness of cut, and m_c - coefficient of main cutting force.
Width of cut b, and thickness of cut h, can determine by equations:

$$b = \frac{a_p}{\sin\chi} \quad ; \quad h = f_a \cdot \sin\chi \tag{3}$$

Where is a_p - depth of cut, f_a - axial feed, κ - tool cutting-edge angle (entering angle).
The specific cutting force unit $k_{c1.1}$ related to the cross-sectional area of the cut $b \cdot h = 1mm^2$, and the coefficient of main cutting force m_c are included into the equation as characteristic data. The specific cutting force unit $k_{c1.1}$ is, in this case, largely dependent on the material of workpiece, the cutting conditions, the tool and the procedural influences. The coefficient of main cutting force m_c characterizes the cutting force behavior of the workpiece material - tool material combination for different thickness of cut.

Feed force (axial force) acts in the direction parallel to the axis of the work and represents the resistance to the axial (longitudinal) feed of tool. For the calculation of feed force F_f a relationship can be established that is similar to that used for the main cutting force F_c as:

$$F_f = k_{f1.1} \cdot b \cdot h^{1-m_f} \tag{4}$$

Where is $k_{f1.1}$ - specific feed force unit, and m_f - coefficient of feed force.
As characteristic data, the specific feed force unit $k_{f1.1}$ related to a cross sectional area of cut of $b \cdot h = 1mm^2$ and the coefficient of feed force m_f are included in the equation. Unlike to the main cutting force equation, this equation to calculate the feed force must be regarded as an possible solution. In most cases, the feed force is determined in dependence of main cutting force.

Passive force (radial force) acts in a radial direction from the center line of the workpiece. In accordance with the rules of calculating the main cutting force F_c, the passive force F_p can be expressed as:

$$F_p = k_{p1.1} \cdot b \cdot h^{1-m_p} \quad (5)$$

Where is $k_{p1.1}$ - specific passive force unit, and m_p - coefficient of passive force.
As characteristic data, the specific passive force unit $k_{p1.1}$ related to a cross sectional area of cut of $b \cdot h = 1mm^2$ and the coefficient of passive force m_p are included in the equation.

2 MATHEMATICAL MODEL OF CORRELATION

In order to determine correlation relationship between cutting force components, experimental results were performed in linear form:

$$y = ax + b \quad (6)$$

and in exponential form

$$y = bx^a \quad (7)$$

Logarithming the exponential form we give

$$\ln y = a \ln x + \ln b \quad (8)$$

Designing by

$$\bar{y} = \ln y \qquad \bar{x} = \ln x \qquad \bar{b} = \ln b \quad (9)$$

we give

$$\bar{y} = a\bar{x} + \bar{b} \quad (10)$$

linear relationship in bilogarithmic scale.
In both cases identical procedure can be applied for experimental data processing (in the first case the input values are direct values of cutting force components, in the second case the input values are logarithms values of cutting force components).
For linear equation (6) constants a and b can determine using the least square method

$$(\Sigma\Delta i)_{min} \quad (11)$$

where Δ_i is the error of the i-th observation.
From the condition of minimum, the normal equations are

$$\Sigma(x_i y_i) - a\Sigma x_i^2 - b\Sigma x_i = 0 \quad (12)$$

$$\Sigma y_i - a\Sigma x_i - Nb = 0 \quad (13)$$

or

$$A_1 a + B_1 b = C_1 \quad (14)$$

$$A_2 a + B_2 b = C_2 \quad (15)$$

where

$$A_1 = \Sigma x_i^2 \qquad A_2 = \Sigma x_i = B_1$$

$$B_2 = N \qquad C_1 = \Sigma(x_i y_i) \qquad C_2 = \Sigma y_i$$

Constants a and b are

$$a = \frac{\begin{vmatrix} C_1 & B_1 \\ C_2 & B_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} = \frac{C_1 B_2 - C_2 B_1}{A_1 B_2 - A_2 B_1} \quad , \quad b = \frac{\begin{vmatrix} A_1 & C_1 \\ A_2 & C_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} = \frac{A_1 C_2 - A_2 C_1}{A_1 B_2 - A_2 B_1} \quad (16)$$

The correlation coefficient is

$$R = a \cdot \frac{\sigma_x}{\sigma_y} \tag{17}$$

where the variance of x and y values

$$\sigma_x^2 = \frac{1}{N} \cdot \Sigma x_i^2 - x^2 \quad , \quad \sigma_y^2 = \frac{1}{N} \cdot \Sigma y_i^2 - y^2 \tag{18}$$

The average of x and y values

$$x = \frac{1}{N} \cdot \Sigma x_i \quad , \quad y = \frac{1}{N} \cdot \Sigma y_i \tag{19}$$

If the correlation coefficient is near one, the correlation between variables is stronger.

3 EXPERIMENTAL INVESTIGATION

The experiments have been performed on the universal lathe "Potisje" PA-C 30, with power of 11 kW. The cylindrical bar of workpiece were held in the machine with a collet to minimize run-out and maximize rigidity. The workpiece material used in this experiment was C60E steel (EN10027-1), R_m = 700-1000 N/mm^2, hardness value of HB = 220. The cylindrical bar specimen that is utilized in this experiments had a diameter of 62 mm and length of 500 mm. Cutting tool was toolholder PCLNR 3225P12 with coated carbide insert CCMT 09T304UR415, rake angle γ = -6, angle of inclination λ = -6, corner radius r_ε = 0.8 mm. Cutting condition was: number of revolution n = 500 o/min, axial feed f_a = 0.249-0.392 mm/o, depth of cut a_p = 2.5-4 mm, tool cutting-edge angle (entering angle) κ = 45°-90°. Sectional area of cut $A_f = b \cdot h = a_p \cdot f_a$ was constant.

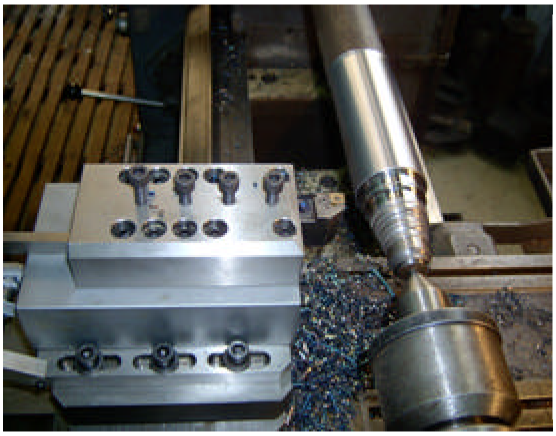

Figure 2. Experimental equipment

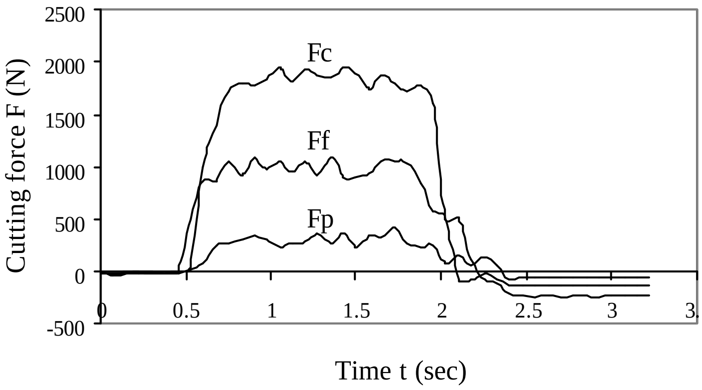

Figure 3. Graph of cutting force components

The cutting forces were measured with a three-component force dynamometer Kistler type 9441, mount on the lathe via a custom designed adapter for the toolholder creating a very rigid tooling fixture. The charge signal generated at the dynamometer was amplified using charge amplifier Kistler type 5007A. The amplified signal is acquired and sampled by using computer Hewlett Packard HP 9000/300. Experimental equipment is shown in figure 2 and graph of cutting force components is shown in figure 3.

Experimental results are shown in table 1. Table 1 shows that the main cutting force is the largest, the feed force is the middle and the passive force is the smallest in longitudinal turning.

Table 1. Experimental results of cutting force components

N°	a_p (mm)	f_a (mm/rev)	F_c (kN)	F_p (kN)	F_f (kN)	$\ln F_c$	$\ln F_p$	$\ln F_f$
1	2	0.999	1.597	0.557	0.742	0.4681	0.5852	0.2984
2	3	0.642	1.684	0.659	0.702	0.5212	0.4170	0.3538
3	4	0.499	1.756	0.787	0.633	0.5630	0.2395	0.4573
4	5	0.392	1.797	0.849	0.605	0.5861	0.1637	0.5025
5	6	0.321	1.866	0.950	0.565	0.6238	0.0513	0.5709
6	7	0.285	1.946	1.049	0.537	0.6658	0.0478	0.6217
7	8	0.249	2.046	1.155	0.493	0.7159	0.1441	0.7072
8	10	0.196	2.144	1.284	0.483	0.7627	0.2500	0.7277

Using the specific methodology, it is determined equations for dependence between components of cutting force, the feed force (axial force) versus the main cutting force (tangential force), and the passive force (radial force) versus the main cutting force (tangential force).The next mathematical models in linear form and exponential form are given.

$$F_p = -1.57071 + 1.33834 \cdot F_c \quad ; \quad R = 0{,}99754 \tag{20}$$

$$F_p = 0.155 \cdot F_c^{2.83} \quad ; \quad R = 0{,}99024 \tag{21}$$

$$F_f = 1.51707 - 0.49721 \cdot F_c \quad ; \quad R = 0{,}97434 \tag{22}$$

$$F_f = 1.536 \cdot F_c^{-1.56} \quad ; \quad R = 0{,}98949 \tag{23}$$

The graphical interpretation of regression lines of passive force versus main cutting force and feed force versus main cutting force, for linear mathematical model, on the figure 4 and 5, are given.

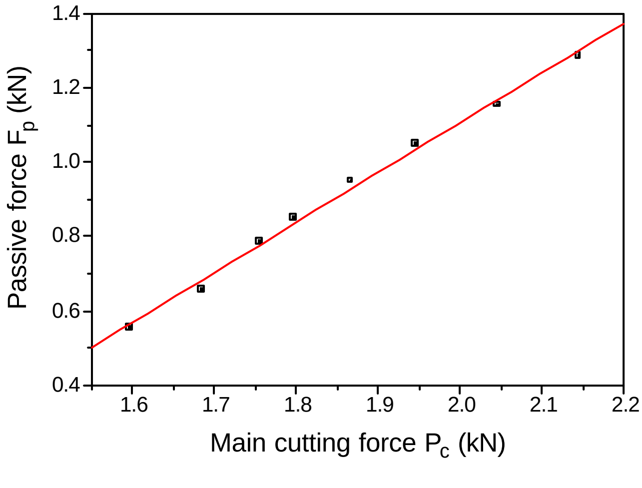

Figure 4. Passive force vs main cutting force

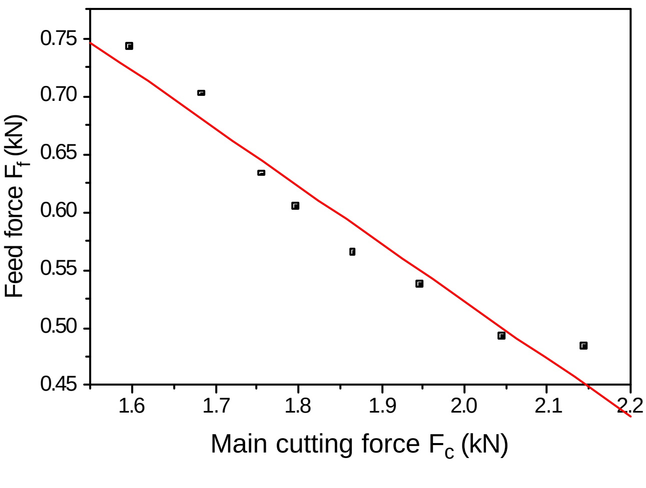

Figure 5. Feed force vs main cutting force

The graphical interpretation of regression lines of passive force versus main cutting force and feed force versus main cutting force, for exponential model (in bilogarithmic scale), on the figure 6 and 7, are given.

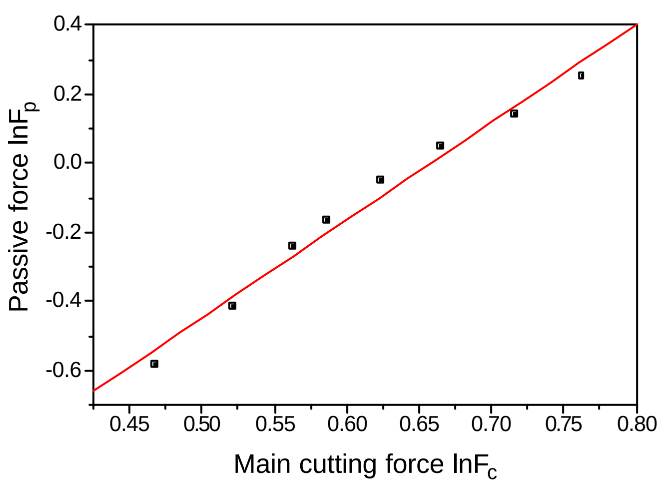

Figure 6. Passive force vs main cutting force (log-log scale)

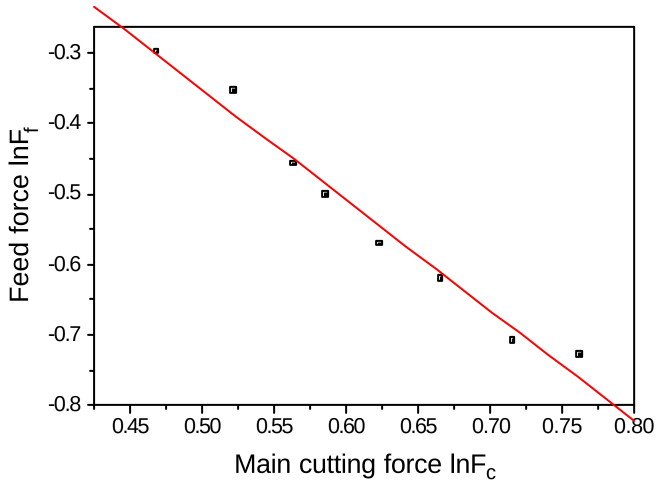

Figure 7. Feed force vs main cutting force (log-log scale)

In accordance with the presented we can generally conclude that, for all proposed models, corresponding coefficients of correlation are sufficiently high (R>0,97). Since correlation coefficient are high, both relationships can be used.

4 CONCLUSION

The main cutting force is the largest, the feed force is the middle and the passive force is the smallest in longitudinal turning of the mild steel by coated cutting tool. The mathematical models for correlation between cutting force components, the linear and exponential relationships have been used. In proposed mathematical models, there is a very strong correlation between observed components. Dependence between cutting force components is approximately linear. Empirical equations for predicting the cutting force components are established for practical applications.

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