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Optimization of Roughness Value from Tribological Parameters in Hard Turning of AISI 52100 Steel

Nilesh Suryakant Gore[1], H. M. Dharmadhikari[2]
[1, 2]*(Mechanical, Maharashtra Institute of Technology, Aurangabad, M.S., India)*

Abstract: *It is difficult to machine the hard material under the different cutting conditions. So the tribological parameters like speed, feed and the depth of cut are very important parameters in the machining of every material. The 52100 steel is the bearing material having the Rockwell hardness value on C scale in between 41 HRC to 65 HRC. The various kinds of cutting tools like ceramics, cBN or PcBN, have been utilised in the machining operations.The different tools have given different values roughness in the hard turning operations on different machines like turret lathe, CNC lathe etc. But the least parameter value i.e. roughness parameter must vary according to the different tools and machines. The experimentation was performed on CNC machine and the cBN insert was used. To optimize the roughness value under this tribological parameter the taguchi L_9 (OA) was utilised and the performance of roughness value was optimized by the regression analysis. The regression equation would be able to predict the roughness value with an accuracy of 98.27% and the last but least 4.69% error was present.*

Keywords: *Speed, Feed, Depth of Cut, Roughness Value, Turning, Hard Turning, Taguchi Method, Hard Material, AISI 52100 steel, Regression, Optimization, Tribology.*

I. Introduction

In recent past, hard turning of steel parts that are often hardened above 45 HRC became very popular technique in manufacturing of gears, shafts, bearings, cams, forgings, dies and moulds [Anoop, A. D., et.al. (2015)]. Hard machining means machining of parts whose hardness is more than 45 HRC but actual hard machining process involves hardness of 46 HRC to 68 HRC [Attanasio, A. et.al. (2012)]. The work piece materials used in hard machining are hardened alloy steel, tool steels, case–hardened steels, nitride irons, hard–chrome–coated steels and heat–treated powder metallurgical parts [Rahbar-kelishami, A., et.al. (2015)]. In order to withstand the very high mechanical and thermal loads of the workpiece and cutting materials with improved performances, such as ultrafine grain cemented carbides, cermets, ceramics, cubic boron nitrides (cBN), polycrystalline cubic boron nitride (PcBN) and polycrystalline diamonds, have been developed and applied [Bagawade, A. D. et.al. (2012)].

Hard turning is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces [Bapat, P. S. et.al. (2015)]. Hard turning is a process which eliminates the requirements of grinding operation. A proper hard turning process gives surface finish Ra 0.4 to 0.8 µm, roundness about 2–5 µm and diameter tolerance ± 3–7 µm [Bartarya, G., and Choudhury, S. K. (2012)]. Hard turning can be performed by that machine which soft turning is done. The new advancements in machine tools technology and use of new cutting tools provide the opportunity to take loads from hardened steels through processes such as lathing and milling. Recent achievements have made it possible to replace hard turning by modern turning (lathing) machines and new cutting tools for many industrial applications [Bouacha, K. et.al. (2010)].

Hard turning is a good alternative to applications not requiring very high quality finishing, obviously works requiring high tolerances see grinding as their first choice [Thiele, J. D. and Melkote S. N. (1999)]. Hard turning of highly hardened parts is a new approach in machining science aimed at increasing productivity and yield through reducing production time and costs of the process [Caruso, S. et.al. (2011)]. This method has been introduced as a suitable alternative to grinding of hardened parts. Through this method the finishing process is done at the same time as the main machining process (i.e. roughing). Some decisive factors leading to this manufacturing trend are: substantial reduction of manufacturing costs, decrease of production time, achievement of comparable surface finish and reduction or elimination of environmentally harmful cooling media [Cho, I. S., Amanov, A., and Kim, J. D. (2015)].

Soft steel must be hardened to increase the strength and wear resistance of parts made from this material. Hardened steels are machined by grinding process in general, but grinding operations are time consuming and are limited to the range of geometries to be produced [Raghavan, S., et. al. (2013)].Machined surface characteristics are important in determining the functional performance such as fatigue strength, corrosion resistance and tribological properties of machined components [Diniz, A. E., and Ferreira, J. R. (2003)]. The quality of surfaces of machined components is determined by the surface finish and integrity obtained after machining. High surface roughness values, hence poor surface finish, decrease the fatigue life of machined components. It is therefore clear that control of the machined surface is essential [Fernandes, F. A. P. et.al. (2015)].

In turning, there are many factors affecting the cutting process behavior such as tool variables, workpiece variables and cutting conditions. Tool variables consist of tool material, cutting edge geometry (clearance angle, cutting edge inclination angle, nose radius, and rake angle), tool vibration, etc., while workpiece variables comprise material, mechanical properties (hardness), chemicals and physicals properties, etc. Furthermore, cutting conditions include cutting speed, feed rate and depth of cut [Guo, Y. B., and Liu, C. R. (2002)]. The selection of optimal process parameters is usually a difficult work, however, is a very important issue for the machining process control in order to achieve improved product quality, high productivity and low cost. The optimization techniques of machining parameters through experimental methods and mathematical and statistical models have grown substantially over time to achieve a common goal of improving higher machining process efficiency [Harris, S. J. et.al. (2001)].

The turning operation is performed with tool materials mixed ceramic (Al_2O_3 + TiC) and cubic boron nitride (cBN), which induces a significant benefit, such as short-cutting time, process flexibility, low surface roughness of piece, high rate of material removal and dimensional accuracy. The uses of cBN cutting tools along with other advancements of machine tools have resulted in the developing of this method. The use of these tools makes it possible to turn hard alloys steels with high degrees of hardness at high turning speeds. The range of applications of hard turning is quite broad and is usually defined based on part requirements and specifications, surface tolerance, surface finish, and machine tools because every machine is not suitable for this sort of operations [Hosseini, S. B. et.al. (2014)].

The ability of polycrystalline cubic boron nitride (PcBN) cutting tools to maintain a workable cutting edge at elevated temperature is, to same extent, shared with several conventional ceramic tools [Hosseini, S. B. et.al. (2015)]. These tools are characterized by high hot hardness, wear resistance and good chemical stability and low fracture toughness. The cBN and ceramic tools are used in the manufacturing industry for hard turning because of its inertness with ferrous materials and its high hardness. Though cBN particles and binder phases such as TiN are harder than carbides in steels, it is still possible that the tool will encounter “soft” abrasive wear. The machining of hardened bearing steel represents grooving proportion of applications involving hard cutting tools such as cBN and ceramics [Hosseini, S. B. et.al. (2012)].

The main challenge in hard turning is whether coolant will be used or not. In maximum cases hard turning will be performed dry. When hard turning will be performed without coolant, part will be hot. Due to this, it will be difficult for process gauging. To cool down the machined part coolant is used through the tool with high pressure. Additional problems are created due to flying cherry red chips [Jin, L., Edrisy, A., and Riahi, A. R. (2015)]. Mainly water-based and low concentration coolants are used in hard turning. In hard turning maximum heat is transferred to chip so if chip will be examined during and after cut then whether the process is well turned or not will be known [Umbrello, D., Ambrogio et.al. (2008)]. Chips should be glowing orange and flow like ribbon during continuous cut. If we will crunch the cooled chip and it will disintegrate then it shows that proper amount of heat is produced. However, the potential benefits promoted by hard turning for surface quality and to increase the rate of productivity depend intrinsically an optimal setting for the process parameters such as cutting speed, feed rate and cutting depth [Jouini, N. et.al. (2013)].

In this work, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed rate and depth of cut) on the performance characteristics surface roughness in finish hard turning of AISI 52100 bearing steel hardened at 60 HRC with cBN tool. In this work, a L_9 Taguchi standard orthogonal array is adopted as the experimental design. The combined effects of the cutting parameters on roughness values are investigated. The relationship between cutting parameters and roughness values through the regression analysis, the different correlations are developed between tribological parameters and roughness value. For betterment of result the 27 runs are conducted and analysis done of 27 runs.

- **Machinability**

The engineering industries strive to achieve either a minimum cost of production or a maximum production rate in machining. These two criteria are closely interrelated with the choice of cutting conditions like speed, feed and depth of cut. The optimization of these conditions depends on, and must be related to, the machinability characteristics of the material. It is becoming increasingly necessary to relate the available engineering raw materials and semi-finished products to specific machinability ratings [Kurt, A., and Seker, U. (2005)]. It is advantageous for the industries to know in advance the machinability characteristics of a material to be processed, in addition to the normal chemical composition and mechanical data, which by themselves are not enough to cover the machining characteristics of the material. The term ‘machinability’ does not lend itself to be defined precisely. However, in the context in which those concerned with manufacture, production and research use this term, it can be defined as the property of the material which governs the ease or difficulty with which it can be machined under a given set of conditions [Le Goic, G. et.al. (2016)].

- **Criteria for machinability**

Machinability can be judged from many considerations depending on the employed machine tool, cutting tool, work material and cutting conditions, and also on the preference of the user for a particular choice. The general criteria commonly adopted for evaluating machinability are tool life / tool wear rate and cutting force or surface finish produced on a job. Assessment of machinability can also be based on specific parameters like torque and thrust during machining, penetration rate ease of chip disposal, temperature of cutting tool, work hardening etc. From the practical considerations, the criteria can be expressed in quantitative terms for purposes of comparison. They are the most commonly accepted measures of machinability [Mahdavinejad, R. A., and Bidgoli, H. S. (2009)].

➢ **Criteria based on tool life**

Tool life is usually the most important of the three main parameters used for assessing machinability. This could be conveniently expressed in terms of cutting speed; because, all the other variables being kept constant, tool life will be a direct function of the cutting speed. By increasing the cutting speed, the tool life may be decreased and by reducing the cutting the tool life may be increased. Thus, cutting speed for producing a predetermined value of tool life, termed as the specific cutting speed, could be made on the basis of comparison of machinability of materials. The cutting speed is a direct indication of the cost at which a part can be based on cutting speed or tool life, provides a firm basis for comparison of various materials [Nayak, S. K. et.al. (2014)].

➢ **Criteria based on cutting forces**

Machinability rating based on the cutting force is important, where it is necessary to limit the values of cutting force in keeping with the rigidity of the machine and to avoid vibrations during machine [Thiele, J. D. et.al. (2000)]. If the cutting force is high and consequently the power consumptions is also high, a larger machine tool may be required, thus increasing the overhead cost and unit cost of the part produced. The higher the cutting forces induced under the set of cutting conditions during the machining of a material, the lower is its machinability index [Paiva, A. P. et.al. (2007)].

➢ **Criteria based on surface finish**

There are many situations where surface finish on the job is of primary importance. Though a given material may allow higher cutting speeds or induce lower cutting forces, it may not produce good surface finish. Where the finish produced on the parts is a cause for rejection, this consideration has an important bearing on the cost. The higher the surface finish obtained on a material under a given set of conditions, the better is its machinability [Patel, M. T., and Deshpande, V. A. (2014)].

- **Variables Affecting Machinability**

Machinability is influenced by the variables pertaining to the machine, the cutting tool, cutting conditions and work material.

➢ Machine variables
➢ Tool variables
➢ Cutting conditions
➢ Work material variables

II. Experimentation

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L_9 orthogonal array (OA) design have been selected. In the present experimental study, spindle speed, feed rate and depth of cut have been considered as process variables. The process variables with their units (and notations) are listed in table 1.

In general the chemical composition for AISI 52100 bearing steel material are as follows: Carbon – 0.98 to 1.10 %, Manganese – 0.25 to 0.45%, Chromium – 1.30 to 1.60 %, Nickel – standard range is not given, Molybdenum – standard range is not given, Sulphur – 0.025 % maximum, Phosphorus – 0.025% maximum, and silicon – 0.15 to 0.30 %, after quenching treatment at 850ºC followed by tempering at 250ºC, an average workpiece hardness of 60 HRC was obtained.

The experiments are realized in wet straight turning operation using the CNC lathe machine and AISI 52100 bearing steel as workpiece material with round bars form (36 mm diameter and 300 mm in length) and with the following chemical composition: Carbon – 1.03 %, Manganese – 0.41%, Chromium – 1.42 %, Nickel – 0.11 %, Molybdenum – 0.04%, Sulphur – 0.006%, Phosphorus – 0.010%, and silicon – 0.24%, the material

AISI bearing steel is having hardness in the range of 59 to 60 HRC. All the above checked parameters of given sample confirms to SAE – 52100 grades, as per the SAE 1970 standard and it is equivalent to EN – 31 grades. A hole was drilled on the face of the workpiece to allow is to be supported at the tailstock, and cleaned by removing a 1.0 mm depth of cut from the outside surface of the workpiece, prior to the actual machining.

The coated cBN tool employed is the cBN7020 from Sandvik Company. Its grade is a low cBN content material with a ceramic phase added (TiN). The insert ISO designation is TNGA 120408 T01020. It was clamped onto a tool holder (ISO designation PSBNR2525K12). Combination of the insert and tool holder resulted in negative rake angle = -6º, clearance angle = 6º, negative cutting edge inclination angle = - 6º and cutting edge angle = 75º. At last surface roughness criteria measurements (arithmetic average roughness Ra) for each cutting condition were obtained from a surftest SJ - 210 Mitutoyo roughness testers.

- **Taguchi Design**

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L_9 (3^3) orthogonal array (OA) design have been selected. In the present experimental work, cutting speed (v), feed rate (f), and depth of cut (d) have been considered as a cutting parameters. The cutting parameters and their associated ranges are given in the table. Taguchi design concept, for three levels and three parameters, nine experiments are to be performed and hence L_9 orthogonal array has selected.

Table 1: Process variables and their limits

Parameters	Level 1	Level 2	Level 3
Cutting Speed (v), m/min	200	240	280
Feed (f), rev/m	0.05	0.10	0.15
Depth of Cut (d), mm	0.10	0.20	0.30

The L_9 orthogonal array of taguchi experiment design sequence results is revealed in below table 2:

Table 2: L_9 orthogonal array taguchi experiment design

Run No.	Cutting parameters level by Taguchi method		
	v	f	d
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The L_9 orthogonal array of taguchi experiment design sequence and the actual reading results is revealed in below table 3:

Table 3: L_9 orthogonal array taguchi experiment design with actual 9 runs

Run No.	Cutting parameters level by Taguchi method			Actual Cutting parameters level by Taguchi method		
	v	f	d	v	f	d
1	1	1	1	200	0.05	0.10
2	1	2	2	200	0.10	0.20
3	1	3	3	200	0.15	0.30
4	2	1	2	240	0.05	0.20
5	2	2	3	240	0.10	0.30
6	2	3	1	240	0.15	0.10
7	3	1	3	280	0.05	0.30
8	3	2	1	280	0.10	0.10
9	3	3	2	280	0.15	0.20

III. Modeling

The modeling has done by the regression analysis software, the regression analysis done by the Minitab software of version 16. The regression analysis done through the software, the new value of roughness had estimated from the regression analysis derived formula. At last the absolute error and the percentage error calculated. The modeling of roughness value from speed, feed, and depth of cut have laid down in table 4.

Table 4: Observation table of modeling of roughness value from speed, feed, and depth of cut

Sr. No.	By Taguchi Method			Actual Values			Exp. Ra in µm	Est. Ra in µm	Absolute Error
	v	f	d	v	f	d			
1	1	1	1	200	0.05	0.1	0.208	0.213	-0.005
2	1	1	1	200	0.05	0.1	0.198	0.213	-0.015
3	1	1	1	200	0.05	0.1	0.200	0.213	-0.013
4	1	2	2	200	0.1	0.2	0.645	0.603	0.042
5	1	2	2	200	0.1	0.2	0.640	0.603	0.037
6	1	2	2	200	0.1	0.2	0.631	0.603	0.028
7	1	3	3	200	0.15	0.3	0.915	0.994	-0.079
8	1	3	3	200	0.15	0.3	0.936	0.994	-0.058
9	1	3	3	200	0.15	0.3	0.955	0.994	-0.039
10	2	1	2	240	0.05	0.2	0.230	0.238	-0.008
11	2	1	2	240	0.05	0.2	0.239	0.238	0.001
12	2	1	2	240	0.05	0.2	0.236	0.238	-0.002
13	2	2	3	240	0.1	0.3	0.678	0.629	0.049
14	2	2	3	240	0.1	0.3	0.671	0.629	0.042
15	2	2	3	240	0.1	0.3	0.665	0.629	0.036
16	2	3	1	240	0.15	0.1	0.760	0.751	0.009
17	2	3	1	240	0.15	0.1	0.775	0.751	0.024
18	2	3	1	240	0.15	0.1	0.769	0.751	0.018
19	3	1	3	280	0.05	0.3	0.215	0.264	-0.049
20	3	1	3	280	0.05	0.3	0.225	0.264	-0.039
21	3	1	3	280	0.05	0.3	0.230	0.264	-0.034
22	3	2	1	280	0.1	0.1	0.320	0.386	-0.066
23	3	2	1	280	0.1	0.1	0.335	0.386	-0.051
24	3	2	1	280	0.1	0.1	0.315	0.386	-0.071
25	3	3	2	280	0.15	0.2	0.755	0.777	-0.022
26	3	3	2	280	0.15	0.2	0.770	0.777	-0.007
27	3	3	2	280	0.15	0.2	0.765	0.777	-0.012

Regression Equation

Ra = 0.213926 - 0.00194167 v + 6.02111 f + 0.894444 d

Table 5: Regression analysis table for roughness value from speed, feed, and depth of cut

Coefficients

Term	Coef	SE Coef	T	P
Constant	0.21393	0.059857	3.5740	0.002
v	-0.00194	0.000224	-8.6719	0.000
f	6.02111	0.179124	33.6143	0.000
d	0.89444	0.089562	9.9869	0.000

Summery Model

S = 0.0379978	R – Sq = 98.27 %	R – Sq (Adj) = 98.04 %
Press = 0.0465680	R – Sq (Pred) = 97.57 %	

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	1.88400	1.88400	0.62800	434.95	0.000
v	1	0.10858	0.10858	0.10858	75.20	0.000
f	1	1.63142	1.63142	1.63142	1129.92	0.000
d	1	0.14401	0.14401	0.14401	99.74	0.000
Error	23	0.03321	0.03321	0.00144		
Lack of Fit	5	0.3156	0.03156	0.00631	68.94	0.000
Pure Error	18	0.00165	0.00165	0.00009		
Total	26	1.91721				

Fits and Diagnostics for Unusual Observations

Obs	Ra	Fit	SE Fit	Residual	St Resid	
7	0.915	0.997093	0.0171498	-0.0820926	-2.42107	R

R denotes an observation with a large standardized residual.

IV. Results And Discussion

As the modeling done through the modeling software, the various statistical correlations formed from the analysis by Minitab software version 16. The various correlations formed and which are having individual tribological property relation with roughness value and combined tribological property relation with the roughness value.

The correlations developed from the statistical analyses, which are given below:

The below given equations are individual correlations with roughness value,

Ra = 0.994926 - 0.00194167 v …. (Eq. 1)

Ra = -0.0731852 + 6.02111 f …. (Eq. 2)

Ra = 0.350037 + 0.894444 d …. (Eq. 3)

The below given equations are combined correlation with roughness value,

Ra = 0.392815 - 0.00194167 v + 6.02111 f …. (Eq. 4)

Ra = 0.816037 - 0.00194167 v + 0.894444 d …. (Eq. 5)

Ra = -0.252074 + 6.02111 f + 0.894444 d …. (Eq. 6)

The final equations have the all parameters effect on roughness value,

Ra = 0.213926 - 0.00194167 v + 6.02111 f + 0.894444 d …. (Eq. 7)

- **Correlation between Experimental and Estimated Roughness value from Speed, Feed, and Depth of cut**

The below given graphical representation 1 show the correlation between the experimental roughness value and the estimated roughness value. The experimental roughness value is the actual roughness value measured by the roughness tester and the estimated roughness values are the values, which are estimated from the regression equation and the main factors speed, feed, and depth of cut tribological parameters have considered.This is the final regression equation which shows the strongest correlation between tribological parameters i.e. speed, feed, and depth of cut and the roughness value, the correlation gives R^2 value 98.27 %. The below given figure 1 show the correlation between experimental and estimated roughness value from speed, feed, and depth of cut.

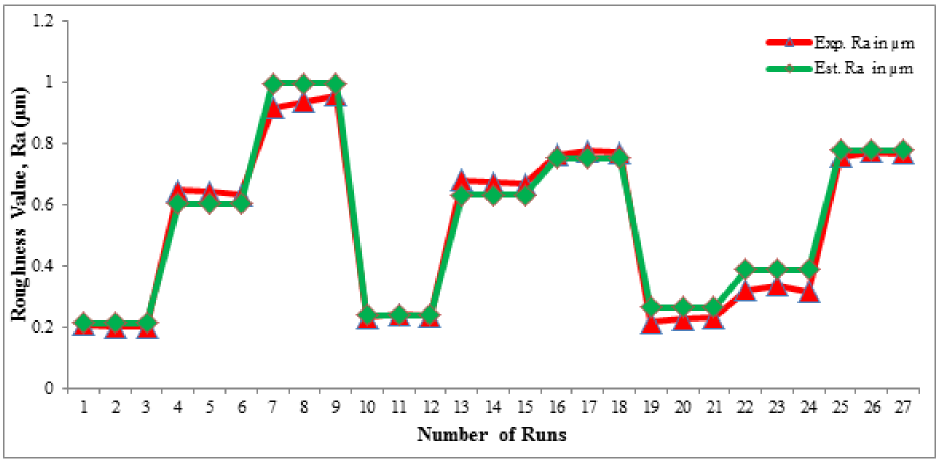

Figure 1: Number of Runs versus Experimental and Estimated Ra from speed, feed, and depth of cut

The below given graph 2 which shows the probability of speed, feed, depth of cut, and roughness value. For speed the mean value is 240 and the standard deviation is 33.28. Total 27 runs or the reading taken for the speed in calculations and the AD value is 2.124 which give the probability less than by the 0.005.For feed the mean value is 0.1 and the standard deviation is 0.04160. Total 27 runs or the reading taken for the feed in calculations and the AD value is 2.124 which give the probability less than by the 0.005.For depth of cut the mean value is 0.2 and the standard deviation is 0.08321. Total 27 runs or the reading taken for the depth of cut in calculations and the AD value is 2.124 which give the probability less than by the 0.005.For the roughness value the mean value is 0.5289 and the standard deviation is 0.2715. Total 27 runs or the reading taken for the roughness value in calculations and the AD value is 1.687 which gives the probability less than by the 0.005.At last the probability values by Anderson – Darling test's (AD test's) for speed, feed, depth of cut, and roughness value are the 0.005, which are less than by 0.05 (5% level of significance) which indicates that the data do not follow the normal distribution. So it fails to accept the null hypothesis.

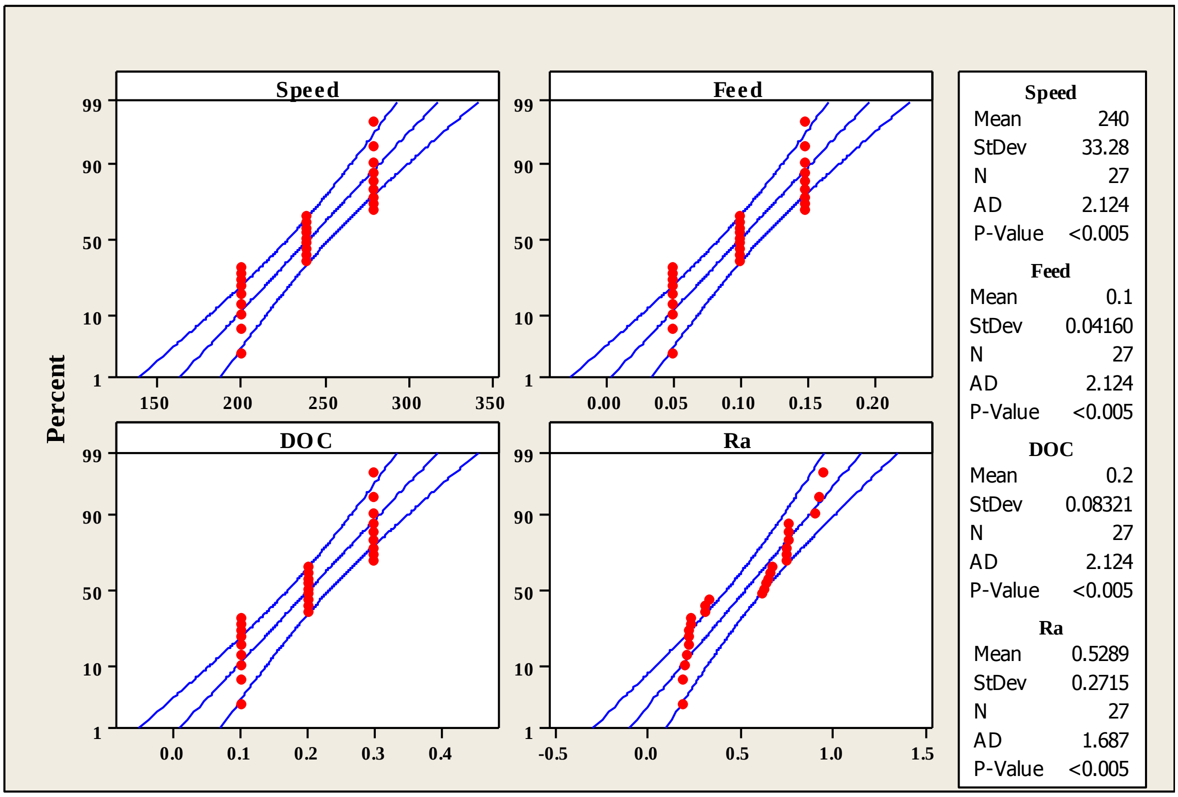

Figure 2: Probability analysis of speed, feed, and depth of cut and Ra value

V. Conclusions

Based on the experimental results presented in the modeling and discussed in the results and discussion section, the following conclusions are drawn on the effect of cutting speed, feed and depth of cut on the performance of cubic boron nitrated insert on roughness value of AISI 52100 steel.

The conclusions drawn from the analysis are given below:

a. In hard turning, the taguchi method has proved to be efficient tools for controlling the effect tribological parameters on roughness value.The speed, feed, and depth of cut plays equally important role in the machining process but in analysis the feed and depth of cut showed an excellent bonding effect on roughness value prediction form the regression analysis. The speed has shown less effect on roughness value.
b. As the number of tribological parameters increases in the correlational analysis the correlation value increases simultaneously. For single tribological parameters the equation would be able to predict the roughness value with accuracy from (R^2 value) 5.66 to 85.09 % and for combine tribological parameters the range of 13.17 to 92.60 %, at last the final equation which gives the accuracy of 98.27 %.
c. The uncertainty analysis or the error which comes under 4.69 % after the calculations.

VI. Future Scope

In future, by using the various machining parameters for turning process can also be optimized as follows:

a. By using the various statistical analysis software's like SPSS, Minitab, SAS, SYSTAT, FEA, etc. the accuracy of the equation will be improved.
b. The various statistical techniques like Regression, Taguchi, Anova, ANN, GA, Fuzzy expert system etc. will improve the performance of equation.
c. By using the statistical analysis charts the accuracy will be improved.
d. By using the various parameters the different correlations can be generated.

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