Feed-Interval Scallop Height Estimation Using Multi-axis CNC Milling Machine

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ABSTRACT

This research presents a mathematical model of feed-interval scallop height, where in a machined surface there are two types of scallop height, the pick(path)-interval scallop and the feed-interval scallop. The pick-interval scallop is generated by the finite pick offset between the successive cutting paths, while the feed-interval scallop is generated by the finite increment between the successive tooth feeds. New model that describes and predicts the geometric generating mechanisms of the feed-interval scallop height have been derived using torus cutter which is commonly used in multi-axis milling machine. The machining parameters (effective tool cutter radius, feed per tooth and the magnitude of tool axis inclination angles) have been considered in theoretical and experimental work to study the effect of these parameters on this type of scallop height.

From theoretical and experimental work it was found that at high-speed machining, the feed-interval scallop is more important to the surface roughness than the path-interval scallop, and the feed-interval scallop is very sensitive to the tool-axis inclination angle. The feed-interval scallop height decreased sharply and quickly within a few degrees of the tool-axis inclination to the normal workpiece surface. In general, an inclination angle equal to 15° is good enough for all tool diameters used in the present work, namely (6,8,10 12 mm).

Keywords: CAD/CAM, Scallop height, CNC milling machine, Feed-interval scallop height, Surface roughness.

1. INTRODUCTION

In machined surface there are two types of scallop height: the pick (path)-interval scallop and the feed-interval scallop. The pick-interval scallop is generated by the finite pick offset between the successive cutting paths, while the feed-interval scallop is generated by the finite increment between the successive tooth feeds. It's found from all pervious papers that the researcher neglects the effect of feed-interval scallop height and they just made them to estimate the pick-interval scallop depending on machining parameters (effective tool cutter radius, geometrical shape of the workpiece, depth of cut …etc) .

In order to achieve high qualified surfaces, the scallop generation mechanism must be well controlled. Vickers and Quan [1] expressed the path-interval scallop height as a function of the curvatures of convex or concave surfaces, the cutter radii, and the path intervals. Kruth and Klewais [2] extended the path-interval scallop height model to include the inclination effect of the cutting axis. Also, Chen [3], discussed the feed-interval scallop but he depended in his research on the numerical analysis method to find the value of this type of scallop using ball cutter, but this method could not detect the accurate magnitudes of feed-interval scallop height, and also the mathematical description of feed scallop height had not been detect in his research in the equation form.

Duroobi [4], studied the pick-interval scallop height in his research in details. Also, he derived the mathematical equations to calculate this type of cusp, while feed-interval scallop height had not been taken into consideration in his research.

In conventional ball-end milling process, because of cutter material limitation, the tooth feed is kept to comparably less than the path pick (sideward step is less than forward step). In general and from the practical researches, the feed/pick ratio is less than one third (1/3). Therefore, the emphasis in the previous works has been focused on studying the geometric generating mechanism of the pick-interval scallop in forward step, while the feed-interval scallop has been largely ignored in side step.

Today, high-speed hard machining technology, the tooth feed of the cutter has been raised to the same level of the path pick. So, in this research the feed-interval scallop will be explained, and a new model that describes and predicts the geometric generating mechanisms of the feed-interval scallop height will be derived using torus cutter which is commonly used in multi-axis milling machine. Also, the machining parameters such as (tool radius, feed per tooth and the magnitude of tool axis inclination angles) will be changed in theoretical and experimental work so as to study the effect of these parameters on the feed-interval scallop height.

2. SCALLOP HEIGHT TYPES

The pick (path)-interval scallop and the feed-interval scallop are explained in **Fig (1)**, hence the pick-interval scallop is generated by the finite pick offset between the successive cutting paths in forward step, while the feed-interval scallop is generated by the finite increment between the successive tooth feeds in side step. [4, 5 & 6].

a. Pick-interval scallop height

This type of scallop as shown in **Fig.(2)** was discussed and estimated in details which is generated by using different geometrical shape of cutter in many papers, such as reference [4].

b. Feed-interval scallop height

The shape and generating mechanism of the feed-interval scallop is exactly the same as the pick-interval scallop. However, note that the pick-interval scallop is simply defined by the static geometric shape of the end cutter in the pure translation motion, but the cutting tool is rotating. Therefore, the dynamical translation and rotation motions of the cutting edge may affect the shape of the feed-interval scallop height. **Fig. (2)**.

From **Fig.(2)** it can be noticed that the arcs represent the effect of the surface contact of cutting tool on the surface of the work piece that can be represented in arcs shape, **Fig(3 a, b and c)** taking into consideration the zooming of the region (a) that appears in **Fig.(2)**.

Fig.(3b) explains the zooming of the region (a), that appears in **Fig.(2)**, which represents the area of feed-interval scallop height which will occur on it. **Fig.(3c)** can one imagine the process during the surface machining that will be occurred as shown in details in **Fig.(4)**.

Fig.(4a) represents the motion between two successive forward steps equal to each other, and this means that the value of feed per tooth will be constant for all machining surface.

While **Fig.(4b)** shows that the distance between two successive motion is not equal to each other, so this means that the value of feed per tooth will be changed according to the geometrical shape of the workpiece surfaces.

Finally from all these figures, the equation of estimating feed-interval scallop height can be derived according to geometrical shape of cutting tool in the following sections.

3. MATHEMATICAL DESCRIPTION MODEL OF FEED-INTERVAL SCALLOP HEIGHT

Fig. (3a & c), the magnitude of (L) can be found as follows:

$$S = R_{11} + R_{12} - L$$
$$\therefore L = -(S - R_{11} - R_{12}) \tag{1}$$

Where,

S: Step over
R_{11}: effective cutter radius of the first arc of tool cutting on the plane of the work piece.
R_{12}: effective cutter radius of the second arc of tool cutting on the plane of the work piece.

The magnitudes of (R_{11} and R_{12}) are demonstrated and derived in reference[7,8,9].
Also the values of ($\alpha 1$, $\alpha 2$) can be found from the equations below:

$$\alpha 1 = \tan^{-1}\left(\frac{L}{Ft}\right) \tag{2}$$

$$\alpha 2 = \tan^{-1}\left(\frac{Ft}{L}\right) \tag{3}$$

Where,

Ft: Feed per tooth.
L : The distance between two intersections opposite points of two neighbor arcs.

Actually, the feed-interval scallop is generated by the dynamic motion and intersection of the multiple sweeping cutting edges. So, This means that the values of ($\alpha 3, \alpha 4$) from **Fig.(5b)**, will be changed according to the dynamic motion of tool cutter, and there are some conditions which must be explained so as to detect the value of the two angles ($\alpha 3, \alpha 4$) and if one of these angles are known, then the magnitude of the line BC which represents the value of feed-interval scallop height (F.S.) can be found according to this angle using simple triangle functions.
So, the conditions can be proposed as follows:

First condition

$$(\alpha 2 + \alpha 3) = 90^\circ \tag{4}$$

For this condition it's easy to find the value of the angle ($\alpha 3$) depending on the value of ($\alpha 2$), as follows:
By substituting Eq. (3) into Eq. (4), the value of ($\alpha 3$) can be found as follows:

$$\alpha 3 = 90^\circ - \left(\tan^{-1}\left(\frac{(1/2)Ft}{(1/2)L}\right)\right)$$

Thus:

$$\tan(\alpha 3) = \frac{BC}{BD}$$

And hence:

$$BC = BD * \tan(\alpha 3) = (1/2)L * \tan(\alpha 3) \tag{5}$$

Second condition

$$(\alpha 2 + \alpha 3) \leq 90^\circ \tag{6}$$

This condition means the summation of ($\alpha 2$) and ($\alpha 3$) may be equal or less than (90°), and Eq. (6) explains that the value of the angle (ADC) in **Fig. (5b)** must be at lest equal to ($\alpha 2$) and in this case the value of feed-interval scallop height must be equal to zero because $\alpha 3 = 0^\circ$, while the maximum value of ($\alpha 2 + \alpha 3$) must be less than (90°), for example:

If the value of $(\alpha 2)$ equal to (30°), then the value of $(\alpha 3)$ can be found as follows:

$$30^\circ + \alpha 3 \le 90$$
$$\alpha 3 \le 60^\circ \quad (7)$$

From the example above, the value of $(\alpha 3)$ is at least equal to (60°), and from Eq.(7), the value of BC in **Fig.(5b)** can be found by substituting the value of $(\alpha 3)$ that was deduced from Eq.(8) into Eq.(5):

$$BC = BD * \tan(\alpha 3)$$

And Thus:

$$BC = BD * \lim_{\alpha 3 = 0^\circ \to 60^\circ} \tan(\alpha 3) \quad (8)$$

From Eq. (8) the length of the line BC which represents the value of (F.S.) can be found by writing a program from which the value of $(\alpha 2)$ can be estimated from Eq.(3), and then the value of $(\alpha 3)$ can be predicted.

<u>Third condition</u>

$$(\alpha 2 + \alpha 3) \ge 90^\circ \quad (9)$$

This condition means that the summation of $(\alpha 2)$ and $(\alpha 3)$ may be equal or more than (90°), and the Eq.(9) explains that the value of the angle (ADC) in **Fig.(5b)** must be at lest equal to $(\alpha 2)$, so in this case the value of feed-interval scallop height must be equal to zero, while the maximum value of ($\alpha 2 + \alpha 3$) is more than (90°), for example:
If the value of $(\alpha 2)$ equal to (75°), then the value of $(\alpha 3)$ can be found as follows:

$$75^\circ + \alpha 3 \ge 90$$
$$\alpha 3 \ge 15^\circ \quad (10)$$

From Eq.(10), the value of BC in Fig. (5b) can be found by substituting the value of $(\alpha 3)$ deduced from Eq. (10) into Eq.(5), as follows:

$$BC = BD * \tan(\alpha 3) \quad \Rightarrow BC = BD * \lim_{\alpha 3 = 15^\circ \to 90^\circ} \tan(\alpha 3) \quad (11)$$

From Eq. (11) the length of the line BC which represents the value of (F.S.) can be found by writing a program from which the value of $(\alpha 2)$ can be estimated from Eq.(3), and then the value of $(\alpha 3)$ can be predicted. Also it can be noticed that the maximum value of (F.S) occurres when the value of $(\alpha 3)$ equal to (45°).
Finally, from the derived equations can one study the effect of feed per tooth (*Ft*), the effective cutter radius (R_{11},R_{12}), and the effect of inclination angle of tool cutter relative to effective radius of cutter on the magnitude of feed-interval scallop height.

4. MATHEMATICAL DESCRIPTION OF EFFECTIVE CUTTER RADIUS OF TORUS (TOROIDAL) CUTTER

From Eq.(1), it can be noticed that R_{11} and R_{12} represent the effective cutter radius of the tool that will be utilized in the present work, where torus cutter will be used in this research as a cutter. So the effective radius of this type of cutter must be calculated depending on equation as follows: [9]

$$R_{effective} = \frac{R_1}{\sin\lambda} + R_2 = \frac{(R_1 + R_2 \sin\lambda)}{\sin\lambda} \tag{12}$$

Where, (R_1) are the radial distance of the cutter bottom and (R_2) the cutter corner radius as shown in **Fig.(6)**, and (λ) represents the lead angle (the inclination angle of the cutter tool axis).
From Eq.(12), the value of the inclination angle can be changed, and this means that the magnitude of the effective radius will also be changed. So this leads to change the value of (L) depending on Eq.(1), which means the value of (F.S) will be affected.

5. PROGRAMMING

In the present work Matlab program have been used so as to estimate the value of (F.S), and in this program the value of the pick-interval scallop height will be set as constant. **Fig.(7).**

6. EXPERIMENTAL WORK

The experimental work had been done in CAD/CAM laboratory , mechanical department in Nanjing University for Aeronautics and Astronautics in China, where multi-axis CNC milling machines had been utilized. The material of the specimens is aluminum and symbol of this type of aluminum as the American standard is (Al 2017) with heat treatment temperature equal to $497 \pm 3\,^{\circ}C$ at 40 ± 2 minutes and cooling temperature in water equal to $20 \rightarrow 30\,^{\circ}C$ for 4 minutes. In addition, the dimensions of the torus cutter used in the present work will be changed to four values(6, 8, 10 and 12 mm),as follows:
$\{(R_1 = 1, R_2 = 2), (R_1 = 2, R_2 = 2), (R_1 = 3, R_2 = 2), (R_1 = 4, R_2 = 2)\}mm$ respectively.
Where the magnitude of inclination angle of machining and the value of the feed per tooth will be changed as shown in **Table (1)**.

Also, electronic microscope connected with computer by a cable and LAN card were used to measure scallop height practically, and the scallop height is gauged by utilizing a spcifice program which is the frontage of the electronic microscope on computer. The technique of this program depends on taking three readings for three different dimensions and then calculating the average of these three readings and the magnitude of the average represents the factor of transformation the (*pix*) unit to (*mm*) unit.

Finally, from **Fig.(8)**, it can be recognized and demonstrated the difference between pick-interval scallop height and feed-interval scallop height.

7. RESULTS AND DISCUSSION

From the mathematical model and experimental work, it can be displayed that is data in curve form as shown in **Fig.(9 and 10)**.
From **Fig.(9)**, which represents the relation between feed per tooth (*Ft*) and feed interval scallop height (F.S) taking into consideration the inclination angle of machining (λ). It was found that the (F.S) will be increased with the increasing value of (*Ft*) for different values of (λ), Also it was found that the changeable value of lead angle (λ) affects on the magnitude of effective cutter radius ($R_{effective}$) , while it was found that the maximum value of effective cutter radius ($R_{effective}$) will occur at lead angle = 15° and this leads to decrease the value of feed interval scallop height, where the increasing value of $R_{effective}$ leads to increase the area of contact between the tool and the workpiece surface and this is the main reason to decrease the magnitude of (F.S).

From **Fig.(10)**, which represents the relation between inclination angle of machining (lead angle λ) and feed interval scallop height (F.S) taking into consideration the tool diameter. It was found that the (F.S) will decrease with the increasing value of tool diameter for different values of (λ), and the minimum value of (F.S) will occur at the lead angle equal to (15°), because at this angle the effective cutter radius will be equal to maximum value (5.86 mm), and this means the area of contact between the tool and the workpiece surface will be increased, so this leads to decrease the value of (F.S).

8. CONCLUSIONS

In the present research the theoretical model and experimental verification of the feed-interval scallop formation (F.S) on the machine surface profile using the torus cutter has been studied . Feed per tooth, effective cutter radius and inclination angle of the tool axis, were taken into consideration in the present work as the cutting parameters, so as to study the effect of these parameters on the magnitude of feed-interval scallop height.

It was found that at the high-speed machining, the feed-interval scallop is more important to the surface roughness than the path-interval scallop. It was also found that the feed-interval scallop is very sensitive to the tool-axis inclination angle. The feed-interval scallop height decreases sharply and quickly within few degrees of the tool-axis inclination to the normal workpiece surface.

In general, an inclination angle equal to 15° is good enough for most tool diameters from the surface roughness viewpoint. Also, the effective cutter radius must be taken in our consideration to study its effect on (F.S) instead of cutter's radius.

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List of symbols

Symbol	Definition
CAD	Computer-Aided Design.
CAM	Computer-Aided Manufacturing.
CC	Shortcut of cutter contact.
CL	Shortcut of cutter location.
CNC	Computer Numerical Control.
R	The cutter radius.
R_1	The radial distance of the cutter bottom.
R_2	The cutter corner radius.
$R_{effective}$	Effective cutter radius
Ft	Feed per tooth.
F.S.	Feed-interval scallop height.
h	Pick-interval scallop height.
S	Stepover.
ϕ	The angle restricted between the axis of the tool and the axis which pass through the cutter contact point.
λ	The lead angle of the cutter relative to the local coordinate system.

Table (1): The changeable magnitude of inclination angle and the value of the feed per tooth that utilized in the present research.

Inclination angle (λ°)	Feed per tooth (Ft) (mm)			
0°	0.1	0.2	0.3	0.4
15°	0.1	0.2	0.3	0.4
30°	0.1	0.2	0.3	0.4
45°	0.1	0.2	0.3	0.4

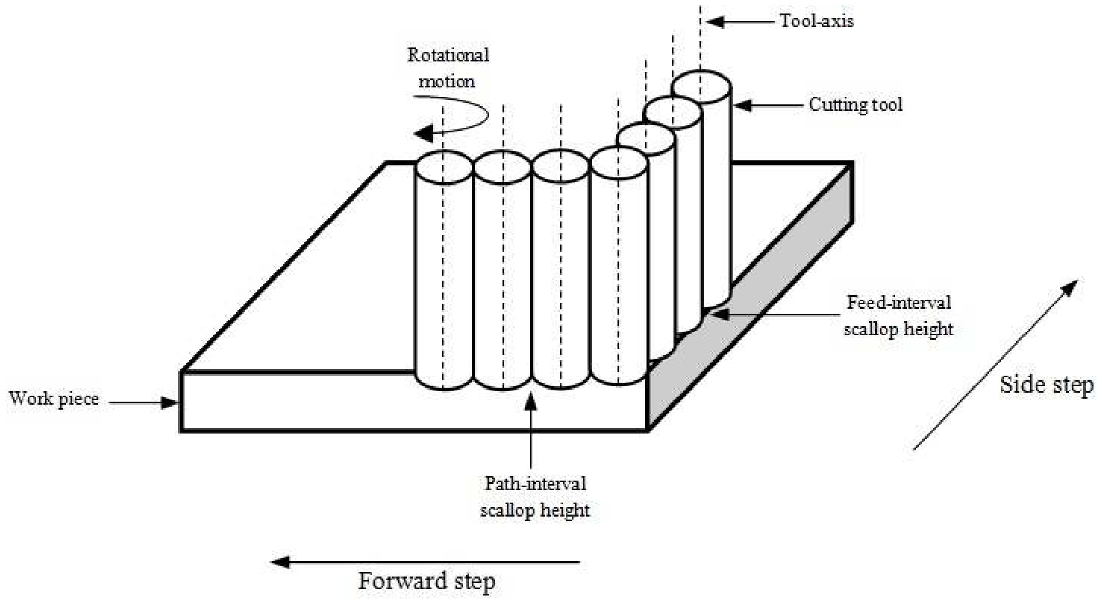


Figure (1): The generation of two types of scallop height depending on the direction of the tool motion.

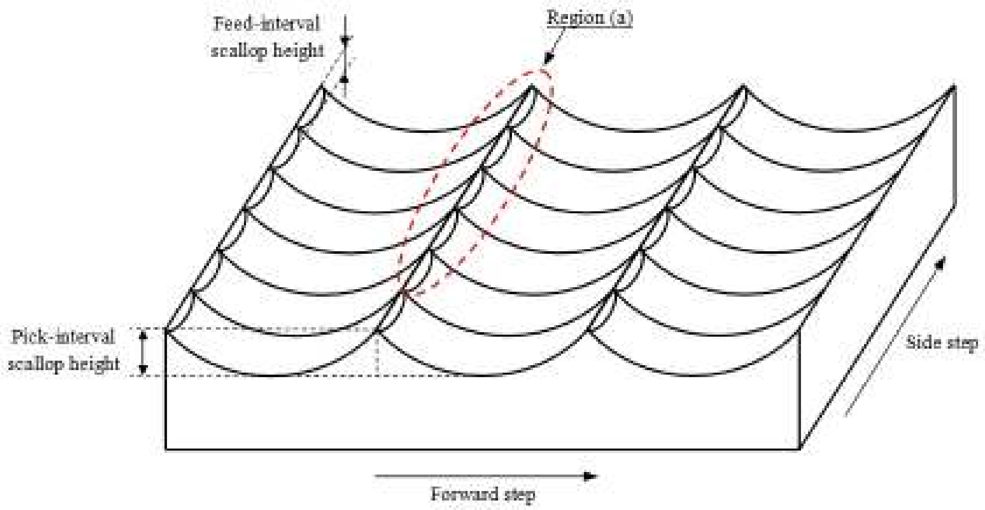


Figure (2): The pick-interval and feed-interval scallop height.

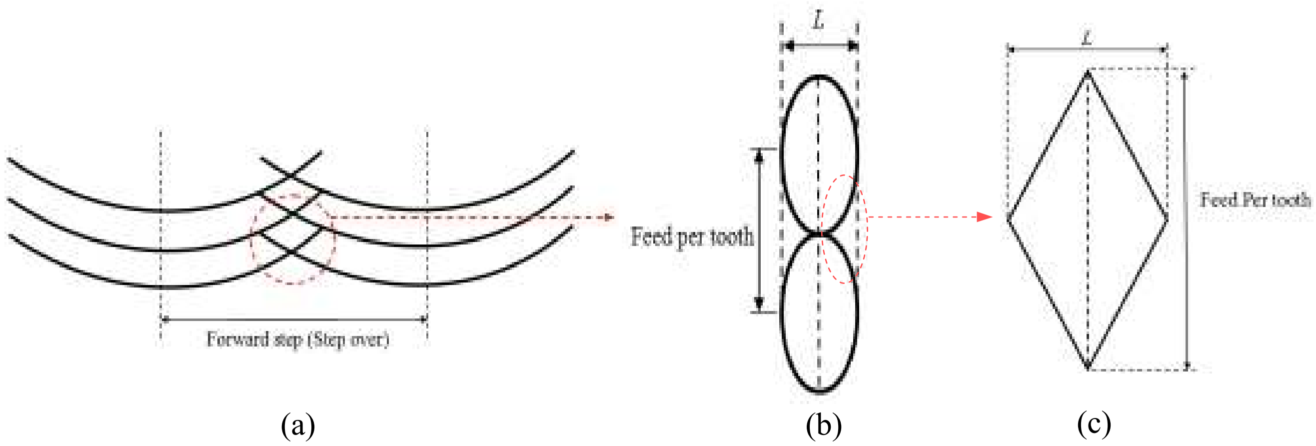


Figure (3 a, b & c): The modeling of the feed-interval scallop.

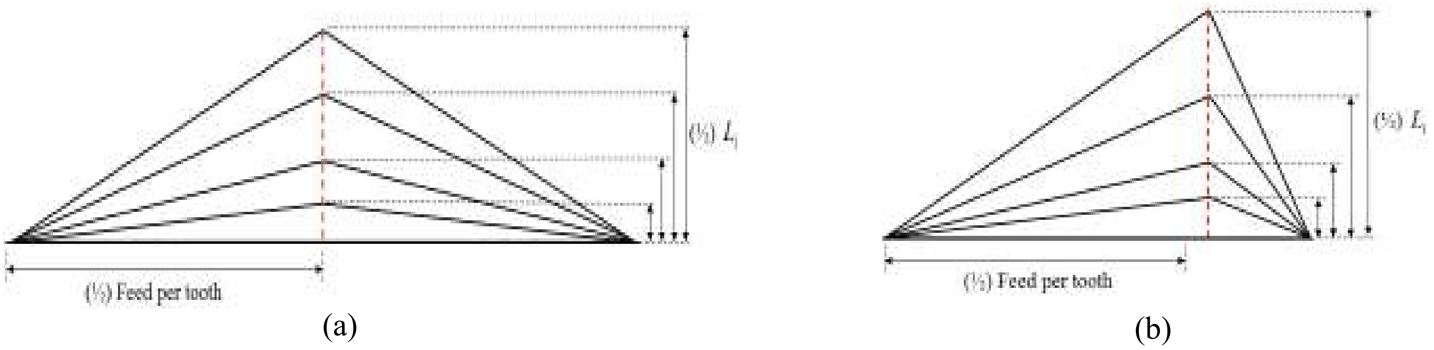


Figure (4 a and b): The feed-interval scallop height generated between two successive motion of forward step over.

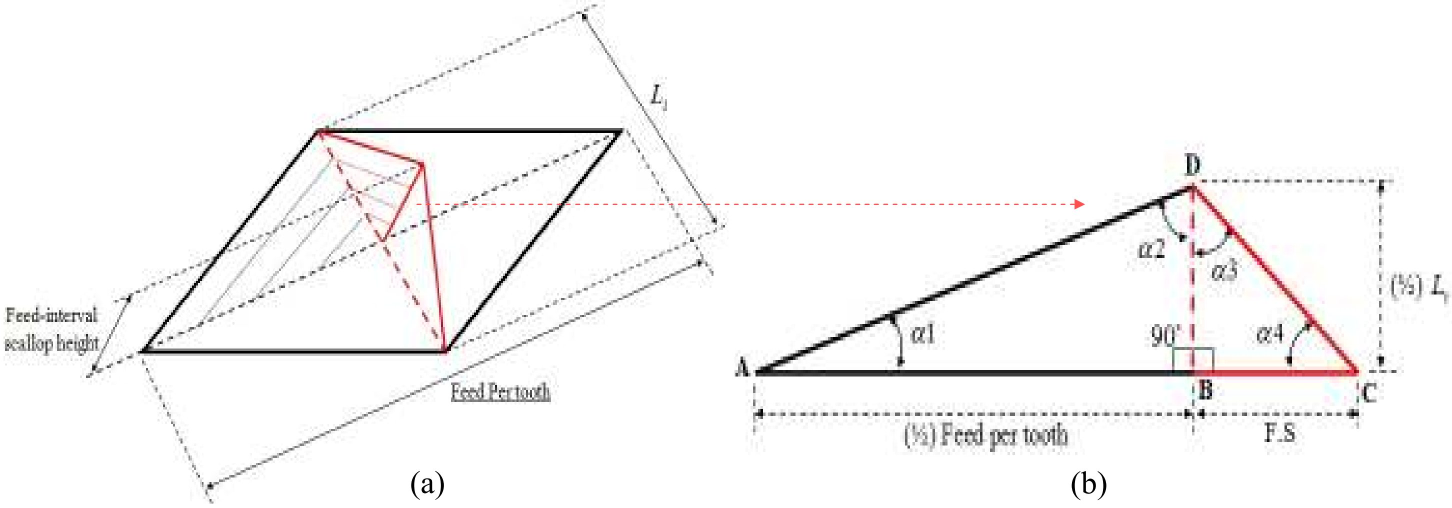


Figure (5 a and b): The mathematical description of feed-interval scallop height.

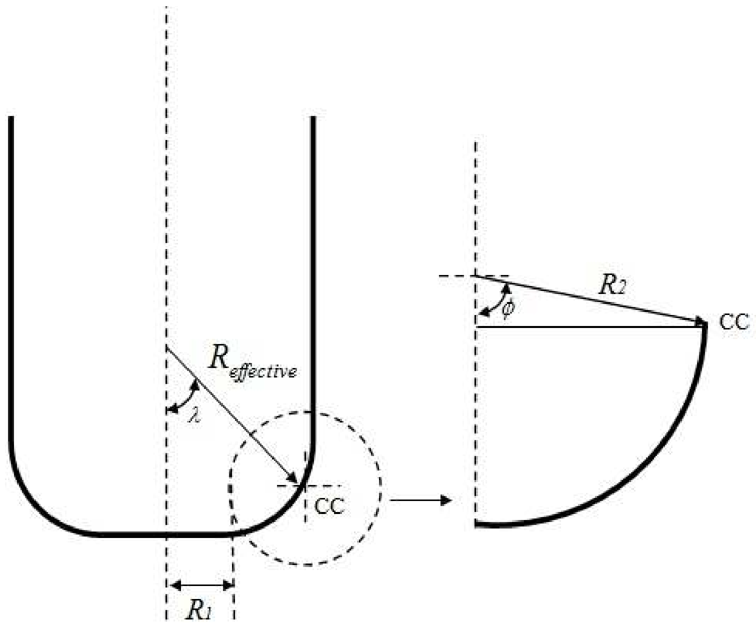


Figure (6): The geometrical shape of torus cutter.

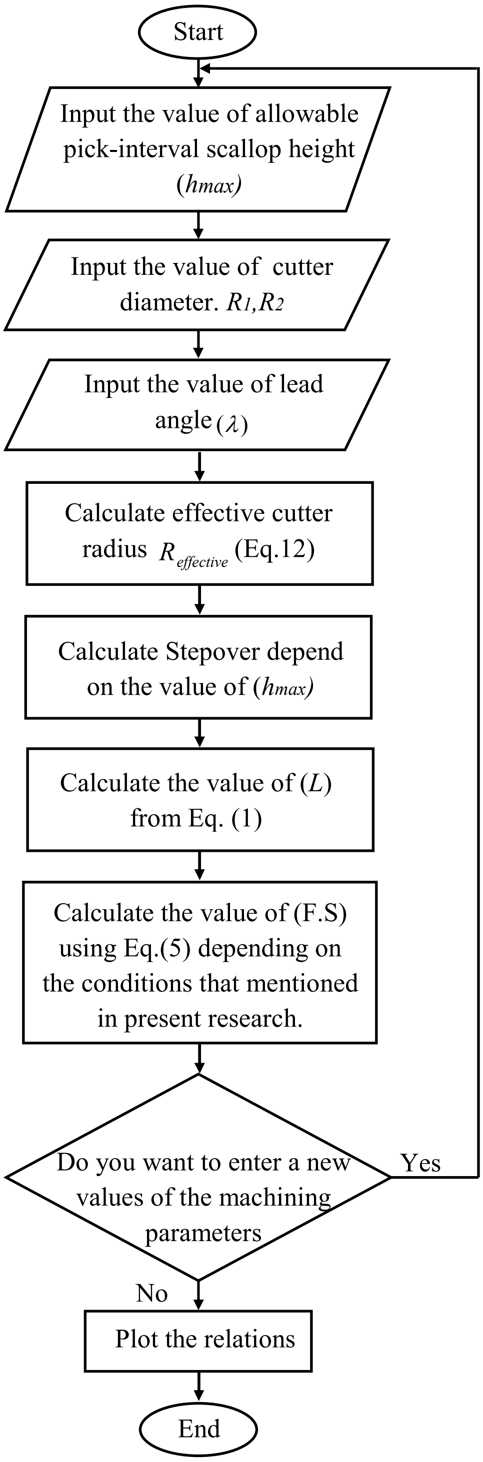
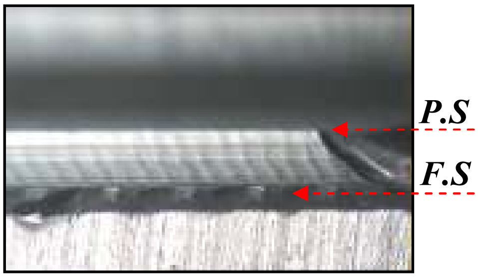


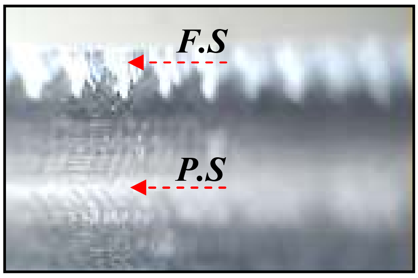
Figure (7): Flowchart explaining the steps of the program built in the present research.

(a) Pick-interval scallop height.

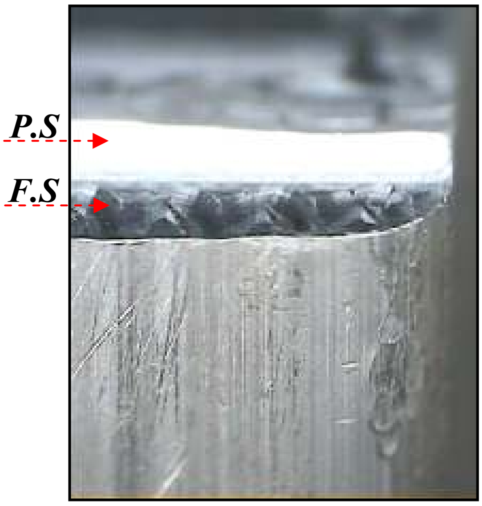


(b) Pick-interval scallop height and feed-interval scallop height.

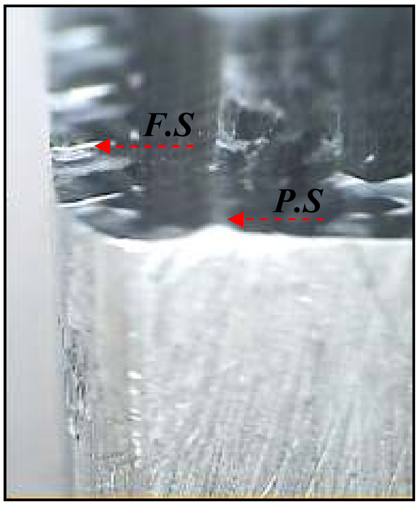
(c)



(d)



(e)



(f)

Figure(8 a, b, c, d, e and f): The two types of scallop height that generated through the machining process using torus cutter in different diameters and different inclination angle of cutting relative to variable values of feed per tooth [*Ft=0.1,0.2,0.3,0.4*] *mm*.

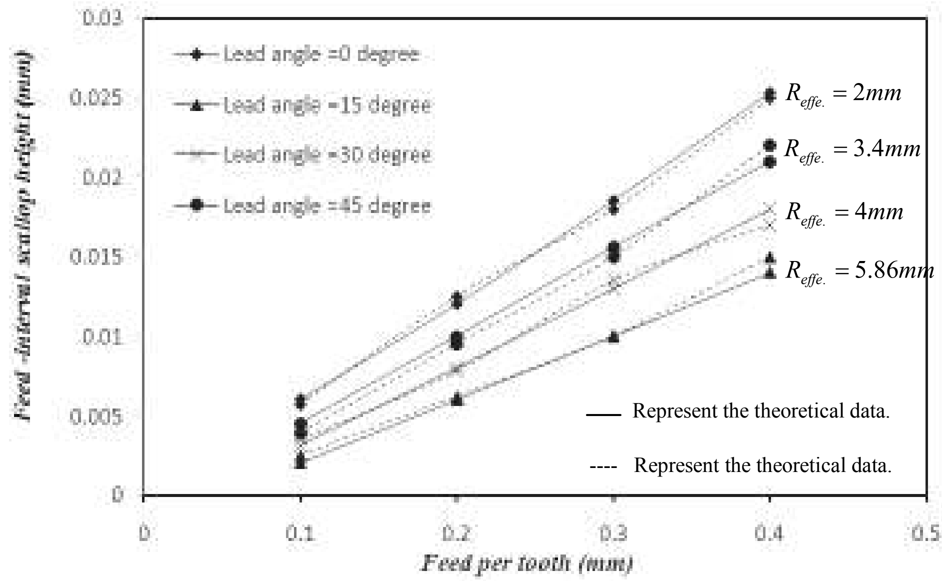


Figure (9): The relation between feed-interval scallop height and feed per tooth relative effective radius of cutter in theoretically and experimentally .

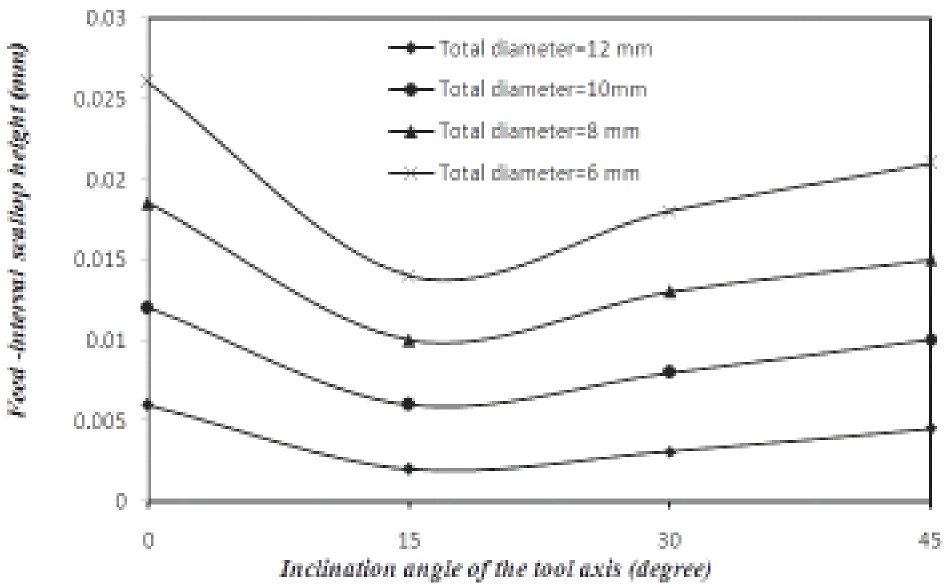


Figure (10): The relation between feed-interval scallop height and inclination angle of the tool axis (λ) relative to total cutter diameters.

حســـاب قيمة الارتفـــاع التــــموجي باتـــجاه التغــذية باستخدام مــكـــائن التــحكم الرقمـــي المتعـــددة المحـــاور

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الخلاصـــة:

في هذا البحث تم اشتقاق المعادلات لبناء موديل رياضيَ يمكن من خلاله حساب قيمة الارتفاع التموجي باتجاه التغذية، حيث أن هناك نوعان من الارتفاعات التموجية، الأول يسمى الارتفاع التموجي باتجاه مسار العدة والأخر يسمى الارتفاع التموجي باتجاه تغذية العدة، ويتكون الأول نتيجة الحركة لعدة القطع بين موقعين متتاليين باتجاه مسار العدة أما الثاني فيتكون نتيجة الحركة لعدة القطع ما بين موقعين متتاليين باتجاه التغذية، تم وصف هذا النوع من الارتفاعات باستخدام العدة (Torus) والذي يستخدم بصورة شائعة في مكائن التفريز المتعددة المحاور، كذلك تم دراسة تأثير بعض من متغيرات القطع على قيمة هذا النوع من الارتفاعات مثل (نصف القطر الفعال للعدة، نسبة التغذية لكل سن قاطع وقيمة زاوية ميلان العدة) حيث تم تغيير قيم تلك المتغيرات نظريا وعملياً لمعرفة تأثيرها على قيمة الارتفاع التموجي باتجاه التغذية. تبين من خلال الجانب النظري والجانب العملي للبحث الحالي وعند قيم سرع قطع عالية، أن قيمة الارتفاع التموجي باتجاه التغذية أهم من قيمة الارتفاع التموجي باتجاه مسار العدة نسبة إلى الخشونة السطحية للسطح المشغل. كذلك وجد أن قيمة الارتفاع التموجي باتجاه التغذية تتأثر بصورة كبيرة بقيمة زاوية ميلان العدة، حيث لوحظ أن قيمة هذا النوع من الارتفاعات تقل بصورة واضحة وسريعة نسبة إلى التغير البسيط في قيمة زاوية الميلان، وبصورة عامة وجد من خلال البحث أن قيمة زاوية الميلان والمساوية إلى 15° هي أفضل قيمة يمكن من خلالها الحصول على اقل قيمة للارتفاع التموجي باتجاه التغذية لكل أقطار العدة المستخدمة خلال البحث الحالي.