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The Influence of Process Variables for Milling Sculptured Surfaces on Surface Roughness

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Abstract

Increasing the variety of products that are being designed with sculptured surfaces, efficient machining of these surfaces has become more important in many manufacturing industries. The objective of the present work is the investigation of milling parameters for the sculptured surfaces that effecting of surface roughness during machining of Al-alloy. The machining operation implemented on C-TEK CNC milling machine. The influence of the selected variables on the chosen characteristics have been accomplished using Taguchi design approach, also ANOVA had been utilized to evaluate the contributions of each parameter on process outcomes. Three strategies of tool path (Zig, Zig-Zag and follow periphery), and three levels of spindle speeds (1700, 2200 and 2700 rpm), with three feed rates (200, 400 and 600 mm/min). The results showed that low surface roughness values produced with the zig-zag strategy, higher speeds (2700) rpm and lower feed rates (200) mm/min. The analysis of variance approach ANOVA showed that the strategy of tool paths was the most affecting variables on surface roughness with percentage of contribution of (42.25 %).

***Keywords*:** *Sculptured surface, surface roughness, ANOVA, tool path strategy.*

1. Introduction

Milling sculptured part surfaces is different from milling the regular surface parts, the cause of that is, it could be traced back to the differences of sculptured and regular surfaces nature especially in the freedom of sculptured surface modeling [1]. The main characteristics of machined sculptured surfaces are the shape and the actual designing parameters. They strongly depend on the parameters for the operation of the surface generation [2]. Milling sculptured surface in carried out with two stages: rough milling and finishing. The first stage of cutting used for removing the large amount of work piece material and leaves slightly oversized material of the part that removed in the next stage. Finishing is the processes that remove the remaining material from the roughing of the sculptured surfaces work piece and gives final dimensions for machining the desired parts. The result surfaces are produced with a numbers of scallop heights. Thus that lead to the surface roughness on the machined parts and it is important to be investigated for improving the surface quality for the final product [3]. Surface roughness of engineering parts is very important variable, where the quality of any machined part depending on it. Detailed assessment is essential for carrying out precisely and analyzing the micro geometry of surfaces [4]. The roughness of surfaces for the manufactured part is one of the important characteristics to insure the quality of the products.

In 2013 Jatin & Sharma [5] investigated the effecting of a various cutting variables (feed rate, cutting speeds depth of cuts) in end mills on the

Surface Roughness. The calculations have done by utilizing Taguchi designing method. In addition to the S/N Ratio, also ANOVA have illustrated to clarify the Impact of variables through the result data. Their studies has been illustrated in milling process for hardened die steel H-13, using flat-end cutter with four flue of solid carbide for finishing process. The results show that surface roughness decreases at the increasing of cutting speeds.

Simunovic (2013) [6] Studied the influence of milling parameters (number of revolution, feed rate and depth of cut) on the surface roughness of aluminum alloy. A statistical (regression) model has been developed to predict the surface roughness by using the methodology of experimental design. Central composite design is chosen for fitting response surface. Also, numerical optimization considering two goals simultaneously (minimum propagation of error and minimum roughness) has been performed throughout the experimental region. It has been found that feed rate and number of revolutions, as well as the interaction between the feed rate and number of revolutions are significant.

Zeljkovic M., et al. (2017) [7]: identify optimum machining parameters on surface quality of sculptured parts. The effect of various machining process parameters such as machining strategy, feed, depth of cut and spindle speed on roughness of surfaces through three-axis end-mill of sculptured parts have been studied by performing a number of experiments constructed according to standard Taguchi's L9 orthogonal array design matrix. Grey relational analysis method was used to find the optimal machining process parameters and analysis of variance was carried out to find the significance and contribution of each machining parameter on performance characteristics.

2. Taguchi Experimental Design Method

Taguchi method is depending on that the machined parts quality must be computed by the deviation amount from the required value. He takes into consideration not only the process mean, but also by the variation magnitudes or "noise" created with manipulating inputs parameters or operation variables. This technique is depending on two groups; a unique kind of matrix called "orthogonal array (OA)", the columns include a number of tests depending on the no. of levels of controlling parameters, and (S/N) the signals to noise ratio [8,9]. The expression 'signal' indicating of the required of the output characteristics values "mean" and the expression 'niose' indicating of unrequired values. S/N ratios calculation is varying based on objectives functions, i.e., a characteristics amount. Designing the method using MINITAB16 program as follow:

STAT ⟶ DOE ⟶ Taguchi ⟶ Create Taguchi design

3. Variance Analysis

The experimental work results could be investigated by (ANOVA) variance analysis to discover the effecting of machining variables (tool path strategies, spindle speeds and feed rates) on surface roughness through the entire process. In the analysis, the ratio between mean square errors and residual called F- ratio and it utilized for determining the importance of a parameter. F ratio correspondent to 95% reliable levels in calculations of the operation variables. P values are the report of importance levels of each parameter (appropriate and inappropriate) [10, 11].

4. Sculptured Surface Representation

In this paper Bezier technique illustrated for representing the proposed study surface. Using the sixth order degree with seven control points to the entire surface for representing the required surface of the product, and the equation of the proposed Bezier surfaces is:

$$F(u,w) = UM_B P M_B^T W^T \qquad \ldots(1)$$

$$M_b = \begin{bmatrix} 1 & -6 & 15 & -32 & 15 & -6 & 1 \\ -6 & 30 & -60 & 60 & -30 & 6 & 0 \\ 15 & -60 & 90 & -60 & 15 & 0 & 0 \\ -32 & 60 & -60 & 20 & 0 & 0 & 0 \\ 15 & -30 & 15 & 0 & 0 & 0 & 0 \\ -6 & 6 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$U = [u^6 \; u^5 \; u^4 \; u^3 \; u^2 \; u \; 1]$$

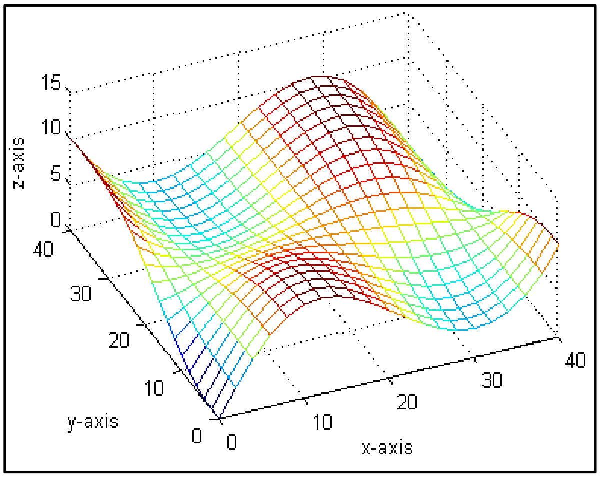
$$W = [u^6 \; u^5 \; u^4 \; u^3 \; u^2 \; u \; 1]$$

Where U and W are the vectors of surface parameters, M_b is the Bezier basis function matrix that represents the Bezier surface and (P) is the vertex information matrix (control point) with (49) control points. The Bezier basis functions are derived from Bernstein polynomial for the parametric coefficients [12].

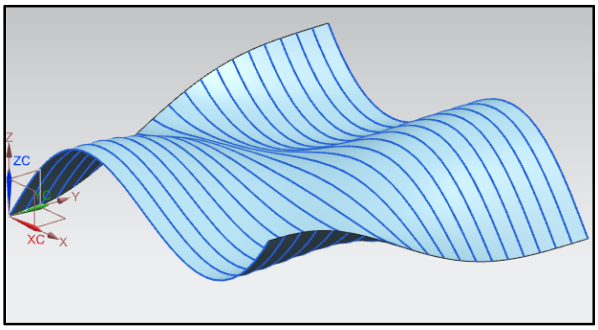
The creation of CAD modeling has been implemented utilizing Bezier technique depend on the algorithm through selecting the required control point matrices using MATLAB software, and transferring the CAD data to UG-NX software for generating the tool paths and post-processing that required for implementing the machining process. The CAD module, where profile of the curves generating the surfaces is modeled-using MATLAB and then transferred to the UGS-NX9-through TXT data-exchanges file to view the required shape. After the construction of the Bezier surface converted to a series of curves using Iso-parametric conversion scheme Figure (1) shows the proposed surface using MATLAB software and the part after transferring the CAD data to UG-NX.

The data of the curves have been represented and saved in a single matrix of (n x 3), where n is the number of rows which is equal to n =1+ 1/Δu, where Δu is the increment of the independent parameter. Each matrix is saved as (txt) file and exported to the UG-NX program.

After importing the curves in UG-NX software, a skinning procedure for these curves have been implemented to accomplish the final shape of the surface.



(a)

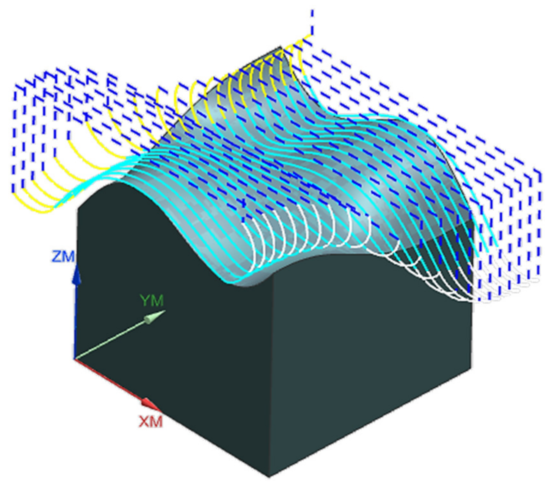


(b)

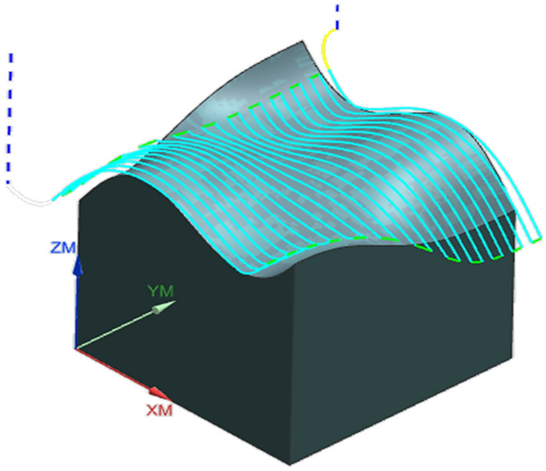
Fig. 1. (a) The proposed surface using MATLAB, (b) Transferring the CAD data to UG-NX software.

5. Tool Path Generation

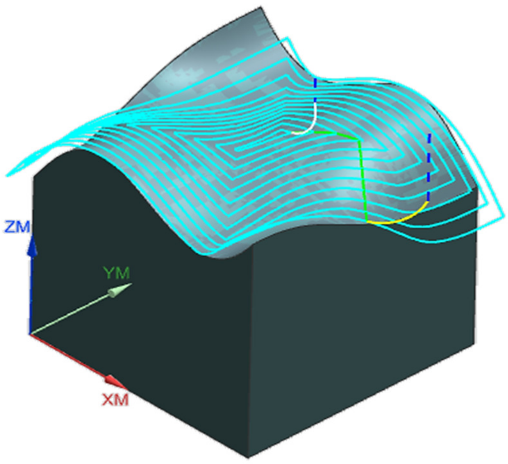
After the completion of representing CAD models, it is followed by the tool path generation for designed part utilizing UG-NX software. There are several steps had to be taken for the creation of the actual tool paths, the process has two phases, first one is creating tool paths for roughing, where the requirement must be chosen for this stage, such as (Machining method, tool Geometries, tools diameter, strategy of tool paths …etc.). The second phase is creating tool path for finish machining. In finishing process the side step value of the tool paths is very small compared to roughing process three deferent strategies have been implemented in this work; Zig, Zig-Zag and follow periphery strategies. Figure (2) shows the three illustrated types of tool path strategy.



(a)



(b)



(c)

Fig. 2. Deferent strategies of tool paths (a) Zig, (b) Zig-Zag, (c) Follow periphery.

6. Machines and Tools

The experiments have been conducted on 3-axis CNC milling machine which is existed in workshop training Center in University of technology, with work piece dimension (40 x 40) mm and thick (40) mm. This operation needs some accessories and experimental setup, the main elements that must be used in the milling machine can be divided into the following elements:

6.1. Machine of Milling Process

Figure (3) shows the 3-axis CNC machine of milling operation type (C-TEK) with model (KM80D) that used in the machining process of the samples which machined in the present work.

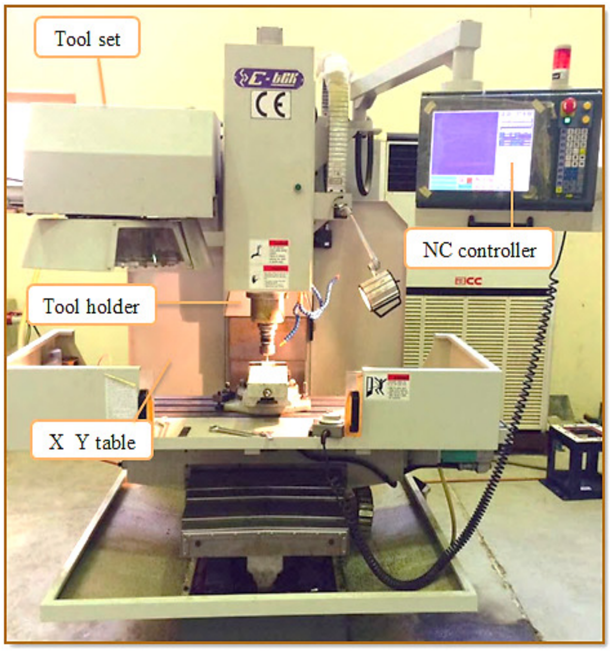


Fig. 3. CNC C-TEK milling machine.

6.2. Cutting Tool

Flat-end milling tools (Ø 10 mm) dia., with four flutes and flute length equal to (40 mm) of High-Speed Steel (HSS) utilized for rough milling phase, and ball-end milling tools (Ø 12 mm) dia. for finishing. The cutting tools are shown in figure (4).

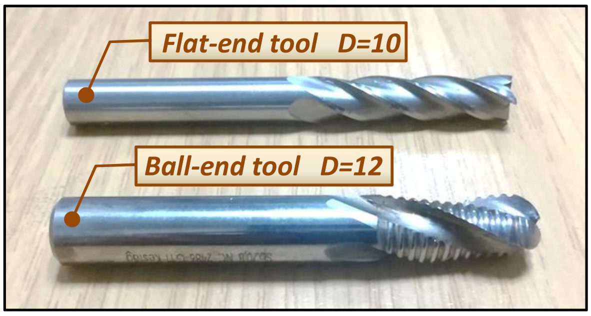


Fig. 4. Cutting tools.

6.3. Work Piece

Al-7024 alloy work piece is chosen to be milled. The chemical composition was tested in the "Central Organization for Standardization and Quality Controls". Tables (1) and (2) show the chemical composing and the mechanical properties of the work piece respectively.

Table 1,
Chemical composition of Aluminum 7024.

Si %	Fe%	Cu %	Mn%	Mg%	Cr%	Ni%
0.18	0.41	2.17	0.19	1.57	0.092	0.014
Zn%	Ti%	Ga %	V %	Pb %	Other	AL%
4.91	0.039	0.012	0.009	0.072	0.134	90.21

Table 2,
Mechanical properties of Aluminum 7024.

Ultimate Tensile Strength (MPa)	Tensile Yield Strength (MPa)	Elongation to Failure (%)	Modulus of Elasticity (GPa)	Hardness Brinell
469	324	20%	73.1	231

6.4. Designing of Experiments

The designing of experimental tests using Taguchi approach had a great influence on the required experimental tests numbers. Accordingly, the experiments of machining required an appropriate design. The overall number of machining experimental tests is (9) experiments, on the basis of (3) levels and (3) variables (3^3). The levels of milling parameters are listed in Table (3).

Table 3,
Cutting variables.

No	Parameter	Level 1	Level 2	Level 3
1	Spindle	1700	2200	2700
2	Speed	Zig	Zig-Zag	Follow Periphery
3	Strategy	200	400	600

The final distributional division of the experimental tests and the level of each experiment are clarified on table (4) depending on the Taguchi experimental design method:

Table 4,
Experimental design of work.

No.	Spindle Speed (r.p.m)	Tool path Strategy	Feed rate (mm/min)
1	1700	Zig	200
2	1700	Zig-Zag	400
3	1700	Follow Periphery	600
4	2200	Zig	400
5	2200	Zig-Zag	600
6	2200	Follow Periphery	200
7	2700	Zig	600
8	2700	Zig-Zag	200
9	2700	Follow Periphery	400

6.5. Implementation the Machining Process

The milling process is done in two processes; rough machining and finishing, removing materials take place on a rapid way as much as possible in rough machining. In this process, a higher material removal rate is used for minimizing the process time. Rough machining in most cases illustrated in parallel levels of layers accessing to the exact depths. The quality of the final surfaces is not reliable, where that layers removed by subsequent process (finishing process). Figure (5) shows the samples after machining.

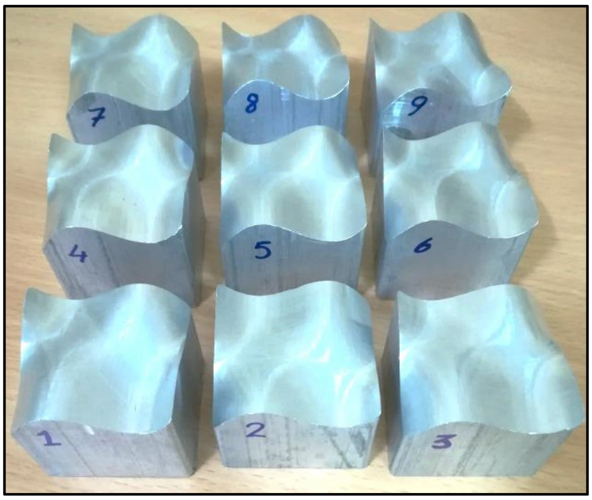


Fig. 5. Samples after machining.

6.6. Surface Roughness Inspection

Pocket-Surf, the portable gauge of surface finish (Mahr Federals patented). The gauge is a pocket sized, which has a suitable economical price, integral portable device, provides a tracing for surface roughness measurement through widely surface types. The instrument probe has a durable cast-aluminum structure to obtain long time accurately dependable surface roughness inspection shown in fig (6-a).

Since the proposed surface in the present work is sculptured surface, the measurement process of the surface roughness for such surfaces needs to make the instrument inclined with suitable angles which make the tracer parallel to the surface, so a special holder has been used to fix the instrument, this holder has the ability to move up and down with inclined motion of multi angles to ensure tracing the surface geometry in parallel way as it illustrated in fig (6-b).

(a)

(b)

Fig. 6. (a) Pocket-surf gauging instrument, (b) measurement process using the movable holder.

7. Result and Discussions

Table (5) represents the experimental results of machining the Al-alloy samples and the surface roughness according to the orthogonal array

Table 5,
The values of measured roughness

No.	Speed	Strategy	Feed rate	Surface Roughness
1	1700	Zig	200	1.12
2	1700	Zig-Zag	400	1.06
3	1700	Follow Periphery	600	1.336
4	2200	Zig	400	1.048
5	2200	Zig-Zag	600	1.096
6	2200	Follow Periphery	200	1.056
7	2700	Zig	600	1.24
8	2700	Zig-Zag	200	0.776
9	2700	Follow Periphery	400	1.26

7.1. Effect of Tool Path Strategies and Feed Rate on Surface Roughness

The figure (7) shows the effecting of tool path strategy and the feed rate on surface roughness, the graph clarified that increasing the feed rate give a high values of the surface roughness and the reason of that belong to increasing the temperature of cutting and the reason of that belongs to increasing the friction between the tool and the metal surface leading to overheat states, and thus will oxidize the outer surface and producing a rough surface finish. On the other hand the better surface finish obtained using Zig-Ziag tool path strategy among them.

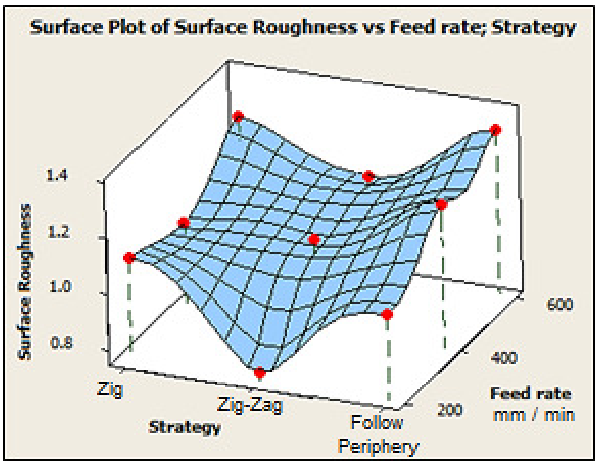


Fig. 7. Effect of the strategy and feed rate on surface roughness.

7.2. Effect of Spindle Speed and Tool Path Strategies on Surface Roughness

Figure (8) shows the effects plot of machining factors (spindle speed and the tool path strategy) on surface roughness, it can be noted that increasing the spindle speed values decreasing the surface roughness, where increasing the revolutions of the cutter will repeat the passing of cutter edge on closer regions removing the numbers of scallop heights. On the other hand the maximum values of surface roughness obtained by using the follow periphery strategy, while the lower values obtained using Zig-Zag strategy.

Through testing multi tools for implementing the finishing stage, it found that using ball-end tool with (12 mm) in diameter for generating tool paths giving lower values of scallop heights which leads to less surface roughness in machined surface in case the diameter doesn't exceed the lowest value of concavity that existing in the surface to prevent occurring the gauging areas. Beside, implementing the follow periphery strategy for generating the required tool path for the surfaces will effect on machining time, where it takes shorter time than using Zig and Zig-Zag strategies. And the reason of that belongs to the distribution of the tool paths, where in this type of strategy the cutter path tracing the regions of the required geometry and its not necessary to reach the regions that doesn't need to be machined, contrariwise with other types that may reach to regions doesn't need for machining just to complete the straight line along the path.

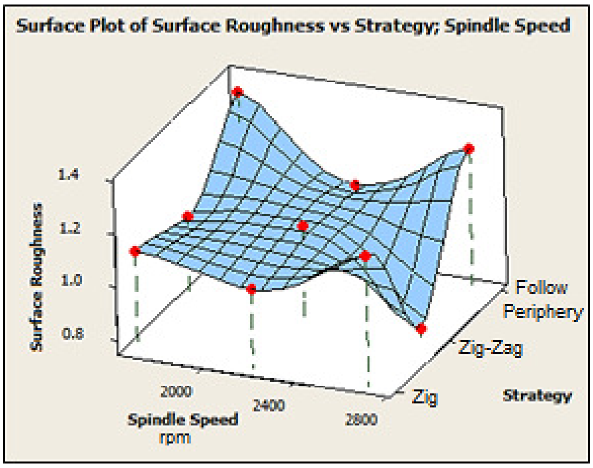


Fig. 8. Effect of spindle speed and strategy on surface roughness.

7.3. Analysis of Variance

The experimental results are analyzed by using analysis of variance (ANOVA) to determine the effect of machining parameters on the surface roughness, surface roughness as the dependent variable, tool path strategy, spindle speed and feed rate as independent variables. The F ratio value of 2.19 for the tool path strategy is greater among the parameters (see Table 6). Therefore, the most influential parameter is tool path strategy (42.3 %) for minimum surface roughness, and the next significant parameter is feed rate with (41.2%). Finally, the spindle speed has the smallest influence with (8.57%). Mean value of surface roughness Ra and signal to noise ratio are shown in figures (9 and 10). These figures clarifies the effect of process parameters on the output roughness, it can be seen that increasing the feed rate increasing the roughness, where the best surface roughness obtained with (200 mm/min). On the other hand, the lower spindle speeds increase the surface roughness values, where heights Ra given with (1700 rpm). And the best surface roughness obtained using Zig-Zag tool path strategy.

Table 6,
Analysis of Variance for Roughness

Source of variance	DOF	Sum of squares	Variance V	F ratio	P (%)
Spindle speed	2	0.0181	0.009	0.28	8.57
Strategy	2	0.0894	0.045	2.19	42.3
Feed rate	2	0.038	0.019	2.10	41.2
Error ,e	2	0.118	0.059		8.02
Total	8	2.07			100

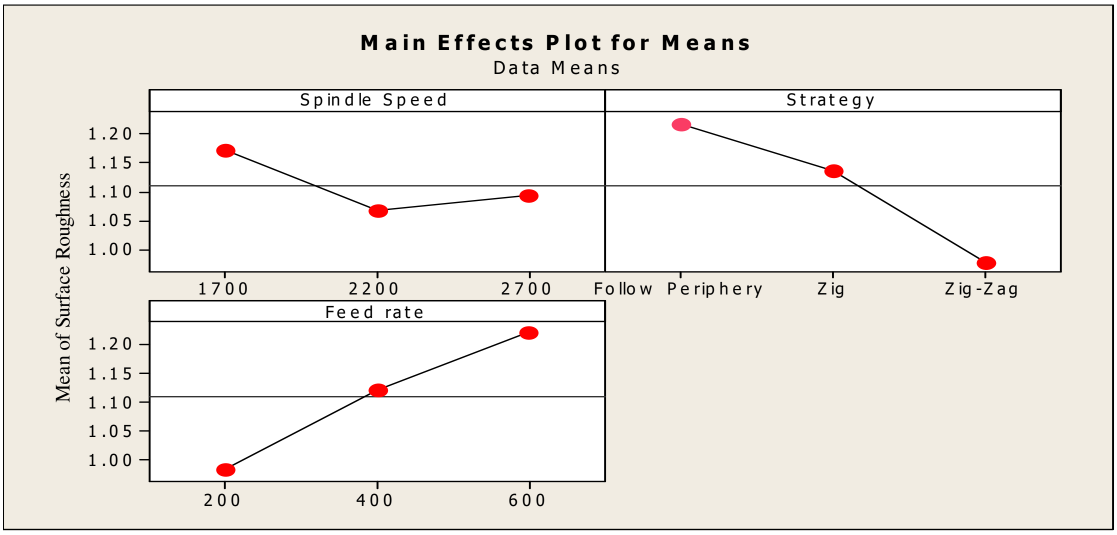


Fig. 9. Main effect plot for means of roughness.

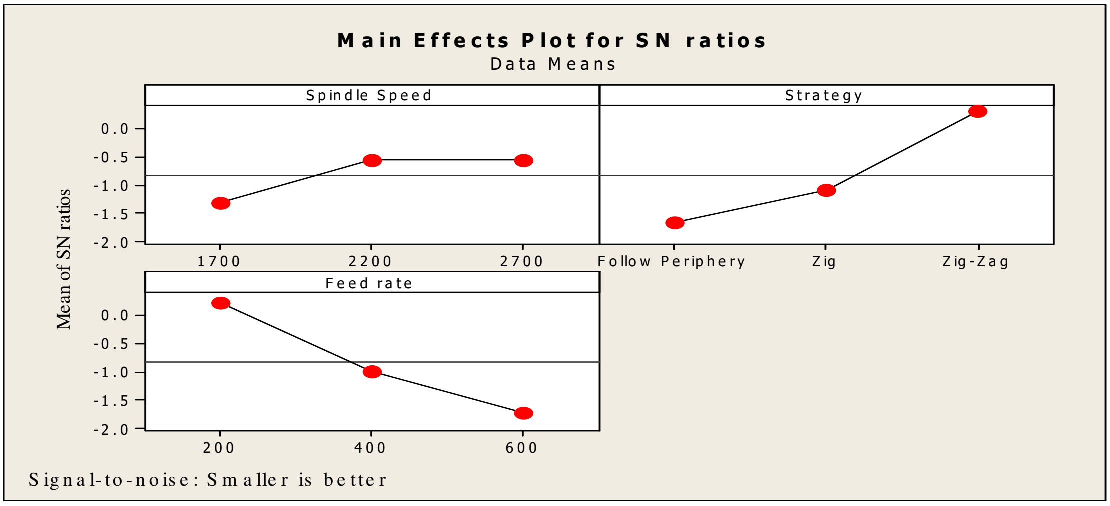


Fig. 10. Main effect plot for means of roughness.

From figure (11) it can be seen that the tool path strategy the most significant parameter affecting on surface roughness, this is because the strategy of motion of tool is responsible for generating the final surface. Then the feed rate, while the spindle speed is the less effective parameter on the process among the other variables.

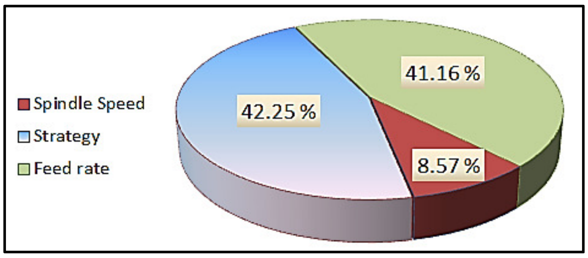


Fig. 11. The percentage of contribution of the three parameters on the process.

8. Conclusions

To summarize the concluded influences that deduced from these experiments could be sum up in:

- The best combination of machining factors for giving the minimum surface roughness (Ra) among (tool path strategies, spindle speed and feed rate) is: (Zig-Zag tool path, 2700 rpm and 200 mm/min) respectively.
- Tool path strategy has the highest effect with (42.25%) the feed rate and the spindle speed has the smallest influence on the surface roughness.
- Using ball-end tool with (12 mm) in diameter for generating tool paths, will give lower value of scallop heights which leads to less surface roughness in machined surface in case the diameter doesn't exceed the lowest value of concavity that existing in the surface to prevent occurring the gauging areas.
- Implementing follow periphery strategy for generating the required tool path for the surfaces will effect on machining time, where it takes shorter time than using Zig and Zig-Zag strategies.

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تأثير متغيرات عملية التفريز للاسطح الحرة على الخشونة السطحية

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الخلاصة

ان الهدف البحث هو التحقيق في مدى تأثير متغيرات عملية التفريز للاسطح الحرة على الخشونة السطحية لتشغيل عينات من الالمنيوم. عملية التشغيل نفذت على ماكنة تفريز مبرمجة نوع C-TEK.تأثير هذه المتغيرات التي تم تحديدها تمت بأستخدام طريقة تاكوشي، كذلك تم استخدام تقنية تحليل العناصر لأختبار نسبة مساهمة كل متغير وتأثيره على العملية. ثلاث استرتيجيات من مسارات العدد وهي (Zig، Zig-Zag و Follow periphery)، و ثلاث مستويات من السرع الدورانية (١٧٠٠، ٢٢٠٠ و ٢٧٠٠ دورة بالدقيقة). اضافة الى ثلاث معدلات للتغذية (٢٠٠، ٤٠٠ و ٦٠٠ملم / دقيقة). النتائج اظهرت ان اقل قيم للخشونة السطحية تم الحصول عليها عند استخدام استراتيجية Zig-Zag واعلى سرعة دورانية (٢٧٠٠ دورة بالدقيقة) واقل معدل تغذية (٢٠٠ ملم/دقيقة) .ان طريقة تحليل العناصر اظهرت ان استرتيجيات مسار العدد هي الاكثر تأثيرا من باقي المتغيرات بنسبة مساهمة وصلت الى (٤٢,٢٥ %).