Taguchi-Based Optimization of Surface Roughness in CNC Turning Operation

Vipindas M P
M Tech student
Department of Mechanical Engineering, Government College of Engineering Kannur, Kerala, India

Dr. Govindan P
Assistant Professor
Department of Mechanical Engineering, Government College of Engineering Kannur, Kerala, India

Abstract — The productivity and quality are two important characteristics those control most of the manufacturing processes. In this paper, quality of machined surfaces in turning operation is optimized through Taguchi method. The comprehensive experimentation and analysis was performed on Al 6061 material based on Taguchi L_9 orthogonal array. The commonly used parameters speed, feed and depth of cut were used for this assessment. The roughness values vary between 0.3 and 4.4.A general linear model was employed to evaluate the parametric effects. It was observed that feed is the significant factor at 95% confidence level. Feed has the strongest influence on the quality of machined surfaces in CNC turning.

Keywords: Optimization, CNC Turning, Taguchi method, General linear model, Significance.

I. Introduction

Among various cutting processes, turning process is one of the most fundamental and most applied metal removal operations in a real manufacturing environment. The surface roughness of the machined parts is one of the most significant product quality characteristic which refers to the deviation from the nominal surface. Surface roughness plays a vital role in many applications such as precision fits, fastener holes, aesthetic requirements and parts subject to fatigue loads. Surface roughness imposes one of the most significant constraints for the selection of cutting parameters and machine tools in development of a process [1]. Turning is the primary process in most of the production activities in the industry and surface finish of turned components has greater influence on the quality of the product. Surface finish in turning has been found to be influenced in varying amounts by a number of factors such as feed rate, work material characteristics, work hardness, unstable built-up edge, cutting speed, depth of cut, cutting time, tool nose radius and tool cutting edge angles, stability of machine tool and work piece setup, chatter, and use of cutting fluids [2]. The need for selecting and implementing optimal machining conditions and the most suitable cutting tool has been felt. Despite Taylor's early work on establishing optimum cutting speeds in single pass turnings, progress has been slow since all the process parameters need to be optimized. For realistic solutions, the many constraints met in practice, such as low machine tool power, torque, force limits and component surface roughness must be overcome. The performance of turning is measured in terms of surface finish, cutting forces, power consumed and tool wear. Surface finish influences functional properties of machined components. Surface finish, in hard turning, has been found to be influenced by a number of factors such as feed rate, cutting speed, work material characteristics, work hardness, cutting time, tool nose radius and tool geometry, stability of the machine tool and the work piece set-up, the use of cutting fluids, etc. It is reported that CBN and ceramic cutting tools are widely used in industries for the machining of the various hard materials [3]. In many applications, the cutting of ferrous materials in their hardened condition can replace grinding to give significant savings in cost and increase in productivity. Cutting tool geometry plays a very important role in hard turning process [4]. The rake angle and the nose radius of the turning inserts directly affect the cutting forces, power and surface finish. The edge strength of the cutting inserts depends upon edge preparation, i.e. by the honing radius, chamfer angles. Some investigations related to the effect of tool geometry have been reported by the researchers. In an investigation, the cutting edge geometry and the work pieces hardness on surface generation in the finish hard turning of AISI 52100 steel is explained [5]. CBN inserts, with various representative cutting edge preparations, were used as the cutting tool materials. It was shown that the effect of edge geometry on surface roughness and cutting forces is statistically significant. Specifically, large edge hones produce higher average surface roughness values than small edge hones.The effect of two factor interactions of the edge geometry and the work piece hardness on the surface roughness is also found to be important. Also large edge hones generate higher forces in the axial, radial and tangential directions than small edge hones. In another investigation, the effect of chamfer angle on the wear of PCBN cutting tool [6] is done. Results show that chamfer angle has a great influence on the cutting force and tool life. All the three force components increase with an increase of the chamfer angle. The optimized chamfer angle, for the maximum tool life as suggested by this study, is 15° [7]. In this study, cutting conditions were kept constant. The effects of tool nose radius on finish hard turning with ceramic tools were analyzed [8]. In this study, surface finish, tool wear, cutting forces, and, particularly, white layers were evaluated at different machining conditions. Results show that large tool nose radii not only give finer surface finish, but also considerable tool wear compared to small nose radius tools. Specific cutting energy also increases slightly with tool nose radius. Large nose radius tools generate shallower white layers when cutting by worn tools [9]. For new tools, small nose radius results in larger uncut chip thickness, and thus, induces deeper white layers. The effects of corner radius and edge radius on tool flank wear were investigated [10]. Results show the interaction of corner radius and edge radius and their effects on process performance, measured in terms of tool flank wear and forces. The General conclusion is that an advantage exists in using a larger corner radius when using a larger edge radius. Currently, a lot of works have been done to improve the capability of machine tools. The continuing development and trends in manufacturing and operations reveals that engineering cannot be sustained using current methods and processes. Some set up parameters or machining processes are affected on main parameters such as tool life. The study of criteria for evaluating the surface roughness represents, today, one of the most important problems for the production of some specific and functional characteristics. For this reason many authors consider the roughness as the fourth dimension of the design [11].Increasing productivity, decreasing costs, and maintaining high product quality at the same time are the main challenges manufacturing face today [12]. Due to the widespread use of high automated machine tools in industry, manufacturing requires reliable monitoring and optimization. Surface roughness also plays an important role as it influences the fatigue strength, wear rate, coefficient of friction, and corrosion resistance of the machined components. In actual practice, all the factors which affect the surface roughness are classified into: tool variables, work piece variables and cutting conditions. Tool variables include tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool overhang, tool point angle, etc. Work piece variables include material, hardness and other mechanical properties. Cutting conditions include speed, feed and depth of cut. To this end, a great deal of research has been performed in order to quantify the effect of various hard turning process parameters to surface quality. The surface roughness increases with an increase in cutting speed [13]. Sundaram and Lambert [14] considered six variables i.e. speed, feed, and depth of cut, time of cut, nose radius and type of tool to monitor surface roughness. To improve the efficiency of turning processes, it is necessary to have a complete process understanding and model. For surface roughness all the cutting parameters speed, feed rate and depth of cut, have significant effect in turning of S45C steel using tungsten carbide with the grade of P-10 [15].Feed rate had the highest effect on surface roughness, spindle speed had a moderate effect, and depth of cut had an insignificant effect in turning of 6061-T6511 Aluminium alloy using insert VNE Versa Turn CCGT 432-AF [16]. Depth of cut was the only significant factor which contributed to the surface roughness in turning SCM 440 alloy steel [17]. L27 Taguchi Orthogonal Array design with machining parameters: speed, feed and depth of cut on three different work piece materials viz. Aluminium, mild steel and brass helped in concluding that feed rate has more significant effect in surface finish in all three materials. It was observed that in case of mild steel and aluminium feed showed some influences while in case of brass depth of cut was noticed to impose some influences on surface finish [18]. ANOVA results shows that feed rate, cutting speed and depth of cut affects the surface roughness by 51.84%, 41.99% and 1.66% respectively in turning of AISI 304austenitic stainless steel bars using TiC and TiCN coated tungsten carbide cutting tool under dry condition [19].The ANOVA reveals that feed rate is dominant parameter under dry, servo cut oil and water and synthetic oil conditions in optimizing the surface roughness while turning Ti6Al4V alloy with different coolant conditions using Taguchi's design of experiments methodology by uncoated carbide tool [20]. Cutting speed has the most dominant effect on the observed surface roughness, followed by feed rate and depth of cut in turning of cold rolled alloy steel 42CrMo4/AISI 4140 using TiN-coated tungsten carbide inserts [21]. Speed has a greater influence on the surface roughness followed by feed and depth of cut while machining Al 6351-T6 alloy with uncoated carbide inserts. From regression equation one can predict the value of surface roughness if the values of speed, feed and depth of cut are known [22].The surface roughness and MRR parameters greatly depend on work piece materials [23].The relationship between feed rate and surface roughness is proportional, in facing operation of EN-8 alloy steel with cermet tool [24]. In order to gain a greater understanding of the turning process it is necessary to understand the impact of the each of the variables, but also the interactions between them. It is impossible to find all the variables that impact surface roughness in turning operations. In addition, it is costly and time consuming to discern the effect of the every variable on the output. In order to simplify the problem, one needs to eliminate or select specific variables that correspond to practical applications. Taguchi method consist of a plan of experiments with the objective of acquiring data in a controlled way, executing the experiments and analyzing data, in order to obtain information about the behaviour of a given process. It uses orthogonal arrays to define the experimental plans and the treatment of the experimental results is based on the analysis of variance (ANOVA).Taguchi method is latest design technique widely used in industries for making the product/process insensitive to any uncontrollable factors such as environmental variables. Taguchi approach has potential for savings in experimental time and cost on product or process, development and quality improvement [25]. This paper analyzes the study on application of the Taguchi method [26,27,28] for identifying the optimal cutting parameters for surface roughness in CNC turning process.

II. TAGUCHI METHOD – AN OUTLINE

Taguchi method, developed by Dr.Genichi Taguchi, is an efficient tool for the design of high quality manufacturing system. Taguchi's Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental runs), and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output; serve as objective functions in the optimization process. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise).The standard deviation cannot be minimized first and the mean brought to the target [29]. The ratio depends on the quality characteristics of the product/process to be optimized. The standard S/N ratios generally used are as follows: Nominal-is-Best (NB) lower-the-better (LB) and Higher-the-Better (HB).Because, irrespective of the quality criteria may be (NB, LB, and HB) S/N ratio should always be maximized. Optimum cutting conditions required for the minimum surface roughness is obtained by using LB criterion. S/N ratio can be obtained from equation S/N= -10 $\log\frac{1}{n}(\Sigma y^2)$.Taguchi method provides a simple, competent and methodical approach to optimize the designs for performance, quality, and cost. The greatest advantages of the Taguchi method are to reduce the cost and to find out significant factors in a shorter time period [30].The methodology is important when the design parameters are qualitative and distinct. Taguchi parameter design can optimize the performance characteristics through the settings of the design parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a world-wide range of industries and countries. It involves the following:

- The process objective is defined, or more explicitly, a target value for a performance measure of the process. This may be a flow rate, temperature, etc. The target of a process may also be a minimum or maximum; for example, the goal may be to maximize the output flow rate. The deviation in the performance characteristic from the target value is used to define the loss function for the process.
- Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as temperatures, pressures, etc. that can be easily controlled. The number of levels that the parameters should be varied at must be specified.
  - Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter, and will be expounded below.
  - Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.
  - Complete data analysis to determine the effect of the different parameters on the performance measure.
  - Analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are all equal, and therefore generalizes *t*-test to more than two groups.
  - ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. The statistical significance of the experiment is determined by a ratio of two variances. This ratio is independent of several possible alterations to the experimental observations. Adding a constant to all

observations does not alter significance. Multiplying all observations by a constant does not alter significance. So ANOVA statistical significance results are independent of constant bias and scaling errors as well as the units used in expressing observations.

A comparison of the design of experiments method and Taguchi method is presented in table1. The choice of optimal cutting parameters is a very significant concern for every machining process in order to improve the quality of machining products, to reduce the machining costs and to raise the production rate. CNC machines play a very key function in manufacturing centers. These machines are capable of achieving reasonable accuracy and surface finish. Processing time is also very low as compared to some of the conventional machining process, which is another important factor that greatly influences production rate and cost. There is a need for a tool that should allow the evaluation of the surface roughness value before the machining of the part and, at the same time, can easily be used in the production-floor environment contributing to the minimization of required time and cost and the production of desired surface quality.

Table 1 A comparison of Design of Experiments and Taguchi Method

Aspect	Design of Experiments	Taguchi Method
Knowledge of the process	Not required	Required
Number of test runs	Large	Smaller
Noise factors	Not included	Included
Variability of system	Ignored	Included
Confirmation runs	Not required	Advisable

III. EXPERIMENTAL PLAN AND PROCESSING CONDITIONS

This study employs the various procedures and techniques of the Taguchi method involving experimental design and selection of parameters, performing an experiment, analysis of data, determining the optimal parameters, and confirmation. The control of feed rate and depth of cut for productivity and surface roughness requires equilibrium between the two. A reduction in the feed rate will cause surface roughness to come near the lowest amount possible with the given tool and work piece setup, but this will give up productivity in cutting time for a particular tool path. Smaller depths of cut usually ensure best possible surface roughness, but this may require additional passes. Spindle speed is the only possible parameter that usually has a positive effect on both response parameters. As feed rate in turning is usually measured in linear distance per revolution, increasing spindle speed will increase linear travel. This usually has a maximum value, which is based upon the cutting speed for a given work piece/tool materials combination. Therefore, this study will need to explore the most appropriate levels of the controlled parameters for the surface roughness and thus avoid decreasing productivity by exactly minimizing surface roughness. Table 2 shows the chemical composition of the work piece on which the experiments were performed.

The maximum allowable feed has a pronounced effect on both the optimum spindle speed and production rate. Feed changes have a more significant impact on tool life than depth of cut changes. The system energy requirement reduces with feed, since the optimum speed becomes lower. Therefore, the largest possible feed consistent with the allowable machine power and surface finish is desirable, in order for a machine to be fully used. It is often possible to obtain much higher metal removal rates without reducing tool life by increasing the feed and decreasing the speed. In general, the maximum feed in a roughing operation is limited by the force that the cutting tool, machine tool, work piece and fixture are able to withstand. The maximum feed in a finish operation is limited by the surface finish requirement and can often be predicted to a certain degree, based on the surface finish and tool nose radius.

Table 2 Chemical composition of the work piece (Al)

Elements	Composition (% by weight)
Al	95.85
Si	0.4
Fe	0.7
Cu	0.15
Mn	0.15
Mg	0.8
Ti	0.15
Zn	0.25
Cr	0.4

The experimental plan was developed based on Taguchi's orthogonal array experimentation technique. In the design, an L_9 Orthogonal Array was selected to satisfy the minimum number of experimental conditions for the factors and all the levels, see table 3.

Table 3 Allocation of processing parameters to standard L9 orthogonal array

Experiment	Feed(A) (mm/rev)	Speed(B) (rpm)	Depth of cut(C) (mm)
1	0.1	500	0.4
2	0.2	500	0.6
3	0.3	500	0.8
4	0.1	1000	0.6
5	0.2	1000	0.8
6	0.3	1000	0.4
7	0.1	1500	0.8
8	0.2	1500	0.4
9	0.3	1500	0.6

Cutting speed is a vital component of tool life equation. When compared with depth of cut and feed, the cutting speed has only a secondary effect on chip breaking, when it varies in the conventional speed range. There are certain combinations of speed, feed and depth of cut which are preferred for easy chip removal which are mainly dependent on the type of tool and work piece material. The process parameter and their ranges are finalized based on the literature and machine operators' experience. Charts providing the feasible region for chip breaking as a function of feed versus depth of cut are sometimes available from the tool manufacturers for a specific insert (or) tool, and can be incorporated in the optimization systems. The turning machines are, of course, every kind of lathes. Lathes used in manufacturing can be classified as engine, turret, automatics, and numerical control etc. The Computer Numerical Controlled (CNC) machine is used in the manufacturing process. The CNC machine would help in functions like program storage, tool offset and tool compensation, program-editing capability, various degree of computation, and the ability to send and receive data from a variety of sources, including remote locations can be easily realized through on board computer. The computer can store multiple-part programs, recalling them as needed for different parts. Considering that the literature suggested that feed rate has a much higher effect on surface roughness than the other two parameters, it was determined that a robust but efficient experiment would include feed rate with more levels than the other factors. The turning operations are carried out on a CNC lathe machine Shaublin 125 CCN with a Fanuc controller is shown in fig.1. Turning of the workpiece has been carried out under wet condition using coolant oil servocut 6050 by 1:20.Coated carbide insert CNMG 120408 (ISO designation) was used for the experiment. Roughness measurement has been done using a portable stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+, UK). The least count of the instrument is 0.01µm.

Fig.1. Shaublin 125 CCN

The surface roughness tester is shown in fig. 2.Minitab 16 Software is used for the detailed analysis.

Fig.2. Talysurf- surface roughness tester

IV. ANALYSIS OF VARIANCE ON EXPERIMENTAL DATA

The function of the analysis of the variance is to investigate which design parameters significantly affect the quality characteristic. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. Statistically, there is a tool called an *F*- test named after Fisher to identify the parameter that has significant effect on the quality characteristic. In performing the *F*-test, the mean of squared deviations due to each design parameter needs to be calculated. The mean of squared deviations is equal to the sum of squared deviations divided by the number of degrees of freedom associated with the design parameter. Then, the *F*-value for each design parameter is simply the ratio of the mean squared deviations to the mean squared error. In general 'F' value indicates the change of the design parameter has significant effect on the quality characteristic. Table 4 shows the obtained values of surface roughness for the original set of trials.

Table 4 Experimental values of surface roughness (Ra) under different processing conditions

Experiment	Feed (mm/ rev)	Speed (rpm)	Depth of cut (mm)	Ra (µm)	S/N ratio
1	1	1	1	0.4	7.95880
2	2	1	2	1.6	-4.08240

3	3	1	3	3.4	-10.6296
4	1	2	2	0.33	9.62972
5	2	2	3	1.97	-5.88932
6	3	2	1	3.2	-10.1030
7	1	3	3	0.4	7.95880
8	2	3	1	1.47	-3.34635
9	3	3	2	4.47	-13.0062

It is observed that there are a large number of variables controlling the process; some mathematical models are required to represent the process. However, these models are to be developed using only the significant parameters influencing the process rather than including all the parameters. In order to achieve this, statistical analysis of the experimental results will have to be processed using the analysis of variance. This is a computational technique that enables the estimation of the relative contributions of each of the control factors to the overall measured response. In the present work, only the significant parameters will be used to develop mathematical models. Later by using Minitab 16 software, the detailed analysis has been performed for the above set of experiment as well as for other replicated trials. The final ANOVA results are presented in table 5.

Table 5 ANOVA table for surface roughness (Ra)

Parameter	Degree Of freedom	F-value	P-value	Significance (95% conf. level)
Feed (mm/rev)	2	27.97	0.035	Significant
Speed (rpm)	2	0.33	0.771	Not significant
Depth (mm)	2	0.49	0.669	Not significant

The general linear model for analysis of variance is presented in fig. 2. The statistical analysis shows that the significant parameter is feed (mm/rev). The highest ‘F’ value was observed for feed (27.97) followed by depth of cut (0.49) and speed (0.33). It is evident that feed and depth control, are more influential in predicting quality of the machined surfaces.

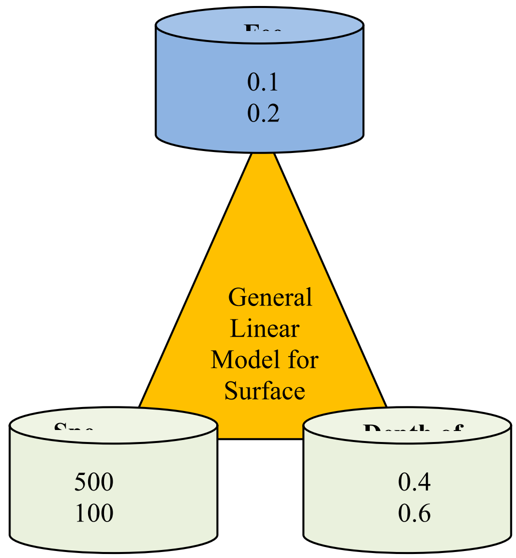

Fig. 2 General linear model for ANOVA analysis

In order to find the optimum set of conditions, the individual level averages of S/N ratios are calculated. The objective is to maximize the S/N ratio (LB) values. Thus, the optimized conditions chosen are A1-B2-C1 and their levels are shown in table 6.

Table 6 Optimum Set of Control Factors

Factors	Feed(A) (mm/rev)	Speed(B) (rpm)	Depth(C) (mm)
Optimum	0.1	1000	0.4

Figure 3 shows the main effects plot for S/N ratio which is obtained from the Anova analysis.

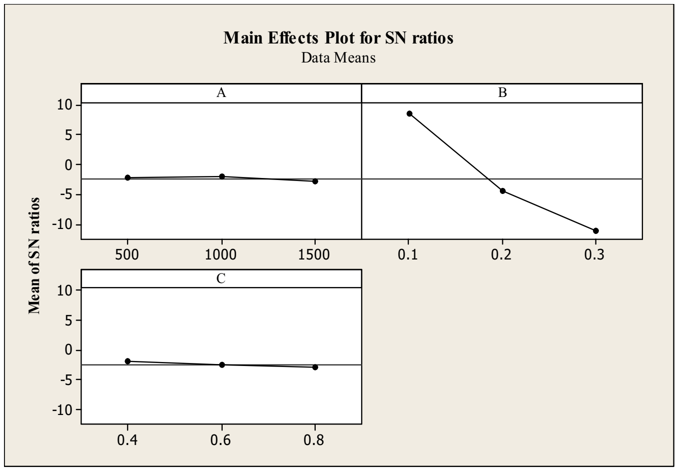

Fig. 3 Main effects plot for S/N ratio

Conducting a verification experiment is a crucial final step of the robust design methodology. The predicted results must be conforming to the verification test, with the optimum set of conditions. The predicted value ($\eta_{predicted}$) of S/N ratio is 9.3446.The conformation experiment is conducted with optimum control factors of spindle speed 1000 rpm, feed-0.1mm/rev and depth of cut 0.4mm. The Surface roughness values are taken and the S/N ratio is calculated for this condition. These values are shown in table 7.

Table 7 Conformation Test Results

Surface roughness (μm)	S/N ratio
0.33	9.5510

The predicted and verification test values of S/N ratio are compared for validity of the optimum condition and is shown in table 8.

Table 8 Comparison of S/N Ratios

$\eta_{predicted}$	$\eta_{conformation}$
9.3446	9.5510

It is found that the S/N ratio value of verification test is within the acceptable limits of the predicted value and the objective is fulfilled. The suggested optimum conditions can be adopted.

V.CONCLUSIONS

The experimental investigation and optimization of CNC turning with the objective function as quality improvement, is presented in this paper. Surface roughness (Ra) was chosen as the response variable. The following conclusions can be drawn from this study:

1) The advantages of Taguchi method in simplifying the experimentation was effectively utilized in this investigation for design and analysis for surface quality.
2) The lowest surface roughness (Ra) of 0.33 μm was achieved corresponding to: *f*: 0.1 mm/rev, *N*: 1000 rpm and *d*: 0.4mm.
3) The most significant parameter in influencing the quality of machined surfaces in turning was feed.
4) The relative significance of parameters influencing surface quality in CNC turning is evaluated based on their 'F' values as: feed (27.97), speed (0.33) and depth of cut (0.49).
5) The quality of machined surface decreases with increase in feed rate.

ACKNOWLEDGMENT

The authors wish to acknowledge support for this work from Dr. T. D. John, The Principal, Dr. K. M. Peethambaran, HOD (Mechanical), Faculty and Staff of Mechanical Engineering Department and all faculty/staff members of Government College of Engineering, Kannur, Kerala.

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