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Influence of Cutter Width on Surface Roughness and Cutter Run Out During Horizontal Milling Operation

Dr. Saad Kareem Sather* & Mohammad Naeem Houshi*

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Abstract

This work focuses on studying the effect of cutter width on the surface roughness and cutter run out during horizontal milling operation, since the contact width in milling operations depends on the cutter geometry, especially (cutter diameter and width). So, three types of helical plain cutters with different widths are taken, (40,63,80mm), used in horizontal milling , when other cutter geometry parameters are constant. As for workpiece material, it was from (structural steel (1.0402)) according to (DIN:C22) specifications, with different cutting conditions (spindle speed, feed rate, and depth of cut) for each cutter, results show that milling cutter, which has larger width (80mm), gives large surface roughness and cutter runout compared with other two types. The results show that the surface roughness and cutter runout decrease with the increase of spindle speed under constant feed rate and depth of cut. While surface roughness and cutter runout increase with increase of feed rate for constant spindle speed and depth of cut .Both the results of fixing spindle speed and feed rate with changing depth of cut show that surface roughness and cutter runout increase with the increase of depth of cut .In addition, cutter runout has a large effect on the surface roughness because it causes an increase in surface roughness of workpiece. Also surface roughness decreases at cutter (80mm width) which causes larger surface roughness than cutters (63mm and 40mm width),. For certain machining parameter as the spindle speed increases from (100 to 210 rpm), feed rate (35 mm/min) and depth of cut (0.1mm), the surface roughness value decreases from (1.61333 to 1.418333) μm at cutter (80mm width.) .When the cutter (63mm width) is used, the surface roughness decreases from (1.5222 to 1.3182) μm , and at cutter (40mm width) the surface roughness decreases from (1.4111 to 1.212)μm. Also in this study, multiple linear regression model is used within (SPSS) software to predict the experimental data for each surface roughness and cutter runout for different three cutters and results show from comparing between predicted and measured values that (SPSS) software gives high prediction accurate .

Keywords: -Cutter width, surface roughness, cutter run out, horizontal milling.

***Production Engineering and Metallurgy Department, University of Technology / Baghdad**

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تأثير عرض عدة التفريز على الخشونة السطحية والأنحراف في التفريز الأفقي

الخلاصة

يركز هذا البحث على دراسة تأثير عرض عدة القطع من خلال تلامسها على خشونة السطح ولامركزية عدة القطع خلال عملية التفريز , وبما انه مساحة التماس تعتمد على الشكل الهندسي لعدة القطع ,خصوصا (قطر العدة وعرضها). لذا تم اخذ ثلاثة عدد حلزونية مختلفة بالعرض مع ثبوت باقي متغيرات الشكل الهندسي وهي كالأتي (80, 63, 40ملم) مستعملة بالتفريز الأفقي. أما بالنسبة لمادة المشغولة فكانت من الفولاذ الهيكلي طبقاً إلى (DIN:C22) وان هذه المادة ملائمة لتحقيق متطلبات البحث من ناحية الكلفة وعمليات القطع. وبعد أن تم أنجاز التجارب المختبرية التي تتضمن ظروف قطع مختلفة (سرعة قطع ,تغذية ,عمق قطع) لكل عدة قطع, فقد بينت النتائج إن عدة القطع التي تمتلك اكبر عرض (80ملم) تعطي اكبر خشونة سطحية للمشغولة ولامركزية عدة القطع مقارنة بالنوعين الآخرين .كما تم دراسة تأثير كل من السرعة الدورانية ومعدل التغذية وعمق القطع على الخشونة السطحية ولامركزية العدة لكل من أدوات التفريز الثلاثة , وقد بينت النتائج انه عند تثبيت معدل التغذية وعمق القطع وذلك لحساب الخشونة السطحية للشغلة ولامركزية العدة مع تغير السرعة الدورانية وللأنواع الثلاثة من أدوات التفريز المذكوره أعلاه , فتبين إن الخشونة السطحية ولامركزية العدة تنخفض بزيادة السرعة الدورانية.وعند تثبيت السرعة الدورانية وعمق القطع لحساب الخشونة السطحية للشغلة ولامركزية العدة مع تغير معدل التغذيه فان الخشونة السطحية ولامركزية العدة تزداد بزيادة معدل التغذيه.أما عند تثبيت السرعة الدورانية و معدل التغذية مع تغير معدل عمق القطع نجد إن الخشونة ولامركزية العدة تزداد بزيادة عمق القطع.كما تم أيضاً دراسة تأثير كل من السرعة الدورانية ومعدل التغذية وعمق القطع على لامركزية أداة القطع خلال عملية التشغيل, وقد بينت النتائج انه عند تثبيت معدل التغذية وعمق القطع وذلك لحساب لامركزية أداة القطع مع تغير السرعة الدورانية أثناء التشغيل وللأنواع الثلاثة من عدد التفريز المذكوره أعلاه , فتبين إن لامركزية عدة القطع تنخفض بزيادة السرعة الدورانية.وعند تثبيت السرعة الدورانية وعمق القطع لحساب لامركزية أداة القطع أثناء التشغيل مع تغير معدل التغذية فان الخشونة السطحية تزداد بزيادة معدل التغذية. بالإضافة إلى إن لامركزية أداة القطع تسبب أيضاً زيادة بقيمة الخشونة السطحية للمشغولةوعندما تزداد السرعة الدورانية (100-210) سرعة دورانية ومعدل تغذية (35ملم/دقيقة) وعمق قطع (0.1ملم) فأن قيمة الخشونة السطحية تقل من (1.61333الى 1.418333) مايكرون عند عدة التفريز ذات العرض(80ملم), وعند أستخدام عدة التفريز ذات العرض(63ملم) فأن الخشونة تقل من (5222. 1- 1.3182) مايكرون وعند عدة التفريز(40ملم) فأن الخشونةتقل من(1.212-1.4111) مايكرون وقد تم أيضا استخدام نموذج الانحدار الخطي المتعدد المتضمن في برنامج الـ(SPSS) لغرض التنبؤ بالبيانات المختبرية لكل من خشونة السطح واللامركزية لأدوات القطع الستة وقد بينت النتائج من خلال المقارنة بين القيم المتنبأ والحقيقية إن هذا البرنامج يعطي دقة تنبؤ عالية .

1- Introduction

Milling is the removal of metal by feeding the workpiece through a rotating multi-toothed cutter. Milling operations may be classified as peripheral (plain) milling or face (end) milling. In peripheral milling, the cutting occurs by the teeth arranged on the periphery of the milling cutter, and the generated surface is a plane parallel to the cutter axis. Peripheral milling is usually performed on a horizontal milling machine. For this reason, it is sometimes called (horizontal milling) .The appearance of the surface and also the type of chip formation are affected by the direction of cutter rotation with respect to the movement of the workpiece. In this regard, two types of peripheral milling are differentiable, namely, up-milling and down-milling(climb milling) .Up-Milling (Conventional Milling) is accomplished by rotating the cutter against the direction of the feed of the workpiece as shown in figure (1) .The tooth picks up from the material gradually; that is, the chip starts with no thickness and increases in size as the teeth progress through the cut. While in down-milling is accomplished by rotating the cutter in the direction of the work feed, as shown in figure (1-b). In climb milling, as implied by the name, the milling cutter attempts to climb the workpiece. Chips are cut to maximum thickness at initial engagement of cutter teeth with the work, and decrease to zero at the end of its engagement. As for present work, it has been used down milling in the peripheral milling case because the cutting forces in down milling are directed downward and also it is characterized by fewer tendencies of chattering and vibration, which leads to improved surface finish and also. [1].

2- Milling cutters geometry

The cutting tools which are used for metals machining have many shapes, each of which are described by their angles or geometries. Every one of these tool shapes have a specific purpose in metals cutting. The primary machining goal is to achieve the most efficient separation of chips from the workpiece [2].Additionally; cutting tool geometry includes tool diameter, length, width, number of flutes and tool angles. Cutting tool geometry has large effect on the chip geometry, chip flow, tool-workpiece contact area, productivity of machining, tool life, the direction and magnitude of the cutting force and quality (surface integrity and machining residual stress) of machining..etc [3].In this study, helical plain cutters are used and they are preferred for large cutting widths to provide smooth cutting and improved surface quality and mainly used on the horizontal milling machines as shown in figure (2) [4].

3- Contact area in milling

Contact area, it can be defined as an area between the lengths of the horizontal line is CL, the circular length of the contact surface between the cutter and the workpiece, and AL is the distance between each flute in axial direction. The length of the vertical line is equivalent to the axial depth of cut **(a)** and PL is equivalent to the effective length of cut, as shown in figures (3) and (4). Additionally, axial depth of cut, radial depth of cut and cutting tool geometry affect the width and length of the contact area When axial and radial depth of cut increase lead to increase of contact area consequently increasing in cutting force and this influences the surface quality [5].

4- Sources of machining errors:

The milling process causes machining errors due to several factors such as:-

Cutter run out, Tool deflection, Thermal effect, Chatter (machine instability),Surface roughness, Tools wear…etc. [6].

In this study, it is focused on studying of surface roughness and cutter run out .

5- Mathematical model of surface roughness and cutter run out

A statistical model is created by regression function from the training data set. The proposed multiple regression model is a three-way interaction equation:-

$$Yi = a_i + b_1X_{1i} + b_2X_{2i} + b_3X_{3i} + b_4X_{1i}X_{2i} + b_5X_{1i}X_{3i} + b_6X_{2i}X_{3i} + b_7X_{1i}X_{2i}X_{3i} \quad \ldots (1)$$

Where:-

Yi: surface roughness Ra (micrometer) or cutter run out Ru (mm).

αi: constant .

β1- β7: coefficients of independent variables or called partial regression coefficients .

Xli: spindle speed (revolutions per minute).

X2i: feed rate (millimeter per minute).

X3i: depth of cut (millimeter).

In this model, the criterion variable is the surface roughness (Ra) or cutter runout (Ru) and the predictor variables are spindle speed, feed rate, and depth of cut. Because these variables are controllable machining parameters, they can be used to predict the surface roughness and cutter runout in milling which will enhance product quality [7, 8, and [9].

For the purpose of the regression prediction model building, it can be performed with the aid of regression function which is existed in SPSS (version 11.0) software.

6- Accuracy of mathematical model

The independent variables of this study are spindle speed, feed rate, and depth of cut, the dependent variable was the surface roughness (Ra) and cutter runout (Ru). The full regression model containing all the main effects and interactions terms was listed in equation (1).

In order to judge the accuracy of the multiple regression prediction model, percentage deviation (φ_i) and average percentage deviation (Φ) are used and defined as:

$$j_i = \frac{|Ra'_i - Ra_i|}{Ra'_i} \times 100\% \quad \ldots\ldots. (2)$$

Where, φ_i: percentage deviation of single sample data

Ra`$_i$: actual Ra measured by surface roughness tester

Ra$_i$: predicted Ra generated by a multiple regression equation

$$\Phi = \frac{\sum_{i=1}^{m} j_i}{m} \quad \ldots. (3)$$

Where Φ: average percentage deviation of all sample data

m: the size of sample data

The equation (3.4) with substitution of surface roughness either in case substitution of cutter runout becomes as following:

$$j_i = \frac{|R'u_i - Ru_i|}{R'u_i} \times 100\% \quad \ldots. (4)$$

where φ_i: percentage deviation of single sample data

Ru`$_i$: actual Ru measured by cutter runout indicator

Ru$_i$: predicted Ru generated by a multiple regression equation

This method would test the average percentage deviation of actual Ra and

Ru (measured by surface roughness tester and cutter runout indicator respectively) and predicted surface roughness (Ra) and cutter runout (Ru) (produced by the multiple regression model), as well as its ability to evaluate the prediction of this model [7, 8].

7- Experimental work

7.1 Experimental Arrangement

7.1.1 Horizontal milling Machine

· The experimental work has been performed on universal milling machine (factory) model (6H81)

7.1.2 Workpiece Material

Structural steel (1.0402) workpieces are used according to (DIN: C22). The chemical composition of workpiece material is achieved in Al-Sumood Company and given in table (1) .

7.1.3 Milling cutters

Three types of high speed steel(HSS) helical plain cutters are used in horizontal milling with different widths (40,63,80mm) width as shown in figure (3) and table (2) shows the geometry properties of helical plain cutters.

7.1.4 Preparation of Workpiece

The workpiece used was made of Structural steel (1.0402). It was prepared by cutting it to (4 specimens) by using reciprocating-saw machine and dimensions of each specimen as follows:-

- Length = 100mm
- High = 100mm
- Width = 100mm

7.1.5 Design of experiments:

Machining conditions are used in this work consist of three parameters as following:-

1- Spindle speed: - Three different spindle speeds (100, 160, and 210) r.p.m are taken, 2- Feed rate:-Three different feed rates (35, 65, and 115) mm/min are selected.

3- Depth of cut: - Three types of depth of cut are used (0.1, 0.3, 0.5) mm.

The experiments are designed by using factorial design which consists of the factors (parameters) and their levels.

8- Results & Discussions

Figure (4) shows the effect of spindle speed and cutter width during horizontal milling on the surface roughness when feed rate and depth of cut is not considered., the surface roughness decreases when the spindle speed increases, and cutter (80mm width) causes larger surface roughness than cutters (63mm and 40mm width), because cutter (80mm width) has larger contact area than other cutters and this causes larger cutting force than other cutters (63mm and 40mm width), consequently the surface roughness is increased. For certain machining parameter as the spindle speed increases from (100 to 210 rpm), feed rate (35 mm/min) and depth of cut (0.1mm), the surface roughness value decreases from (1.61333 to 1.418333) µm at cutter (80mm width.) .When the cutter (63mm width) is used, the surface roughness decreases from (1.5222 to 1.3182) µm , and at cutter (40mm width) the surface roughness decreases from (1.4111 to 1.212) µm. These results indicate that the spindle speed has significant effect on milling quality because increasing of spindle speed leads to reduce of cutting forces.

- Figure (5) shows the effect of feed rate and width of the milling cutter in the horizontal milling on the surface roughness when the effects of spindle speed and depth of cut are not considered (constant).

As it is shown in this figure, the surface roughness increases when the feed rate increases. When cutter (80mm width) is used with the feed rate of (35 mm/min), spindle speed (100 rpm) and depth of cut (0.1mm), the obtained surface roughness has largest value which is 1.61333 μm. When cutter (63mm width) is used, the surface roughness is obviously lower than that at cutter (80mm width), but when cutter (40mm width) is used the surface roughness value equals 1.4111 μm and is lower than both cutters (80mm and 63mm width) for the same machining condition, because cutter (40mm) width has less contact area and this leads to reduce of cutting forces and this affect surface roughness.

- Figure (6) shows the effect of depth of cut and width of the milling cutter on the surface roughness in horizontal milling, when the effect of spindle speeds and feed rate is not considered. This figure also shows that surface roughness increases when the depth of cut increases. For machining condition, depth of cut (0.3 mm) ,feed rate (35mm/min) and spindle speed (100 rpm) and when cutter (80mm width) is used, surface roughness value (1.7811μm) is obtained which is larger than surface roughness values when cutters (63mm and 40mm width) are used, because cutter (80mm) width has larger contact area than other cutters , in addition to depth of cut(0.3mm), all this lead to increase of cutting forces. Consequently, increase of surface roughness.

8.4 The effect of milling parameters and cutter type on the Cutter Run out

Figures (4, 5 and 6) show the effect of each milling process parameter studied on cutter runout for three different cutters as follows:-

- Figure (4) shows the effect of spindle speed and width of milling cutter in horizontal milling on the cutter runout when feed rate and depth of cut is not considered .As it is shown in this figure, the cutter runout decreases when the spindle speed increases, and cutter (80mm width) causes larger cutter runout than cutters (63mm width and 40mm width) because it has larger contact area than other cutters and this leads to increase cutting force and vibration. For certain machining parameter as the spindle speed increases from (100 to 210 rpm) , feed rate(35 mm/min) and depth of cut (0.1mm) cutter runout value decreases from (0.14 to 0.11 mm) when cutter (80mm width.) is used . But by using cutter (63mm width), the cutter runout decreases from (0.12 to 0.10 mm), and at cutter (40mm width) cutter runout decreases from (0.11 to 0.09 mm). These results indicate that the spindle speed has a significant effect on cutter runout and on surface quality.

- Figure (5) shows the effect of feed rate and width of the milling cutter in the horizontal milling on the cutter run out when the effects of spindle speed and depth of cut are constant .As it is shown in this figure the cutter run out increases when the feed rate increases .When cutter (80mm width) is used with machining condition, (feed rate 35 mm/min, spindle speed 100 rpm and depth of cut 0.1mm), the obtained cutter runout has largest value (0.14mm). In using cutter (63mm width) , the cutter runout is obviously lower than cutter run out when cutter(80mm width) is used and equals to (0.12mm), but when cutter (40mm width) is used, cutter run out value equals to (0.11mm) and is lower than both cutters (80mm and 63mm width) for the same machining condition, because cutter (40mm width) has less contact area than other cutters (80mm and 63mm width) and this causes less cutting force consequently less vibration during milling operation and this means that vibration is function for cutter run out.

Figure (6) shows the effect of depth of cut and width of the milling cutter on the cutter runout in horizontal milling, when the effect of spindle speeds and feed rate is not considered. As it is shown in this figure, the cutter runout increases when the depth of cut increases. When cutter (80mm width) is used with machining condition, depth of cut (0.3 mm) ,feed rate (35mm/min) and spindle speed (100 rpm) , cutter runout value is (0.16mm) which is larger than cutter runout values when cutters (63mm and 40mm width) are used, because cutter (80mm) width has larger contact area than other cutters , in addition to depth of cut(0.3mm), all this lead to increase of arbor deflection . Consequently, increase of cutter runout.

8.1 Prediction of Surface Roughness with SPSS software for different milling cutters:-

1. A statistical model for the prediction with values of the surface roughness was created by regression function in SPSS software from the training data set.

Where *Yi* is the predicted surface roughness Ra for cutters(80,63 and 40 mm width) respectively. The result of average percentage deviation (Φ) shows that the training data set (m=19) were 3.194717% , 1.174621% and 0.936172% for cutters (80mm width , 63mm width and 40mm width) respectively and the testing data set (m=8) were 6.149893% , 1.321737% and 1.30443% for cutters (80mm width , 63mm width and 40mm width) respectively .

This means that the statistical model could predict the surface roughness (Ra) with about 96.8% ,98.8% and 99% accuracy of the training data set and approximately 93.8% , 98.6% and 98.6% accuracy of the testing data set for cutters (80mm width , 63mm width and 40mm width) respectively .

8.2 Prediction of Cutter Run out with SPSS software for different milling cutters:

1. A statistical model for the prediction with values of the cutter runout was created by regression function in SPSS software from the training data set.

$$yi = 8.752 * 10^{-2} - 8.54 * 10^{-5} x_1 + 6.85 * 10^{-4} x_2 + 0.19 * x_3 - 1.59 * 10^{-6} x_1 x_2 - 5.93 * 10^{-4} x_2 x_3 - 3.44 * 10^{-4} x_1 x_3 + 2.89 * 10^{-6} x_1 x_2 x_3 \ldots(10)$$

Where *Yi* is the predicted cutter runout Ru for cutters (80, 63 ,40mm width) respectively. The result of average percentage deviation (Φ) shows that the training data set (m=19) were 1.366851% , 1.678284% and 2.141836% for cutters (80mm width , 63mm width and 40mm width) respectively and the testing data set (m=8) were 2.93446% , 2.82006% and 3.087664% for cutters(80, 63 and 40mm width) respectively .

This means that the statistical model could predict the cutter runout (Ru) with about 98.6% ,98.3 and 97.8% accuracy of the training data set and approximately 97.06% , 97% and 96.9% accuracy of the testing data set for cutters (80mm width , 63mm width and 40mm width) respectively .

9-Conclusions

From this work is concluded the following :

1- using cutter (80mm) width in horizontal milling causes larger surface roughness and cutter run out than other cutters (63mm and 40mm) width respectively, provided that other parameters of cutter geometry are constant. This means, when cutter width is increased surface roughness and cutter run out are increased.

2- The spindle speed has a greater impact on milling quality. When spindle speed increases, surface roughness and cutter runout reduce.

3- other parameters, (feed rate and depth of cut) are increased, surface roughness and cutter runout are increased, too.

11- References

[1] Helmi A.Youssef and Hassan El-Hofy,"Machining technology, machine tools and operations ", (2008). New York, London

[2] Society of Manufacturing Engineers, "Cutting tool geometries", Fundamental of Manufacturing Processes. 2010,www.sme.org,Catlog,Pdf .

[3] J.Paulo Davim , "Machining fundamentals and recent advances" ,department of mechanical engineering ,university of Aveiro , Campus Universitário de Santiago 3810-193 Aveiro Portugal ,(2008) .

[4] George Schneider, Jr.Cmfge, "Cutting tool applications".

[5] Wen-Hsiang Lai ,"Modeling of cutting forces in end Milling operations" Tamkang Journal of Science and Engineering, Vol. 3. No. 1, PP. 15-22, (2000).

[6] M.Y.Kris Law, A. Geddam , Error compensation in the end milling of pockets: a methodology" , journal of materials processing technology, Vol.139,PP.21-27, 2003.

[7] Dr. Mike S. Lou, Dr. Joseph C. Chen and Dr. Caleb M. Li, "Surface Roughness Prediction Technique For CNC End-Milling", Journal of industrial technology, Vol. 15, No.1 (1999).

[8] Jaharah A. Ghani ,Firdaus Mohamad and Mohamad. Nizam Ab. Rahman "The reliability of tool life prediction model in end milling", Mechanical journal,June, No. 21, PP. 65-71, (2006).

[9] Abn. Rashid M.F.F., Gan S.Y., and Muhammad N.Y., " Mathematical Modeling to Predict Surface Roughness in CNC Milling", World academy of Science, Engineering and Technology,Vol.53,PP. 393-396, (2009).

Table (1) Chemical composition

Metal	C %	Mn%	P%	S%	Si%	Ni%	Cr%	Cu%	Fe%
Structural steel (1.0402)	0.25	0.53	0.044	0.024	0.09	0.06	0.03	0.09	Remain

Table (2) Geometry properties of helical plain cutters

Plain cutters	Material	Out side diameter (mm)	Inside diameter (mm)	No. of flutes	Face width (mm)	Helix angle
4	H.S.S	Ø50	Ø22	8	80	35°
5	H.S.S	Ø50	Ø22	8	63	35°
6	H.S.S	Ø50	Ø22	8	40	35°

Table (3) Cutters run out

Cutting tool width	Run out (mm)
80mm width	0.14
63mm width	0.12
40mm width	0.10

Table (4) original experimental data for both predicted and measured surface roughness and cutter run out for cutter (40mm) width

No.	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Measured Ru(mm)	Predicted Ru(mm)	Measured Ra(µm)	Predicted Ra(µm)
1	100	35	0.1	0.11	0.111886	1.4111	1.42036
2	160	35	0.1	0.10	0.1019659	1.300	1.290808
3	210	35	0.1	0. 09	0.09369915	1.212	1.182848
4	100	65	0.1	0.13	0.126754	1.5321	1.51762
5	160	65	0.1	0.12	0.1144921	1.401	1.40992
6	210	65	0.1	0.11	0.10427385	1.31	1.32017
7	100	115	0.1	0.15	0.151534	1.669	1.67972
8	160	115	0.1	0.13	0.1353691	1.611	1.60844
9	210	115	0.1	0.12	0.12189835	1.551	1.54904
10	100	35	0.3	0.14	0.140878	1.521	1.55422
11	160	35	0.3	0.13	0.1280437	1.411	1.432732
12	210	35	0.3	0.12	0.11734845	1.3	1.331492
13	100	65	0.3	0.15	0.153922	1.633	1.62412
14	160	65	0.3	0.14	0.1397863	1.500	1.514332
15	210	65	0.3	0.12	0.12800655	1.411	1.422842
16	100	115	0.3	0.17	0.175662	1.711	1.74062
17	160	115	0.3	0.16	0.1593573	1.671	1.650332
18	210	115	0.3	0.14	0.14577005	1.582	1.575092
19	100	35	0.5	0.17	0.16987	1.700	1.68808
20	160	35	0.5	0.16	0.1541215	1.601	1.574656
21	210	35	0.5	0.14	0.14099775	1.511	1.480136
22	100	65	0.5	0.18	0.18109	1.722	1.73062
23	160	65	0.5	0.17	0.1650805	1.6022	1.618744
24	210	65	0.5	0.16	0.15173925	1.5111	1.525514
25	100	115	0.5	0.20	0.19979	1.801	1.80152
26	160	115	0.5	0.19	0.1833455	1.7333	1.692224
27	210	115	0.5	0.17	0.16964175	1.6012	1.601144

Table (5) original experimental data for both predicted and measured surface roughness and cutter run out for cutter (63mm) width

No.	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Measured Ru(mm)	Predicted Ru(mm)	Measured Ra(µm)	Predicted Ra(µm)
1	100	35	0.1	0.12	0.12165985	1.5222	1.53342
2	160	35	0.1	0.11	0.11239516	1.4121	1.399521
3	210	35	0.1	0.10	0.104674585	1.3182	1.2879385
4	100	65	0.1	0.14	0.13659115	1.6512	1.64478
5	160	65	0.1	0.13	0.12497044	1.5111	1.527819
6	210	65	0.1	0.12	0.115286515	1.412	1.4303515
7	100	115	0.1	0.16	0.16147665	1.811	1.83038
8	160	115	0.1	0.14	0.14592924	1.701	1.741649
9	210	115	0.1	0.13	0.132973065	1.6611	1.6677065
10	100	35	0.3	0.15	0.15075755	1.6811	1.658
11	160	35	0.3	0.14	0.13874948	1.5233	1.534871
12	210	35	0.3	0.13	0.128742755	1.400	1.4322635
13	100	65	0.3	0.16	0.16383545	1.772	1.745
14	160	65	0.3	0.15	0.15048332	1.621	1.629629
15	210	65	0.3	0.14	0.139356545	1.531	1.5334865
16	100	115	0.3	0.18	0.18563195	1.921	1.89
17	160	115	0.3	0.17	0.17003972	1.851	1.787559
18	210	115	0.3	0.15	0.157046195	1.710	1.7021915
19	100	35	0.5	0.18	0.17985525	1.800	1.78258
20	160	35	0.5	0.17	0.1651038	1.711	1.670221
21	210	35	0.5	0.15	0.152810925	1.60	1.5765885
22	100	65	0.5	0.19	0.19107975	1.812	1.84522
23	160	65	0.5	0.18	0.1759962	1.722	1.731439
24	210	65	0.5	0.17	0.163426575	1.631	1.6366215
25	100	115	0.5	0.21	0.20978725	1.944	1.94962
26	160	115	0.5	0.20	0.1941502	1.861	1.833469
27	210	115	0.5	0.18	0.181119325	1.722	1.7366765

Table (6): Original experimental data for both Predicted and Measured surface roughness and cutter run out for cutter (80mm) width:-

No.	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Measured Ru(mm)	Predicted Ru(mm)	Measured Ra(μm)	Predicted Ra(μm)
1	100	35	0.1	0.14	0.140241795	1.61333	1.618531
2	160	35	0.1	0.13	0.127186662	1.525333	1.5002776
3	210	35	0.1	0.11	0.116307385	1.418333	1.4017331
4	100	65	0.1	0.15	0.151267905	1.7675	1.756909
5	160	65	0.1	0.14	0.137628258	1.6221	1.6325464
6	210	65	0.1	0.13	0.126261886	1.523	1.5289109
7	100	115	0.1	0.17	0.169644755	2.001	1.987539
8	160	115	0.1	0.16	0.155030918	1.911	1.8529944
9	210	115	0.1	0.14	0.142852721	1.7686	1.7408739
10	100	35	0.3	0.16	0.164859385	1.7811	1.670501
11	160	35	0.3	0.15	0.150982786	1.6222	1.5813416
12	210	35	0.3	0.14	0.139418954	1.500	1.5070421
13	100	65	0.3	0.17	0.176109715	1.881	1.940699
14	160	65	0.3	0.16	0.161789974	1.722	1.8242984
15	210	65	0.3	0.15	0.149856857	1.633	1.7272979
16	100	115	0.3	0.19	0.194860265	2.333	2.391029
17	160	115	0.3	0.18	0.179801954	2.211	2.2292264
18	210	115	0.3	0.16	0.167253362	2.001	2.0943909
19	100	35	0.5	0.19	0.189476975	1.900	1.722471
20	160	35	0.5	0.18	0.17477891	1.822	1.6624056
21	210	35	0.5	0.16	0.162530523	1.701	1.6123511
22	100	65	0.5	0.2	0.200951525	1.9441	2.124489
23	160	65	0.5	0.19	0.18595169	1.8231	2.0160504
24	210	65	0.5	0.18	0.173451828	1.733	1.9256849
25	100	115	0.5	0.22	0.220075775	2.911	2.794519
26	160	115	0.5	0.21	0.20457299	2.801	2.6054584
27	210	115	0.5	0.19	0.191654003	2.511	2.4479079

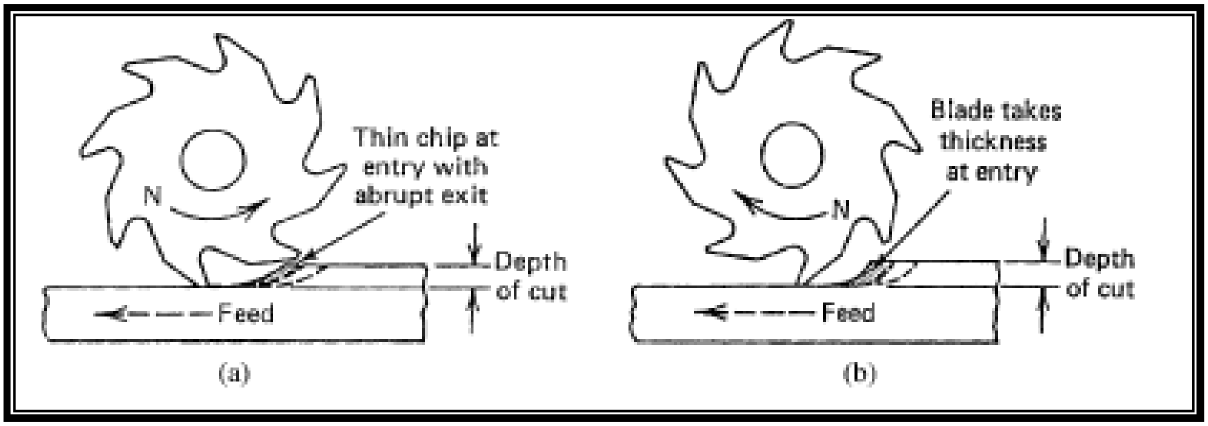


Figure (1) :(a) Up (Conventional) milling; (b) Down (Climb) milling [1].

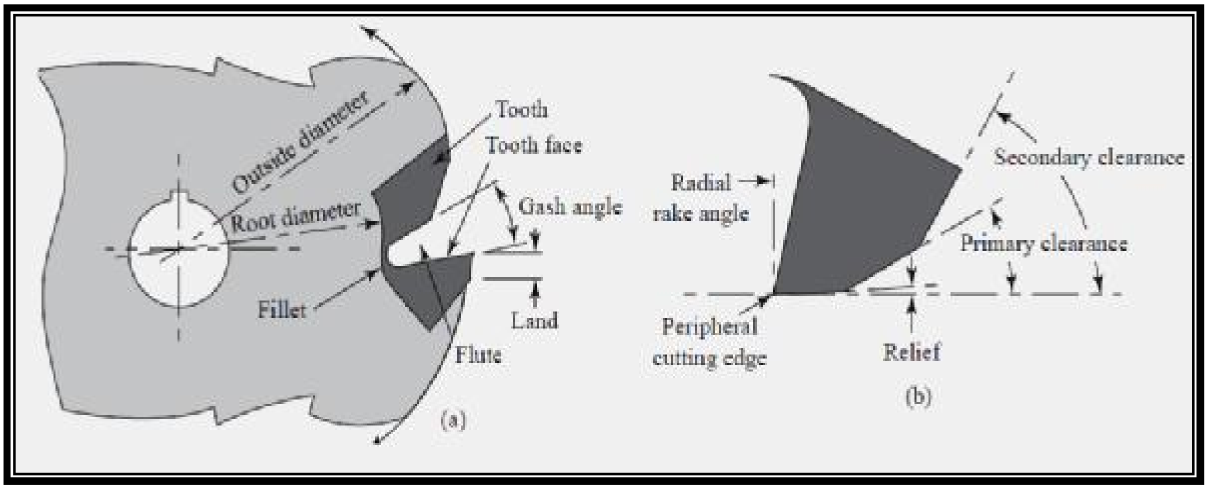
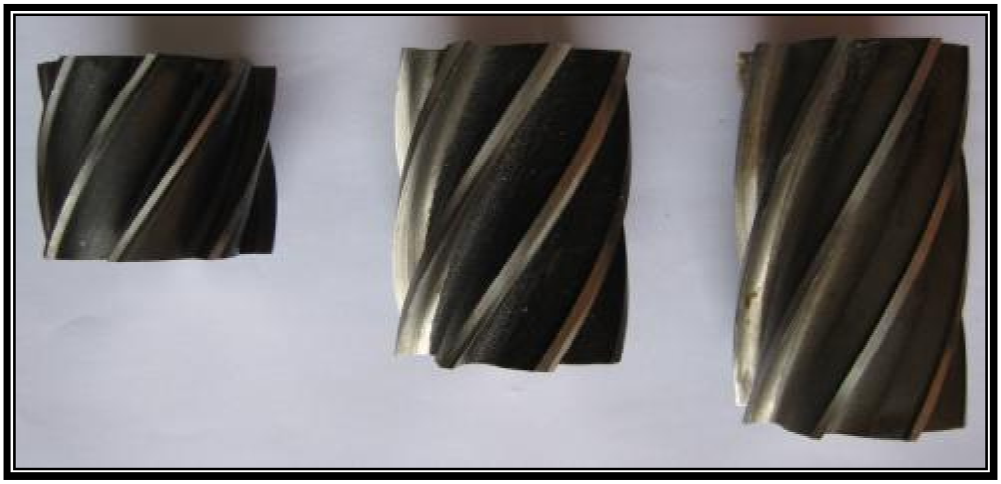


Figure (2): Geometric Properties of the helical plain cutter [4].



Figures (3) Helical plain cutters

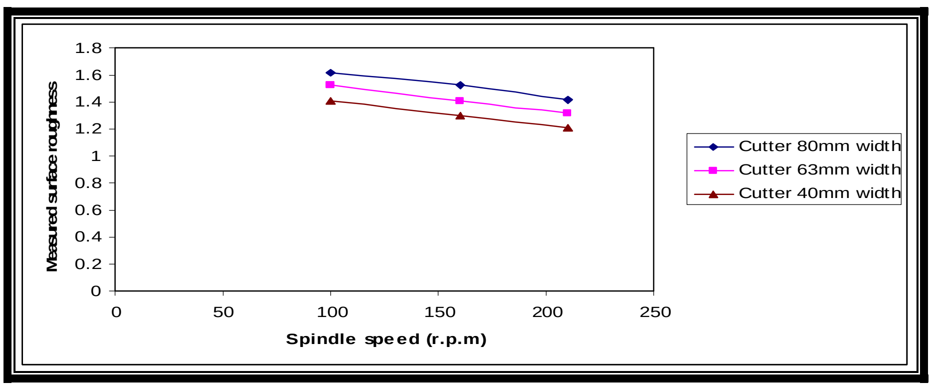


Figure (4): The effect of spindle speed (100,160,210 rpm) and helical plain cutters on the surface roughness at a constant feed rate and depth of cut.

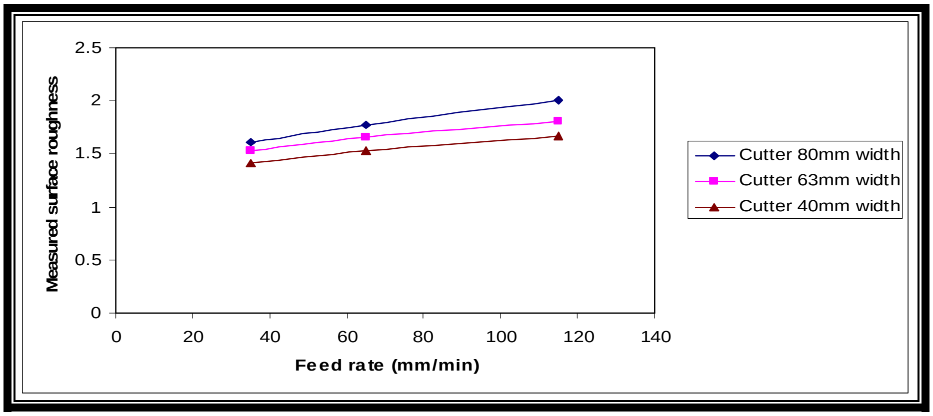


Figure (5): The effect of feed rate(35,65,115mm/min) and helical plain cutters on the surface roughness at a constant spindle speed and depth of cut .

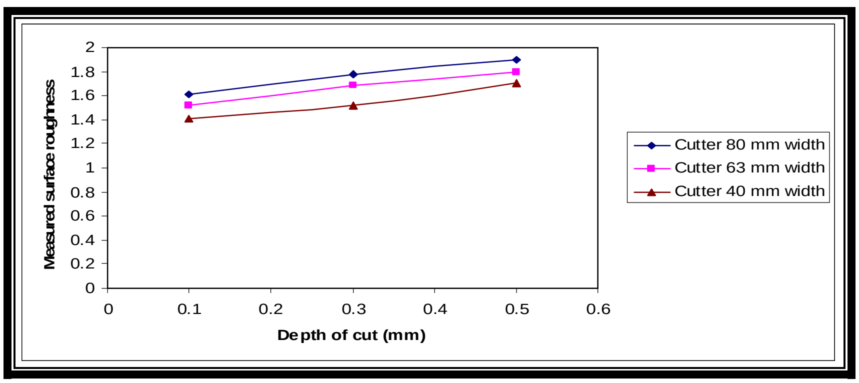


Figure (6): The effect of depth of cut(0.1, 0.3, 0.5mm) and helical plain cutters on the surface roughness at a constant of spindle speed and feed rate.

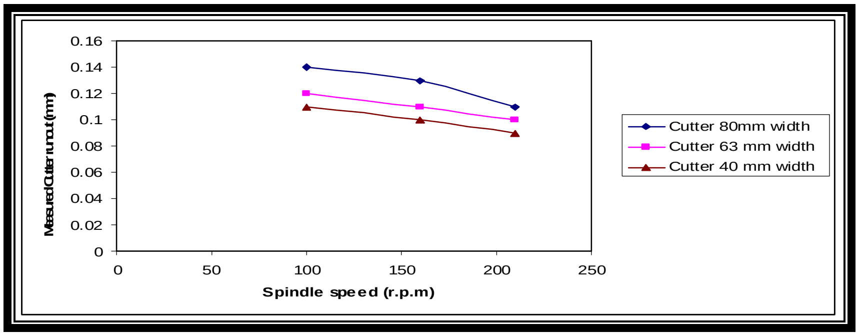


Figure (7): The effect of spindle speed (35,65,115mm/min) and helical plain cutters on the cutter runout

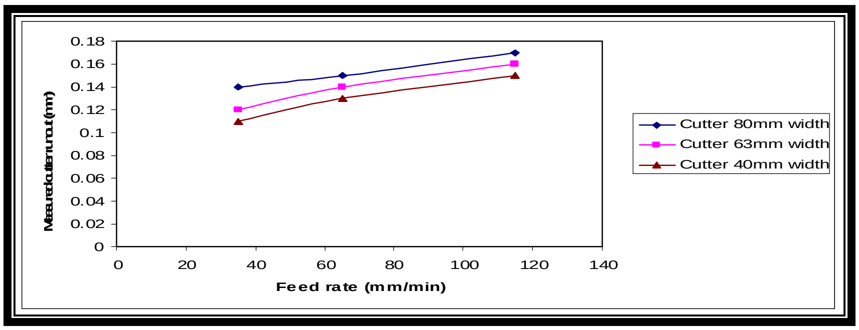


Figure (8): The effect of feed rate (35,65,115mm/min) and helical plain cutters on the cutter runout

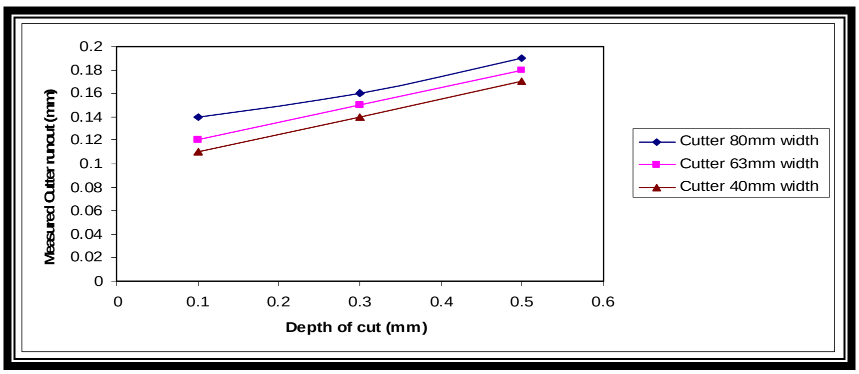


Figure (9): The effect of depth of cut (0.1, 0.3, 0.5mm) and helical plain cutters on the cutter runout