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Optimization of Turning Process for Surface QualityImprovement of Hard AISI M7 Tool Steel

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Abstract: In this study, the Taguchi technique is used to examine the impact of changing an insert's geometric parameter, such as its nose radius, on surface roughness during a CNC turning operation for AISI(M7). The process parameters that are varied throughout the experimental trials include cutting speed, feed rate, cut depth, and insertnose radius. The performance characteristics in the CNC turning of AISI(M7) employing TNMG160404, TNMG160408, and TNMG160412 Tin coated carbide inserts on CNC turning centre are studied using a L9 orthogonal array and the signal-to-noise (S/N) ratio. The feed rate and nose radius were shown to have the greatesteffects on surface roughness during the CNC turning process.

Keywords- Insert, Taguchi, S/N ratio, AISI M7, Surface Roughness, Nose radius.

1. Introduction

The turning process is an essential machining procedure that is used in all industries, making it a significant one.The technology of CNC turning machines has advanced dramatically in the modern era. Cutting forces, tool wear,surface finish, and chip formation are among the many aspects of machining performance that are influenced by tool geometry parameters. Recently, there has been much emphasis placed on the economic need of optimizing tool shape in order to maximize tool life in machining. When inserting the cutting tool's edge into a rotating workpiece, different angles are essential. These angles consist of the lead or entrance angle, tool nose radius, rakeangle, effective rake angle, and angle of inclination.

Alok, A., & Das, M. (2019) [1] executed a new type of coating material, HSN2 with 12 µm thickness on carbideinsert by using physical vapor deposition technique for machining hard AISI 52100 steel of hardness 55 HRC is evaluated. DSC and TGA also characterize the coated carbide insert's thermal and oxidative stability. The primarycutting, radial, and feed pressures, maximum flank wear, and surface quality of the workpiece are all related to the input process parameters of cutting speed, feed rate, and depth of cut. The impact of cutting parameters on machinability is studied statistically. Also, regression models are created to link input and output process characteristics. This is followed by a response surface optimization and validation test. Percentage errors for maincutting force, radial force, feed force, surface roughness (%), and flank wear (%) were identified in the confirmation test. The greatest tool wear recorded is 292 m, which is acceptable under ISO 3685. Among all output parameters, cutting speed is shown to be the most effective. The current effort is unique in that it involves machining AISI 52100 steel with a 55 HRC hardness at 102–287 m/min with a new coating material HSN2 with a 12 m thickness.

Aouici, H., et al. (2012) [2] investigated experimentally the effects of cutting speed, feed rate, workpiece hardnessand depth of cut on surface roughness, and cutting force components in the hard turning. To mill the AISI H11steel, Sandvik used cubic boron nitride (CBN 7020), which is a mix of 57 percent CBN and 35 percent TiCN. They used four-factor (cutting speed, feed rate, hardness, and depth of cut) and three-level fractional experiment designs using ANOVA. This technique generated mathematical models for surface roughness and cutting force components (RSM). While the depth of cut and workpiece hardness have the greatest impact on cutting force components, both feed rate and workpiece hardness have statistical relevance on surface roughness. Finally, optimal cutting conditions ranges for industrial production are recommended.

Aouici, H., et al. (2011) [3] investigated turning conditions of hardened AISI H11 (X38CrMoV5-1), and the effects of cutting parameters on flank wear (VB) and surface roughness (Ra) using the CBN tool. The response surface approach is used in the machining trials (RSM). In this study, the combined impacts of three cutting parameters are investigated (cutting speed, feed rate, and cutting duration) on two performance outputs (VB and Ra) (ANOVA). The optimal cutting conditions for each performance level are derived using a quadratic regression model. The data suggest that cutting time affects flank wear the most, followed by cutting speed. Also, the feed rate seems to have the main influence on workpiece surface roughness.

Azizi, M. W., et al. (2012) [4] investigated the effect of cutting parameters (cutting speed, feed rate, and depth of cut) and workpiece hardness on surface roughness and cutting force components. On AISI 52100 steel with coated Al2O3 + TiC mixed ceramic cutting tools. The experiment was planned using Taguchi's L27 orthogonal array. The response table and ANOVA enabled us to test the linear regression model's validity and identify relevant factors impacting surface roughness and cutting forces. The statistical study shows that the depth of cut, workpiece hardness, and feed rate have a statistically significant influence on the cutting force components than the cutting speed. To connect cutting parameters and workpiece hardness with surface roughness and cutting forces, empirical models were created. The desired function technique for multiple response factor optimization was used to find the optimal machining settings to create the lowest surface roughness with the least cutting force components. Finally, validation experiments were conducted to validate the proposed empirical models.

Azizi, M. W., et al. (2020) [5] optimized machining parameters to achieve the desired technical parameters such as surface roughness, tool radial vibration, and material removal rate using response surface methodology (RSM).The hard turning of EN19 alloy steel with GC3015) cutting tools was examined. In order to achieve the needed surface finish quality and production rate, manufacturers of hard and high precision components confront a major challenge. RSM can handle this issue by creating a mathematical model and conducting tests. The statistical study employed a face-centered central composite design (FCCD) with cutting parameters (cutting speed, feed rate, and depth of cut). It was shown that cutting parameters correlated with surface roughness, tool vibration, and materialremoval rate. Using a desirability function, numerical and graphical optimization was used to find the best cuttingsettings for reducing surface roughness, tool vibration, and material removal rate. Finally, validation experimentswere conducted to validate the mathematical models.

Bouzid, L., et al. (2015) [6] attempted to statistically model the relationship between cutting parameters (speed, feed rate, and depth of cut), cutting force components (Fx, Fy, and Fz), and workpiece absolute surface roughness(Ra). A chemical vapor deposition–coated carbide tool is used to machine martensitic stainless steel (AISI 420). A full-factorial design (43) is used to examine the experimental findings using both ANOVA and RSM. The optimal cutting conditions are obtained utilizing mutually responsive surfaces and desired functions, with residualvalues checking the model's adequacy. The findings show that depth of cut (Fx: 86%) dominates (Fy: 58%) and feed rate (Fz: 81%) influences surface roughness behavior (Ra: 81 percent). Also, the anticipated and actual cutting force components and surface roughness were in excellent agreement. The findings are also tested for mistakes (Fx: 6.51 percent, Fy: 4.36 percent, Fz: 3.59 percent, and Ra: 5.12 percent). Finally, ideal cutting rangesfor industrial production are anticipated.

Cakir, M. C., et al. (2009) [7] examined the effects of cutting parameters (cutting speed, feed rate, and depth of cut) onto surface roughness through the mathematical model developed by using the data gathered from a series of turning experiments performed. A second study was conducted to assess the impact of two well-known coating layers on surface roughness. The trials were performed for two CNMG 120408 (ISO designation) carbide inserts with the same geometry and substrate but varied coating layers to assure identical cutting conditions. Cold-work tool steel AISI P20 was machined. A thin TiAlN layer (31micro m) is PVD coated on Insert 2, while a TiCN underlayer, an Al2O3 intermediate layer, and a TiN outer layer are all deposited by CVD on Insert 1. The overall average error of the model was 4.2 percent for Insert 1 and 5.2 percent for Insert 2, proving the equations' dependability.

Chinchanikar, S., et al. (2013) [8] investigated the performance of coated carbide tool considering the effect of work material hardness and cutting parameters during turning of hardened AISI 4340 steel at different levels of hardness. Multiple linear regression models were used to identify relationships between cutting parameters and performance metrics such as cutting forces, surface roughness, and tool life in the area of cutting parameters, thecreated models are trustworthy and may be utilized successfully to anticipate reactions. ANOVA was used to identify highly significant parameters (ANOVA). Less cutting force is necessary to machine tougher materials, according to experimental evidence. Cutting forces are influenced by the depth of cut, then feed rate. Surface roughness is influenced by cutting speed, feed, and depth of cut. Particularly when working with tougher materials, cutting speed and depth of cut become the most important elements affecting tool life. Ideal cutting conditions areestablished by RSM and Desirability Function. Cutting pressures, surface roughness, and tool life was found to be reduced by using lower feed rates, deeper cuts, and restricting cutting speeds to 235 and 144 m/min for 35 and45 HRC work materials, respectively.

Das, D. K., et al. (2014) [9] investigated surface roughness during hard machining of EN 24 steel with the help ofcoated carbide insert. The test was done in dry circumstances. The process parameters were optimized using the Grey-based Taguchi method. The adequacy of the surface roughness prediction models constructed using regression analysis was also tested. Hard machining produces a surface roughness of 0.42 microns. The best depthof cut (Ra) and cutting speed (Rz) for the grey-based Taguchi technique were found to be 0.4 mm, 0.04 mm/rev,and 130 m/min, respectively. Feed is the most important parameter for both Ra and Rz. The prediction models have strong R2 values (0.993 and 0.934). This shows a better model fit and is very significant.

Das, S. R., et al. (2015) [10] investigated the dry hard turning of AISI 4140 steel using PVD-TiN coated Al2O3+TiCN mixed ceramic inserts. In this study, the combined influence of cutting parameters (cutting speed, feed, and depth of cut) on performance variables including surface roughness and flank wear is investigated (ANOVA). Cutting feed, followed by cutting speed, is shown to have the greatest impact on surface roughness. Although the depth of cut is not statistically significant, flank wear is a function of the depth of cut. To establish the procedure, SEM observations are done on the machined surface and worn tool. In the examined range, abrasion was the predominant wear mechanism. Tool wear and surface roughness were also investigated. It was used to anticipate the appropriate surface roughness and flank wear. Based on RSM, mathematical models for surface roughness (Ra) and flank wear (VB) were established with 95% confidence. Finally, under optimal cutting circumstances (obtained via response optimization), tool life was tested to justify coated ceramic inserts in hard turning. Because TiN-coated ceramic has a longer tool life (51 minutes), it has a lower projected machining costper item (Rs. 12.31).

Das, S. R., et al. (2017) [11] addressed surface roughness, flank wear, and chip morphology during dry hard turning of AISI 4340 steel (49 HRC) using CVD (TiN/TiCN/Al2O3/TiN) multilayer coated carbide tool. The influence of cutting settings on tool and workpiece flank wear and surface roughness were studied using Taguchi's L9 Orthogonal array (OA) and ANOVA. SEM was used to examine the surface topography of machined workpieces, wear processes of worn coated carbide tools, and chip morphology of produced chips (SEM). Thus, multiple regression analysis was used to create a mathematical model for each answer, and numerous diagnostic tests were run to ensure the model's validity and usefulness. Finally, to demonstrate the economic viability of coated carbide tools in hard turning, a cost study based on Gilbert's method was done (suggested by the response optimization technique). The findings reveal that feed and cutting speed affect surface roughness and flank wear statistically. Faster-cutting speed improved surface polish and increased flank wear. Tool wear is generated by abrasion from the flank land rubbing on the machined surface and high cutting temperatures. Chip morphology indicates saw-tooth chip formation with severe serration produced by cyclic fracture propagation driven by plasticdeformation. The overall machining cost per item for hardened AISI 4340 steel with a coated carbide tool is $0.13(i.e. Rs. 8.21 in Indian rupees). The research concluded that a multilayer TiN/TiCN/Al2O3/TiN coated carbide tool for hard turning in dry cutting conditions is a cost-effective alternative to standard cylindrical grinding. It alsoprovides cheaper alternatives to CBN and ceramic tools.

Davoodi, B., et al. (2015) [12] investigated the effects of cutting parameters on tool life of PVD TiAlN-coated carbide tools, and volume of workpiece material removed during the machining of the N-155 iron–nickel-base superalloy is evaluated. Cutting factors included cutting speed and feed rate at five levels. RSM was used to modelthe interactions between machining parameters and output variables (RSM). ANOVA was used to test the mathematical model and its variables. Overall, the findings demonstrated excellent agreement between observed tool life, material eliminated, and model predictions. The cutting tool inserts were also SEM investigated, and wear processes were studied at different cutting speeds. The most common tool failure mechanism was adhesion. Finally, the desired function technique was used to optimize tool life and material removal for optimal productivity.

Davoodi, B., et al. (2014) [13] investigated the effects of cutting speed and undeformed chip thickness on cuttingand feed force components, and tooltip temperature was experimentally investigated in order to remove the cuttingfluid. AA5083-O wrought alloy with high Mg content (4.5%) was machined dry and wet using coated carbide tools. They used two-factor (cutting speed and undeformed chip thickness) and five-level fractional experiment designs using ANOVA. This method was used to construct mathematical models for cutting and feed force components and tool tip temperature (RSM). The results reveal that the undeformed chip thickness affects the output variables. AA5083 may be machined without cutting fluid at high cutting speed and low undeformed chipthickness. In dry and wet machining, cutting speed and chip thickness have statistical relevance to the cutting and feed force components. Finally, suitable turning conditions for industrial production were provided.

Devi, K. D., et al. (2015) [14] studied an optimization problem that seeks the identification of the best process condition or parametric combination for the said manufacturing process. Single-objective optimization refers to problems involving just one quality feature. It is difficult to pick the ideal option that meets all quality standards concurrently when more than one characteristic is considered. The current research used Response Surface Methodology to solve a Multi-Objective Optimization issue by straight turning brass bar. The research sought to determine the ideal process environment for both quality and productivity. Finally, the research examines the impact of four input factors on output parameters: cutting speed, feed, depth of cut, and coolant type. The estimated ideal setting minimized surface roughness and maximized MRR, tool life, and machinability index. The confirmatory test validated the ideal outcome.

Dureja, J. S., et al. (2009) [15] attempted to model the tool wear and surface roughness, through response surface methodology (RSM) during hard turning of AISI-H11 steel with TiN-coated mixed ceramic inserts. Analyzing the response factors flank wear and surface roughness using ANOVA and factor interaction graphs in the RSM, the influence of machining parameters such as cutting speed, feed rate, depth of cut, and workpiece hardness was explored. This model best fits the experimental data. Optimization of numerous response components using a desirability function. The validation trials predicted response factors within 5% error. Surface roughness is influenced by feed rate and workpiece hardness, whereas flank wear is influenced by feed rate and depth of cut. The tool wear was monitored using a toolmaker's microscope, and some of the typical inserts were characterizedby SEM-EDX. There is abrasion, notch wear, and chipping of the tool surface from rubbing and impingement ofhard particles in the work material.

Dureja, J. S., et al. (2014) [16] attempted to investigate tool wear (flank wear) and surface roughness during finishhard turning of AISI D3 steel (58HRC) with coated carbide (TiSiN-TiAlN coated) cutting tool. The Taguchi L9 (3)3 orthogonal array was used for design. They used the S/N ratio and ANOVA to find important factors impacting tool wear and surface roughness. Cutting speed and feed influenced tool wear (flank wear), and feed influenced surface roughness (Ra). Regression analysis was used to generate mathematical models for tool wear and surface roughness. The confirmation trials using Taguchi's optimum parameter combination predicted the response factors with less than 5% error. To decrease tool wear and surface roughness, the Desirability function module in RSM was used. The optimum solution via desirability function optimization was compared to the optimal Taguchi set of parameters. Both strategies provide similar optimization outcomes.

On the strength of the exhaustive review of work done by previous investigators [1- 16], it is found that a very little work has been found in use of inserts with different nose radius as a parameter for optimizing the surface properties. The study demonstrates detailed methodology of the proposed optimization technique which is basedon Taguchi technique for surface finish of work piece have been optimized.

2. Design Of Experiment

The Taguchi Method was used to design the trials in the current study. This optimisation approach is the oldest. Applying this strategy to industrial optimisation challenges is straightforward and adaptable. It is an optimisationtechnique recognized in industry. Minitab 14 software is used in this study to build the orthogonal matrix. The number of process factors taken into consideration in the research determines which specific orthogonal matrix is chosen from the typical orthogonal array. The four process parameters employed in this study are cutting speed, feed rate, depth of cut, and nose radius. There are three levels, and the total degree of freedom (DOF) for all four parameters is equal to 4 × (3-1) = 8. Therefore, minimum number of experiment equal to total DOF for parameters +1 = 8 + 1= 9. In this research work, the interactions between factors are not considered. So, L9 (3^4) orthogonal array of Taguchi is selected.

3. Experimentation Phase

3.1 Process Parameters and Levels Use

The cutting speed, feed, depth of cut, and insert nose radius are used to programme the CNC turning lathe. A crucial first step in the Taguchi optimisation approach is the selection of the process parameters and the finalization of their level. Table 1 displays the levels and parameters utilised in the experiment. Since real operating parts, such twist drills, are used for trials in the current research project, the levels are established by referencing the actual conditions that are present at the work station.

Table 1. Process Parameters and Levels

Levels	Control factors			
	Cutting Speed	Feed Rate	Depth of Cut	Nose Radius
L1	150	0.15	0.5	0.4
L2	220	0.22	0.75	0.8
L3	300	0.28	0.8	1.2

3.2 Design of Orthogonal Matrix

In the present work there are three levels and four factors. According to Taguchi approach L9 has been selected so,according to Taguchi L9 array design matrix of variables is formed.

Table 2. Design of Orthogonal Matrix

Exp.No.	Cutting speed (m/min) A	Feed rate (mm/rev) B	Depth of cut(mm) C	Nose radius(mm) D
1	150	0.15	0.5	0.4
2	150	0.22	0.75	0.8
3	150	0.28	0.8	1.2
4	220	0.15	0.75	1.2
5	220	0.22	0.8	0.4
6	220	0.28	0.5	0.8
7	300	0.15	0.8	0.8
8	300	0.22	0.5	1.2
9	300	0.28	0.75	0.4

3.3 Cutting Tools and Workpiece Material Size

The cutting tool selected for present work is Tin coated carbide inserts. The inserts (ISO coding) used in present work are TNMG160404, TNMG160408, and TNMG160412. All inserts have zero clearance angle. The tool holder used is HCLNL 2525M0904.The work piece material used for present experimental work is AISI M7 circular bars (ϕ 18mm x 120mm).

3.4 Chemical Compositions and Properties

The chemical composition of AISI M7 is as shown in Table 2. The properties of material depend up on the chemical composition of material. The AISI M7 material is generally used for manufacturing taps, broaches, reamers, twist drills. It is cutting tool material.

Table 3. Chemical Composition of AISI M7[12]

Element	Symbol	%
Carbon	C	0.84-1.05%
Chromium	Cr	3.75-4.50 %
Molybdenum	Mo	7.75-8.50%
Tungsten	W	6.0/6.75
Vanadium	V	1.80-2.20%
Cobalt	Co	Nil

The properties of AISI M7 are given as, Density = 7.95 x 1000 Kg/m3, Melting point = 4680^0, Hardness = 62/65HRC, Compressive yield strength = 3250 Mpa, Poisson's ratio = 0.27/0.30 and Elastic modulus = 210Gpa.

3.5 Experimental Unit and Procedure

The trials are conducted on CNC turning centre for AISI M7 materials that is shown in Figure1. ACE DesignersLtd. CNC turning centre with Fanuc Oi-mate-TD controller is used to carry out the trials.

Figure1. Experimental unit

The specification of experimental unit is as shown in Table 1. The all trials are conducted in dry environmentand at 2800 Rpm spindle speed. The factors such as tool wear, tool vibration are not considered in present study.

Table 4: Specification of CNC Turning Center [11]

Parameters	Value
Max.turning diameter	300 mm
Max.turning length	400 mm
Max.spinde speed	3500 rpm
Supply voltage	380 v/4.5v
Number of axis	2
Control voltage	24 VDC
Back up fuse	63
Rated current	24/22 Amps
Environment	Dry

The CNC machine is programmed as per design of matrix and one by one two sets of nine trials are conducted forsurface roughness. The surface roughness value is recorded with help of Make–Strumentazione, Model RT10G, and L.C.0.001µm. The top view of surface roughness tester is shown in Figure 2.

Figure 2. Surface Roughness Testing by Accurate Lab

The S/N ratio is calculated using Eq.1. The results for S/N ratio calculations are shown Table 5. The condition ofS/N ratio used to find out minimum surface roughness is given as follows:
Condition of S/N ratio for surface roughness: smaller is better

$$S / N = -10 \ *log(\Sigma(Y^2) / n)) \qquad \text{(Eq.1)}$$

Table 5: Response Table of Ra with S/N Ratio

A	B	C	D	Surface Roughness Ra	S/N
150	0.15	0.5	0.4	2.3	-7.2
150	0.22	0.75	0.8	2.6	-8.4
150	0.28	0.8	1.2	2.3	-7.3
220	0.15	0.75	1.2	0.7	2.5
220	0.22	0.8	0.4	3.3	-10
220	0.28	0.5	0.8	3.4	-10
300	0.15	0.8	0.8	1.3	-2.5
300	0.22	0.5	1.2	1.2	-1.9
300	0.28	0.75	0.4	3.8	-11

4. Optimum Response Value Calculation

The optimal settings and the predicted optimal values for surface roughness is found out individually by Taguchi'sapproach. The optimum response value can be calculated using following formulation.
Let T' = average results for 9 runs of response factor

$$T' = \frac{\sum_{i=1}^{9} M}{9} \qquad \text{(Eq. 2)}$$

Response factor$_{optimum}$ = T'+ (A_{n1} – T') + (B_{n2} – T') + (C_{n3} – T') + (D_{n4}– T') (Eq.3)

Where A_{n1} , B_{n2} ,C_{n3}, D_{n4} are corresponding mean values of response factor.

Table 8 shows these individual optimal values and its corresponding settings of the process parameters for the specified performance characteristics. It is observed that the feed is most significantly influences the surface roughness followed by nose radius. The mean values for both response factors are calculated by Minitab 14 software.

Table 7: Means of Ra at Different Levels

Levels	Mean value of Ra			
	A	**B**	**C**	**D**
L1	2.430	1.445	2.332	3.155
L2	2.497	2.420	2.390	2.477
L3	2.135	3.197	2.340	1.430

The optimum response values are calculated by equation (5). The final optimum result with their level areshown in Table 8.

Table 8: Predicted Optimal Values and Setting of Process Parameters

Response Factors	Units	Optimum Parameters Level	Optimum Predicted Value
Ra	µm	A3 B1 C2 D3	0.350

5. Result And Discussion

The graphs are developed using Minitab 14 software. These results are analyzed using S/N ratio for the purpose of identifying the significant factors which affect the surface roughness. The graphs show the variation of individual response with the four parameters i.e. cutting speed, feed, depth of cut and nose radius separately. In the plots, the x-axis shows the value of each process parameter at three level and y-axis the response value. Figure 3 shows the main effect plot for surface roughness. It is observed that the maximum surface finish or minimum roughness is obtained at the 300 m/min of cutting speed, 0.15mm/rev of feed, 0.75mm depth of cut and 1.2mm nose radius.

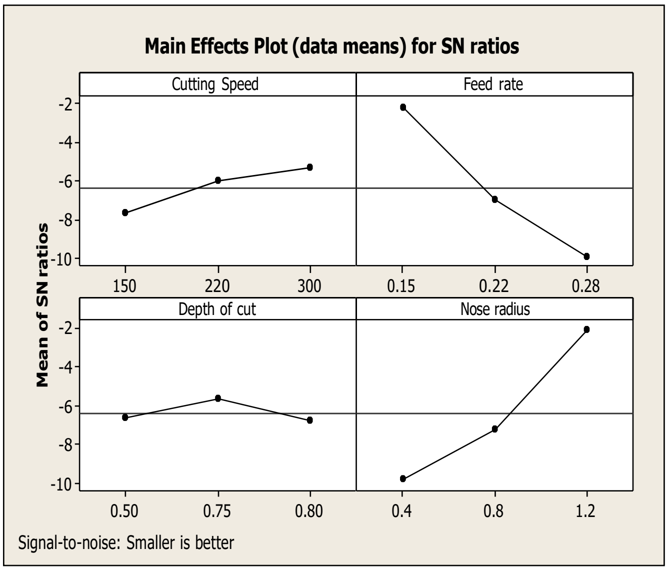

Figure 3. Main effect plots for Ra

6. Conclusion

The turning tests are performed on AISI M7 work piece using three different Tin coated carbide insert of varyingnose radius on CNC machine. The effect of cutting speed, feed rate, depth of cut and nose radius are studied on the machined surface roughness. The analysis of the experimental observations highlights that Ra values in CNC turning process is greatly influenced by feed rate and nose radius. The optimal level of process parameters for optimum value of surface finish (0.312 µm) is cutting speed 300 m/min, feed rate 0.15mm/rev, depth of cut 0.75mm, nose radius 1.2mm.

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