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Formulation Techniques in Regression Analysis to Estimate the Roughness Value from Tribological Parameters in Hard Turning of AISI 52100 Steels

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Abstract:*To machine any material the tribological parameters play an important role in the machining. The main important tribological parameters are speed, feed, and depth of cut. The hard material like EN-31 or AISI 52100 steels are having hardness in between the range of 41 HRC to 69 HRC on C scale of Rockwell hardness. To machine hard materials like this, the special purpose tools or the machinesare required. Most of the times the grinding process perform to machine these kinds of materials. But the alternatives like ceramics, cBN, PcBN tools are also available to machine these materials instead of grinding. The different tools are giving different values of roughness after machining, but the roughness value can be optimized by using the different statistical techniques by comparing the different combinations of tribological parameters while performing the machining operations on the hard materials.*

The various statistical software's and techniques are available in the market. But the most viable technique available for correlation is the regression analysis. The different types of models (i.e. linear, quadratic, and cubic) are available in regression analysis to correlate various tribological parameters. The operations perform on the AISI 52100 steel materials of hardness 58 HRC by varying the tribological parameters according to the L_9 *Taguchi Design. The modeling is done through the linear regression analysis, quadratic regression analysis, and cubic regression analysis and the comparison between different models of estimated versus experimental roughness value. The result analysis shown and conclude that the estimated correlations would be able to predictswith accuracy of 99.50% to 99.90% and last but the least 6.19% uncertainty is present in the experimentations.*

Keywords: *AISI 52100 steel, Hard Turning,Regression, Linear Regression, Quadratic Regression, Cubic Regression, Modeling.*

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), H.M. Dharmadhikari (2015)*].

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 research 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 58 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.

A. 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)*].

B. Variables Affecting Machinability

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

a. Machine variables
b. Tool variables
c. Cutting conditions
d. Work material variables

C. Workpiece Material

As the workpiece is having steel material of grade AISI 52100, the details of workpiece material are given in below table 1:

Table 1: Chemical Composition of 52100 Steel

Sr. No.	Chemical Composition	Observations	Specified for 52100 Grade Steel
1	% C	1.03	0.90 to 1.20
2	% Mn	0.41	0.25 to 0.45
3	%Cr	1.42	1.30 to 1.60
4	%Ni	0.11	-
5	%Mo	0.04	-
6	%S	0.006	0.025 max
7	%P	0.010	0.025 max
8	%Si	0.24	0.15 to 0.30
9	Hardness	58 HRC	-

II. EXPERIMENTATIONS

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 2.

In general the chemical composition for AISI 52100 bearing steel material are as follows: Carbon – 0.90 to 1.20 %, 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 58 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 (35 mm diameter and 250 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 56 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 cBN 7020 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.

A. 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 2: Process variables and their limits

Parameters	**Level 1**	**Level 2**	**Level 3**
Cutting Speed (v), m/min	120	180	240
Feed (f), rev/m	0.10	0.15	0.20
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 3:

Table 3: 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 4:

Table 4: 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	120	0.10	0.10
2	1	2	2	120	0.15	0.20
3	1	3	3	120	0.20	0.30
4	2	1	2	180	0.10	0.20
5	2	2	3	180	0.15	0.30
6	2	3	1	180	0.20	0.10
7	3	1	3	240	0.10	0.30
8	3	2	1	240	0.15	0.10
9	3	3	2	240	0.20	0.20

III. MODELING

The modeling has done by the regression analysis software, the regression analysis done by the Minitab software. 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 has given in table 5.

Table 5: 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	120	0.10	0.10	0.5610	0.5601	0.0009
2	1	2	2	120	0.15	0.20	0.8021	0.7857	0.0164

3	1	3	3	120	0.20	0.30	0.9917	1.0113	-0.0196
4	2	1	2	180	0.10	0.20	0.5433	0.5518	-0.0085
5	2	2	3	180	0.15	0.30	0.7915	0.7774	0.0141
6	2	3	1	180	0.20	0.10	0.9101	0.9097	0.0004
7	3	1	3	240	0.10	0.30	0.5409	0.5434	-0.0025
8	3	2	1	240	0.15	0.10	0.6663	0.6757	-0.0094
9	3	3	2	240	0.20	0.20	0.9108	0.9013	0.0095

Regression Equation

$$Ra_{(Est.)} = 0.219 - 0.000658\,v + 3.89\,f + 0.311\,d \qquad \text{...(Eq. 1)}$$

Table 6: Regression analysis table for roughness value from speed, feed, and depth of cut

Coefficients

Term	Coef	SE Coef	T	P
Constant	0.21888	0.02896	7.56	0.001
v	-0.000658	0.0001014	-6.49	0.001
f	3.8913	0.1217	31.98	0.000
d	0.31117	0.06084	5.11	0.004

Summery Model

S = 0.014920	R – Sq = 99.50 %	R – Sq (Adj) = 99.27 %
Press = 0.00424972	R – Sq (Pred) = 98.25 %	

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	0.242292	0.242292	0.080764	363.69	0.0000029
v	1	0.009346	0.009346	0.009346	42.08	0.0012982
f	1	0.227137	0.227137	0.227137	1022.81	0.0000006
d	1	0.005809	0.005809	0.005809	26.16	0.0037236
Error	5	0.001110	0.001110	0.000222		
Total	8	0.243403				

Fits and Diagnostics for Unusual Observations

Obs	Ra	Fit	SE Fit	Residual	St Resid	
3	0.9917	1.01156	0.0116495	-0.0198611	-2.13720	R

R denotes an observation with a large standardized residual.

From the above analysis it has been seen that, the R^2 value shows the speed, feed, and depth of cut explains 99.50% of the variance in roughness value, indicating that the model fits the data extremely well which means that speed, feed, and depth of cut explanatory power in roughness value is 99.50%. 0.50% is unexplained variance.

A. Regression analysis by Linear Model

The regression analysis done through the Minitab software, and the estimated roughness value predicted from the experimental roughness value by the linear regression model. The linear regression equation would be able to predict the estimated roughness value with an accuracy of 93.41%. The table 7 shows the information between experimental and estimated roughness value,

Table 7: Experimental and Estimated Roughness Value by Linear Regression Model

Runs	Exp. Ra (μm)	Est. Ra in μm	Est. Ra (μm) by Linear
1	0.5610	0.5601	0.5617
2	0.8021	0.7857	0.8017
3	0.9917	1.0113	0.9903
4	0.5433	0.5518	0.5441
5	0.7915	0.7774	0.7911
6	0.9101	0.9097	0.9091
7	0.5409	0.5434	0.5417
8	0.6663	0.6757	0.6665
9	0.9108	0.9013	0.9098

B. Regression analysis by QuadraticModel

The regression analysis done through the Minitab software, and the estimated roughness value predicted from the experimental roughness value by the quadratic regression model. The quadratic regression equation would be able to predict the estimated roughness value with an accuracy of 99.80%. The table 8 shows the information between experimental and estimated roughness value,

Table 8: Experimental and Estimated Roughness Value by Quadratic Regression Model

Runs	Exp. Ra (μm)	Est. Ra in μm	Est. Ra (μm) by Quadratic
1	0.5610	0.5601	0.5648
2	0.8021	0.7857	0.7916
3	0.9917	1.0113	1.0044
4	0.5433	0.5518	0.5501
5	0.7915	0.7774	0.7806
6	0.9101	0.9097	0.9091
7	0.5409	0.5434	0.5482
8	0.6663	0.6757	0.6578
9	0.9108	0.9013	0.9099

C. Regression analysis by CubicModel

The estimated roughness value predicted from the experimental roughness value by the cubic regression model. The cubic regression equation would be able to predict the estimated roughness value with an accuracy of 99.90%. The table 9 shows the information between experimental and estimated roughness value,

Table 9: Experimental and Estimated Roughness Value by Cubic Regression Model

Runs	Exp. Ra (μm)	Est. Ra in μm	Est. Ra (μm) by Cubic
1	0.5610	0.5601	0.5665
2	0.8021	0.7857	0.7896
3	0.9917	1.0113	1.0130
4	0.5433	0.5518	0.5465
5	0.7915	0.7774	0.7799
6	0.9101	0.9097	0.9023
7	0.5409	0.5434	0.5437
8	0.6663	0.6757	0.6698
9	0.9108	0.9013	0.9031

D. Comparison between Linear, Quadratic, and Cubic Regression Model

The linear regression model would be able to predict roughness value with accuracy 99.50% and 99.80% by quadratic models, and 99.90% by cubic regression model. The table 10 shows the information about comparison between experimental roughness value and the linear, quadratic, and cubic regression model,

Table 10: Experimental and Estimated roughness value

Runs	Exp. Ra (μm)	Est. Ra in (μm)	Est. Ra (μm) By Linear Model	Est. Ra (μm) By Quadratic Model	Est. Ra (μm) By Cubic Model
1	0.5610	0.5601	0.5617	0.5648	0.5665
2	0.8021	0.7857	0.8017	0.7916	0.7896
3	0.9917	1.0113	0.9903	1.0044	1.0130
4	0.5433	0.5518	0.5441	0.5501	0.5465
5	0.7915	0.7774	0.7911	0.7806	0.7799
6	0.9101	0.9097	0.9091	0.9091	0.9023
7	0.5409	0.5434	0.5417	0.5482	0.5437
8	0.6663	0.6757	0.6665	0.6578	0.6698
9	0.9108	0.9013	0.9098	0.9099	0.9031

IV. RESULTS AND DISCUSSION

From the modeling various correlational equations generated between tribological parameters and the roughness value. This kind of correlational equations can also be generating in any combination of tribological parameters and the roughness value, but the fact is that every correlational equation having different value of R^2. Following are the correlations available to estimate the roughness value from various tribological parameters:

The regression equation shows the correlations between speed, feed, and depth of cut and roughness value, other equations would also be possible.

$$Ra_{(Est.)} = 0.219 - 0.000658\, v + 3.89\, f + 0.311\, d \qquad \text{... (Eq. 1)}$$

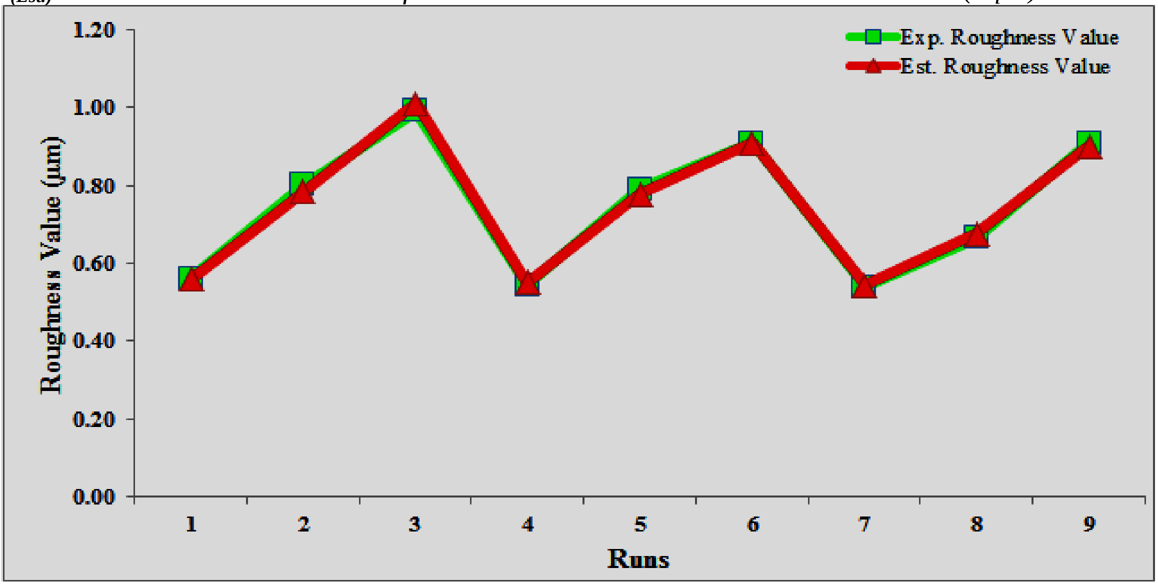

Figure 1: Exp. and Est. Roughness Value versus Runs

The linear regression equation model shows the correlation between experimental roughness value and the estimated roughness value, and the model would be able to predict the estimated roughness value with an accuracy of 99.50%. The graph 2 shows the correlation between experimental and estimated roughness value versus runs.

The regression equation by linear model

$$Ra_{(Est.)} = 0.00349 + 0.9951\, Ra_{(Exp.)} \qquad \text{...(Eq. 2)}$$

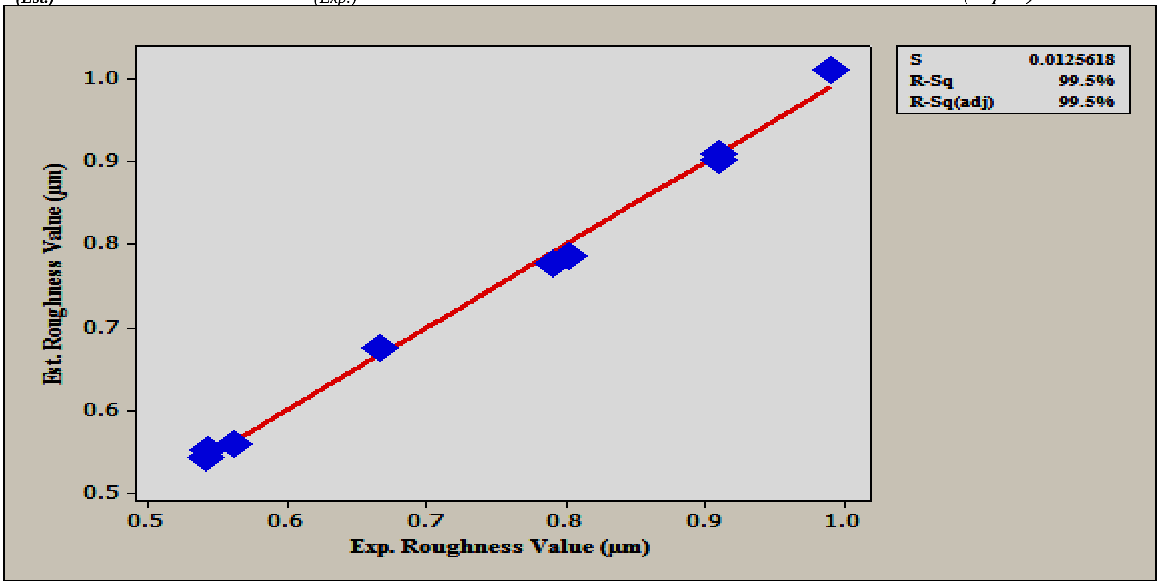

Figure 2: Exp. Roughness Value versus Est. Roughness Value by linear model

The quadratic regression equation model shows the correlation between experimental roughness value and the estimated roughness value, and the model would be able to predict the estimated roughness value with an accuracy of 99.80%. The graph 3 shows the correlation between experimental and estimated roughness value versus runs.

The regression equation by quadratic model

$$Ra_{(Est.)} = 0.2271 + 0.3653\, Ra_{(Exp.)} + 0.4220\, (Ra_{(Exp.)})^2 \qquad \text{...(Eq. 3)}$$

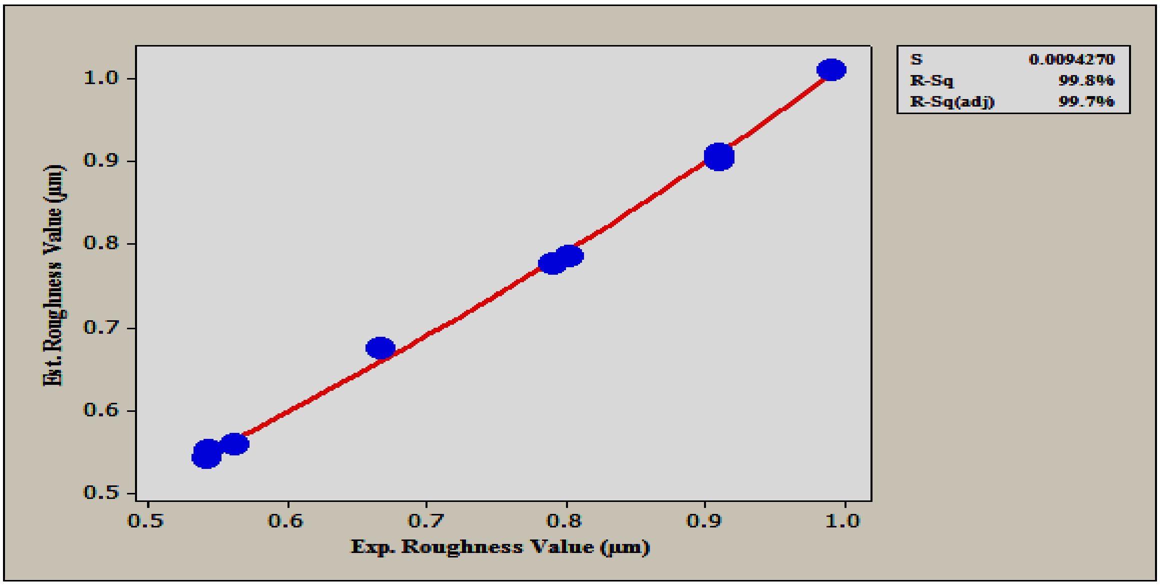

Figure 3: Exp. Roughness Value versus Est. Roughness Value by quadratic model

The cubic regression equation model shows the correlation between experimental roughness value and the estimated roughness value, and the model would be able to predict the estimated roughness value with an accuracy of 99.90%. The graph 4 shows the correlation between experimental and estimated roughness value versus runs.

The regression equation by cubic model

$\mathbf{Ra}_{(Est.)} = -1.055 + 5.643\, Ra_{(Exp.)} - 6.625\, (Ra_{(Exp.)})^2 + 3.063\, (Ra_{(Exp.)})^3$ …(Eq. 4)

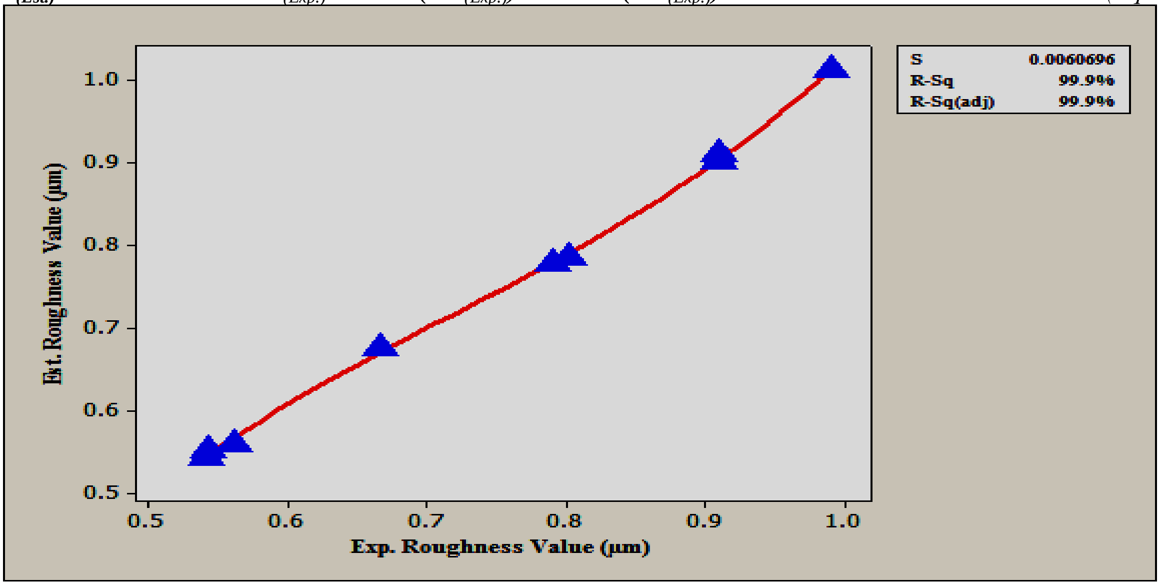

Figure 4: Exp. Roughness Value versus Est. Roughness Value by cubic model

The linear, quadratic, and cubic regression equation model shows the correlation between experimental roughness value and the estimated roughness value, and the models would be able to predict the estimated roughness value with an accuracy of 99.50% by linear, 99.80% by quadratic, and 99.90% by cubic regression model. The graph 5 shows the comparison correlation model between experimental and estimated roughness value versus runs.

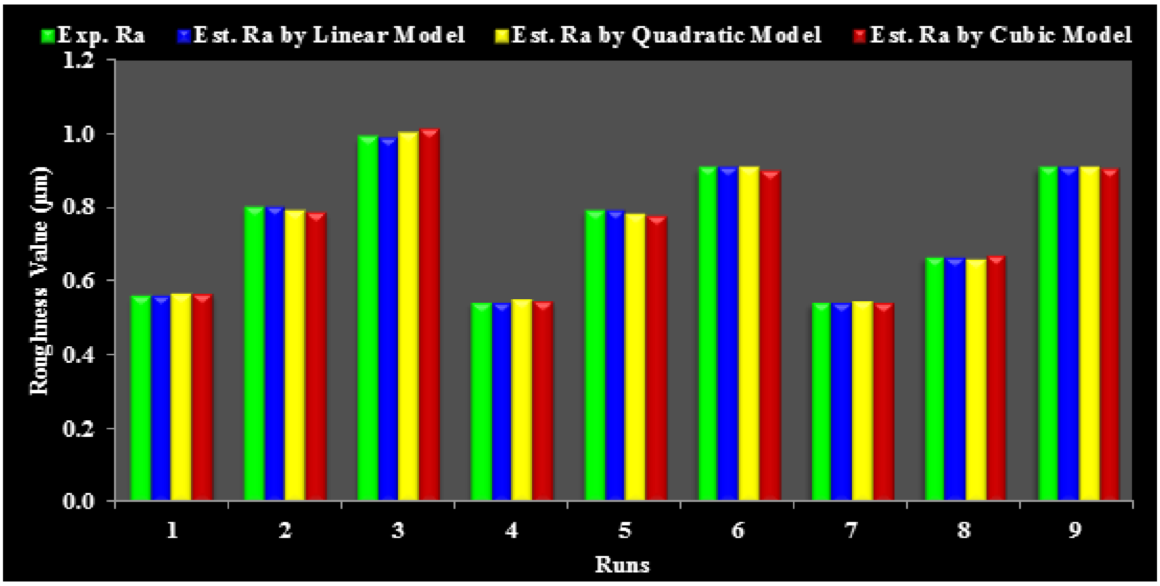

Figure 5: Comparison between Linear, Quadratic, and Cubic regression model of Ra versus Runs

V. CONCLUSIONS

It is established that the tribological parameters have predominate effect on roughness value of the hard material i.e. AISI 52100 steels. From the results obtained it is found that the roughness value is predominantly affected by the tribological parameters of speed, feed, and depth of cut.

- 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 play an equally important role in the machining process but the in analysis the feed and depth of cut showed an excellent bonding effect on roughness value prediction from the regression analysis. The speed had showed less effect on roughness value.
- As the number of parameters increases in the correlation, the correlation value i.e. R^2 value also increases simultaneously. The final equation would able to predict the roughness value with accuracy of 99.50%, after these the linear, quadratic, and cubic regression analysis models have given different values that are 99.50%, 99.80%, and 99.90%. It means the cubic regression analysis model would give most accurate R^2 value than the linear, quadratic regression models for roughness value. The overall uncertainty in the estimated roughness value is found to be ± 6.19% which is acceptable.

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