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Taguchi-Based Surface Roughness Optimization for Slotted and Tapered Cylindrical Products in Milling and Turning Operations

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Abstract**—**The research follows a systematic approach to optimize the parameters for parts machined by turning and milling processes. The quality characteristic chosen is surface roughness since the surface finish plays an important role for parts that require surface contact. A tapered cylindrical surface is designed as a test specimen for the research. The material chosen for machining is aluminum alloy 6061 due to its wide variety of industrial and engineering applications. HAAS VF-2 TR computer numerical control (CNC) vertical machining center is used for milling and HAAS ST-20 CNC machine is used for turning in this research. Taguchi analysis is used to optimize the surface roughness of the machined parts. The L_9 Orthogonal Array is designed for four controllable factors with three different levels each, resulting in 18 experimental runs. Signal to Noise (S/N) Ratio is calculated for achieving the specific target value of 75 ± 15 µin. The controllable parameters chosen for turning process are feed rate, depth of cut, coolant flow and finish cut and for milling process are feed rate, spindle speed, step over and coolant flow. The uncontrollable factors are tool geometry for turning process and tool material for milling process. Hypothesis testing is conducted to study the significance of different uncontrollable factors on the surface roughnesses. The optimal parameter settings were identified from the Taguchi analysis and the process capability C_p and the process capability index C_{pk} were improved from 1.76 and 0.02 to 3.70 and 2.10 respectively for turning process and from 0.87 and 0.19 to 3.85 and 2.70 respectively for the milling process. The surface roughnesses were improved from 60.17 µin to 68.50 µin, reducing the defect rate from 52.39% to 0% for the turning process and from 93.18 µin to 79.49 µin, reducing the defect rate from 71.23% to 0% for the milling process. The purpose of this study is to efficiently utilize the Taguchi design analysis to improve the surface roughness.

Keywords**—**CNC milling, CNC turning, surface roughness, Taguchi analysis.

I. Introduction

THE diversity of customer requirements in the global market has led to the development of new materials, products, and processes in the manufacturing industry. Today, computer numerically controlled (CNC) machines are largely used for mass production to meet the demand. Since its invention in the late 1940s by John T. Parsons, CNC machines have evolved a long way over the decades [1]. Previously, numerically controlled (NC) machines had parameters which could not be changed, whereas the newer CNC machines are controlled by parametric programs that allow real time adjustments, making them more efficient and capable of manufacturing designs of different shapes and sizes. However, there still exist numerous problems in the manufacturing industry such as higher defect rates where the customer specifications are not met due to inappropriate parameter settings. Improperly set parameters may lead to problems during the machining process, including those that could affect the quality of the final product. For instance, a higher feed rate and lower spindle speed may result in a poor surface finish [2].

Cylindrical designs are becoming more and more popular since the load bearing capacity is relatively higher for cylindrical surfaces due to the contact force distribution. Slots are usually milled to cylindrical parts to fit in the assembly. The contact area can be increased by designing a tapered area of contact, thereby maximizing load bearing capacity, as in cone roller bearings [3], [4]. Tapered cylindrical surfaces can bear higher axial and radial loads and therefore have wider industrial applications [5]. Such a complicated product design with a slot and taper requires multiple iterations to set the best parameters to manufacture the parts with precision to meet the customer specifications. A systematic procedure is required to identify the optima parameter settings to serve the customer needs in an efficient way, irrespective of the machine, tools, and processes used for manufacturing. Taguchi parameter design introduced by Taguchi [6] in the early 1950s is an efficient tool to identify the optima parameter settings.

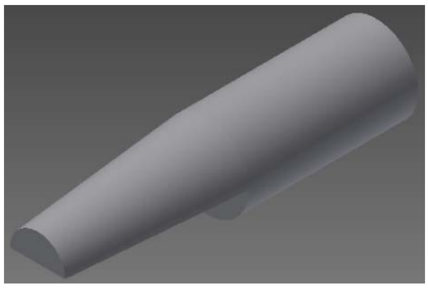

Fig. 1 3D model of workpiece

A tapered cylindrical part, as shown in Fig. 1, is chosen as the workpiece for the research. The part can be manufactured in two different methods. The first method is by turning the tapered surface on a CNC turning center followed by milling

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the slot on a CNC milling machine, which requires removing the part from the CNC turning machine and machining it again in the CNC milling machine. The second method is by mounting the cylindrical raw material directly on a CNC milling machine to mill the tapered surface and the slot in the same machine. The latter reduces the number of operations required to manufacture the workpiece, thereby making it more efficient by saving time and cost to the manufacturer. However, the surface roughness may vary for both methods. Therefore, this research will aim at optimizing the surface roughness of the milling process to make it viable to manufacture the workpiece by using CNC milling machine alone. The machining experiments for the research were performed on the HAAS ST-20 CNC machine (Fig. 2) for the turning process and HAAS VF-2 TR CNC machine (Fig. 3) for the milling process.

Fig. 2 HAAS ST-20 CNC Machine

Fig. 3 HAASVF-2 TR CNC Machine

Surface roughness is an important quality characteristic of a machined part and is therefore investigated as a criterion to identify the capabilities of the CNC milling machine to machine the slotted and tapered cylindrical part. For the milling process, the industrial machined parts usually have a surface roughness of 125 µin from initial machining. Lower surface roughness can be obtained by changing the parameter settings. However, this will lower the production rate by increasing the machining time which is unnecessary. For instance, a lower surface roughness value of 60 µin will slow down the production rate compared to a relatively higher surface roughness value of 90 µin which would still meet the requirements with a higher production rate. This research focuses on optimizing the surface roughness by maintaining the production rate. Therefore, an arbitrary value of 75 ± 15 µin is chosen for this research.

Yang and Tarng optimized the cutting parameters for turning operations based on Taguchi method [7]. In the research, higher the better quality characteristics were chosen for tool life and optimal cutting performance. Hasçalık et al. optimized the turning parameters for surface roughness and tool life based on Taguchi method [8]. Zhang et al. optimized the end milling operation using Taguchi design method with spindle speed, feed rate and depth of cut as controllable factors and tool wear and temperature range as uncontrollable factors [9]. J. A. Ghani optimized surface finish and the resultant cutting force in end milling process for hardened steel using the controllable factors of spindle speed, feed rate, and radial depth of cut in three different levels [10]. The milling parameters were optimized for achieving a lower surface roughness value and therefore lower the better equation was used to calculate the S/N ratio.

Various researches were conducted in the past to optimize the surface roughness. Rashid et al. [11], Al-Hazza et al. [12] and Agarwal [13] studied on modeling the surface roughness of machining processes. The controllable factors considered were spindle speed, feed rate, and depth of cut. The uncontrollable factors influencing the surface roughness in the study were tool geometry and material of the tool. Chen and Hundal [14] devised a systematic approach for identifying the turning center capabilities with vertical machining center in milling operation for flat cuts.

The part has a tapered cylindrical surface with a base diameter of 1.15 inches and a height of 2 inches, tapered at an angle of 5° and will be machined using both the CNC turning machine and the CNC milling machine to evaluate the surface roughness.

The purposes of this paper are summarized as follows:

a. To find whether the slotted tapered cylindrical can be manufactured using CNC milling machine alone meeting the customer demand instead of a two-step process of milling the part in a CNC milling machine after turning in a CNC turning machine resulting in additional movement and setup leading to higher production costs.
b. To study the effects of the uncontrollable parameters on the surface roughness.

II. Methodology

A. Experimental Procedure

Genichi Taguchi developed the Taguchi method [14] in the early 1950's, based on the experimental design methods [15] developed originally by Fisher [16]. Taguchi's method utilizes the orthogonal arrays invented by Rao [17], [18] to design the matrix to select subset of combinations of multiple factors at multiple levels. Orthogonal arrays are combinational arrangements for conducting experiments to determine the optimum mix of several factors. The controllable and noise factors are identified to perform the test runs based on the designed Taguchi L_9 Orthogonal Array and the optima parameter values are calculated based on equations for S/N ratios. The equations for S/N ratio depend on the type of characteristic; lower the better, nominal the better, or higher the better. Hypothesis testing is performed to analyze the effect of the noise factor by using t-test. A null hypothesis and an alternate hypothesis are proposed and the hypotheses are then rejected or not rejected based on the t-test result.

Fig. 4 illustrates the approach used in this research to identify the optimum parameters to attain the target surface roughness and to study the effects of the uncontrollable parameters. The surface roughnesses of the baseline parts are measured and the Gage Repeatability & Reproducibility (Gage R&R) studies are conducted for Measurement System Analysis. The baseline process capability, C_p, and the process capability index, C_{pk}, are calculated to assess both the processes with baseline parameters. The optimal parameter settings are found out using the required characteristic from the Taguchi analysis. Confirmation runs with the optimal parameter settings are conducted for both processes and the corresponding surface roughness are measured. The process capability values, C_p and C_{pk}, are calculated for both the processes from the surface roughness obtained using the optimal parameter settings in the confirmation run to verify improvement.

B. Average Surface Roughness (R_a)

The average surface roughness (R_a) is defined by ASME B46.1, as the mean arithmetic absolute value of the deviations from the profile heights from the mean line, measured within the length of evaluation. In other words, R_a is the average value of a set of individual measurements of a surfaces peaks and valleys. The average surface roughness can be mathematically expressed as in (1) [1]:

$$R_a = \frac{1}{L}\int_0^L |Y(x)|\ dx \tag{1}$$

where, R_a = average surface roughness; L = evaluation length; Y = the ordinate of the profile curve.

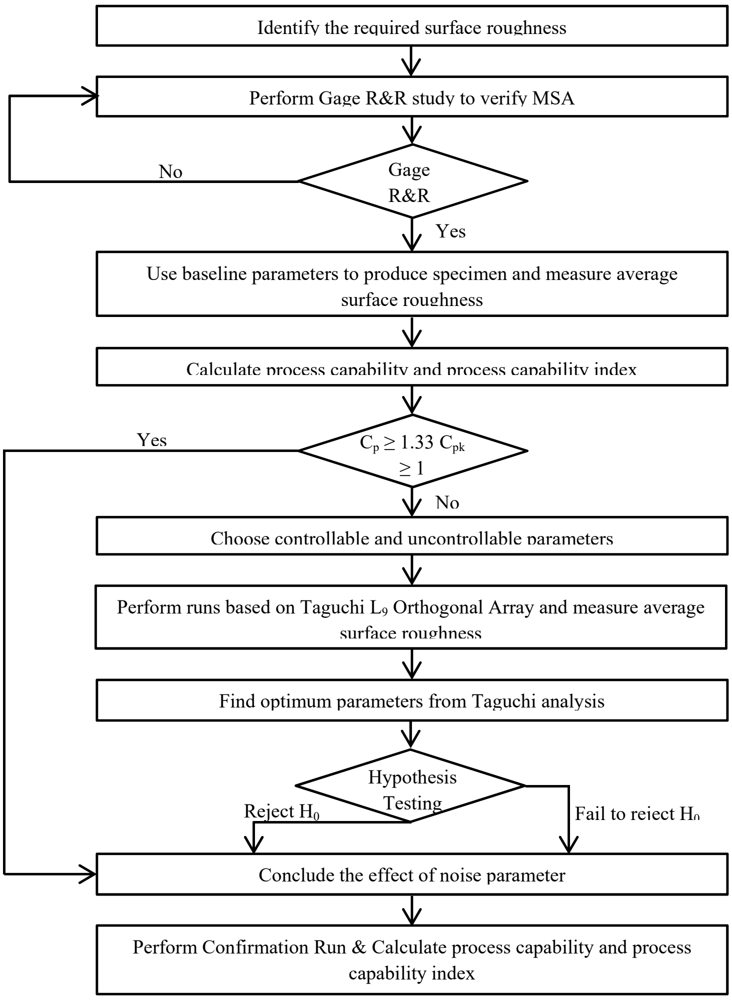

Fig. 4 Research flow chart for studying surface roughness

C. Operating Parameters

The operating parameters for CNC turning are feed rate (in/min), depth of cut (in), spindle speed (rpm), coolant flow (on/off), tool type, finish cut (in), and cycle time (sec). The controllable factors chosen are feed rate, depth of cut, coolant flow, and finish cut and the uncontrollable factor is the tool radius (1/32" or 1/64"). The operating parameters for CNC milling are feed rate (in/min), step over (in), spindle speed (rpm), coolant flow (on/off), spindle load (kW), tool type, and cycle time (sec). The controllable factors chosen are feed rate, spindle speed, step over, and coolant flow and the uncontrollable factor is tool material (high speed steel or carbide). The four controllable parameters are assigned three levels each for the Taguchi L_9 Orthogonal Array design. The parameters are chosen based on their interaction with the surface roughness characteristics of the part machined using both the processes.

III. Experimental Design and Setup

The parts were designed using Autodesk Inventor software for both three-axis CNC milling and CNC turning processes (Figs. 1 & 2). Both parts are identical with 5° angle of taper on a cylindrical surface of length 2 inches and a base diameter of 1.15 inches and 0.80 inch. The baseline parameters for both milling and turning processes are given in Table I. Ten parts each for both CNC milling and CNC turning processes were machined to measure the baseline values of surface roughness.

The surface roughness is measured on a Mitutoyo SJ-301 Surface Roughness Tester. Measurement System Analysis is conducted by the Gage R&R studies. For the turning process, the equipment variation is calculated to 21.74% and an appraiser variation of 4.06%, resulting in an overall 22.12% Gage R&R. A 30% of Gage R&R is acceptable, which means measurement system analysis performed for turning process is within the acceptable range. Table II shows the data obtained for the Gage R&R study for the turning process. Two appraisers measured the ten manufactured parts three times each to calculate the appraiser variation and the equipment variation.

TABLE I
BASELINE PARAMETERS

Turning Parameters	Milling Parameters
Feed rate: 0.0045 in/min	Feed rate: 25 in/min
Depth of Cut: 0.20 in	Spindle Speed: 7500 rpm
Coolant: OFF	Step Over: 0.02 in
Finish Cut: 0.025"	Coolant: OFF
Tool radius: 1/64"	Tool: Carbide

TABLE II
GAGE R&R STUDY DATA FOR TURNING PROCESS

App	Trial #	Part 1	2	3	4	5	6	7	8	9	10	Average
App1	1	66.14	64.96	57.48	54.33	62.99	63.39	60.63	62.99	59.06	59.84	61.18
	2	66.14	64.17	57.09	55.12	61.81	62.99	60.24	61.42	59.84	60.24	60.91
	3	66.54	64.96	58.27	54.72	62.20	63.39	59.45	62.20	59.84	59.45	61.10
	Average	66.27	64.70	57.61	54.72	62.34	63.25	60.10	62.20	59.58	59.84	**61.06**
	Range	0.39	0.79	1.18	0.79	1.18	0.39	1.18	1.57	0.79	0.79	**0.91**
App2	1	63.78	64.96	58.66	57.09	61.81	61.02	62.20	60.63	57.48	60.63	60.83
	2	62.60	64.17	57.48	56.30	62.20	61.02	63.39	61.81	57.09	59.84	60.59
	3	64.17	64.57	57.09	57.09	61.02	61.81	62.60	62.60	59.06	60.63	61.06
	Average	63.52	64.57	57.74	56.82	61.68	61.29	62.73	61.68	57.87	60.37	**60.83**
	Range	1.57	0.79	1.57	0.79	1.18	0.79	1.18	1.97	1.97	0.79	**1.26**

TABLE III
BASELINE RUN DATA (IN μIN)

Part	1	2	3	4	5	6	7	8	9	10
Turning	64.57	62.21	57.09	53.94	59.45	62.60	60.24	61.81	59.84	60.01
Milling	98.03	97.24	92.13	90.16	98.43	91.65	101.58	88.58	93.31	80.71

The baseline run conducted for both processes machined ten parts of each for baseline part measurement using the baseline parameter settings given in Table I. The surface roughnesses measured for each of the ten parts of both the processes are given in Table III. The turning process has an average surface roughness of 60.17 μin with a standard deviation of 2.85 μin. The milling process has an average surface roughness of 93.18 μin with a standard deviation of 5.72 μin. The baseline process capability, C_p, and the process capability index, C_{pk}, are calculated from the above data and the turning process has a C_p of 1.76 and a C_{pk} of 0.02. The milling process has a C_p of 0.87 and a C_{pk} of 0.19. The baseline defect rates for turning and milling processes are calculated as 52.39% and 71.23%, respectively. Figs. 5 and 6 show the process capability graphs generated using Minitab process capability report for baseline turning and milling processes respectively.

The calculated value of process capability (C_p) for the turning process from the baseline measurements is above 1.33, which indicates that most parts are within the specification limit. However, the statistical analysis indicates that the values are concentrated towards the lower specification limit, i.e., the parts have a lower surface roughness than the targeted surface roughness value. The cycle time for the baseline turning process was observed to be 157 seconds. Varying the parameters such as increasing the feed rate which could increase the surface roughness, but decrease the cycle time, could optimize the turning process. This could eventually speed up the manufacturing process, which would be of great use in mass production. The calculated value for process capability (C_p) for the milling process from the baseline measurements is below 1.33, with a very high defect rate. This means that there is a need for optimizing the process to reduce the surface roughness. The cycle time was measured to be 411 seconds.

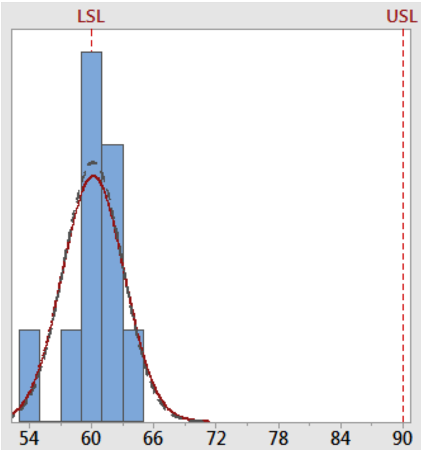

Fig. 5 Process Capability Graph for Turning process Baseline Run

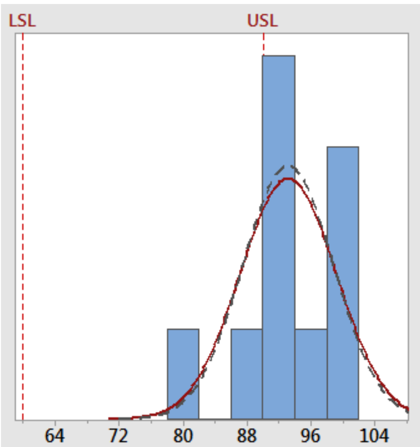

Fig. 6 Process Capability Graph for Milling process Baseline Run

The optima parameter settings for both the processes are identified by the Taguchi experimental design. An L_9 Orthogonal Array (OA) is designed by using the four controllable factors at three different levels and the uncontrollable factor. The different levels of the controllable factors along with the uncontrollable factors are given in Tables IV and V. The L_9 OA gives nine different combinations of the different levels of the controllable factors for each of the uncontrollable factor, giving a total of 18 experiments for the Taguchi experimental design. The Taguchi experimental design test runs were ran in a randomized order for both the CNC turning and CNC milling processes to eliminate the possibility of biases due to previous machining conditions that may arise in the L_9 OA design.

The S/N ratios are calculated based on the characteristic (higher the better, nominal the better, or lower the better characteristic). Nominal the better characteristic is used for both turning and milling processes. The equation for S/N ratio for nominal the better characteristic is given in (2):

$$\eta = 10\log(\bar{y}^2/s^2) \quad (2)$$

where, η = S/N Ratio; $\bar{y}$ = mean of measurements; s^2 = variance.

TABLE IV
TAGUCHI DESIGN PARAMETERS AND LEVELS FOR TURNING MACHINE

Turning Parameters	Level 1	Level 2	Level 3
Controllable Factors			
A - Feed Rate (in/min)	0.0045	0.005	0.0055
B - Depth of Cut (in)	0.05	0.10	0.15
C - Coolant (ON/OFF)	ON	ON	OFF
D - Finish Cut (in)	0.015	0.02	0.025
Non- Controllable Factors			
1 - Tool Radius 1/32"			
2 - Tool Radius 1/64"			
Response Variable			
Surface Roughness			

TABLE V
TAGUCHI DESIGN PARAMETERS AND LEVELS FOR MILLING MACHINE

Milling Parameters	Level 1	Level 2	Level 3
Controllable Factors			
A - Feed Rate (in/min)	10	15	20
B - Spindle Speed (RPM)	7000	7500	8000
C - Step-Over (in)	0.010	0.015	0.020
D - Coolant (ON/OFF)	ON	ON	OFF
Non-Controllable Factors			
1 - Tool Material HSS			
2 - Tool Material Carbide			
Response Variable			
Surface Roughness			

IV. RESULTS AND ANALYSIS

Based on the L_9 OA designed, 9 parts each for the two uncontrollable factors with a combination of the three different levels of the controllable factors, giving a total of 18 parts, were run for both the milling and turning processes. The complete Taguchi L_9 OA for turning and milling processes are given in Tables VI and VII.

The effects of the different levels of each parameter on surface roughness and S/N ratio are given in the response tables (Tables VIII and IX). The response table represents the average response variables for the three different levels of each controllable factor. The relationship between the controllable factors and the surface roughnesses for the turning process are summarized as: (a) surface roughness decreases with an increase in feed rate; (b) surface roughness increases slightly with an increase in depth of cut; (c) surface increases significantly when the coolant is turned off; (d) an increase in finish cut reasonably increases the surface roughness. The relationship between the controllable factors and the surface roughnesses for the milling process are summarized as: (a) an increase in feed rate largely decreases the surface roughness; (b) an increase in spindle speed decreases the surface roughness in a similar pattern as that of feed rate; (c) a change in step over significantly varies the surface roughness; (d) surface roughness increases when the coolant is turned off. The optima parameter setting is determined from the response of surface roughnesses and S/N ratios. Nominal the better characteristic is chosen for both the processes and therefore, the optima parameter level is determined by the value closest to the nominal value for the surface roughness response table and the highest positive value for the S/N ratio response table. For both the turning and milling processes, the optima parameter settings for the surface roughness response table and the S/N Ratio response table gave the same optima parameter settings and the prediction value. The optima parameter settings based on the above mentioned analysis for turning process are first level of feed rate – 0.0045 in/min (A_1), third level of depth of cut – 0.15 in (B_3), coolant off (C_2) and third level of finish cut – 0.025 in (D_3) with a prediction value of 66.44 µin. For the milling process, the optima parameter settings were identified as the first level of feed rate – 10 in/min (A_1), first level of spindle speed – 7000 RPM (B_1), third level of step over – 0.020 in (C_3) and coolant on (D_1) with a prediction value of 77.91 µin. The confirmation runs are carried out using the optima parameter settings.

TABLE VI
TAGUCHI EXPERIMENTAL RUN RESULTS FOR TURNING PROCESS

No.	Factors				Tool Radius				Y-Bar	Var.	S/N Ratio
	A(FR)	B(DoC)	C(Coolant)	D(FC)	1/32"	1/64"	1/32"	1/64"			
1	1(.0045)	1(0.05)	1(ON)	1(0.015)	**Y11**	**Y12**	40.55	70.87	55.71	459.50	8.30
2	1(.0045)	2(0.10)	2(ON)	2(0.020)	**Y21**	**Y22**	42.52	74.80	58.66	521.11	8.20
3	1(.0045)	3(0.15)	3(OFF)	3(0.025)	**Y31**	**Y32**	53.15	76.38	64.76	269.78	11.92
4	2(.005)	1(0.05)	2(ON)	3(0.025)	**Y41**	**Y42**	36.22	79.92	58.07	954.88	5.48
5	2(.005)	2(0.10)	3(OFF)	1(0.015)	**Y51**	**Y52**	37.01	79.13	58.07	887.30	5.80
6	2(.005)	3(0.15)	1(ON)	2(0.020)	**Y61**	**Y62**	38.19	74.80	56.50	670.30	6.78
7	3(.0055)	1(0.05)	3(OFF)	2(0.020)	**Y71**	**Y72**	36.22	79.92	58.07	954.88	5.48
8	3(.0055)	2(0.10)	1(ON)	3(0.025)	**Y81**	**Y82**	34.65	76.77	55.71	887.30	5.44
9	3(.0055)	3(0.15)	2(ON)	1(0.015)	**Y91**	**Y92**	35.83	75.59	55.71	790.58	5.94

TABLE VII
TAGUCHI EXPERIMENTAL RUN RESULTS FOR MILLING PROCESS

No.	Factors				Tool Material				Y-Bar	Var.	S/N Ratio
	A(FR)	B(SS)	C(SO)	D(Coolant)	HSS	Carbide	HSS	Carbide			
1	1(10)	1(7000)	1(0.010)	1(ON)	**Y11**	**Y12**	79.13	76.38	77.76	3.80	-15.90
2	1(10)	2(7500)	2(0.015)	2(ON)	**Y21**	**Y22**	80.77	78.74	79.75	2.06	-16.01
3	1(10)	3(8000)	3(0.020)	3(OFF)	**Y31**	**Y32**	85.04	83.46	84.25	1.24	-16.25
4	2(15)	1(7000)	2(0.015)	3(OFF)	**Y41**	**Y42**	80.32	79.92	80.12	0.08	-16.03
5	2(15)	2(7500)	3(0.020)	1(ON)	**Y51**	**Y52**	77.95	79.13	78.54	0.70	-15.94
6	2(15)	3(8000)	1(0.010)	2(ON)	**Y61**	**Y62**	86.22	83.86	85.04	2.79	-16.29
7	3(20)	1(7000)	3(0.020)	2(ON)	**Y71**	**Y72**	84.65	87.01	85.83	2.79	-16.33
8	3(20)	2(7500)	1(0.010)	3(OFF)	**Y81**	**Y82**	84.25	87.80	86.02	6.28	-16.34
9	3(20)	3(8000)	2(0.015)	1(ON)	**Y91**	**Y92**	95.28	90.55	92.91	11.16	-16.67

TABLE VIII
RESPONSE TABLE FOR SURFACE ROUGHNESS AND S/N RATIO FOR TURNING

Surface Roughness					S/N Ratio				
Level	A(FR)	B(DoC)	C(Coolant)	D(FC)	Level	A(FR)	B(DoC)	C(Coolant)	D(FC)
1	59.71	57.28	56.73	56.50	1	9.47	6.42	6.69	6.68
2	57.55	57.48	60.30	57.74	2	6.02	6.48	7.73	6.82
3	56.50	58.99		59.51	3	5.62	8.21		7.61

TABLE IX
RESPONSE TABLE FOR SURFACE ROUGHNESS AND S/N RATIO FOR MILLING

Surface Roughness					S/N Ratio				
Level	A(FR)	B(SS)	C(SO)	D(Coolant)	Level	A(FR)	B(SS)	C(SO)	D(Coolant)
1	80.59	81.23	82.94	83.31	1	-16.05	-16.08	-16.17	-16.19
2	81.23	81.44	84.26	83.46	2	-16.09	-16.10	-16.24	-16.20
3	88.25	87.40	82.87		3	-16.44	-16.40	-16.17	

Hypothesis testing is conducted after finding out the optima parameter settings from the Taguchi data analysis. The hypothesis testing is conducted to validate the effect of the uncontrollable factors, tool geometry (1/32" and 1/64") for the turning process and tool material (high speed steel and carbide) for the milling process. To determine if the uncontrollable factors cause a significant difference in the results, t-tests are conducted for both turning and milling processes. The hypotheses are defined for turning and milling processes as follows:

Turning:

- H_0: $\mu(_{1/32" \text{ tool}}) = \mu(_{1/64" \text{ tool}})$
- H_0: $\mu(_{\text{HSS tool}}) = \mu(_{\text{Carbide tool}})$

Milling:

- H_1: $\mu(_{1/32" \text{ tool}}) \neq \mu(_{1/64" \text{ tool}})$
- H_1: $\mu(_{\text{HSS tool}}) \neq \mu(_{\text{Carbide tool}})$

For the turning process, the null hypothesis states that there is no difference in the mean surface roughnesses while using a 1/32" tool or a 1/64" tool and the alternate hypothesis states that the tool geometry makes a difference in the average surface roughness. For the milling process, the null hypothesis states that there is no difference in the mean surface roughness while using a high speed steel tool or a carbide tool and the alternate hypothesis states that the tool material makes a difference in the average surface roughness. The t-values are calculated from (3):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2(\frac{1}{n_1}+\frac{1}{n_2})}} \quad (3)$$

where, $\bar{x}$ = average surface roughness for the uncontrollable factors; s^2 = variance; n = number of measurements.

With 16 degrees of freedom for the L_9 OA and a 99% confidence interval, the t-values are calculated. The t-critical value for an alpha value of 0.01 is ± 2.921. For the turning process, the t-value (-17.285) exceeds the t-critical value (-2.921). Therefore, the t-test rejects the null hypothesis. This means that, the tool geometry is a major factor for surface roughness, i.e., the surface roughness of the turning process is significantly affected by changing the tool geometry. For the milling process, the t-value (0.318) does not exceed the t-critical value (2.921). Therefore, the t-test fails to reject the null hypothesis. This means that, the tool material is not a major factor for surface roughness, i.e., the surface roughness of the milling process is not significantly affected by the tool material being high speed steel or carbide. Since nominal the better characteristics are chosen, 1/64" tool is chosen for turning process and carbide tool is used for milling process as the surface roughness values are closer to the nominal value of 75 µin.

The optima parameter settings are identified from the Taguchi data analysis based on the L_9 OA, as discussed earlier. The confirmation runs are performed based on the optima parameter settings and ten parts each for both turning and milling processes are machined to verify if the new parameter settings have brought the surface roughness values within the specification limits and reduced the defect rates. Each of the ten parts was measured three times and the average value of the surface roughness was calculated for both turning and milling processes. The surface roughnesses measured for each of the ten parts of both the processes are given in Table X.

TABLE X
CONFIRMATION RUN DATA (IN µIN)

Part	1	2	3	4	5	6	7	8	9	10
Turning	70.08	68.11	68.90	70.87	67.32	66.54	66.93	67.72	69.69	68.90
Milling	77.56	81.89	77.95	79.13	80.32	79.53	79.92	79.13	78.35	81.10

The turning process has an average surface roughness of 68.50 µin with a standard deviation of 1.35 µin. For the turning process, the baseline run data (Table III) show that the C_p and C_{pk} values are 1.76 and 0.02 respectively, with a defect rate of 52.39%. However, the turning process takes 157 seconds to machine one part with an average surface roughness of 60.17 µin with the baseline parameters. The change in parameters have decreased the cycle time from 157 seconds to 94 seconds, reducing the time required by over 40% to machine one part with an improved average surface roughness of 68.50 µin, closer to the nominal value. The C_p and C_{pk} values improved to 3.70 and 2.10 respectively with 0% defect rate calculated with a target of 75 ± 15 µin.

The milling process has an average surface roughness of 79.49 µin with a standard deviation of 1.30 µin. For the milling process, C_p and C_{pk} values are 3.85 and 2.70 respectively, for the confirmation run, compared to their respective baseline run values of 0.87 and 0.19. The cycle time for machining one part has increased from 411 seconds to 987 seconds. But, the optima parameter settings have decreased the average surface roughness value from 93.18 µin to 79.49 µin, which is much closer to the nominal value. The defect rate calculated for the target value of 75 ± 15 µin has also been significantly reduced from 71.23% to 0%. Even though the cycle time for the process is increased for the milling process while reducing the surface roughness, it only requires the milling operation to machine the part. This eliminates the need for using the turning process, and therefore reduces the overall cycle time required for machining the part since only a single process is involved in the manufacturing process. It also reduces the overall cost and resources required and therefore making it more efficient. Figs. 7 and 8 show the process capability graphs generated using Minitab process capability report for the confirmation run for turning and milling processes respectively, using the optima parameter settings. It is evident that the bell curves are leaner and fits within the specification limits for the confirmation run using the optima parameter settings from the Taguchi analysis, compared to the process capability graphs from the baseline run (Figs. 5 and 6).

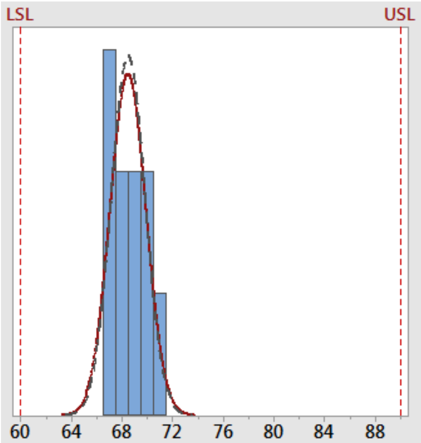

Fig. 7 Process Capability Graph for Turning process Confirmation Run

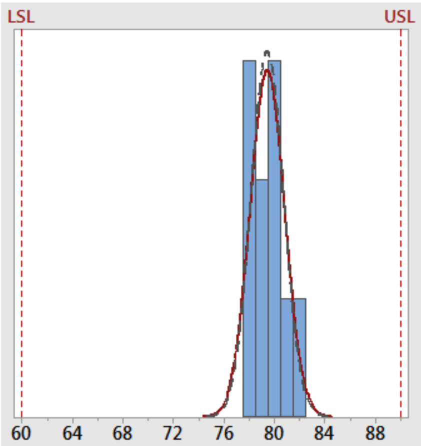

Fig. 8 Process Capability Graph for Milling process Confirmation Run

V. Conclusion

This research studies the significance of the various controllable factors such as feed rate, depth of cut, effect of coolant, and finish cut for the turning process and feed rate, spindle speed, step over, and the effect of coolant for the milling process and delivers an effectual way to identify the optima parameter settings to optimize the surface roughness to the targeted value of 75 ± 15 µin for the designed part. The parameter settings for turning process were determined as feed rate 0.0045 in/min, depth of cut 0.15", without coolant, and finish cut of 0.025" and for milling process as feed rate 10 in/min, spindle speed 7000 rpm, step over 0.02", and with the coolant. The uncontrollable factors chosen were tool geometry for turning process and tool material for the milling process. The result from the hypothesis testing shows that the tool geometry affects the surface roughness significantly for the turning process and the tool material does not play a significant role in the surface roughness for the milling process. For the confirmation runs, 1/64" tool was chosen for the turning process and carbide tool was chosen for the milling process due to the proximity of surface roughness values to the nominal values, as observed from the Taguchi analysis.

Taguchi analysis provides an efficient way for improving the process. This is evident from the improvement in the process capability and process capability index values. For the turning process, the C_p and C_{pk} values were improved from 1.76 and 0.02 to 3.70 and 2.10 respectively. The average surface roughness increased from 60.17 µin to 68.50 µin, decreasing the defect rates from 52.39% to 0%. It is also seen that, the process is further optimized by reducing the cycle time by over 40% for machining a single part. Therefore, a lower surface roughness will slower the production process, as in the baseline machining, which can be speeded up by changing the parameters to increase the surface roughness which will still meet the customer demand and yields more production. For the milling process, the C_p and C_{pk} values were improved from 0.87 and 0.19 to 3.85 and 2.70 respectively. The average surface roughness was reduced from 93.18 µin to 79.49 µin and the defect rate was reduced from 71.23% to 0% for the given specification limits of 75 ± 15 µin. Therefore, it can be concluded that the milling process alone can be used for machining parts that requires a combination of both turning and milling. Even though this process increases the cycle time for milling the part, it only requires machining the part once in the milling machine to achieve an acceptable surface roughness. This method can eliminate the need for turning the raw material, which is an additional manufacturing operation that could incur additional costs, resources and time, thereby making the manufacturing process more efficient. However, further studies could further investigate and optimize the cutter path for the milling process to reduce the surface roughness.

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