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Research Article

ANALYZING THE EFFECTS OF DIFFERENT TOOL PATHS ON FORM ERRORS IN THE MILLING OF FREEFORM SURFACES

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ABSTRACT

Machining of free-form surfaces is an important place in terms of design and performance in transportation, electronics and aeronautical industry. Problems such as form error and surface roughness were frequently encountered in the manufacture of these surfaces. For the solution of the problems, reprocessing is done, which causes time and resource loss. To eliminate these losses, the parts must be produced in the desired quality at one time. In order to find out the causes of form errors and to remove the adverse effects, the distribution on the surface must be determined correctly. Form errors should be examined in a way to cover the point, region and the whole part.

In this study, a surface created with B-Spline curve has been processed with different tool paths. Surfaces were scanned in 3D and form errors were determined. Point, regional and whole parts are examined and the tool path that creates minimum form error is determined.

Keywords: B-spline curve, free-form surfaces, form error.

1. INTRODUCTION

In industries such as electronics, automotive, aerospace, defence industry, medical, moulding, many products are designed as a free-form surface to meet the needs of the consumer as well as to obtain aesthetic image. These surfaces are converted into products on CNC milling using CAD / CAM programs.

Manufacture of free-form surfaces takes place in three stages as well as manufacturing methods for existing parts: rough, semi-rough and finish machining. Generally, flat end milling tools are used for roughing, radial tools are used for semi-roughing and finish operation.

Conventional CNC milling used in the manufacture of free form surfaces only provide linear and circular interpolation. In conventional CNC milling, it is necessary to create many straight lines and circles using CAM systems to approximate contour geometry with free-shaped surfaces under given tolerances. This leads to the formation of form errors depending on the strategy of the tool path.

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The m ost effective method currently used to study the effects of different toolpaths on form errors is the 3D surface scan process. In this process, the surface of the machined parts is scanned with 3D surface scanners and compared with the reference surface, form errors are determined by calculating the difference between the selected points on the surface and the reference surface. This classical method causes account densities especially on free-form complex surfaces. At the same time, additional operations are required to compare the machined surfaces with many different methods and to determine in which regions the form error concentrate. To solve the problem of form error, it is tried to obtain high productivity by optimizing the processing methods based on scientific knowledge, and this situation becomes an increasingly important concept. In the literature, studies done in this respect are generally divided into 4 groups as side stepping, forward step-contact point-shear force, tool dimension and optimization of different tool paths.

The first group is the work done to optimize the side step of the team and to reduce the tool path heights to the minimum. In their work, Lartigue et al [1], have formed the optimum tool path by proportioning the lateral step amount to the channel height, so that a spherical head and a cubic B-Spline curved surface can be processed better. At the intersection of the tool paths, they have ensured that the tool width and the starting point of the next tool path take the most shavings. Haldar [2] investigated the production technique and modelling of the cubic Bezier surface using the MATLAB program. In his work he created a surface using the MATLAB program and developed an ISO-Scallop and ISO-Parametric toolpath algorithm to process this surface. NC (Numerical Control) codes obtained according to this algorithm are tested in the CNC Fanuc simulation program and calculate the processing length.

In another study, Ding et al. [3] have developed an adaptive tool path strategy that allows plane intersection points with respect to surface shapes to leave at least chips in the next step. In the work done, the tool path is constantly updated and the maximum surface quality is tried to be obtained by calculating the next plane of the tool. In other studies in this group; Utilizing the NURBS curves to shorten toolpaths [4], ensuring that the tool follows a path that minimizes surface errors starting from a reference point on mathematically non-mathematical surfaces [5-6-7], Combining co-planar and co-elevation methods, the position of the tool is determined in two stages, the intersection of the roads leaving minimal scratch residue, then the height position to provide minimum surface roughness [8-9-10] and on a free-form surface, tool guides are used to open the tool path to reduce surface roughness [11].

In the second group work, tool path generation techniques were generally used in terms of contact area, rotation angle and shear force at the contact point of the cutting tool. Tool paths are created to minimize the surface roughness by creating algorithm that directs the tool on the surface with minimum cutting force [12-13].Abbas [14] performed a similar study and developed an algorithm to define the forward step function to determine the maximum distance between the contact points of the cutting tool (Centre Contac-CC) within the given tolerance. As an example of the third group of studies, Chiou et al. [15] provided tool selection that can remove the maximum chip size according to the surface shape, and then tool path formation to provide the minimum surface roughness with the tool.

In the fourth group, Kurt et al. [16] and Zebala [17] have compared surface roughness performances by using tool paths found in CAM programs for surfaces with free-form different materials. In terms of roughness, the most efficient tool path strategies have been identified. In other studies, free-form or radial moulds and similar pieces were produced with composite materials and surface qualities were investigated [18-19].

When the above studies are examined, it is seen that, while examining form errors in the manufacture of freeform surfaces, the development of new tool path algorithms and focusing on determining the effects of tool paths in finish machining in CAM programs. However, in case of similar form errors in the same regions, the effect of the machining time is used as a decomposition feature while the tool path is selected.

In this study, a surface formed with a B-Spline curve was processed with different tool paths to detect form errors. In order to eliminate the adverse effects caused by only pointwise information in the detection of the form errors, the whole form error map of the surface is extracted by the image processing method. By comparing the obtained results, the reasons of form errors are discussed and the strategy of the tool path which forms at least form error is determined.

2. EXPERIMENTAL PART

2.1. Obtaining CAD Model of Freeform Surface Created by B-Spline Curve Theory

Free-shaped surfaces are designed using parametric curves such as Bezier, Spline, B-spline, and NURBS. B-spline curves are widely used computer aided geometric design other associated fields, due to their excellent mathematical and algorithmic properties. In practical applications, designers of the need manipulating a given curve in to a design shape. For this reason, the surface was formed by using B-spline curves in this study. A B-Spline is defined by the curve grade d, knot vectors 0, t_1, ..., tm and the base functions (Ni, d(t)). Accordingly, base functions [20];

$$N_{i,0}(t)=\begin{cases} 1, & \text{if } t \in [t_i,\ t_1+1) \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$N_{i,d}(t)=\frac{(t-t_i)}{t_{i+d}-t_i}N_{i,d-1}(t)+\frac{(t_{i+d+1}-t)}{t_{i+d+1}-t_{i+1}}N_{i+1,d-1}(t)$$

$$i = 0,...,n \ \text{ and } d \geq 1. \tag{2}$$

calculated as.

If the knot vectors contain a sufficient number of repeated values, it may be possible to see the (for the same i value) condition in the part of the form. In this case 0/0 = 0 is assumed.

A B-Spline curve with the degrees d (or d + 1), the control points b0, ..., bn and knot values t0, ..., tm can be expressed as [a, b] = [td, tm-d] [21].

$$B(t)=\sum_{i=0}^{n} b_i N_{i,d}(t) \tag{3}$$

Taking the above functions into consideration, the parameters of the curve to be used in the experiments to be performed are randomly determined as follows.

The basic functions of the B-Spline curve (Table 1) are as follows: d = 2, knots t0 = 7, t1 = 9, t2 = 11, t3 = 13, t4 = 15, t5 = 17, t6 = 20, control point values b_0(10, 10), b_1(30, 3), b_2(60, 10), b_3(70, 2).

Table 1. Basic functions of B-spline curve.

Interval	**Equation**	**Knot Interval**
t_1-t_2	$P_2 = \frac{5}{2}(t^2\text{-}15t+49),\ (-17t^2+336t-1697)$	$9 \leq t \leq 11$
t_2-t_3	$P_3 = \frac{5}{2}(t^2\text{-}14t+49), \frac{1}{4}\ (7t^2\text{-}168t+1027)$	$11 \leq t \leq 13$
t_3-t_4	$P_4 = -\frac{5}{2}\ (t^2\text{-}32t+229),\ -\frac{1}{8}\ (8t^2\text{-}418t+2847)$	$13 \leq t \leq 15$

The above expressions are calculated with the help of MATLAB program. The B-spline surface shows similar properties to the curves that form it. The basic function of the B-spline surface is defined as [22];

$$S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{p} T(P_{i,j}) N_{i,d}(u) N_{j,e}(v) \tag{4}$$

By using the B-spline basis functions, u and v components of the curve are taken in the same form but separately, and the tensor products are obtained as the resultant surface in Fig. 1 This surface was created using the SOLIDWORKS 2014 package program to represent the 3D shape.

Figure 1. Generation of free form surface

2.2. Material

Experimental materials as transportation, medical and electronic industries in many industrial areas as widely used Al 7075 alloy was selected. The chemical composition of the alloy appears in Table 2. In addition to being easily process able, this material has low density, high corrosion resistance, strength, electrical and thermal conductivity. Mechanical properties of the material are shown in Table 3.

Table 2. Chemical composition of Al 7075 alloy (% weight)

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
89.5	0.0567	0.2763	1.4024	0.0108	2.3800	0.2009	6.0294	0.0778	0.0675

Table 3. Mechanical properties of Al 7075 alloy

Heat Treatment (Temper)	Tensile Stress (MPa)	Yield Strength (MPa)	Tensile Strength (%)	Shear Modulus (MPa)	Elasticity (GPa)
T651	572	503	11	331	72

The freeform surfaces obtained using different toolpaths were machined on a single die with dimensions of 600x400x50 mm to provide precision in manufacturing, bonding and reference point.

HSSCo-M35- 12 mm-2 cutting edge-straight tool in accordance with DIN 1889 / B standard in rough machining, carbide-10 mm-2 cutting edge-spherical tool in DIN 6528 standard in semi rough machining and carbide-8 mm-2 cutting edge -spherical tool in DIN6528standard in finish machining was used. CNC milling used in manufacturing is TMC 700 V Taksan brand, with a maximum spindle speed of 8000 rpm and a spindle power of 5.5 kw. In the experiments, boron oil was used as cooling fluid. The machining parameters used in the rough, semi rough and finish operations are as in Table 4.

Table 4. Processing parameters for rough and semi rough and finish toolpaths.

	Tool Diameter (mm)	Feed rate (mm/rev)	Spindle Speed (m/min)	Step Down (mm)	Maximum Side Step (mm)
Rough	12	1300	2000	1	
Semi Rough	10	1500	3000	1	
Finish	8	1500	4000		0,1

2.3. Experimental Design

The tool paths algorithm in SOLIDCAM 2013 program was used for milling the surface created by using B-Spline curve. The surface machining was divided into three parts as rough, intermediate and finish machining. In rough machining, one tool path, in semi rough machining three different tool paths, and in finish machining, four different tool path algorithms were used (Table 5). Strategies that have been widely used in the literature were selected when team paths were determined.

Table 5. Tool paths used in the manufacture of freeform surfaces.

Experiment Code	Rough Machining	Semi Rough Machining	Finish Machining
1	HM	Intermediate Rough	Parallel Scan
2	HM	Intermediate Rough	Parallel to Curve
3	HM	Intermediate Rough	Parallel Linear
4	HM	Intermediate Rough	Parallel Fixed z
5	HM	Contour rough	Parallel Scan
6	HM	Contour rough	Parallel to Curve
7	HM	Contour rough	Parallel Linear
8	HM	Contour rough	Parallel Fixed z
9	HM	Parallel rough	Parallel Scan
10	HM	Parallel rough	Parallel to Curve
11	HM	Parallel rough	Parallel Linear
12	HM	Parallel rough	Parallel Fixed z

2.4. Method

Fig. 2 shows the organization scheme of this work to determine the effects of tool paths on form errors in the manufacture of freeform surface based on the B-spline curve theory.

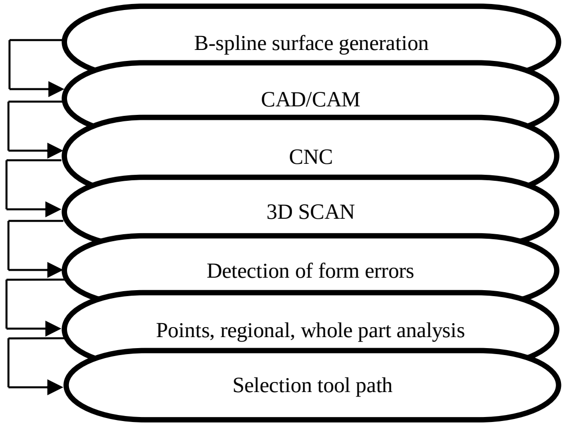

Figure 2. Scheme of organization

The parts were machined using AL7075 material on the CNC vertical milling centre by the specified toolpaths (Fig. 3-a). After the production of the samples of the experiments, form errors were detected using the 3D scanner. Form error were measured by comparing the curvature, surface, and gauge data of the sample pieces, based on the SOLIDWORK plot of the reference piece. The scanning process was carried out using the 3D scanning system named " Breuckmann Smart Scan R5 ". In order to facilitate the measurement and obtain clearer results, the surface was divided into 9 equal area to detect form errors (Fig. 3-b). Measurements were made from 10 to 14 points in each area according to the surface width (Fig. 3-c). The form error is applied to the MATLAB program by a series of operations, the data is first converted to graphics and then the image is processed. Finally, the data received by image processing are interpreted.

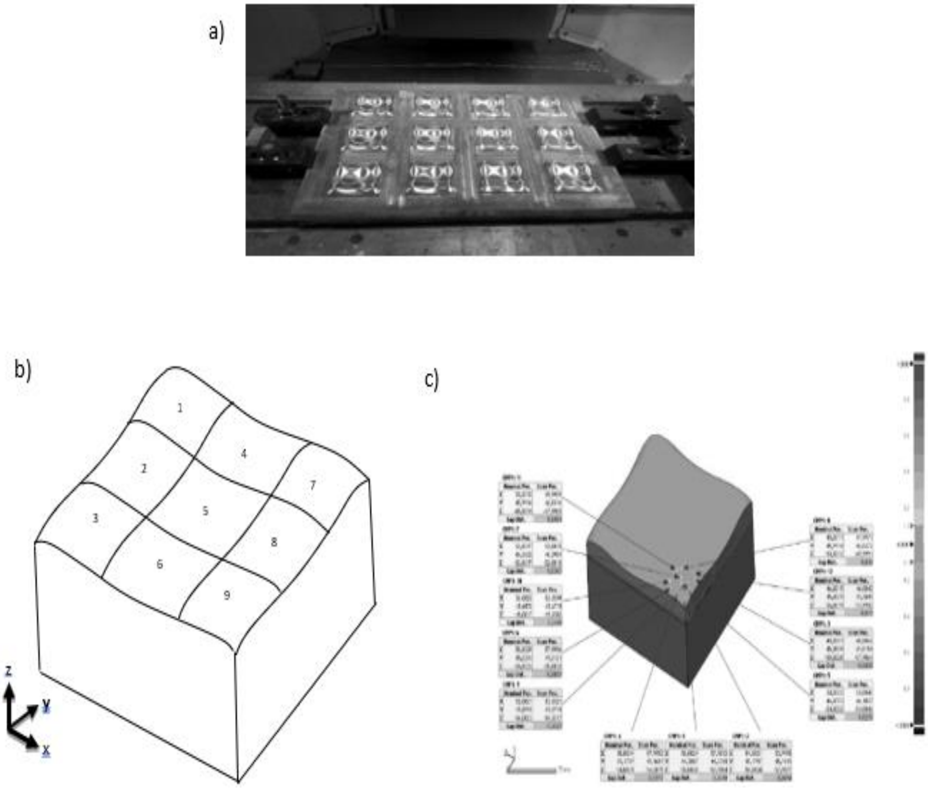

Figure 3. After milling operations. a) Machined surface b) 9 equal area c) 3D scan view

3. RESULTS

3.1. Detection of form error

It has been determined that the tool paths formed by using B-Spline curves are rough, semi rough and finish machining surfaces have an important effect on form error.

After the surface has been processed, the data obtained by 3D scanning for the determination of the size of form errors are compared and the results are given in Table 6.

Table 6. Average form error values.

Experiment Code	1.Area (mm)	2.Area (mm)	3.Area (mm)	4.Area (mm)	5.Area (mm)	6.Area (mm)	7.Area (mm)	8.Area (mm)	9.Area (mm)
1	0,3536	0,3287	0,3271	0,3788	0,4212	0,3443	0,3266	0,287	0,2271
2	0,374	0,3544	0,3681	0,3443	0,2142	0,3729	0,4217	0,3597	0,2781
3	0,3133	0,2916	0,3183	0,3588	0,4357	0,3296	0,3367	0,2896	0,2617
4	0,4292	0,2504	0,3194	0,2396	0,2677	0,2523	0,4589	0,2373	0,3269
5	0,5167	0,4473	0,4159	0,4433	0,4578	0,3547	0,4488	0,3508	0,3369
6	0,2275	0,1828	0,2559	0,1646	0,2228	0,2322	0,2606	0,2519	0,2618
7	0,2868	0,2258	0,2454	0,2438	0,3616	0,2684	0,3166	0,2299	0,2684
8	0,4793	0,3718	0,3522	0,3804	0,4027	0,2992	0,569	0,3698	0,3634
9	0,471	0,4226	0,3983	0,4529	0,4827	0,3915	0,4586	0,3762	0,3459
10	0,4672	0,4181	0,4313	0,4153	0,365	0,3633	0,4874	0,3232	0,3326
11	0,3819	0,325	0,3121	0,3637	0,4256	0,3301	0,3546	0,3247	0,2665
12	0,5038	0,2231	0,2727	0,1956	0,2275	0,1769	0,4369	0,2557	0,2243

When Table 6 is examined, it is seen that different values are obtained for each tool path. Regional form errors are shown in the next section as maps, and the effect of the whole part is examined.

3.2. Converting data to graphics and image process

The form-feed data was first converted to graphics with the codes prepared in the MATLAB program. In the chart, certain form error intervals are represented with different colours. The generated graphics are shown in Fig. 4.

The data are transformed into a graph showing the spatial distribution of form errors in the MATLAB program for image processing. In order to make a comparison, three colours corresponding to three different value ranges are used in the graph. The blue colour indicates the reference surface size (form-free area). The red colour indicates form errors of up to 0.05 mm. Green colour indicates form errors greater than 0.05 mm. When the graphics are visually examined, it is seen that the blue colour decreases and the green and red colours increase especially in the team climb and landing points. As stated in the literature, this is due to the change of the tool contact surface, the sudden increase and decrease in the cutting forces, the negative effects of the amount of chips accumulated in front of the tool and the tool deflection [23].

The first step of image processing is to obtain images. The graphics prepared with the form error data were cut and photographed in the same size and in the same place using the MATLAB package program. Each photograph was read again with Matlab program and image processing techniques were applied (Fig.5).

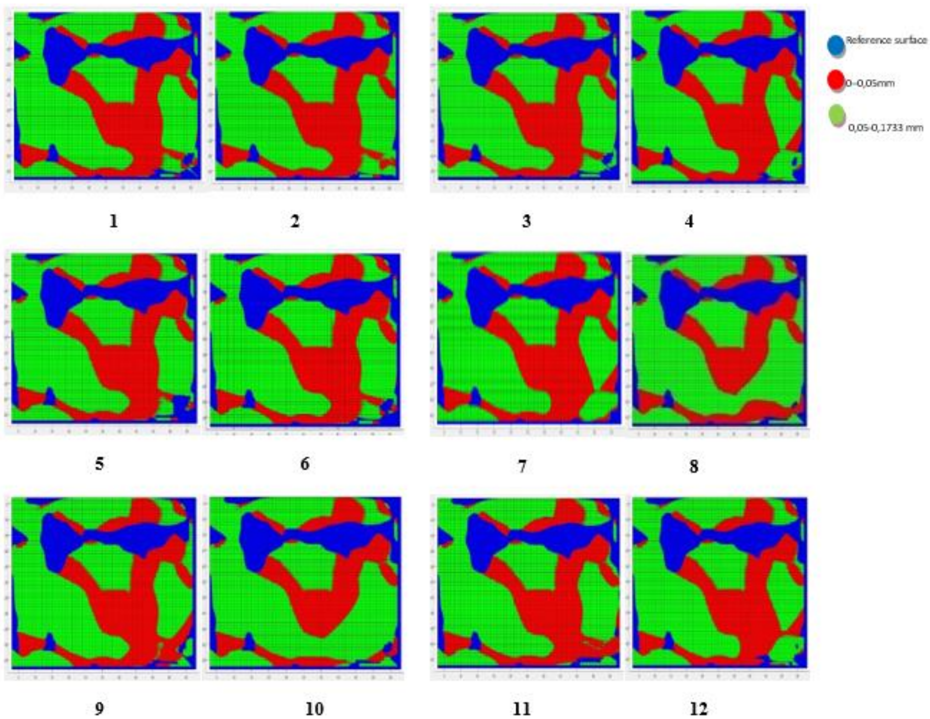

Figure 4. Graphics of form error data.

The application is based on three different colours on the basis of the graphic is how much space each colour covers. Thus, the areas specified by blue colour (reference surface), red colour (form errors up to 0.05 mm), green colour (form errors greater than 0.05 mm) were quantified in % of the total area.

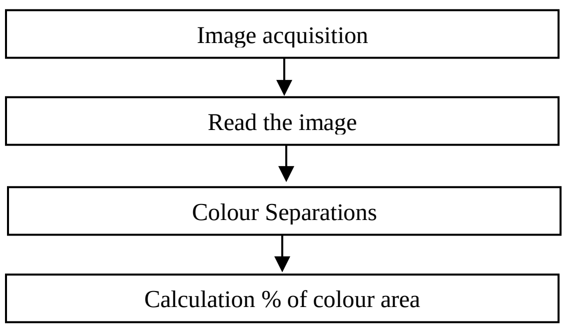

Figure 5. Stage of image process.

The data obtained as a result of the image processing application are shown in Table 7.

Table 7. Result of image processing.

Part	Blue	Red	Green	%Blue	%Red	%Green
1	396229,1	377124,6	435953,6	32,76	31,19	36,05
2	396416,8	383257,4	438589,4	32,54	31,46	36,00
3	398092,8	382295	436261,1	32,72	31,42	35,86
4	399252	387523,6	434777,4	32,68	31,72	35,59
5	398434,6	380472,5	435792,9	32,80	31,32	35,88
6	398118,5	380862,8	436018,4	32,77	31,35	35,89
7	395812,6	389356	436676,1	32,39	31,87	35,74
8	398684,1	380995,1	443091,6	32,60	31,16	36,24
9	396563	389108,6	435662,8	32,47	31,86	35,67
10	401655,5	378543	445025	32,78	30,90	36,32
11	397052,6	387647	436793,8	32,51	31,74	35,76
12	397648	387485,1	434848,8	32,59	31,76	35,64

4. DISCUSSION

When Table 7 is examined, the 5-way (HM-Contour Rough-Parallel Scan) reference surface ratio is 32.80%, which is the tool path with the lowest form error. When the form errors as a surface area are examined, the difference between the different tool paths seems to be small, but this is a big mistake to be solved especially for the medical and defence industries. The stage that most influences the formation of form error is the finish machining phase. In the parallel scan tool path, the tool always moves in the same direction (x-direction) along the curve and does not change direction until the end of the part. When the tool comes to the end of the part, it makes a side step in the y direction and does not change direction again until the other end of the part. The side step moves out of the part so that it is only machined in the x direction on the part. This reduces the occurrence of contact point change, chip accumulation and force change originating from the tool without changing direction, thus reducing form errors [24].

Form errors are mostly seen in the 7th tool path set (HM-Contour Rough-Parallel Linear). The reference surface realization rate in this tool path set is 32, 39%. The parallel linear tool path used in the finishing operation makes a linear movement in the direction opposite to the parallel scan tool path. In addition, the contour rough tool path generates force change and chip debris at several points because the long cutting direction is perpendicular to the cutting direction. This has caused a form error.

5. CONCLUSION

After milling a free-form surface, the form error information has been obtained by scanning. This information was determined as points and evaluated according to the milling areas on the surface. Then, the surface was evaluated as a whole by image processing methods and the following results were obtained:

-The minimum form error is seen in the HM-Contour Rough-Parallel Scan tool path strategy.

-Form errors are more decisive in the finishing process.

-The tool paths which is moving in a single long path (such as parallel scan) have shown lower form errors.

-Form errors are high in tool paths where tool movement perpendicular to the cutting direction (such as contour rough) is performed at short intervals.

- Form errors are mostly seen in the 7th tool path set (HM-Contour Rough-Parallel Linear).

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