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RESEARCH

Cutting Parameters Optimization for Surface Roughness in Turning Operation of Polyethylene (PE) Using Taguchi Method

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ABSTRACT

In any machining process, it is most important to determine the optimal settings of machining parameters aiming at reduction of production costs and achieving the desired product quality. This paper discusses the use of Taguchi method for minimizing the surface roughness in turning polyethylene. The influence of four cutting parameters, cutting speed, feed rate, depth of cut, and tool nose radius on average surface roughness (R_a) was analyzed on the basis of the standard L_{27} Taguchi orthogonal array. The experimental results were then collected and analyzed with the help of the commercial software package MINITAB. Based on the analysis of means (ANOM) and analysis of variance (ANOVA), the optimal cutting parameter settings are determined, as well as level of importance of the cutting parameters.

1. INTRODUCTION

Polyethylene (PE) is a semi-crystalline thermoplastic with high toughness and chemical resistance, and is one of the most common and widely used polymers. PEs are cheap, flexible and durable. They evolved into two forms: "low density polyethylene" (LDPE) which is used to make films for food warping and packaging materials, and "high density polyethylene" (HDPE) which is used for containers, plumbing and automotive fittings.

Thermoplastic polymer are composites extensively used in a variety of applications in different fields of engineering, such as aircraft, automobile, robots and machines, due to an excellent property profile, and hence replaced many traditional metallic materials [1]. Nowadays plastic has been widely employed in the industrial sector. Due to the need of high dimensional accuracy and good surface finish, components of plastic for these ends should be produced by means of machining processes instead of moulding processes [2]. However, there is a limited number of papers about machining of polyethylene in the literature.

Gaitonde et al. [1] applied Taguchi's quality loss function approach for simultaneously minimizing the power and specific cutting force during turning of polymers. Taguchi's optimization was performed with tool material, feed rate and cutting speed as the process parameters. Gaitonde et al. [3] developed RSM based second-order mathematical models for analyzing the influence of cutting speed and feed rate on machining force, cutting power, and specific cutting pressure during turning of polyamides. Eriksen [4] examined the influence of cutting parameters (feed rate, cutting speed and tool nose radius) and the fibre orientation on the surface roughness in turning of short fiber reinforced thermoplastic. The results showed that the roughness of the machined surfaces was highly influenced by the feed rate and tool nose radius, whereas the influence of cutting speed was negligible.

Rapid development of new materials, cutting tools and cutting fluids promote research of machinability for new materials and tribological characteristic of cutting tools and cutting fluids [5]. In many cases, the plastic machining now in use is simply the result of know-how gained from previous experience. In addition, most machining methods depend on the use of existing machines and tools developed for the fabricator of wood and metals, and little has been done to develop cutting equipment or methods especially suited to plastics. Thus, it has been rather difficult to machine all plastics successfully, owing to the many kinds and grades of plastics available and the lack of a basic understanding of their inherent machinability [6].

In this paper, Taguchi method [7] was applied to optimize cutting parameters in turning of polyethylene for achieving better surface finish.

2. OPTIMIZATION METHOD

A lot of researches have been conducted for determining optimal process parameters. Kwak [8] presented the Taguchi and response method to determine the robust condition for minimization of roundness error of workpieces. Yang and Tarng [9] employed Taguchi method and optimal cutting parameters of steel bars for turning operations.

The Taguchi technique is a methodology for finding the optimum setting of the control factors to make the product or process insensitive to the noise factors [7]. Taguchi's techniques have been used widely in engineering design, and can be applied to many aspects such as optimization, experimental design, sensitivity analysis, parameter estimation, model prediction, etc. The distinct idea of Taguchi's robust design that differs from the conventional experimental design is that of designing for the simultaneous modeling of both mean and variability [7].

Taguchi based optimization technique has produced a unique and powerful optimization discipline that differs from traditional practices. While, traditional experimental design methods are sometimes too complex and time consuming, Taguchi methodology is a relatively simple method.

Taguchi method uses a special highly fractionated factorial designs and other types of fractional designs obtained from orthogonal arrays (OAs) to study the entire experimental region of interest for experimenter with a small number of experiments. This reduces the time and costs of experiments, and additionally allows for an optimization of the process to be performed. The columns of an OA represent the experimental parameters to be optimized and the rows represent the individual trials (combinations of levels).

Traditionally, data from experiments is used to analyze the mean response. However, in Taguchi method the mean and the variance of the response (experimental result) at each setting of parameters in OA are combined into a single performance measure known as the signal-to-noise (*S/N*) ratio. Depending on the criterion for the quality characteristic to be optimized, different *S/N* ratios can be chosen: smaller-the-better, larger-the-better, and nominal-the-better. For example, the S/N ratio for smaller-the-better criterion is employed when the aim is to make the response as small as possible. This category of the S/N ratio is defined as:

$$\eta_i = S / N = -10\, log\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^2\right). \qquad (1)$$

where η_i is *S/N* ratio in the i-th trial, y_{ij} is the j-th observed value of the response (quality characteristic) in i-th trial, n is the number of individual observations in i-th trial, due to noise factors or repetition of trial. Regardless of the category of the quality characteristic, a higher algebraic value of *S/N* ratio corresponds to better quality characteristic, i.e. to the smaller variance of the output characteristic around the desired (target) value.

A full explanation of the method can be found in many references including [7,10].

3. EXPERIMENTAL PROCEDURE

3.1 Material and machining conditions

The material used for cutting was unreinforced polyethylene. Polyethylene and other thermoplastics can be turned on a lathe with tools ground for plastics, at speed up to 550 m/min. The mechanical properties of the work material are: density = 0.94 g/cm^3, tensile strength = 40 N/mm^2, module of elasticity = 3500 N/mm^2, Charpy impact resistance > 3.7 KJ/m^2. The test specimens were in the form of bar, 92 mm in diameter and 500 mm in length (Fig. 1).

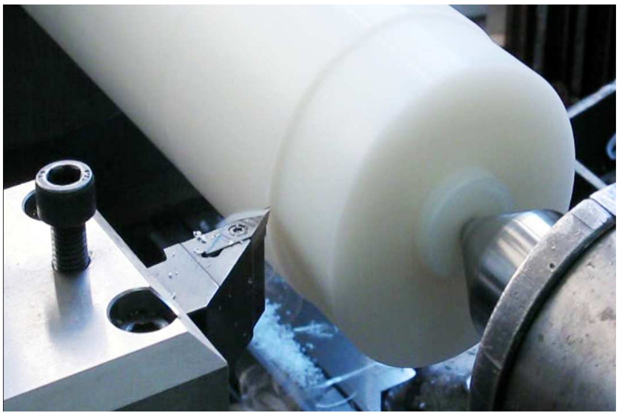

Fig 1. Experimental setup.

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 = 7°, clearance angle α = 7°, cutting edge angle χ = 93° and cutting edge inclination angle λ = 0°.

In the study, the average surface roughness (R_a) was considered. It was measured at three equally spaced positions around the circumference of the workpiece using the profilometer Surftest Mitutoyo SJ-301.

3.2 Experimental plan

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 [3,4]. Three levels for cutting speed, feed rate and depth of cut and two levels for tool nose radius were considered (Table 2).

Table 1. Experiment plan, results and S/N ratios for the average surface roughness.

Trial no	Designation	Cutting speed V_c, (mm)	Feed rate f, (mm/rev)	Depth of cut a_p, (mm)	Tool nose radius r, (mm)	R_a (μm)		η (dB)
1	$A_1B_1C_1D_1$	65.03	0.049	1	0.4	1	2	-6.69056
2	$A_1B_1C_2D_2$	65.03	0.049	2	0.8	2.2	2.12	-5.2047
3	$A_1B_1C_3D_1$	**65.03**	**0.049**	**4**	**0.4**	1.77	1.87	-7.16704
4	$A_1B_2C_1D_1$	65.03	0.098	1	0.4	2.18	2.38	-7.02538
5	$A_1B_2C_2D_1$	65.03	0.098	2	0.4	2.21	2.28	-6.71585
6	$A_1B_2C_3D_2$	65.03	0.098	4	0.8	2.25	2.08	-5.17915
7	$A_1B_3C_1D_2$	**65.03**	**0.196**	**1**	**0.8**	1.78	1.85	-11.7675
8	$A_1B_3C_2D_1$	65.03	0.196	2	0.4	3.96	3.79	-12.9969
9	$A_1B_3C_3D_1$	65.03	0.196	4	0.4	4.42	4.51	-14.0748
10	$A_2B_1C_1D_2$	**115.61**	**0.049**	**1**	**0.8**	5.01	5.1	-3.40603
11	$A_2B_1C_2D_1$	115.61	0.049	2	0.4	1.5	1.46	-1.76337
12	$A_2B_1C_3D_1$	115.61	0.049	4	0.4	1.21	1.24	-5.43696
13	$A_2B_2C_1D_1$	**115.61**	**0.098**	**1**	**0.4**	1.86	1.88	-6.15087
14	$A_2B_2C_2D_2$	115.61	0.098	2	0.8	2.06	2	-3.55882
15	$A_2B_2C_3D_1$	115.61	0.098	4	0.4	1.57	1.44	-6.44596
16	$A_2B_3C_1D_1$	**115.61**	**0.196**	**1**	**0.4**	2.14	2.06	-12.4236
17	$A_2B_3C_2D_1$	115.61	0.196	2	0.4	4.19	4.17	-12.73
18	$A_2B_3C_3D_2$	115.61	0.196	4	0.8	4.36	4.3	-13.0745
19	$A_3B_1C_1D_1$	**213.88**	**0.049**	**1**	**0.4**	4.45	4.56	-5.74199
20	$A_3B_1C_2D_1$	213.88	0.049	2	0.4	2.02	1.85	-1.33044
21	$A_3B_1C_3D_2$	213.88	0.049	4	0.8	1.2	1.13	-2.9009
22	$A_3B_2C_1D_2$	213.88	0.098	1	0.8	1.46	1.33	-3.1999
23	$A_3B_2C_2D_1$	213.88	0.098	2	0.4	1.41	1.48	-7.78397
24	$A_3B_2C_3D_1$	**213.88**	**0.098**	**4**	**0.4**	2.42	2.48	-6.46507
25	$A_3B_3C_1D_1$	213.88	0.196	1	0.4	2.1	2.11	-12.0086
26	$A_3B_3C_2D_2$	213.88	0.196	2	0.8	4.18	3.78	-12.2769
27	$A_3B_3C_3D_1$	213.88	0.196	4	0.4	4.1	4.12	-12.8899

Table 2. Cutting parameters and their levels used in experiment.

Cutting parameter	Level		
	1 (low)	2 (medium)	3 (high)
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	-

The cutting parameters were arranged in standard Taguchi's $L_{27}(3^{13})$ 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 [4] was used to reassign level 1 to level 3. The plan of experimental layout to obtain average surface roughness (R_a) is shown in Table 1. Following the Taguchi's $L_{27}(3^{13})$ OA, 54 experiment trials were performed at random order to avoid systematic errors.

Since the objective of experiment is to optimize the cutting parameters to get better (i.e. low value) of average surface roughness *S/N* ratio the average *S/N* ratios for smaller the better for average surface roughness were calculated using the Eq. 1. The *S/N* ratios are given in Table 1.

4. ANALYSIS AND DISCUSSION

The experimental results were analyzed with analysis of means (ANOM) and analysis of variance (ANOVA). The analyses have been obtained by using the statistical software MINITAB. The calculations of ANOM and ANOVA are described in detail by Phadke [7].

4.1 Analysis of means

ANOM is the process of estimating the factor effects. Based on the ANOM, one can derive the optimum combination of the cutting parameters, with respect to average surface roughness (R_a). The optimum level for a factor is the level that gives the highest value of S/N ratio in the experimental region [7].

The results of ANOM are presented in Fig. 2. From the Fig. 2, one can observe that the optimal ANN combination of cutting parameter levels is $A_{2(3)}B_1C_2D_2$. Considering material removal rate as an additional criteria the optimal value of each cutting parameter are selected as follows: (A) cutting speed, 213.88 m/min, (B) feed rate, 0.049 mm/rev, (C) depth of cut, 2 mm, and (D) tool nose radius, 0.8 mm.

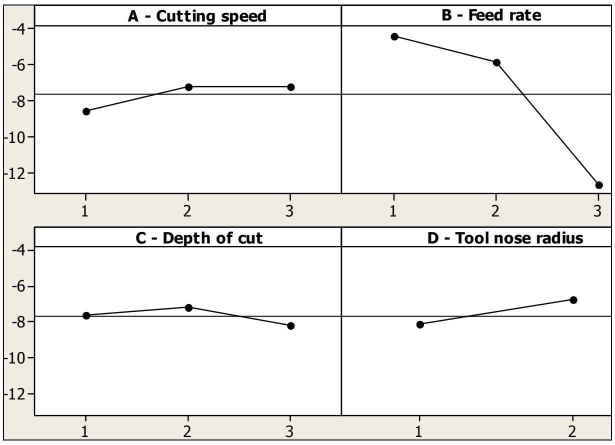

Fig. 2. Effect of cutting parameters on S/N ratio

4.2 Analysis of variance

The purpose of the analysis of variance is to investigate which cutting parameters significantly affect the surface quality characteristics. ANOVA was performed using the *S/N* ratios as the response (Table 2). ANOVA is accomplished by separating the total variability of the *S/N* ratios, which is measured by the sum of the squared deviations from the average of the *S/N* ratio, into contributions by each of the cutting parameters and the error.

In ANOVA, the ratio between the variance of the cutting parameter and the error variance is called Fisher's ratio (F). It is used to determine whether the parameter has a significant effect on the quality characteristic by comparing the *F* test value of the parameter with the standard *F* table value ($F_{0.05}$) at the 5 % significance level. If the *F* test value is greater than $F_{0.05}$, the cutting parameter is considered significant. Table 3 shows the results of ANOVA for average surface roughness.

Table 3. Analysis of variance (ANOVA) for S/N ratios.

Source	Degrees of freedom	Sum of squares	Mean square	F	F-tab
Cutting speed	2	10.725	5.363	3.15	3.52
Feed rate	2	353.344	176.672	103.67	3.52
Depth of cut	2	4.803	2.401	1.41	3.52
Tool nose radius	1	11.302	11.302	6.63	4.38
Error	19	32.381	1.704		
Total	26	412.554			

In ANOVA, for a degree of freedom of 2 for the numerator (effect) and 19 for the denominator (error), the factor is significant with 95 % confidence if *F* exceeds 3.52, and with 90 % confidence for *F* higher than 2.61 [6]. From the ANOVA results, it can be seen that cutting parameters, namely feed rate and tool nose radius are statistically significant with 95 % confidence for affecting average surface roughness (R_a). The effect of cutting speed is significant with 90 % confidence. Finally, the change of the depth of cut in the range given in Table 1 has an insignificant effect on the R_a.

Figure 3 shows the percentage contribution of each cutting parameter to the total variation, indicating their degree of influence on the R_a. Feed rate is the most influential parameter followed by tool nose radius and cutting speed, whereas the influence of depth of cut is negligible.

It can be seen from Fig. 3 that changing the cutting parameters (feed rate, tool nose radius, and cutting speed) between the chosen parameter levels (Table 2) contributes to 91 % of the total variation in the R_a. Furthermore, the relatively small percent contribution of error confirms the absence of significant factor interactions.

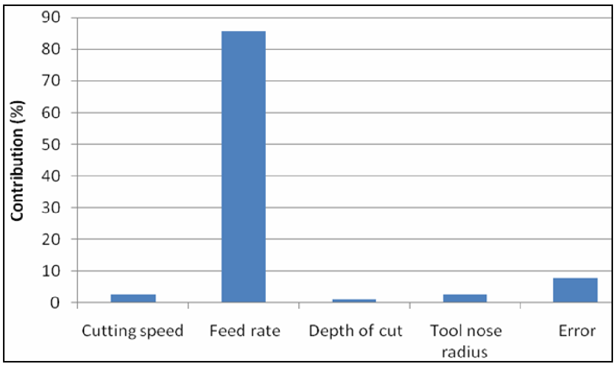

Fig. 3. Cutting parameters percentage contribution

It can be seen from Figure 3 that changing the cutting parameters (feed rate, tool nose radius, and cutting speed) between the chosen parameter levels (Table 1) contributes to 91 % of the total variation in the R_a. Furthermore, the relatively small percent contribution of error confirms the absence of significant factor interactions.

4.3 Verification

Confirmation testing is necessary and important step in the Taguchi method. Taguchi prediction of *S/N* ratio under optimum conditions is η_{est} = -2.52882 dB with corresponding surface roughness values of R_a = 1.27 µm. Once the optimal combination of cutting parameters is selected, the final step is to predict and verify the expected response through the confirmation test. Since the optimal combination of cutting parameters ($A_3B_1C_2D_2$) is not included in the OA, the confirmation experiment was conducted. Three confirmation experiment trials were conducted at the optimum settings of the process parameters to obtain average surface roughness value. The predicted and experimentally observed values are compared in Table 4.

Table 4. Comparation of predicted and experimental values

	Taguchi optimal settings	
	Predicted	**Experimental**
R_a (µm)	1.27	1.51
S/N (dB)	-2.52882	-2.7974

In order to judge the closeness of the η_{est} and observed value of S/N ratio, the confidence interval (CI) is determined. The CI is given by [10]:

$$CI = \sqrt{\frac{F_{\alpha(1,f_e)} \cdot V_e}{n}} . \qquad (2)$$

where $F_{\alpha(1;fe)}$ is the *F* value from statistic table at a confidence level of (1-α) at degrees of freedom (DoF) = 1, and error DoF = 19, V_e is the error variance, and *n* is defined as:

$$n = \frac{N}{1+\nu} . \qquad (3)$$

where *N* is the total number of experiments and ν is the total DoF of all parameters. At the 95 % confidence level, the CI is ± 1.487. Since the prediction error is within CI value the optimal combination of cutting parameter levels can be validated.

5. CONCLUSION

This paper described the application of Taguchi method for optimization of cutting parameter settings for minimizing the average surface roughness in turning of polyethylene. Four cutting parameters, cutting speed, feed rate, depth of cut, and tool nose radius were considered and arranged in the L_{27} OA. ANOVA results indicate that the feed rate is far the most significant parameter, followed by tool nose radius, and cutting speed, whereas the influence of depth of cut is negligible. The ANOVA resulted in less than 10 % error indicating that the interaction effect of process parameters is small. The optimum levels of the process parameters for minimum surface roughness are as follows: cutting speed - 213.88 m/min, feed rate - 0.049 mm/rev, depth of cut - 2 mm, and tool nose radius - 0.8 mm.

The Taguchi method is relatively simple yet a powerful optimization approach that could be efficiently applied for machining optimization problems.

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