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Robust Conditions for Cutting Force Minimization in Polyamide Turning Process

Modeling and optimization is an important aspect of machining processes. Optimization of cutting forces is critically important in turning operations because cutting forces are directly related to several machining performance characteristics. This paper focuses on modeless optimization approach for minimization of cutting force in polyamide turning process. The influence of four cutting parameters, such as cutting speed, feed rate, depth of cut and tool nose radius on main cutting force was analyzed on the basis of the standard L27 Taguchi's orthogonal array. The collected experimental results were analyzed with the help of analysis of means and analysis of variance. The near optimal turning parameters settings were determined considering Taguchi's robust design methodology.

Keywords: *Polyamides, robust optimization, cutting force, turning process.*

1. INTRODUCTION

Because metallic materials are one of themost important engineering materials, their machinability has been studied extensively by manufacturing researchers and practitioners. On the other hand, machinability of plastic engineering materials has been given less attention. Machinability of plastic engineering materials can be assessed by different criteria. Regarding plastic materials the most important include tool life, cutting forces, power, specific cutting pressure and surface roughness [1].

Each type of plastic has unique properties, and therefore can be assumed to have different machining characteristics-far different from those of metallic materials familiar to many manufacturing engineers [2]. As high performance plastic engineering materials have been increasingly used in industry, the machining quality is becoming a central factor for the development of new processes and materials. Nevertheless, the knowledge about the plastic engineering materials behaviour under machining is very limited, as well as the definition of suitable models for the prediction of cutting forces [3]. In the scientific literature, Kobayashi's book "Machining of plastics" [4] has become reference for a long time in this field. Due to theirs specific characteristics, machining of plastic engineering materials greatly differ from machining of metallic materials. It is well known that cutting forces are affected by the wear state of cutting tool and rake angles of cutting tool. Cutting force increases considerably as tools become dull. Also, both the cutting force and the thrust force are higher for negative or zero rake angles than for the recommended positive rake angles [2].

In plastic engineering materials machining it is important to know the amount of the main cutting force. Knowing this, the load of cutting tool can be made more constant as well as the remnant stress in the material chipped can be reduced to minimum in the case of proper cutting parameter settings [5].

Gaitonde et al. [1] developed the second-order response surface mathematical models for analyzing the influence of cutting speed and feed rate on machining force, cutting power, and specific cutting pressure during turning of unreinforced polyamide (PA6), and reinforced polyamide with 30% of glass fibers (PA66 GF30). Keresztes et al. [5] investigated the effect of feed rate and depth of cut on main cutting force, specific cutting resistance in turning different engineering polymers (cast PA6, polyoxymethylene and ultra-high-molecular-weight polyethylene). The machining results were compared with the tensile properties of the materials. Marin [6] investigated the influence of depth of cut, cutting speed and feed rate on main cutting force in turning extruded polyamide PA 66 with 50 mm in diameter using uncoated cemented carbides without chip breaker. It was observed that depth of cut and feed rate have most influence on main cutting force, whereas the influence of cutting speed is negligible. In 2006 Mata et al. studied the physical cutting of polyamide composites by means of the theoretical model of Merchant [7]. This study was extended in 2007 by Davim et al. [8]. Dhokia et al. [9] developed a predictive model using a design of experiments (DOE) method to obtain optimized machining parameters, by utilizing genetic algorithm (GA), for a specific surface roughness in ball-end machining of polypropylene.

This paper presents the application of robust optimization methodology, i.e. Taguchi methodology [10], for identification of the near optimal turning parameter values which minimize the cutting force in polyamide turning process. The turning experiment was planned and conducted according to Taguchi's experimental design using L_{27} orthogonal array in which four turning parameters such as cutting speed, feed rate, depth of cut and tool nose radius were arranged.

Received: August 2013, Accepted: December 2013
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doi:10.5937/fmet1502114L
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2. EXPERIMENTAL DETAILS

2.1 Workpiece material

The material used for cutting was unreinforced polyamide PA-6 produced by Quattroplast Ltd. (Hungary). Polyamides (also known as nylon) are polymers containing the amide group. The mechanical properties of the work material are: density = 1.14 g/cm^3, tensile strength is about 80 N/mm^2, module of elasticity is 3200 N/mm^2, Charpy impact resistance is over 3 KJ/m^2. The test specimen was in the form of bar, 92 mm in diameter and 50 mm in length.

A tensile test, also known as tension test, as a probably the most fundamental type of mechanical test is performed on test material. For this test plastic samples are machined from stock shape (Figure 1).

The sample is gripped on both ends using a tensile testing machine. The tensile tester pulls on the specimen at a constant rate of 10 mm/min until it breaks into two pieces. The tensile force and stretch (elongation) are measured. The result of this test is a graph of load (tensile force) versus displacement (stretch), shown on Figure 2.

2.2 Machining conditions and experimental plan

The machine used for the experiments was the universal lathe machine "Potisje PA-C30" with a 11 kW power, speed range n = 20÷2000 rpm, and longitudinal feed rate range f = 0.04÷9.16 mm/rev. Cutting tool was SANDVIK Coromant tool holder SVJBR 3225P 16 with inserts VCGX 16 04 04-AL (H10) and VCGX 16 04 08-AL (H10). The tool geometry was: rake angle γ = 7º, clearance angle α = 7º, cutting edge angle χ = 93º, and cutting edge inclination angle λ = 0º.

In the present study, four cutting parameters, namely, cutting speed (V_c), feed rate (f), depth of cut (a_p), and tool nose radius (r) were considered. The cutting parameter ranges were selected based on machining guidelines provided by workpiece and tool manufacturer's recommendations and previous researches [1, 5].

Three levels for cutting speed, feed rate and depth of cut and two levels for tool nose radius were considered (Table 1). The cutting parameters were arranged in standard Taguchi's L_{27} (3^{13}) orthogonal array (OA). Cutting parameters V_c, f and a_p were assigned to columns 1, 2 and 5, respectively. Cutting parameter r was assigned to column 12. As tool nose radius had only two levels, the dummy-level technique [10] was used to reassign level 1 to level 3. Following the Taguchi's L_{27} (3^{13}) OA, 54 experiment trials were performed at random order to avoid systematic errors. The combination of cutting parameter values and average values of main cutting force are given in Table 2.

Table 1. Turning parameters and levels used

Cutting parameter	Level		
	1	2	3
A – V_c (m/min)	65.03	115.61	213.88
B – f (mm/rev)	0.049	0.098	0.196
C – a_p (mm)	1	2	4
D – r (mm)	0.4	0.8	-

Fig. 1. Tensile test sample

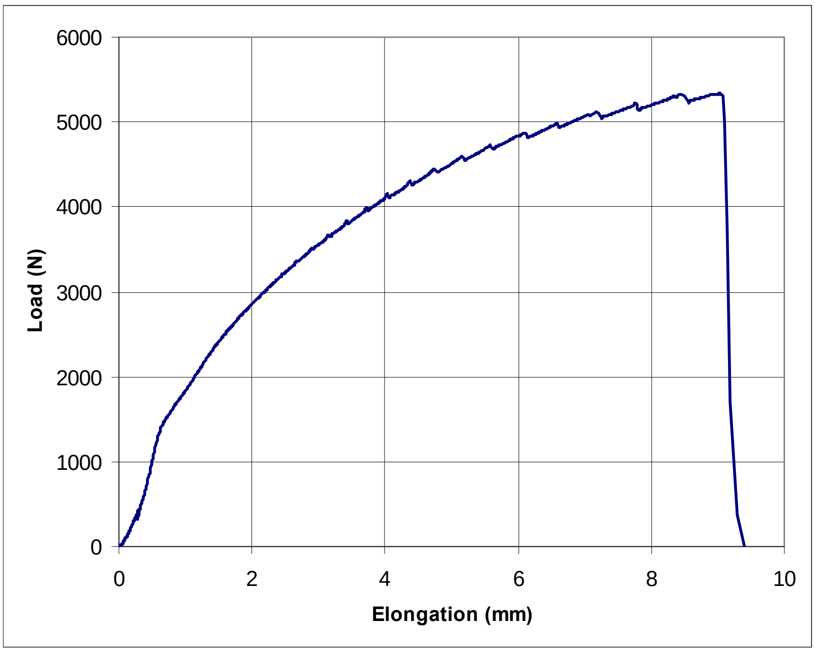


Fig. 2. Tensile test diagram of PA-6 polymer

Table 2. Experimental plan and main cutting force results

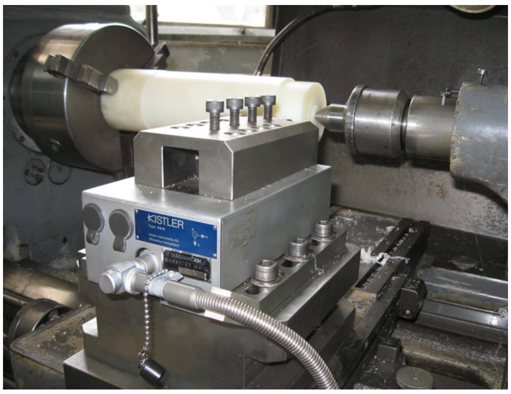
Trial no	Cutting speed V_c, (m/min)	Feed rate f, (mm/rev)	Depth of cut a_p, (mm)	Tool nose radius r, (mm)	Main cutting force (N)	
1	65.03	0.049	1	0.4	24	20
2	65.03	0.049	2	0.8	32	36
3	65.03	0.049	4	0.4	55	60
4	65.03	0.098	1	0.4	28	26
5	65.03	0.098	2	0.4	45	43
6	65.03	0.098	4	0.8	85	85
7	65.03	0.196	1	0.8	50	49
8	65.03	0.196	2	0.4	70	73
9	65.03	0.196	4	0.4	140	140
10	115.61	0.049	1	0.8	25	21
11	115.61	0.049	2	0.4	25	25
12	115.61	0.049	4	0.4	49	50
13	115.61	0.098	1	0.4	24	26
14	115.61	0.098	2	0.8	46	50
15	115.61	0.098	4	0.4	80	81
16	115.61	0.196	1	0.4	45	50
17	115.61	0.196	2	0.4	71	76
18	115.61	0.196	4	0.8	141	143
19	213.88	0.049	1	0.4	12	13
20	213.88	0.049	2	0.4	25	26
21	213.88	0.049	4	0.8	50	53
22	213.88	0.098	1	0.8	20	27
23	213.88	0.098	2	0.4	35	38
24	213.88	0.098	4	0.4	70	71
25	213.88	0.196	1	0.4	40	40
26	213.88	0.196	2	0.8	76	73
27	213.88	0.196	4	0.4	130	132

2.3 Cutting forces

The relative forces in a turning operation are important in the design of machine tools. The machine tool and its components must be able to withstand these forces without causing significant deflections, vibrations, or chatter during the operation. There are three principal forces during a turning process:

- The cutting or tangential force acts downward on the tool tip allowing deflection of the workpiece upward. It supplies the energy required for the cutting operation.
- The axial, thrust or feed force acts in the longitudinal direction. It is also called the feed force because it is in the feed direction of the tool. This force tends to push the tool away from the chuck.
- The radial force acts in the radial direction and tends to push the tool away from the workpiece.

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 tool holder creating a very rigid tooling fixture (Figure 3). The charge signal generated at the dynamometer was amplified using amplifier Kistler type 5007A. The amplified signal is acquired and sampled by using computer Hewlett Packard HP 9000/300. In the process of analogue to digital conversion new digital values are sampled from the analog signal using sampling frequency of 200 samples per second.



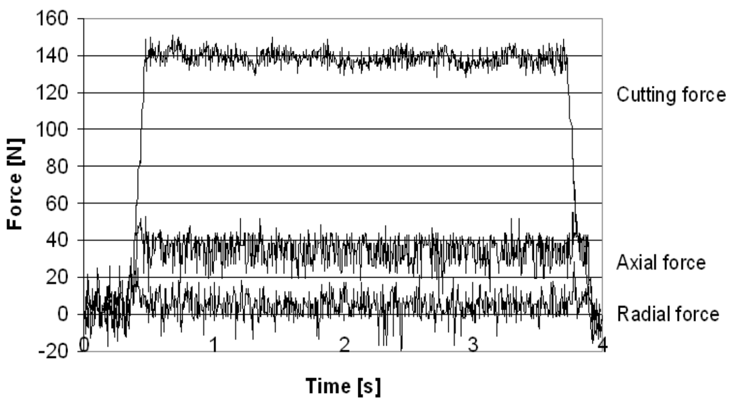


Fig. 3. a) Experimental setup for measurement of cutting forces using dynamometer Kistler type 9441, b) Principal forces during a turning process

3. ANALYSIS AND DISCUSSION

Taguchi methodology was used to identify the near optimal cutting parameter levels so as to identify robust conditions minimizing the main cutting force. Instead of average values obtained in experimental trials, the Taguchi methodology uses S/N ratios, which combine information about the mean and variance, to interpret the results. To determine near optimal cutting parameter values, main cutting force experimental results i.e. its corresponding S/N values of “smaller-is-better” category were analyzed using the analysis of means (ANOM) and analysis of variance (ANOVA) [11]. The results of ANOM are presented in response graphs (Figure 4).

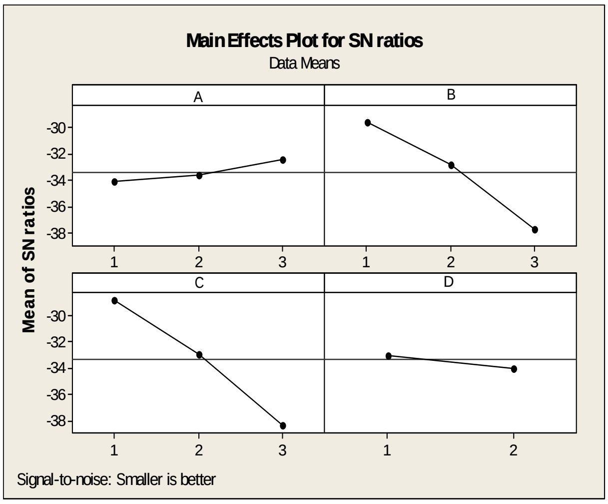


Fig. 4. Main effect plot of S/N ratio for main cutting force

As seen from Figure 4, the optimal parameter setting is A3B1C1D1. It is clear that high cutting speed, low feed rate, low depth of cut and smaller tool nose radius are preferred to minimize main cutting force. Thus, for the present investigation, the optimal combination of parameter levels in terms of real values is: cutting speed V_c = 213.88 m/min, feed rate f = 0.049 mm/rev, depth of cut a_p = 1 mm, and tool nose radius r = 0.4 mm.

More precise determination of the optimal cutting parameter levels is based on ANOVA from which one can also obtain relative importance of the each process parameter and interactions. The results of ANOVA are summarized in Table 3.

Table 3. Turning parameters and levels used

Source	Degrees of freedom	Sum of squares	Mean square	F	p	Significant
V_c	2	13.12	6.56	10.05	0.001	yes
f	2	304.08	15.04	232.84	0.000	yes
a_p	2	410.11	205.06	314.03	0.000	yes
r	1	5.64	5.64	8.64	0.008	yes
Error	19	12.41	0.65			
Total	26	745.36				

As seen from ANOVA results, all selected cutting parameters are statistically significant with p-values less than 0.05. Figure 5 shows the percentage contribution of each cutting parameter to the total variation, indicating their degree of influence on the main cutting force.

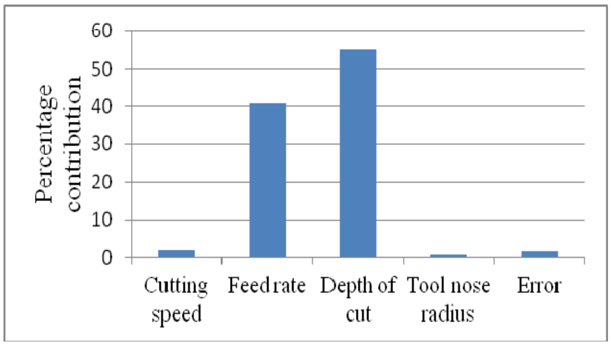


Fig. 5. Percentage contribution of turning parameters on S/N ratio for main cutting force

Depth of cut and feed rate are the most influential parameters whereas percentage contributions of the cutting speed and tool nose radius are negligible. Small percentage contribution of error term indicates that there are no significant interactions between the cutting parameters. It can be seen from Figure 5 that changing the feed rate and depth of cut between the chosen parameter levels contributes to 96 % of the total variation in the main cutting force. Because there are no significant interaction, one can adapt previously determined optimal cutting parameter values.

Verification is necessary and important step in the Taguchi methodology [10]. Since optimal cutting parameter values correspond to experimental trial no 19, no verification test was conducted. Taguchi prediction of S/N ratio under optimum conditions is η_{est} = -23.7692 dB compared to -21.9451 dB which is obtained in experimental trial 19. In order to judge the closeness of the predicted and observed value of S/N ratio, the confidence interval (CI) is determined. In other words, the confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence [12]. At the 95% confidence level, the CI is ± 1.547. Since the difference between predicted and observed values i.e. prediction error is within CI value, the optimal combination of cutting parameter levels can be validated.

4. CONCLUSION

This paper presented the robust optimization methodology for minimization of the main cutting force in polyamide turning process. Four turning parameters were varied in the experiment, i.e cutting speed, feed rate, depth of cut and tool nose radius. On the basis of the experimental results and derived analysis, the following conclusions can be drawn:

- Depth of cut followed by feed rate is the most significant cutting parameter affecting the main cutting force.
- The effect of the cutting speed is much smaller, whereas the effect of tool nose radius is negligible.
- The interaction effects of the cutting parameters are not pronounced.
- The obtained results suggest that high cutting speed, low feed rate and depth of cut, and smaller tool nose radius are beneficial for minimization of the main cutting force in polyamide turning process.

Robust optimization methodology proposed by G. Taguchi offers simple and modeless approach for process optimization.

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РОБУСТНИ УСЛОВИ ЗА МИНИМИЗАЦИЈУ ОТПОРА РЕЗАЊА КОД ПРОЦЕСА СТРУГАЊА ПОЛИАМИДА

Драгољуб Лазаревић, Предраг Јанковић, Милош Мадић, Анђела Лазаревић

Моделирање и оптимизација су важни аспекти код процеса обраде. Оптимизација отпора резања код процеса стругања је од нарочитог значаја имајући у виду да су отпори резања у директној вези са неколико перформанси обраде. У овом раду је представљен оптимизациони приступ за минимизацију отпора резања код процеса стругања полиамида. На основу експеримента који је реализован у складу са стандардним Тагучијевим ортогоналним низом L_{27} извршена је анализа утицаја четири параметара стругања као што су брзина резања, корак, дубина резања и радијус врха ножа. Добијени експериментални резултати су анализирани помоћу анализе средњих вредности и анализе варијансе. Приближно оптимална подешавања параметара стругања су одређена у складу са Тагучијевом робустном методологијом.