Experimental Investigation and Measurement of Surface Roughness and Cutting Forces while Turning AlCu3MgMnPb Aluminium Alloy

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The main aim of this scientific article is to assess the contribution of surface layers by determining the experimental investigation and practical measurement of surface roughness Ra and selected components of cutting forces while external turning of AlCu3MgMnPb aluminium alloy. In these experimental procedures, a number of turning tests have been carried out by using a universal lathe machine tool and cutting forces and surface roughness scientific measuring devices. These realized measurements have been successively investigated and experimentally verified with the prepared trial samples. These presented experimental measurements describes the authors investigation of cutting forces while turning by the piezoelectric dynamometer Kistler type 5001 and surface roughness Ra with the Talysurf CLI 100 measuring device. This scientific article, together with measured and calculated results, is the fundamental that will help to optimizing the quality and used other technological and cutting parameters of turning technological process.

Keywords: Surface Roughness, Tangential Cutting Force, Axial Cutting Force, Dynamometer, Aluminium Alloy

1 Introduction

In the recent couple of years, because of its unique combination of mechanical properties, aluminium alloys has become as one of the most common machining metals mostly in the engineering, automotive and aerospace industry. Structural features of aluminium alloys significantly affect its machinability [11, 13].

Some of the basic problems when machining aluminium alloys is the surface quality, tool wear, microgeometry and cutting forces [1-3]. This is not a novel subject, as it has attracted a great many other researchers who have contributed to the development of the status of metal machining. An approach to this subject is proposed here from a systems theory point of view, aiming at providing a model for process of control purposes. One of the most important facts related to the cutting forces and surface roughness is its influence on tool wear rates, since mainly the cutting forces acts as a factor limiting the efficiency attainable by the use of machine tools [2, 3].

The behaviour of aluminium alloy under a wide variety of feature combinations during processing and applied cutting methods has been the subject of ongoing research [4, 5]. A successful machining technological process cannot be based specifically on the surface quality and dimensional accuracy, which indicates mainly economical production. In this presented scientific research of authors, in order to further study the surface roughness Ra and cutting forces of the AlCu3MgMnPb alloy, were used chosen types of changeable cutting inserts for the all realized experimental measurement of machining, which were utilized to external turn of experimental specimens, and then selected kinds of cutting inserts were studied and then compared, and the effect of applied cutting parameters to the surface roughness Ra of the turned specimens are also investigated in the machining. In turning of selected aluminium alloy have to be taken into characteristics that the geometry of used cutting edge has well defined geometric shape. This, together with the kinematics of the movement has effect on the micro geometry of the machined surface. From applied cutting conditions it has the following influence on achievable cutting forces and surface roughness Ra on cutting speed v_c and feed rate f [6]. The numerical analysis of cutting forces in metals machining have not only practical but also theoretical importance too. Theoretical knowledge of the cutting forces refines the theories about the cutting process. In practice, again knowledge of the importance of cutting forces for design tools, the selection of cutting conditions, calculations and design of machine tools etc. Cutting forces in machining is a limiting factor for the machinability [12].

They affect the power consumption during machining, such as turning where high cutting forces represent required high cutting performance, which is often limited by the law applicable power requirement of machine [7-11].

Cutting forces can cause deformation of workpiece and cutting tool, which may cause formation of vibration and material deformation. Cutting tool durability is very short at very high cutting forces. It's caused by pushing it out the cutting edge of the tool inserts. High cutting forces give rise to a high temperature of machining, which causes the excessive back tool wear by the plastic deformation. Size values of cutting forces affecting workpiece material, cutting tool geometry and applied cutting conditions [12, 13]. With the processing performance advantages observed in the authors used literature sources, the objective in this presented experimental investigation was to determine the optimum surface roughness Ra and measured and calculated values and processes of cutting forces with the usage of applied cutting process in terms of used machining parameters.

2 Materials and methods

All experimental measurements (surface roughness and cutting forces) were realized for different cutting conditions while turning of aluminium AlCu3MgMnPb alloy. Chemical composition of AlCu3MgMnPb alloy is 0.23% Si, 0.37% Fe, 2.79% Cu, 0.67% Mn, 0.65% Mg, 0.09% Zn, 0.02% Ni, 0.03% Cr, 0.81% Pb, 0.09% Sn, 0.03% Ti, 0.14% Bi, 94% Al and was measured by spectral analysis method through the Spectrolab JrCCD evaluation device. For the all realized experiments, the Colchester Tornado T4 CNC lathe machine was used. All the applied specimens used in these investigations were 75 mm in diameter. At the end of the process, the effects of cutting speed and feed rate on surface roughness and the cutting forces measurements were investigated in these experiments. Different changeable cutting inserts were used in all turning applications. Coated carbide inserts K10 and H10 quality and DP cutting inserts especially for use with aluminium alloys were employed, and a new cutting tool was used for each turning experiment. All the measured values are given in Table 1 and 2. The surface roughness values were measured by the Talysurf CLI 1000 surface roughness device. During the cutting forces measurements were performed under these conditions. Used machine has a universal CNC lathe machine tool, with variable speed control and incrementally graduated with sliding doors, without the use of the process fluid. As dynamometer have been used three component piezoelectric equipment Type 5001 recorder with BBC GOERZ type 330 and a computer with installed software for evaluation software DASYLAB 3.5. The structure of the dynamometer has to meet more strict requirements concerning the natural frequency and wide frequency response and small cross-sensitivity. The ring elements must be machined identical and symmetrical to prevent cross-sensitivity and they should have certain surface quality and high measurement tolerance.

3 Experimental procedure

The aim of the all realized investigations of this scientific paper is to perform a set of experimental measurements with three-component piezoelectric dynamometer Type 5001 [7, 8, 10, 12, 13] and measure the components of cutting forces in the external longitudinal turning based on a change in cutting speed, feed rate motion, depth of cut, and the radius of the changeable cutting insert made of cemented carbide and the next results to achieve by statistical process method of least squares. Further experiments were repeated with Ø75 x 100 mm samples of AlCu3MgMnPb alloy for investigation of surface roughness changes depending on cutting speed, feed rate and depth of cut. The variation of surface roughness change $Ra = f(v_c)$ can be seen in Table 5 for various coated carbide and polycrystalline diamond changeable inserts at r_ε = 0.2; 0.4; 0.8 mm. Graphical dependence of surface roughness on cutting speed $Ra = f(v_c)$ can be seen in Figure 8. How to reflect the change of feed rate f to the change of surface roughness Ra at constant v_c = 400 m·min^{-1}, and constant a_p = 1.0 mm with coolant, in the same machine tool, shows Table 6 and graphical dependence in Figure 9 for turning of AlCu3MgMnPb alloy. In the process of realized experiments of cuttin forces will be monitored and measured the partial dependence F_c = function of depth of cut (a_p) and F_c = function of feed rate (f).

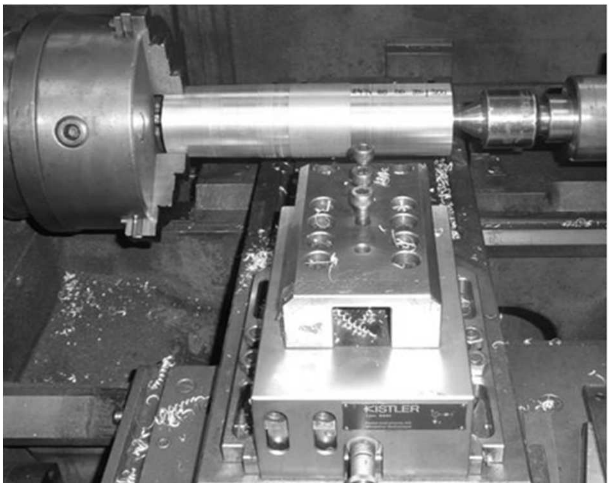

Fig. 1 *Experimental set-up of three component dynamomenter Kistler Type 5001 based on piezoelectric cells and clamped in lathe machine tool*

4 Results and discussion

The value of frequency of rotation of the spindle is n = 1845 min^{-1}, measured using a revolution counter. Variables of the cross section are $S = a_p \cdot f$ [mm^2]. Changing the cross-abstracted layer that is to say depth of cut a_p [mm] at a constant feed rate f_o = 0.1 mm, respectively f the feed at a constant depth of cut a_{po} =1.0 mm = const. The aim was to determine the constants C_{Fc}' and C_{Fc}'' exponents X_{Fc} and Y_{Fc} from cutting forces:

$$F_c = C_{F_c} \cdot a_p^{x_{Fc}} \cdot f^{y_{Fc}} \text{ [N]} \quad (1)$$

The exponential equation after linearization using decimal logarithms entry is in following logarithmical form:

$$\log F_{c_i} = \log C_{F_c} + x_{F_c} \cdot \log a_{p_i} + y_{F_c} \cdot \log f_i \quad (2)$$

Where: i = 1,2, -6 is number of measurements N

The measured data are arranged in Table 1 and Table 2, for f_o = 0.1 mm = const. and a_{po} = 1.0 mm = const. to determine the partial constants C_{Fc}' and C_{Fc}'' and exponents of single parametric dependence method of least squares:

$$F_c = C_{F_c}' \cdot a_p^{x_{Fc}} \quad \text{for the } f_o = 0.101 \text{ mm = const.} \quad (3)$$

$$F_c = C_{F_c}'' \cdot f^{y_{Fc}} \quad \text{for the } a_{po} = 1.0 \text{ mm = const.} \quad (4)$$

Tab. 1 *Measured values of F_c and F_f for the cutting insert CC: DCGT 11T304–K10 (H10)*

a_p [mm]	0.25	0.5	0.75	1.0	1.25	1.5
F_c [N]	22	45	67	90	107	127
F_f [N]	5	11	15	20	24,5	29

Tab. 2 *Measured values of F_c and F_f for the cutting insert CC: DCGT 11T304–K10 (H10)*

f [mm]	0.023	0.054	0.1	0.15	0.2	0.3
F_c [N]	28	52	87	123	164	224
F_f [N]	14	15	20	23	24	26

The formula of the main cutting force F_c is then written in the following form:

$$F_c = C'_{F_c} \cdot a_p^{x_{F_c}} \quad (5)$$

With the linearization of formula (5) using the decimal logarithms can be then written in the following form:

All the calculated values from the Table1 can be seen in Table 3.

$$\log F_{c_i} = \log C'_{F_c} + x_{F_c} \cdot \log a_{p_i} \quad (6)$$

Tab. 3 *Measured values of F_c and F_f for the cutting insert CC: DCGT 11T304–K10 (H10)*

No.	F_{ci} [N]	a_{pi} [mm]	log F_{ci}	log a_{pi}	log a_{pi}^2	log a_{pi} · log F_{ci}
1	22	0.25	1.34242	-0.60206	0.36246	- 0.80822
2	45	0.5	1.65321	- 0.30103	0.09062	- 0.49766
3	67	0.75	1.82607	- 0.12494	0.01561	- 0.22815
4	90	1.0	1.95424	0	0	0
5	107	1.25	2.02938	0.09691	0.00939	0.19666
6	127	1.5	2.10380	0.17609	0.00310	0.37046
Σ			10.90900	-0.75500	0.48677	-0.96691

Then is applied the substitution of the relations by the method of least squares:

$$x_{F_c} = \frac{N \cdot \sum \log a_{p_i} \cdot \log F_{c_i} - \sum \log a_{p_i} \cdot \sum \log F_{c_i}}{N \cdot \sum \log a_{p_i}^2 - \left(\sum \log a_{p_i}\right)^2} \quad (7)$$

$$x_{F_c} = \frac{6 \cdot (-0.96691) - (-0{,}755) \cdot (10.909)}{6 \cdot (0.48677) - (-0.755)^2} =$$

$$= \frac{-5.80146 + 8.23630}{2.921 - 0.57} = \frac{2.43484}{2.351} = 1.0357 = tg\alpha_1$$

Then obtained value is: $\alpha_1 = arctg\ 1.0357 = 46^o$

$$\log C'_{F_c} = \frac{\sum \log F_{c_i} - x_{F_c} \cdot \sum \log a_{p_i}}{N} = \frac{11.691}{6} = 1.94848 \quad (8)$$

Then obtained value is: $C_{Fc}' = 10^{1.94848} = 88.8137$

It can be written the equation for the shape of the main cutting force $F_c = 88.8137 \cdot a_p^{1.0356}$ [N]

The same procedure as before we done can be written to determine the constant C_{Fc}'' and exponent Y_{Fc}, for the following ratio $F_c = f(f)$:

$$F_c = C''_{F_c} \cdot f^{y_{Fc}} \quad (9)$$

$$\log F_{c_i} = \log C''_{F_c} + y_{F_c} \cdot \log f_i \quad (10)$$

All the calculated values from the Table 4 are shown in Table 4:

Tab. 4 *The logarithms of cutting force Fc and displacements of measured force*

	F_{ci} [N]	f_i [mm]	log F_{ci}	log f_i	log f_i^2	log f_i · log F_{ci}
1	28	0.023	0.44716	-1.63827	2.68393	- 0.73257
2	52	0.054	0.71600	- 1.26761	1.60684	- 0.90761
3	87	0.101	0.93952	- 1.00432	1.00866	- 0.94358
4	123	0.162	1.08991	- 0.79048	0.62486	- 0.86155
5	164	0.224	1.21484	-0.65758	0.43241	- 0.79885
6	224	0.282	1.35025	-0.54975	0.30222	-0.74229
Σ			5.7577	- 5.90801	6.65892	-4.9864

Then is applied the substitution of the relations by the method of least squares again:

$$y_{F_c} = \frac{N \cdot \sum \log f_i \cdot \log F_{c_i} - \sum \log f_i \cdot \sum \log F_{c_i}}{N \cdot \sum \log f_i^2 - (\sum \log f_i)^2} \quad (11)$$

$$y_{F_c} = \frac{6 \cdot (-4.9864) - (-5.90801) \cdot (5.7577)}{6 \cdot 6.65892 - (-5.90801)^2} =$$

$$= \frac{4.0981}{5.048} = 0.812 = tg\alpha_2$$

Then obtained value is: $\alpha_2 = arctg\ 0.812 = 39^o$

$$\log C''_{F_c} = \frac{(\sum \log F_{c_i} - y_{F_c} \cdot \sum \log f_i)}{N} = \frac{10{,}556}{6} = 1{,}759 \quad (12)$$

Then obtained value is: $C_{Fc}'' = 10^{1.759} = 57.411$

Now it can be written the equation for the shape of the main cutting force $F_c = 57{,}411 \cdot f^{0.812}$ [N]

The calculated values are reported in double logarithmic coordinate system can be seen in Figure 2 and 3.

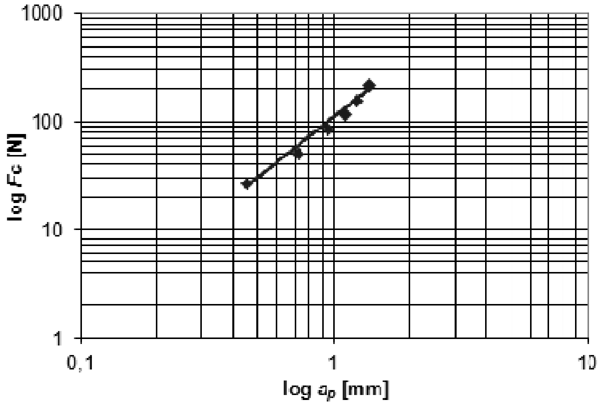

Fig. 2 *Graphical dependence of the $F_c = f(a_p)$ in the double logarithmical coordinate system*

Graphical dependences of the measured values of cutting forces depending on the depth of cut and feed rate are shown in Figures 4, 5, 6, 7, and their shape is as follows.

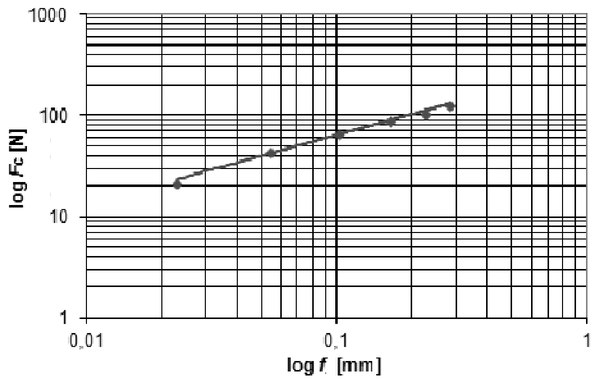

Fig. 3 *Graphical dependence of the $Fc = f(f)$ in the double logarithmical coordinate system*

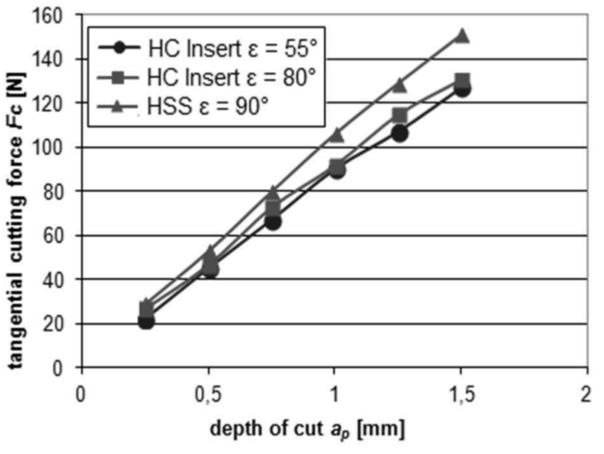

Fig. 4 *Obtained graphical dependences of the tangential cutting force F_c versus cutting parameter depth of cut a_p in turning with the selected types of cutting inserts*

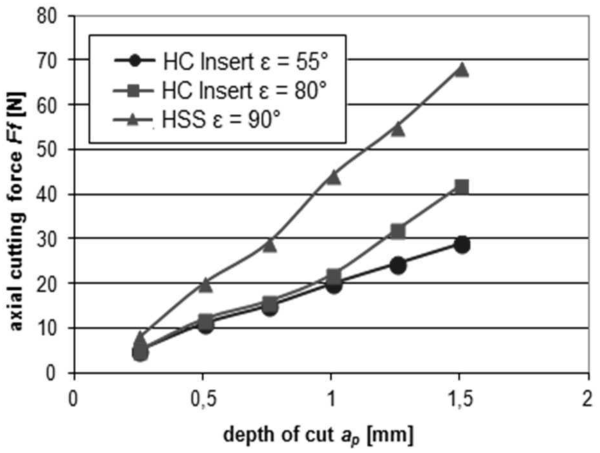

Fig. 5 *Obtained graphical dependences of the axial cutting force F_f versus cutting parameter depth of cut a_p in turning with the selected types of cutting inserts*

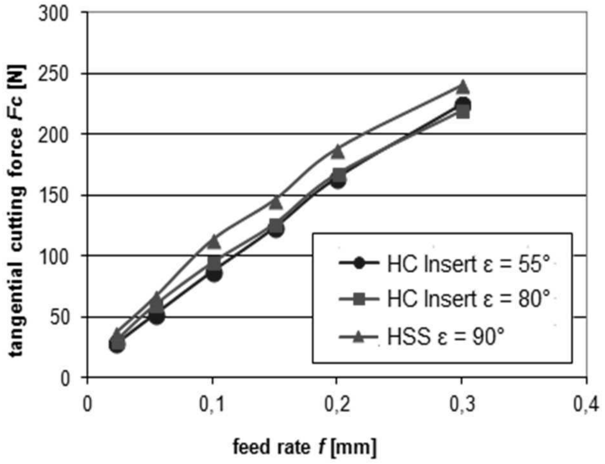

Fig. 6 *Obtained graphical dependences of the tangential cutting force F_c versus cutting parameter feed rate f in turning with the selected types of cutting inserts*

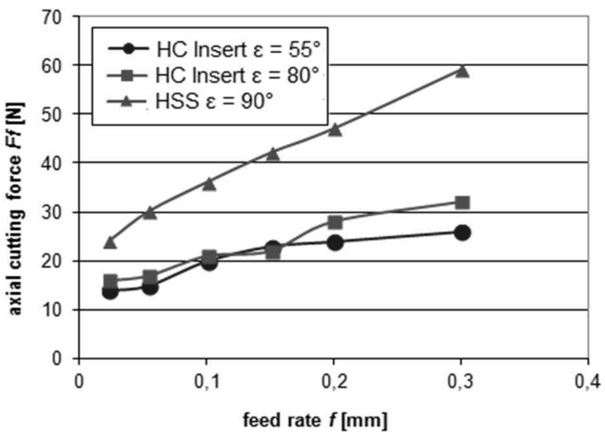

Fig. 7 *Obtained graphical dependences of the axial cutting force F_f versus cutting parameter feed rate f in turning with the selected types of cutting inserts*

Experimental investigation of surface roughness $Ra = f(v_c)$, $Ra = f(f)$ dependences in turning of the selected Al alloy were also tested. All measured and obtained values can be seen in the next following tables and figures.

***Tab. 5** Measured values of change of surface roughness versus cutting speed when applied various types of cutting inserts*

v_c [m·min^{-1}]	r_ε= 0.2 mm	r_ε= 0.4 mm				r_ε= 0.8 mm
	Carbide insert ε =55°	Carbide insert ε =35°	Carbide insert ε =55°	Carbide insert ε =80°	Diamond insert ε =80°	Carbide insert ε =55°
	Ra [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]
25	3.74	2.01	1.9	2.1	0.6	1.01
50	3.81	2.04	2.01	2.12	0.58	1.04
100	3.88	2.08	1.97	2.13	0.6	1.05
200	3.93	2.09	1.99	2.13	0.57	1.07
400	3.94	2.1	2.02	2.14	0.59	1.07
600	4.0	2.09	2.01	2.15	0.59	1.06
850	4.01	2.1	1.99	2.4	0.61	1.09
1000	4.04	2.13	1.97	2.53	0.63	1.13

***Tab. 6** Measured values of change of surface roughness versus feed rate when applied various types of cutting inserts*

f [mm]	r_ε= 0.2 mm	r_ε= 0.4 mm				r_ε= 0.8 mm
	Carbide insert ε =55°	Carbide insert ε =35°	Carbide insert ε =55°	Carbide insert ε =80°	Diamond insert ε =80°	Carbide insert ε =55°
	Ra [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]	*Ra* [μm]
0.05	0.37	0.29	0.43	0.54	0.27	0.22
0.08	0.78	0.73	0.68	0.96	0.4	0.34
0.1	1.31	1.06	1.02	1.31	0.48	0.48
0.125	2.41	1.52	1.47	1.7	0.49	0.72
0.15	4.05	2.12	1.93	2.13	0.61	1.07
0.25	11.91	5.68	5.01	4.14	1.42	2.81

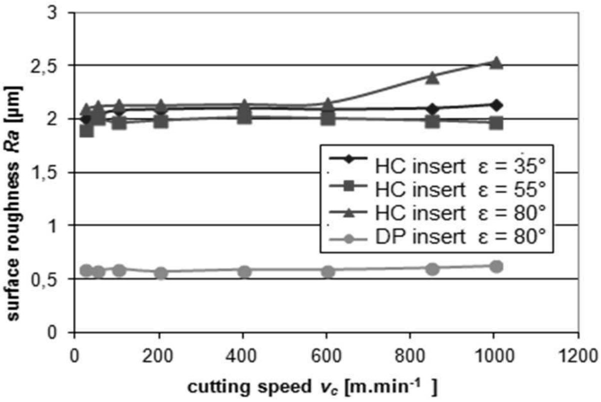

***Fig. 8** Graphical dependence of Ra = f (v_c) versus cutting speed v_c while machining with the various geometrical types of cutting inserts*

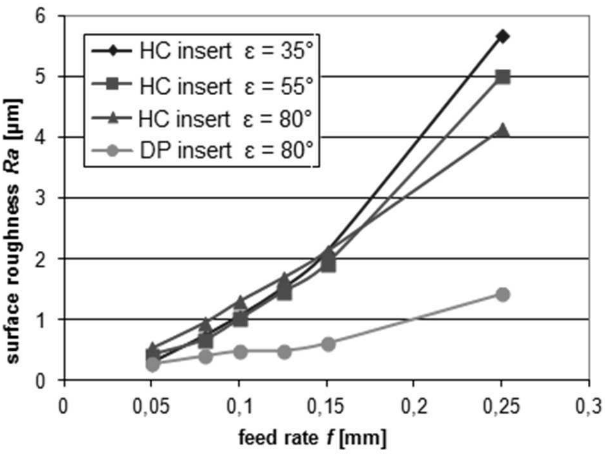

***Fig. 9** Graphical dependence of Ra = f (f) versus feed rate f while machining with the various geometrical types of cutting inserts*

5 Conclusion

All realized experimental measurements of cutting forces in turning of aluminium AlCu3MgMnPb alloy with the piezoelectric dynamometer Kistler of type 5001 have brought a fact, that the cutting speed increases of cutting force F_c resizing shift and a change in the depth of cut, dry with v_c = 400 m . min^{-1}, f_0 = 0.1 mm, a_{p0} = 1 mm. Graphical dependences of tangential cutting force F_c and axial cutting force *Ff* on the size of the feed and cutting depth (can be seen in Figures 4, 5, 6, 7) are processed by the usage of method of least squares in a logarithmic coordinate system (also can be seen in Figures 2 and 3). The angle between the obtained dependence (can be seen in Figures 2 and 3) and horizontal axis of the graph (log a_p and log *f*) represents the one impact of these physical parameters on tangential component of cutting force F_c. With the increasing size of the angle increases the impact of the main physical parameters a_p *and f* on the cutting force F_c. The theoretical benefit is also a fact that cutting forces F_c and F_f are significantly smaller in turning AlCu3MgMnPb alloys, such as in turning steel with the same strength (only 30% of the value of steel component F_f only 20 %) and grow well with the growth of feed rate *f* and depth of cut a_p. The practical benefit is the finding that in hardened aluminium alloy machinability is attained by surface roughness *Ra* very good and improves with increasing of the hardness (strength). Effect of cutting speed of change of force F_c was not measured. That opens the new ways for further research in this area, to optimize the technological process of turning machine parts made from aluminium alloys in the production of their dominant functional areas. The next step in the future study of the technological process of production of components for the automobile industry, the team of authors will study the integrity of the machined surface in terms of tool wear *VB* [mm] and tool life *T* [min] of study and areas of technological system cutting insert workpiece in the cutting process with the influence of apllied cutting parameters v_c [m.min^{-1}] and *f* [mm].

Acknowledgement

Authors would like to acknowledge the experimental facility provided by the Faculty of mechanical engineering (University of Zilina), Faculty of special technology (A. D. University of Trencin) and Faculty of Education (University of Hradec Kralove) to carry out this experimental work and research.

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DOI: 10.21062/ujep/55.2018/a/1213-2489/MT/18/1/66