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Optimization of Surface Finish in Milling Operation Using Live Tooling via Taguchi Method

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***Abstract*—The main objective of this research is to optimize the surface roughness of a milling operation on AISI 1018 steel using live tooling on a HAAS ST-20 lathe. In this study, Taguchi analysis is used to optimize the milling process by investigating the effect of different machining parameters on surface roughness. The L_9 orthogonal array is designed with four controllable factors with three different levels each and an uncontrollable factor, resulting in 18 experimental runs. The optimal parameters determined from Taguchi analysis were feed rate – 76.2 mm/min, spindle speed 1150 rpm, depth of cut – 0.762 mm and 2-flute TiN coated high-speed steel as tool material. The process capability Cp and process capability index Cpk values were improved from 0.62 and -0.44 to 1.39 and 1.24 respectively. The average surface roughness values from the confirmation runs were 1.30 μ, decreasing the defect rate from 87.72% to 0.01%. The purpose of this study is to efficiently utilize the Taguchi design to optimize the surface roughness in a milling operation using live tooling.

***Keywords*—Live tooling, surface roughness, Taguchi analysis, Computer Numerical Control (CNC) milling operation, CNC turning operation

I. Introduction

TIME plays a vital role when processing parts with multiple operations, such as parts requiring both turning and milling operations. Machining parts with multiple operations requires moving parts from one machine center to another. Usually the cycle time between a turning center and milling center results in an imbalanced work flow. The time taken to unclamp the part from turning center and fix to the milling center takes more than the expected time as it depends upon the skill of the operator. The result of excessive time in moving the workpiece between machines reduces productivity, increases the work load of operators, raises inventory cost and wastage of valuable time which are all detrimental to an efficient manufacturing process. Live tooling can be fitted to the turning center with slight modification to the tool turret, which develops the turning center into a multitasking machine to perform the milling operations, eliminating the switching between the turning and milling center. The live tooling is driven by Computer Numerical Control (CNC) to perform the milling operations while the workpiece remains in orientation with the main spindle.

Quality of the product helps the business to sustain in this competitive globalized world and surface finish is a crucial factor impacting quality as it affects the performance of the part and life span. The factors influencing the formation of surface roughness are very dynamic, complicated and process dependent. Several factors will influence the final surface roughness such as controllable factors (spindle speed, feed rate and depth of cut) and uncontrollable factors (tool wear and workpiece) [1]. Surface roughness can be simply described as the deviation of the surface from the flat ideal surface and is often a good indicator of performance of mechanical components since the irregularities in the surface may lead to nucleation signs for cracks and corrosion [2]. In some cases surfaces should be intentionally rough, such as those on bearings which hold lubricating particles. Surface finish is important for tolerances, reduces assembly time, and thus reduces operation time leading to overall cost reduction.

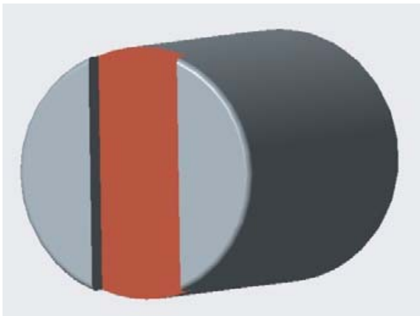

Fig. 1 3D Model of Workpiece

Live tooling is a good option for parts which require turning and milling operations, where the surface finish, tolerance and cutting tool life are critical. A primary concern with using live tooling is if the surface finish produced using live tooling is comparable to that produced by the corresponding conventional milling operation. The research presented in this paper focused on determining optimal parameters for a milling operation using live tooling in a turning center. The main research thrust was efficiently determining optimized live tooling parameters to achieve the desired surface finish, while considering a noise factor. A systematic approach is needed to determine the optimal parameters and various manufacturing processes.

II. Methodology

Suresh et al. studied the machining behavior of AISI 1018 steel in turning operations, finding that speed has the maximum effect on the surface finish (i.e. at high speeds, surface finish is least affected) and in order to obtain good surface finish the feed rate should be kept low [2]. Zhang et al. studied the optimal parameter set-up in an end milling

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operation by using the Taguchi design method: spindle speed, feed rate, and depth of cut were controllable factors; tool wear and tool temperature range were named as uncontrollable factors. The study also indicated the effect of spindle speed and feed rate on surface roughness are larger than depth of cut [3]. Taguchi design utilizes the orthogonal arrays invented by Rao [4], [5] to design the matrix to select subset of combination 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 optimal parameter values are calculated based on the equation for S/N ratios. Babu and Babu studied the correlation among the cutting parameters on surface roughness and cutting force in turning, concluding that for surface roughness feed rate is the main influencing parameter, with a percentage contribution of 7.035% followed by cutting speed and depth of cut [6]. Factors such as vibration of the machine, obliqueness in workpiece, tool wear, workpiece temperature, and variation in material composition also contribute to the surface roughness [1].

III. Experimental Design

In this study, a cylindrical bar of AISI 1018 steel length 38.1 mm, diameter 25.4 mm as shown in Fig. 1 was used to carry out the experiment on a HAAS ST-20 by 9.525 mm titanium nitrate (TiN) coated 2-flute high-speed steel end mill. Fig. 2 illustrates the approach which is used in this research to determine the optimum parameters needed to attain the target surface finish. The surface roughness produced using the baseline parameters are measured and Gage R&R (repeatability & reproducibility) of the Surftest is conducted to ensure the equipment is within the specified limit. The baseline process capability C_p and the process capability index C_{pk} are calculated for the baseline parameters. The optimal parameter settings are established using the required characteristics from the Taguchi analysis. Confirmation runs with the optimal parameter settings are conducted and surface roughness values are obtained. The process capability values, C_p and C_{pk}, are calculated for the confirmation runs which use the optimal parameter settings.

The device used to measure the surface roughness of parts was a Federal Pocket Surf III. The baseline data of the ten parts are 1.71, 1.60, 1.45, 1.45, 1.51, 1.78, 1.61, 1.72, 1.65, 1.60 all are in microns (µ), the mean and standard deviation of surface finish are calculated as 1.70 µ and 5.14 respectively. The baseline process capability, C_p, and the process capability index, C_{pk} are 0.62 and -0.44 respectively, and the defect rate was 87.72% with a target of 1.27 µ. Minitab was used to calculate these values. The cycle time for the baseline turning process was observed to be 121 seconds. As the process capability is below 1.33, there is a need to optimize the process to achieve the desired surface roughness.

Feed Rate, Spindle Speed, Depth of Cut and Tool Material were determined as the most significant factors based on the literature review. Taguchi design for the optimization of surface finish by varying the process parameters was applied. The operating parameters were Feed Rate, Spindle Speed, Depth of Cut for both rough pass and finish pass, and Tool Material. The optimal parameter settings were identified by the Taguchi experimental design. An L_9 orthogonal array (OA) was constructed using the four controllable factors at three differing levels; the uncontrollable factors were assigned two levels as shown in Table I. The controllable factors were Feed Rate, Spindle Speed, Depth of Cut and Tool Material; the uncontrollable (noise) factor was Environment Temperature. The parameters were chosen based on their effect on surface roughness characteristics of machined parts.

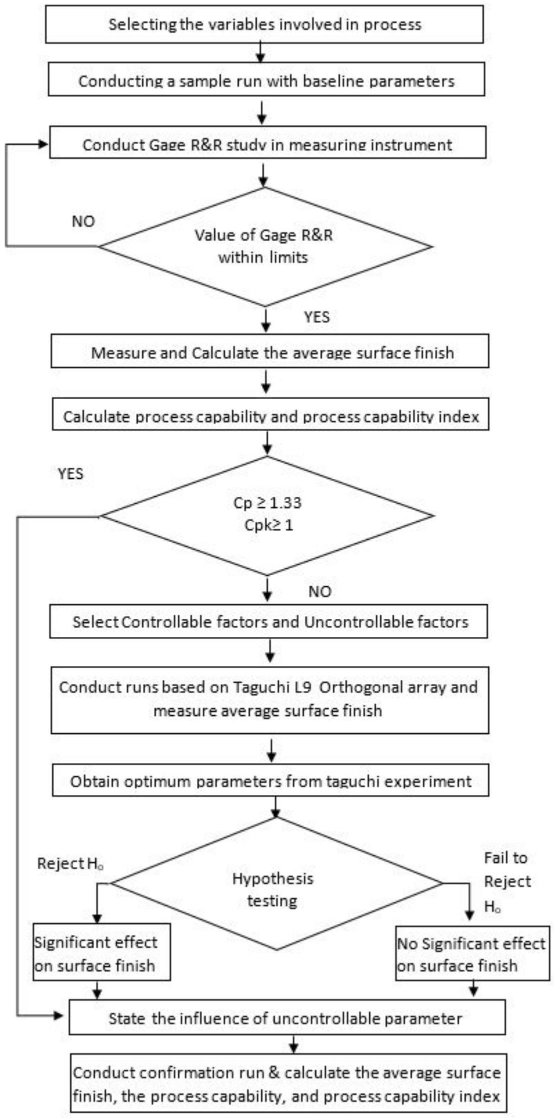

Fig. 2 Flow Chart for achieving Surface Roughness

The optimal parameter settings for milling operation are obtained from analyzing the signal to noise ratio (S/N). They are determined by the characteristics (higher the better, nominal the better, and lower the better). Nominal the better characteristics are chosen for determining the optimal parameter settings. The maximized S/N ratio gives us the optimal factor level. The nominal the better equation is as:

$$\eta = 10\log\left(\frac{\bar{y}^2}{s^2}\right) \quad (1)$$

where, η denotes the signal to noise ratio, $\bar{y}$ denotes the mean of the measured values of surface roughness of the taguchi experiment run, and s denotes the variance of the surface roughness. A total of 18 experimental runs are conducted, as per the Taguchi OA design as shown in Table II. The S/N ratios for all the runs are computed as shown in Table IV. Table I provides different levels of each machining parameter, and the fourth controllable factor is selected as tool material. The first two levels are conducted with 2-flute TiN coated high speed steel and the third level is conducted with a 2-flute carbide end mill. The feed rate is incremented by 50.8 mm for each level and the depth of cut is incremented by 1.27 mm for each level. The two levels of non-controllable factors lead to a total of 18 runs to determine the optimal parameter settings. The environment temperature is chosen close to the room temperature of 70-75 °F for one level, and the second level is below the normal room temperature of 60-65 °F: This determines the influence of temperature over the response variable (surface finish).

IV. Result and Analysis

The effects of various machining factors on the surface roughness can be analyzed by the response table as shown in Table III. The response table represents the average surface finish (response variable) for the corresponding machining parameter (controllable factor) from the Taguchi experiment nominal the better characteristics are chosen, and the nominal value is 1.27 µ. The optima parameter settings from Table III response for surface roughness is the third level of feed rate A3 – 177.8 mm/min, second level of spindle second level of depth of cut C2 - 0.635 mm and second level of tool material D2- HSS. The signal to noise ratio indicates the effect of the input on the output without any effect of the noise factor. The highest positive value in the signal to noise ratio response table is chosen to determine the optimal parameter. The response for the signal to noise ratio is shown in Table IV, the following settings were chosen as optimal parameters: A1- 76.2 mm/min; B2 -1150 rpm; C3 -76.2 mm, D2- HSS. The confirmation runs use these parameter settings.

TABLE I
Taguchi Parameters Design

Designation	Variable	Levels	1	2	3
Controllable Factors					
A	Feed Rate (mm/min)		76.2	127	177.8
B	Spindle speed (rpm)		800	1150	1500
C	Depth of Cut (mm)		0.508	0.635	0.762
D	Tool Type(HSS/Carb)		HSS	HSS	Carbide
Non-Controllable Factors					
1	Environment Temperature		Room Temperature (70 -75)°F		
2			Cooler Temperature (60 - 65)°F		

TABLE II
Taguchi Experimental Run Data

Run	Feed Rate (mm/m)	Spindle Speed (rpm)	Depth of cut (mm)	Tool Material (HSS/Carb)	Temperature (60-65°F)	Temperature (70-75°F)	Y-Bar	S/N Ratio
1	1(76.2)	1(800)	1(0.508)	1(HSS)	50	52	51.000	31.141
2	1(76.2)	2(1150)	2(0.635)	2(HSS)	53	54	53.500	37.577
3	1(76.2)	3(1500)	3(0.762)	3(Carb)	13	14	13.500	25.617
4	2(127)	1(800)	2(0.635)	3(Carb)	19	23	21.000	17.413
5	2(127)	2(1150)	3(0.762)	1(HSS)	61	59	60.000	32.553
6	2(127)	3(1500)	1(0.508)	2(HSS)	51	54	52.500	27.871
7	3(177.8)	1(800)	3(0.762)	2(HSS)	57	58	57.500	38.204
8	3(177.8)	2(1150)	1(0.508)	3(Carb)	23	28	25.500	17.162
9	3(177.8)	3(1500)	2(0.635)	1(HSS)	59	47	53.000	15.912

TABLE III
Response Table for Surface Roughness

Level	A	B	C	D
1	39.3	43.2	43.0	54.7
2	44.5	46.3	55.5	54.5
3	45.3	39.7	43.7	20.0

TABLE IV
Response Table for Signal to Noise Ratio

Level	A	B	C	D
1	31.4	28.9	25.4	26.5
2	25.9	29.1	23.6	34.6
3	23.8	23.1	32.1	20.1

To determine the effect of the uncontrollable factor (environment temperature) on the response variable (surface roughness), hypothesis t- testing is conducted. The hypotheses are as follows:

- H_0: $\mu_{(70\text{-}75)°F} = \mu_{(60\text{-}65)°F}$
- H_1: $\mu_{(70\text{-}75)°F} \neq \mu_{(60\text{-}65)°F}$

The null hypothesis H_0 states that there is no significant difference in the average surface roughness alternative hypothesis states that there is significant difference. With 16 degrees of freedom for the L_9 OA and a confidence interval of 99%, t-values during different environment temperatures, and the critical values are calculated. The t-critical value for an alpha value of 0.01 is ± 2.75. For the milling process, the calculated t-test value was 0.06, which does not exceed the critical t value of ± 2.75. Therefore, the null hypothesis fails to be rejected. This means that environmental temperature does not have a significant effect on the surface roughness. The optimal parameter settings are determined from the L_9 Orthogonal Taguchi analysis, as outlined earlier. A confirmation run was performed to determine the improved surface roughness. Each part was measured three times and the average surface roughness was as using the optimal parameter settings, the data from 10- confirmation run are 1.29, 1.29, 1.29, 1.37, 1.42, 1.27,

TABLE V
COMPARISON OF BASELINE AND EXPERIMENTAL DATA

Parameters	Baseline Data	Experimental data
Mean of Ra (μ)	1.70	1.29
SD (σ)	6.16	2.33
Defect Rate (%)	87.15	0.01
C_p	0.62	1.39
C_{pk}	-0.44	1.24

1.24, 1.29, 1.21, 1.27 all are in microns (μ). Table V compares the baseline data with the confirmation run experimental data and the mean of the surface finish in the experimental run was 1.29 μ and standard deviation was 2.33. Comparing with the baseline data, a drastic improvement in the process is evident. The sample mean was changed from 1.70 μ to 1.29 μ, and the standard deviation was reduced from 6.16 to 2.33. The defect rate was reduced from 87.15% to 0.01%, with 1.27 μ as nominal value.

V. CONCLUSION

This study demonstrates the significance of feed rate, spindle speed, tool material and depth of cut in efforts to achieve a desired surface roughness. Taguchi analysis provides an efficient way for improving the process: it uses a systematic procedure at low cost and requires a small number of experiments. The surface roughness of the workpiece has been optimized by investigating the effect of machining parameters at different levels. The parameter settings were determined as follows: feed rate – 76.2 mm/min, spindle speed 1150 rpm, depth of cut – 0.762 mm and 2-flute TiN coated high-speed steel as the tool material. The average surface roughness has been shifted from 1.70 μ to 1.29 μ, decreasing the defect rate from 87.72% to 0.01%. The C_p and C_{pk} values have improved from 0.62 and -0.44 to 1.39 and 1.24 respectively. The live tooling eliminates the need for slotting in the milling machine. The same operation can be carried out in a turning machine; this can eliminate an additional manufacturing process and its associated processing costs, resources, and time. However, reducing the feed rate increased the cycle time. Further studies could investigate and optimize the milling process with a higher feed rate, in order to reduce the cycle time without sacrificing quality.

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