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PRECISION TURNING EFFECT ON SURFACE PROFILE PARAMETERS AND FATIGUE LIFE

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ABSTRACT

The main objective of this paper is to investigate the effect of precision turning parameters; namely, cutting speed, feed rate, tool rake angle and tool nose radius on both surface profile parameters and fatigue life. A series of cutting tests were carried out using a computerized numerically controlled CNC turning machine. The response surface method (RSM) was used to minimize the number of experiments to be conducted without loss of accuracy for results. The experimental results reveal that the precision machining parameters effectively improve the surface characteristics and fatigue life. The highest fatigue life was obtained with a combination of a low speed, low tool nose radius, medium feed and medium tool rake angle. Also, high number of cycles to failure was obtained at the combination of high tool rake angle with high tool nose radius.

KEYWORDS: Fatigue Life, Precision Turning, Response Surface Methodology, Surface Profile Parameters

INTRODUCTION

Machining is the principal manufacturing process in the world today with some 10-15% of the value of all goods being attributed either directly or indirectly to in machining [1]. As technology advances and devices become smaller and/or more complex, the need for highly precise manufacturing processes is becoming increasingly important. A prime example of this is in die aerospace industry, which relies on components with exact dimensions to assemble and ensure proper operation of spacecraft, satellites, and even the international space station.

A number of innovative techniques for precision machining have been developed to enable the construction of these and other high-tech contrivances. In recent decade, intense international competition has focused the attention on manufacturers on automation as means to increase productivity and improve quality. To realize full automation in machining, computer numerically controlled (CNC) machine tools have been implemented. CNC machine tools require less operator input, provide greater improvements in productivity, and increase the quality of the machined part.

In recent researches, the hard turning, the high-speed machining, the precision turning, and the ultra-precision machining are the very important topics, as a result of the advanced technology of tool materials [2-15]. The main purpose of hard turning is to replace finishing processes such as grinding. This offers many possible benefits over a grinding process, such as lower equipment cost, shorter set-up time, reduced number of process steps, and better surface characteristics. Precision and ultra-precision cutting usually produce advanced components with not only a high dimensional accuracy but also a good surface integrity such as small surface roughness and residual stress. The cutting thickness is very small, only a few micrometer or less than one micrometer [6, 11].

The quality of the machined surfaces of many cylindrical parts plays a very important role in the performance. It improves fatigue strength, corrosion resistance and/or creep life. Surface roughness also affects several functional attributes of parts contact causing surface friction, wearing, ability of distributing and holding a lubricant and cooling.

The main objective of this work is to investigate, in a comprehensive manner, the effects and interacts of four main parameters controlled in a precision turning parameters such as cutting speed, feed rate, tool rake angle and tool nose radius on some surface parameters such as average roughness and cycles to failure (fatigue life) for medium carbon (1040) steel, which is one of the principle materials being utilized in manufacturing many parts, using CNC lathe machine. CNC lathe is widely used in a variety of manufacturing industries including the aerospace and automotive sectors.

EXPERIMENTAL WORK

Workpiece Material

In this study, medium carbon (1040) steel was used as a workpiece material. This material was selected because of its importance in industry and being the material of many engineering components. The chemical composition in weight percent is given in Table 1.

Table 1: Chemical Composition of Medium Carbon (1040) Steel

Material	**Medium Carbon(1040) Steel**				
Element	Mo	Cr	Mn	Si	C
Weight%	0.2	1.1	0.7	0.3	0.41

Workpiece Preparation

The material was received in the form of bars having external diameter of 12mm. Workpieces were prepared to the required dimensions that shown in Figure1.

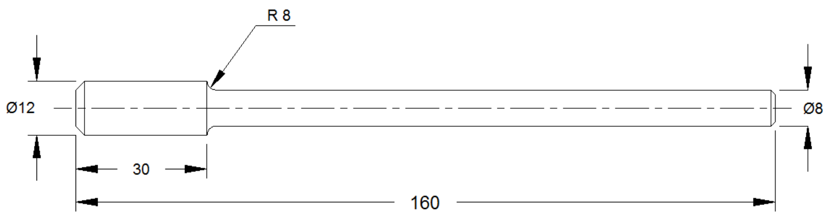


Figure 1: Workpiece Geometry

Machining Conditions

In this work, a series of precision turning test were conducted under lubricated conditions on a CNC Machine. Only four precision parameters were chosen, namely; cutting speed, feed, tool rake angle and tool nose radius. Other parameters such as, depth of cut and inclination angle were held constant throughout the work. The cutting tool used was cemented carbide inserts with different tool rake angle and different tool nose radius. The precision turning process parameters along with their ranges are given in Table 2.

Table 2: Experimental Parameters and Levels

	Levels				
	-2	**-1**	**0**	**1**	**2**
Cutting speed, m/min, **(X_1)**	25	37	49	61	73
Feed, µm/rev, **(X_2)**	50	150	250	350	450
Tool rake angle, degree, **(X_3)**	0	5	7	10	11
Tool nose radius, mm, **(X_4)**	0.2	0.4	0.6	0.8	1
Depth of cut, µm	**100**				
Cutting conditions	**Lubricated, soluble oil**				

Experimental Design and Analysis

The main objective of this work is to investigate the effect of the above stated parameters of precision turning parameters on surface roughness and fatigue life. Therefore, a simple and adequate experimental design, response surface methodology (RSM), with the Box and Hunter method [16] was found to be suitable for this study. (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which output or response influenced by several variables and the goal is to find the correlation between the response and the variables. It can be used for optimizing the response. It is an empirical modeling technique devoted to the evaluation of relations existing between a group of controlled experimental factors and the observed results of one or more selected criteria. A detailed description of this method is presented elsewhere [17].

In this study, each parameter has five levels selected from practice, as shown in Table 2. According to a central composite second-order rotatable design with four independent variables, 31 experiments were conducted with the combination of values that are shown in Table 3 which summarize the precision turning conditions and their coded levels. The values of the levels of each turning parameter used in this work were coded to simplify the experimental arrangement.

Measurements

Once the experiments were done, the surface profile parameters of the specimens were then measured. The portable Surtronic 25 device (Taylor Hobson) was used for the measurements. In order to reduce human errors during the measurement, the reading was taken for three times at different points. The process was repeated to all specimens. The fatigue testing machine used in this work was a single cantilever rotating bending model. Fatigue tests were carried out at room temperature with constant frequency. A sinusoidal cyclic load with a stress ratio R=-1 (minimum load/maximum load) was applied throughout the experiment. Each specimen was griped using the chuck at one end while the load is applied on the other end. The load is applied just after the specimen started to rotate. Once the specimen was broken, the shut sensor stopped the machine automatically. The number of cycles to failure was then counted and displayed on the screen of the machine.

Table 3: Experimental Design Matrix and Results

No	Cutting Speed, m/min		Feed, mm/rev		Rake Angle, Deg.		Nose Radius, mm		Surface Parameters				Fatigue Life
	Code, X1	Act	Code, X2	Act	Code, X3	Act	Code, X4	Act	Ra (µm)	Ry (µm)	Rz (µm)	Rq (µm)	FL
1	-1	1500	-1	150	-1	5	-1	0.4	0.45	2.42	1.52	0.58	6680
2	1	2500	-1	150	-1	5	-1	0.4	0.70	3.16	1.95	0.81	3730
3	-1	1500	1	350	-1	5	-1	0.4	0.61	3.60	2.26	0.64	5960
4	1	2500	1	350	-1	5	-1	0.4	0.85	3.23	2.41	0.76	4110
5	-1	1500	-1	150	1	10	-1	0.4	0.57	3.20	2.21	0.83	3990
6	1	2500	-1	150	1	10	-1	0.4	0.67	3.50	2.25	0.85	2590
7	-1	1500	1	350	1	10	-1	0.4	0.60	3.50	2.24	0.68	2540
8	1	2500	1	350	1	10	-1	0.4	0.60	2.64	1.95	0.68	2540
9	-1	1500	-1	150	-1	5	1	0.8	0.47	2.45	1.75	0.59	3000
10	1	2500	-1	150	-1	5	1	0.8	0.55	4.11	3.33	0.90	2500
11	-1	1500	1	350	-1	5	1	0.8	0.54	2.60	1.81	0.77	3370
12	1	2500	1	350	-1	5	1	0.8	0.73	3.33	3.12	1.04	3460
13	-1	1500	-1	150	1	10	1	0.8	0.66	3.40	2.40	0.75	5400
14	1	2500	-1	150	1	10	1	0.8	0.59	4.09	2.88	0.80	5800
15	-1	1500	1	350	1	10	1	0.8	0.61	2.65	1.93	0.75	4550
16	1	2500	1	350	1	10	1	0.8	0.55	2.54	2.19	0.75	5650
17	-2	1000	0	250	0	7	0	0.6	0.55	2.73	1.93	0.69	4510
18	2	3000	0	250	0	7	0	0.6	0.75	3.40	2.87	0.95	3260

Table 3: Contd.,

19	0	2000	-2	50	0	7	0	0.6	0.43	2.98	1.98	0.65	4750
20	0	2000	2	450	0	7	0	0.6	0.48	2.42	1.83	0.62	4950
21	0	2000	0	250	-2	0	0	0.6	0.50	2.80	1.75	0.65	3390
22	0	2000	0	250	2	11	0	0.6	0.51	2.86	1.80	0.65	3820
23	0	2000	0	250	0	7	-2	0.2	0.80	3.40	2.24	0.82	4440
24	0	2000	0	250	0	7	2	1	0.78	3.34	2.87	0.91	4520
25	0	2000	0	250	0	7	0	0.6	0.61	2.80	2.22	0.80	4680
26	0	2000	0	250	0	7	0	0.6	0.60	2.85	2.20	0.78	4630
27	0	2000	0	250	0	7	0	0.6	0.57	2.92	2.30	0.81	4140
28	0	2000	0	250	0	7	0	0.6	0.54	2.70	2.10	0.76	4510
29	0	2000	0	250	0	7	0	0.6	0.56	2.64	2.34	0.76	4470
30	0	2000	0	250	0	7	0	0.6	0.54	2.62	2.11	0.77	4330
31	0	2000	0	250	0	7	0	0.6	0.52	2.80	2.21	0.76	4460

MODELS, RESULTS AND DISCUSSIONS

Table 3 shows the arrangement and the results of the 31 experiments that carried in this work based on the central composite second-order rotatable design. These results are used to deduce the mathematical models which is one of the main objectives of this work.

Mathematical Models

This section presents a study of the development of response models for precision turning in terms of cutting speed (X_1), feed rate (X_2), tool rake angle (X_3) and tool nose radius(X_4). Using the results presented in Table 3 the response surface for surface profile parameters (Ra, Rq, Ry, Rz) and cycles to failure as functions of the four parameters used in this work are deduced as the following models:

$$\mathbf{Ra = 0.56286 + 0.04708\, X_1 + 0.02208\, X_2 - 0.00125\, X_3 - 0.01625\, X_4 + 0.02335\, X_1^2 - 0.02540\, X_2^2 - 0.01290\, X_3^2 + 0.05835\, X_4^2 + 0.00062\, X_1X_2 - 0.04937\, X_1X_3 - 0.02812\, X_1X_4 - 0.04313\, X_2X_3 - 0.00688\, X_2X_4 + 0.01812\, X_3X_4}$$

$$\mathbf{Ry = 2.7614 + 0.1717\, X_1 - 0.1400\, X_2 + 0.0308\, X_3 - 0.0083\, X_4 + 0.1026\, X_1^2 + 0.0113\, X_2^2 + 0.0438\, X_3^2 + 0.1788\, X_4^2 - 0.25000\, X_1X_2 - 0.1712\, X_1X_3 + 0.1975\, X_1X_4 - 0.2175\, X_2X_3 - 0.2263\, X_2X_4 - 0.0150\, X_3X_4}$$

$$\mathbf{Ry = 2.0986 + 0.2433\, X_1 - 0.0283\, X_2 + 0.0003\, X_3 + 0.1617\, X_4 + 0.0926\, X_1^2 - 0.0311\, X_2^2 - 0.0636\, X_3^2 + 0.1314\, X_4^2 - 0.0688\, X_1X_2 - 0.1863\, X_1X_3 + 0.2063\, X_1X_4 - 0.1550\, X_2X_3 - 0.1400\, X_2X_4 - 0.0700\, X_3X_4}$$

$$\mathbf{Rq = 0.77714 + 0.06333\, X_1 - 0.001470\, X_2 - 0.0001\, X_3 + 0.02917\, X_4 + 0.01384\, X_1^2 - 0.03241\, X_2^2 - 0.02866\, X_3^2 + 0.02509\, X_4^2 - 0.01375\, X_1X_2 - 0.05375\, X_1X_3 + 0.01625\, X_1X_4 - 0.04375\, X_2X_3 + 0.03625\, X_2X_4 - 0.03125\, X_3X_4}$$

A model for fatigue life is deduced as:

$$\mathbf{FL = 4460.0 - 317.1\, X_1 - 46.2\, X_2 + 46.3\, X_3 + 72.9\, X_4 - 158.4\, X_1^2 + 82.8\, X_2^2 - 228.4\, X_3^2 - 9.7\, X_4^2 + 236.9\, X_1X_2 + 331.9\, X_1X_3 + 455.6\, X_1X_4 - 218.1\, X_2X_3 + 135.6\, X_2X_4 + 1118.1\, X_3X_4}$$

To check the adequacy of the models, the F-ratio test was carried out and the results are presented in Table 4. It can easily be noted that the value of each of the linear, the square and the interaction presented in that Table is larger than the standard F-ratio value. Also, the lack of fit is smaller than that given in the standard F- ratio value. Therefore, the obtained regression equations have a good fit to the experimental results.

RESULTS AND DISCUSSIONS

Figures (2a : 2f) show, as an example, three-dimensional curves for the effect of various combination of precision turning parameters (cutting speed, feed rate, tool rake angle and tool nose radius) on average surface profile parameters for medium carbon(1040)steel workpieces that were machined under lubricated conditions. The graphs were constructed from the experimental results using response surface methodology (RSM) and the above equations of (Ra, Rq, Ry, and Rz, and FL). It is worth mentioning that each curve represents the effects of two input parameters while the other two parameters were kept constant at level 0 (see Tables 2 and 3).

Effect of Cutting Parameters on Surface Roughness

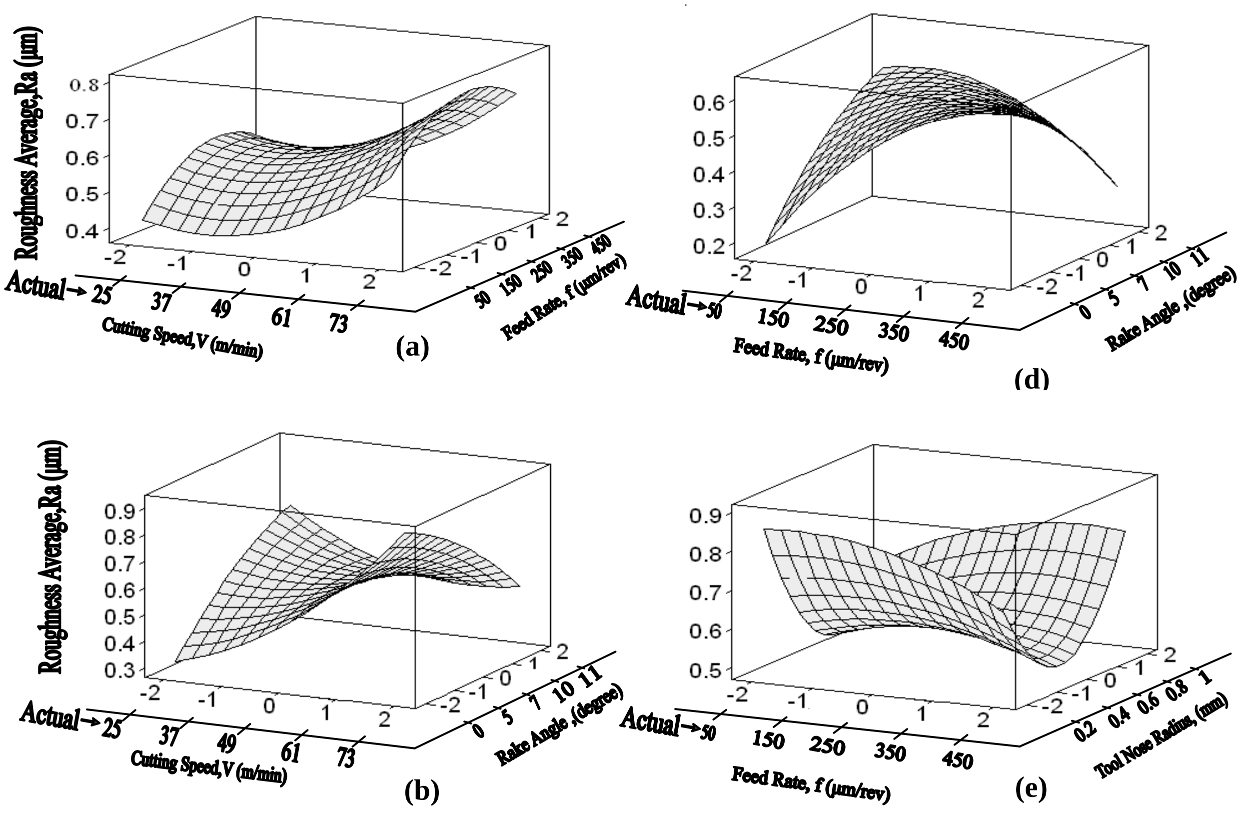
The precision turning results will be discussed in terms of each of the precision turning parameters. The effect of cutting speed on average roughness at various feeds, tool rake angle and tool nose radius can be assessed from Figures 2-a, 2-b, and 2-c, respectively. The results shown in Figure 2-a reveal that for a given feed, the surface average roughness increases gradually with an increase in cutting speed. It is believed that at low chip thickness, in precision machining, the built-up edge (BUE) begins to form at high speed. It can be seen from Figure 2-b that there is an interaction between cutting speed and tool rake angle. This means that the effect of cutting speed on the surface average roughness is not the same for all values of feed rates. It can be seen that at low tool rake angle, an increase in cutting speed leads to an increase in average roughness whereas at high tool rake angle the average surface roughness decreases gradually with an increase in cutting speed as a result of decreasing in friction coefficients at high speeds with increasing the tool rake angle.The effect of cutting speed on the average surface roughness for different tool nose radius is shown in Figure 2-c. It can be seen that at low tool nose radius, an increase in cutting speed leads to a slightly increase in the surface average roughness whereas at high tool nose radius, as the cutting speed increases the surface average roughness deceases first till it reaches a minimum value. With a further increase in cutting speed, surface average roughness begins to increase gradually reaching a maximum value at the highest speed used in this work.

Table 4: F-Test for the Surface Profile Parameters and Fatigue Life

Source	Sum of Squares	Degree of Freedom	Mean Square	F -Ratio
Ra				
Regression	0.306225	14	0.021873	22.60
Linear	0.071283	4	0.017821	18.41
Square	0.147504	4	0.036876	38.10
Interaction	0.087438	6	0.014573	15.06
Residual Error	0.015485	16	0.000968	
Lack-of-Fit	0.008942	10	0.000894	0.82
Pure Error	0.006543	6	0.001090	
Total	**0.321710**	**30**		
Rq				
Regression	0.322757	14	0.023054	41.71
Linear	0.117100	4	0.029275	52.97
Square	0.084907	4	0.021227	38.41
Interaction	0.120750	6	0.020125	36.41
Residual Error	0.008843	16	0.000553	
Lack-of-Fit	0.006300	10	0.000630	0.325
Pure Error	0.002543	6	0.000424	
Total	**0.33160**	**30**		

Table 4: Contd.,

Ry				
Regression	6.00804	14	0.42915	24.09
Linear	1.20215	4	0.30054	16.87
Square	1.13304	4	0.28326	15.90
Interaction	3.67285	6	0.61214	34.36
Residual Error	0.28504	16	0.01782	
Lack-of-Fit	0.21056	10	0.02106	1.70
Pure Error	0.07449	6	0.01241	
Total	**6.29308**	**30**		
Rz				
Regression	5.01049	14	0.357892	24.65
Linear	2.06760	4	0.516900	35.61
Square	0.85521	4	0.213803	14.73
Interaction	2.08768	6	0.347946	23.97
Residual Error	0.23227	16	0.014517	
Lack-of-Fit	0.18498	10	0.018498	2.35
Pure Error	0.04729	6	0.007881	
Total	**5.24275**	**30**		
FL				
Regression	32125197	14	2294657	48.36
Linear	2643283	4	660821	13.93
Square	2441576	4	610394	12.86
Interaction	27040338	6	4506723	94.97
Residual Error	759242	16	47453	
Lack-of-Fit	560042	10	56004	1.687
Pure Error	199200	6	33200	
Total	**32884439**	**30**		
The standard valued of F-ratio for the significance level a=0.01 and degrees of freedom 4 and 16 is $F_{0.01\,(4,16)} = 4.8$, at degree of freedom 6 and 16 $F_{0.01(6,16)} = 4.2$, and at degree of freedom 10 and 6 is $F_{0.01\,(10,6)} = 7.9$				



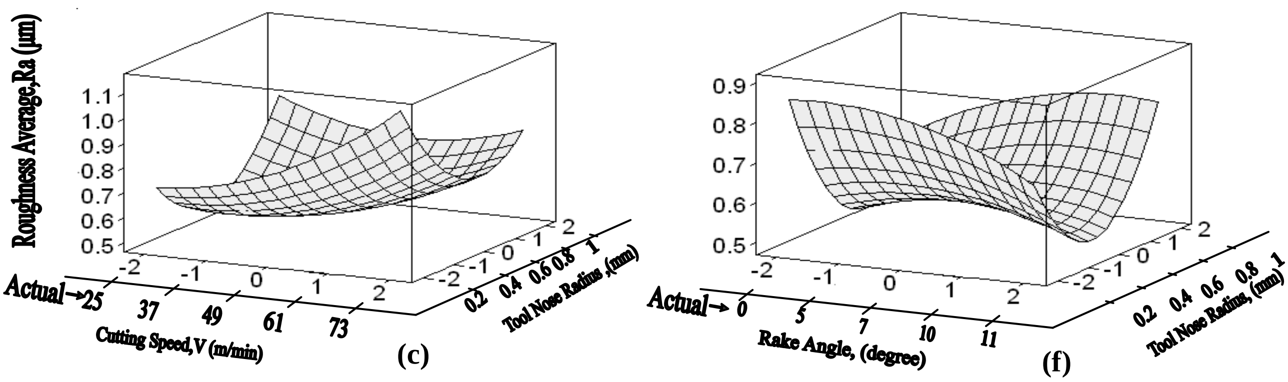


Figure 2: Effects of Different Precision Turning Parameters on Average Surface Roughness

The formation of built up edge in precision turning may be occur at high speed in the case of lubricated condition. At low cutting speed the lubrication action of the fluid is significant because there is sufficient time for the fluid to penetrate into the chip-tool interface that leads to a reduction in friction coefficient which, in turn, causes an increase in the shear angle, a reduction in chip thickness and chip-tool contact length and hence a reduction in surface roughness [18]. By increasing the cutting speed, the lubrication action of the cutting fluid is greatly reduced. This is undoubtedly due to the shorter time available for the lubricant to penetrate into chip-tool interface. Hence, surface average roughness is higher than that at lower speeds.

The effect of feed rate on the average roughness for different cutting speed is shown in Figure 2-a. It can be seen that for a given cutting speed, an increase in feed causes first an increase in average roughness till it reaches a maximum value. With a further increase in feed, surface average roughness begins to decrease gradually reaching a minimum value. It can be seen form Figure 2-d that there is an interaction between feed and tool rake angle. At low tool rake angle, an increase in feed leads to an increase in surface roughness whereas at high tool rake angle the surface average roughness gradually decrease with an increase in feed rate as a result of decreasing in the friction coefficient at this condition. It can be clearly seen that the best result was obtained using low feed with low tool rake angle and medium cutting speed using 0.6mm tool nose radius. Figure 2-e shows the effect of feed for different tool nose radius. It can be seen that there in an interaction between feed and tool rake angle. The best result was obtained using low feed with the medium value of tool nose radius, tool rake angle and cutting speed.

Figures 2-b, 2-d, and 2-f show the effect of tool rake angle on surface roughness for different speed, feed and tool nose radius, respectively. The results reveal that tool rake angle interact with speed, feed and tool nose radius. This means that the effect of tool rake angle for different values of cutting speed, feed and tool nose radius in not the same. It can be seen that at low speed or low feed the surface average roughness increases with an increase in tool rake angle whereas at high speed or feed, an increase in tool rake angle leads to a considerable reduction in surface roughness. The lowest value of average surface roughness (high surface finish) can be obtained with the combination of lowest tool rake angle with the low value of cutting speed and/or the low value of feed with medium tool nose radius. The reason for that may be as a result of decreasing the friction coefficient which slightly decreases both normal and friction cutting in precision machining.

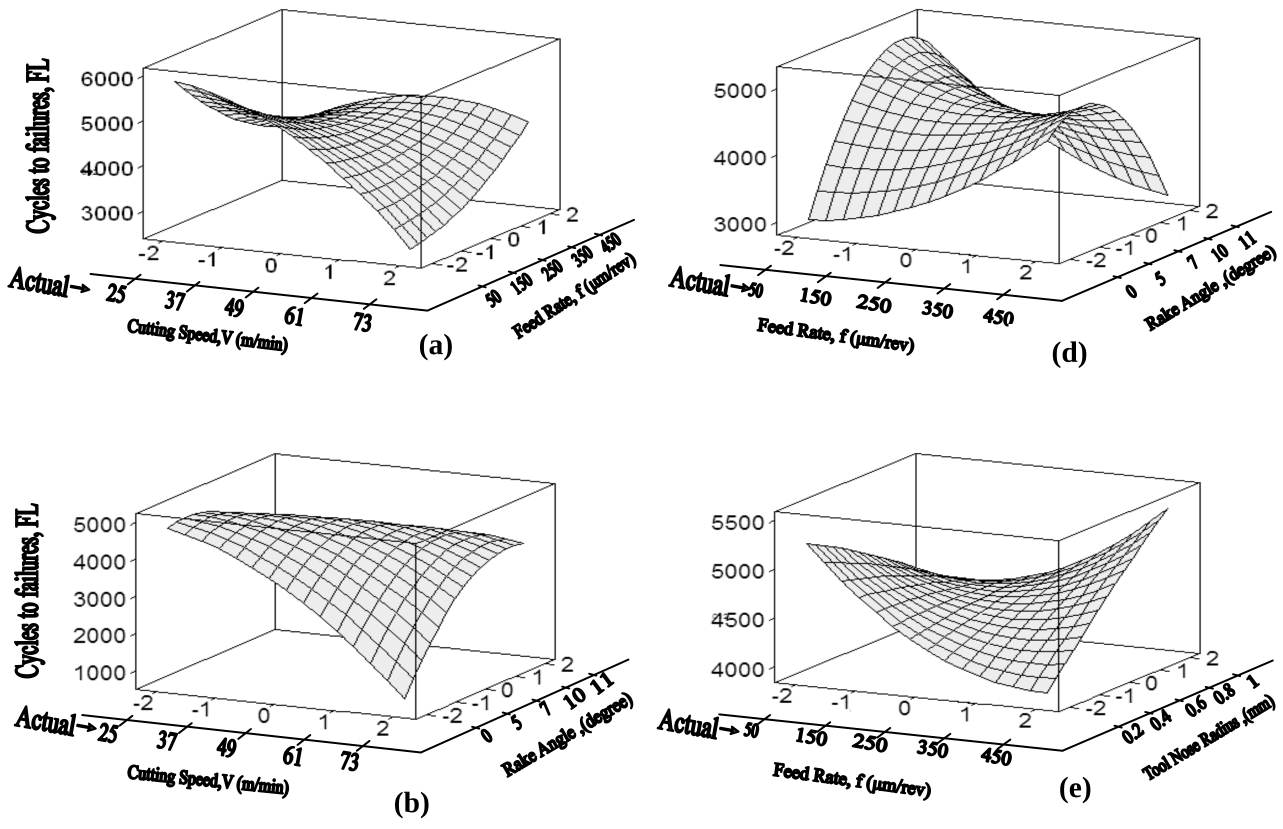
The effects of tool nose radius on surface average roughness for different speeds, feeds and tool rake angles can be assessed from Figures 2-c, 2-e and 2-f, respectively. The results of these figures reveal that for a given speed, feed and tool rake angle as the tool nose radius increases the surface average roughness decreases first till it reaches a minimum value (at tool nose radius of 0.6mm). With a further increase in tool nose radius, surface average roughness begins to increase gradually reaching a maximum value at the highest tool nose radius used. It is believed that increasing tool nose radius more than 0.6mm causes a slightly increase in the component of the resultant tool force as a result of increasing the contact area between tool and workpiece. Therefore, an increase in the thrust force component of the resultant tool force will increase the surface average roughness.

Effect of Precision Turning Parameters on Fatigue Life

Using the proposed model that was obtained by the RSM method, the relationship between the fatigue lives (cycles to failure) and the precision turning parameters is shown in Figure 3.

Figures 3-a, 3-b and 3-c show the effects of cutting speed on the fatigue life of machined surfaces at various feeds, tool rake angles and tool nose radius, respectively. It can be seen from these figures that there are three interactions; the first is between cutting speed and feed as shown in Figure 2-a. At low feeds, an increase in cutting speed leads to a considerable decrease in the fatigue life (cycles to failure). However, at high feeds, an increase in cutting speed results in a slight increase in the fatigue life.

The second interaction is between cutting speed and tool rake angle. The third interaction is between cutting speed and tool nose radius. The trend of the results is the same as the interaction between cutting speed and feeds. At low tool rake angle or low tool nose radius, a considerable decrease in fatigue life is obtained as cutting speed increases. However, at high tool rake angle or high tool nose radius, the fatigue life slightly increases with an increase in cutting speed. The results reveal that fatigue life significantly depends upon machined surface roughness which can reduce or enhance the crack initiation period [19].



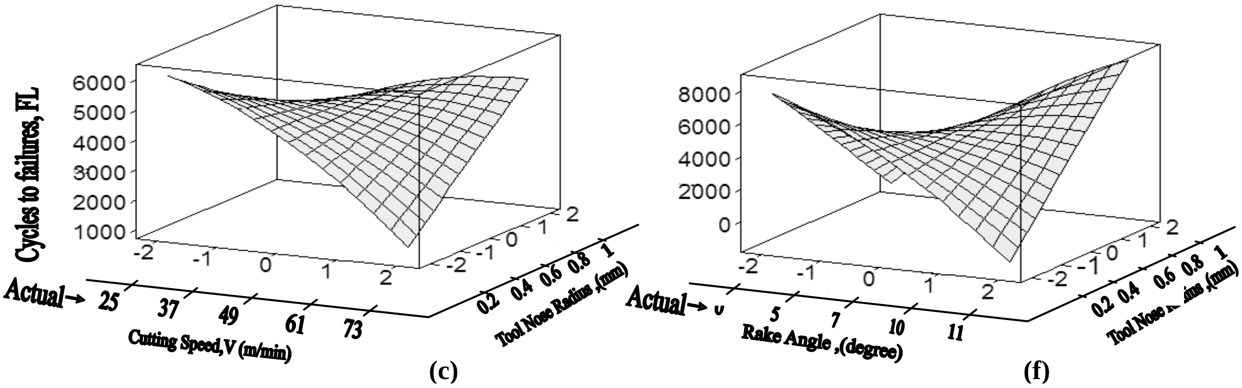


Figure 3: Effect of Precision Turning Parameters on Cycles to Failure (Fatigue Life)

The effect of feed on the fatigue life for different tool rake angle and tool nose radius can be assessed in Figures 3-d and 3-e, respectively. Figure 3-d shows an interaction between feed and tool rake angle. It can be seen that at low tool rake angle an increase in feed leads to an increase in fatigue life whereas at high tool rake angle, the cycles to failure decreases gradually with an increase in feed as a result of increasing in machined surface roughness (see Figure 2-d) which enhance the crack initiation period. Figure 3-e shows another interaction between feed and tool nose radius. An increase in feed at low tool nose radius increases the fatigue life whereas an increase in feed at high tool rake angle decreases the fatigue life. The best result can be obtained either at low feed and low tool nose radius or at high feed with high tool nose radius. It is believed that the increase in the tool nose radius within the range used in this work causes an increase in the amount of surface deformation as the tool passes along the surface of the workpiece. This will lead to an increase in the fatigue life as a result of increasing in surface quality, compressive residual stress and the homogeneity of surface layers, which in turn, leads to an increase in the number of cycles (the fatigue life).

Figure 3-f shows another interaction between tool rake angle and tool nose radius. At low tool nose radius, the cycles to failure decreases considerably as the tool rake angle increased whereas the cycles to failure considerably increases with an increase in tool rake angle at medium speed and feed. The highest value of cycles to failure was obtained at the combination of high tool rake angle with high tool nose radius. This may be due to the high pressure between the large nose radius and the workpiece, which in turn, leads to an increase in the thermal softening and then decreasing workpiece resistance to deformation resulting in a high surface quality.

It should be pointed out here that in precision machining, the machine, cutting tool, and structural system have very complicated dynamic characteristics and much work should be carried out in trying to understand the mechanics of forming the BUE and chatter. This will provide designers with the information to improve the dynamic characteristics of machine tools.

CONCLUSIONS

Based on the analysis of experimental results, the following conclusions can be drawn:

- Second-order surface profile parameters prediction models have been developed. Analysis of variance has indicated that these models are adequate for the obtained experimental results.
- For a given feed rate, the surface average roughness increases gradually with an increase in cutting speed.
- Feed rate interacts with both tool rake angle and tool nose radius. The best result of surface roughness was obtained using low feed with medium values of tool nose radius, tool rake angle and cutting speed.

- The results reveal that fatigue life significantly depends upon machined surface roughness which can reduce or enhance the crack initiation period.
- Cutting speed interacts with feed, tool rake angle and tool nose radius in the case of studying the precision turning parameters on fatigue of life.
- The highest fatigue life was obtained with a combination of a low speed, low tool nose radius, medium feed and medium tool rake angle. Also, high value of cycles to failure was obtained at the combination of high tool rake angle with high tool nose radius
- Much work should be carried out in the field of precision machining in trying to understand the mechanics of forming the BUE and chatter in attempting to provide designers with the information to improve the dynamic characteristics of machine tools.

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