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Some Investigations on Surface characteristics in Precision Turning of Nylon and Polypropylene

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***Abstract*— The use of plastic with superior characteristics has increased in several sections such as equipment of precision, electronics and optics. 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. Nylon and Polypropylene are the commercially available polymers which fulfill the requirements of precision products. The focus of the present paper is to understand the effect of machining parameters on surface flatness of Nylon and Polypropylene obtained by precision CNC turning. The experiments were conducted according to Taguchi L9 design. The machining parameters chosen for turning are feed rate, cutting speed, depth of cut and insert clearance angle. Feed rate is an effective parameter in precision turning for both polymers. Minimum surface flatness value obtained as 16.65 µm and 10.7 µm in precision machining of Nylon and Polypropylene respectively.**

***Key Words* — ANOVA, Nylon, Polypropylene, Precision Turning, Surface flatness, Taguchi DOE.**

I. INTRODUCTION

Nowadays plastic has been widely employed in the industrial sector. The use of plastic with superior characteristics has increased in several sections such as equipment of precision, electronics and optics. 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 [13]. When the objective is to produce components in plastic with high dimensional accuracy, it is applied the machining process as final operation. In some cases, it is economically viable to produce the components in plastic using only machining processes. The plastics reaction during machining depends mainly on the mechanical, thermal and rheological properties. Consequently, any evaluation of the machining characteristics should take into account the peculiar properties of the material to be used. When examining the machined surface of a plastic in full detail, it is noted that, while in some cases the roughness is high and with cracks, in others the surface comes covered with undesired feed marks. It may occur that the excessive heat, generated by the machining, causes burning (thermosetting) or gumming (thermoplastic) in the machined surface, demanding a process of finish [4].

Nylon and Polypropylene are the commercially available polymers which fulfill the requirements of precision products [5]. Nylons are crystalline thermoplastics with good mechanical properties to allow its use in structural as well as in precise small parts. Nylons have tensile properties comparable to some extent of aluminum alloys. Polypropylene is similar to high density polyethylene, but its mechanical properties make it more suitable for molded parts than polyethylene. It has excellent fatigue resistance, and it is often used for precise parts in automobiles and aero applications. A unique property of polypropylene is its low density.

However, shaping of these polymers into desired precise products to required precision and accuracy is a challenging task. It has been observed from the available literature that very few researchers have conducted research in precision machining of polymers. The information required for successful and rapid manufacturing of a precise polymeric product is less adequate. The precision machining using a precision turning lathe enables a high flexibility in the production of precision products. Higher form and shape accuracies can be achieved by the precision turning process than with conventional grinding and polishing techniques [13]. The present investigation aims at quantitative as well as qualitative analysis of surface topography of the machined surface produced using CNC turning operations on Nylon and Polypropylene. The analysed results could help prescribe suitable machining techniques that produce most favorable and acceptable surfaces for precision applications.

II. LITERATURE REVIEW

The precision machining methods such as precision CNC turning have been used by very few researchers to analyse the machinability of polymers in the past. The paragraph below throws light on some of the earlier studies related to precision machining of polymers. Salles [5] investigated that the influence of the cutting speed and the feed rate in the turning surface roughness of UHMWPE. Carr [11] performed single point diamond turning of various polymers. It has been reported that the rake angle has a major role on the surface roughness, which further influences the direction of crack propagation into the surface. It was found that the rake angle of -2° produces better surface finish. Grabchenko [6] investigated the mechanism of surface formation using photo emission technique during machining of polymers. A single point diamond turning of CD/DVD pick up lens on PMMA has been carried out by Liu [8]. He achieved the form accuracy obtained by him was less than 1 micron within a tolerance of 1 micron. Gubbels [9], [10] performed precision turning on polycarbonate and PMMA using different cutting

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environments. It is observed that the type of cutting environment during machining influences the tool wear pattern in diamond turning. He further explained the tribo-chemical wear as a predominant phenomenon as compared to other wear. Mamalis [7] investigated the wear of diamond tool in ultra precision and diamond turning operations. He observed that the latent defects of diamond crystals or misalignment by the operations are the reasons for macro wear on diamond tool wedge. According to Kobayashi [4], different types of discontinuous chips can be formed when great compressive stresses are involved or when a brittle material is machined. It can also happen when a thermoplastic is machined at a large rake angle or a great cutting depth.

III. Experimental Work

A. Process, Equipment and Tooling

Precision CNC turning process was employed for investigation on surface flatness of polymers. The work material used for process was Nylon and Polypropylene. Table I shows the specifications of CNC turning machine used for carrying out the experiments.

Table I Specifications of CNC Turning machine

Machine type	Ultra precision lathe PD Spinner	
Model and make	PD-3-01/04-840 D, Germany	
Diameter capacity	Usual turning diameter, mm	120
Axes	Max. X stroke, mm	120
	Max. Z stroke, mm	400
	Max. speed X/Z, mm	400
Main spindle	Spindle nose (5000 l/min), mm	110
	Spindle nose (8000 1/min), mm	100
	Power chuck (5000 1/min), mm	140
	Power chuck (8000 1/min), mm	125
Sub spindle	Speed, rpm	8000
	Max. force clamping cylinder, dN	500 (6 bar)
Tailstock	Dia. of quill, mm	40
	Stroke of quill, mm	100
	Force max., N	3000 (6 bar)
Servo turret	Number of tool positions, piece	12
	Live tools, piece	8
	Speed of live tool, rpm	6000
Torque	Main spindle, Nm	42
	Sub spindle, Nm	23
	Live tool, Nm	3.5
Coolant	Quantity, litre	115

B. Experimental Design

A Taguchi experimental design L9 orthogonal array was used for designing the parameter combinations for each experimental trial (See Table II). In this orthogonal array, number of factors are 4 and number of levels are 3. Hence total numbers of runs are 9. The response variable chosen is the arithmetic average of surface flatness for both the experiments in CNC turning of Nylon and Polypropylene. The input control factors selected for CNC turning of Nylon are: depth of cut (20-50-80 µm), feed rate (0.01-0.05-0.09 mm/rev), spindle speed (1500-2500-3500 rpm) and insert clearance angle (0-7-11 degrees). In the case of CNC turning of Polypropylene are: depth of cut (5-40-75 µm), feed rate (0.03- 0.08- 1.3 mm/rev), spindle speed (1000-2000-3000 rpm) and insert clearance angle (0-7-11 degrees). Table III and Table IV show the experimental runs with the assigned factors to each of the columns of OA for CNC turning process respectively.

C. Experimental Procedure

Initially the nine workpieces to the required length from a long rod of Nylon and Polypropylene were cut as substrates for both experiments. These substrates are exactly made to size of Ø25 × 8 mm thickness. The both sets of nine experiments were performed on ultra precision CNC lathe.

Table II Standard experimental design of L9 (3^4) orthogonal array

Expt. Run	**Column**			
	Factor A	**Factor B**	**Factor C**	**Factor D**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table III Experimental layout using L9 orthogonal array for Nylon

Expt. Run	**Depth of cut (micron)**	**Feed (mm/min)**	**Spindle speed (rpm)**	**Insert clearance angle (Degrees)**
1	20	0.01	1500	0^0
2	20	0.05	2500	7^0
3	20	0.09	3500	11^0
4	50	0.01	2500	11^0
5	50	0.05	3500	0^0
6	50	0.09	1500	7^0
7	80	0.01	3500	7^0
8	80	0.05	1500	11^0

9	80	0.09	2500	0^0

Table IV Experimental layout using L9 orthogonal array for Polypropylene

Expt. Run	**Depth of cut (micron)**	**Feed (mm/min)**	**Spindle speed (rpm)**	**Insert clearance angle (Degrees)**
1	05	0.03	1000	0^0
2	05	0.08	2000	7^0
3	05	1.3	3000	11^0
4	40	0.03	2000	11^0
5	40	0.08	3000	0^0
6	40	1.3	1000	7^0
7	75	0.03	3000	7^0
8	75	0.08	1000	11^0
9	75	1.3	2000	0^0

The substrate of 25 mm diameter was hold in the jaws of the power chuck (see Fig. 1). Three types of carbide inserts with different clearance angles are attached on the tool pockets, which are attached on turret head. Initially the rough cuts of 80 µm were taken on each substrate. Then all the substrates were machined as per the L9 experimental design. Finally for protection of CNC machined surfaces from dust and foreign particles, each substrate is covered with the help of food rapped paper.

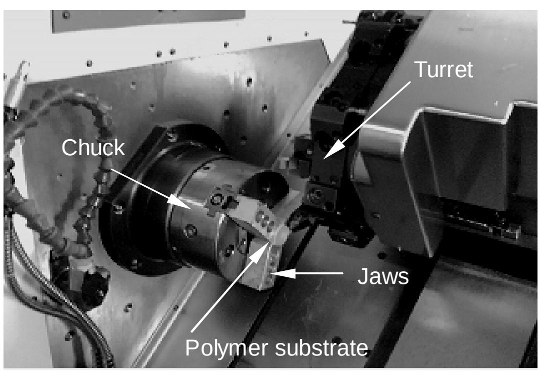

Fig. 1 Close view of set up of CNC turning operation

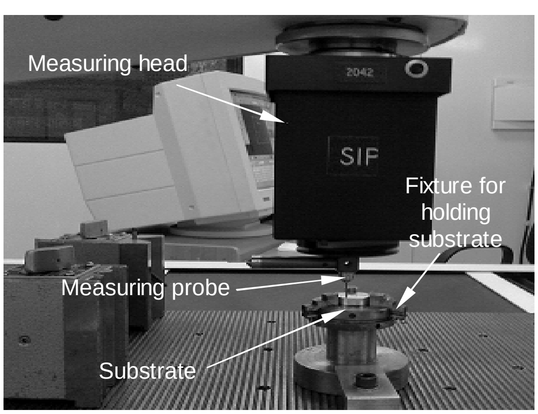

Fig. 2 Universal Measuring Machine (UMM)

All CNC turned machined surfaces were measured by contact type of measurement in a controlled environment temperature. The instrument is used for measuring the flatness of machined surfaces is CNC Universal measuring machine (see Fig. 2). The SIP caps 4 measuring center is a 3-coordinate CNC universal measuring machine capable of a vast array of applications with high precision. Caps 4 is a high performance dynamic precision instrument which can be incorporated equally well in production and metrology environments [15].

IV. Results And Discussion

For flatness measurement of CNC turned polymeric surfaces, contact type instrument is used (UMM). Both types of machined polymer's namely Nylon and Polypropylene substrates were measured on its 25 mm diameter machined surface. Each substrate is fixed in to the fixture for holding zero level. Ruby material's probe of the machine was taken 25 to 30 points on each substrate, given the value of the flatness in terms of micron as shown in Table V.

A. Analysis of Surface Flatness of CNC turned Nylon

Fig. 3 and Table VI show the main effects plots for flatness (ANOM) and the table of analysis of variance (ANOVA). It is observed from the ANOVA table, there is no statistically significant factor in this experiment. Since the P-value in the ANOVA table for any input parameter is not less than 0.05, there is a not statistically significant relationship between any input parameter and the response variables at the 95.0% confidence level. Notice that the highest P-value is 0.5760 in the ANOVA table. Since the P-value is not less than 0.05, that term is not statistically significant at the 95.0% confidence level. The percentage contribution of the input variables influencing, feed rate: 48.22%, clearance angle: 21.41%, spindle speed: 17.68% and depth of cut: 12.68%. The effect of each input variables on the surface roughness in detail using ANOM plots.

Table V Flatness values of CNC turned Nylon and Polypropylene

Substrate No.	**Flatness Values (µm)**	
	CNC Turned Nylon substrates	**CNC turned Polypropylene substrates**
1	81.3	49.4
2	52.1	10.8
3	61.1	27.9
4	87.7	32.4
5	161.9	13.4
6	59.8	54.0
7	59.6	27.8
8	16.65	10.7
9	38.8	94.2

There is a linear effect when the feed rate changes from 0.01 mm/rev to 0.05 mm/rev, flatness is increases from 75 micron to 130 micron. At lower feed rates, shear plane is generated upward from the point of the insert and chips produced by shearing action along this plane. These chips having small shear marks, also machined surface is not quiet better. But when the feed rate is higher, chips produced in continuously form having more shear marks. So it will affect the final surface quality of machined surface i.e. in this case flatness in not maintained on machined surface. Effects plot shows that here is also linear trend when clearance angle changed from 0^0 to 7^0, flatness is reduced from 95 micron to 55 micron. In CNC turning operation, when the clearance angle of the insert is 0^0 then there is a more friction between tool and workpiece contact region. Also there is a linear effect when the spindle speed changes from 2500 to 3500 rpm that time flatness is increases from 60 micron to 95 micron. During machining of Nylon, small continuous unbreakable chips are produced. The effects plot shows that there is a linear effect of depth of cut on flatness of machined surface. When the depth of cut is changed from 20 micron to 50 micron, flatness is also increases from 65 micron to 95 micron.

Table VI ANOVA table for flatness in CNC turning of Nylon

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Depth of cut, *d*	2	2237.6	2237.6	1118.80	0.34	0.5760
Feed, *f*	2	8508.2	8508.2	4254.08	0.33	0.5844
Spindle speed, *s*	2	3120.2	3120.2	1560.11	0.04	0.8442
Clearance angle, γ	2	3777.5	3777.5	1888.75	0.01	0.9371
Residual error	0	-	-	-	-	-
Total	8	17643.5	-	-	-	-

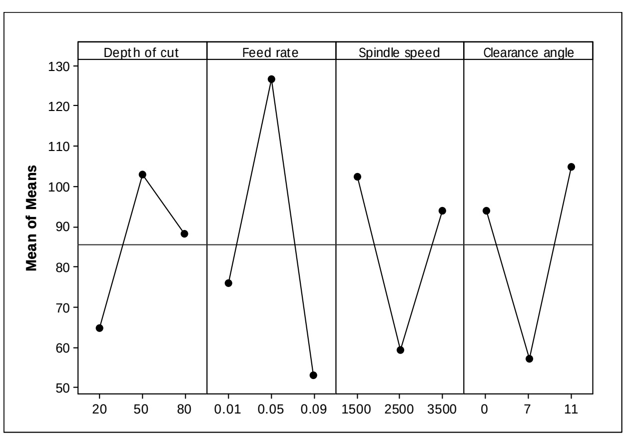

Fig. 3 Main effects plots for flatness in CNC turning of Nylon

B. Analysis of Surface Flatness of CNC turned Polypropylene

The main effects plots for flatness (ANOM) and the table of analysis of variance (ANOVA) are shown in Fig. 4 and Table VII. It is observed from the ANOVA table, there is no statistically significant factor in this experiment. Since the P-value in the ANOVA table for any input parameter is not less than 0.05, there is a not statistically significant relationship between any input parameter and the response variables at the 95.0% confidence level. Notice that the highest P-value is 0.075 in the ANOVA table. Since the P-value is not less than 0.05, that term is not statistically significant at the 95.0% confidence level. The percentage contribution of the input variables influencing, feed rate: 57.14%, clearance angle: 22.92%, spindle speed: 13.80% and depth of cut: 6.12%. The effect of each input variables on the surface roughness in detail using ANOM plots.

The effect plot shows that flatness has linear effect with clearance angle. As the insert clearance changed from 0^0 to 7^0 and at 11^0 flatness of the component gradually decreased from 55 micron to 25 micron. As that clearance angle is increases then friction between tool and workpiece is decreases. It will affect the final machined surface topography. Spindle speed having linear effect on flatness as spindle speed changes from

Table VII ANOVA table for flatness in CNC turning of Polypropylene

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Depth of cut, *d*	2	356.50	356.50	178.25	0.42	0.5363
Feed, *f*	2	3326.64	3326.64	1663.32	4.54	0.075
Spindle speed, *s*	2	803.64	803.64	401.82	0.43	0.5326
Clearance angle, γ	2	1334.44	1334.44	667.22	2.04	0.1962
Residual error	0	-	-	-	-	-
Total	8	5821.22	-	-	-	-

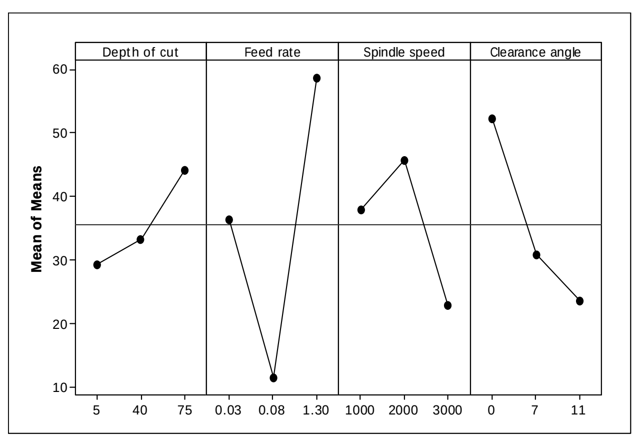

Fig. 4 Main effects plots for flatness in CNC turning of Polypropylene

1000 rpm to 2000 rpm, flatness is also increased from 38 micron to 48 micron. The effect plot shows that there is a linear effect of feed rate on flatness of the machined surface. When the feed rate is changes from 0.08 mm/rev to 1.3 mm/rev, flatness is also increased from 15 micron to 60 micron. Polypropylene is softer than Nylon, its melting point is less than Nylon. At lower feed rates, shear plane is generated upward from the point of the insert and chips produced by shearing action along this plane. The trend shows that depth of cut having a linear effect on flatness of the machined surface. As depth of cut increases from 5 to 40 to 75 micron, flatness is also increases from 30 to 32 to 44 micron respectively. In CNC machining of polymers when the depth of cut is low, continuous chips are produced by smooth shearing action.

V. CONCLUSIONS

Following conclusions can be drawn from the investigation carried out on surface flatness assessment of Nylon and Polypropylene by precision machining process.

- It is observed that the feed rate is an effective parameter in precision turning for both Nylon and Polypropylene polymers. The feed rate affects the flatness of the surface because softer than other polymers.
- Also the larger degree insert clearance angle showing the better surface quality than the smaller insert clearance angle of inserts. The insert clearance angle is increases, there is a less friction between tool and the workpiece. It will affect the final surface quality of machined polymer.
- In case of minimum depth of cut the machined surface topography is much better than in higher depth of cuts. Polypropylene is having great machined surface quality than in machining of Nylon.

It is found that minimum surface flatness value obtained as 16.65 µm and 10.7 µm in precision machining of Nylon and Polypropylene respectively.

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