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An Experimental Study of the Cutting Forces in Metal Turning

Cutting forces are classified among the most important technological parameters in machining process. Cutting forces are the background for the evaluation of the necessary machining power, as well as for dimensioning of the tools. Cutting forces are also having a major influence on the deformation of the work piece machined, its dimensional accuracy, and machining system stability.

Keywords*: Metal cutting, cutting forces, cutting parameters*

1. Introduction

One of the most promising techniques for detection of cutting condition involves the measurement of cutting forces.

In all classical metal cutting procedures in the area of contact between tool and material appears a cutting force, which can be decomposed after three orthogonal components. In practice, the resulting value of the cutting force is less of importance, relevant being its components, which are used in calculations of: fixing devices for the material, tools, resistance of the various parts of the machine tools, to calculate the propulsion power of the driving electric motors, the calculation of processing accuracy a.s.o.

Figure 1 [8] shows the decomposition scheme of the resulting force in its three orthogonal components: feed force F_f , radial force F_p and tangential force F_c.

The **feed force** F_f is oriented in the same direction as the longitudinal axis of the piece, which coincides with the feed direction. This component is used for calculating the feed mechanism, the tool a.s.o.

The **passive force** F_p is oriented in radial direction seeking to dismiss the toll, and to depart it from the machined surface. This component affects the accuracy of the geometric shape and dimensional accuracy of the work piece.

The **main cutting force** F_c is oriented in the machining direction, being the most important component in size and role. This component determines the size of the resistant torque that has to be transmitted by the main shaft of the machine tool and the power consumption during the cutting process.

The resultant cutting force can be calculated with following equation:

$$R = \sqrt{F_f^2 + F_p^2 + F_c^2}\ , \tag{1}$$

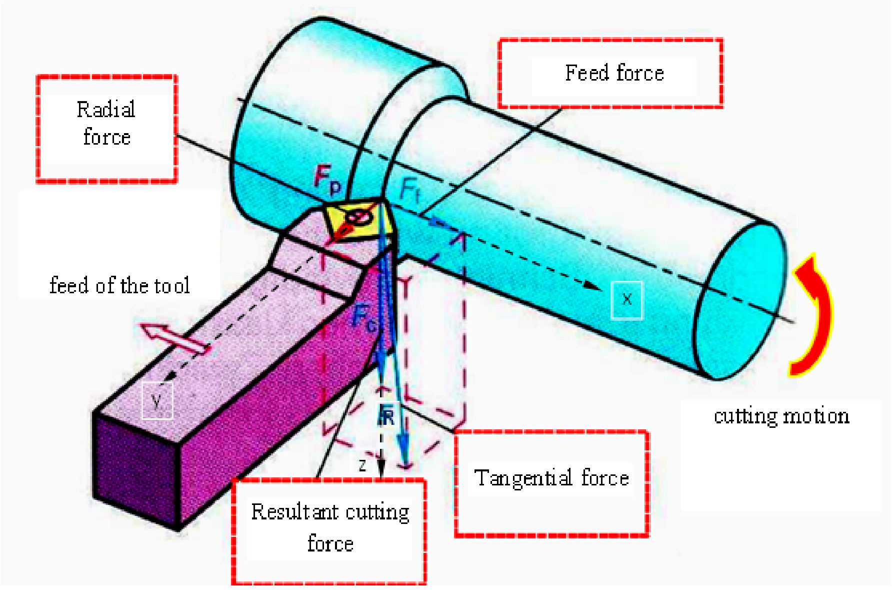

Figure 1. Cutting force components in turning

In the domain specific literature are indicated expressions for calculating the components of the cutting force for various cutting operations, which were obtained by analytical means or through experimental methods. For practical calculations, there are preferred the experimental obtained relationships because they yield values closer to reality than the analytical formulas, as a result of the fact that the analytical relations have been obtained after many simplifying assumptions.

The most common equation available for the estimation of the cutting forces is according to [10]:

$$F_i = C_{F_i} \cdot f \cdot t\ , \tag{2}$$

where:

C_{Fi}- specific cutting energy coefficient [N/ mm^2];

f- feed rate [mm/ rev];

t- depth of cut [mm];

i- index for the three components of the cutting forces (f, p and c).

2. Experimental set-up

Having realized the importance of the choice of most appropriate cutting conditions in metal machining, this research primarily focuses on machining mild steel, using HSS made tools, due to their lower cost, ready availability and a wide range of applications. The influence of cutting parameters on cutting forces can be studied by using the adjusted statistical approach.

The cutting experiments were carried out on a precision turning lathe (type SN 560) and the work piece material was mild steel. Machining was carried out using standard high speed steel tools with a 25 mm square shank. Cutting process was carried out without the use of cutting fluid being continued until the flank wear of the tool achieved a maximum value VB_{max}= 0,6 mm. The starting work piece diameter was 70mm and 500 mm long. Details of the tests, cutting conditions, tool material and work piece material are listed in table 1.

Table 1.

Details of the tests	
Machine tool	**Turning lathe SN 560**
Work piece material	
Steel grade	C45 (1.0503), acc. to SR EN 10.083-2
Hardness	Brinell 200
Tool specification	
Material grade	HS6-5-2C (1.3343), acc. to SR EN ISO 4957
Cutting conditions	
Cutting speed [m/min]	43,96; 69,24; 87,92; 109,9; 138,47; 175,84
Feed rate [mm/ rev]	0,1; 0,2; 0,315; 0,4; 0,63 and 0,8
Depth of cut [mm]	0,5; 0,75; 1 and 1,5
Cutting fluid	none

For measuring the cutting forces was used a dynamometer type 9257B from KISTLER.

Schematic diagram of the experimental set-up is shown in figure 2.

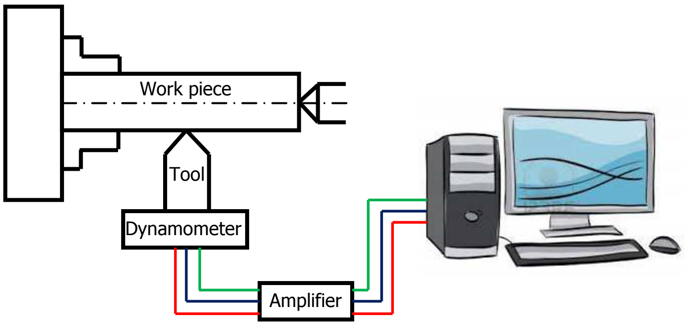

Figure 2. Experimental set-up

3. Experimental results and discussion

The cutting parameters and the responses are shown in table 2.

Table 2.

No.	Speed n [rev/ min]	Cutting speed v [m/min]	Feed rate f [mm/rev]	Depth t [mm]	Main force F_c [N]	Feed force F_f [N]	Pass. force F_p [N]
1	315	69,24	0,1	1	200	141	58
2			0,2		374	277	135
3			0,315		484	383	139
4			0,4		583	496	167
5			0,63		724	645	177
6			0,8		747	756	185
7	315	69,24	0,2	0,5	475	266	236
8				0,75	682	419	294
9				1	796	520	314
10				1,5	1052	708	327
11	200	43,96	0,2	0,5	460	355	195
12	315	69,24			390	285	165
13	400	87,92			385	280	161
14	500	109,9			370	266	152
15	630	138,47			353	246	138
16	800	175,84			338	228	124

3.1 Effect of feed rate on cutting forces

The results presented in figure 3 are showing the effect of the feed rate on the evolution of the cutting forces. By increasing the feed rate, the section of sheared chips is increasing and consequentially the removal of material requires higher forces. It can be observed that for all the tested feed rates the main force is dominating, compared to both others forces.

The effects of the feed rates on the cutting forces are as follows: the increase in the feed rate from 0,1 to 0,8 mm/ rev increases the components of the cutting forces (F_c, F_f and F_p) successively of: 273,5%, 436,17% and 218,97%.

It is noted that the feed force (F_f) is very affected by the feed rat, being followed by the main cutting force (F_c) and lastly by the passive force (F_p).

Based on experimental data, obtained for a cutting depth of t = 1 mm, respective for a cutting speed of v= 69,24 m/ min, it have been deducted following mathematical formulas which are showing the variation of the cutting force components for the feed rate average f= 0,1 – 0,8 mm/ rev:

$$F_c = 209{,}67 \cdot f^{0{,}7448}, \tag{3}$$

$$F_f = 141{,}34 \cdot f^{0{,}9298}, \tag{4}$$

$$F_p = 68{,}727 \cdot f^{0{,}6131}, \tag{5}$$

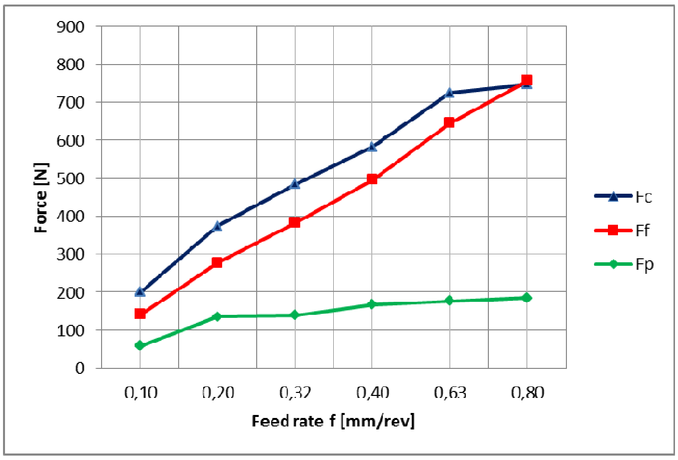

Figure 3. Cutting forces vs. feed rate at v= 69,24 m/ min and t= 1 mm

3.2 Effect of depth of cut on cutting forces

The obtained values (Figure 4) are illustrating the evolution of the cutting forces depending on the depth of cut. By increasing the depth of cut from 0,5 to 1,5 mm, it has been recorded an increase of the cutting forces (F_c, F_f and F_p) of 121,47%, 166,17%, respective 38,55%.

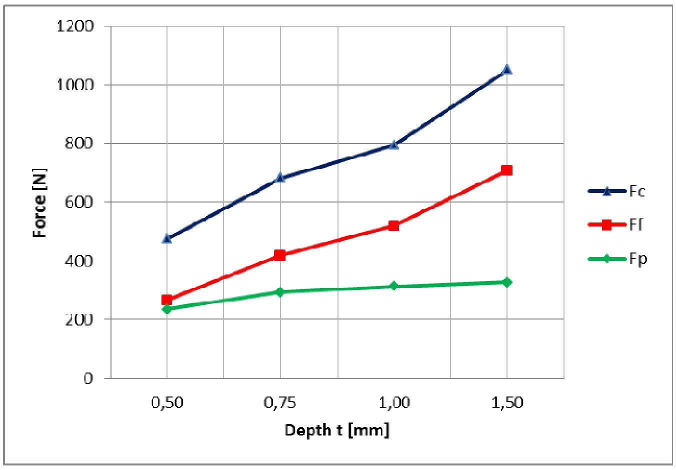

Figure 4. Cutting forces vs. depth of cut at v= 69,24 m/ min and f= 0,2 mm/rev.

It is noted that the feed force (F_f) is very affected by the variation of the depth of cut, being followed by the main cutting force (F_c) and lastly by the passive force (F_p).

Based on experimental data, obtained for a feed rate of f = 0,2 mm/ rev., respective for a cutting speed of v= 69,24 m/ min, it have been deducted following mathematical formulas which are showing the variation of the cutting force components for the depth of cut average t= 0,5 – 1,5 mm:

$$F_c = 468{,}06 \cdot t^{0{,}545}, \tag{6}$$

$$F_f = 262{,}24 \cdot t^{0{,}6799}, \tag{7}$$

$$F_p = 240{,}56 \cdot t^{0{,}2376}, \tag{8}$$

3.3 Effect of cutting speed on cutting forces

Figure 5 shows that an increase of the cutting speed leads to a reduction of the cutting force components.

This phenomenon can be explained by the fact that by increasing the cutting speed, the temperature in the cutting zone is raising, which makes the metal cutting more plastic and, consequentially, the efforts necessary for machining are decreasing. By examining the shape of the three curves, it has been recorded a very clear decrease of all the three components of the cutting force until a cutting speed of 69 m/min, beyond this limit the decrease being slower.

It is noted that the three components of the cutting force (F_c, F_f and F_p) are decreasing each with 26,52%, 35,77%, respective 36,41%, by increasing the cutting speed from 43,96 to 175,84 m/ min.

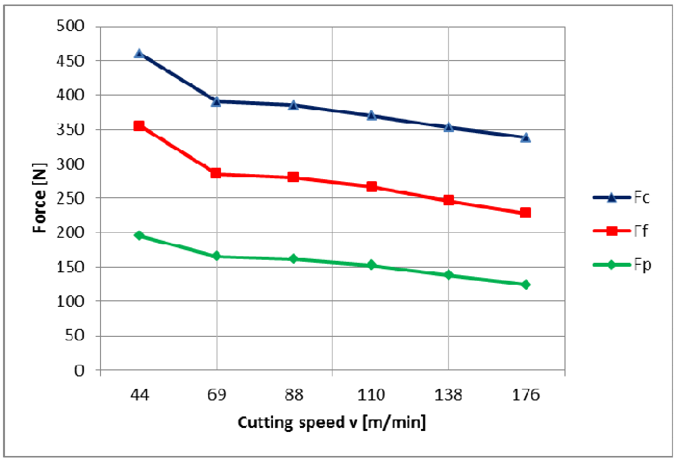

Figure 5. Cutting forces vs. cutting speed at t= 0,5 mm and f= 0,2 mm/rev.

According to the above results, the passive force (F_p) is the most sensitive component for the variation of the cutting speed, being followed by the feed force (F_f) and lastly by the main cutting forces (F_c).

Similar to the two previous presented cases, by maintaining a constant feed rate of f = 0,2 mm/ rev., respective a constant depth of cut t= 0,5 mm, it have been deducted following mathematical formulas which are showing the variation of the cutting force components for a cutting speed average v= 43,96- 175,84 m/min.

$$F_c = 452{,}84 \cdot v^{-0{,}158}, \tag{9}$$

$$F_f = 350{,}16 \cdot v^{-0{,}224}, \tag{10}$$

$$F_p = 197{,}75 \cdot v^{-0{,}226}, \tag{11}$$

4. Conclusions

The tests of longitudinal turning, carried out on C45 steel grade, using HSS made tools, without the use of cutting fluid, enabled us to study the influence of the cutting parameters on the cutting forces.

It could be concluded that, by raising the feed rate (f) and the depth of cut (t), the components of the cutting force (F_c, F_f and F_p) are increasing, while, by raising the cutting speed (v), the cutting forces are decreasing.

It is also to be noted that from the three cutting parameters (f, t and v) the increase of the feed rate has greatly affected the cutting forces. Furthermore, the most sensitive component of the cutting force at the variation of the cutting parameters is the feed force (F_f).

The established mathematical models have defined the degree of influence of each component of the cutting parameters on the cutting forces.

While the results declared through this experimental work may be generalized to a considerable extend, until working on Mild Steel and using HSS tool, the mathematical models are limited to the extreme range of the specified cutting parameters values. Future research work may be directed to optimization of cutting parameters, which was beyond the scope of this research, as it was mainly focused towards the identification of most influencing factors.

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