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Selecting optimal tools for arbitrarily shaped pockets

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Abstract As a result of slicing a 3D part into 2D pockets for generating tool paths, pockets are becoming more commonly used. When a pocket is machined, the question of which of the many feasible tools for cutting the pocket is best always arises. Will cutting be more efficient if multi-tools are used? Will the algorithm to choose the optimal tools be timesaving enough? This paper presents a method in which an upper bound $O(N)$ is used to choose the optimal cutting tool combination, where N is the number of feasible tools available. The proposed method is quick and sufficient for computer-aided process planning (CAPP) and computer-aided manufacturing (CAM) environments.

Keywords Tool selection · Pocket · Tool path · CAM · CAPP

1 Introduction

Many researchers have addressed the generation of tool paths [1–3], and some important means of machining products more efficiently have been developed [4–6]. Many factors influence the efficiency of cutting. Some critical issues include the sizes of the tools and the cutting conditions. Traditionally, the tool size is manually chosen. The end user of computer-aided machining (CAM) software uses a trial-and-error method or personal experience to select tools of the appropriate sizes. Glaeser et al. [7] proposed freedom of interference as a criterion by which to select tools automatically. However, an interference-free tool may be feasible, but not optimal, as indicated in Fig. 1. The depth of the pocket is 4 mm. Using one interference-free tool to machine the pocket yields tool paths 4,901.81 mm long, and takes 81.94 min under the

cutting conditions of 59 mm/min and 1,688 rpm. If two tools are used to machine the pocket, the cutting time is reduced greatly to 11.01 min, but also, the wear of the tool is reduced. The improvement in the cutting time associated with multi-tool machining is very great, and this study will present an efficient method for choosing optimal tools and cutting conditions.

Before optimal tools are chosen, three types of data must be obtained. They are as follows:

1. Tool data, including tool diameters and their permissible cutting heights.
2. Part data, including mechanical strength, the pockets' geometries, depths, surface finishes, and tolerances.
3. Machine data, including power and permissible spindle speed.

Given these data, optimal tool diameters and cutting conditions can be determined.

2 Selecting optimal tools

The ability to generate tool paths must be developed before the performance test of a tool. This paper adopts the algorithm presented by You et al. [8] for avoiding local gouging and for generating tool paths.

Bala and Chang's approach [9] to select tools is restricted to two tools, but the optimal tool combination may exceed two tools. Many possible combinations of tools will occur when machining a part. Suppose N different tools are available and feasible. The sum of all possible tool combinations is $C_1^N + C_2^N + \dots + C_i^N + \dots + C_N^N$, where $C_i^N = \frac{N!}{(N-i)!i!}$, $1 \leq i \leq N$. This sum equals $2^N - 1$. No general algorithm exists for directly connecting optimal tool combinations with arbitrarily shaped pockets. Differently shaped pockets may require different tool combinations. If all possible combinations are calculated to determine the optimum, then the search times will have an upper bound $O(2^N)$. Kyoung et al. [10] proposed a branching and bounding procedure to determine the

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Fig. 1 An interference-free tool may not be optimal

optimal tool combination and to largely reduce the times for searching the possible combinations. However, this search time is still too large if N is very high. In the general case, at least 25 tools with diameters from 1 mm to 50 mm are available. Even when the branching and bounding procedure is used, the calculating times will reach thousands of combinations. Hence, a more effective method for reducing the amount of computation is required.

In pursuit of this goal, the following four hypotheses are presented:

1. Every tool has an optimal set of cutting conditions. The prerequisite for the optimal tool combination is that every tool must be equipped with optimal cutting conditions.
2. For a pocket with no residue, the optimal number of tools is one.
3. For a pocket with local residues, the optimal number of tools may be one or two.

Fig. 2 Global residue and local residue

4. For a pocket with global residues, the optimal number of tools is less than four.

Hypothesis 1 describes the effect of cutting conditions on the performance of the tool. A high cutting velocity will reduce the life of the tools. A too large a feed rate will cause the tool to break. A too large an axial depth of cutting will cause the tool and machine to vibrate. However, reducing these cutting parameters will reduce the performance of the tool and, thereby, increase the cutting time.

The axial depth of cut is, herein, set to one diameter of the tool to reduce the probability of unexpected tool breakage. If the depth of a pocket is deeper than one diameter, then the axial depth of every cut will equal the depth of the pocket divided by the number of cutting layers. The radial depth of the cut is fixed at half of the diameter. Hence, the tool offset must equal half of a diameter. This paper applies spiral tool paths to maintain the direction of cutting in down-mill for rough machining and in up-mill for finish machining.

The cutting velocity is related to the material properties of a part. Consider carbon steel for example; the cutting velocity is inversely proportional to the strength or hardness of the part. Many toolmakers have suggested the optimal cutting velocity V_0 and feed-rate F_0 for various tools at one radius axial depth of cut. These data can be used as the basis to adjust F_0 when different values of axial depth of cut is used. If the axial depth of the cut is less than or more than one radius, then the feed rate increases or decreases, respectively. The rate of increasing or decreasing feed rate depends on the rigidity of the machine. The suggesting relationship, $F = F_0 \times \sqrt{\frac{r}{h_a}}$, holds, where h_a is the axial cut depth and r is the radius of the tool. As h_a is reduced, the feed rate increases. However, if the feed rate increases, the working relief angle of the tool declines. Hence, a constraint should be set to ensure that the working relief angle does not diminish too much; that is, if $F \geq 4 \times F_0$, then $F = 4 \times F_0$.

Fig. 3 The larger the tool, the shorter the tool path

Fig. 4a–f Optimal tool combination. **a** Rough tool and local residue. **b** Finish tool and the removal of residue. **c** Optimal tool machining. **d** Residue-free tool (local optimal). **e** Optimal rough tool. **f** Optimal finish tool

Hypothesis 2 states that the optimal number of tools is one if all of the candidate tools leave no residue in the pocket. The residue is the area left uncut in the pocket after the cutting of a tool. Figure 2 illustrates local and global residue. Global residue is generally formed due to the presence of (an) island(s) inside the pocket or (a) neck area(s) on the pocket profile. Local residue is usually called undercut. They are generally formed due to the small curvature of a profile edge. Figure 3 is drawn to explain hypothesize 2. To leave no local residue in the pocket, the diameter of a candidate tool should be equal to or smaller than the diameter of the smallest concave edge of the pocket profile. A total of 15 tools for cutting the pocket are qualified, with diameters from 1 mm to 20 mm. As the

tool's diameter increases, the total lengths of the tool paths become shorter. The tool with the largest diameter obtains the shortest tool path. Any other tool or combination of tools will get a longer tool path. Hence, the optimal tool is the largest of these 15 candidate tools and its diameter is equal to the one of the smallest concave edge of the pocket profile.

Hypothesis 3 presents the influence of the presence of the local residue. When the tool's curvature is larger than the curvature of the concave edge of the pocket profile, local residue is produced and the optimal number of tools may still be one or may reach two. If two tools are selected for machining, then the larger is used as the rough tool to remove the main area of the pocket. The smaller tool is

Table 1 Cutting data of the profile in Fig. 4a

Rough tool				Finish tool		Total
Diameter	R.P.M.	F.P.T	Time	Diameter	Time	Time
34 mm	280	0.158	0.77	20 mm	1.04	1.81
32 mm	298	0.151	0.83	20 mm	0.92	1.75
30 mm	318	0.142	0.90	20 mm	0.79	1.69
28 mm	341	0.133	0.96	20 mm	0.67	1.63
26 mm	367	0.124	1.04	20 mm	0.54	1.58
24 mm	397	0.113	1.12	20 mm	0.42	1.54
22 mm	434	0.102	1.21	20 mm	0.29	1.5
20 mm	477	0.1	1.33	20 mm	0	1.33

F.P.T.=feed per tooth

Fig. 5 Formation of the optimal tool combination

used as a finish tool to remove the local residue produced by the rough tool, as shown in Fig. 4a,b. If the diameter of the tool increases, the rough cutting time becomes shorter, but the residue area becomes larger. A larger residue corresponds to a greater finishing time. Sometimes, machining with two tools may not be faster than machining with one. The profile in Fig. 4c demonstrates this situation. The diameter of the smallest concave edge of the pocket profile is 20 mm. The tool with diameter 20 mm is superior to other tools with diameter smaller than 20 mm, and it can be regarded as a local optimal tool. Furthermore, if a tool with diameter larger than 20 mm is adopted to cut the pocket, local residue will be left in the pocket. An additional tool should be used to remove the local residue. Because the local optimal tool outperforms other tools whose diameters are smaller than 20 mm, the optimal combination of tools will be the local optimal and another tool whose diameter is larger than 20 mm. Table 1 shows

Fig. 6a–d Maximum number of optimal tools. **a** Cutting by one tool (local optimal). **b** Cutting by optimal rough tool. **c** Cutting by optimal semi-rough tool. **d** Finish cutting

the cutting data of the profile in Fig. 4c. Tools with diameters from 34 mm to 22 mm are pair-wisely combined with the local optimal tool to calculate the cutting time. These data show that the combination of tools with diameters 22 mm and 20 mm spend the shortest time cutting than any other combination of tools. But, in this case, the local optimal tool is also the global optimal tool. This tool outperforms any other combination of tools. The number of tools in the optimal combination is still

Table 2 Cutting data of the profile in Fig. 4d

Rough tool				Finish tool		Total
Diameter	R.P.M.	F.P.T	Time	Diameter	Time	Time
50 mm	191	0.208	1.88	20 mm	2.04	3.92
48 mm	198	0.203	1.93	20 mm	1.91	3.84
46 mm	207	0.198	1.98	20 mm	1.79	3.77
44 mm	217	0.192	2.03	20 mm	1.67	3.7
42 mm	227	0.186	2.08	20 mm	1.54	3.62
40 mm	238	0.18	2.13	20 mm	1.42	3.55
38 mm	251	0.173	2.17	20 mm	1.29	3.46
36 mm	265	0.166	2.22	20 mm	1.17	3.39
34 mm	280	0.159	2.26	20 mm	1.04	3.3
32 mm	298	0.151	2.31	20 mm	0.92	3.23
30 mm	318	0.142	2.37	20 mm	0.79	3.16
28 mm	341	0.134	2.43	20 mm	0.67	3.1
26 mm	367	0.124	3.66	20 mm	0.54	4.2
24 mm	397	0.114	3.93	20 mm	0.42	4.35
22 mm	434	0.102	4.26	20 mm	0.29	4.55
20 mm	477	0.1	4.66	20 mm	0	4.66

maintained at one. Figure 5a plots the data of cutting time of Table 1 as three curves, and illustrates the formation of the optimal rough tool. However, if the dimension h in Fig. 4c is increased as shown in Fig. 4d, then the tool with diameter 20 mm is not the global optimal one. Table 2 presents the detailed cutting data of the changed profile. Figure 5b plots the data of cutting time as three curves, and shows that the number of tools in the optimal combination is two. Their diameters are 28 mm and 20 mm. The key factor in determining the number of tools in the optimal combination is the ratio of the pocket area to the local residue area. When the pocket area is much larger than the local residue area, a roughing tool must be used to remove the main area of the pocket first.

Hypothesis 4 explains that, when a global residue appears, the maximum number of optimal tools is three. Global residues frequently develop in the neck area of a pocket profile or the narrow area between an island and a pocket. If global residue appears, using the curvature of the smallest concave edge of the pocket profile to determine the optimal tool combination does not suffice. Consider the profile in Fig. 1 as an example. The radius of the smallest concave edges of the profile is 23.64 mm, but if this value is adopted as the radius of the tool, then the tool will be too large to cut the neck area. Consequently, the radius of the tool must be shrunk until it can remove the material from the neck area. If the removal of local and global residues is both considered, the residue-free tool can be the local optimal. Figure 6a depicts the situation. The tool can remove all the material from the pocket, but it still has the disadvantage of being time-consuming. Hence, the pocket needs multi-tool-machining. The main area of the pocket requires an optimal rough tool to cut. Meanwhile, when the global and local residues are considered, another optimal semi-rough tool may be required to remove the neck area and some parts of local residue, and a third optimal finish tool may be needed to remove local residues. Figure 6b–d illustrates the three situations respectively.

3 Verification

The optimal semi-rough tool T_2 and the optimal finish tool T_1 will be selected according to the process in Fig. 7. A total of 25 tools with diameters from 1 mm to 50 mm is available before choosing. Tests begin with the maximum available tool diameter $D_{upperLimit}$. The first test determines whether the tool is too large for the pocket. It is a test of feasibility and can be easily conducted by checking the condition of quasi-offset. If a tool is too large, then the quasi-offset will not be successfully constructed. After passing the feasibility test, the tool will be identified as T_{max} and the next test, involving the appearance of global residue, will begin. The appearance of the self-intersection of the quasi-offset or the intersection of the quasi-offsets of the pocket and its island(s) allow global residues to be recognized. The tools that pass the global and local residue tests are called T_2 and T_1 , respectively.

Fig. 7 Process for choosing the optimal semi-rough tool T_2 and the optimal finish tool T_1

If no global residue appears in the pocket, then T_2 will be set to nil. The number of optimal tool combinations may be

Fig. 8 Determination of the optimal rough tool

Table 3 Cutting data of the profile in Fig. 8

Rough tool				Finish tool		Total
Diameter	R.P.M.	F.P.T	Time	Diameter	Time	Time
50 mm	191	0.225	0.59	4 mm	64.65	65.24
48 mm	198	0.22	0.64	4 mm	64.61	65.25
46 mm	207	0.216	0.68	4 mm	64.56	65.24
44 mm	217	0.211	0.72	4 mm	64.46	65.18
42 mm	227	0.206	0.75	4 mm	64.43	65.18
40 mm	238	0.201	0.79	4 mm	64.39	65.18
38 mm	251	0.196	0.82	4 mm	64.36	65.18
36 mm	265	0.191	1.10	4 mm	48.37	49.47
34 mm	280	0.186	1.38	4 mm	46.16	47.54
32 mm	298	0.18	1.7	4 mm	33.45	35.15
30 mm	318	0.174	2.05	4 mm	31.06	33.11
28 mm	341	0.168	2.39	4 mm	25.21	27.6
26 mm	367	0.162	3.01	4 mm	22.06	25.07
24 mm	397	0.155	3.61	4 mm	15.66	19.27
22 mm	434	0.149	4.37	4 mm	9.51	13.88
20 mm	477	0.142	4.78	4 mm	7.74	12.52
18 mm	530	0.135	4.76	4 mm	6.25	11.01
16 mm	596	0.1	7.27	4 mm	5.47	12.74
14 mm	682	0.089	8.5	4 mm	4.58	13.08
12 mm	795	0.077	10.44	4 mm	3.45	13.89
10 mm	955	0.066	13.55	4 mm	1.5	15.05
8 mm	1067	0.0496	18.51	4 mm	0.82	19.33
6 mm	1232	0.027	41.31	4 mm	0.54	41.85
5 mm	1509	0.022	56.65	4 mm	0.33	56.98

two or one, of which these situations are covered by hypotheses 2 and 3. If global residue appears inside the pocket, as addressed by hypothesis 4, then $T_2 = \text{nil}$. At this moment, every tool, from $T_{\max}$ to T_2 , is pair-wisely combined with T_2 to test the cutting time and to determine which tool is qualified to be the optimal rough tool T_3 .

Consider Fig. 1 as a sample for testing. The pocket has four neck areas. The total area is 10,749.5 mm². The minimum diameter of the concave arc edges is 23.63 mm.

The width of the smallest neck area is 4.7 mm. The diameter of the maximum feasible tool $T_{\max}$ is 50 mm. After the choosing process depicted in Fig. 7 is performed, the diameter of the non-global-residue tool T_2 equals that of T_1 and its radius is 4 mm. Furthermore, the optimal rough tool T_3 can be obtained by pair-wisely combining T_2 with other feasible tools from $T_{\max}$ to T_2 . Table 3 presents the cutting data of these tool combinations. Figure 8 plots the data of cutting time of Table 3 as three curves and

Fig. 9a, b Verifying test.**a** Cutting by rough tool.**b** Cutting by finish tool

illustrates that the diameter of the optimal rough tool T_3 is 18 mm. Figure 9 shows the machining of the optimal rough and finish tools.

The time required to perform the calculations in this example to select the optimal tool combination is 0.56 s. The calculations are performed on a Windows 2000 operating system using a personal computer with a 1,500-MHz CPU made by AMD. The calculating time is appropriate for industrial application.

4 Discussion and conclusions

The number of tools used in optimal multi-tool machining is always less than four, according to the four hypotheses presented in this paper. This result eliminates the possibility of the tool combination C_i^N , where $i > 3$, and $C_i^N = \frac{N!}{(N-i)! \cdot i!}$, so IT meets the requirement of a limited number of available tool positions of a CNC machine.

However, even though the number of optimal multi-tool machines can be confined to three or fewer, the combination of freely selecting tools has an upper bound $O(N^3)$. Dynamic programming is used here to find the optimal semi-rough and finishing tools within $2N$ units of searching. The following optimal rough tool test requires searching for less than N units. Therefore, the method presented by this paper can successfully reduce the upper bound of the search from $O(2^N)$ to $O(N)$, and, thus, meets the requirements of computer-aided process planning (CAPP) and computer-aided manufacturing (CAM) environments.

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