THE INVESTIGATION OF THE MACHINABILITY OF AN ENGINEERING PLASTIC (PA-6) WITH THE HELP OF DESIGN OF EXPERIMENTS

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The development of engineering plastics and their use in the industry has been growing very dynamically in the last few decades. The machining surface finish of engineering plastics can be done by turning. In this article the machinability of a general purpose engineering plastic (polyamide, PA-6) is investigated during dry turning with the help of design of experiments. The goal of research is to create empirical models with which the surface roughness parameters (Ra – average surface roughness, Rz – ten-point high surface roughness) can be easily estimated as a function of the input cutting parameters. During the cutting experiments the cutting parameters (v_c – cutting speed, f – feed, a_p – depth of cut) are systematically changed. After that we set out to find cutting parameter values which result in the lowest possible surface roughness.

Keywords: design of experiment, engineering plastic, polyamide, PA-6, surface roughness parameters

1. Introduction

Engineering plastics are a group of plastics that have better mechanical and/or thermal properties than the more widely used commodity plastics. Because of their favorable properties, they can substitute traditional structural materials. Engineering plastic surfaces can be finish machined by cutting. Due to the increasing use of engineering plastics, nowadays many researchers investigate their machinability. Such research is usually done with the help of design of experiments because a lot of information can be obtained from relatively few well-chosen experimental runs.

Kumar et al. [1] investigated cutting forces (tangential and feed force) by turning a unidirectional glass fiber reinforced plastics (UD-GFRP) composite. They applied Taguchi's L_{18} orthogonal array in their experiments. The process parameters and levels were as follows: tool nose radius: 0.4-0.8 mm; tool rake angle: -6°-0°-6°; feed rate: 0.05-0.1-0.2 mm; cutting speed: 55.42-110.84-159.66

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m/min; depth of cut: 0.2-0.8-1.4 and the cutting environment: dry, wet, and cooled. The experiments are carried out with a Carbide (K10) tool, the tool holder was SVJCR steel EN47. They investigated the tangential and feed force. From their results the following conclusion can be drawn: the tangential force decreases with a decrease in tool nose radius, feed rate and depth of cut, but it increases with a decrease in cutting speed and in a dry cutting environment. The tangential force decreases as the tool rake angle increases. The feed force in the workpiece decreases with a decrease in feed rate, depth of cut, tool nose radius and in a dry cutting environment, but the feed force increases with an increase in cutting speed and the feed force increases with a decrease in tool rake angle. The depth of cut is the parameter which has the greatest influence on the tangential and feed force. They developed models for tangential force and feed force using regression modelling and the predicted optimum values for multi-response optimization (tangential force and feed force) are 39.93 N and 22.56 N respectively at a tool nose radius of 0.4 mm, a feed rate of 0.05 mm/rev, a cutting speed of 55.75 m/min and a depth of cut of 0.20 mm.

Lazarevic et al. [2] also used the Taguchi (L_{27}) method to minimize the surface roughness in turning polyamide PA-6. The influence of four cutting parameters: cutting speed (65,03 115.61 and 213.88 m/min), feed rate (0.049, 0.196 and 0.098 mm), depth of cut (1, 2 and 4 mm), and tool nose radius (0.4 and 0.8 mm) and their interactions on average surface roughness (*Ra*) were analyzed. The tool holder code was: SVJBR 3225P 16 and the insert codes were VCGX 16 04 04-AL (H10) and VCGX 16 04 08-AL (H10). From their work the conclusion can be drawn: the feed rate was the most significant parameter, followed by tool nose radius, and depth of cut, whereas the influence of cutting speed was negligible on surface roughness. The combination of low levels of cutting parameters greatly helped minimize average surface roughness.

Hanafi et al. [3] constructed a fuzzy rule based model and second order quadratic response surface predictive models for cutting force in the turning of reinforced polyetheretherketone reinforced with 30% of carbon fiber composite (PEEK CF30). The tool holder code used was SDJCL 2020 K11 and the insert used was TiN coated ISCAR WNMG 080408-TF. The three components of turning force were recorded. The three cutting parameters were changed at three levels such as: cutting speed (100-200-300 m/min), depth of cut (0.25-0.75-1.5 mm) and feed rate (0.05-0.15-0.2). The obtained coefficients of models were all found to be very close to unity.

Mata et al. [4] constructed predictive models on unreinforced and reinforced polyetheretherketone (PEEK) with 30% of carbon fibres (PEEK CF 30) and 30% of glass fibres (PEEK GF 30). Their goal was to establish relationships between the cutting conditions (cutting speed: 50-100-200 m/min and feed rate: 0.05-0.1-0.15-0.2 mm) on two aspects of machinability, namely, power and specific cutting pressure. The insert was a DCMW 11T3 04FPDC10 PCD tool and the tool holder code was SDJCL 2020 K11. Their results showed that the power increases with an increase in feed rate while the specific cutting pressure decreases. The reinforcements to PEEK improve the material properties, but at the cost of increased power and specific cutting pressure.

Hanafi et al. [5] applied grey relational theory and Taguchi optimization methodology in order to optimize the cutting parameters for PEEK reinforced with 30% of carbon fibers. They turned the material using TiN coated (WNMG080408-TF) tools and a SDJCL 2020 K11 tool holder under dry conditions. The objective of optimization was to simultaneously achieve minimum power consumption and the best surface quality. In their investigation the cutting parameters were changed at three levels (v_c = 100-200-300 m/min; f = 0.02-0.15-0.2; a_p = 0.25-0.75-1.5). In their results they found the optimal cutting parameter setting that enabled them to achieve simultaneous minimization of surface roughness and cutting power. Their results revealed that depth of cut is the most influencing parameter. It is followed by cutting speed and feed rate.

Geier and Mátyási [6] examined carbon fibre-reinforced plastics (CFRP) during drilling. The primary objective of their study was to make a mathematical model of the changing of cutting forces and the macro-geometrical properties with the help of the Central Composite (CC), experimental design method.

Farkas and Kalácska [7] compared the effects of different technological parameters (cutting speed, cutting feed, depth of cut) on the microgeometrical characteristics (*Ra*, *Rz*). They chose several polymers: PA-6, polyoxymethylene (POMC), polyethylene terephthalate (PET), polyether ether ketone (PEEK) and always cut the work pieces without cooling using different parameters (v_c = 200–250–315–400 m/min; f = 0.05–0.08–0.12–0.16–0.2–0.25–0.315–0.4; a_p = 0.5 mm). In their results they constructed equations with which the surface roughness parameters can be estimated.

The authors have already investigated the machinability of aluminum alloys during fine turning with the help of design of experiments [8] [9] [10]. They constructed predictive models for surface roughness parameters (*Ra*, *Rz*), where the quantitative input parameters were cutting speed, feed and depth of cut and the qualitative input parameters were the edge materials of the tool and the type of raw materials [11]. In addition to the general surface roughness parameters (*Ra*, *Rz*), the authors also investigated the statistical parameters of surface roughness (*Rsk* – skewness, *Rku* – kurtosis) and they found that the statistical parameters of surface roughness do not depend on the cutting parameters, only on tool edge geometry [12].

In this article the machinability of polyamide (PA-6) is investigated. The turning examinations were carried out with the help of design of experiments. Our main goal was to construct empirical models with which the surface roughness parameters (*Ra* – average surface roughness, µm; *Rz* – ten-point high, µm) can be easily estimated from the input cutting parameters, such as cutting speed, feed and depth of cut.

2. Materials and methods

2.1 Equipment used in the experiment

The cutting experiments were carried out on (PA-6) engineering plastic. Polyamide-6 (semi-crystalline, thermoplastic) plastic has a lot of advantages, for example: excellent wear resistance, excellent sliding properties, good chemical resistance; favorable electrical properties and the unreinforced types are non-flammable. Of course it has disadvantages, too: it is sensitive to oxidation, it has high water absorption (therefore it can only be cut in a dry environment), it is not transparent, its impact resistance is relatively poor when it is dry and below freezing point.

The most common mode of processing of molded and extruded PA-6 rods is cutting. One reason for this is that PA-6 blocks, rods, plates, tubes can be produced easily by bulk polymerization (Fig. 1.). The size of polyamide rods which were used for the experiment was: Ø60 mm. Their hardness was Shore D: 78.4±0.55.

Fig 1. Polyamide blocks and rods before cutting

The cutting experiments were performed on a MAZAK SUPER QUICK TURN 10MS CNC lathe (P_{max} = 11 kW; n_{max} = 6000 1/min). The tests were carried out with a hard metal insert. Its code was TaeguTec TDA 6.00-3.00 K10 and the tool holder code was TaeguTec T-Clamp TTER 20 20-6. (Fig. 2.)

Fig. 2. The tools used in the experiments

2.2 Average surface roughness parameter (*Ra*)

The average surface roughness parameter is the most universally used roughness parameter for general quality control. This parameter is easy to measure, easy to define and gives a general information of the surface (Fig. 3.)

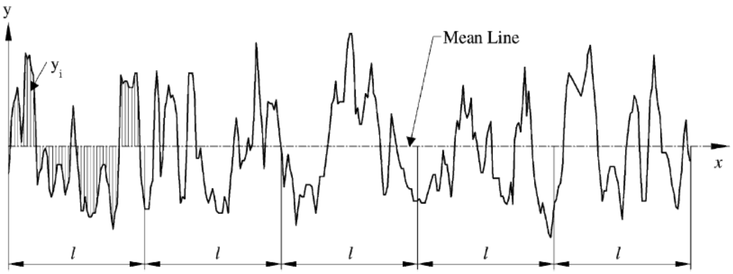

Fig. 3. Specifying average height (*Ra*) [13]

The mathematical definition and the digital implementation of the average surface roughness parameter are as follows [13]:

$$Ra = \frac{1}{l}\int_0^l |y(x)|dx \quad (1)$$

$$Ra = \frac{1}{n}\sum_{i=1}^{n}|y_i| \quad (2)$$

2.3 Ten-point high surface roughness parameter (*Rz*)

The *Rz* parameter is more sensitive to occasional high peaks or deep valleys of the surface than the *Ra* parameter. It can be defined with two methods according to definition. The ISO (International Organization for Standardization) defines *Rz* parameter as the difference in height between the average of the five highest peaks and the five lowest valleys along the assessment length of the profile. The another DIN (Deutsches Institut für Normung) defines this parameter as the average of the summation of the five highest peaks and the five lowest valleys along the assessment length of the profile (Fig. 4.).

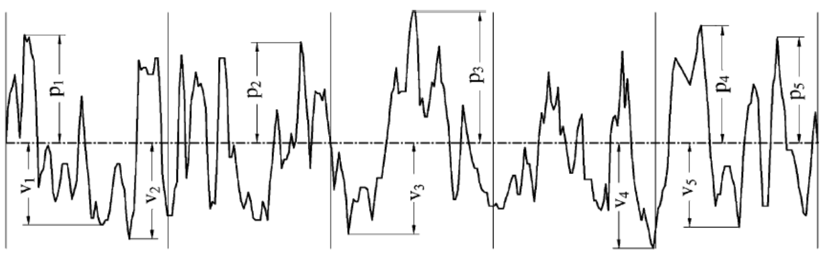

Fig. 4. Definition of *Rz* parameter ($Rz_{(ISO)}$, $Rz_{(DIN)}$) [13]

The mathematical definitions of the two types of *Rz* as follows [13]:

$$Rz_{(ISO)} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i - \sum_{i=1}^{n} v_i\right) \quad (3)$$

$$Rz_{(DIN)} = \frac{1}{2n}\left(\sum_{i=1}^{n} p_i + \sum_{i=1}^{n} v_i\right) \quad (4)$$

where *n* is the number of samples along the assessment length.

The *Ra* and *Rz* surface roughness parameters were measured with a Mitutoyo SJ-301 surface roughness tester. Parameters connected to surface roughness measurements were: l = 4 mm, λc = 0.8, N = 5. The measurements were repeated six times at six reference lines equally positioned at 60° and the results presented were the averages of the measured values. (Fig. 5.)

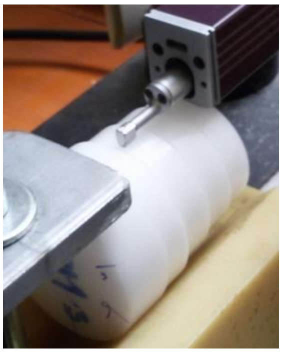

Fig. 5. The measuring of the cut surface of polyamide

2.4 The method used in the tests

The turning tests were performed with the response surface method (RSM) and within it, the so-called central composite design (CCD). During the cutting tests three input factors (v_c - cutting speed, m/min; f - feed, mm and a_p - depth of cut, mm) were changed. Each factor had five different levels. The measured output parameters, as dependent variables, were the *Ra* and the *Rz* surface roughness parameters. Our goal in the experiments was to find the relationship between the independent input parameters (v_c, f, a_p) and dependent output parameters (*Ra*, *Rz*) as follows:

$$Y = \Omega(v_c, f, a_p) \quad (5)$$

where the response function is Ω, in the following form:

$$Y = b_0 + b_1 \cdot v_c + b_2 \cdot f + b_3 \cdot a_p + b_{11} \cdot v_c^2 + b_{22} \cdot f^2 + \\ + b_{33} \cdot a_p^2 + b_{12} \cdot v_c \cdot f + b_{13} \cdot v_c \cdot a_p + b_{23} \cdot f \cdot a_p + \varepsilon \qquad (6)$$

where b_0, b_i and b_{ij} are the calculated coefficients; v_c, f and a_p are the input parameters and ε is the error. The experimental runs and their positions are shown in Fig. 6.

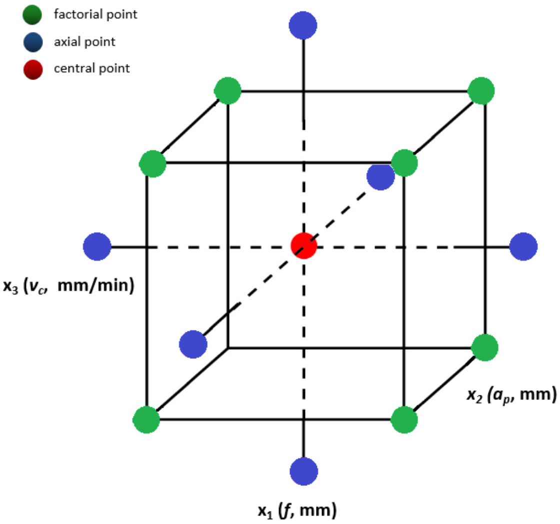

Fig. 6. The location of the experimental runs of the central composite design

The values of the three input factors and their levels are shown in Table 1.

Table 1

The three input factors and their five levels

Levels	Factors		
	v_c, m/min	f, mm	a_p, mm
-1.28719	100	0.050	0.50
-1	167	0.089	0.67
0	400	0.225	1.25
1	633	0.361	1.83
1.28719	700	0.400	2.00

Table 2 contains the experimental runs of the central composite design.

Table 2

The cutting parameters of the experimental runs (two repetitions in the centre point)

Experimental runs	v_c, m/min	f, mm	a, mm
1	167	0.089	0.67
2	167	0.089	1.83
3	167	0.361	0.67
4	167	0.361	1.83

5	633	0.089	0.67
6	633	0.089	1.83
7	633	0.361	0.67
8	633	0.361	1.83
9	100	0.225	1.25
10	700	0.225	1.25
11	400	0.050	1.25
12	400	0.400	1.25
13	400	0.225	0.50
14	400	0.225	2.00
15 (C)	400	0.225	1.25
16 (C)	400	0.225	1.25

3. Results

The significance test carried out before the construction of the phenomenological models. (Table 3.)

Table 3

The significant parameters affecting the surface roughness (x – significant; 0 – not significant)

	Ra, µm	*Rz*, µm
v_c	x	x
f	x	x
a_p	x	x
v_c^2	x	0
f^2	x	x
a_p^2	x	x
$v_c \cdot f$	x	0
$v_c \cdot a_p$	x	x
$f \cdot a_p$	0	0

The models constructed only contain the significant parameters. The reduced models constructed to estimate the two surface roughness parameters (together with the R^2 values characterizing the goodness of fit) are represented by the following equations (based on eq. 6):

$$Ra = 0.42 + 2.24 \cdot 10^{-4} \cdot v_c - 3.87 \cdot f + 0.74 \cdot a_p - 1.52 \cdot 10^{-6} v_c^2 + \\ + 11.45 \cdot f^2 - 0.36 \cdot a_p^2 + 1.76 \cdot 10^{-3} \cdot v_c \cdot f + 4.99 \cdot 10^{-4} \cdot v_c \cdot a_p \quad (7)$$

$(R^2 = 0.78)$

$$Rz = 3.70 - 3.01 \cdot 10^{-3} \cdot v_c - 19.19 \cdot f + 2.728 \cdot a_p + \\ + 58.08 \cdot f^2 - 1.38 \cdot a_p^2 + 2.42 \cdot 10^{-3} \cdot v_c \cdot a_p \quad (8)$$

$(R^2 = 0.71)$

The graphical representations of eq. (7) and (8) show (Fig. 7 and 8) that the surface roughness parameters as a function of feed have a minimum value and the surface roughness values decrease if the cutting speed increases.

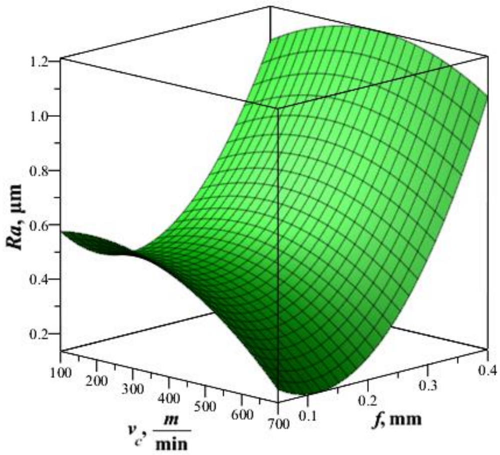

Fig. 7. Surface plot of eq. (7)
(hold value: a_p = 0.5 mm)

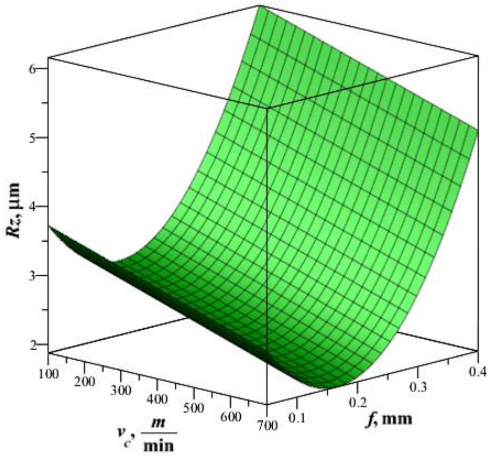

Fig. 8. Surface plot of eq. (8)
(hold value: a_p = 0.5 mm)

3.1 Checking the Equations

The equations were checked by plotting the calculated and measured surface roughness values against the experimental runs and comparing them. Figure 9 shows that the values calculated from equations (7) (8) approximated the measured values well in the case of PA-6.

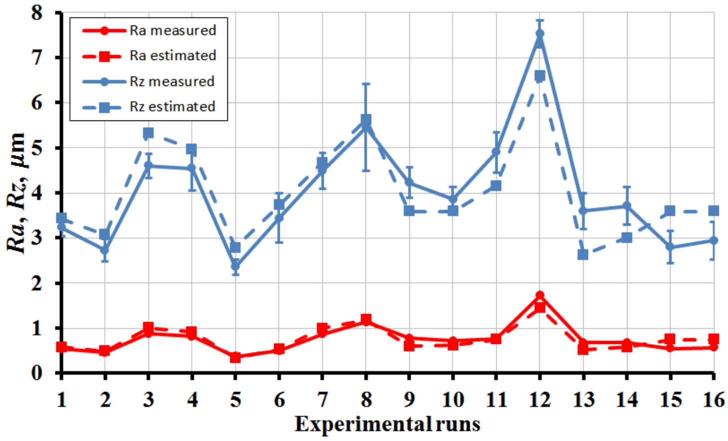

Figure 9. The measured and estimated values of surface roughness parameters plotted against experimental runs

In the case of *Ra* surface roughness parameter the fitting of calculated values is better than in the case of *Rz* surface roughness parameter. The reason the reason may be is, that the deviation of the measured surface roughness parameters is higher in the case of *Rz* parameter than in the case of *Ra* parameter.

3.2 The examination of residuals

The probability plots of the difference of the calculated and measured values (the error of estimation) shows that the expected values of error are approximately zero and have normal distribution (Fig. 10 and 11).

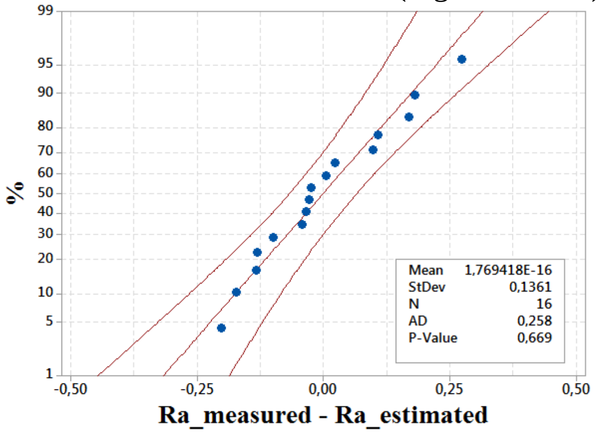

Fig. 10. Probability plots of the error of *Ra*

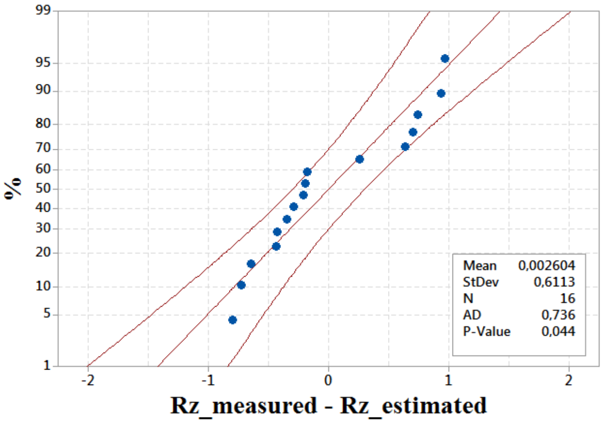

Fig. 11. Probability plots of the error of *Rz*

3.3 Determination of cutting parameters in order to minimize surface roughness

One of the important criteria of machined parts is that surface roughness should minimal. A cutting parameter combination can be calculated where eq. (7) and eq. (8) have a minimum.

$$Ra \rightarrow \text{Min} \tag{9}$$
$$Rz \rightarrow \text{Min} \tag{10}$$

In the range of the examined cutting parameters the minimum of *Ra* and the minimum of *Rz*, based on eq. (7) and (8) are:

The *Ra* surface roughness parameter has its minimum value if: v_c = 700 m/min; f = 0.12 mm; a_p = 0.5 mm and the *Rz* surface roughness parameter has its minimum value if: v_c = 700 m/min; f = 0.16 mm; a_p = 0.5mm. The expected values are: *Ra* = 0.15 µm and *Rz* = 1.8 µm.

It can be stated that in order to minimize both surface roughness parameters, high cutting speed (v_c = 700 m/min), small depth of cut (a_p = 0.5 mm) and a feed rate of f = 0.12…0.16 mm are recommended.

4. Conclusion

In this article the machinability of engineering plastic (PA-6) was examined with the help of design of experiments. In summary, the following can be stated:

- The design of experiments is a suitable method for cutting research because a lot of information can be obtained from relatively few well-chosen experimental runs, thus the number of expensive and time-consuming measurements can be reduced.

- Reduced phenomenological models were constructed with which the surface roughness parameters (*Ra* – average surface roughness, *Rz* – ten-point high surface roughness parameter) can be estimated easily from the input cutting parameters.

- The examination of residuals showed that their expected values are about zero and have normal distribution.

- To minimize surface roughness, the recommended cutting parameters are the following: cutting speed - v_c = 700 m/min; depth of cut - a_p = 0.5 mm; and feed rate - f = 0.12..0.16 mm.

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