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INFLUENCE OF THE CUTTING PARAMETERS ON FORCE, MOMENT AND SURFACE ROUGHNESS IN THE END MILLING OF ALUMINUM 6082-T6

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Abstract. *In this paper the performances, i.e. cutting force, moment and surface roughness, in the end milling of aluminum 6082-T6 with solid carbide end mill were measured and analyzed for different values of the cutting parameters: number of revolutions, feed rate and depth of cut. The cutting force and moment were measured using a Kistler piezoelectric dynamometer. Surface roughness was measured using a Mahr profilometer. The results were analyzed in the Minitab 17 software package, in order to determine the influence of the given factors on the performances and modeling of the milling process.*

Key Words: *Cutting Force, Moment, Surface Roughness, Aluminum*

1. Introduction

The cutting force, moment and surface roughness are the most important indicators of machinability of materials and are very significant for the theory of cutting processes.

By separating the cutting layer from the machining surface, the cutting edge of the cutting tool encounters the force. This force removes a layer of material and separates it from the workpiece in the form of chips. Depending on the machining conditions, the magnitude of force can vary widely. The force is the main indicator of wear control, the quality of the machined part, and the shape of chips and vibrations. Knowing the cutting force enables one, among other things, to determine the energy balance of the machine tool, do the calculation and dimensioning of the elements of the kinematic system of machine tool, do the calculation and dimensioning of the cutting tool, optimize the machining process and enhance the efficiency of the process based on the calculation of the optimal values of the cutting parameters [1]. The force can be determined by measuring the components by the dynamometer.

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The force components in the end milling process can be decomposed into [2]:

- F_c-cutting (tangential) force,
- F_f-feed (radial) force, and
- F_p-thrust (axial) force.

The machined surface quality is evaluated by surface roughness of the machined part and it is one of the most significant product quality characteristics [3, 4]. Surface roughness depends on the cutting conditions, especially the form of cutting tools, tool wear, deposits, vibration, etc. The basic parameters for monitoring surface roughness are:

- R_a-arithmetic average of the absolute values,
- R_z-medium unevenness depth, and
- R_{max}-maximum unevenness depth.

Milling achieves surface roughness from N5 to N12 with the arithmetic average of absolute values R_a of 0.4 to 50 µm, respectively.

The experimental measurement of cutting force and surface roughness in the milling process has been investigated by a large number of researchers and so has the application of analytical methods for modeling. One of the most important analytical models of the cutting force was created by Kienzle and Victor [5] in the 1950s. Ganesh Babu [6] investigated the effects of the cutting parameters (cutting speed, feed rate and depth of cut) on the cutting force during end milling of AlSiC metal composite material using the Response Surface Methodology (RSM). The experiment was conducted using a four teeth high-speed steel end milling cutter with 10 mm in diameter on the vertical milling machine. The cutting forces were measured with a Kistler piezoelectric dynamometer, type 9257B. The cutting forces increased when the depth of cut increased. Tsai [7] investigated the influence of the feed per tooth and the tool diameter on the cutting force in milling aluminum 6060-T6. The experiment was conducted using a carbide end milling cutter with two teeth and with diameters of 12, 16, and 20 mm, the spindle speed of 1000 rev/min and the depth of cut of 1 mm, while the feed rate was varied with values of 200, 260, 300, 360 and 400 mm/min. The cutting forces were measured with a Kistler piezoelectric dynamometer, type 9257B. The cutting forces were simulated by the Recursive Least Square (RLS) method and compared with the experimental values. Thamban [8] investigated the machining parameters (spindle speed, feed rate and depth of cut) during end milling aluminum 6061-T6 with coated tungsten carbide and diamond coated end milling cutter with 10mm in diameter. All the components of the cutting forces were measured with a Kistler piezoelectric dynamometer, type 9257B. The cutting force was observed to be increasing with depth and feed rate during the end milling for both the cutting tools (coated and uncoated). Turgut [9] investigated the effect of machining parameters (cutting speed, feed rate and depth of cut) on the cutting force and surface roughness in the face milling operation of AlSiC metal matrix composites. The cutting force and surface roughness were measured at cutting speeds of 300, 350, 400 and 450 m/min, feed per tooth of 0.1, 0.15 and 0.20 mm/tooth and depth of cut of 0.5 and 1 mm. The experiment was conducted using coated and uncoated milling cutters of 32 mm in diameter on the vertical machining center Johnford VMC-850 without using coolant. The cutting forces were measured with a Kistler piezoelectric dynamometer, type 9257B. Increasing the feed per tooth and depth of cut increased the cutting force for all the cutting conditions, but increasing cutting speed decreased the cutting force. The best results of the cutting force were obtained with the cutting speed of 400 m/min and the feed rate of 0.1mm/tooth. Jeykumar [10] investigated the influence of spindle speed, feed rate and depth of cut on the cutting force, tool wear and surface roughness in the end milling operation of Al6061/SiC using the Response Surface Methodology. The experiment was conducted using a milling cutter with indexable inserts made of tungsten carbide on the milling machine HMT-FNIU. The cutting forces were measured using a Kistler piezoelectric dynamometer, type 5070. The experimental results were compared with the mathematical model developed using the Response Surface Methodology.

The objective of this study is to determine the influence of the factors (spindle speed, feed rate and depth of cut) on the performances (cutting force, moment and surface roughness) in the end milling of aluminum alloy 6082-T6. The obtained mathematical model facilitates planning the milling process.

2. EXPERIMENTAL STUDY

In the experimental measurements of the force, moment and surface roughness in the end milling samples of aluminum alloy 6082-T6 were used, with the following dimensions of the workpiece: 50x30x400 mm. The chemical composition of the aluminum alloy 6082-T6 is given in Table 1.

Table 1 Chemical composition of Al 6082-T6

Chemical elements	Composition [%]
Al	95.2-98.3
Cr	0.25
Cu	0.1
Fe	0.5
Mg	0.6-1.2
Mn	0.4-1.0
Si	0.7-1.3
Ti	0.1
Zn	0.2
Others	0.15

The cutting tool that was used in the experiment was solid carbide end mill JS413160D2SZ3.0, manufactured by SECO, Fig 1. The geometry of the end milling cutter is given in Table 2 [11].

Fig. 1 Solid carbide end mill SECO

Table 2 Cutting geometry of solid carbide end mill

Diameter-Dc[mm]	16
Max depth of cut-a_p [mm]	32
Diameter of tool shrank-d_m [mm]	16
Length of cutting tool- l_2 [mm]	100
Number of teeth- z_n	3
Helix angle-ω [°]	40
Cutting tool edge angle-κ [°]	90
Rake angle-ε [°]	20

For design of the experiment the selected factors of the milling process were spindle speed (n), feed rate (V_f) and depth of cut (a_p). They were the main factors that influence the cutting force, moment and surface roughness. The factors were varied on two levels. The levels of factors are shown in Table 3.

Table 3 Levels of factors

Factors	Levels		
	-1	0	+1
Spindle speed-n [rev/min]	320	405	560
Feed rate-V_f [mm/min]	62	93	175
Depth of cut-a_p [mm]	0.4	0.7	1.2

The experimental research was carried out on the “Prvomajska” UGH universal milling machine, under the laboratory conditions. The force and moment were measured with a Kistler piezoelectric dynamometer, type 9123C. The experimental setup is shown in Fig. 2.

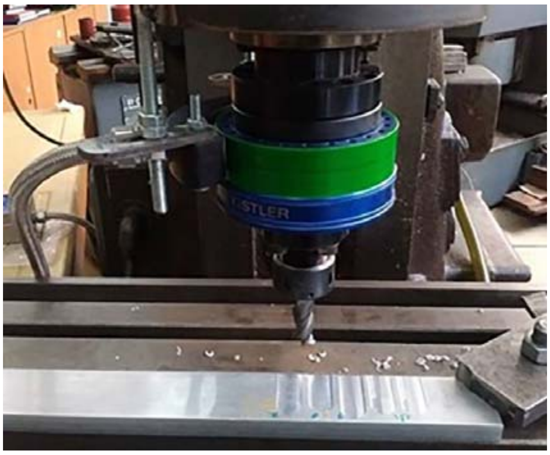


Fig. 2 Universal milling machine “Prvomajska” UGH

Surface roughness was measured on a Mahr profilometer under the laboratory conditions, Fig. 3.

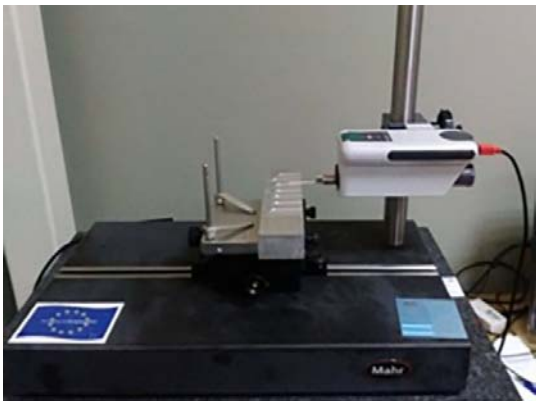


Fig. 3 Mahr profilometer for measuring surface roughness

The plan of the experiment and measurement results of force F_c, moment M and surface roughness R_a is shown in Table 4.

Table 4 The plan of the experiment and measurement results

No.	n [rev/min]	V_f [mm/min]	a_p [mm]	n [rev/min]	V_f [mm/min]	a_p [mm]	F_c [N]	M [Nm]	R_a [µm]
1	-1	-1	-1	320	62	0.4	37.3	0.30	2.907
2	-1	-1	1	320	175	1.2	125.0	0.9	1.600
3	-1	1	-1	320	62	0.4	98.6	0.76	5.191
4	-1	1	1	320	175	1.2	211.8	2.42	4.267
5	1	-1	-1	560	62	0.4	31.6	0.26	1.673
6	1	-1	1	560	175	1.2	76.7	0.69	1.757
7	1	1	-1	560	62	0.4	74.6	0.57	3.348
8	1	1	1	560	175	1.2	174.9	1.45	3.301
9	0	0	0	405	93	0.7	55.0	0.55	1.945
10	0	0	0	405	93	0.7	50.0	0.50	1.976
11	0	0	0	405	93	0.7	60.0	0.58	1.988

3. Analysis of Results and Discussion

The cutting force, moment and surface roughness measurement results were analyzed by using the analysis of variance (ANOVA) in the Minitab 17 software package.

It is clear from the results of ANOVA that depth of cut (a_p) and feed rate (V_f) are the dominant factors affecting the cutting force. The factors influencing the force are: spindle speed (n), feed rate (V_f), followed by spindle speed (n), while the interaction between feed rate and depth of cut ($V_f a_p$) and that between spindle speed and depth of cut (na_p) are also significant. The interaction between spindle speed and feed rate (nV_f) and three ways interaction ($nV_f a_p$) is not significant based on the P-value because its value is greater than 0.1 [12, 13, 14]. F-value is used to determine whether group means are equal, it is just a matter of including the correct variances in the ratio. The analysis of variance for the cutting force is given in Table 5.

Table 5 Analysis of variance for cutting force

Factors and interactions	Sum of square	Mean square	F-value	P-value
N	1650.3	1650.3	66.01	0.015
V_f	10461.8	10461.8	418.47	0.002
a_p	14990.5	14990.5	599.62	0.002
nV_f	6.0	6.0	0.24	0.674
na_p	385.0	385.0	15.40	0.059
V_fa_p	814.1	841.1	32.56	0.029
nV_fa_p	110.3	110.3	4.41	0.171

All factors and interactions have a significant effect on the moment. The analysis of variance for the moment is given in Table 6.

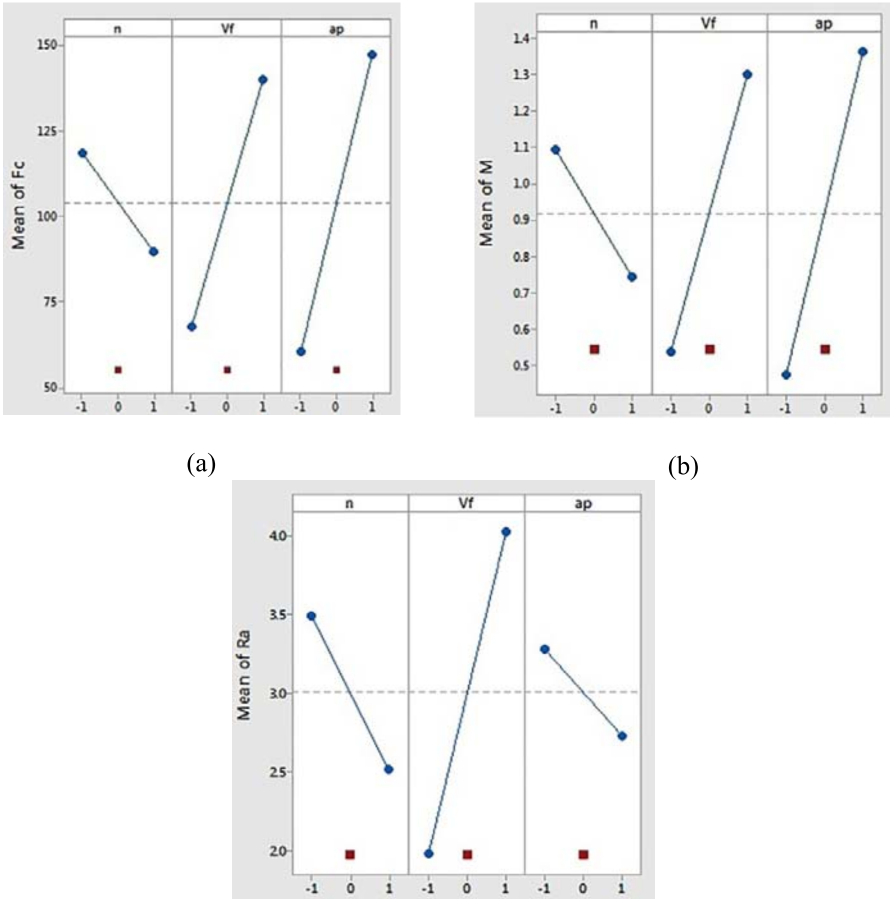
Table 6 Analysis of variance for moment

Factors and interactions	Sum of square	Mean square	F-value	P-value
N	0.24851	0.24851	152.15	0.007
V_f	1.16281	1.16281	711.93	0.001
a_p	1.59311	1.59311	975.37	0.001
nV_f	0.10351	0.10351	63.38	0.015
na_p	0.11281	0.11281	69.07	0.014
V_fa_p	0.28501	0.28501	174.50	0.006
nV_fa_p	0.04651	0.04651	28.48	0.033

All factors and interactions have a significant effect on surface roughness. The analysis of variance for surface roughness is given in Table 7.

Factors and interactions	Sum of square	Mean square	F-value	P-value
N	1.8876	1.88762	3834.04	0.000
V_f	8.3436	8.34561	16947.08	0.000
a_p	0.6017	0.60170	1222.15	0.001
nV_f	0.3750	0.37498	761.63	0.001
na_p	0.6430	0.64298	1305.98	0.001
V_fa_p	0.0079	0.0794	16.12	0.057
nV_fa_p	0.0330	0.03302	67.08	0.015

Based on the obtained data, the influence of the factors on the cutting force, moment and surface roughness in the end milling of aluminum 6082-T6 can be determined. The greatest effect on the cutting force and moment during the end milling of aluminum 6082-T6 with solid carbide end mill has the depth of cut, followed by the feed rate and the spindle speed. By increasing the depth of cut and the feed rate, the cutting force and the moment increase, while increasing the spindle speed causes decrease of the cutting force and moment, Fig. 4 (a), (b). The effect on surface roughness during the end milling of aluminum 6082-T6 has the feed rate. By increasing the feed rate, surface roughness increases, while increasing the spindle speed and depth of cut causes decrease of surface roughness, Fig. 4 (c).



(a) (b)

(c)

Fig. 4 Influence of n, V_f and a_p on: a) cutting force, b) moment and c) surface roughness

To simulate the process in terms of the cutting force, a mathematical model was developed using the multiple regression method. The mathematical model is given in Eq. (1):

$$F_c = 103.81 - 14.36n + 36.16V_f + 43.29a_p + 10.09V_f a_p - 6.94na_p \quad (1)$$

The coefficient of determination is R^2=99.85%, while the adjusted coefficient of determination is $R^2(adj)$=99.26%.

The mathematical model of the moment is given in Eq. (2):

$$M = 0.9188 - 0.1763n + 0.3812V_f + 0.4462a_p - 0.1137nV_f - 0.1187na_p + +0.1888V_f a_p - 0.0763nV_f a_p \quad (2)$$

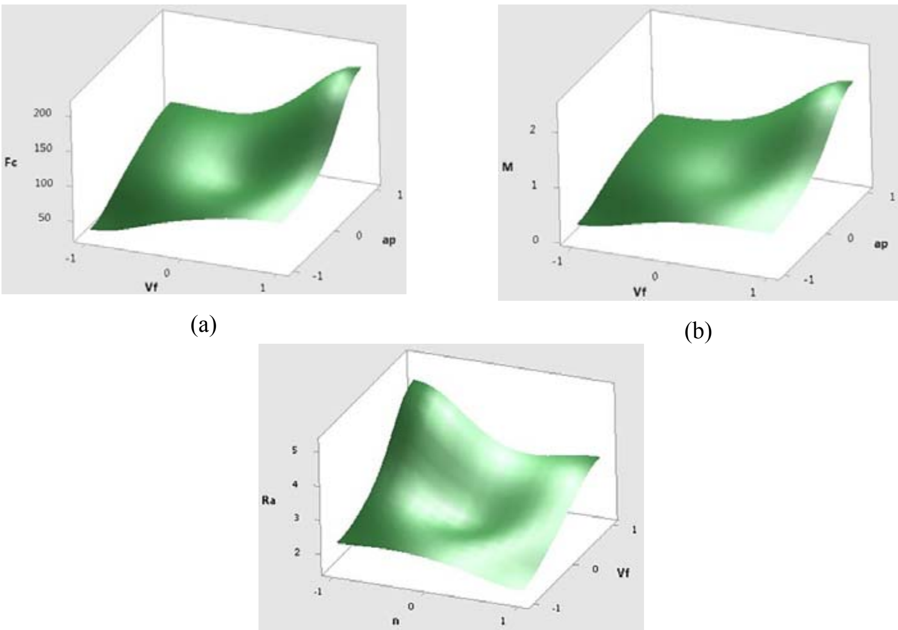
The coefficient of determination for the moment is R^2=99.92%, while the adjusted coefficient of determination is $R^2(adj)$=99.58%.

The mathematical model of surface roughness is given by Eq. (3):

$$Ra = 3.0055 - 0.48575n + 1.02125V_f - 0.27425a_p - 0.2165nV_f + 0.2835na_p + 0.0315V_f a_p - 0.06425nV_f a_p \quad (3)$$

The coefficient of determination of surface roughness is R^2=99.99%, while the adjusted coefficient of determination is $R^2(adj)$=99.97%.

Based on the 3D surface plots of the cutting force, moment and surface roughness one can study the relations among the influencing factors during the end milling of aluminum alloy 6082-T6, Fig. 5.



(a) (b)

(c)

Fig. 5 3D surface plots of a) cutting force, b) moment and c) surface roughness

4. CONCLUSIONS

Investigating the cutting force, moment and surface roughness is important for the process of milling. The cutting force and moment are the basic criteria for evaluation of machinability, while surface roughness is the basic criteria for the quality of parts. The knowledge of these performances facilitates the effective planning of the machining process.

The measurement of the cutting force, moment and surface roughness was carried out for different values of spindle speed (320.405 and 560 rev/min), feed rate (62, 93 and 175 mm/min) and depth of cut (0.4, 0.7 and 1.2 mm) in the laboratory conditions on a universal milling machine during the milling of aluminum alloy 6082-T6 with solid carbide end mill, manufactured by Seco, without cooling. The cutting force and moment were measured using a Kistler piezoelectric dynamometer, while surface roughness was measured on a Mahr profilometer.

Based on the experimental results of the cutting force, moment and surface roughness, an analysis was performed in the Minitab 17 software package. In the end milling of aluminum 6082-T6, the greatest impact on the cutting force and moment is achieved by the depth of cut, followed by the feed rate and the spindle speed. By increasing the cutting depth and the feed rate the main cutting force and moment grow as well, while increasing the spindle speed reduces them. On the other hand, the feed rate has the greatest influence on surface roughness. By increasing the feed rate, surface roughness increases as well, while increasing the speed and depth of cut causes decrease of surface roughness, i.e. a better quality of processing is achieved.

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