KUFA JOURNAL
OF ENGINEERING
ISSN 2071-5528
PRINTED IN IRAQ

Volume 3, Number 2 pp.47- 68 , 2012

SURFACE ROUGHNESS AND ROUNDNESS ERROR PREDICTION MODELS IN TURNING LOW CARBON STEEL

Dr. SAMIR A. ALRABII and Dr. MUTHANNA H. S.
Department of Mechanical Engineering / University of Technology
(Received:21/6/2011 ;Accepted :22/2/2012)

ABSTRACT

Cutting tests were conducted to longitudinally turn low carbon steel using HSS tools with cutting fluid. The experimental design used was based on response surface methodology (RSM) using a central composite rotatable (CCD) design. The primary cutting tests confirmed the use of proper specimen design with length to diameter ratio (L/D) of 2 in the subsequent cutting tests of this research. Further cutting tests were carried out to turn low carbon steel with L/D=2 to determine the effect of using different cutting conditions on the surface roughness and roundness error (out of roundness) of the machined surfaces. At the end of each cutting test, the surface roughness and roundness error measurements were taken and analyzed using "DESIGN EXPERT 8" experimental design software. Mathematical models of responses (surface roughness and roundness error) as functions of the conditions (cutting speed, feed, and depth of cut) were obtained and studied. A quadratic predicted model for surface roughness showed that the feed, cutting speed and their squares and interactions were more effective than the depth of cut because of its little influence on the surface roughness. Also, the resultant two-factor interaction (2FI) model for roundness error exhibited that cutting speed, feed and the interaction of feed and speed were significant parameters, while the depth of cut had no effect. The predicted models indicated that at higher cutting speed and various feed levels, both responses decreased, resulting in a smooth machined surface with lower roundness error. But, both models exhibited that at lower cutting speed and higher feeds, the surface roughness and roundness error increased, producing a rough machined surface with higher out of roundness error.

***KEYWORDS:** Surface Roughness, Roundness Error, Longitudinal Turning, HSS, Low Carbon Steel, Design of Experiment, Response Surface Methodology.*

النماذج المنبئة لخشونة السطح والخطأ الدوراني في خراطة الصلب الواطئ الكربون

الخلاصة

أنجزت أختبارت قطع لخراطة الصلب الواطئ الكربون طوليا بأستخدام عدد قطع ذات السرع العالية (HSS)وسائل تبريد. أستند التصميم التجريبي على أساس أستخدام أسلوب الأستجابة السطحية (RSM)بأستخدام التصميم المركب المركزي(CCD) الدوار. أكدت أختبارات القطع الاولية على أستخدام تصميم العينة المناسب بنسبة طول الى قطر 2 في أختبارات القطع اللاحقة لهذا البحث . اجريت أختبارات قطع أخرى لخراطة عينات الصلب الواطئ الكاربون بنسبة طول الى قطر 2 لأيجاد تأثير ظروف التشغيل المختلفة على خشونة السطح والخطأ الدوراني (الخروج عن الدورانية) للسطوح المشغلة. عند نهاية كل أختبار قطع ، أخذت قياسات خشونة السطح والخطأ الدوراني وتم تحليلها بأستخدام برنامج (DESIGN EXPERT 8) للتصميم التجريبي. تم أيجاد ودراسة النماذج الرياضية للأستجابات (خشونة السطح والخطأ الدوراني) بدلالة الظروف (سرعة القطع ، التغذية ، عمق القطع). أظهر النموذج التربيعي(Quadratic) المنبأ لخشونة السطح بأن التغذية وسرعة القطع ومربعاتها وتداخلاتها كانت فعالة أكثر من عمق القطع بسبب تأثيره القليل على خشونة السطح. كما أظهر النموذج ذوالتداخل ثنائي- العوامل (2FI) للخطأ الدوراني بأن سرعة القطع والتغذية وتداخل سرعة القطع مع التغذية عوامل مهمة فيها بينما لم يكن لعمق القطع اي تأثير . ووفقا لجميع النتائج المستحصلة ، بيينت النماذج المنبئة بأنه عند سرعة القطع العالية ومستويات تغذية مختلفة ، فقد قلت كلا الاستجابتين مكونة" سطح مشغل ناعم مع أدنى خطأ دوراني. لكن كلا النموذجين أوضحا بأنه عند سرعة القطع الواطئة وتغذيات عالية ، فقد أزدادت كل من خشونة السطح والخطأ ألدوراني مولدة" سطح مشغل خشن مع أعلى خطأ دوراني.

INTRODUCTION

Turning is one of the machining processes used to produce high quality machined components with external and internal profiles. In turning operations, the dimensional accuracy, tool wear and quality of the surface finish are three important factors that the manufacturers must be able to control [1].Also, surface roughness and roundness are considered the most critical quality measures in many mechanical engineering parts due to increasingly high demands for quality in industry.

An amplified stylus profilometer is the most popular and prevalent contact instrument used to measure the surface roughness in industry and research laboratories, because it is fast, repeatable, easy to interpret, relatively inexpensive, and utilized as a standard for comparison purpose [2]. The surface finish can be characterized by various height parameters, and the average roughness (Ra) or center line average (CLA) method is most widely used in industry for specifying surface roughness [3].

Roundness is a very important surface characteristic that can affect the performance and behavior of machined parts. The effect of some turning parameters on roundness error of turned specimens has been theoretically and experimentally investigated in turning mild steel at different cutting speeds, feeds and depth of cuts [4].Majority of the machined workpieces which are round and symmetrical in shape have the ratio of length to diameter normally less than three and they are overhung clamped and machined with three jaw chucks. In such turning processes, a deviation of shape called out-of-roundness is commonly observed, and its magnitude is dependent upon the workpiece specifications and cutting as well as clamping conditions [5].Roundness is a geometric property of a cylindrical workpiece. Cho and Tu [6] reported that the roundness modeling is essential for the advanced tolerance analysis of an assembly of circular and cylindrical parts. The roundness error or out of roundness (deviation from a perfect circle) is among many parameters that can be used in evaluating the macro-geometrical deviations in precisely machined parts [7]. The assessment of roundness error is normally associated with the surface roughness, particularly in rotary bearings, because these two factors are affecting the efficiency of the bearing properties of the mating parts. In addition, the roundness measurement technique is also a contact method, in which an amplified stylus profilometer is used to measure the roundness error. However, the roughness and roundness are different types of measurements that require different techniques. There are many procedures of obtaining a numerical assessment of roundness error. The least square center (LSC) method is most widely used in industry to specify the roundness error as the radial separation of two circles divided by the magnification utilized [8].During turning operations, the workpiece clamping system and the selection of the cutting conditions are of prime importance. They both have a significant influence on workpiece roundness error, due to the dynamic behavior of the chuck-axis-workpiece system. This dynamic behavior is conditioned by selected machining parameters (cutting speed v, depth-of-cut d, feed rate f) and the design of the workpiece (length L and diameter D). The main aim of the work was to evaluate the influence of the aforementioned parameters (v, d, f, L/D) on workpiece roundness error during turning AISI-1045 steel [9]. Thus, surface roughness and roundness error are considered significantly important for evaluating the surface quality of the turned parts, leading to the need to formulate prediction models for roughness and roundness error as function of operating conditions.

Surface roughness and roundness error can be used as response parameters to evaluate the quality of the turned parts. In order to know the surface quality and dimensional precision properties in advance, it is necessary to determine which process conditions will meet specifications related to surface roughness and roundness error. Furthermore, most of previous research work in turning operation using RSM or factorial designs have been focused and directed at the analysis and prediction of tool wear behavior and mechanism of different cutting tools, tool life, cutting forces, cutting tool geometry, workpiece hardness, flow stress, and chip thickness and microhardness as a function of both machining parameters and/ or use of different coated tools. However, little work on the machining of steels has been given to the analysis and prediction of surface roughness and roundness error by RSM. Therefore, the aim of the present paper is to study the effect of varying machining parameters on surface roughness and roundness error during longitudinal turning of low carbon steel using HSS tools and cutting fluid in order to develop prediction models for these by using RSM. The machining parameters studied are cutting speeds, feeds, and depth of cuts. The software Design Expert 8thwas used to develop the RSM models with the aid of variance (ANOVA) statistical method to analyze the collected data. Results of test runs are reported, as well as the, prediction models produced with 95% confidence level.

Response surface methodology

Today, the applications of optimization techniques in metal cutting processes is essential for a manufacturing unit, and their methods are considered to be a vital tool for continual improvement of the output quality products and processes, including modeling of input-output and in-process parameters relationship and determination of optimal cutting conditions [10]. Aggarwal and Singh [11] stated that the Response Surface Methodology (RSM) is one of the latest techniques for optimizing the machining parameters in turning processes. RSM is a collection of mathematical and statistical techniques that are used for modeling and analysis of problems, in which a response of interest is influenced by several variables, and the objective is to optimize this response [12]. The use of RSM helps to reduce the number of tests required to achieve a statistically sound results, and it aims at producing a surface prediction model for multiple parameters. This methodology was first used by Wu [13] in tool life testing, and the number of experiments required to develop a surface roughness equation was markedly reduced as compared to the traditional one variable at a time approach. Consequently, further research studies have utilized RSM and factorial design of experiments to cross examining the impact of individual factors and factors interactions, solving the surface roughness prediction problem during dry or wet turning operations. Design and RSM are now widely used in place of one-factor-at a time experimental approach which is time consuming and exorbitant cost [14-27].

EXPERIMENTAL WORK

Work material preparation

The material used in this work was a low carbon steel(St 37.0) in form of bar of 50 mm diameter and in the annealed and cold rolled condition.The chemical composition of this material supplied by the manufacturer is given in Table 1. Since the length of the free end of the workpiece from the machine chuck has normally a great effect on the surface roughness and roundness error during the turning operation, it was first decided to use different free end lengths and maintain the diameter constant.For the sake of material saving, a minimum length of 30 mm from each bar was utilized by the machine chuck for enough support and fixing, and three lenghts were selected as 50 mm, 75 mm, and 100 mm with a length (L) to diameter (D) ratio not more than two (i.e., 1, 1.5, and 2, respectively) becausemajority of the machined workpieces which are round and symmetrical in shape have the ratio of length to diameter normally less than three, and they are overhung clamped and machined with three jaw chucks [5].

Therefore, three specimens were cut with the following dimensions: 50 mm dia. x 80 mm length, 50 mm dia. x 105 mm length, and 50 dia. x 130 mm length. Each specimen was first surface cleaned by turning with a new carbide tool to remove the hard surface oxide. Cutting tests were then carried for these bars at a cutting speed of 30 m/min, feed of 0.45 mm/rev, and depth of cut of 2 mm in a longitudnal turning by high-speed steel(HSS) cutting tools with a cutting fluid to determine the effect of the L/D ratio on the surface roughness and roundness error. According to the results of these tests, it was finally decided to use only a ratio of L/D of 2 (i.e., the specimen dimension is 50 mm dia. x 130 mm length) during turning the low carbon steel material in the next cutting teststo achieve the aim of the present paper.

Cutting tool preparation

HSS cutting tools are greately needed in industry to machine carbon steels due to their strength and toughness properties. In this work, HSS cutting tools with 5% cobalt (M-grade SI 6) were used with specific cutting angles, such that the tools cut orthogonoly.This meant a back rake angle (αb), side rake angle(αs), and side cutting angle (Ψ) of zero degrees, resulting in a rake angle (α) of zero degrees as well as high relief angles. The tool signature is listed below (Figure 1 illustrates the tool geometry):

(i) αb: back rake angle = 0◦;

(ii) αs: side rake angle = 0◦;

(iii) ERA: end relief angle = 16◦;

(iv) SRA: side relief angle = 21.5◦;

(v) ECEA: end cutting edge angle = 23◦;

(vi) Ψ: side cutting edge angle = 0◦;

(vii) NR: nose radius = 0.25 mm.

Experimental design and testing

Cutting conditions used in the whole experimentation were selected according to the practical experience [28]. The parameters were chosen such that they take into consideration the limitations of the machine and in order to avoid excessive chatter. These conditions are given in Table 2 with three levels. The experimental design used was the response surface methodology using a central composite rotatable design for 2^3 factors, with 6 central points and $\alpha = \pm 2$. 20 tests were performed according to the experimental design matrix (*8 factorial points + 6 axial points +6center points*). The tests were performed at random using the run order listed in Table 3. Each parameter was tested at different code levels of −2, −1, 0, +1, and +2, whereby each level tested conformed to an actual value equivalent to the coded value.

The machine used to perform the cutting tests was a Bulgarian SLIVEN 400. The work material bars were cut in a longitudinal turning operation using cutting fluid (water-soluble coolant) for only one pass per test to ensure taking the measurements of the surface roughness and roundness error at various positions of the machined surface. Since cutting tests were performed with speed kept constant, variations in diameter of workpiece were taken into account when selecting the RPM of the machine, at which turning took place in the subsequent passes for the following tests.

A water-soluble coolant (a soluble 0il, which is an oily emulsion freely miscible in water) was used as the cutting fluid during turning all test samples. The cutting fluid is commonly used as a coolant for lubricating and cooling purposes by reducing the harmful effects of friction and high temperatures during turning operations [28].+

Surface roughness test

At the end of each cutting test,the surface roughness of the machined specimen was measured using a portable surface roughness tester type surtrouic 3+at the metrology laboratory. This instrument uses a tracer or pickup incoporating a diamond stylus and a transducer. Running the stylus tip across the specimen surface generates electrical signals, corresponding to surface roughness. The electrical signals are amplified, converted from analog to digital, processed according to algorithm, and displayed. The roughness was measured at four angles (0°, 90° , 270° and 360°) of the specimen cross section using a cut-offof 0.8 mm,especially at the end of the pass (near the machine chuck), and the average of four readings was determined and taken as the roughness height value (Ra) with maximum error ± 0.5µm.All experimental average surface roughness measurements are given in Table 4. The surface roughness readings (Ra values) for all test samples were directly taken from the digital screen of the roughnes measuring instrument, and therefore, there was no need to take the roughness trace or shape for each machied sample.

Roundness test

At the end of the surface roughness mesurements, the roundness of the machined surface was measured using a Mitutoyo round testing machine at the metrology laboratory.This instrument also uses an amplified stylus profilometer to measure the roundness error. Four measurements were then takenat four positions along the whole pass (starting from the free end of the specimen and moving towards the machine chuck) and the average of these readings was obtained and taken as the roundness error value with maximum error ± 1 μm. Table 4 lists the average experimental roundness mesurements.

RESULTS AND DISCUSSION

Effect of length to diameter ratio on surface roughness

Primary cutting tests were first conducted to turn longitudinally low carbon steel specimens with three L/D ratios at a cutting speed of 30 m/min, feed of 0.45 mm/rev and depth of cut in order to find the effect of the specimen design on the surface roughness and roundness error. At the end of these tests, four surface roughness measurements at different angles on the machined surface and for each L/D ratio were plotted, as depicted in Figure 2, showing that the surface roughness values almost remained constant as the ratio L/D increased from 1 to 2. This means that the increase of the length from the free end of the specimen to the machine chuck had no effect on the surface roughness when the L/D ratio increased from 1 to 2. Therefore, it was decided to use specimens with L/D = 2 in the subsequent tests of this work because of material saving requirement.

Effect of length to diameter ratio on roundness error

For the same specimens machined in primary tests as mentioned above, four roundness error measurements at different positions along the machines surface were taken for each L/D ratio. The results were then plotted, as illustrated in Figure 3, indicating that the roundness error values for L/D=1 were high and then decreased and almost stayed unchanged for the L/D ratios 1.5 and 2. This also explains that the increase of the length from the free end of the specimen to the machine chuck had no significant effect on the roundness error with increasing the L/D ratio from 1 to 2 due to the proper supporting and fixing the specimen by the machine chuck . Eventually, specimens with L/d =2 were selected to be used in the next tests of this research due to material saving purpose.

Surface roughness model

The average responses obtained for surface roughness were used in calculating the models of the response surface per response using the least-squares method. For surface roughness prediction model, a reduced cubic model in coded terms was analyzed with backwards elimination regression of insignificant coefficients at an exit threshold of alpha = 0.1.After the examination of analysis results, testno.19 or run 3 (center point with code 0, 0, 0) was ignored in the runs in order to achieve a robust model, and the analysis performed again. In order to obtain a formula with actual factors rather than coded factors, some coefficients were removed, since they were aliased and not fitted for back elimination. The terms removed wereA^2C, ABC, A^2B, A^2, AC, and BC, while the other terms and cubic ones were found aliased by the stepwise regression. Therefore, the only considered terms of this surface roughness model were cutting speed(A), feed(B), depth of cut (C), the interaction between speed and feed (AB), the squared feed (B^2), the squared cut(C^2), the interaction of cutting speed and squared feed (AB^2) in addition to the intercept.

The final surface roughness predicted model (equation) in terms of coded factors is:

$$\textbf{Surface Roughness} = +14.22 - 1.29\,A + 2.94\,B + 0.29\,C - 3.20AB - 0.93B^2 - 1.36C^2 - 6.95AB^2$$

And, the final model (equation) in terms of actual factorsis, showing that the feed had the highest impact and then cutting speed, but the depth of cut had a little effect on the roughness of the machined surface.

$$\textbf{Surface Roughness} = +136.83078 - 5.42375 * v - 713.23967 * f + 22.34580 * d + 25.66667 * v * f + 885.35889 * f^2 - 5.44270 * d^2 - 30.88889 * v * (f)^2$$

Table 5 shows the analysis of variance produced by the used software for the remaining terms. The model is a quadratic and significant at 95% confidence. It is noted that only the depth of cut had a very little effect on the surface roughness, while the other terms of the predicted model had greater influence on the roughness. The lack of fit test indicates a good model.

Looking at the normal probability plot (Figure 4) or the surface roughness data, the residuals generally that falling on a straight line implying errors are normally distributed. Also, according to Figure 5 that shows the residuals versus predicted responses for surface roughness data, it is seen that no obvious patterns or unusual structure, implying models are accurate.

Figure 6 reveals the contour graph of cutting speed versus feed with surface roughness as a response, showing the cutting speed and feed interaction. It is clear that the increase in cutting speed up to 40 m/min generally led to a decrease in the surface roughness values at both lower and higher levels of feed. This reduction in roughness at higher speeds and was due to the higher negative influence of the model terms related to the feed (f), speed (v), squared depth of cut (d^2) and speed multiplied by squared feed ($v*f^2$), and that resulted in a smooth surface due to more likely higher induced cutting temperature and lower required cutting forces with increasing speed and less work material being removed, especially at lower feeds and cutting depths. But, increasing the cutting feed from 0.3 to 0.6 mm/rev at lower cutting speed of 20 m/min caused an increase in the surface roughness values. This increase at lower speeds was owing to the positive influence of the model terms associated with the depth of cut (d), squared feed (f^2) and speed multiplied by the feed (v*f), resulting in a rough machined surface due to the higher material removal caused by higher cutting forces and lower cutting temperature that normally produced, particularly at lower speeds.

In addition, according to the 3D surfaces shown in Figures 7-9 for surface roughness, cutting speed and feed at different depth of cuts (1.5, 2.0, and 2.5 mm, respectively), it can be seen that the depth of cut had a little influence on the surface roughness values.

Surface roughness and type of chip formed during cutting tests

The type of chip formed during the cutting process depends mainly on the work material conditions (ductile or brittle), material and tool geometry, cutting conditions (cutting speed, feed and to some extent depth of cut), temperature and friction at the chip-tool and work-tool interfaces [28]. Since the material used in this work is low carbon steel (ST 37.0) which is normally considered as a ductile material due to its lower carbon content and mechanical properties, especially the hardness and tensile strength, therefore, only a continuous type of chip was seen to form during all cutting tests of the present research. In other words, no discontinuous type of chip was observed to produce during these cutting tests, because this type of chip tends to be formed during cutting brittle materials, such as cast iron and cast brass.

Thus, the resulting surface roughness obtained during the cutting tests of this work can be interpreted in terms of the used cutting condition, stability of the built-up-edge (BUE) layer formation, friction and cutting forces, cutting temperature and tool wear [28]. According to Table 4, after turning the material over a cutting speed range (10-20 m/min) and at various feed rates and depth of cuts, the average surface roughness value increased from (18.05 µm at 10 m/min) to (28.5 µm at 20 m/min), and a continuous curled type of chip formed. The increase in roughness may be attributed to the effect of higher compressive cutting forces required to remove a higher volume of material, resulting in unstable BUE layers adhered to the tool flank and rake face. Also, during cutting, the particles or fragments embedded in the tool flank face will coarsen the machined surface.

While turning above the cutting speed (20 m/min) up to 40 m/min at different feed rates and depth of cuts, the average surface roughness value was found to decrease gradually up to (2.75 µm) at (40m/min), and a continuous curled type of chip also produced during cutting over this speed range. The decrease of the roughness could be more likely ascribed to the formation of stable BUE layers welded to the tool flank and rake faces (no BUE fragments or the absence of BUE particles) because of the rise of tool cutting temperature and moderate compressive cutting forces necessary for material removing, thus smoothen the machined surface.

When cutting tests conducted at a cutting speed (50 m/min), the average surface roughness value slightly increased up to (12.9 µm), as well as, a continuous (oxidized ribbon) type of chip formed, and this might be owing to the higher temperature effect (at higher cutting speed), causing the softening of both tool flank and rake faces, deteriorating the tool geometry (tool angles), and eventually resulting in higher tool wear. Finally, it was decided not to perform any cutting test at a cutting speed over (50 m/min) in order to avoid the tool damage by the catastrophic failure. For this reason, the cutting fluid was used during all cutting tests at various cutting conditions so as to prevent the effects of the friction and cutting temperature rise, and thus it will improve the surface finish of the machine surface when compared with the dry cutting operations.

Roundness error model

Similarly, the average responses obtained for roundness error were used in calculating the models of the response surface per response using the least-squares method. For roundness error measurements, a reduced cubic model in coded terms was analyzed with backwards elimination of insignificant coefficients at an exit threshold alpha = 0.1, followed by a stepwise elimination of some variables in order to achieve a significant model at 95% confidence. After the examination of analysis results, test no. 9 (run no.4) and test no.10 (run no.11) were ignored in the runs in order to perform a robust model and the analysis performed again. The terms removed wereA^2C, ABC, C (depth of cut), A^2B, A^2, B^2, AC, BC, and C^2, in addition to other terms that aliased by the stepwise elimination. So, the terms A, B and AB are only significant in the predicted model.

Table 6exhibits that the model (two-factor interaction) is significant at 95% confidence level, and that cutting speed and feed are significant factors as well as the interaction of speed and feed, but the depth of cut (term C) is not. The lack of fit test manifests a good model. The final predicted roundness error (equation) model in coded terms is:

Roundness Error =+20.39-7.25 *A +1.87*B -3.00* A * B

And, the final model in actual factors, indicating that the feed had the highest impact on the roundness error, is:

Roundness Error = + 9.51389 + 0.17500 * v + 72.50000 * f - 2.00000 * v * f

According to Figure 10 for the normal probability plot or the roundness error data, the residuals generally that falling on a straight line, implying errors are normally distributed. Also, Figure 11 illustrates the residuals versus predicted responses for roundness error data, it is seen that no obvious patterns or unusual structure, implying models are accurate.

Figure 12 shows the contour graph of cutting speed versus feed with roundness error as a response. Because the depth of cut had no important effect on the roundness error, only the two-factor interaction is revealed. It is seen when the cutting speed was increased up to 40 m/min at lower and higher levels of feed, the roundness error decreased due to the reduction of the surface roughness effect (i.e., formation of a smooth machined surface) at these cutting conditions. Whereas, the increase of feed from 0.3 to 0.6 mm/rev at lower cutting speed (20 m/min) resulted in an increase in the roundness error owing to the increase of the surface roughness influence (i.e., formation of a rough machined surface) during cutting at these conditions.

7. Conclusions

A quadratic prediction model for surface roughness and a two-factor interaction prediction model for roundness error, as a function of used cutting conditions (cutting speed, feed, and depth of cut) during wet turning low carbon steel, were developed at 95% confidence. These models (equations) showed that the depth of cut had a little effect on the surface roughness, but it had no influence on the roundness error, while the feed had the greatest impact on both responses. Also, the cutting speed and the interaction between speed and feed were effective terms in both models. Besides, the squared feed, squared depth of cut and the interaction between the cutting speed and squared feed in the predicted surface roughness model were found influential. Eventually, according to the all results obtained in the present work, the predicted models indicated that at higher cutting speed and different feed levels, both responses decreased, resulting in a smooth machined surface with lower roundness error. But, both models exhibited that at lower cutting speed and higher feeds, the surface roughness and roundness error increased, producing a rough machined surface with higher out of roundness error.

REFERENCES

[1[Lahidgji, B.,"Determining Deflection for Metal Turning Operations", *Journal of Industrial Technology*, 13, (2), pp. 21-23, 1997.

[2]Mitsui, K., "In-Process Sensors for Surface Roughness and Their Applications", *Precision Engineering*, 9, pp. 212-220, 1986.

[3] Gorlenko, O. A., "Assessment of Surface Roughness Parameters and Their Interdependence", *Precision Engineering*, 3:2, 1981.

[4] Hadi, Y. A., Vargese, S., and Ibrahim, A. A., " Effects of Machining parameters in Turning on Roundness Error of Machined Components", *International Journal of Materials Engineering and Technology*, vol.2, Issue 1, pp. 55-68, 2009

[5] Rahman, M., and Naranayan, V., and Venkatesh, V. C., "Optimization of Error-of-Roundness in turning Processes", *CIRP Annals-Manufacturing Technology*, vol.35, Issue 1, pp. 377-380, 1986.

[6] Cho, N. and Tu, J., "Roughness Modeling of Machined Parts for Tolerance Analysis", *PrecisionEngineering*, vol. 25, No.1, pp. 35-47, 2001.

[7] Kahng, C. H., Lord, H. W., and Davis, T. L., "The Effect of Chucking Methods on Roundness Error in Boring Process", *ASME, Journal of Engineering Industry*, Series B, vol.90, No.1, pp. 223-238, 1976.

[8] Gayler, J. F. W., and Shotbolt, C, R., "*Metrology for Engineers*", 5th Edition, Cassell & Co. Ltd., 1990.

[9] Lopez, P. J. N., Simao, J., Alvir, E. M. R., and Rincon, J. L., "Influence of the Machining Parameters on Workpiece Roundness Error during Turning Operations", *Material Science Forum, Advances inMaterials Processing Technologies*, vol. 526, pp. 127-132, 2006.

[10] Mukherjee, I., and Ray, P. K., "A Review of Optimization Techniques in Metal Cutting Processes", *Computers and Industrial Engineering*, vol.50, Issue 1, pp. 15-34, 2005.

[11] Aggarwal, A., and Singh, H., "Optimization Techniques- A retrospective and Literature Review", *Sadhana*, vol.30, Part 6, pp. 699-711, 2005.

[12] Montgomery, D. C., "*Design and Analysis of Experiments*", 5th Edition, John Wiley & Sons Inc., 2001.

[13] Wu, S. M., "Tool Life Testing by Response Surface Methodology", Part I and Part II, *Journal ofEngineering Industry*, pp. 105-116, 1964.

[14] Taraman, K., "Multi-Machining Output-Multi Independent Variable Turning Research by Response Surface Methodology", *International Journal of Production Research*, 12, pp. 232-245, 1974.

[15] Hassan, G. A., and Sulimon, S. M. A., "Experimental Modeling and Optimization of Turning Medium Carbon Steel", *International Journal of production Research*, 28, pp. 1057-1065, 1990.

[16] EI-Baradie, M. A., "Surface Roughness Model for Turning Grey Cast Iron (154 BHN), *Proc. Inst.Mech. Eng.*, 207, pp. 43-50, 1993.

[17] Choudhury, I. A., and EI-Baradie, M. A., “Surface Roughness Prediction in Turning of High Strength Steel by Factorial Design of Experiments”, *J. Mat. Proc. Technol.,* 67, pp. 55-61, 1997.

[18] Feng, C-X, “An Experimental Study of the Impact of Turning Parameters on Surface Roughness”, *Proceedings of the Industrial Engineering Research Conference*, Institute of Industrial Engineering, 2001.

[19] Noordin, M. Y., Venkatesh, V. C., Sharif, S., Elting, S., and Abdullah, A., “Application of Response surface Methodology in Describing the Performance of Coated Carbide Tools When Turning AISI 1045 Steel”, *Journal of Materials Processing Technology*, 145, pp. 46-58, 2004.

[20] Sahin, Y., and Motorcu, A. R., “Surface Roughness Prediction Model in Machining of Carbon Steel by PVD Coated Cutting Tools”, *American Journal of Applied Sciences*, I, (1), pp. 12-17, 2004.

[21] Sahin, Y., and Motorcu, A. R., “Surface Roughness Model for Machining Mild Steel with Coated Carbide Tool”, *Materials and Design*, vol.26, issue 4, pp. 321-326, 2205.

[22]Oktem, H., Erzurumlu, T., and Kutaran, H., “Application of Surface Response Methodology in the Optimization of Cutting Conditions for Surface Roughness”, *Journal of Materials Processing*, vol.170, 1-2, pp. 11-16, 2005.

[23] Caker, M. C., Ensarioglu, C., and Demirayak, I.,“ Mathematical Modeling of Surface Roughness for Evaluating the Effect of Cutting Parameters and Coating Material”, *Journal of Materials Processing Technology*, vol.209, Issue 1, pp. 102-109, 2009.

[24] Shahabi, H. H., andRatnam, M. M., “Prediction of Surface Roughness and Dimensional Deviation of Workpiece in Turning: A Machine Vision Approach”, *International Journal of Advanced Manufacturing Technology*, 48, pp. 213–226, 2010.

[25]Singh, H., and Kumar, P., “Mathematical Models of Tool Life and Surface Roughness for Turning Operation through Response Surface Methodology”, *Journal of Scientific and Industrial Research*, vol.66, pp. 220-226, 2007.

[26] Abhang L. B., and Hameedullah, M., “Statistical Modeling of Surface Roughness produced by Wet turning Using Soluble Oil-water Mixture Lubricant”, *Proc. of Int. Conf. on Advances in Mechanical Engineering*, 2010.

[27]Karin Kandananond, “Using the Response SurfaceMethod to Optimize the Turning Process of AISI 12L14 Steel”, *Advances in Mechanical Engineering*, vol. 2010, Article ID 362406, 6 pages

[28] Kalpinjian, S,, “*Manufacturing Processes for Engineering Materials*”, 3rd Edition, Addison Wesley Publishing Co., 1997.

Table 1: Chemical composition of the work material used

Element (%)	C	P	S	N
ST 37.0	Max 0.17	Max 0.04	Max 0.04	0.012

Table 2: Cutting Conditions to be used in experimentation with respective coding

Parameter	Symbol	Levels (Coding)				
		-2	-1	0	1	2
Speed (m/min)	v	10	20	30	40	50
Feed (mm/rev)	*f*	0.15	0.30	0.45	0.60	0.75
Depth of Cut (mm)	*d*	1.0	1.5	2.0	2.5	3.0

Table 3: Experimental design matrix used

Test Number	*Run Number*	Speed, v (m/min)		Feed, f (mm/rev)		Depth of Cut, d (mm)	
		Code	Value	Code	Value	Code	Value
1	2	-1	20	-1	0.3	-1	1.5
2	1	1	40	-1	0.3	-1	1.5
3	17	-1	20	1	0.6	-1	1.5
4	8	1	40	1	0.6	-1	1.5
5	5	-1	20	-1	0.3	1	2.5
6	7	1	40	-1	0.3	1	2.5
7	20	-1	20	1	0.6	1	2.5
8	11	1	40	1	0.6	1	2.5
9	13	-2	10	0	0.45	0	2
10	19	2	50	0	0.45	0	2
11	15	0	30	-2	0.15	0	2
12	10	0	30	2	0.75	0	2
13	16	0	30	0	0.45	-2	1
14	12	0	30	0	0.45	2	3
15	4	0	30	0	0.45	0	2
16	9	0	30	0	0.45	0	2
17	6	0	30	0	0.45	0	2
18	18	0	30	0	0.45	0	2
19	3	0	30	0	0.45	0	2
20	14	0	30	0	0.45	0	2

Table 4: Experimental design matrix used for cutting conditions in terms of actual factors with the average experimental values of surface roughness and roundness error.

Test No.	Run No.	Type of point	Cutting speed (m/min)	Feed rev/min	Depth of cut, mm	Average surface roughness (µm)	Average roundness error (µm)
1	2	Factorial	20.00	0.30	1.5	14.1	23
2	1	Factorial	40.00	0.30	1.50	5.75	16
3	17	Factorial	20.00	0.60	1.50	23.4	32
4	8	Factorial	40.00	0.60	1.50	2.85	10
5	5	Factorial	20.00	0.30	2.50	14.55	24
6	7	Factorial	40.00	0.30	2.50	2.75	14
7	20	Factorial	20.00	0.60	2.50	28.5	34
8	11	Factorial	40.00	0.60	2.50	3.3	15
9	13	Axial	10.00	0.45	2.00	18.05	13
10	19	Axial	50.00	0.45	2.00	12.9	10
11	15	Axial	30.00	0.15	2.00	4	18
12	10	Axial	30.00	0.75	2.00	17.05	26
13	16	Axial	30.00	0.45	1.00	8.4	15
14	12	Axial	30.00	0.45	3.00	9.2	20
15	4	Center	30.00	0.45	2.00	11.3	15
16	9	Center	30.00	0.45	2.00	16.05	19
17	6	Center	30.00	0.45	2.00	10	26
18	18	Center	30.00	0.45	2.00	15.3	17
19	3	Center	30.00	0.45	2.00	6.95	24
20	14	Center	30.00	0.45	2.00	16.02	19

Table 5: Analysis of variance (ANOVA) for response surface roughness quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	835.60	7	119.37	23.60	< 0.0001	**significant**
A-Cutting speed (v)	13.26	1	13.2	62.62	0.1337	
B-Feed (f)	138.06	1	138.0	627.29	0.0003	
C-Depth of cut (d)	1.32	1	1.32	0.26	0.6192	
AB	81.92	1	81.92	16.19	0.0020	
B^2	21.94	1	21.94	4.34	0.0614	
C^2	47.02	1	47.02	9.30	0.0111	
AB^2	193.21	1	193.21	38.19	< 0.0001	
Residual	55.64	11	5.06			
Lack of Fit	22.73	7	3.25	0.39	0.8662	**not significant**
Pure Error	32.9	1	48.23			
Cor Total	891.24	18				

Std. Dev.	2.257	R-Squared	0.9376
Mean	12.29	Adj R-Squared	0.8978
C.V. %	18.30	Pred R-Squared	0.8556
PRESS	128.66	Adeq Precision	16.068

Table 6: Analysis of variance (ANOVA) for response roundness error 2FI model.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	548.75	3	182.92	17.84	< 0.0001	**significant**
A-Cutting speed (v)	420.50	1	420.50	41.02	< 0.0001	
B-Feed (f)	56.25	1	56.25	5.49	0.0345	
AB	72.00	1	72.00	7.02	0.0190	
Residual	143.53	14	10.25			
Lack of Fit	55.53	9	6.17	0.35	0.9183	**not significant**
Pure Error	88.00	5	17.60			
Cor Total	692.28	17				

Std. Dev.	3.2	R-Squared	0.7927
Mean	20.39	Adj R-Squared	0.7482
C.V. %	15.70	Pred R-Squared	0.7201
PRESS	193.79	Adeq Precision	13.582

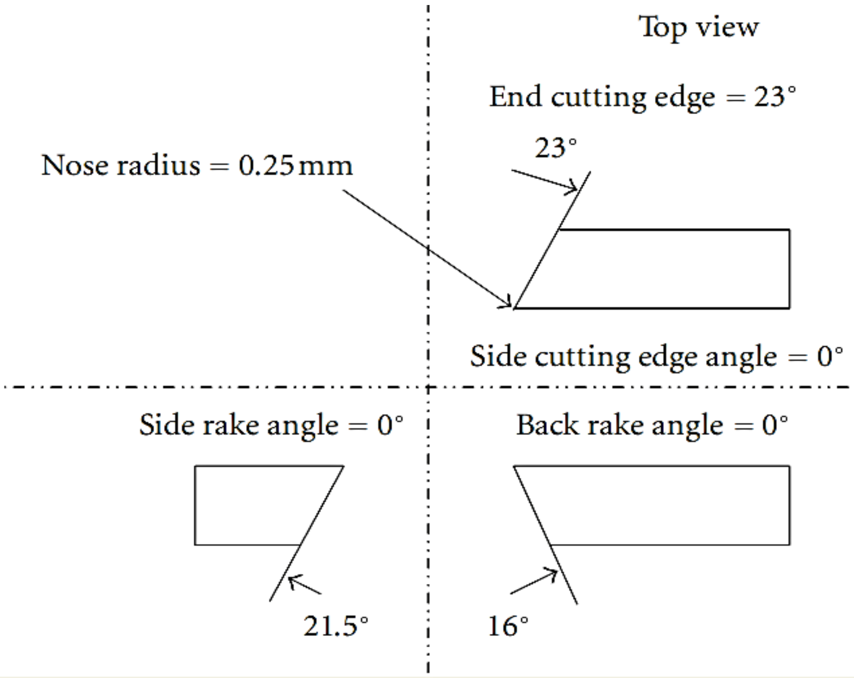

Figure 1: Cutting tool geometry.

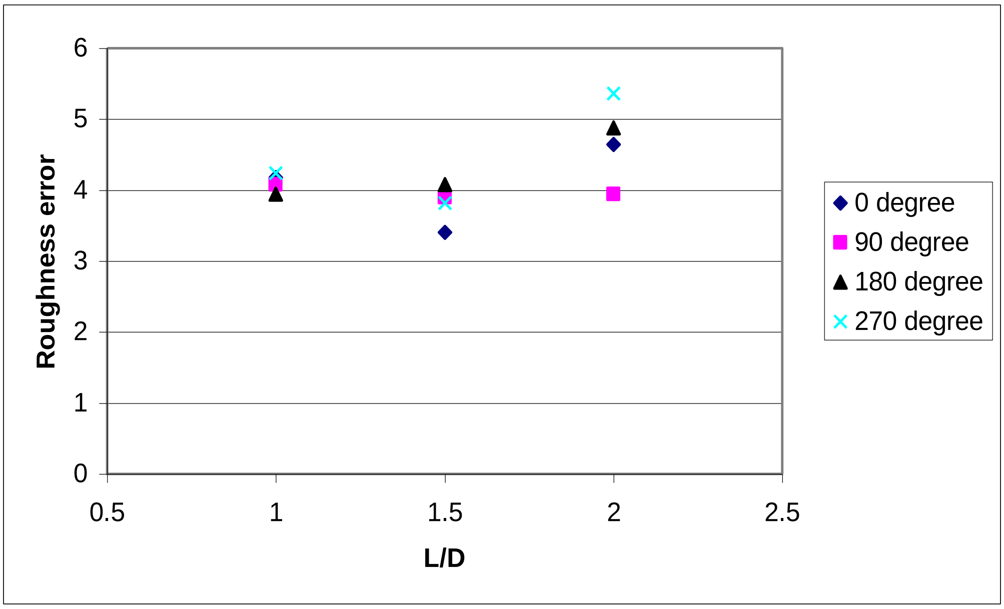

Figure 2: Effect of L/D ratio on surface roughness.

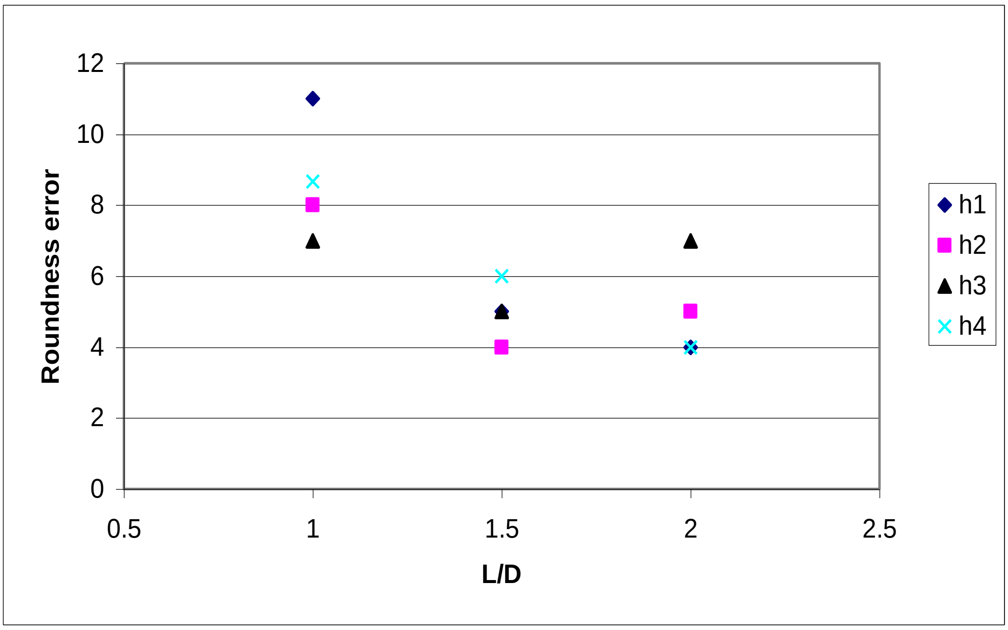

Figure 3: Effect of L/D ratio on roundness error

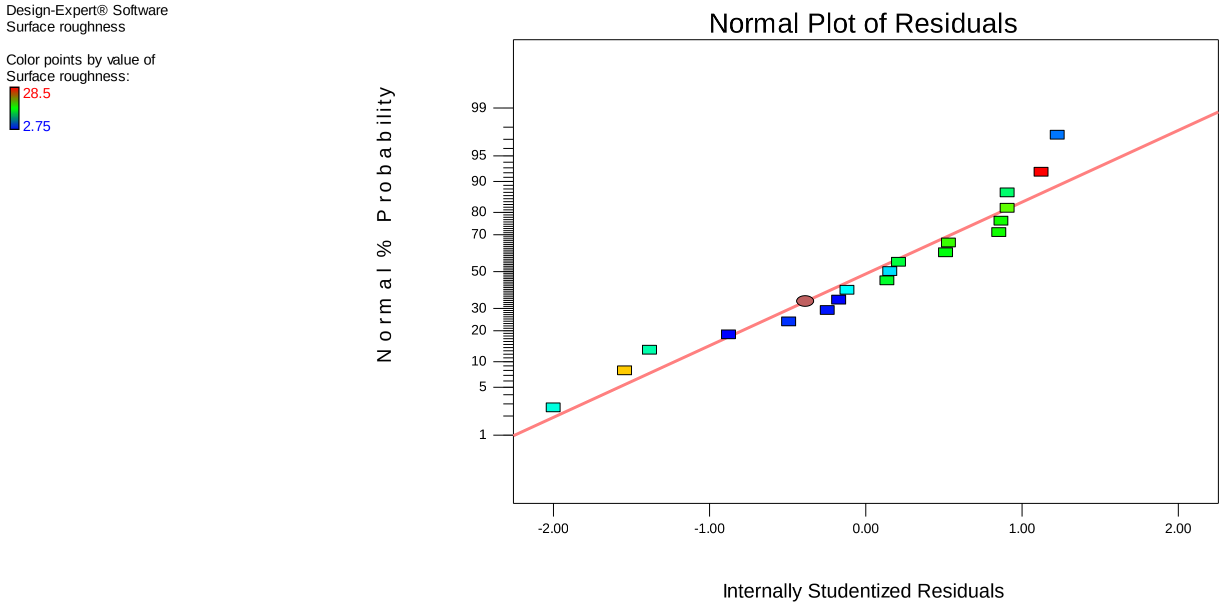

Figure 4: Normal probability plot of residuals for surface roughness.

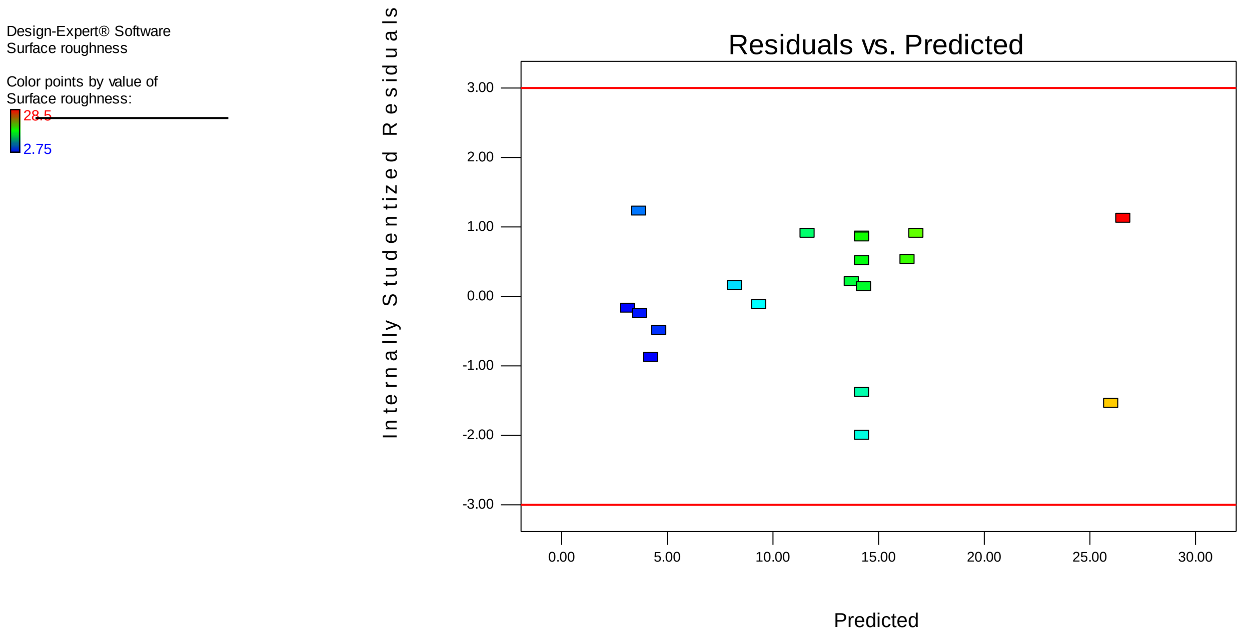

Figure 5: Residual versus predicted response for surface roughness.

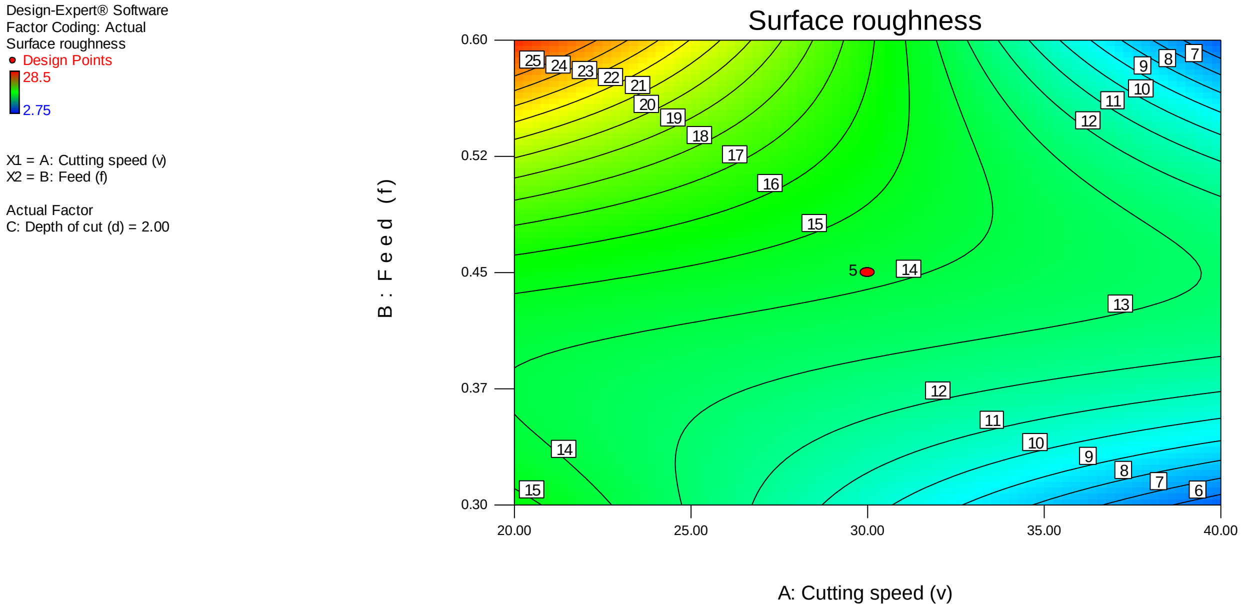

Figure 6: Contour graph of surface roughness as a function of speed and feed.

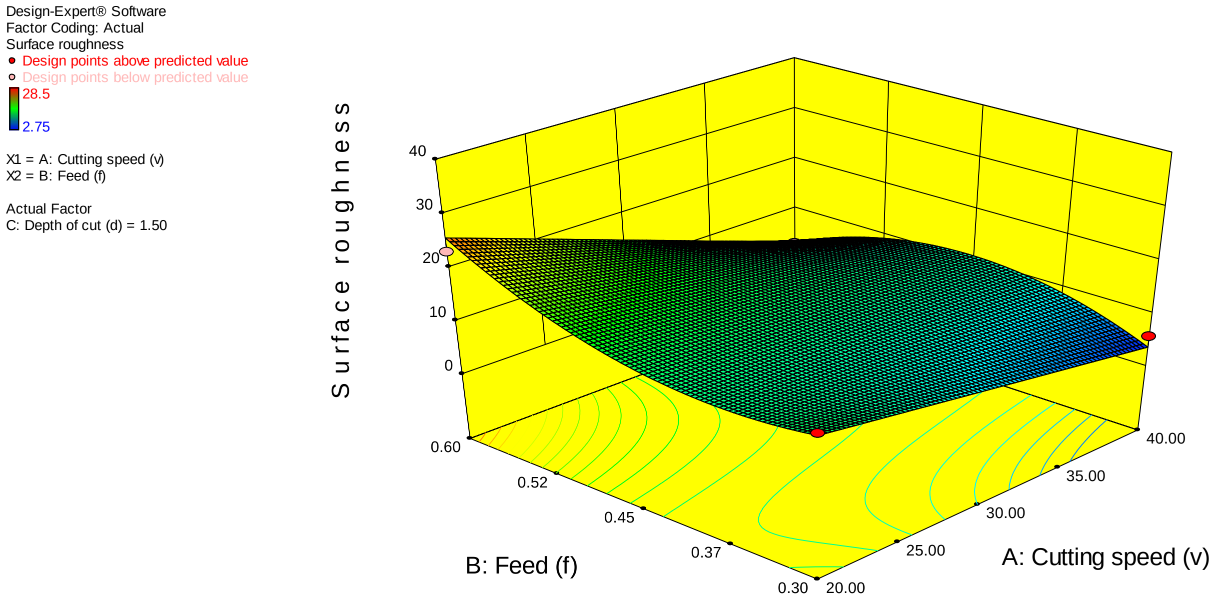

Figure 7: 3D surface at depth of cut 1.5 mm.

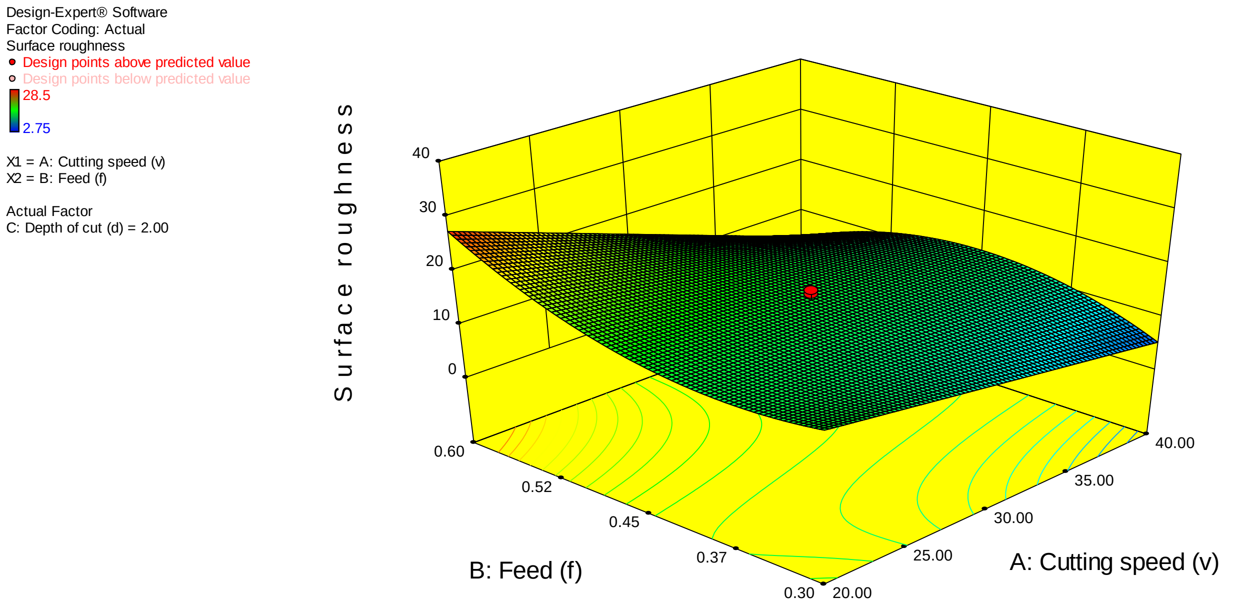

Figure 8: 3D surface at depth of cut 2.0 mm.

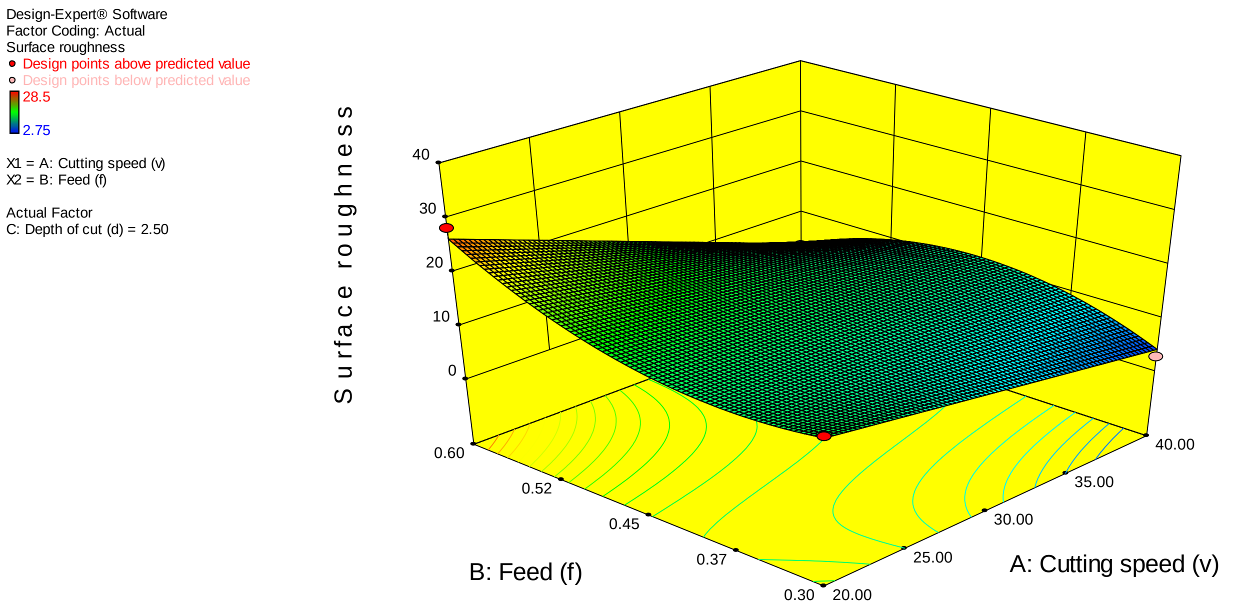

Figure 9:3D surface at depth of cut 2.5 mm.

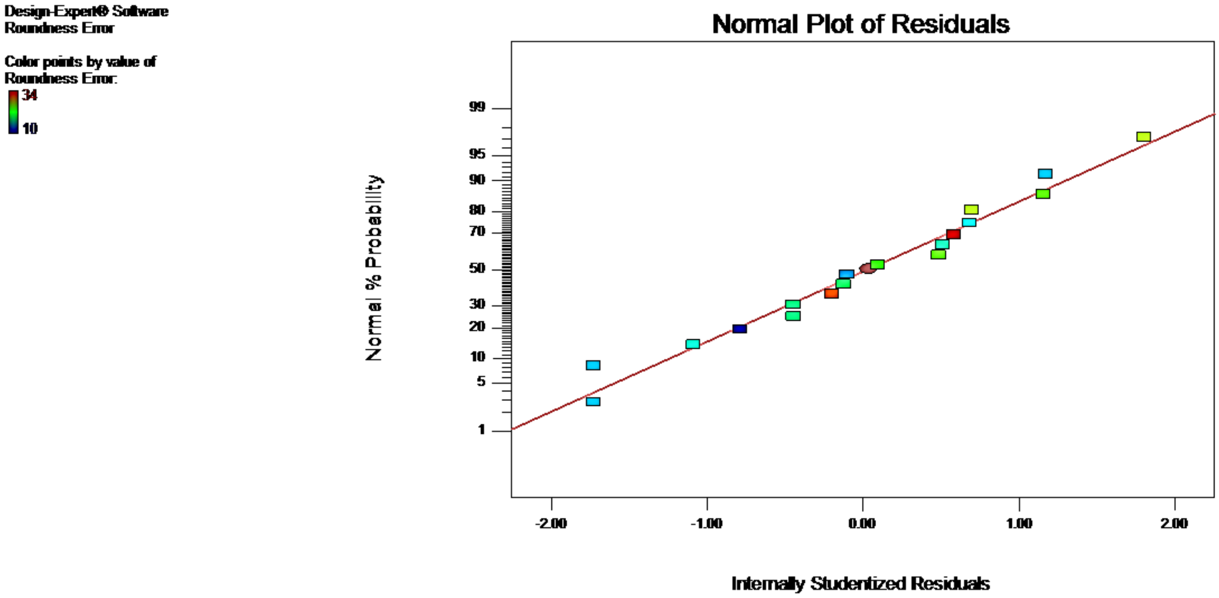

Figure 10: Normal probability plot of residuals for roundness error

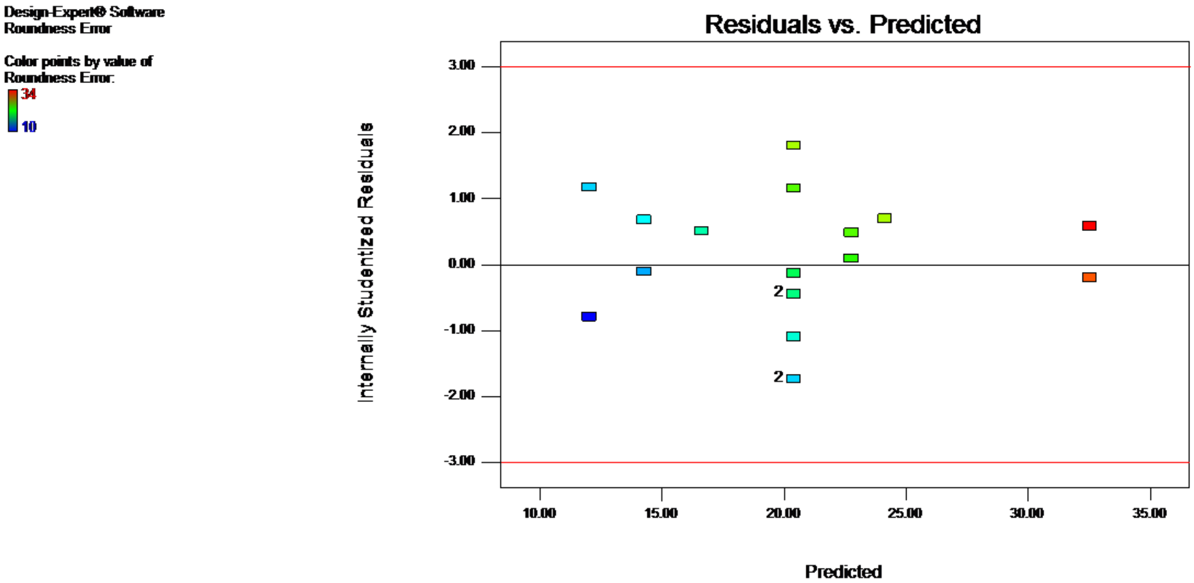

Figure 11: Residual versus predicted response for roundness error

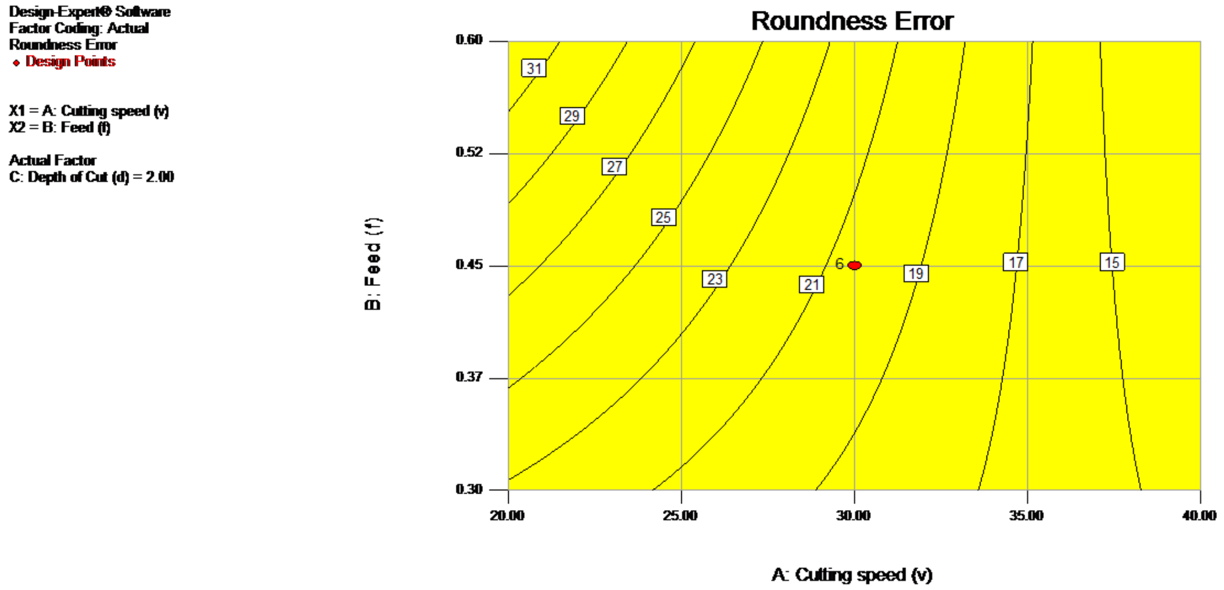

Figure 12: Contour graph of roundness error as a function of speed and feed.