Retraction:

Le, T. S., Nguyen, D. T., Chau, M. Q., Truong, T. H., & Nguyen, L. H. (2020).
A Study on the Effect of Tool-Path Strategy When Machining a Saddle-Free Surface in 3-Axis CNC Machine. International Journal on Advanced Science, Engineering and Information Technology, 10(6), 2320.
doi:10.18517/ijaseit.10.6.13054

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Available online: 31 December 2020

This article has been retracted by International Journal on Advanced Science, Engineering and Information Technology

Editorial team, following clear correspondence and confirmation with authors.

The paper is retracted from 29 November 2021.

International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 6
ISSN: 2088-5334

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Abstract*— The development of the CNC machine and its advantages led to the constantly developing fields for this system, which are CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing). However, surface issues were rarely mentioned in these studies, but mainly on tool path calculations or cutting modes. Reasonable selection of cutting tools, optimal tooling strategy for surfaces, and cutting mode parameters impact productivity and form quality of details containing complex surfaces. This study evaluates free surface based on Gaussian curvature and mean curvature, thereby providing a suitable instrument selection for the evaluated free surface areas. In this paper, the authors analyze and select tools and tool paths when machining freedom faces on 3-axis CNC machines to satisfy surface shaping accuracy requirements and reduce machining time related to the traditional freedom-face machining method. Before doing experimental research, the authors designed experimental samples on CATIA V5R20, simulating the machining process to verify the theoretical calculation. Empirical models for machining on 3-axis CNC milling machines were built and measured the parameters on 3-coordinate measuring machines to evaluate the effect of tool selection and tool paths in the machining of freedom surface areas. Experimental results show that the tool path when machining freedom surfaces dramatically affects the quality of freedom surface shaping. Moreover, the experimental results also show that when processing saddle-face samples, the one direction tooling path should be selected.

***Keywords*— CNC machine; tool-path strategy; saddle-free surface; milling machine.**

I. INTRODUCTION

CAD / CAM / CNC technologies have been applied in industrial production in Vietnam and are proving to be of great efficiency, contributing to change in the industry in recent decades. The CNC machines have increasingly improved structures and the same with technology level. Thereby, productivity and product quality when processing on CNC machines have significant improvements, contributing significantly to the machining and automatic machining industry's development. Because of their advantages, more and more scientists are interested in deep research of both fields in theory and practical applications.

Several researchers published documents about the freedom line and surface, which have high applicability and scholarly. Sarkar et al. [1] have studied the tool paths calculating methods in surface shaping and the problem of cutting tool wear (for flat head cutting cases) when machining molds on CNC milling machines. Yasir et al. [2] have studied the affecting factors to the quality of shaping the free surface of the concave elliptical structure when machining on CNC machines. Ma et al. [3] have researched and built the method of real-time interpolation of free profiles in shaping the surface of machined parts on 3-axis CNC machine tools. In the project, Walhof [4] introduced a method of automatically setting tool-paths based on technology requirements in the G-Code language used for a 3-axis multipurpose CNC milling machine. Moreover, the paper solves the problem of automatically setting up the processing programs by G-code for complex surface machining. It is specifically applied to machining the involute surface of straight teeth bevel gear on a 3-axis multipurpose CNC milling machine [5]. The result was an algorithm and software called "Bevel gears" that allowed to set up a processing program based on G-Code, which compatible with BAZ-15 Heidenhen 3-axis CNC milling machine for machining the involute surface with any parameter of a cone gear. This software was written on Visual Basic. Zhang et al. [6] have shown the 3 level B-spline model's application method and continuous conditions. The authors formulated an algorithm to interpolate the toolpath according to NURBS level 3. The authors gave the final results were the results chart of the NURBS approximation for the toolpath.

In the study by Gan et al. [7], the authors have proposed shaping surfaces and applications in mechanical engineering. In this document's content, the authors present the application of the free form surface and some common mechanical shape such as forming the surface with a disc tool, forming the surface with toothed rack tools, shaping surfaces with screw-shaped tools and contents related to surface shaping. Especially in this study, the authors gave a summary of 10 free form surface types classification. This is a relatively detailed classification of free form surfaces. Huo et al. [8] have presented the method of setting the tool paths for 3-axis multipurpose milling machines in programming the machining of involute surfaces of the bevel gear teeth used the G-code language for the 3-axis milling machine. The authors solved the automatic setup of processing programs according to G-code to process complex faces. The result was an algorithm and software called "Bevel gears" that allowed to set up a processing program based on G-Code compatible with BAZ-15 Heidenhen 3-axis CNC milling machine for machining the involute surface of a bevel gear of any parameter. In the paper [9], the authors mentioned the level 3 NURBS interpolation function to handle the high-speed toolpath smoothly. In the end, the authors give the results chart of the NURBS approximation for these tool-paths. In addition, several studies only briefly mention the free form surface without analyzing and evaluating the solutions to make a plan to machining the NURBS free form surfaces on CNC machines. Researches on the geometry of cutting tools as well as the determination of tool-paths are quite limited. Lots of studies are mostly considered to optimize tooling paths when machining on a specific section (2D). The study [10] has built a local surface zoning diagram based on Gaussian curvature and average curvature that is used as a reference to build an algorithm to divide the smoothly free surface zoning into local surface areas.

The development of the CNC machine and its advantages led to the service areas for this system that are constantly developing, such as CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing). CAD supports the design process to become faster, easier, and more accurate. CAM supports the processing, freeing people from bigger and more complex calculations by integrated interpolation formulas. Therefore, at this time, productivity as well as precision of the manufacturing products with CAD/CAM/CNC applications no longer depend entirely on CNC machines but also on other factors in the design process (using CAD) and in processing (using CAM). At present, the use of CNC machines, as well as CAD/CAM software, are not effective. For example, how to choose a reasonable cutting tool, choose the best toolpath for the surface, select the cutting mode parameters appropriately...will also greatly affect the productivity, the quality of shaping details containing complex surfaces [11].

The research related to the processing and shaping of free form surfaces has attracted a lot of scientists. Many studies have been published which have great applicability in relation to the machining of free surface on CNC machines. Valvo ELO et al. [12] present a method of interpolation of toolpath following NURBS on open-source technology. This method is highly effective when processing soft curves. Chen and Wang [13] presented a method of creating tool-paths based on the height of metal left behind after each moving of the cutter (scallop height). Paul K. Wright et al. [45] studied the toolpath making method for machining free surfaces on 3-axis CNC machines. In this study, the authors propose an algorithm to detect the impact area, causing a rough cut on the surface [14]. Chen et al. [15] have shown the method of generating tool-paths using smooth spiral lines, mainly applied for high-speed machining. This method can simplify the construction of radial and spiral tool-paths, also lead to the ability to smooth the complex surfaces. In the project, Shang et al. [16] have depicted a method for creating tool-paths when machining sample surfaces. In this method, the authors use the 2D modeling method to be converted into separate data points to create tool-paths by image processing techniques to map discrete samples on the part's surface. Grid mappings are used to smooth the surfaces on a plane. On this plane, the discrete model is collapsed, rotated, and moved to the desired position. Then using the mapping of the workpiece surface to the surface path, the model is mapped back to the surface of the part. This method is independent of the processing on the surface parameter domain, so surface pieces do not limit it. Gahlot Tanay, Kamat Amey, and Swain Pravati [17] have studied the method of creating tooling paths for 3D models to automate the production of some parts to achieve high productivity. In this study, the authors used a zigzag toolpath to do the research. Gahlot et al. [17] proposed a plan to create tooling paths for machining free surfaces on optical equipment using ultra-precise multi-axis machines. In this study, the technique of neighbor cutting contact point technique is applied. Li et al. [18] studied an optimal method of processing a part with free surface based on clustering of the field vector guiding the cutting tool in contact with the free face, after clustering into specific machining areas by spiral toolpath and zigzag. In this study, the authors gave a very clear research direction on the free surface machining process. If the previous methods only focused on solving toolpath generation, this method proposed a new direction to classify machining into different areas based on the direction of the tool axis with the machining surface. Clustering is the process of partitioning a data set into groups with similar properties. After performing this study, the surface areas were divided into sub-regions or local regions. After partitioning by this vector cluster method, it is possible to flexibly select the toolpath corresponding to each clustered area to achieve machining efficiency. Bo et al. [19] have studied the method of determining toolpaths when machining Bezier lines and faces on multi-axis milling machines through two steps: (1) Step 1: Forward-step, for this step, that it is necessary to determine the maximum distance of the toolpath between the two closest tool paths and to ensure a certain error. (2) Step 2: Step-side, in this step, that it is necessary to determine the maximum distance between two toolpaths side by side so that the smallest deviation.

Currently, the application of CAD/CAM/CNC technology in production is prevalent. Because of this technology's advantages, many scientists are always interested in CAD/CAM/CNC studies [20]. Currently, researches related to CAD/CAM/CNC in Vietnam are quite limited. There are many studies in the world to improve productivity and product quality when machining on CNC machines. However, surface issues are rarely mentioned in these studies, but mainly on toolpath calculations or cutting modes. In this study, the authors found that selecting appropriate tools and tool-paths when processing parts containing a free surface is both scientific and very practical, which has great potential to apply to the production. In this paper, the authors focused on evaluating free surfaces based on Gaussian curvature and average curvature (K and H), thereby offering a reasonable tool selection for evaluated free surface areas. In addition, for each evaluated surface area, after selecting a suitable tool, it will be studied the appropriate toolpath and the corresponding surface area for this selected tool. The authors have conducted experiments to evaluate the influence of tools and tool-paths on the quality of free surface shaping. Giving a plan for the selection of reasonable tools and tool-paths in the processing of details contains free surface.

II. Materials And Method

A. Materials

1) *Workpiece:* Sample 1: Workpiece size 100x100x50; Smooth and unpartitioned surfaces. Sample 2: Workpiece size 100x100x50; Smooth surface has passed through the partition and determined the contour corresponding to each surface piece. Materials: PA plastic, physical properties are shown in Table I. Sample 3: Experimental sample made of 6000 series aluminum, designed with free saddle surface, the dimensions of X-Y axes are 75x65mm.

TABLE I
PHYSICAL PROPERTIES OF PA RESIN

Tension (MPa)	**Modulus of elasticity (Gpa)**	**Hardness (HB)**	**Density**	**Melting point (^{o}C)**	**Friction coefficient**	**Bending force (MPa)**
87	1.9 - 3.2	90	1.2	240	0.1	136

2) *CNC milling machine:* Hamai 3VA 3-axis CNC milling machine: Working space, XxYxZ = 800x450x450; Table size 1300x520; Maximum load capacity 800kg; Spindle speed: 6000rpm; Type of tool head: BT40; Number of blades: 24. Manford MCB-850 3-axis CNC machine: Working space XxYxZ = 1000x500x400mm; Maximum spindle speed: 8000rpm; Tool carriage: 16; Accuracy: 0.001 mm.

3) *Cutting tool:* Flathead milling cutter used for roughing step and ball end milling cutters used for the finishing. In particular, the ball end milling cutter uses 2 different sizes. For sample 1 without partitioning, to avoid the heel phenomenon, should use a 3mm diameter cutter. For sample 2, when partitioning the surface, was used 2 cutters, the 3mm cutter was used for machining the concave surface, the 8mm cutter was used for machining the flat and convex sections. Cutting tool parameters are shown in Table II.

TABLE II
CUTTER PARAMETERS

Parameters	**Flathead milling cutter**		**Ball end milling cutter**		
Diameter, D (mm)	6	12	10	8	3
Edge radius, RC (mm)	-	-	5	4	1.5
Overall length, L (mm)	75	75	75	75	75
Cutting length, Lc (mm)	30	30	28	28	28
Length, l (mm)	34	34	32	32	32
Body diameter, db (mm)	6	12	10	8	3

Three-coordinate measuring machine (CMM): To test the surface after machining in this experiment, a 3-coordinate measuring machine with model SVA NEX9106 was used. The machine parameters are shown in Table III.

TABLE III
PARAMETERS OF 3-COORDINATE MEASURING MACHINE SV SVEX 9106

Measuring range	X-axis (mm)	850
	Y-axis (mm)	1000
	Z-axis (mm)	600
Measuring the ratio	Linear	
Minimum display value	0.01(µm) (0.1µm) when using the TP200 gauge head	
Machine table	Effective along the (X) axis (mm)	1000
	Depth according to (Y)(mm)	1810
	Height from the table (mm)	725
The maximum product size	Maximum height (mm)	770
	Maximum weight (kg)	1000

B. Experimental Set-up

Some experimental tests are set up to evaluate the effect of toolpath elements (Toolpath, T), vertical step (Feed rate, F), horizontal step (Stepover, S) on free-form shaping accuracy on a 3-axis CNC milling machine. Indeed, there are three common and efficient types of tool-paths used for free surface finish machining: Back and forth; Spiral; one direction, in which back and forth can become a zigzag.

1) *Back and forth:* A strategy to guide tools along the zigzag lines by moving the cutting tool back and forth on the surface of the workpiece in the XY plane. In this tooling strategy, in order to reduce machining time, the spindle direction is proposed to run along the direction of the longest edge on the workpiece surface.

2) One direction: A strategy to guide cutting tools along the parallel lines on the machining surface. At the end of each line, the tool will move up to a specific reference surface, then go back to the previous area and then move horizontally to a distance by horizontal step, then translate the tool and the surface to follow the next path for processing.

3) Spiral: A strategy to guides the cutting tool along a spiral, in which the tool can come from the center of the machining face and outward or vice versa. When the cutting tool moves to the center, it will move vertically up to the end.

In this study, the Taguchi planning method was used [21]. The Taguchi method is based on a statistical analysis of tests to meet surfaces with pre-set requirements to achieve the most optimal experimental design parameters. The advantage of this method is that many objects are considered with different influences. This approach's holistic view is to bring the quality concept into the design stage to optimize parameters instead of thorough testing to determine the quality after machining.

To determine the effect of tool-paths on the quality of surface shaping of parts containing free surfaces. The prototype was designed to be a part that contains a smooth, free surface, in this study, the saddle was selected because it is one of the common surfaces in molds [22].

Three machining parameters include the feed rate (F), transverse step (S), and toolpath (T) are used to study the influence on the saddle surface shaping. Other parameters such as cutting speed, cutting depth, tool radius or other geometrical parameters of the tool may also be selected as research parameters, but the influence of these parameters on the accuracy not as much as F, S, and T.

Each of the parameters F and S respectively evaluated with 3 levels. These parameters depend on the cutting tool and workpiece material that have different optimum values [23]. This optimal value can be found in the catalogs of manufacturers. In this experiment, however, this effect was minimal, as it was possible to select within a range of values and still, the results were relatively accurate with the Taguchi method. The parameters F, S and T are taken from Table IV. The orthogonal array of Taguchi with 3 influence parameters, each has 3 impact levels shown in Table V. With 3 parameters considered, each parameter has 3 influence levels so the number of experiments will be 3^3 = 9 times

TABLE IV
F, S, T PARAMETERS

Affecting Factors	**Effecting level**		
	L.1	L.2	L.3
F (mm/min)	400	600	800
S (mm)	1.0	1.5	2.0
T	Back and forth	One direction	Spiral

TABLE V
ORTHOGONAL ARRAYS OF TAGUCHI L9 (3^3)

Experiment No.	**Machining parameters**			**Delta**	**MSD**	**S/N ratio**
	F	S	T			
1	L.1	L.1	L.1	0.0505	0.2232	13.0338
2	L.1	L.2	L.2	0.1151	0.1645	15.6715
3	L.1	L.3	L.3	0.0807	0.1596	15.9338
4	L.2	L.1	L.2	0.3156	0.3136	10.0698
5	L.2	L.2	L.3	-0.0892	0.1137	18.9002
6	L.2	L.3	L.1	-0.1561	0.2159	13.3192
7	L.3	L.1	L.3	-0.1798	0.1816	14.8128
8	L.3	L.2	L.1	-0.1672	0.1982	14.0625
9	L.3	L.3	L.2	-0.2045	0.3138	10.0695

III. RESULTS AND DISCUSSION

A. The Effect of Tool Selection and Surface Partitioning on Machining Time

The measurement of the height level z of samples 01 and 02 is shown in Table VI and Table VII.

TABLE VI
PARAMETERS OF MEASURING THE HEIGHT Z POINTS ON THE SURFACE OF SAMPLE 1

Surface	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	-0.036	0.91[illegible]	4.314	9.881	12.31	9.883	4.41	0.641	-0.021	0.004
2	-0.016	0.515	3.651	8.051	10.658	8.368	3.516	0.469	-0.028	-0.002
3	-0.047	0.527	2.774	4.567	5.124	3.367	1.341	0.044	-0.048	-0.01
4	-0.065	0.007	0.349	1.028	1.569	1.288	0.463	0.015	-0.063	-0.02
5	-0.083	-0.428	-1.304	-1.983	-1.741	-1.068	-0.379	-0.14	-0.062	-0.03
6	-0.09[illegible]	-0.571	-2.591	-5.089	-6.113	-4.672	-1.835	-0.403	-0.077	-0.028
7	-0.106	-0.971	-4.937	-10.59	-13.242	-10.411	-4.687	-0.906	-0.12	-0.027
8	-0.184	-1.701	-6.549	-15.291	-18.37	-13.667	-6.339	-0.97	-0.108	-0.019
9	-0.166	-2.239	-9.037	-17.799	-21.292	-16.905	-6.937	-1.125	-0.085	-0.014
10	-0.107	-2.064	-11.069	-18.427	-21.449	-15.88	-6.719	-1.275	-0.148	-0.009
11	-0.112	-1.554	-8.214	-17.446	-21.396	-16.487	-6.392	-1.028	-0.082	-0.01

TABLE VII
PARAMETERS OF MEASURING THE HEIGHT Z POINTS ON THE SURFACE OF SAMPLE 2

Surface	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0.711	4.902	9.668	12.234	9.301	3.419	0.498	-0.035	0.019	-0.002
2	-0.079	0.697	3.628	8.553	10.297	7.646	2.851	0.525	-0.05	-0.023
3	-0.101	0.244	1.431	4.016	5.282	4.233	1.892	0.097	-0.079	-0.04
4	-0.126	-0.078	0.325	1.041	1.228	0.915	0.258	-0.094	-0.106	-0.055
5	-0.153	-0.348	-0.816	-1.606	-1.825	-1.429	-0.666	-0.246	-0.131	-0.061
6	-0.156	-0.677	-2.539	-5.532	-6.852	-5.181	-2.378	-0.567	-0.153	-0.056
7	-0.176	-1.11	-4.903	-11.115	-13.249	-10.221	-4.273	-1.114	-0.167	-0.044
8	-0.168	-1.857	-8.274	-15.627	-18.842	-13.965	-6.677	-1.105	-0.132	-0.028
9	-0.139	-1.674	-8.574	-17.803	-21.34	-16.159	-7.32	-1.277	-0.118	-0.02
10	-0.126	-1.013	-7.297	-17.256	-21.57	-16.644	-7.744	-1.457	-0.146	-0.016
11	-0.136	-1.661	-7.613	-17.601	-21.521	-16.665	-6.112	-1.574	-0.13	10.001

B. Evaluation of Forming Accuracy

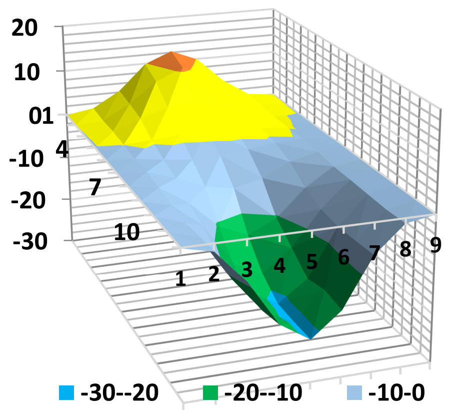

Fig. 1 The data diagram of free surface machining measurement of Sample 1

In Fig. 1 and Fig. 2, the surface regeneration at the measuring locations, we find that the two surfaces are not much different. Of course, this comment seems not satisfactory because the number of measurement points is still small. But if the number of measurement points increases, the result is still the same because the surface shaping process on the CNC milling machine is the interpolation process. If the number of measurement points is large, the surface is smoother, but there is no change in form.

The diagram in Fig. 3 shows that at the boundary of the graph (flat and convex areas) of Sample 1 and Sample 2 are quite similar and there are certain deviations from the design pattern. Meanwhile, in the central area (concave area), there is a certain deviation of Sample 2 from Sample 1 and the design pattern; However, the deviation is not much, this can be caused by measurement.

Because smaller sized cutters machine the Sample 2 concave surface areas, the amount of cusp left will be less. In this area, errors can only occur because the boundary separation has a boundary limit during processing, so if any errors occur, it is because the boundary has not been smoothed. In Fig. 3, the convex and flat areas and the contiguous area between convex regions and the flat regions and the concave regions, are similar. This shows that when using a small and large diameter cutter on a convex or concave area with the selected cutting modes, the surface is quite similar. This will lead to shorten the machining time quite a lot.

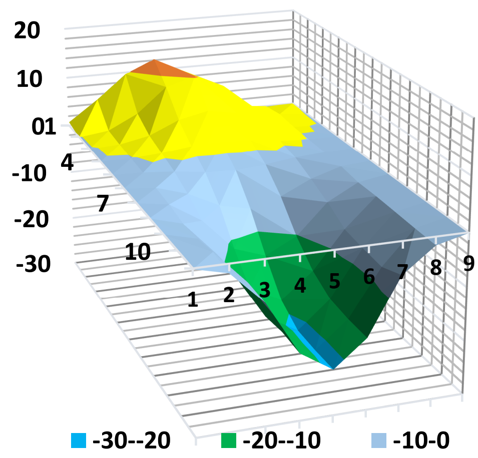

Fig. 2 The diagram of free surface machining measurement of Sample 2

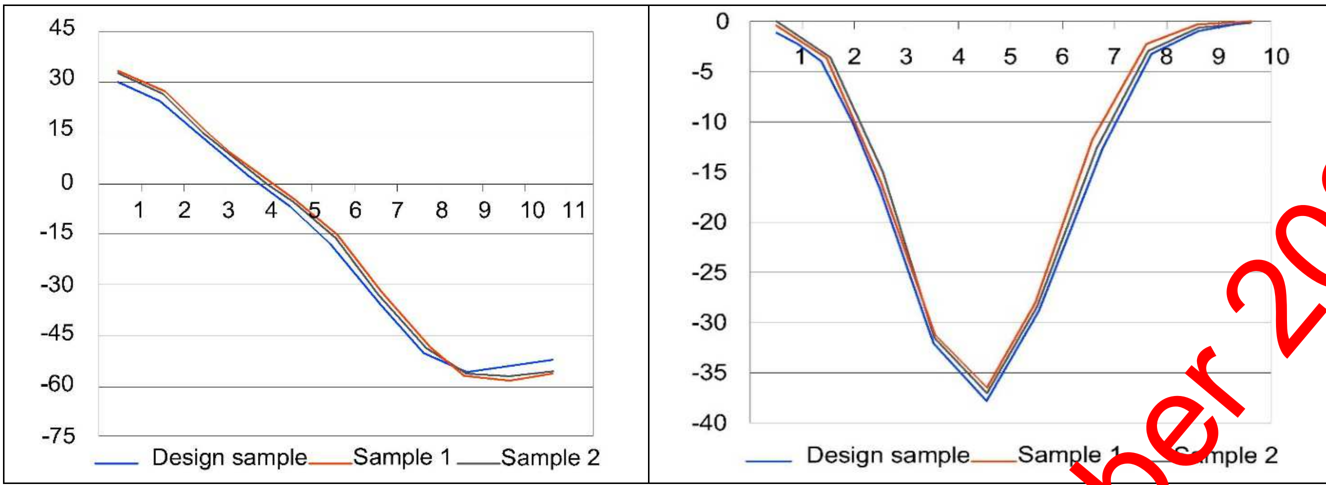

Fig. 3 Comparing 2 surfaces vertically and horizontally

C. Evaluate the Machining Time and the Length of Tool-Path

When machining free surfaces, besides forming accuracy, time is also an essential factor because it evaluates the machining method's efficiency. The summary of important parameters to consider the processing time of the part containing the free surface shows that: For surfaces that have not been partitioning, the tooling length recorded is 231315.145mm, the processing time is 2h 4 minutes 42 seconds, total time machining is 2h 6 minutes 41 seconds. For a partitioned surface using two cutters to finish for each facepiece, the toolpath length is 207725.142mm; the machining time is 1h 40 minutes 25s, the machine time 1h 43 minutes 31s.

The extra time of the free surface partitioned is 1min 8s. The extra time when machining a free surface without partitioned is 55 seconds. The difference is 13 seconds; this is known as the time to change the tool because the partitioned surface uses more knives than the non-partitioned ones. However, the machining time of free-form surface partitioned is less than the non-partitioned ones is 24 minutes 8 seconds.

D. Evaluate the Effect of Toolpath Styles on the Shaping Accuracy of a Free Surface

The measurement results on the NEX9106 3-coordinate measuring machine are listed in Table VIII from column 1 to column 9 corresponding to 9 experimental samples; column 0 is the z-axis parameter of sample 03.

Effect diagram of experimental parameters on the surface forming quality (Fig. 4). In Fig. 4, the toolpath's effect to the quality of surface shaping is in sequence: One Direction> Back and ford> Spiral. However, this is only qualitative, not quantitative. ANOVA variance analysis gives us a more accurate method (Table IX).

TABLE VIII
RESULTS OF MEASUREMENTS AT SPECIFIED LOCATIONS ON THE SAMPLE SURFACE

No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	26.621	26.732	26.2[illegible]4	26.215	26.175	26.065	26.275	26.666	26.375
2	27.225	27.974	27.8[illegible]1	27.921	28.013	27.223	26.375	26.837	26.805
3	27.763	27.804	2[illegible]23	28.466	28.528	27.732	27.126	27.784	27.334
4	27.225	27.[illegible]71	27.938	27.984	28.179	27.417	26.574	27.012	26.674
5	25.625	26.894	26.445	26.281	26.628	25.697	25.241	25.546	25.307
6	24.861	2[illegible].803	24.896	25.012	25.160	24.137	24.636	23.984	24.565
7	26.475	26.3[illegible]6	26.545	26.451	26.954	26.738	26.158	26.124	26.958
8	27.012	26.835	27.035	27.045	27.257	26.677	26.710	26.748	26.324
9	26.474	2[illegible].198	26.716	26.674	26.812	26.326	26.315	25.776	25.614
10	24.861	24.949	25.285	24.882	25.254	24.629	25.935	24.395	25.198
11	2[illegible]24	25.147	25.814	25.216	25.546	25.516	25.315	25.952	25.478
12	26.[illegible]45	26.878	26.426	26.714	27.211	26.428	26.729	26.635	26.991
13	27.387	27.032	26.946	27.402	27.574	27.183	27.422	27.114	27.149
14	26.851	26.245	26.678	26.091	26.124	26.818	27.035	26.346	26.546
15	25.244	25.014	25.247	25.213	25.725	25.874	25.514	25.699	25.331
16	26.764	26.869	26.369	26.587	26.968	26.906	26.495	26.535	26.443
17	28.357	28.002	28.114	28.254	28.54	27.847	28.114	27.990	27.856
18	28.845	28.681	28.595	28.655	28.961	28.536	28.678	28.444	28.125
19	28.357	28.057	28.048	28.214	28.593	28.101	28.298	28.691	28.545
20	26.754	26.624	26.914	26.589	26.203	26.347	26.248	26.651	26.924

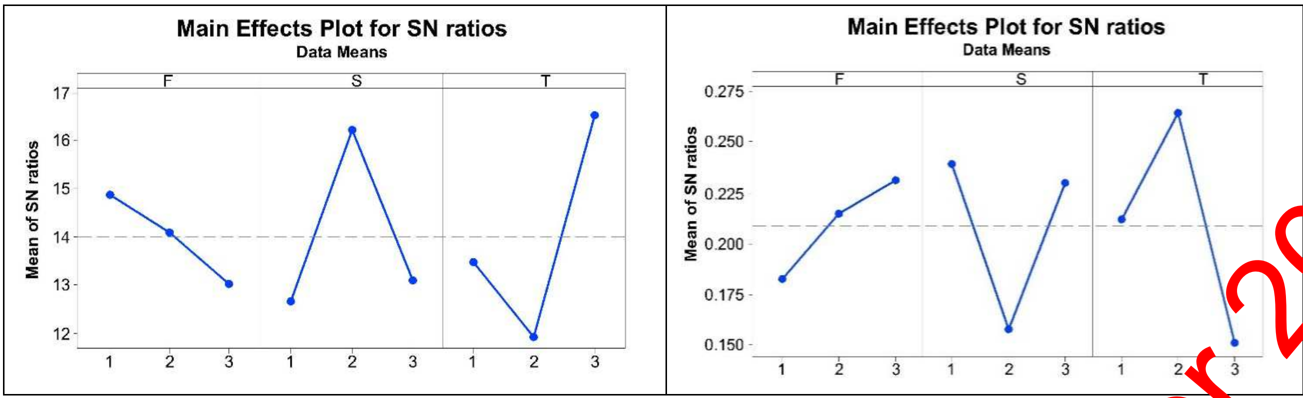

Fig. 4 S/N ratios

TABLE IX
ANOVA ANALYSIS OF PARAMETERS AFFECTING SURFACE SHAPING

Source	Degree of freedom	Sum of squares	Mean squares	F ratio	Contribution (%)
A: F	2	0.003675	0.001835	1.68	10.053
B: S	2	0.011653	0.005825	5.21	31.885
C: T	2	0.018981	0.009492	8.45	51.927
Error	2	0.002242	0.001122	-	6.133
Total	8	0.036551	-	-	100

In Table IX, analyzing the effect of the parameters shows that the toolpath's effect on the surface forming quality is 51.927%. This implies that the processing of free surfaces, besides the tooling and the horizontal step, the toolpath style also affects the surface forming accuracy when machining on CNC machines. Based on the experiments, we have concluded that the One direction style gives the highest forming accuracy when processing parts containing a saddle free surface. Experiments show that the effect of tool-paths on the quality of the parts' surface shapes is large, accounting for nearly 52%. The effects of Feed rate and Step-Over are less, respectively, 32% and 10%. About 6% of the remaining is due to signal interference.

IV. CONCLUSION

The study has built an experimental model processing containing smooth, free surfaces, including three areas: convex, flat, and concave. The results obtained during the processing further clarify the advantages of the proposed method. At the same time, the study has established the experiment to evaluate the effect of tooling strategy when machining a saddle free surface in a 3-axis CNC machine. The results showed that the effect of tool-path on Free surface machining on 3-axis CNC machines is large. Although in the shaping process of free form surfaces, we often pay attention to parameters such as the tool's longitudinal motion. It causes errors when linear interpolation of surfaces or the translational motion horizontal causes errors because the metal is not cut after each step. The results show that the effect of the tooling strategy is much more significant. This is all the more assertive in the free-hand machining process; the choice of tooling strategy is crucial.

The appropriate selection of tools and tool-paths in free-face shaping on 3-axis CNC milling machines reduces machining time while keeping forming errors within a permissible value compared to the traditional processing method. The method of selecting the appropriate cutting tool when machining free surfaces by dividing smooth surfaces into local surface areas is vital for improving the productivity and quality of products containing free surface when machined on 3-axis CNC machines. The results of this research have practical implications and have the potential for industrial applications.

ACKNOWLEDGMENT

This research is supported by Industrial University of Ho Chi Minh City (IUH) under grant number 68/HĐ-ĐHCN. Additionally, the authors are grateful to Ho Chi Minh City University of Technology (HUTECH) for providing necessary facilities during the research.

REFERENCES

[1] S. Sarkar and P. P. Dey, “Tool path planning for machining free-form surfaces,” *Trans. FAMENA*, vol. 39, no. 1, pp. 65–78, 2015.

[2] M. Yasir, T. L. Ginta, B. Ariwahjoedi, A. U. Alkali, and M. Danish, “Effect of cutting speed and feed rate on surface roughness of AISI 316l SS using end-milling,” *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 4, pp. 2496–2500, 2016.

[3] J. Ma, D. Song, Z. Jia, G. Hu, W. Su, and L. Si, “Tool-path planning with constraint of cutting force fluctuation for curved surface machining,” *Precis. Eng.*, vol. 51, pp. 614–624, 2018.

[4] D. Walhof, *The Democratic Theory of Hans-Georg Gadamer*. Springer, 2016.

[5] K. Xu, M. Luo, and K. Tang, “Machine based energy-saving tool path generation for five-axis end milling of freeform surfaces,” *J. Clean. Prod.*, vol. 139, pp. 1207–1223, 2016.

[6] Y. Zhang, R. Xu, X. Li, X. Cheng, G. Zheng, and J. Meng, “A tool path generation method based on smooth machine rotary angle and tilt angle in five-axis surface machining with torus cutters,” *Int. J. Adv. Manuf. Technol.*, pp. 1–11, 2020.

[7] W.-F. Gan, J.-Z. Fu, H.-Y. Shen, Z.-Y. Chen, and Z.-W. Lin, “Five-axis tool path generation in CNC machining of T-spline surfaces,” *Comput. Des.*, vol. 52, pp. 51–63, 2014.

[8] G. Huo *et al.*, “Cnc tool path generation for freeform surface machining based on preferred feed direction field,” *Int. J. Precis. Eng. Manuf.*, vol. 20, no. 5, pp. 777–790, 2019.

[9] S. Sun, Y. Sun, J. Xu, and Y.-S. Lee, “Iso-planar feed vector-fields-based streamline tool path generation for five-axis compound surface machining with torus-end cutters,” *J. Manuf. Sci. Eng.*, vol. 140, no. 7, 2018.

[10] Y. Sun, S. Sun, J. Xu, and D. Guo, “A unified method of generating tool path based on multiple vector fields for CNC machining of compound Nurbs surfaces,” *Comput. Des.*, vol. 91, pp. 14–26, 2017.

[11] M. Q. Chau, “Modeling 3D surface milling process using a ball-end milling cutter,” *J. Mech. Eng. Res. Dev.*, 2020.

[12] E. L. O. Valvo, S. Drago, I. M. Chimica, and V. Scienze, “An Efficient Nurbs Path Generator for a Open Source CNC,” *Recent Adv. Mech. Eng.*, pp. 173–180, 2014.

[13] Y. Chen and Y. Wang, “Isoscallop of self-adaptive tool orientation with toroidal cutter under optimum orientation of MCPs,” 2012, doi: 10.4028/www.scientific.net/AMR.562-564.713.

[14] M. Q. Chau, “An overview study on the laser technology and applications in the mechanical and machine manufacturing industry,” *J. Mech. Eng. Res. Dev.*, 2019, doi: 10.26480/jmerd.05.2019.16.20.

[15] L. Chen, Y. Li, and K. Tang, “Variable-depth multi-pass tool path generation on mesh surfaces,” *Int. J. Adv. Manuf. Technol.*, 2018, doi: 10.1007/s00170-017-1367-x.

[16] Z. Li, L. Shang, W. Wang, and T. Qiu, “Path Generation for Robotic Polishing of Free-form Surfaces,” 2019, doi: 10.1109/ICMA.2019.8816490.

[17] T. Gahlot, A. Kamat, and P. Swain, “Automating toolpath generation for 3-Axis CNC,” 2016, doi: 10.1109/ICIT.2016.7474860.

[18] H. Li, N. J. Naples, X. Zhao, and A. Y. Yi, “An integrated approach to design and fabrication of a miniature endoscope using freeform optics,” *Adv. Opt. Technol.*, 2016, doi: 10.1515/aot-2016-0031.

[19] P. Bo, M. Bartoň, D. Plakhotnik, and H. Pottmann, “Towards efficient 5-axis flank CNC machining of free-form surfaces via fitting envelopes of surfaces of revolution,” *CAD Comput. Aided Des.*, 2016, doi: 10.1016/j.cad.2016.04.004.

[20] M. Q. Chau and D. T. Nguyen, “A study on factors affecting the welding flux in the case of wire welding,” *Test Eng. Manag.*, 2020.

[21] R. Çakiroğlu and A. Acir, “Optimization of cutting parameters on drill bit temperature in drilling by Taguchi method,” *Meas. J. Int. Meas. Confed.*, 2013, doi: 10.1016/j.measurement.2013.06.046.

[22] G. S. Phull, S. Kumar, and R. S. Walia, “Conformal cooling for molds produced by additive manufacturing: A review,” *Int. J. Mech. Eng. Technol.*, 2018.

[23] D. N. Nguyen, A. T. Hoang, X. D. Pham, M. T. Sai, M. Q. Chau, and V. V. Pham, “Effect of sn component on properties and microstructure CU-NI-SN alloys,” *J. Teknol.*, 2018, doi: 10.11113/jt.v80.11867.