Pick-Interval Scallop Height Estimation Using Three Types of Geometrical end Mill Cutters on CNC Milling Machine

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ABSTRACT

This research presents the theoretical model, simulation and experimental verification to predict the magnitude of scallop height using 3 and 5-axis milling machine, where the effect of geometrical shape of the workpiece relative to the effect of geometrical shape of the tools had been studied, taking into consideration three different types of milling tools (Ball, Flat and Torus) corresponding to the type of machines that had been used to calculate the scallop height (h) in each point. Also, four different types of surfaces shape (Horizontal, Concave, Inclined and Convex) surface had been utilized to study the effect of these shapes on the value of scallop height. Besides, the effect of cutting direction in each plane had been studied in both types of milling operation (three and five axis milling machine). Finally, the value of stepover had been changed so as to acquaint the effect of this parameter on the magnitude of scallop height on both types of milling operation.

It was established that the scallop height is most influenced by the step over, cutting direction, geometrical shape of the cutter and inclination angle of the plane. The results also show that in 5-axis machining by utilizing different cutters, the angle of inclination of the tool axis was most affects the value of scallop height. It was also concluded that Torus cutter is better than other two cutters (Ball and Flat end mill cutters).

Keywords: Scallop Height, Milling Machine, CNC Three and Multi-Axis Machine.

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حساب قيـــــمة الارتـــــفاع التموجــــــي باستخـــــدام انــــواع ثلاثـــــــة للعـــــدد القاطعـــــة علـــى مكــــــائن التــفريــــز ذات التــحكم الرقمــــي

الخلاصة

إن هذا البحث يعرض نموذج نظري، محاكاة وجانب عملي للتنبؤ بقيمة الارتفاع التموجي باستخدام مكائن التحكم الرقمي لثلاث وخمس محاور، حيث تم الأخذ بنظر الاعتبار تأثير كل من الشكل الهندسي للسطح المشغل نسبة إلى السطح الهندسي للعدة المستخدمة، مع الأخذ بعين الاعتبار ثلاثة أنواع مختلفة من أدوات التفريز (كروي، مستوي، كروي_ مستوي) نسبة إلى نوع الماكنة المستخدمة في البحث وذلك لحساب قيمة الارتفاع التموجي في كل نقطة. كما تم دراسة تأثير الشكل الهندسي للسطح المشغل من خلال استخدام أربعة أنواع مختلفة من أشكال السطوح (أفقي ، مقعرة، مائل ومحدب). إلى جانب ذلك، تم دراسة تأثير اتجاه القطع في حالة استخدام نوعين من مكائن التحكم الرقمي (ثلاث وخمس محاور). أخيرا، تم تغيير قيمة خطوة العدة وذلك لغرض دراسة تأثير هذا المحدد على قيمة الارتفاع التموجي لكلا النوعين من مكائن التفريز المستخدمة في البحث.

لقد ثبت إن قيمة الارتفاع التموجي تتأثر بقيمة كل من خطوة العدة، اتجاه القطع، الشكل الهندسي للعدة القاطعة وزاوية ميلان السطح المشغل. كذلك أظهرت النتائج المستحصلة أن قيمة زاوية ميلان محور العدة القاطعة له تأثير كبير على قيمة الارتفاع التموجي في حالة استخدام مكائن التفريز لخمس محاور باستخدام عدد قطع مختلفة. كذلك تم التوصل إلى أن العدة (Torus) هي أفضل عدة للتشغيل مقارنة مع العدد الأخرى (كروي ومستوي).

List of symbols

CC	Shortcut of cutter contact.
CL	Shortcut of cutter location.
h	The scallop height. (mm or micron)
Oa	The center of the approximated arc for the adjacent tool paths.
O_c	The center of the approximated arc for the effective cutting profile.
R	The cutter radius.(mm)
R_1	The radial distance of the cutter bottom. (mm)
R_2	The cutter corner radius. (mm)
$R_{\psi,Eff,X_L=0}$	Effective cutting radius of the cutter on the YL-ZL plane. (mm)
$R_{\psi,Eff,Z_L=0}$	Effective cutting radius of the cutter on the XL-YL plane. (mm)
R_C	The radii of the equivalent cutters. (mm)
R_{C1}	The radii of the equivalent cutters at P1. (mm)
R_{C2}	The radii of the equivalent cutters at P2. (mm)
R_a	Effective radius of the curvature for the profile of the workpiece.(mm)
θ	The angle along the ZT-axis.(degree)
θ_a	The angle of the approximated arc for the adjacent tool paths. (degree)
θ_{c1}	The angle between $\overline{O_{c1}P_1}$ and $\overline{O_{c1}I}$.(degree)

θ_{c2}	The angle between $\overline{O_{c2}P_2}$ and $\overline{O_{c2}I}$.(degree)
θ_{a1}	The angle between $\overline{O_aP_1}$ and $\overline{O_aI}$.(degree)
θ_{a2}	The angle between $\overline{O_aP_2}$ and $\overline{O_aI}$.(degree)
ϕ	The angle restricted between the axis of the tool and the axis which pass through the cutter contact point which is equal to inclination angle of the plane. (degree)
ϕ_i	The inclination angle of the surface at CC point. (degree)
ξ	Angle of cutting direction. (degree)

ρ The principal curvature of the effective cutting profile.(mm)

INTRODUCTION

Surface roughness is the dependent output variable. Different models for surface roughness were developed. Prediction accuracy of the best model may be effected on the functional properties of the product, and the effective parameters on surface roughness value can be divided into controlled and non-controlled parameters. The most important controlled cutting parameters are the spindle speed, feed rate, and depth of cut, while non-controlled cutting parameters are vibrations, tool wear, machine motion errors, material non-homogeneity of both the tool and workpiece, chip formation.[1,2]In milling operations, the magnitude of scallop height is generally dependent on the cutting tool geometry, the workpiece geometry, the cutting conditions, and the machine-tool rigidity.

G. Yu. [3], studded in his work the gouging that's occurred when using 5-axis milling machine, while Yuan [4], explained in his research the problem and the error using for end-filleted cutter, and he made his analysis depending on the geometry of the tools that was utilized in his research. Also, Lee [5], derived in his paper the geometrical shape of different end mills. Many researchers have studied the cutter selection problem [6,7 & 8],which selected cutters based on the geometry constrains. Two cutters were usually selected to machine the part. With their approaches, the smaller cutter size was first chosen as equal to the workpiece's smallest corner radius. The larger one was then chosen such that the unmachined area that remained after its use could be removed by the smaller cutter with one pass along the boundary of the finishing cutter. Since only geometric constrains were taken into account in the above researches, the number of selected cutters was restricted to one or two for each operation. The selected cutters might not be the optimal ones. To solve this problem, some researchers selected cutters based on the generated tool paths [9,10,11 & 12].

It can be noticed from the previous researches that most of researchers studied the geometrical shape of the cutters and it's affect on the surface quality, while they neglect the effect of the geometrical shape of the workpiece and their affect on the value of scallop height.

So, in the present research the effect of geometrical shape of the workpiece relative to the effect of geometrical shape of the tools will be studied, taking into consideration three different types of milling tools (Ball, Flat and Torus) corresponding to the type of machines that will be used to calculate the scallop height (h) in each point. Also, four different types of surfaces shape (Horizontal, Concave, Inclined and Convex) surface should be utilized to study the effect of these shapes on the value of scallop height. Besides, the effect of cutting direction in each plane will be studied in both types of milling operations (three and five axis milling machine). Finally, the value of stepover will be changed so as to study the effect of this parameter on the magnitude of scallop height on both types of milling operation.

TOOL GEOMETRY DESCRIPTION

The cutter geometry can be described by several parameters as shown in Figure.(1), where:[4]

β_1 = the angle from radial line through the cutter tip to the cutter bottom.

β_2 = the taper angle between the cutter side and the cutter axis.

H = the shaft height measured along the cutter axis.

In order to define a cutter correctly, the above parameters must fulfill the following constrains:

$R_1 \geq 0$, $R_2 \geq 0$, $0^\circ \leq \beta_1 < 90^\circ$, $-90^\circ < \beta_2 < 90^\circ$

Note that β_2 is positive when sloping outward, negative when sloping inward from the cutter side.

As shown in Figure.(2), based on the generalized cutter geometry, three common used cutters can be easily defined as follows:

(a) Torus or Torialdal (Fillet–end)cutter: $R_1 + R_2 = R$, $\beta_1 = 0^\circ$, and $\beta_2 = 0^\circ$.

(b) Cylindrical (Flat-end) cutter: $R_1 = R$, $R_2 = 0$, $\beta_1 = 0^\circ$, and $\beta_2 = 0^\circ$.

(c) Ball-end cutter: $R_1 = 0$, $R_2 = R$, $\beta_1 = 0^\circ$ and $\beta_2 = 0^\circ$.

SCALLOP HEIGHT

A scallop height is an uncut volume left between a pair of adjacent tool paths, and its generated by the finite pick offset between the successive cutting paths. To calculate scallop heights, it can be found in Figure.(3 a & b), that at the moment of the cutter is sliding to the CC point, the effective cutting profile of the cutter with its orientation at the CC point is equivalent to an end mill cutter with the radius Rc which is equal to $(1/\rho)$ [13]. The scallop height problem can be simplified as the geometric relationships of three approximated arcs which belong to the machined surface and the two effective cutting profiles of the equivalent end mill cutters .As shown in Figure.(4), the small portion of the machined surface between adjacent tool paths is approximated by the arc from P1 to P2 with its center at O_a , radius as Ra, and angle as

θ_a . Note that Ra is the normal radius of curvature along the path interval direction, the radii of the equivalent cutters at P1 and P2 are denoted as R_{C1} and R_{C2}, respectively. The effective cutting profiles for the equivalent the cutters at P1 and P2 are approximated by the arcs with their centers at O_{C1} and O_{C2}, and radii as R_{C1} and R_{C2}, respectively. The intersection point of these two approximated arcs is denoted as I, and the intersection point of $\overline{O_a I}$ and the approximated arc for the machined surface is denoted as M.

To build the mathematical model for estimating the of scallop height values at each point, work must be divided into three groups depending on the types of cutters, and then these groups will be classified into four subdivision groups, each one represents the profile of the specimen (horizontal, concave, inclined and convex), and finally all equations that calculate (h) in different types of geometrical surfaces can be presented utilizing three types of cutters (ball, flat and torus cutter), as follows:

Calculating scallop height by using ball end cutter

This group is divided into four divisions:

- **Horizontal Plane:**

From the **Figure.(5B)**, it can be concluded that the equation that calculates scallop height is as follow:

$$h = R_{ci} - R_{ci} \cdot \cos(\theta_{ci}) \qquad \ldots(1)$$

Where:

Rci: Effective cutting radius, and it can be calculated according to reference [14].

$$\theta_{ci} = \sin^{-1}\left(\frac{d}{2 \cdot R_{ci}}\right) \text{, where d: is the step over} \qquad \ldots(2)$$

- **Concave Plane**
- From the **Figure.(6 C)**, it can be concluded that the equation that calculates scallop height is as follows:

$$h = R_{ai} - \overline{O_a I} \qquad \ldots(3\text{ a})$$

$$\overline{O_a I} = \sqrt{(G^2 + J^2)} \qquad \ldots(3\text{ b})$$

Where:

$$G = R_{ci} \cdot \sin(\theta_{ci}) = d/2 \cdot \cos(\phi_i)$$

ϕ_i : the inclination angle of the surface at CC point.

$$J = (R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))$$

$$\therefore \overline{O_a I} = \sqrt{\left[R_{ci} \cdot \sin(\theta_{ci})\right]^2 + \left[(R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))\right]^2}$$

$$\therefore h = R_{ai} - \sqrt{\left[R_{ci} \cdot \sin(\theta_{ci})\right]^2 + \left[(R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))\right]^2} \qquad \ldots(3\ c)$$

Inclined Plane

From **Figure (7 B)**, it can be seen that the effective cutter radius of the ball cutter stays constant and equals to (R_2) along the inclined plane in each machine mode (3 and multi-axis machine) surface, and the equation that can calculates scallop height from it is similar to equation (1) as follows:

$$h = R_{ci} - R_{ci} \cdot \cos(\theta_{ci})$$

$$\theta_{ci} = \sin^{-1}\left(\frac{d}{2 \cdot R_{ci}}\right)$$

Convex Plane

From the **Figure (8)**, it can be concluded that the equation that calculate scallop height is as follows:

$$h = \overline{O_a I} - R_{ai} \qquad \ldots(4a)$$

$$\overline{O_a I} = \sqrt{(G^2 + J^2)} \qquad \ldots(4b)$$

Where:

$G = R_{ci} \cdot \sin(\theta_{ci}) = d/2 \cdot \cos(\phi_i)$

ϕ_i : the inclination angle of the surface at CC point.

$$J = \left[R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})\right]$$

$$\therefore \overline{O_a I} = \sqrt{\left[R_{ci} \cdot \sin(\theta_{ci})\right]^2 + \left[R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})\right]^2}$$

$$\therefore h = \sqrt{\left[R_{ci} \cdot \sin(\theta_{ci})\right]^2 + \left[R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})\right]^2} - R_{ai} \qquad \ldots(4c)$$

Where *Ra* is the effective radius of the curvature for the profile of the workpiece

Calculating scallop height using flat cutter

In flat cutter when the cutter is normal to the workpiece the scallop height is equal to zero under the condition($R>d$) and this is be realized either when utilizing multi axis machine whose cutter is normal to the workpiece in each point on the surface, or in three axis machine on the horizontal surface only. So, scallop height will be composed and it can be calculated using flat cutter in three axis machine in inclined, concave and convex shape only, because the tool is not normal to the surface plane depending on this type of machine.

As shown in Figure.(9 C) the equation that calculates the scallop height can be found as follow:

$$\cos(\phi_i) = \frac{X_i}{d} \Rightarrow X_i = d \cdot \cos(\phi_i) \qquad \ldots (5\text{ a})$$

$$\sin(\phi_i) = \frac{h}{X_i} \Rightarrow h = X_i \cdot \sin(\phi_i) \qquad \ldots (5\text{ b})$$

$$h = d \cdot \cos(\phi_i) \cdot \sin(\phi_i) \qquad \ldots (5\text{ c})$$

Calculating scallop height by using torus cutter

Horizontal plane

From **Figure.(10 B)**

$$h = 0 \text{ for } R_1 \geq d \, .$$

From **Figure.(10 C)**:

$$h = R_{ci} - R_{ci} \cdot \cos(\theta_{ci})$$

$$\theta_{ci} = \sin^{-1}\left(\frac{d}{2 \cdot R_{ci}}\right)$$

Concave plane

$$h = R_{ai} - \overline{O_a I}$$

$$\overline{O_a I} = \sqrt{(G^2 + J^2)}$$

Where:

$$G = R_{ci} \cdot \sin(\theta_{ci}) = d/2 \cdot \cos(\phi_i)$$

ϕ_i : the inclination angle of the surface at *CC* point.

$$J = (R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))$$

$$\therefore \overline{O_a I} = \sqrt{\left[R_{ci} \cdot \sin(\theta_{ci})\right]^2 + \left[(R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))\right]^2}$$

$$\therefore h = R_{ai} - \sqrt{[R_{ci} \cdot \sin(\theta_{ci})]^2 + [(R_{ai} - R_{ci}) + (R_{ci} \cdot \cos(\theta_{ci}))]^2}$$

Inclined plane

From **Figure (10 E)**, if torus cutter is used in three-axis machine torus cutter will be treated as ball cutter with small effective radius, whereas, if torus cutter is used in multi-axis machine, this cutter can be treated as flat cutter, and the magnitude of (*h*) will be equaled to zero corresponding to the magnitude of the step over (*d*) and radial distance of the cutter bottom (R_1), [$R_1 \succ d$].

Convex plane

Figure (10 D), will be found that the deriving equations below are similar to deriving equation that used for ball cutter except the magnitude of (R_{ci}) which can be gotten from equations in appendix, as follows:

$$h = \overline{O_a I} - R_{ai}$$

$$\overline{O_a I} = \sqrt{(G^2 + J^2)}$$

Where:

$$G = R_{ci} \cdot \sin(\theta_{ci}) = d/2 \cdot \cos(\phi_i)$$

ϕ_i : the inclination angle of the surface at *CC* point.

$$J = [R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})]$$

$$\therefore \overline{O_a I} = \sqrt{[R_{ci} \cdot \sin(\theta_{ci})]^2 + [R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})]^2}$$

$$\therefore h = \sqrt{[R_{ci} \cdot \sin(\theta_{ci})]^2 + [R_{ai} + (R_{ci} - (R_{ci} \cdot \cos(\theta_{ci})]^2} - R_{ai}$$

THE EFFECT OF THE CUTTING DIRECTION ANGLE

In the present work the angle of cutting direction (ξ) is changed in three times (zero, 30° and 60°) so as to study the effect of changing this angle on the magnitude of scallop height, and from the experimental work the researcher found that the magnitude of step over (d) will be changed according to the inclination angle of the surface (ϕ) and also depending on the angle of cutting direction (ξ) , **Figure(11)**. Where, (*h*) cannot be calculated from all derived equations above-mentioned unless the magnitude of (*d*) is known, hence, it is important to derive a relation that connect between step over with the value of inclination angle of the surface (ϕ) and also with the angle of cutting direction (ξ), as follows:

From **Figure (12 A)**:

$$\cos(\xi_i) = \frac{d_i}{X_i} \Rightarrow X_i = \frac{d_i}{\cos(\xi_i)} \quad \ldots (6\ a)$$

$$\cos(90 - \xi_i) = \frac{d_i}{Z_i} \Rightarrow Z_i = \frac{d_i}{\cos(90 - \xi_i)} \ldots (6\ b)$$

Where:

Xi =distance parallel to *X*-axis in the horizontal plane.

Zi= distance parallel to *Z*-axis in the horizontal plane.

ξ_i = angle of the cutting direction.

From **Figure (12 B)**:

In (concave, inclined and convex plane) *Xi* is represent to *Xi+1* as follow:

$$\cos(\phi_i) = \frac{X_i}{X_{i+1}} \Rightarrow X_{i+1} = \frac{X_i}{\cos(\phi_i)} \quad \ldots (6\ c)$$

Where:

ϕ : Angle of inclination surface at *CC* point.

From equation (6c), the magnitude of *Xi+1* depends on the angle of inclination surface (ϕ).

From **Figure (12 C)**:

It was observed that the magnitude of *Zi* is still constant by making a project of this distance, so the magnitude of the step over can be conclude by finding the angle between the step over *di+1* and the inclination distance *Xi+1*.

$$\tan(\xi_{i+1}) = \frac{X_{i+1}}{Z_i} \Rightarrow \xi_{i+1} = \tan^{-1}\left(\frac{X_{i+1}}{Z_i}\right) \ldots (6d)$$

$$\cos(\xi_{i+1}) = \frac{d_{i+1}}{X_{i+1}} \quad \ldots (6e)$$

So the new step over can be calculated as:

$$d_{i+1} = X_{i+1} \cdot \cos(\xi_{i+1}) \quad \ldots (6f)$$

EXPERIMENTAL WORK AND THE RESULTS

The effect of geometrical shape of the three cutters (ball, flat and torus) to the value of the scallop height depending on the parameters [step over (*d*), angle of cutting direction (ξ) and inclination angle of the surface (ϕ)] is demonstrated, also a comparison will be made between these cutters according to the above parameters. Figure (13)

Inclination angle of the surface (ϕ)

Figurers (14,15 & 16), represent graphic relations that explicate a comparison between theoretical and experimental results, and also between three cutters corresponding to inclination angle of the surface on the magnitude of scallop height along the parts of different planes at constant step over in 3 and 5 axis machining respectively.

Where, Figure (15) demonstrates the effect of inclination angle of the surface on the value of scallop height by using (ball , flat and torus) cutters on 3-axis machining. The ball cutter does not affect the inclination angle of the surface (ϕ) because the head of ball cutter is spherical and this means that the effective radius remains constant and does not depend on the rotation angle of the tool axis or on the magnitude of inclination angle of the surface. As for flat cutter, (ϕ) influences the value of (*h*) because the equation (5c), which is relied mainly on the value of (ϕ). As for torus cutter, the magnitude of (*h*) somewhat remained constant by using torus cutter because torus cutter imitates ball cutter when the tool axis is not normal to the surface plane, and also it imitates flat cutter when the tool axis is normal to the surface plane.

Figure (16), demonstrates the effect of inclination angle of the surface on the value of scallop height by using (ball , flat and torus) cutters on 5-axis machining. The scallop height occurred when using ball cutter only, Also it can be observed that the magnitude of (*h*) is equal to zero for any value of (ϕ)using flat or tours cutter for step over less than the magnitude of cutter radius, and the manner of torus cutter here is similar to flat manner because the tool axis in 5-axis machining is normal to the surface plane in each point.

Best value of cutting direction angle

Figure (14), shows a good agreement between theoretical and experimental results and this indicates to the rightness of the mathematical proposed model. So simulation process can be depended relying on Matlab and UGS program to predict the magnitude of scallop height, and the best value of cutting direction angle (ξ) can be concluded for each plane by using different cutters.

Figures (17,18 & 19) which represent the graphic relations between angle of cutting direction and the magnitude of scallop height along the parts of different planes, and from these Figures it can be noticed that different values of angles which are change from zero to (90°) was taken. Also from derived equations of scallop height it can be observed that the angle of cutting direction (ξ) set in equations of calculating the magnitude of (*h*) in purport of (Sin) or (Cos) function, so the Figures (17),(18) and (19) are similar to graphic relation of (Sin) and (Cos) function. In addition, from the following Figures it can be observed that the best value of cutting direction angle which verifies the minimum value of scallop height in general for each plane using different cutters equals to (80°).

CONCLUSIONS

The material of the specimen is aluminum and the symbol of this type of aluminum as the as the American standard is (A1 2017). Based on this work and on the experimental results, it is possible to conclude the following conclusions:

- Cutting direction angle (ξ) affects the magnitude of scallop height and this effect depends on the geometry of cutter and the value of inclination angle of the surface. The surface which is produced by applying angle of cutting direction ($\xi = 60^{\circ}$) is better than the surface which is produced by applying ($\xi = 0^{\circ}$ & $\xi = 30^{\circ}$) according to the value of scallop height, so it is concluded that there is a best angle of cutting direction between ($0 \rightarrow 90^{\circ}$) which verifies the minimum value of scallop height, and depending on simulation process it is observed that the best angle of cutting direction which verifies the minimum value of scallop height in general for each plane using ball, flat and torus cutter is (80°).
- For ball cutter in the case of applying 3 and 5-axis machining it is noticed that this cutter does not affect the value of inclination angle of the surface because of spherical head of this cutter, so it is concluded that (ϕ) does not affect the value of pick-interval scallop height by using this type of cutters.
- For flat cutter in the case of applying 3-axis machining the angle of inclination surface influences the value of scallop height and the magnitude of the angle (ϕ) between (0°) to (60°) causes an increase of the value of scallop height and more than that angle (60°) the surface roughness starts to decrease. Hence, it can be concluded that there is an optimum angle of inclination surface which verifies the minimum value of scallop height. Also for applying 5-axis machining it is concluded that (ϕ) does not have an effect on the value of pick-interval scallop height.
- The torus cutter produces scallop height value between those of ball and flat cutter. So it can be concluded that torus cutters has the advantages of two other cutters, and it would be beneficial to use torus cutter with small geometrical dimensions at inclination angles that are as small as possible to avoid gouging through machining sculpture surfaces.
- In general for all three types of cutters utilize 5-axis machine is better than use 3-aixs machine because it verifies less value of scallop height and this leads to decrease the value of surface roughness, but the angle of inclination cutter on the machining surface must be specified so as to reach to minimum value of scallop height.

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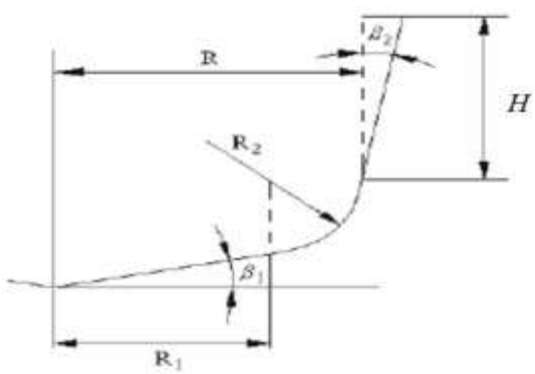


Figure (1) The definitions of a generalized cutter.[4]

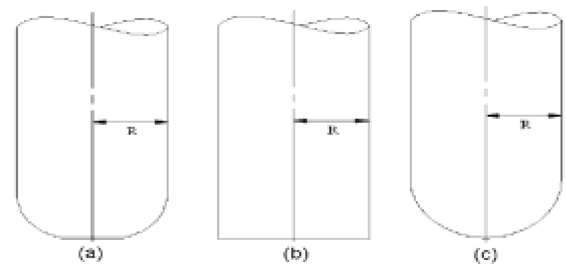


Figure (2) Different types of the end milling cutters. (a) torus cutter, (b) flat cutter, (c) ball cutter

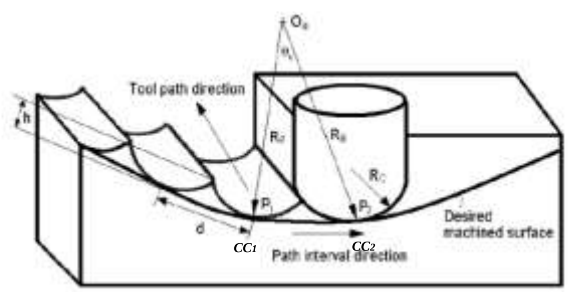


Figure (3a) Scallop heights for a concave machined surface.

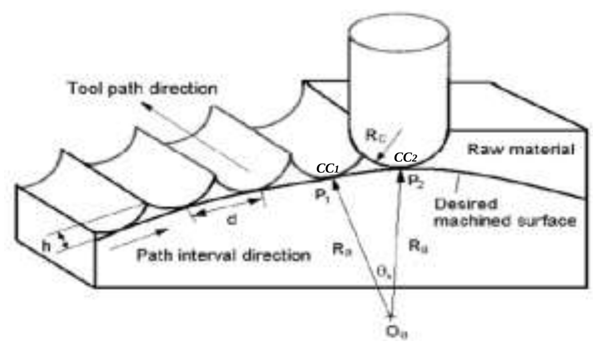


Figure (3 b) Scallop heights for a convex machined surface

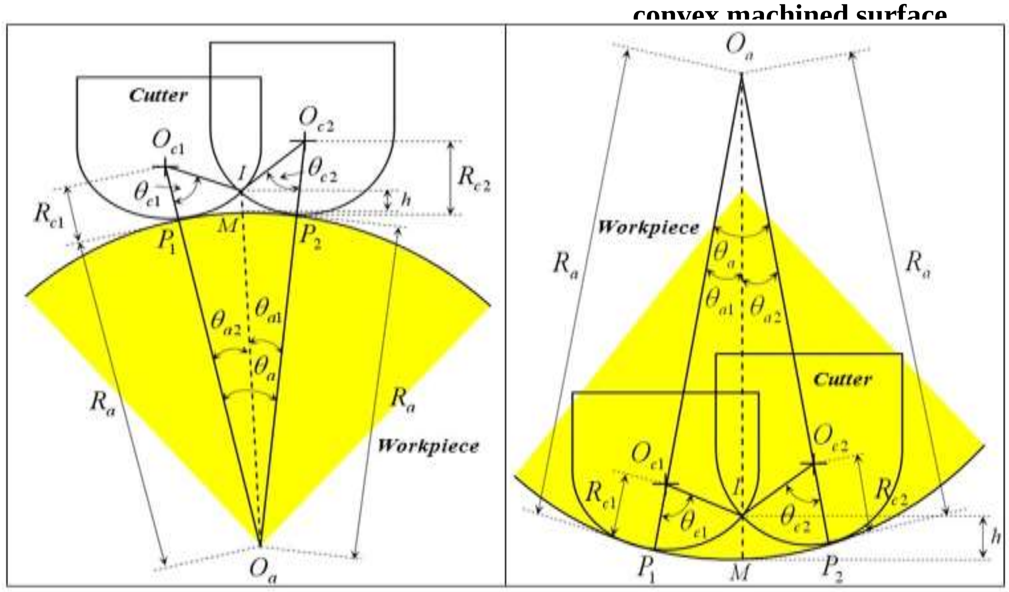


Figure.(4). Symbols of the mathematical model proposed

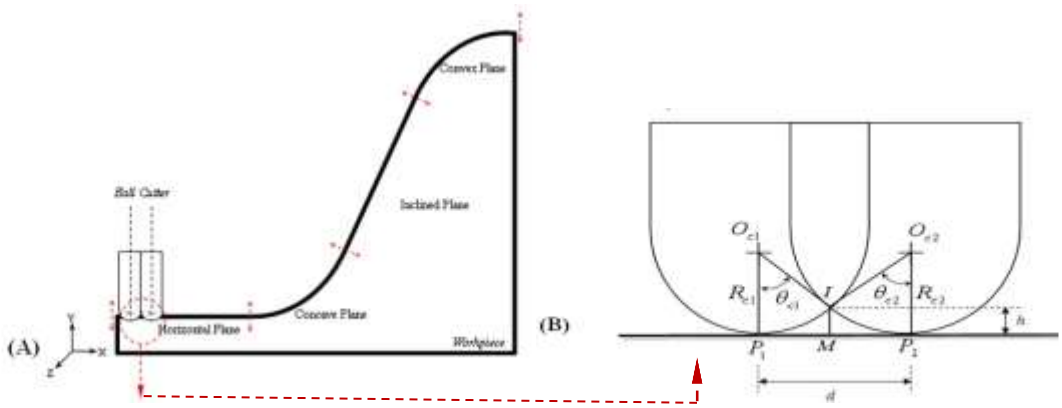


Figure.(5 A,B). Scallop height in horizontal plane by using ball cutter.

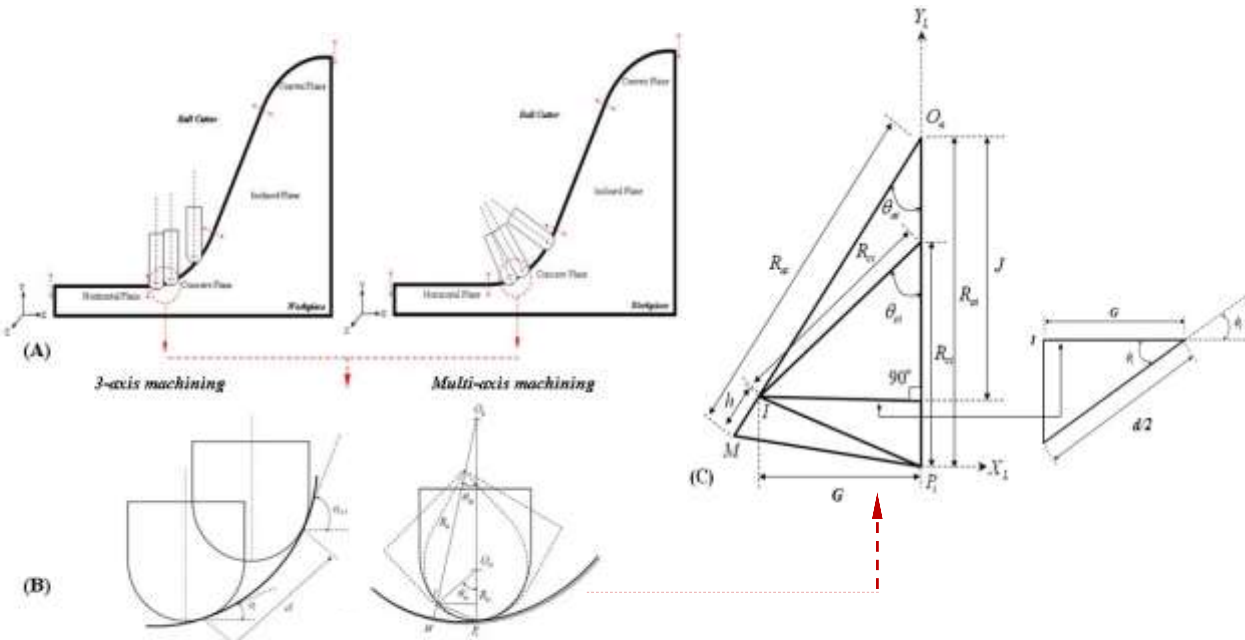


Figure (6 A,B and C). Scallop height in concave plane by using ball cutter for three and multi-axis machining.

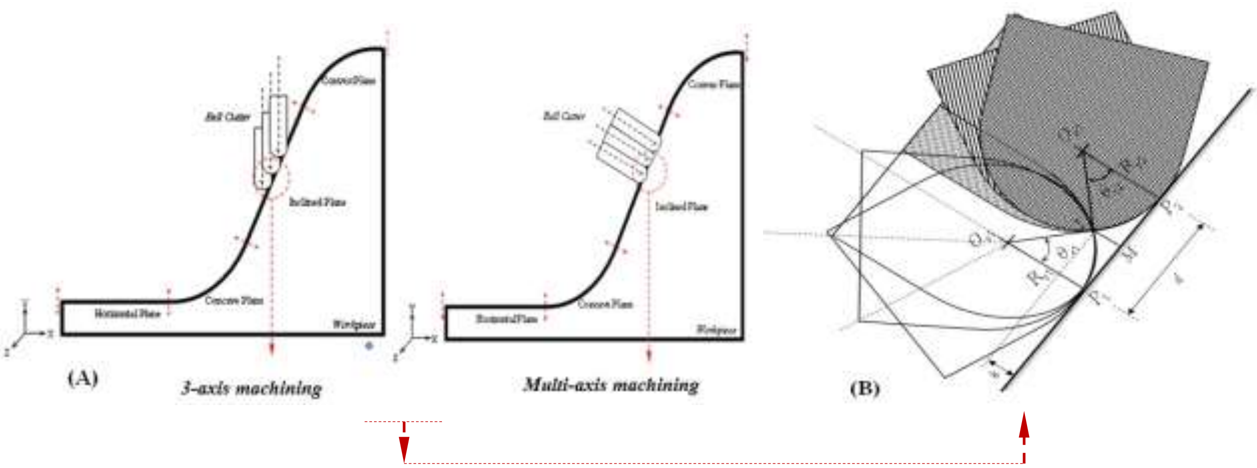
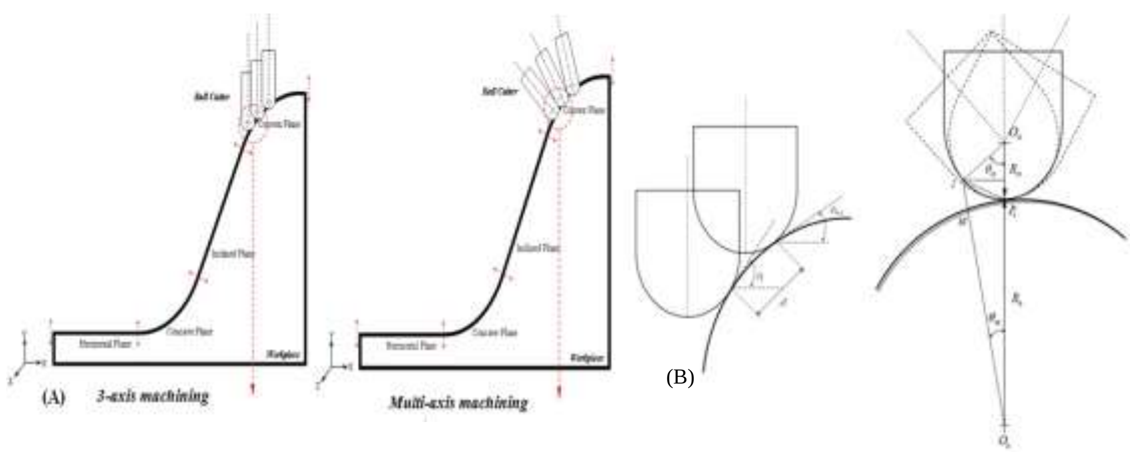


Figure.(7 A and B). Describes scallop height in inclined plane by using ball cutter for three and multi-axis machining.



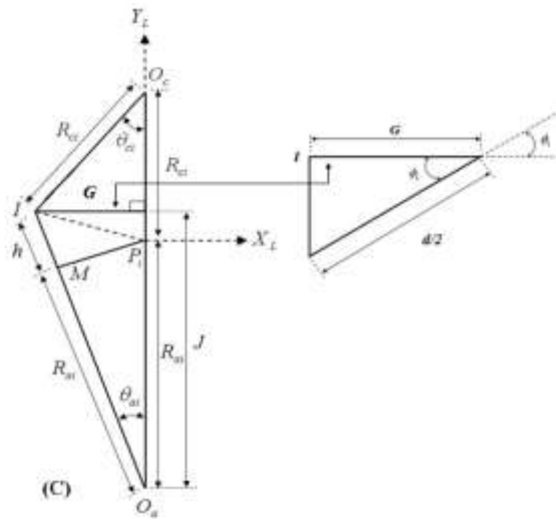
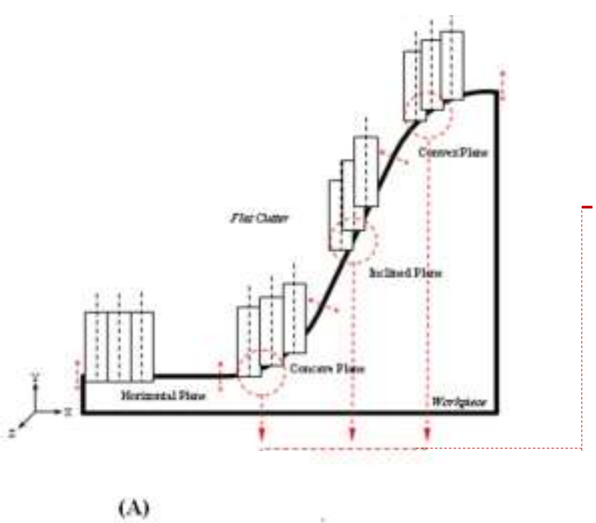


Figure (8 A, B and C). Scallop height in concave plane by using ball cutter for three and multi-axis machining.



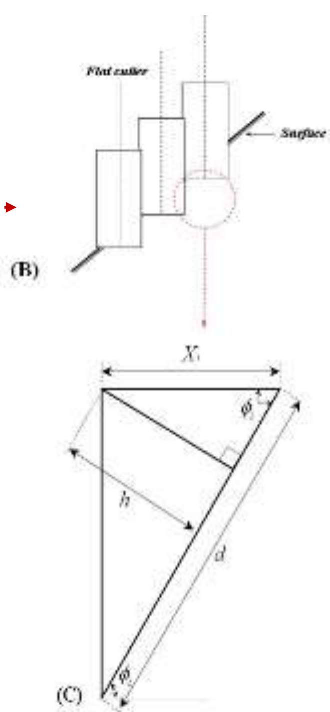


Figure.(9 A, B and C). Describes scallop height in concave, inclined and convex plane by using flat cutter in three axis machine.

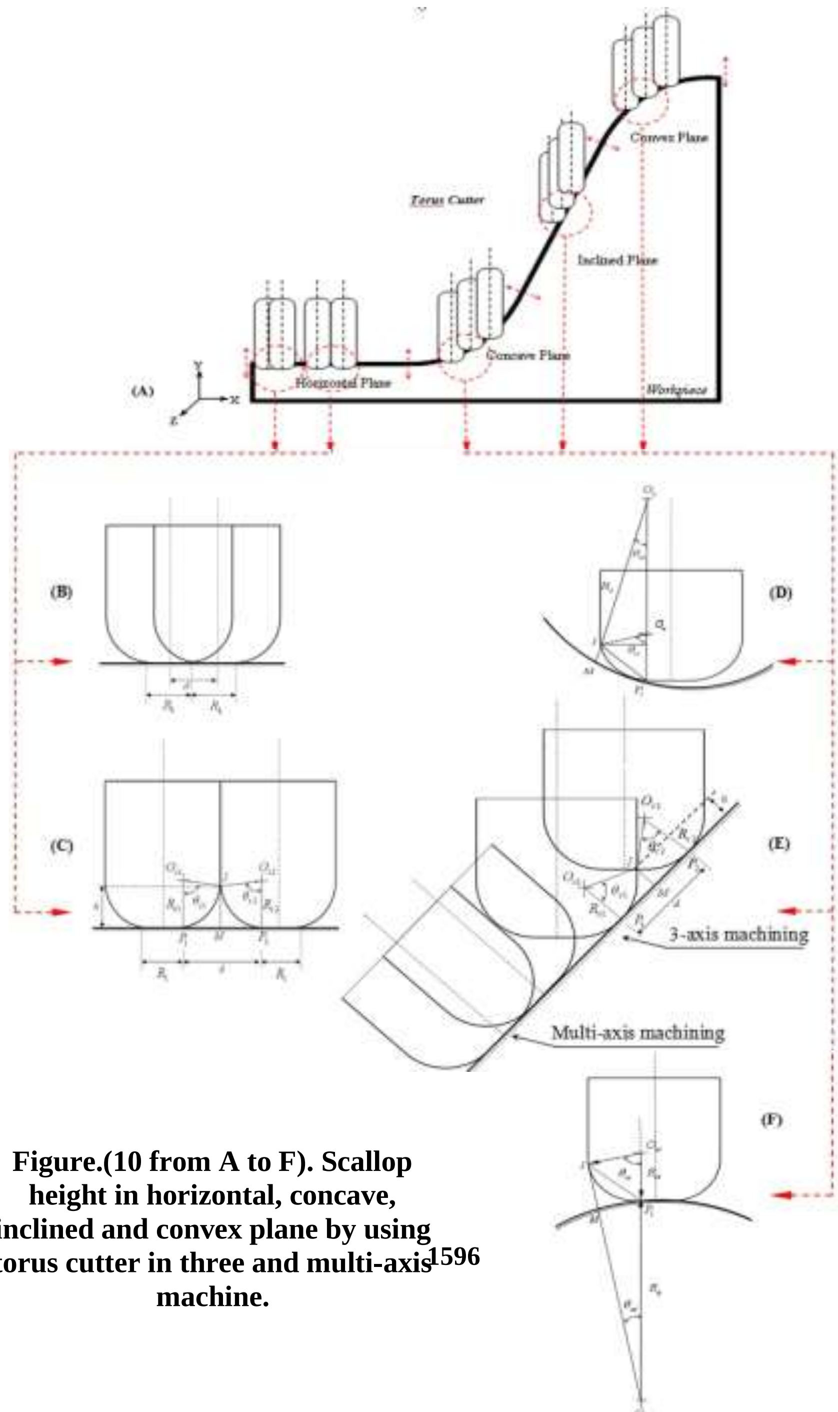


Figure.(10 from A to F). Scallop height in horizontal, concave, inclined and convex plane by using torus cutter in three and multi-axis machine.

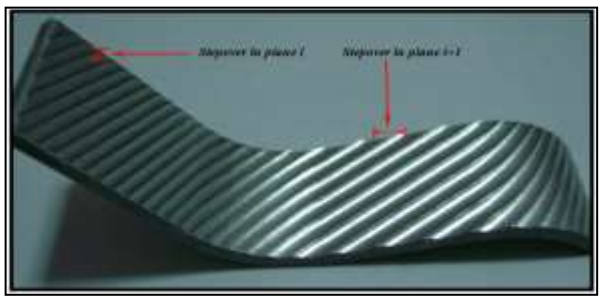


Figure (11) The magnitude of step over is change along the inclined plane when the angle of cutting direction $0^\circ \prec \xi \prec 90^\circ$.

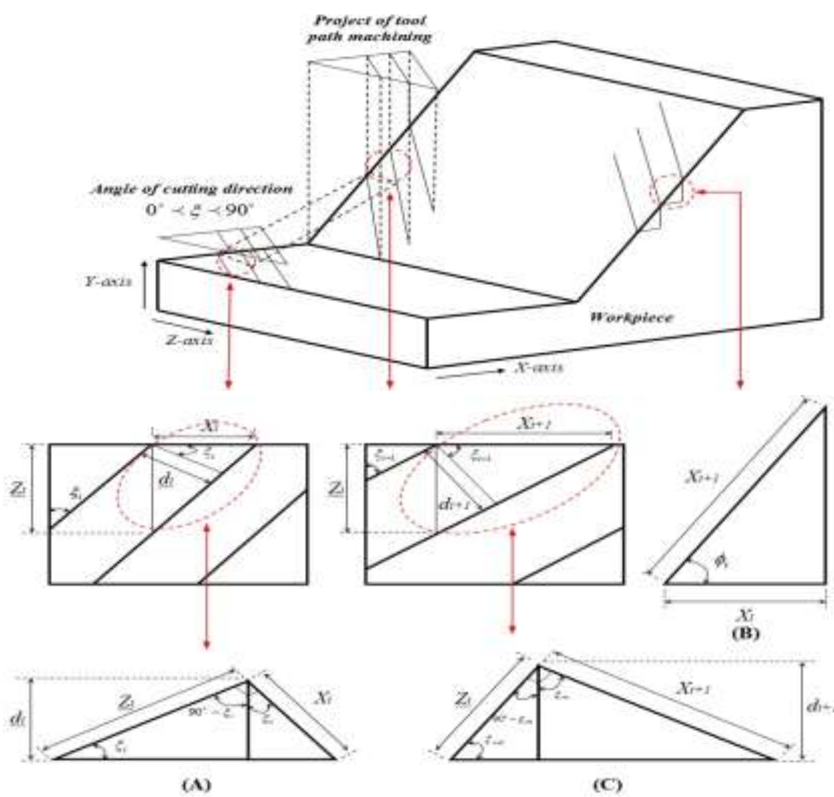


Figure (12 A,B and C) shows how step over is calculated in each plane if the angle of cutting direction $0^\circ \prec \xi \prec 90^\circ$: (A) explains step over in horizontal plane for ($0^\circ \prec \xi \prec 90^\circ$). (B) explains the geometrical shape to find Xi+1.(C) explains step over in inclined plane for ($0^\circ \prec \xi \prec 90^\circ$).

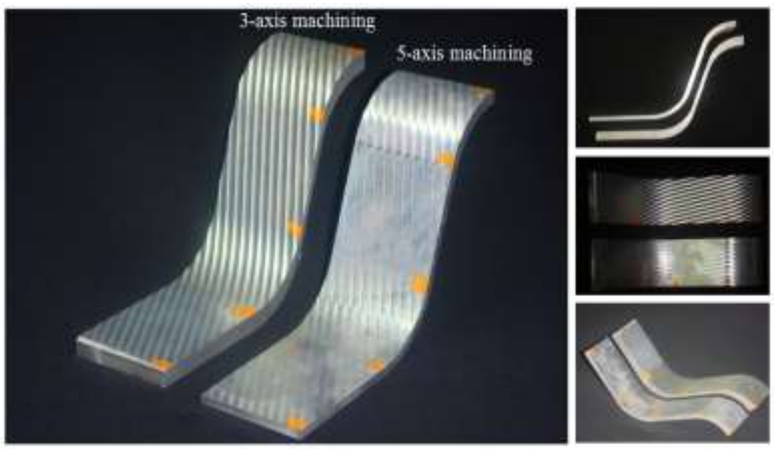


Figure.(13). The specimens after machining using 3 and 5-axis machine in CAD/CAM laboratory in Nanjing University in China.

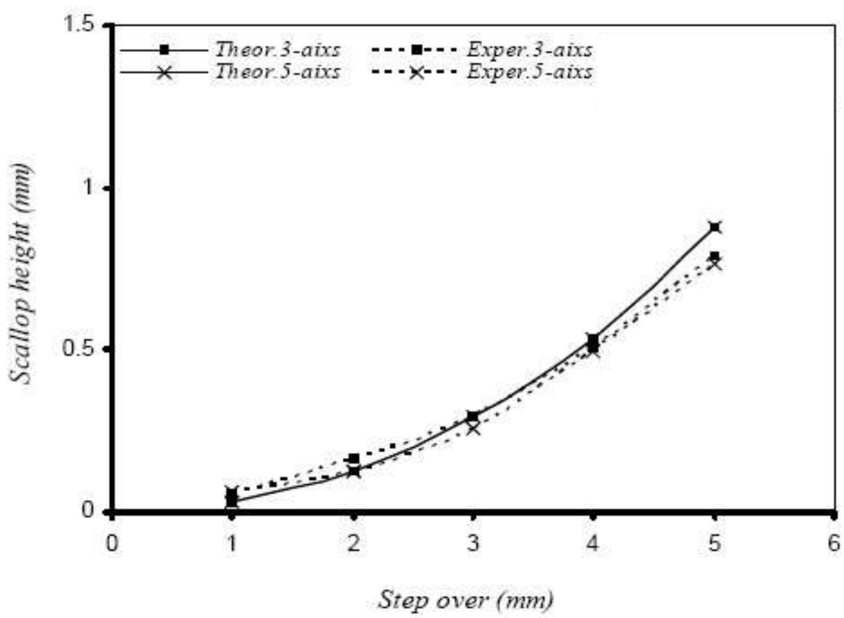


Figure.(14) Comparison between theoretical and experiment results.

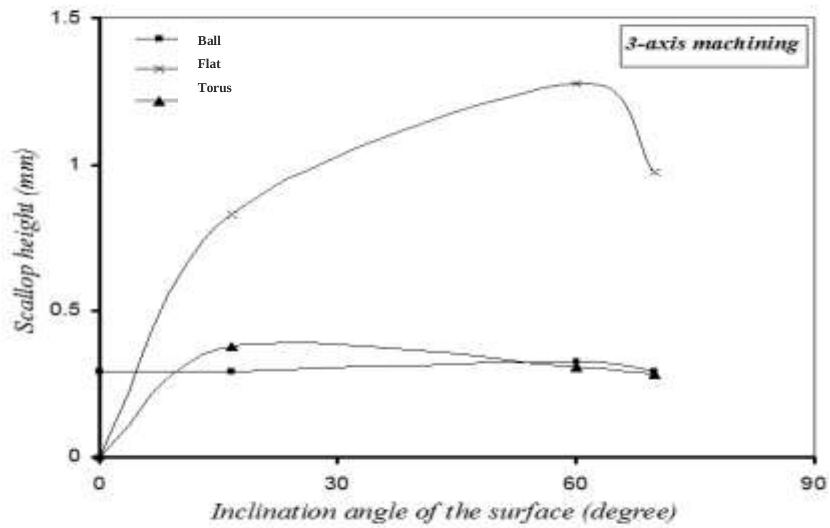


Figure (15) The effect of inclination angle of the surface on the value of scallop height using (ball, flat and torus) cutters on 3-axis machine.

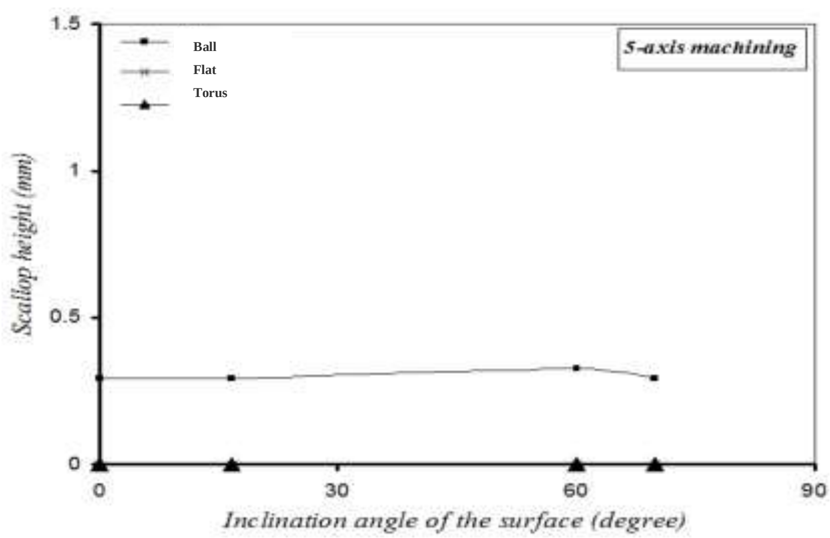


Figure.(16) The effect of inclination angle of the surface on the value of scallop height using (ball, flat and torus) cutters on 5-axis machine.

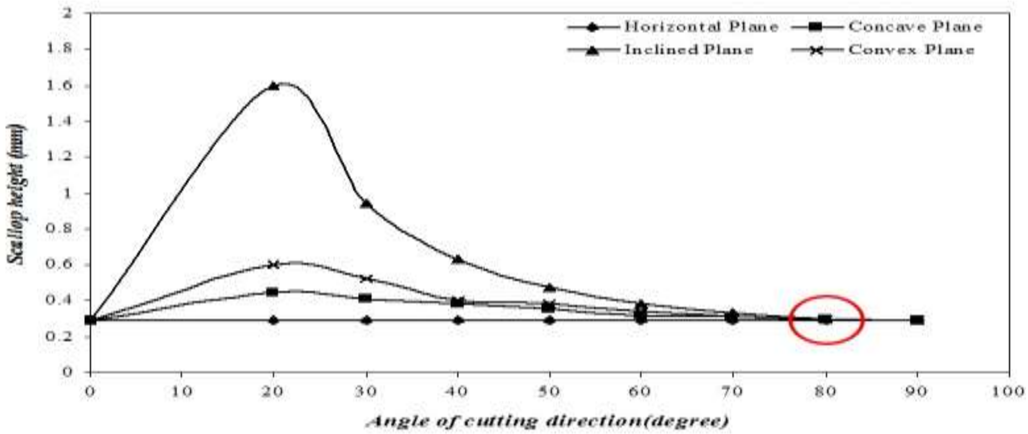


Figure (17) Best cutting direction angle for each plane using ball cutter.

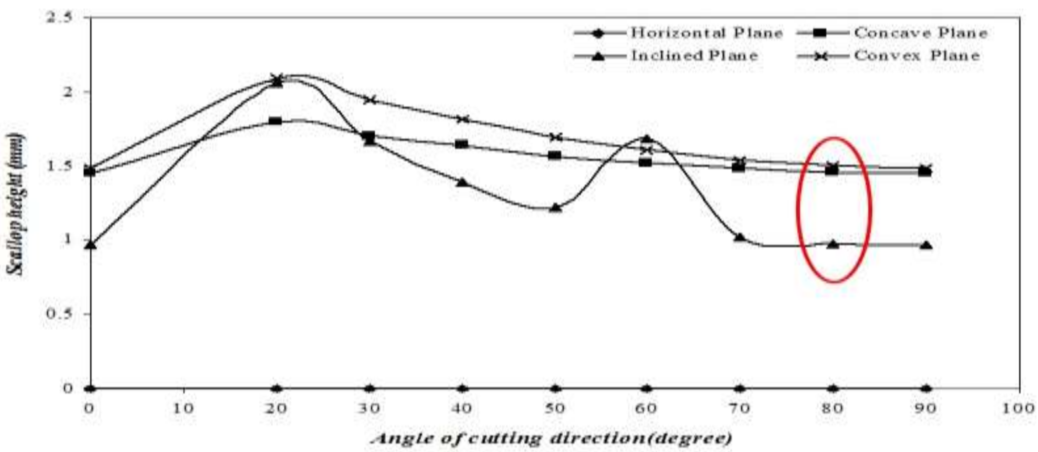


Figure (18). Best cutting direction angle for each plane using flat cutter.

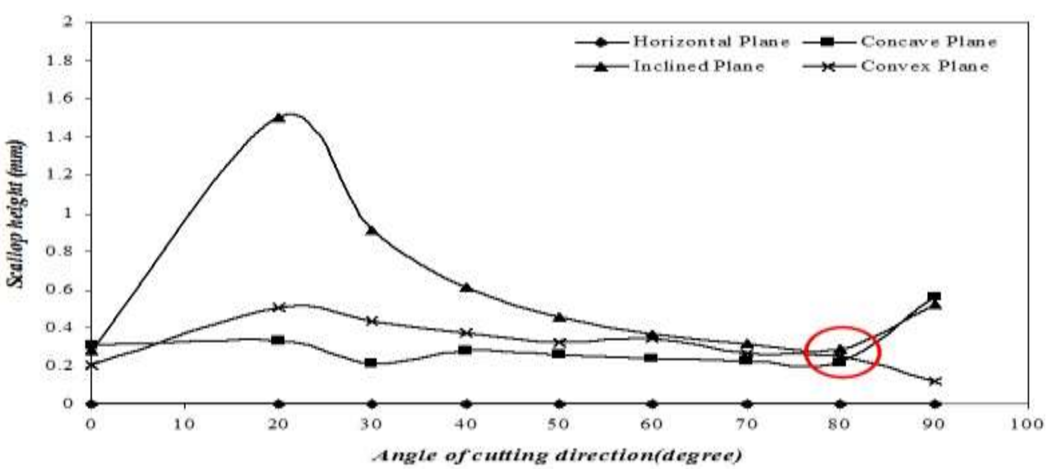


Figure.(19). Best cutting direction angle for each plane by using torus cutter.