Investigation of the Machining Parameters and the Environment of Polyamide 6 on Surface Roughness Using Experimental and Statistical Methods

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ABSTRACT

This study investigates experimentally and statistically the influences of the Machining Parameters (MPs) and environments on the surface roughness (R_a) of Polyamide 6 (PA6) during the turning operation. The experiments were conducted using a lathe machine, carbide cutting tool, and roughness tester. The statistical approach was implemented using Taguchi Experiment Design (TED) and Analysis of Variance (ANOVA). The parameters and their values were: cutting velocity (V_C) of 125, 200, and 250 m/min; feed rate (F_R) of 0.05, 0.1, and 0.15 mm/rev; and cutting depth (D_C) of 2, 4, and 6 mm. The environments used were: dry (D), compressed air (A), and air-water mixture (A+W). The research aimed to improve the cutting surface quality of PA6 based on the R criterion. The results revealed that the F_R is the most influential factor on R compared to other factors. The effect percentages on R were 61%, 15%, 13%, and 11% for F_R, Machining Environments (MEs), D_C, and V_C, respectively. The optimum combination has been

achieved based on an F_R of 0.05 mm/rev, air with water, a D_C of 2 mm, and a V_C of 125 m/min, providing a minimum total average surface roughness (R_a) of 1.2 µm for PA6. The study demonstrates that an optimum combination can enhance the cutting surface quality, reduce the machining costs, and provide a pathway for producing high-performance PA6 components.

Keywords-Polyamide 6; cutting velocity; feed rate; cutting depth; machining environment; surface roughness; Taguchi design; ANOVA

I. INTRODUCTION

Plastic is a vital component of daily life, with plastic products ranging from high-technology items, like prosthetic hip and knee joints, to throw-away food containers [1]. One of the factors contributing to the widespread use of plastic in a variety of industrial applications is its wide range of properties and ease of processing [2]. Most plastic products in the market are manufactured using the molding process, but there is often a need for plastic parts with specific shapes and in small quantities, especially in the engineering field [3]. The molding process is not economically feasible due to the high costs of mold manufacturing; therefore, various operating processes, such as turning and milling, are employed to produce these parts [4]. PA6 is a thermoplastic material of the nylon polymer family known for its excellent mechanical and thermal properties [5]. It is a semi-crystalline polymer, meaning that under appropriate cooling conditions its molecules can arrange into ordered crystalline regions embedded within an amorphous matrix [6]. This structure contributes to its unique combination of strength, toughness, and thermal stability [7]. The semi-crystalline structure and low thermal conductivity of PA6 pose challenges during machining, particularly in achieving an optimal surface finish and minimizing the tool wear [8]. Research has employed different plastic materials and has relied on the surface roughness (R_a) to evaluate their results, due to the importance of this variable in expressing the quality of the processed surfaces. Authors in [9] studied the effect of optimal variables, including spindle speed, feed rate (F_R), and cutting depth (D_C) on the Tool Life (TL), surface roughness (R_a), and Material Removal Rate (MRR) of Polyoxymethylene (POM) in the TP using Taguchi Experiment Design (TED) and Analysis of Variance (ANOVA). Authors in [10] investigated the influence of the cutting tool metal type on *Ra* and cutting force (F_C) for polytetrafluoroethylene using TED. Authors in [11] deployed the Response Surface Methodology (RSM) to optimize the cutting velocity (V_C), F_R, and D_C for decreasing the R_a and increasing the MRR when machining POM. Authors in [12] experimentally found that the D_C is the most influential parameter on the R_a of high-density polyethylene, and V_C is the most effective variable on the R_a of PA6. Authors in [13] studied the prediction methodology of R_a for PA utilizing an artificial neural network in the milling operation, taking the Machining Parameters (MPs) and humidity conditions into consideration. Authors in [14] used TED and ANOVA to study and optimize the V_C, F_R, D_C, and cutting tool rake angle for reducing the cutting forces and geometry deformation of aluminum products. Authors in [15] studied the effect of pointed, relief, lead, and edge radius angles of cutting tools on the R_a of PA6 in the TP, utilizing high-speed steel cutting tool, TED, and ANOVA. The optimization and the effect of the edge radius angle and nose radius of the cutting tool on the F_C of cast nylon 6 have been investigated in [16] using TED and ANOVA. Authors in [17] studied the influence of the nozzle diameter and raster angle on the mechanical properties of 3D printed nylon-carbon fibers using fused deposition modeling. Authors in [18] studied the effect of V_C, sheet metal temperature, and punch edge radius on the copper product deformation using the numerical approach.

The impact of different parameters on selected materials has been investigated using various techniques, including statistical, numerical, and artificial intelligence. However, shortcomings were found in previous research, regarding the minimization of the R_a of PA6 under high cutting quality, the limited improvement percentages in PA6 quality, and the analysis of the effect percentages of MPs and MEs on PA6. Therefore, the current study addresses this research gap by investigating the influence of selected MPs and MEs on the *Ra* of PA6 in the TP. This research focuses on reducing the R_a of PA6 by managing MPs, including F_R, D_C, V_C, and MEs, such as dry (D), compressed air (A), and air-water mixture (A+W). The Design of Experiments (DOE), TED, and ANOVA were applied to achieve the research objectives. The aim of the present study is to determine the most influential parameter and environment on the R_a of PA6.

II. RESEARCH METHODOLOGY

A. Materials and Experimental Design

The PA6 was chosen as a material for this study, with its physical properties being summarized in Table I [19]. A PA6 rod with a diameter of 40 mm and a length of 500 mm was used in experiments. Samples of 30 mm length were prepared for the testing. The experiments were designed using the Taguchi L9 orthogonal array, which entails four parameters, including V_C, F_R, D_C, and MEs (D, A, and A+W), as shown in Table II. The Taguchi L9 orthogonal array was chosen because it enables the efficient optimization of multiple parameters (factors) with fewer experiments while maintaining the statistical reliability. Specifically, this study used four factors with three levels each, and the L9 array was a well-established design for such situations, balancing experimental effort and robustness.

TABLE I. PHYSICAL PROPERTIES OF PA6

Property	Value	Unit
Density	1.14	g/cm³
Water absorption at balance	2.6	%
Melting point	223	°C
Thermal conductivity	0.24	W/m.K
Tensile strength	45-85	MPa
Heat deflection temperature at 0.46 MPa load	170-180	°C
Heat deflection temperature at 1.8 MPa	55-65	°C
Glass transition temperature	60	°C

The MP and ME values were chosen based on previous literature and experimental tests to obtain better results in terms of lower R_a of PA6.

TABLE II. MPs OF USED SAMPLES

MPs (unit)	Level 1	Level 2	Level 3
D_C (mm)	2	4	6
F_R (mm/rev)	0.05	0.1	0.15
V_C (m/min)	125	200	250
MEs	A	A+W	D

B. Experimental Setup

The experiments were conducted deploying a CU-500 lathe, with its specifications being listed in Table III. A carbide cutting tool, Mitsubishi CNMG 120408 UE6020, and a PCLNR 2525 M12 tool holder were used for machining. A custom-designed cooling system was employed to create different MEs, including D, A, and A+W. The SRT5000 roughness tester was used to measure R_a.

TABLE III. SPECIFICATIONS OF THE LATHE MACHINE

Specifications	Values
Number of velocities of the rotating head	21
Rotary head velocity range	20-2000 rpm
Engine power	7.5 KW
Longitudinal feeding field	0.04-12 mm/rev
Occasional feeding field	0.02-6 mm/rev

C. Statistical Methods

The flowchart for the research methodology is presented in Figure 1. TED is a robust statistical approach for designing experiments that evaluate the impact of multiple factors simultaneously. This method is particularly useful for optimizing processes and products to be insensitive to uncontrollable factors while maintaining the cost-effectiveness [20]. DOE is a systematic method employed to determine the most effective set of experiments for studying complex processes. By conducting experiments at different levels of these factors, TED minimizes the number of trials while maximizing the predictive knowledge of the process [21]. The Signal-to-Noise Ratio (*SNR*) is a key metric in the TED analysis, calculated to assess the influence of MPs on R_a. For R_a, the "smaller is better" criterion is applied, as lower roughness values indicate better surface quality. The *SNR* and average R_a can be calculated using (1) and (2) [22]. The latter can be applied to determine the optimum combination of MPs that yield the closest to ideal R_a values [11]. The delta value is calculated as the difference between the largest and smallest average values of *SNR* for each factor. The factors are then ranked based on their delta values, with the highest delta indicating the most significant influence on R_a [23]. The ANOVA is used to quantify the percentage of contribution of each MP to R_a. The ANOVA equations are [16-18]:

$$SNR = -10\,log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i| = \frac{1}{n}\sum(y_1^2 + y_2^3 + y_3^2) \quad (2)$$

$$m = \frac{1}{n}\sum_{i=1}^{n} n_i \bar{x}_i \quad (3)$$

$$TSS = \sum \bar{x}_i{}^2 \quad (4)$$

$$SSM = n\,x\,m^2 \quad (5)$$

$$NOS = TSS - SSM \quad (6)$$

$$DOF = NOS - 1 \quad (7)$$

$$SSF = n[(A_1 - m)^2 + (A_2 - m)^2 + (A_3 - m)^2] \quad (8)$$

$$MS = \frac{SSF}{DOFF} \quad (9)$$

$$POC = \frac{100\,x\,SSF}{TSS} \quad (10)$$

where y_i is the surface roughness value at the i^{th} test, m is the overall mean of samples, n is the number of samples or experiments, and n_i is the sample size. $\bar{x}_i$ is i^{th} sample mean, *TSS* is the total sum of squares, *SSM* is the sum of squares due to mean, *NOS* is the number of stages of a variable i, *DOF* is the degree of freedom, *SSF* is the sum of squares for factor, A_1, A_2, and A_3 are arithmetic mean of *SN* for a variable i at level 1, 2, and 3, respectively, *MS* is the mean of squares, *DOFF* is the degree of freedom for factor A_1, A_2, and A_3, and *POC* is the percentage of contribution.

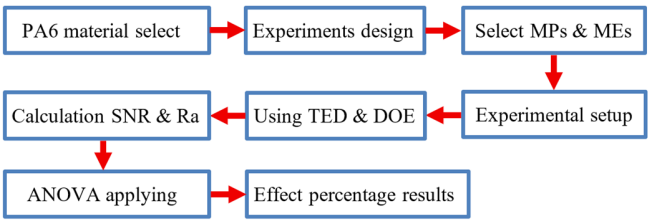

Fig. 1. Flowchart of the research methodology.

III. RESULTS AND DISCUSSION

A. Results

The *SNR* was calculated using the smaller-is-better criteria. For each MP, the SNR values at the three test levels were computed using (1), and the results are displayed in Table IV. Equation (2) was utilized to obtain the three levels of R_a, including R_{a1}, R_{a2}, and R_{a3} of PA6, and the outcomes are presented in Table IV. The data in Table IV can be shown by different figures, where each point on the chart represents one stage of the studied parameter. This means that each point practically represents 3 samples or experiments. The R_{a1}, R_{a2}, and R_{a3} of each sample are summed and then divided by three to obtain the total R_a for each sample.

B. Discussion

Figures 2(a) and 2(b) illustrate the relationships between the V_C and total R_a at D_C values of 2, 4, and 6 mm and at F_R values of 0.05, 0.1, and 0.15 mm/rev. It is indicated that the low V_C values of 125 and 200 m/min result in minimum total R_a values of 1.2 μm at D_C of 2 mm and F_R values of 0.05 and 0.1 mm/rev. In contrast, the high V_C value of 250 m/min results in a maximum total R_a of 2.5 μm at D_C of 2 mm and F_R of 0.15 mm/rev. When using low V_C, the turning tool requires a long time to contact and cut the PA6, which leads to a minimal burr formation on the finished product and results in better surface quality with the lowest R_a.

TABLE IV. R_a AND *SNR* USING TED METHOD

Sample no.	MP				Test results			Total	*SNR*
	V_C (m/min)	F_R (mm/rev)	D_C (mm)	MEs	R_{a1} (µm)	R_{a2} (µm)	R_{a3} (µm)	R_a (µm)	
1	125	0.05	2	A	1.30	1.10	1.18	1.2	-1.556
2	200	0.10	2	A+W	1.05	1.23	1.20	1.2	-1.309
3	250	0.15	2	D	2.60	2.32	2.45	2.5	-7.816
4	200	0.05	4	D	1.59	1.46	1.76	1.6	-4.126
5	250	0.10	4	A	2.00	2.40	2.07	2.2	-6.704
6	125	0.15	4	A+W	1.92	1.94	2.08	2.0	-5.939
7	250	0.05	6	A+W	1.22	1.12	1.31	1.2	-1.721
8	125	0.10	6	D	1.39	1.43	1.24	1.4	-2.644
9	200	0.15	6	A	2.40	2.27	2.34	2.3	-7.374

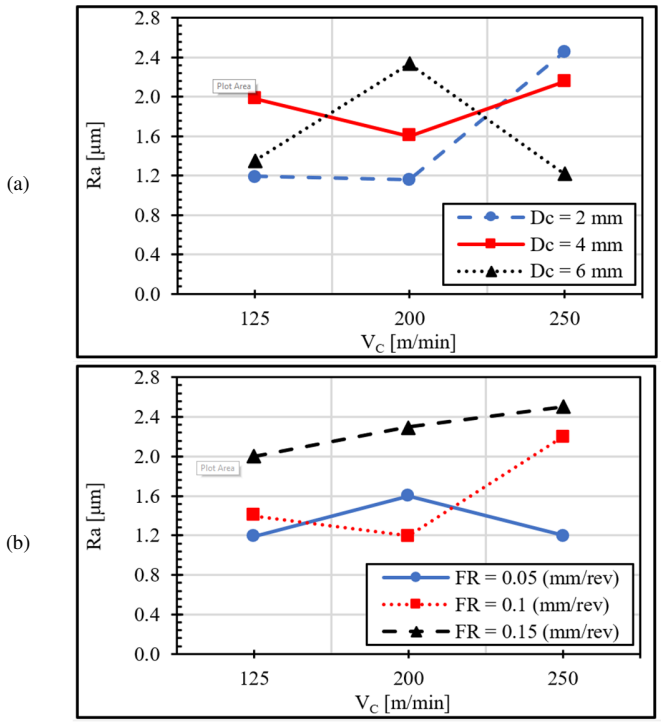

Fig. 2. Relationship between V_C and total R_a at various: (a) D_C, (b) F_R.

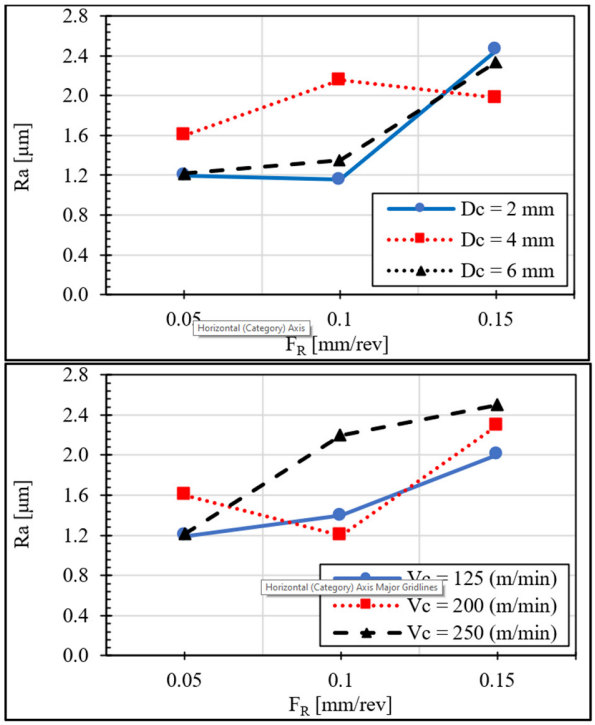

Fig. 3. Relationship between F_R and total R_a at various: (a) D_C, (b) V_C.

A high V_C increases the friction between the turning tool and product, raising the temperature, which lowers the final product quality, resulting in the highest R_a. It also increases the wear of the turning tool, leading to decreased TL. It also increases the F_C and vibration, thus reducing the surface finish of PA6. In contrast, a low V_C results in lower F_C and vibration, improving the surface finish of PA6. A low V_C also lowers the wear, leading to increased TL.

Figures 3(a) and 3(b) illustrate the relationships between the F_R and total R_a at D_C values of 2, 4, and 6 mm and at V_C values of 125, 200, and 250 m/min. It is observed that the low F_R values of 0.05 and 0.1 mm/rev result in the lowest total *Ra* value of 1.2 µm at a D_C value of 2 mm and at V_C values of 125 and 200 m/min. The high F_R of 0.15 mm/rev leads to the highest total R_a of 2.5 µm at D_C of 2 mm and V_C of 250 m/min.

A low F_R leads to a higher surface quality under the lowest surface roughness of PA6. It causes the turning tool to move slowly across the PA6 workpiece during the machining process, resulting in a smooth surface finish. In contrast, a high F_R makes the tool move faster, leading to a rough surface finish. A low F_R also reduces the friction and temperature at the interface of the turning tool, resulting in smaller PA6 deformation and better surface finish. A high F_R increases the friction and temperature, leading to higher deformation and lower surface quality.

A low F_R increases the contact time on the PA6, resulting in high accuracy and improved surface finish of the material. A high F_R reduces the control over the PA6 chip formation, leading to excessive tearing of the product and resulting in low cutting quality. A low F_R decreases the vibration during the turning operation, which leads to better surface quality. In contrast, a high F_R increases the vibration, which reduces the surface quality. A low F_R offers a longer time to the control

system during the turning operation, allowing a better adjustment of the turning tool, which leads to more precision of the final PA6 surface.

The comparative analysis between Figures 3(a) and 3(b) focuses on the effect of F_R on R_a at different values of V_C, rather than D_C values. The specific emphasis is due to the highly sensitive relationship between the F_R and V_C compared with D_C. Figure 3(a) shows a different trend from Figure 3(b) in the R_a values at different F_R, D_C, and V_C.

Figures 4(a) and 4(b) portray the relationships between the D_C and total R_a at V_C values of 125, 200, and 250 m/min and at F_R of 0.05, 0.1, and 0.15 mm/rev. It is demonstrated that the low D_C of 2 mm leads to a minimum total R_a of 1.2 µm at V_C values of 125 and 200 m/min and at F_R values of 0.05 and 0.1 mm/rev. The high D_C of 6 mm results in a maximum total R_a of 2.5 µm at a V_C of 250 m/min and at F_R of 0.15 mm/rev. The low D_C minimizes the MRR and deformation of PA6, reducing the required FC and resulting in a clean surface finish with the lowest roughness. The wear and vibration are also reduced, improving the stability of the turning tool, and resulting in a smoother surface finish. R_a, MMR, and F_C depend on MPs. A high MRR increases both R_a and F_C, while a low MRR results in lower R_a and F_C.

The average *SNR* percentages of each stage of the test for MPs and MEs are outlined in Table V, along with the delta and rank for each MP and ME, and the ANOVA results. F_R represents the most effective parameter on R_a compared with other parameters, as indicated by its first-rank position in Table V, at an effect percentage of 63%. As seen in Table V, V_C, D_C, and MEs are considered close in influence at 11%, 13%, and 15%, respectively, while F_R has the largest influence. The experimental study in [12] suggests that the V_C is the most effective variable on R_a for PA6. In contrast, in the current study, the V_C has the lowest influence on R_a compared to other variables. This difference is due to the use of various MEs (D, A, and A+W) and the corresponding trial values of V_C, F_R, and D_C.

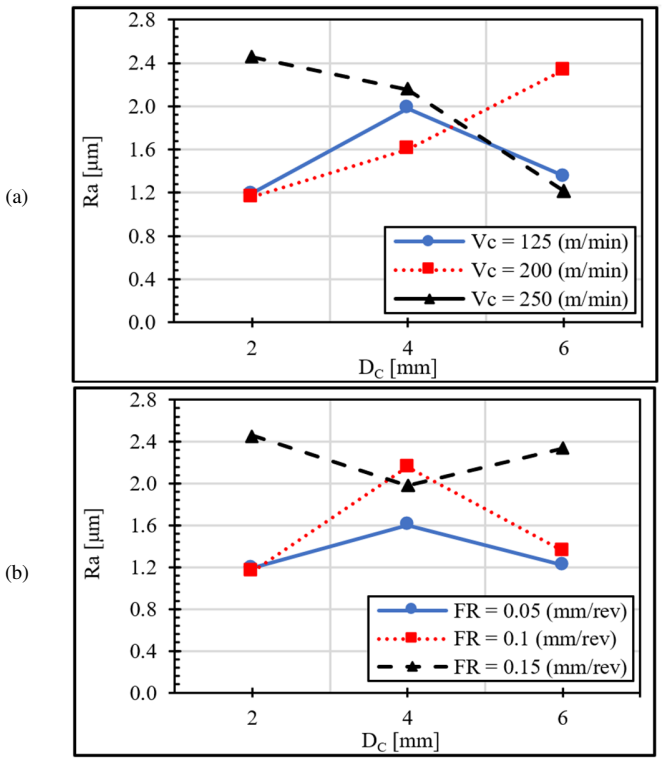

Fig. 4. Relationship between D_C and total R_a at various: (a) and V_C, (b) F_R.

TABLE V. SNR, DELTA, RANK, AND ANOVA RESULTS

MP	*SNR* Average percentage			Delta	Rank	ANOVA results			
	Stage 1	Stage 2	Stage 3			*POC* (%)	*MS*	*TSS*	*DOF*
V_C	-3.380	-4.270	-5.414	2.034	4	11	3.1200	6.2400	2
F_R	-2.468	-3.552	-7.043	4.576	1	61	17.147	34.293	2
D_C	-3.560	-5.600	-3.913	2.040	3	13	3.5280	7.0560	2
ME	-5.211	-2.990	-4.862	2.222	2	15	4.2780	8.5560	2

IV. CONCLUSIONS

Various studies have experimentally explored the Polyamide 6 (PA6) material without focusing on minimizing the average surface roughness (R_a), investigating the Machining Parameters (MPs) and Machining Environments (MEs), or analyzing the impact of these factors. The present research addressed the knowledge gap of the PA6 turning process by lowering R_a, providing a comprehensive analysis of the combined effects of different MPs and MEs, and limiting the influence percentages for each parameter and all MEs using the experimental and statistical approaches. This study systematically quantified the influence of these parameters and environments to improve the quality of machined PA6 surfaces. The former successfully achieved minimum and maximum R_a values of 1.05 µm and 2.45 µm, respectively, which are considered improvements over the R_a of 2.39 µm and 11.14 µm reported in [12].

The study highlights the critical role of MPs, including the cutting velocity (V_C), feed rate (F_R), cutting depth (D_C), and MEs, such as dry (D), compressed air (A), and air-water mixture (A+W), on the R_a of PA6. F_R is indisputably the most dominant variable, contributing 61% of the overall effect. A low F_R of 0.05 mm/rev resulted in a fine finish of 1.2 µm, while a high F_R of 0.15 mm/rev yielded a much coarser 2.5 µm finish. The MEs were the second most dominant variable; using the A+W environment significantly improved the R_a compared with A and D. This improvement can be attributed to cooling and lubrication. The D_C and V_C, on the other hand, had much smaller effects, contributing 13% and 11%, respectively.

The current study identified the optimum parameters and environments for achieving a superior surface finish: V_C of 125 m/min, F_R of 0.05 mm/rev, D_C of 2 mm, and A+W environment. This particular combination can be utilized by manufacturers to achieve a low R_a of 1.2 µm, which could improve the productivity and quality of the end product.

Future studies should extend this investigation to different machining operations, such as drilling, and examine its effect on the Tool Life (TL) and cutting force. Creating a predictive software simulation based on these results could also benefit the process optimization at the industry level.

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