Tool path generation for a car rear door die: UMO versus rest milling tool paths

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Abstract. Tool path generation for sculptured surfaces that contain many concave and convex features involves gouging and undercut problems. Past research has paid little attention to tool path generation for hard materials, which require careful and precise planning. In this paper, a comparison is made between traditional unit machining operation (UMO) and rest milling-based tool paths for the various machining steps (roughing, semi-finishing and finishing) of a car’s rear door, designed by NURBS surfaces. The experimental work involves the machining of two dies in a 3-axis CNC machine. Each die comprises two parts: punch (convex) and die (concave). Various tool path patterns (contour, zig-zag, zig, concentric zig-zag) are generated and compared via NX8 software. The results show a great saving of time and less tool consumption by using a rest milling technique over UMO techniques.

1. Introduction

The machining of free-form surfaces has gained huge importance in recent years because it has become relevant to a large variety of industrial applications. For example, complex surface designs are required in the automobile, aerospace, electronics and biomedical manufacturing industries. There is therefore demand for a precise and effective tool path generation method that can be implemented with reasonable machining time.

Qiang Zou et al. [1] presented a new method for the optimization of the tool path distribution pattern by utilizing a group of iso-level tool paths defined over the surface and quantified as a scalar function, so that the required tool path was applied by finding the function that minimized energy functionality with respect to iso-scallop and smoothness. Xu Liu et al. [2] proposed a region-based tool path instead of applying a tool path as a single machining region. The tensor field was formulated to estimate the machining strip width produced by a ball end mill. Zezhong C. Chen and Qiang Fu [3] proposed another method for generating tool paths, using the medial axis transform to find the maximum cutting tool diameter able to access the pocket space, and then performed an optimization model to select the tool path.

Jinting Xu et al. [4] presented a tool path generation method for the CNC machining of a point cloud, by first constructing a base surface which approximately reflected the characteristics and variation of the surface and then generating the tool path. Yuwen Sun et al. [5] developed a multiple vector-field based tool path for CNC machining of compound NURBS surfaces in which the preferred directions of feed were mapped in the parametric domain. Three surfaces were machined to ensure the validity of the proposed method. Wen Feng Gan et al. [6] proposed an improved space filling curve tool path planning for the machining of T-spline free-form surfaces, in which paper the tool path was compared with a traditional CAM system and the efficiency of the proposed method shown. I. Lazoglu et al. [7]
developed a tool path generation method for the optimization of cutting forces in sculptured surface machining. Minimum cost connection method was used as the optimization algorithm for the mean and maximum cutting forces. A. F. de Souza et al. [8] studied ball-end milling for the manufacture of dies and molds; they concluded that positioning the center of the tool tip in the machining area would increase the plastic deformation that yields a rough surface finish and higher cutting forces.

Yao An Lu et al. [9] proposed a multi-criteria optimization method for flat end milling; this algorithm comprised a differential evolution algorithm combined with a linear optimization algorithm, and these algorithms were validated on two different free form surfaces.

Readers of the literature may notice that little attention has been paid to the tool path generation for hard materials, which has numerous applications in modern industry and requires more careful and precise planning than other materials that are easier to machine. Any mistake in the tool path generation could lead to catastrophic tool failure, because the depth of cut is critical to the operation.

In this paper, a study of tool path generation for machining two dies of car posterior door surface, modeled by compound NURBS surfaces, is presented and analyzed for two methods. The first is the conventional unit machining operation (UMO) and the second is the rest milling technique. Each die is composed of two parts, the punch (convex) and the die (concave).

2. 2. Surface Design

Modern car door design involves many features with a large number of control points. This complicates the design process and makes it very difficult to model the designed part in a single surface patch. So, we utilized the NURBS surface modelling technique to design a car door.

Compound NURBS surfaces provide $C^4$ continuity conditions without restricting the control points to follow continuity criteria between surface patches as in composite Bezier surface modelling method. In addition, NURBS surface modelling can produce surfaces for a specific degree independently of the number of control points of the surface. The authors used compound cubic NURBS patches with total 400 (20*20) control points in the geometric modelling process. After that surface offset was applied to find the surface of the punch. The designed surface is shown in Figure 1, the solid model of die piece is shown in Figure 2 and the solid model of the punch shown in Figure 3.
3. Experimental set-up

A 3-axis vector 610 CNC milling was used to perform machining operations, as shown in Figure 4a. The raw materials were four blocks of Ck-50 hard steel with 450*300*45 mm. dimensions. The cut-off operation was accomplished by CNC plasma machine. The workpieces were fixed using fixtures mounted in a T-slot bed. Figure 4b shows the machining set-up. Three types of tools were used in the machining processes: milling inserts, flat end and ball-end mill cutters. The milling inserts were used for facing and shouldering operations. These tools are used for machining planar areas where a large amount needs to be removed. They have high rigidity and the cutting inserts are cheap and easily changed. Two diameters were used (63mm and 20mm). A flat end mill cutter with 14mm diameter was used for machining holes and other geometries. Ball end mill cutters are used extensively in various machining stages, due to their ability to produce curved shapes. Four diameters are used (16mm, 12mm, 10mm and 6mm) as shown in Figure 4c.
4. Figure 4. (a) Vector 610 CNC milling machine. (b) Machining set-up. (c) Ball end mill cutters.

5. 4. Machining first die pieces with UMO-based tool paths

4.1 Machining first die piece
- First, a facing operation to remove 2mm stock thickness using 63mm cutting inserts to provide straight planar surface and get rid of the rust of the material.
- The second step was a roughing operation with a 16mm ball-end cutter with maximum cutting depth (a) of 0.25 mm, as shown in Figure 5.
Figure 5. (a) NX Tool path (b) the workpiece after the second step.

One of the commonest mistakes in tool path generation is to accumulate a stock of remaining metal during roughing, which causes a great problems later in the semi-finishing and finishing operations, especially for compound surfaces that have features with increased possibility of gouging. For example, if we set a stock of 1 mm to the machined part for the operation above, the excess metal (un-cut thickness) value would rise, making it harder for the finishing operation to be done without more cut levels, which increases the time required to perform the machining process. If there is no increase in the cut levels at finishing, a great possibility for tool breakage arises from the increased volume of excess metal to be removed. For hard materials, the thickness of excess metal to be machined must be lower than 10% of the cutter diameter [10], otherwise there is an increased possibility of tool breakage. Figure 6 shows machining tool path analysis in NX for both cases.
Figure 6. Tool path analysis (a) without stock (b) with stock 1 mm.

Figure 7. Six positions with high value undercut thicknesses after the second step.
The third step was semi-finishing, with a 12mm ball-end cutter. To avoid tool breakage, we created two passes of the zig-zag tool path, in order to properly machine positions with high excess metal. The proposed tool path and the machined surface results are shown in Figure 8.

![Tool Path and Machined Surface](image_url)

**Figure 8.** The third machining step (a) tool path (b) machined surface.
The fourth step comprised machining with 4-step layer concentric zig-zag finishing with a 10mm ball cutter. From figures 7c and 9c, the maximum under-cut (UC) is 4.269 mm and 4.917 mm respectively. The UC for this step is 2.42 mm (see Figure 10). Therefore, we must generate multi step tool path, to avoid tool breakage.

**Figure 9.** Six positions with high value under-cut thicknesses after the third step.
Figure 10. Six positions with high value undercut thicknesses after the fourth step.

- Step five was the finishing of the die piece by use of a 3-step follow periphery tool path. It may be seen from figures 8a and 10a that the UC is 3.592 mm and 4.239 mm respectively. After finishing this step, (see Figure 11a) the UC is 2.9 mm. Figure 12 shows the machined surface.
Figure 11. Six positions with high value un-cut thicknesses after the fifth step.

Figure 12. The machined surface after the fifth step.
4.1.2 Machining first punch piece

Punch machining involves the removal of larger amounts of material than die machining, thus the following steps were followed:

- The geometric model of the punch was modified to create a space for clamps to be mounted, to fix the workpiece. Also, we modified the acting sculptured punch surface to be machined by a ball-end cutter, to permit the removal of larger amount of material from planar areas of the punch, as shown in Figure 13a. A follow part tool path was generated using a 3-insert 63 mm diameter cutter, as shown in Figure 13b.

![Figure 13. (a) modified geometric model (b) generated tool path.](image)

- The second step was machining with a 16mm-ball-end cutter, following a periphery tool path distribution as in Figure 14. Five positions with high uncut thickness are shown in Figure 15.
Figure 14. Tool path generated in step 2.

Figure 15. Five positions with high undercut thickness value after step 2.

- The third step was semi-finishing with 12mm ball-end mill cutter. Figure 15a shows the UC is 2.24 mm and this can be compared with the Figure 16a where the UC is 1.54 mm. In order to safely machine the workpiece, two passes following a periphery tool path were generated.
• In the fourth step, the workpiece was finished with a 6mm ball-end cutter. Figure 16a shows that the UC is 1.5 mm, and this can be compared with Figure 17a where the UC is 0.4 mm. So, we generated 4 passes following periphery tool paths in order to safely machine the workpiece. The final machined surface is shown in Figure 18.
5. Machining the second die pieces using a rest milling technique

5.1 Machining the second die piece

For machining the second die and second punch the rest milling technique was used as a different method for tool path generation. In this technique, the tool path of each step is connected to the previous step, so no time is wasted by having the tool path idle. Also, the rest milling approach provides a safer tool path, better for preventing a higher increase in depth of cut which may lead to abrupt tool breakage.

- First step was machining with a 63-mm 3-insert mill cutter, using a follow-part tool path generation strategy. The tool path and the machined part after this step are shown in Figure 19.
- Step 2 involved machining with a 16 mm ball end mill cutter with rest milling technique with a zig-zag distribution pattern. Figure 20 shows the machined surface after this step.

Figure 18. The final machined part.

Figure 19. (a) Tool path generated. (b) The machined surface after this step.
In step 3, a 12 mm ball end mill cutter for the rest milling technique, with a zig-zag distribution pattern, was used to machine the part. The machined part after this step is shown in Figure 21.

In step 4, the workpiece was machined using a 10 mm ball cutter with a zig-zag tool path generation pattern by the rest milling method.

Step 5 involved rest milling with a 6 mm ball end mill cutter using a zig-zag distribution pattern.

Step 6 comprised finish milling with a 6 mm ball end mill cutter using a follow periphery distribution pattern. The finished workpiece is shown in Figure 22 and finally, Figure 23 shows a tool path analysis of the generated tool path.
5.2 Machining the second punch

- The first step was machining with 3-insert 63 mm end mill cutter using a follow path distribution pattern, the machined surface is shown in Figure 24.
- Step 2 involved rest milling with a 16 mm ball mill cutter with a zig-zag distribution pattern. The generated tool path and the machined surface are shown in Figure 25a.
- The third step included rest milling with a 12 mm ball mill cutter with a zig-zag distribution pattern. The machined surface is shown in Figure 25b.
- The fourth step was rest milling with a 10 mm ball mill cutter with a zig-zag distribution pattern.
- Step 5 was rest milling with a 6 mm ball mill cutter with zig-zag distribution pattern.
- Step 6 was finishing with 6 mm ball mill cutter with a follow periphery distribution pattern. The final machined surface is shown in Figure 25c and tool path analysis is shown in Figure 26.
Figure 23. Six positions with high un-cut thickness value after step 6.

Figure 24. The machined surface after step 1.
Figure 25 (a) the machined surface after step 2. (b) The machined surface after step 3. 
(c) Final machined second punch surface.
6. Results and discussion

We have introduced three tool path generation output parameters which include machining time, maximum undercut thickness (UC) and the overcut (OC). These parameters determine the efficiency of the proposed tool path pattern. The tool path distribution pattern used is highlighted with yellow mark.

6.1 Results of machining the first die

• First step, the roughing tool path using 16 mm ball end cutter. is shown in Table 1, below.
  
- N=1000 rpm. $S_{max}$=8 mm. $f$=400 mm/min. $a=0.25$

| operation               | TPG method            | machining time | UC     | OC     |
|-------------------------|-----------------------|----------------|--------|--------|
| roughing-16mm           | follow part           | 17:02:57       | 4.373  | 0.2105 |
| roughing-16mm           | zig-zag               | 16:16:47       | 6.983  | 0.2090 |
| roughing-16mm           | zig                   | 17:38:18       | 7.555  | 0.71   |
| roughing-16mm           | trochoidal            | 23:22:15       | 5.115  | 0.2241 |
| roughing-16mm           | follow periphery      | 17:05:11       | 4.654  | 0.2105 |

• Second step :- the semi-finishing tool path using 12 mm. ball end cutter.
  
- N=1000 rpm. $S_{max}$=6 mm. $f$=400 mm/min. finish step=0.25 mm.

| operation               | TPG method           | machining time | UC     | OC     |
|-------------------------|----------------------|----------------|--------|--------|
| semi-finish 12mm        | follow periphery     | 0:49:50        | 5.600  | 0.68   |
| semi-finish 12mm        | zig-zag 0°           | 0:53:16        | 4.915  | 0.2447 |
| semi-finish 12mm        | zig-zag 45°          | 0:55:02        | 4.654  | 0.6772 |
| semi-finish 12mm        | zig-zag 90°          | 0:53:14        | 5.295  | 0.1991 |


- **Step 3**: the semi-finishing tool path using 10 mm ball end cutter.
  
  \[ N=1000 \text{ rpm. } S_{\text{max}}=5 \text{ mm. } f=400 \text{ mm/min. finish step}=0.5 \text{ mm.} \]

| Operation | TPG Method | Machining Time | UC | OC |
|-----------|------------|----------------|----|----|
| semi-finish 10mm | follow periphery | 3:10:00 | 4.654 | 0.2483 |
| semi-finish 10mm | zig-zag 0° | 3:22:48 | 4.244 | 0.2154 |
| semi-finish 10mm | zig-zag 45° | 3:31:28 | 3.554 | 0.088 |
| semi-finish 10mm | zig-zag 90° | 3:24:17 | 4.45 | 0.15 |
| semi-finish 10mm | concentric zig-zag | 3:24:25 | 4.399 | 0.3594 |

- **Fourth step**: the semi-finishing tool path using 6 mm ball end cutter.
  
  \[ N=1000 \text{ rpm. } S_{\text{max}}=0.01 \text{ mm. } f=400 \text{ mm/min. finish step}=0.5 \text{ mm.} \]

| Operation | TPG Method | Machining Time | UC | OC |
|-----------|------------|----------------|----|----|
| finish 6mm | follow periphery | 15:08:08 | 2.33 | 0.2258 |
| finish 6mm | zig-zag 0° | 16:30:56 | 2.88 | 0.2676 |
| finish 6mm | zig-zag 45° | 17:04:20 | 2.5 | 0.2089 |
| finish 6mm | zig-zag 90° | 16:31:07 | 2.49 | 0.2057 |
| finish 6mm | concentric zig-zag | 16:12:14 | 2.749 | 0.2356 |

6.2 *Results of Machining First Punch*

- **Step 1**: primary roughing with 63 mm 3-insert cutter.
  
  \[ N=1000 \text{ rpm. } S_{\text{max}}=31.75 \text{ mm. } f=400 \text{ mm/min. } a=0.3 \text{ mm.} \]

| Operation | TPG Method | Machining Time | UC | OC |
|-----------|------------|----------------|----|----|
| roughing-63mm | follow part | 12:13:22 | 1.074 | 0.1912 |
| roughing-63mm | zig-zag | 9:05:07 | 26.48 | 0.0878 |
| roughing-63mm | zig | 18:00:14 | 16.64 | 0.1921 |
| roughing-63mm | trochoidal | 16:34:30 | 63 | 0.889 |
| roughing-63mm | follow periphery | 14:01:47 | 35 | 0.1972 |

- **Step 2**: second roughing operation with 16 mm ball end mill cutter.
  
  \[ N=1000 \text{ rpm. } S_{\text{max}}= 8 \text{ mm. } f=400 \text{ mm/min. } a=0.3 \text{ mm.} \]

| Operation | TPG Method | Machining Time | UC | OC |
|-----------|------------|----------------|----|----|
| roughing-16mm | follow part | 14:36:01 | 2.173 | 1.742 |
| roughing-16mm | follow periphery | 14:05:57 | 2.28 | 1.742 |
| roughing-16mm | zig-zag | 12:58:28 | 5.22 | 1.947 |
| roughing-16mm | zig | 15:00:27 | 5.22 | 1.949 |
**Step 3:** semi-finishing operation with 12 mm. ball end mill cutter

N=1000 rpm. \( S_{\text{max}} = 6 \text{ mm}, f=400 \text{ mm/min.} \) finish step=0.2 mm.

Table 7. Results of roughing with 12 mm. ball cutter for first punch.

| operation                | TPG method     | machining time | UC  | OC  |
|--------------------------|----------------|----------------|-----|-----|
| semi-finish 12mm         | follow periphery | 1:02:33         | 3.446 | 1.727 |
| semi-finish 12mm         | zig-zag 0°     | 1:02:17         | 3.547 | 1.727 |
| semi-finish 12mm         | zig-zag 45°    | 1:03:49         | 7.6  | 1.65 |
| semi-finish 12mm         | zig-zag 90°    | 1:05:37         | 3.594 | 2.66 |
| semi-finish 12mm         | zig 0°         | 1:09:37         | 3.547 | 1.727 |
| semi-finish 12mm         | concentric zigzag | 1:05:03        | 3.371 | 2.422 |

**Step 4:** finishing operation with 6 mm. ball end mill cutter

N=1000 rpm. \( S_{\text{max}} = 0.01 \text{ mm}, f=400 \text{ mm/min.} \) finish step=0.4 mm.

Table 8. Results of 4 step-finishing with 6 mm. ball cutter for first punch.

| operation     | TPG method   | machining time | UC  | OC  |
|---------------|--------------|----------------|-----|-----|
| finish 6mm    | follow periphery | 31:46:14       | 0.64 | 0.58 |
| finish 6mm    | zig-zag 0°   | 31:32:11        | 0.65 | 0.56 |
| finish 6mm    | zig-zag 45°  | 32:20:44        | 0.63 | 0.66 |
| finish 6mm    | zig-zag 90°  | 32:53:18        | 0.85 | 0.56 |
| finish 6mm    | zig 0°       | 32:05:25        | 0.87 | 0.703 |
| finish 6mm    | concentric zigzag | 31:24:53      | 0.65 | 0.703 |

6.3 Results of machining second die

**First step:** roughing operation with 63 mm 3-insert cutter

N=1000 rpm. \( S_{\text{max}} = 31.75 \text{ mm}, f=400 \text{ mm/min.} \) a=0.25 mm.

Table 9. Results of roughing with 63 mm. cutter for second die.

| operation      | TPG method   | machining time | UC  | OC  |
|----------------|--------------|----------------|-----|-----|
| roughing-63mm  | follow part  | 2:41:17        | 12.88 | 0.287 |
| roughing-63mm  | zig-zag      | 1:57:23        | 18.98 | 0.205 |
| roughing-63mm  | zig          | 1:58:13        | 18.98 | 0.205 |
| roughing-63mm  | trochoidal   | 7:50:20        | 14:54 | 0.246 |
| roughing-63mm  | follow periphery | 2:42:03      | 12.88 | 0.274 |

**Second step:** rest milling operation with 16 mm ball cutter

N=1000 rpm. \( S_{\text{max}} = 8 \text{ mm}, f=400 \text{ mm/min.} \) a=0.25 mm.

Table 10. Results of rest milling with 16 mm. ball cutter for second die.

| operation      | TPG method   | machining time | UC  | OC  |
|----------------|--------------|----------------|-----|-----|
• Third step :- rest milling operation with 12 mm. ball cutter

N=1000 rpm. $S_{\text{max}}= 6$ mm. $f=400$ mm/min. $a=0.25$ mm.

**Table 11.** Results of rest milling with 12 mm. ball cutter for second die.

| operation          | TPG method | machining time | UC  | OC  |
|--------------------|------------|----------------|-----|-----|
| semi-finish 12mm   | follow part| 2:00:36        | 3.123| 0.366|
| semi-finish 12mm   | follow periphery| 2:11:00 | 3.123| 0.366|
| semi-finish 12mm   | zig-zag    | 0:50:36        | 3.422| 0.353|
| semi-finish 12mm   | zig        | 1:35:53        | 3.422| 0.348|

• Fourth step :- rest milling operation with 10 mm. ball cutter

N=1000 rpm. $S_{\text{max}}= 5$ mm. $f=400$ mm/min. $a=0.25$ mm.

**Table 12.** Results of rest milling with 10 mm. ball cutter for second die.

| operation          | TPG method | machining time | UC  | OC  |
|--------------------|------------|----------------|-----|-----|
| semi-finish 10mm   | follow part| 1:44:45        | 2.464| 0.353|
| semi-finish 10mm   | follow periphery| 1:50:30 | 2.464| 0.353|
| semi-finish 10mm   | zig-zag    | 0:31:48        | 2.685| 0.353|
| semi-finish 10mm   | zig        | 0:54:02        | 2.685| 0.353|

• Fifth step :- rest milling operation with 6 mm. ball cutter

N=1000 rpm. $S_{\text{max}}= 3$ mm. $f=400$ mm/min. $a=0.25$ mm.

**Table 13.** Results of rest milling with 6 mm. ball cutter for second die.

| operation          | TPG method | machining time | UC  | OC  |
|--------------------|------------|----------------|-----|-----|
| semi-finish 6mm    | follow part| 1:49:52        | 2.18 | 0.353|
| semi-finish 6mm    | follow periphery| 1:59:15 | 2.18 | 0.353|
| semi-finish 6mm    | zig-zag    | 1:02:15        | 2.18 | 0.353|
| semi-finish 6mm    | zig        | 2:49:00        | 2.18 | 0.353|

• Sixth step :- finishing operation with 6 mm. ball cutter

N=1000 rpm. $S_{\text{max}}= 0.01$ mm. $f=400$ mm/min.

**Table 14.** Results of finish milling with 6 mm. ball cutter for second die.

| operation          | TPG method | machining time | UC  | OC  |
|--------------------|------------|----------------|-----|-----|
| finish 6mm         | follow part| 5:02:52        | 1.374| 0.356|
| finish 6mm         | zig-zag 0° | 5:31:32        | 1.284| 0.356|
| finish 6mm         | zig-zag 45°| 5:43:08        | 1.435| 0.362|
| finish 6mm         | zig-zag 90°| 5:32:25        | 1.300| 0.356|
| finish 6mm         | zig 0°     | 5:58:46        | 1.284| 0.356|
| finish 6mm         | concentric zigzag | 5:24:33 | 1.327| 0.355|
6.4 Results of machining second punch

- **Step 1**: roughing operation with 63 mm. 3-insert cutter
  
  \[ N = 1000 \text{ rpm}, \quad S_{\text{max}} = 47.25 \text{ mm}, \quad f = 400 \text{ mm/min}, \quad a = 0.3 \text{ mm}. \]

  | operation            | TPG method | machining time | UC  | OC  |
  |----------------------|------------|----------------|-----|-----|
  | roughing-63mm        | follow part| 14:15:53       | 14.4| 1.222|
  | roughing-63mm        | zig-zag    | 10:53:30       | 21.47| 6.3|
  | roughing-63mm        | trochoidal | 14:43:10       | 17.46| 6.302|
  | roughing-63mm        | follow periphery | 25:57:44 | 32.6 | 1.645|

- **Second step**: rest milling operation with 16 mm. ball end mill cutter
  
  \[ N = 1000 \text{ rpm}, \quad S_{\text{max}} = 6.4 \text{ mm}, \quad f = 400 \text{ mm/min}, \quad a = 0.3 \text{ mm}. \]

  | operation            | TPG method | machining time | UC  | OC  |
  |----------------------|------------|----------------|-----|-----|
  | rest milling-16mm    | follow part| 5:38:46        | 1.789| 1.101|
  | rest milling-16mm    | follow periphery | 7:42:51 | 1.789| 1.101|
  | rest milling-16mm    | zig-zag    | 5:09:15        | 2.18 | 1.098|
  | rest milling-16mm    | zig        | 8:23:13        | 2.22 | 0.807|
  | rest milling-16mm    | trochoidal | 8:31:29        | 1.79 | 0.805|

- **Third step**: rest milling operation with 12 mm. ball end mill cutter
  
  \[ N = 1000 \text{ rpm}, \quad S_{\text{max}} = 6 \text{ mm}, \quad f = 400 \text{ mm/min}, \quad a = 0.25 \text{ mm}. \]

  | operation            | TPG method | machining time | UC  | OC  |
  |----------------------|------------|----------------|-----|-----|
  | rest milling-12mm    | follow part| 1:34:33        | 1.67 | 1.105|
  | rest milling-12mm    | follow periphery | 1:51:59 | 1.67 | 1.105|
  | **rest milling-12mm**| zig-zag    | **34:52**      | **1.789**| **1.105**|
  | rest milling-12mm    | zig        | 1:01:42        | 1.789| 1.092|

- **Fourth step**: rest milling operation with 10 mm. ball end mill cutter
  
  \[ N = 1000 \text{ rpm}, \quad S_{\text{max}} = 5 \text{ mm}, \quad f = 400 \text{ mm/min}, \quad a = 0.25 \text{ mm}. \]
Table 18. Results of rest milling with 10 mm. cutter for second punch.

| operation                  | TPG method | machining time | UC  | OC  |
|----------------------------|------------|----------------|-----|-----|
| rest milling-10mm          | follow part| 1:04:41        | 1.789 | 0.809 |
| rest milling-10mm          | follow periphery | 1:17:23   | 1.46  | 0.809 |
| rest milling-10mm          | zig-zag    | 18:48          | 1.745 | 1.105 |
| rest milling-10mm          | zig        | 32:17          | 1.789 | 1.092 |

Fifth step: rest milling operation with 6 mm. ball end mill cutter

N=1000 rpm. \( S_{\text{max}} = 3 \) mm. \( f = 400 \) mm/min. \( a = 0.15 \) mm.

Table 19. Results of rest milling with 6 mm. cutter for second punch.

| operation                  | TPG method | machining time | UC  | OC  |
|----------------------------|------------|----------------|-----|-----|
| rest milling-6mm           | follow part| 2:55:43        | 0.69 | 0.696 |
| rest milling-6mm           | follow periphery | 3:53:20   | 0.69  | 0.696 |
| rest milling-6mm           | zig-zag    | 1:35:08        | 0.84  | 0.696 |
| rest milling-6mm           | zig        | 3:07:49        | 0.84  | 0.696 |

Sixth step: finish milling operation with 6 mm. ball end mill cutter

N=1000 rpm. \( S_{\text{max}} = 0.01 \) mm. \( f = 400 \) mm/min.

Table 20. Results of finish milling with 6 mm. cutter for second punch.

| operation                  | TPG method | machining time | UC  | OC  |
|----------------------------|------------|----------------|-----|-----|
| finish 6mm                 | follow part| 4:57:53        | 0.65 | 0.58 |
| finish 6mm                 | zig-zag 0° | 4:59:35        | 0.611 | 0.557 |
| finish 6mm                 | zig-zag 45°| 5:06:43        | 0.67  | 0.604 |
| finish 6mm                 | zig-zag 90°| 5:10:13        | 0.82  | 0.789 |
| finish 6mm                 | zig 0°     | 5:30:39        | 0.611 | 0.557 |
| finish 6mm                 | concentric zigzag | 5:03:36 | 0.75  | 0.705 |

6.5 Comparison of the machining methods

The total machining time for the die and punch using the UMO and rest milling techniques, and the percentage of reduction in time using rest milling techniques, are given in Table 21 (below).

Table 21. Total machining time for the die and punch using the UMO and rest milling techniques, and the percentage of reduction in time using rest milling techniques.

| part | UMO milling time | Rest milling time | percentage |
|------|------------------|-------------------|------------|
|      | time (h:m:s)     | seconds           | seconds    |            |
| Die  | 36:28:46         | 131326            | 57600      | 228 %      |
| Punch| 59:08:06         | 212886            | 98480      | 216 %      |
6.6 Discussion of the acquired results

Rest milling is more effective than traditional UMO tool paths because it links the various machining steps and eliminates the time consumed when the tool is idle. Also, machining sculptured surfaces with multiple gouge regions by machining with tool paths that have large diameter size cutters leaves a high volume of excess metal in the gouge regions, while this regions may be machined precisely if a rest milling toolpath was applied. Clearly, the use zig-zag tool paths in rest milling techniques are more effective than traditional paths because they move in horizontal and vertical directions, in contrast to contour-based tool paths that move along the periphery, which consumes more time than zig-zag tool paths.

7. Conclusions

The rest milling technique has been proven effective in the reduction of machining time because it limits inactivity in machining time that occurs with unit machining-based operations. In our study, the percentage reduction of machining time achieved was 228% for die machining (concave shape) and 216% for punch machining. Rest milling also permits the use of large diameter cutters, which allow the removal of greater volumes of chips in less time, an option that is not available in UMO-based operations due to the high uncut thickness left after machining with large diameter cutters. The follow periphery (contour) path distribution pattern is the best in terms of time efficiency in UMO techniques, and the zig-zag pattern is the most time efficient in a rest milling technique.

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