

Experimental Analysis and Optimization of Coaxiality Error Analysis with CNC Turning Process on Cast Nylon-6

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Abstract—In manufacturing industries that involve machining processes like turning, Material Removal Rate (MRR) and Surface Roughness are critical factors in ensuring product quality. Cast Nylon-6 was chosen as the material for this study. Turning is a key machining process used extensively to produce cylindrical parts and to achieve a smooth surface finish. With the increasing use of plastic materials in component fabrication, turning operations play a vital role in achieving high dimensional accuracy. Key challenges in turning include the cost of tooling and its impact on machinability. The results of the study indicated that the output parameters reflected a low surface roughness and high geometric precision. The study revealed that the minimum surface roughness (2.33 μm) was obtained by applying the lowest values of spindle speed, feed rate, and depth of cut. Conversely, the highest material removal rate (MRR) was achieved using a combination of high speed of spindle, high rate of feed, and low depth of cut. Furthermore, the smallest coaxial error occurred when machining at a low spindle speed along with a high rate of feed and high depth of cut.

Index Terms—CNC Turning, Cast Nylon, Surface Roughness, Co-axial error, Material Removal Rate.

I. INTRODUCTION

Polymers, often referred to as plastics, are organic materials valued for their formability and are commonly processed through moulding methods such as injection, blow, compression, and transfer moulding. Injection moulding, which accounts for 70–80% of polymer manufacturing, frequently encounters problems such as warpage, sink marks, and inadequate surface finish, often necessitating additional machining. Machining becomes essential when high

dimensional accurateness and surface eminence are needed, especially in precision applications such as electronics, optics, and machinery. Processes like turning, drilling, and milling help achieve these standards, with parameters like cutting speed, feed rate, and depth of cut influencing the results. Polymer composites-created by reinforcing base polymers with fibers (e.g., glass or carbon) offer improved mechanical characteristics and are widely utilized in automotive, aerospace, and defense applications. Special tools, such as carbide or diamond tools, are employed to enhance machining performance and prevent material damage. The performance of a material is heavily influenced by its surface characteristics, the surrounding atmosphere, and the conditions under which it operates. Surface engineering is a scientific field focused on techniques that tailor the surface properties of engineering components to meet specific performance needs during use. While surface appearance, such as texture and color, may be important, engineering components typically require much more. They must function reliably and efficiently in a range of conditions, including harsh or demanding environments. Modern industrial settings often expose materials to complex forms of wear, combining both chemical and physical damage. Therefore, the surface properties of any component must be carefully engineered to suit the specific conditions it will encounter.

II. LITERATURE SURVEY

Kobayashi et al. [1] investigated ultra-precision machining of polymethyl methacrylate (PMMA).

Their study revealed that a reduction in rate of feed leads to improved surface smoothness. In their study on turning operations for PMMA, Jagtap et al. [2] identified spindle speed as the most influential parameter. They found that lower spindle speeds result in improved surface flatness. Keresztes et al. [3] explored the machinability of various polymers, including PA 6 (Mg), PA 6 (Na), POM C (Polyoxymethylene), and HD 1000 (UHMWPE). Their findings indicate that PA 6 (Mg) exhibits the highest cutting force and resistance, making it the toughest among the materials tested. Salles et al. [4] investigated the impact of machining on the surface quality of Ultra High Molecular Weight Polyethylene (UHMWPE). Their findings revealed that surface roughness amplified with higher rate of feed, while speed of cutting had minimal influence on surface quality. Similarly, Pawade [5] explored the effects of machining parameters on the surface flatness of Nylon and Polypropylene (PP) during precision turning. Additionally, Lazarevic et al. [6] examined turning processes on Polyamide 6 (PA 6) and observed that lower feed rates, shallower depths of cut, and smaller tool nose radii resulted in reduced surface roughness. Silva et al. [7] examined the precision turning of polyamide 66 (PA66) both with and without glass fiber reinforcement. Mehdi et al. [8] observed that incorporating nano calcium carbonate into PA6 during turning operations reduces cutting forces but does not significantly influence surface roughness. Kini et al. [9] led a study on the finish turning of ± 300 filament wound GFRP pipes using carbide inserts. Their findings indicated that surface roughness diminished as rate of feed and speed of cutting increased. Gupta et al. [10] determined that among the turning parameters for GFRP, depth of cut had the utmost impact, followed by rate of feed, influencing both surface roughness and rate of material removal. Kumar et al. [11] observed that the machining behavior of unidirectional GFRP significantly differs from that of metals, involving mechanisms such as plastic deformation, rupture, and shearing. The machinability of GFRP is strongly influenced by fiber properties such as flexibility, orientation, and toughness. Hussain et al. [12] reported that during turning of GFRP, surface roughness increases with rate of feed but reduces with higher cutting speeds and greater fiber orientation angles, with depth of cut having minimal influence. Cutting forces were primarily affected by

feed rate, followed by speed of cut and fiber orientation. In plastic drilling operations, surface finish was shown to be dependent on parameters like speed of spindle, rate of feed and diameter of drill bit. Quadrini et al. [13] discovered during drilling of glass fiber-reinforced polyamide that thrust force is heavily influenced by chip formation. Discontinuous chip formation led to increased thrust with drilling speed and reduced thrust with increased feed rate.

III. MATERIAL SELECTION

S. No.	Parameter	Specification
1	Work Material	Cast Nylon 06
2	Material Dimensions	Dia - 30mm Length - 100mm

Cast Nylon-6 is ideal for industrial and mechanical applications, especially in moist or wet conditions like pumps and valves. Common uses include gears, bearings, bushings, rollers, fittings, and electrical insulators. Its advantages include excellent machinability, dimensional stability, high impact and creep resistance, fatigue endurance, strength, stiffness, and chemical resistance to fuels and solvents, making it durable and reliable in demanding environments.

IV. EXPERIMENTAL DESIGN

Design of Experiments (DoE) is a statistical method for efficiently analysing factors influencing a system while minimizing bias, resources, and time. Polymers, despite their versatility, have limitations compared to metals, including lower melting points, higher thermal expansion rates, and susceptibility to permanent deformation under heavy loads or stress.

1. Smaller-The-Better,
2. Larger-The-Better,
3. Nominal is Best.

The Smaller-the-better criterion minimizes response values like surface roughness, using $\frac{S}{N} = -10 \cdot \log_{10}(n\sum Y^2)$, where Y is the response, and n is the number of observations. The Larger-the-better criterion maximizes outputs like MRR, calculated as $\frac{S}{N} = -10 \cdot \log_{10}\left(n\sum\left(\frac{1}{y^2}\right)\right)$, emphasizing higher values. The Nominal-is-best criterion targets consistency around a specific value, with $\frac{S}{N} = -10 \cdot \log_{10}(s^2)$, where s is the standard deviation, ensuring process stability.

Table: 4.1 Process parameters and their levels

S. No	Spindle Speed (N) (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	700	0.02	0.25
2	900	0.04	0.30
3	1100	0.06	0.35

Table: 4.2 Process parameters and variables

S. No	Spindle Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	700	0.02	0.25
2	700	0.04	0.30
3	700	0.06	0.35
4	900	0.02	0.30
5	900	0.04	0.35
6	900	0.06	0.25
7	1100	0.02	0.35
8	1100	0.04	0.25
9	1100	0.06	0.30

Table 4.1 defines three key CNC turning parameters for cast nylon-6: spindle speed (700, 900, or 1100 RPM), feed rate (0.02, 0.04, or 0.06 mm/rev), and depth of cut (0.25, 0.30, or 0.35 mm). Using a Taguchi L9 orthogonal array in Table 4.2, nine experimental runs systematically combine these settings to analyse their effects on coaxiality error. Each parameter level appears three times across the runs, ensuring balanced representation. This method reduces the required tests from 27 to 9 while enabling robust statistical analysis, including factor effects, interactions, and S/N ratios. Results will optimize parameters for precision and support predictive modelling.

V. EXPERIMENTAL RESULTS AND OPTIMIZATION OF CAST NYLON-6

The table 5.1 exploits the nine experimental runs on Cast Nylon-6, systematically varying three key machining parameters: spindle speed (700, 900, or 1100 RPM), feed rate (0.02, 0.04, or 0.06 mm/rev), and depth of cut (0.25, 0.30, or 0.35 mm). The resulting measurements revealed significant variations in performance metrics: machining time spanned from 2.46 minutes (Run 9) to 6.12 minutes (Run 1), surface roughness ranged between 2.33 μm (Run 1) and 2.62 μm (Run 5), material removal rate fluctuated from 1.405 gm/sec (Run 1) to 9.902 gm/sec (Run 9), and

coaxial error exhibited values from 0.166 (Run 4) to 0.212 (Run 1).

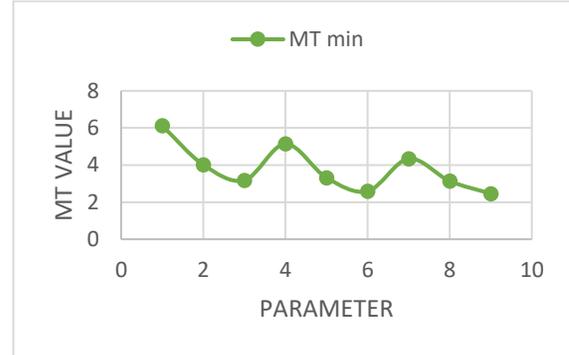


Figure: 5.1 Parameter Vs Machining Timing

Figure 5.1 demonstrates that machining time decreases substantially with higher spindle speeds and feed rates, with values spanning 0 to 7 minutes across the experiments. The shortest machining time of 2.46 minutes was achieved in Run 9, utilizing a spindle speed of 1100 RPM, a feed rate of 0.06 mm/rev, and a depth of cut of 0.30 mm.

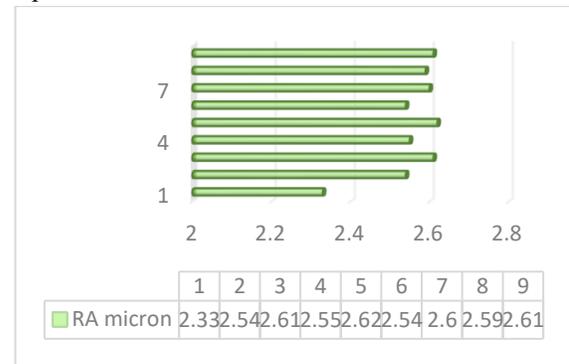


Figure: 5.2 Parameter Vs Roughness Average

Figure 5.2 illustrates that surface roughness values cluster tightly between 2.33 and 2.62 μm , with the highest roughness (2.62 μm) occurring in Run 5 at 900 RPM spindle speed, 0.04 mm/rev feed rate, and 0.35 mm depth of cut. Lower feed rates, such as 0.02 mm/rev, consistently produced smoother surfaces.

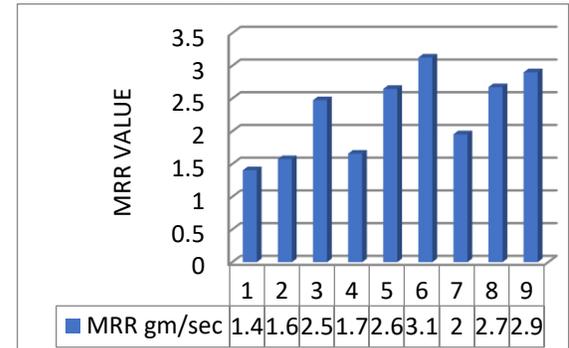


Figure: 5.3 Parameter Vs MRR

Figure 5.3 highlights a dramatic variation in material removal rate, ranging from 1.405 to 9.902 gm/sec. The peak MRR of 9.902 gm/sec occurred in Run 9 under high-speed conditions (1100 RPM, 0.06 mm/rev feed, 0.30 mm depth), while MRR fell below 2 gm/sec at the lowest feed rate (0.02 mm/rev).

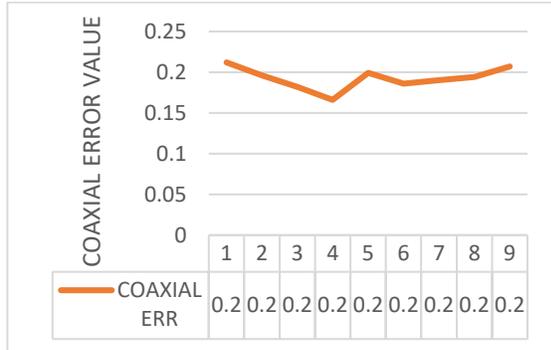


Figure: 5.4 Parameter Vs Co-Axial ERR

Figure 5.4 shows that coaxial error remains consistent across all runs, ranging narrowly between 0.166 and 0.212. The lowest error (0.166) occurred in Run 4 with 900 RPM spindle speed, 0.02 mm/rev feed rate, and 0.30 mm depth of cut. Minimal surface roughness (2.33 μm) was achieved with low speed, feed, and depth of cut, while maximum MRR required higher speed, feed, and lower depth of cut. Lower spindle speed with higher feed and depth of cut resulted in the minimum coaxial error.

Tables 5.2 to 5.6 collectively present the impact of spindle speed, feed rate, and depth of cut on machining outcomes, highlighting the importance of parameter

optimization. Table 5.2 shows that higher spindle speeds and feed rates reduce machining time (MT), with Trial 9 (1100 RPM, 0.06 mm/rev) achieving the shortest MT (2.46 min) and best S/N ratio (-7.8187), while Trial 1 (700 RPM, 0.02 mm/rev) recorded the longest MT (6.12 min) and poorest S/N ratio (-15.7350). Table 5.3 highlights surface roughness (Ra), which improves with lower feed rates and moderate depths of cut. Trial 1 (0.02 mm/rev, 0.25 mm) achieved the best Ra (2.33 μm) and S/N ratio, while higher feed rates in Trial 3 (0.06 mm/rev, 0.35 mm) led to the worst Ra (2.61 μm). Table 5.4 emphasizes productivity, showing that material removal rate (MRR) increases with higher machining parameters. Trial 6 (900 RPM, 0.06 mm/rev, 0.25 mm) recorded the highest MRR (3.127 g/sec) and S/N ratio (9.90256), contrasting with Trial 1's lowest MRR (1.405 g/sec) and S/N ratio. Table 5.5 explores machining precision, with Trial 4 (900 RPM, 0.02 mm/rev, 0.30 mm) achieving the lowest coefficient of error (CO-ERR) of 0.166 and highest S/N ratio (15.5978), while Trial 1 exhibited reduced precision (CO-ERR 0.212, S/N ratio 13.4733). Lastly, Table 5.6 analyses MRR using weight-based data, with initial weights of 84 g and final weights ranging from 75.21 g to 77.67 g, further demonstrating the influence of machining parameters on material removal efficiency. These findings underscore the necessity of optimizing parameters to enhance productivity, quality, precision, and stability in machining processes.

Table: 5.1 Data Analysis and Optimization of Cast Nylon-6

S.No	Spindle Speed (N) (RPM)	Feed Rate (mm/Rev)	Depth of Cut (mm)	MT (min)	RA (μm)	MRR (gm/sec)	Coaxial Error
1	700	0.02	0.25	6.12	2.33	1.405	0.212
2	700	0.04	0.30	4.02	2.54	1.575	0.196
3	700	0.06	0.35	3.18	2.61	2.475	0.182
4	900	0.02	0.30	5.14	2.55	1.658	0.166
5	900	0.04	0.35	3.32	2.62	2.648	0.199
6	900	0.06	0.25	2.59	2.54	3.127	0.186
7	1100	0.02	0.35	4.34	2.60	1.954	0.190
8	1100	0.04	0.25	3.14	2.59	2.675	0.194
9	1100	0.06	0.30	2.46	2.61	2.902	0.207

Table: 5.2 Machining Time (MT) and S/N Ratios

Trial	Design	Spindle speed (N)	Feed Rate	Depth of cut	MT	SN Ratio
1	A ₁ B ₁ C ₁	700	0.02	0.25	6.12	-15.7350
2	A ₁ B ₂ C ₂	700	0.04	0.30	4.02	-12.0845

3	A ₁ B ₃ C ₃	700	0.06	0.35	3.18	-10.0485
4	A ₂ B ₁ C ₂	900	0.02	0.30	5.14	-14.2193
5	A ₂ B ₂ C ₃	900	0.04	0.35	3.32	-10.4228
6	A ₂ B ₃ C ₁	900	0.06	0.25	2.59	-8.2660
7	A ₃ B ₁ C ₃	1100	0.02	0.35	4.34	-12.7498
8	A ₃ B ₂ C ₁	1100	0.04	0.25	3.14	-9.9386
9	A ₃ B ₃ C ₂	1100	0.06	0.30	2.46	-7.8187

Table: 5.3 Surface Roughness and S/N Ratios

Trial	Design	Spindle speed (N)	Feed	Depth of cut	Ra	SN Ratio
1	A ₁ B ₁ C ₁	700	0.02	0.25	2.33	-7.34712
2	A ₁ B ₂ C ₂	700	0.04	0.30	2.54	-8.09667
3	A ₁ B ₃ C ₃	700	0.06	0.35	2.61	-8.33281
4	A ₂ B ₁ C ₂	900	0.02	0.30	2.55	-8.13080
5	A ₂ B ₂ C ₃	900	0.04	0.35	2.62	-8.36603
6	A ₂ B ₃ C ₁	900	0.06	0.25	2.54	-8.09667
7	A ₃ B ₁ C ₃	1100	0.02	0.35	2.60	-8.29947
8	A ₃ B ₂ C ₁	1100	0.04	0.25	2.59	-8.26600
9	A ₃ B ₃ C ₂	1100	0.06	0.30	2.61	-8.33281

Table: 5.4 MRR and S/N Ratios

Trial	Design	Spindle speed (N)	Feed Rate	Depth of Cut	MRR	SN Ratio
1	A ₁ B ₁ C ₁	700	0.02	0.25	1.405	2.95353
2	A ₁ B ₂ C ₂	700	0.04	0.30	1.575	3.94561
3	A ₁ B ₃ C ₃	700	0.06	0.35	2.475	7.87150
4	A ₂ B ₁ C ₂	900	0.02	0.30	1.658	4.39169
5	A ₂ B ₂ C ₃	900	0.04	0.35	2.648	8.45836
6	A ₂ B ₃ C ₁	900	0.06	0.25	3.127	9.90256
7	A ₃ B ₁ C ₃	1100	0.02	0.35	1.954	5.81849
8	A ₃ B ₂ C ₁	1100	0.04	0.25	2.675	8.54648
9	A ₃ B ₃ C ₂	1100	0.06	0.30	2.902	9.25395

Table: 5.5 CO-ERR and S/N Ratios

Trial	Design	Spindle speed (N)	Feed Ratio	Depth of Cut	Co-Err	SN Ratio
1	A ₁ B ₁ C ₁	700	0.02	0.25	0.212	13.4733
2	A ₁ B ₂ C ₂	700	0.04	0.30	0.196	14.1549
3	A ₁ B ₃ C ₃	700	0.06	0.35	0.182	14.7986
4	A ₂ B ₁ C ₂	900	0.02	0.30	0.166	15.5978
5	A ₂ B ₂ C ₃	900	0.04	0.35	0.199	14.0229
6	A ₂ B ₃ C ₁	900	0.06	0.25	0.186	14.6097
7	A ₃ B ₁ C ₃	1100	0.02	0.35	0.190	14.4249
8	A ₃ B ₂ C ₁	1100	0.04	0.25	0.194	14.2440
9	A ₃ B ₃ C ₂	1100	0.06	0.30	0.207	13.6806

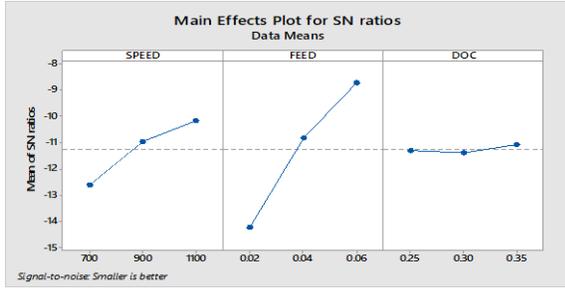


Figure: 5.5 MT Graph for SN ratio-MT

Figure 5.5 shows the Main Effects Plot for S/N Ratios, where lower values indicate better performance. Higher spindle speeds (700 to 1100 RPM) improve S/N ratios, reducing variability, while increased feed rates (0.02 to 0.06 mm/rev) significantly enhance stability. Depth of Cut has minimal impact, with a nearly flat trend.

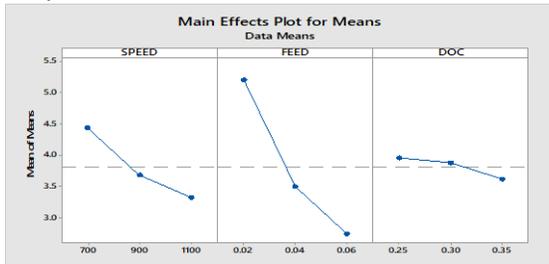


Figure: 5.6 MT Graphs for means-MT

Figure 5.6, the Main Effects Plot for Means, illustrates the influence of factors on average responses like machining time. Higher speeds (700 to 1100 RPM) reduce mean values, indicating more efficient machining, while increased feed rates (0.02 to 0.06 mm/rev) sharply decrease mean values, improving performance. Depth of Cut has a minor effect, with only slight reductions in mean values as it increases. The plots emphasize the critical impact of speed and feed on machining performance, while DOC plays a comparatively smaller role.

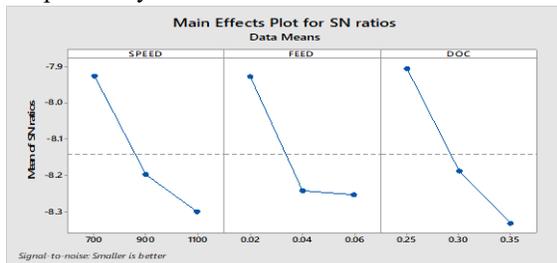


Figure: 5.7 Ra Graph for SN ratio

Figure 5.7 analyzes the S/N ratio for surface roughness (Ra), aiming to minimize variability and achieve consistent results despite uncontrolled factors. With the "Smaller is better" criterion, the Y-axis represents

the mean of S/N ratios, calculated as $-10\log_{10}(\text{mean}(y^2))$. Higher S/N ratios indicate greater robustness in minimizing Ra.

Figure 5.8 analyzes the raw mean values of surface roughness (Ra) to identify parameters that minimize Ra's magnitude, focusing on absolute surface quality. Unlike Figure 5.7, which targets robustness against variability using S/N ratios, Figure 5.8 focuses on the average measured Ra in micrometers. Together, these graphs provide a comprehensive approach to optimizing machining parameters for low and consistent surface roughness.

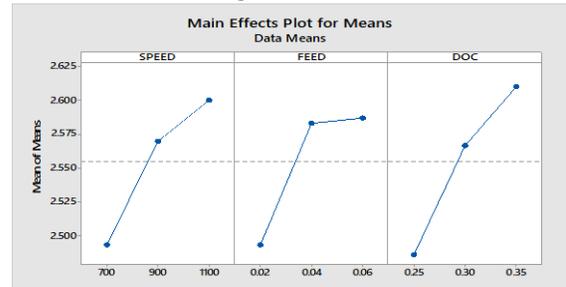


Figure: 5.8 Ra Graphs for means

Figure 5.9 shows the S/N Ratio analysis for MRR under the "Larger is better" criterion, evaluating parameter settings for high, consistent material removal rates. The Y-axis identifies the most robust parameter levels, where higher S/N ratios indicate settings that achieve reliably high MRR with minimal variability from uncontrolled factors.

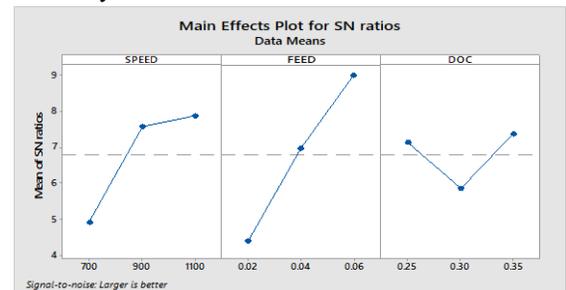


Figure: 5.9 MRR Graph for SN ratio-MRR

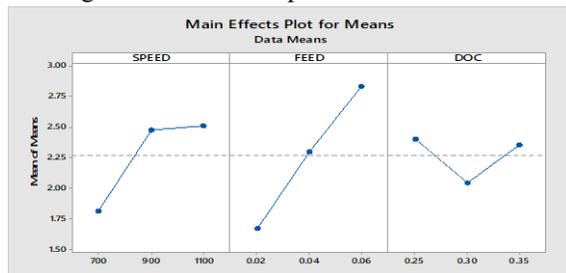


Figure: 5.10 MRR Graphs for means-MRR

Figure 5.10 analyzes the raw average Material Removal Rate (MRR), showing on the Y-axis the

highest mean MRR achieved for each parameter level. Unlike Figure 5.9, which evaluates robustness and consistency using S/N ratios, this graph focuses solely on maximizing the mean output, identifying parameter settings that yield the highest average MRR without accounting for variability.

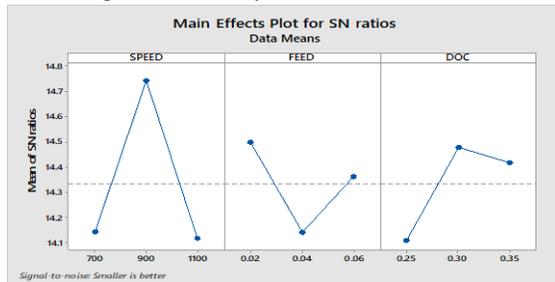


Figure: 5.11 CO-ERR Graph for SN ratio



Figure: 5.12 CO-ERR Graphs for means

Figure 5.11 presents the S/N Ratio analysis for CO-ERR, aiming to minimize its magnitude and variability. It plots the average S/N ratio for each level of speed, feed, and DOC, identifying parameter settings that yield the highest S/N ratios, indicating more consistent and lower CO-ERR values. Figure 5.12 analyzes the mean CO-ERR response, showing the average measured value for each parameter level to identify settings that minimize the CO-ERR magnitude. Unlike the S/N ratio graph, it focuses on the direct impact of parameters on the average outcome, excluding variability. Together with the S/N ratio graph, it provides complementary insights, enabling optimization for both the smallest average CO-ERR and consistent low-error performance.

VI. RESULT AND CONCLUSION

This study focuses on evaluating how turning parameters influence surface roughness and dimensional accuracy when machining CAST NYLON-6 using carbide ceramic inserts. The input variables considered during the process were Rotational speed, material feed, and cutting depth,

while the resulting geometrical deviations were recorded as response measures. The experimental model was developed using the Taguchi design method, and the results were analysed through ANOVA. The findings indicate that the output responses exhibited a low average surface roughness and a high level of geometrical accuracy. The Taguchi analysis of optimal control factor and ANOVA responses were below mentioned.

Optimal Control Factor for Drilling Process

- Machining Timing- A₂ (Speed -900 RPM) B₁ (Feed -0.02 mm/Rev) C₃ (DOC-0.35 mm)
- Surface roughness- A₂ (Speed -900 RPM) B₃ (Feed -0.06 mm/Rev) C₁ (DOC-0.25 mm)
- MRR- A₂ (Speed -900 RPM) B₁ (Feed -0.02 mm/Rev) C₃ (DOC-0.35 mm)
- Co-Axial Error – A₁ (Speed -700 RPM) B₃ (Feed -0.06 mm/Rev) C₂ (DOC-0.30 mm)
- Machining Timing - Feed-80 %
- Surface roughness –Depth of cut- 36%
- MRR– Feed-64 %
- Co-Axial Error- Speed-23%

From the research analysis concluded the Lowest feed, speed and depth of cut were used to achieve the minimal roughness average of 2.33µm. Higher speed, feed and lower depth of cut was induced to achieve the maximum MRR. The minimum coaxial error was obtained the lesser spindle speed and higher feed, depth of cut status.

REFERENCES

- [1] Kobayashi, Hirakawa, Ultra precision machining of Plastics. Part 1. Polymethyl Methacrylatel, Polymer-Plastic technology and engineering (1984), Vol. 22, No. 1, pp. 15-25.
- [2] Patton, Plastics technology: Theory, Design, Manufacturel, Reston publishing company, Mumbai, 1986.
- [3] Brydson, Plastics materialsl, Butterworth scientific, London, 5th edition, 1989.
- [4] ASM international Handbook, Material selection and designl, Volume 20, 1997
- [5] Crawford, Plastic engineeringl, Butterworth Heinemann, 3rd edition, 1998.
- [6] Grabchenko, Verezub, Lavrynenko, Horvath, Mamalis, Precision cutting of optical polymer components for bio-engineering applications,

- Journal of Materials Processing Technology (2000), Vol. 97, pp. 126-131.
- [7] Salles, Goncalves, Effects of machining parameters on surface quality of the ultra- high molecular weight polyethylene (UHMWPE), Conamet/SAM-SIMPOSIO Materia (2002).
- [8] Quadrini, Squeo, Tagliaferri, Machining of glass fiber reinforced polyamide, Express Polymer Letters (2007), Vol. 1, No. 12, pp. 810-816.
- [9] Cheng, Feng, Tan, Wei, Optimization of injection mould based on fuzzy mouldability evaluation, Journal of materials processing technology (2008), No. 208, pp. 222-228.
- [10] Silva, Davim, Festas, Abrao, Machinability study on precision turning of PA66 polyamide with and without glass fiber reinforcing, Materials and Design (2009), Vol. 30, pp. 228–234
- [11] Kini, Chincholkar, Effect of machining parameters on surface roughness and material removal rate in finish turning of ± 300 glass fiber reinforced polymer pipes, Materials and Design (2009), Vol. 31, pp. 3590-3598.
- [12] Mathivanan, Nouby, Vidhya, Minimization of sink mark defects in injection moulding process Taguchi approach, International Journal of Engineering, Science and Technology (2010), Vol. 2, No. 2, pp. 13-22.
- [13] Keresztes, Kalacska, Zsidai, Dobrocsi, Machinability of engineering polymers, Sustainable Construction and Design (2011), pp. 106-114.