OPTIMIZING THE REST MACHINING DURING HSC MILLING OF PARTS WITH COMPLEX GEOMETRY

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ABSTRACT

The process of HSC milling of complex geometry is carried out in several stages that include the rest machining, which is typical for manufacturing of parts with complex geometry. Since the rest machining is a more extensive stage than previously imagined, selection of favorable milling strategy in the rest machining stage requires a closer view. This paper presents the solution to the generation of milling strategies for rest machining by using commercial CAM systems, which offer a broad possibility for the organization of time-optimal machining sequence to assure the demanded surface quality. By application of these strategies, the standard tool paths are generated based on geometric computations only, not considering allowance dividing between the ball end milling tools, which are necessary for re-machining the residual materials areas at the workpiece with many cavities. In this work used algorithm makes it possible to select the optimal tool combination for rest machining with respect to surface quality.

KEYWORDS: *HSC-machining, milling strategies, rest machining, NC-programming, Graph theory, Dijkstra's algorithm*

I. INTRODUCTION

Improvement of the properties of machines and tools for HSC milling opens always new potentials for the reducing processing times in die and marking manufacturing. To tap these potentials, the entire manufacturing sequence should be analyzed and optimised both the process parameters, and the process structure with consideration of the heredity caused influences between the process stage. Research results from the last 20 years have supplied extensive knowledge about the more relevant influencing variables on the result of the HSC milling process. These works describe mainly the optimisation of the process stage: roughing and finishing. The rational machining of the workpiece can thus be determined from different materials of light machinable dusting materials up to hardened steel [1-12]. The residual material re-machining (called rest machining) stage, which plays an important time-determining role when milling worpkieces with complex geometry, was not regarded in this research, or was examined as a special case of finishing only marginally.

Residual material re-machining takes up too much time during processing of geometry with deep cavities [1-4]. Confined areas require ever smaller slender mills, which can be operated for firmness reasons only with low numbers of revolutions and low feed rate. The results of practical experience show that this allocated time amounts to a portion of up to 30% of the entire lead time. Therefore, the investigation of rest machining stage structure and its influence on previous stages offers a new possibility for backward optimisation of entire process chain with the goal of minimizing of lead time. By optimal high-speed rest machining of parts with complex geometry, manual polishing using as a finish operation, can be reduced or eliminated and thus a minimal total manufacturing costs are achieved [4].

An objective of this paper is to given an overview of the milling strategies for rest machining, which are responsible for efficient milling. Thereby, in this work has been analysed the milling strategies for rest machining of complex surface areas on the basis of the technological possibilities of commercial NC programming systems. They are shown in an image.

Besides the aspects from the area of the CAM solutions for HSC milling, the presentation of a method for organization of the optimal process structure in the finishing stage, particularly in the rest machining stage, is a further emphasis of this paper. For it, the surface formation at the rest machining is described mathematically. The developed model is used for optimising the milling stage using Dijkstra algorithm. Finally, the results of the work are described.

II. PROCESS CHAIN: HCS-MILLING

Milling strategies, as well as the tools and machines, take a special position at the planning of the HSC process. The use of the possible cutting parameters do not inevitably result shorter lead times in HSC milling, if the milling strategies sequence and allowance dividing within one milling stage are not optimally accomplished. The well-known HSC milling sequences of complex parts usually consist of three stages: roughing, finishing and re-machining of residual materials. In the roughing stage, a clear reduction the entire lead time can be achieved by using large tools, which enable the maximum possible stock removal rate. This effect naturally depends strongly on construction part geometry. The selected tool geometry and pertinent cutting parameters may be optimal for roughing, but the produced rough contour can lead to the clear expenditure increase during the subsequent finishing stage. How, the two stages are to be combined with each other, is examined in [5] and on the basis of the knowledge about technological heredity between these stages, an approach for designing the process chain is explained.
The workpiece geometry is complete if all surfaces including the radii, narrow, ribs, deep areas and small openings have achieved the demanded accuracy and quality. After the finishing, materials, which cannot be cleared with the finishing tool remain in these areas. Since the finishing of the entire workpiece contour with the smallest mill is not time optimal, the machining of residual materials is unavoidable. Commercial CAM systems offer different solutions for the automatic recognition of the residual material areas and automatic tool path generation on the basis the parameters of the preceding finish stage (fig. 1).

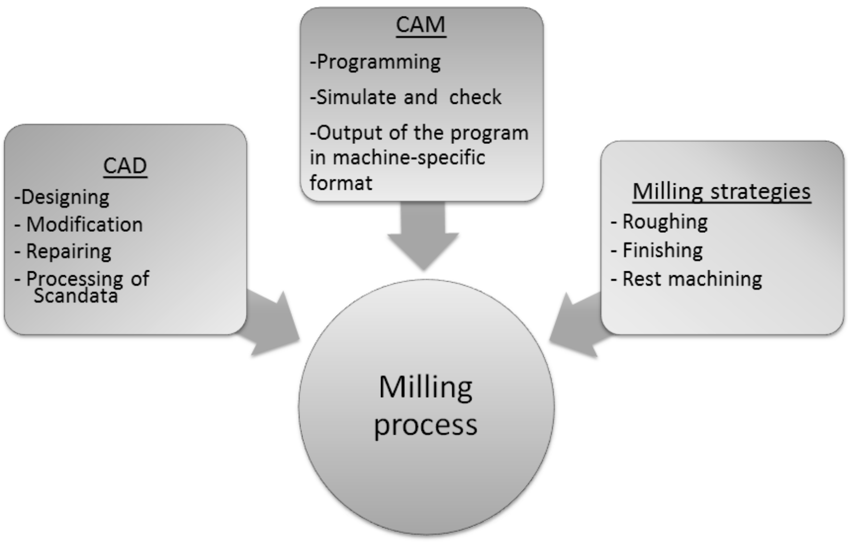


Figure 1. CAD/CAM-sided influences on HSC milling

Thus they relieve the complex work from the programmer to the tool path generation. Nevertheless a high measure of know-how is necessarily to generate of qualitative and time-optimal NC-programs. For the creation of the tool path, the programmer needs to enter the path parameters, such as step over distance between the tool path and cut depth into system. Nowadays, the users lack any support for selection of tool diameter, cutting parameter and milling strategies, to lay out a process chain with minimum lead time [1]. From there, development of an approach for the fixing of the optimal rest machining strategies is very helpful for the programmer.

III. REST MACHINING STRATEGIES

Volumes of the residual materials determine the extent of working at the last stage. The residual material areas are usually recognized automatically by means of CAM function during programming and necessary tool path are generated. The generation of tool paths is thereby based on two methods:
-Recognition of the surface areas and finishing of these areas with the small milling tool,
- Determination of the material volumes and removal of the material with a suitable milling tool.

Surface based residual materials re-machining

The machining of fastidious materials makes a special demand on the development of this stage. Inevitably slender mills used do not always offer optimal cutting conditions due to dynamic behavior of the tool. In order to meet fair these requirements, the CAM/CAD system provider developed different adapted milling strategies to remove residual materials (fig. 2).

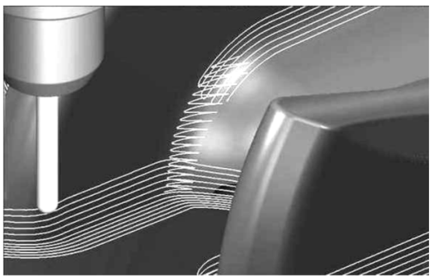
These strategies offer the programmer the possibility to create a safer process. Thus, the users are able to realize for machine , workpiece and tool a careful milling process, which affects the tool life positively.

At the generation of programs for surface based residual materials re-machining, the characteristics of the end ball milling are considered. In the case of ball end milling of a free formed surface, the cutting condition varies according to the contact position of the cutting edge in relation to the workpiece [6, 7]. Since the tool engages along the 3D-surfaces in the direction of downward or upward, not only the tool, but also the entire production system is subject to strong loads. Therefore, the rest machining of the strongly curved surfaces is separated automatically into steep and shallow areas, as a function of the inclination angle. Determination of the inclination angle and milling direction (Z-constant or contour parallel) is left to the programmer. With lightly curved surfaces the re-machining of residual materials takes place along fillets in a step. Accordingly, the areas are not divided. The fillets milling strategy is suitable for the finishing of corners, where the cusps remain after preceding working. Ideally the milling tool will have the same radius as the fillet. Here, the residual materials can be eliminated by means of parallel-lying paths.

Pencil tracing milling serves to clear the cusp marks left from previous machining operations in a way that is independent of previous tool diameter. This strategy is useful for machining corners where the fillet radius is the same or less than the tool radius.

Volume based residual material re-machining

This case is typical for the milling of the workpiece with close and deep cavities. Because the finishing tools are largely selected for economic reasons, they cannot reach every hole, cavity etc. (fig. 2). The materials within these areas can be removed efficiently only with a suitable milling tool, whose diameter is clearly smaller than finishing millers. Here, the approach of the finished contour corners to the target contour requires not only finishing of these surfaces with a small mill, but also removal of the residual material volumes, which significantly increases the expense. The layout of the rest machining stage depends strongly on material properties. Light machinable materials such as uriol, graphite, plastic material etc. make it possible to remove the residual material volume and then to finish the contour surface with the same tool cleanly. When using materials of higher strength (like steel, cast iron, etc.) it is necessary to pre-rough these areas, in order to reduce the tool load at the finishing of residual material areas. The programs for residual material roughing are created by means of the conventional rest machining programming CAM-module.

	Milling modus	Diagramm	Specifics
Surface based machining	Milling of steep areas		- Dividing in dependence on the inclination angle of the tool to the workpiece.
	Milling of shallow areas		

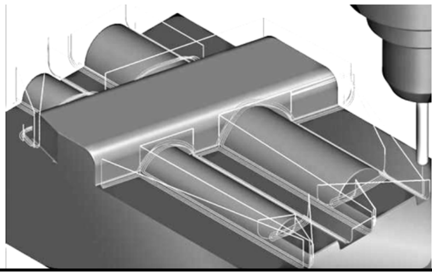
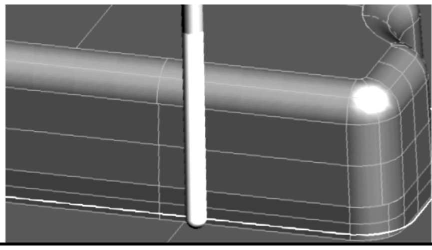
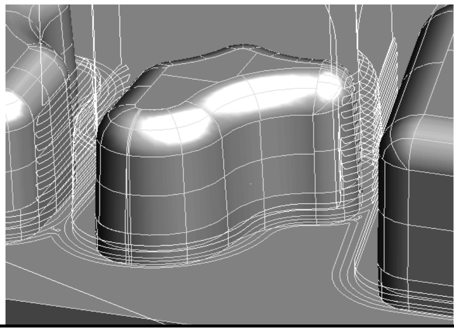
	Fillet machining		-Taking place without allocation, - Undedicated for geometry with very steep surfaces.
	Cleaning the tool trace		- Consists only of a tool path.
Volume based machining	Machining the residual materials at the narrow and deep areas		- First the area is roughed and then finished.

Figure 2. Strategies for high speed milling of sculptured surface.

IV. Tool Engagement Parameters

The tool guidance is of particular importance for the HSC milling process. It determines the direction and dimension of the cutting forces when tool penetration, which affects again the dynamic behavior of the production system. Conditioned by free formed surface, frequent change of milling direction leads to variation of the surface quality [3, 6-12]. Moreover, the unavoidable employing of the slender milling tools caused by complex cavity, leads to an additional damage of the surfaces quality. In this case, finishing expense of the fillet of the workpiece contour is determined by radii of surface. The difference between tool and fillet radii requires the use of several mills. The programmer comes not always with sufficient information about the influences of the different tool diameter combinations. He decides on the basis of experiences, if the residual material can be removed with a tool, or the use of several intermediate tools is necessary (fig. 3).

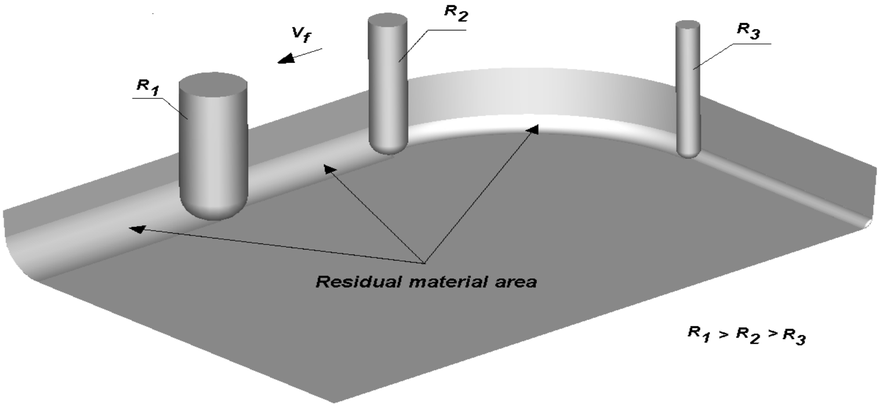


Figure 3. Tool sequence at the rest machining

Hence, the geometrical view of cutting conditions is very relevant for optimal organization of the rest machining stage. On the one hand a time-optimal process chain can be laid out, on the other hand it supplies the knowledge to influencing variables on the surface quality.

The rest machining takes place mainly by means of the ball end milling tool, which experiences continuously changing cutting conditions along the curved contour. In the surface based rest machining the fillet is finished with the end ball mill by step-by-step. Programmer selects normally only the stepover distance for tool path. Cut depth forms here automatically on the basis the differences of radii previous tool/current tool (fig. 4).

The tool ways are created from outside to inside in order to avoid the tool collisions with the workpiece. With constant stepover, more roughness develops at first trajectory than with the following tool way due to the different tool diameter. To obtain in the first tool path a certain roughness, appropriate stepover distance b_0 is to be determined here as follows (fig. 4):

$$b_0 = b_1 + b_2 \tag{1}$$

Where:

$$b_1 = \sqrt{r^2 - (r - R_z)^2} \quad ; \; b_2 = \sqrt{r^2 - (R - R_z)^2} \tag{2}$$

$$b_0 = \sqrt{2 \cdot r \cdot R_z - R_z^{\,2}} + \sqrt{2 \cdot R \cdot R_z - R_z^{\,2}} \tag{3}$$

At the following paths, the permissible roughness can be regarded constant with this formula for the stepover:

$$b_{con} = 2\sqrt{r^2 - (r - R_z)^2} \tag{4}$$

With the choice of the permissible stepover, the demanded surface roughness can be assured.

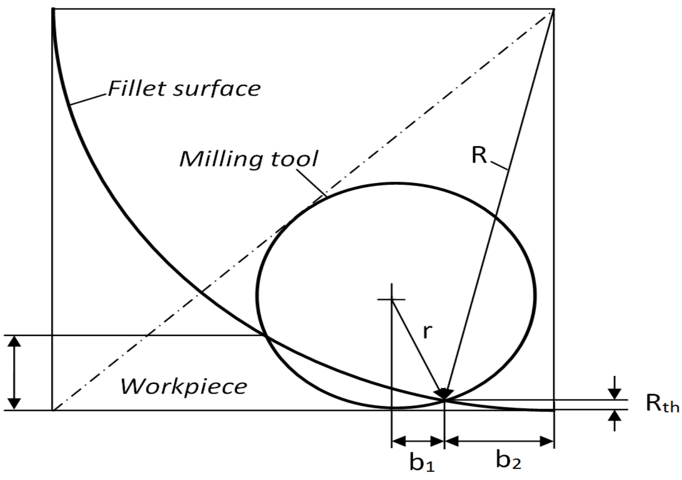


Figure 4. Cutting conditions at ball end milling

V. REST MACHINING OPTIMIZATION

In die and mould manufacturing, the short machining time is often the main criterion for flexibility of enterprises and their ability to survive in the market. For this reason, minimizing the time as per customer order is accepted as optimality criteria. The target function, which meets this criterion, should be arranged and explicitly described by the process input parameters.

The investigations of the rest machining show that the inherited contour (residual material) has dominant influence on process result during the surface forming in the fillets. At the planning of this stage, the volumes of the residual material make it possible to combine the previous and following milling stages. To minimize the total milling time for the rest machining, a mathematical connection is to be provided between the using milling tools.
Here, a objective of optimisation is the fixing of technically defined process variant. Where, the necessary surface roughness should be ensured by the cutting parameters and allowance allocation.

5.1 Theoretical modelling

Target function is the total time (t_t), which consist of machining (t_s) and auxiliary time (t_a):

$$t_t = t_s + t_a \tag{5}$$

As auxiliary time, the tool change time is regarded. The machining time depends on control variables v_f, b and length of the fillet L. With consideration of the stepover distance b, which is limited by permissible roughness R_Z, the machining time t_m is determined as follows:

$$t_s = \frac{L \cdot n}{v} \tag{6}$$

where n is the number of tool path along the contour:

$$n = 1 + \frac{R - r - b_0}{b_{con}} \tag{7}$$

If the Eq. (7) is considered in Eq. (6), the time can be presented as Eq. (8):

$$t_s = \frac{L}{v}\left(1 + \frac{R - r - b_0}{b_{con}}\right) \tag{8}$$

The target function can be expressed:

$$t_t \rightarrow \min \tag{9}$$

At the process optimising, the technological allocation of allowance leads to different combinations of the milling tools (fig. 5). To achieve the minimum total time, an optimal combination is to be selected from this milling tools sequences. The total time can be described in general form for several mill sequences with consideration of Eq. (3), (4) and (8) in such a way:

$$t_{\Sigma} = \frac{L}{v} \cdot \sum_{i=1}^{k} \left[1 + \frac{r_i - r_{i+1} - \sqrt{2 \cdot r_{i+1} \cdot R_z - R_z^{\,2}} - \sqrt{2 \cdot r_i \cdot R_z - R_z^{\,2}}}{2\sqrt{r_{i+1}^{\,2} - (r_{i+1} - R_z)^2}} \right] \tag{10}$$

The representation of the entire milling time for rest machining with different tools makes it clear that the difference between the fillet and finishing tool radii plays a crucial role at the combination. With same tool relationship of $R_{foll.}/R_{prev.}$, the optimum of tool combination lies rather in the range of the larger values of toll radii. Fig. 6 shows an example calculation using the Eq. (8) for the entire milling time of rest machining with different tool stepping. Here, two cases are to be seen. With the first case the finishing tool radius amount to 12 mm and fillet to 2 mm. Reduction of residual material volume takes place via the employment from differently mills, which are determined on the basis of conditions $R_{foll.}/R_{prev}$. Thus, it arise the different tool sequences, which reflects in entire milling time. In the second case the finishing tool has the 10 mm radius and the expenditure of the re-machining of residual materials is accordingly smaller. By using of very large tool relationships, the rest machining runs in each step fast, however the frequent tool change increases entire milling time significantly. At minimum number of tools, the milling time is higher due to the removing material volumes.

In practice, the task of determination of optimal tool relationships is the selection of the tool sequence from existing tool stock. Thus, the solution of the optimising will be reduced to the determination of optimal combinations of different mills in consideration of the technological restrictions.

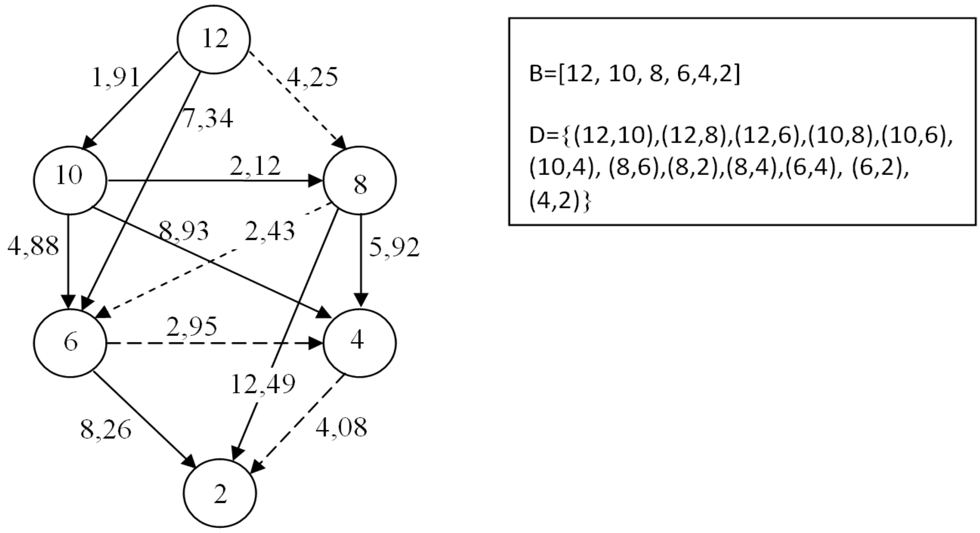


Figure 5. Graph of milling tools sequences at the rest machining (for an example: L=10 m, v_f=5 m/min, R_z=0,05 mm, t_a =0,5 min)

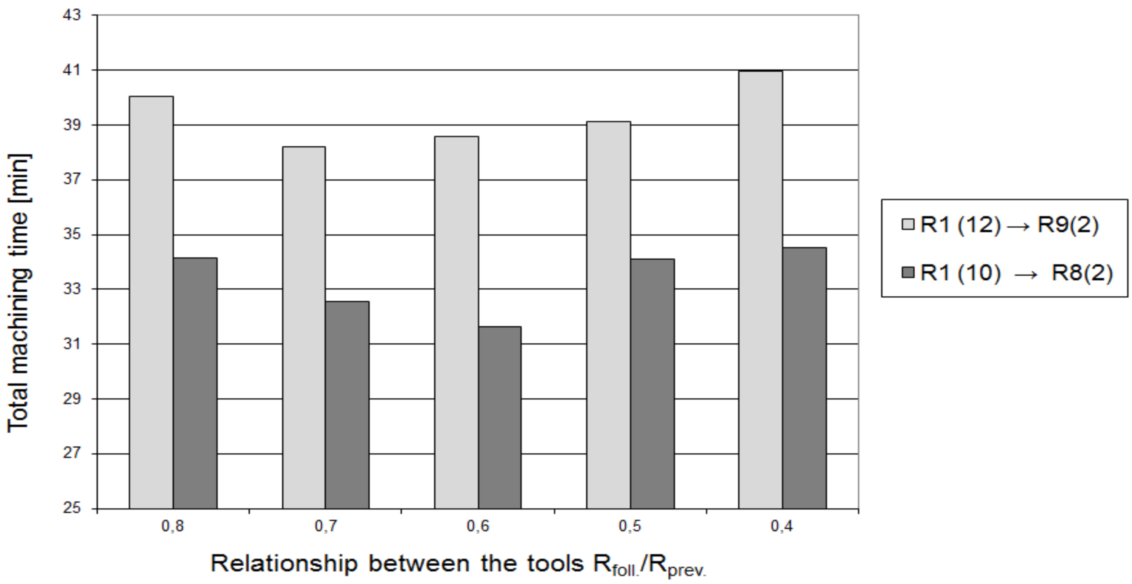


Figure 6. Milling time of the rest machining with different tool combinations (v_f =10 m/min, L=50 m, R_z=0,05 mm, t_a=0,5 min)

5.2 Process optimisation

Obviously, it is a question of a combinatorial optimisation. In order to reach the minimum of the entire machining time, an optimal solution is to be found from possible mill sequences. Here, a subset should be designed from large quantity of discrete elements (milling tool sequence), which meets the additional conditions and optimality criteria. The optimal solution is step by step examined and generated by means of special algorithm. If the milling times between the two following mill will be identified with T_{ij}, then the problem lets to describe mathematically with the help of the graph theory as follows. Certain number of tools $B_1,\ldots., B_n$ is given, which represents the node point of the graph (fig. 5). The graph has the bi-directional characteristic, which means that the movement is possible only from the large tools to small tools. An optimal mill sequence has now the characteristic that under all tool sequence ($B_1,\ldots, B_n$), the sum

$$\sum_{j'=1}^{n-1} Ti_j i_{j+1} \tag{11}$$

is minimal.

The sum places the entire time for the res machining stage. In graph, the mill sequence is equivalent to the consequence of the distance, which stretches between the node only in a direction. The total milling time corresponds to the sum of the weightings value of the distance, namely the milling time T_{ij}.

That is a classical problem of the graph theory, where the shortest route from the designed graph should be found [13, 14]. Since the edges of the graph are arranged and only positive values have, the Dijkstra algorithm can be used for finding the shortest route. With this algorithm it is possible to select the optimal route, which describes the optimal milling sequence, by employment of minimal effort.

VI. RESULT AND DISCUSSION

The application of the Dijkstra algorithm for example showed in the fig. 6 is represented in the table 1. The method for the construction the table 1 is described in detail in [13]. In the first line is to seen the node of the graph from the initial point to end point in according to sinking tool radius. The first column shows the possible routes in graph beginning from the initial point (12). In compliance with Dijkstra algorithm all nodes of the graph are visited after each other. The visited node is presented in the column 2. In same line of visited nodes, the distance of given point (B_j) to other points (in this case: total milling times T_{ij}) are registered. Each node gets the value of the covered route. If between the nodes there is no connection because of the technological condition, the node receives for it a value of ∞. When several routes lead to a node, only smallest route value stored in these node and the other routes will be excluded from the view. Thus, the end point (2) can be arrived quickly. The last line in table 1 indicates the lengths of the shortest routes, for this case is the optimally route 12-8-6-4-2. In order to make the routes better more descriptive, in the field „previously "only the nodes, which offer to shortest route tree, are shown. In graph is lifted out the optimal route with broken path (fig. 5). For computational implementation of the *Dijkstra* algorithm, standard programs exist, which are showed in technical literatures [13].

Analysis of the technological possibilities for milling strategies in the rest machining provides the findings, that the quantitative and qualitative process results can be strongly affected by the organization of the process structure in this stage. Though, the milling tool sequence plays a crucial role. A new employment for the determination of the mill sequence offers a possibility to reduce the process expenditure regarding time and costs.

Table 1. Selection of the shortest route by means of Dijkstra algorithm according to [11]

Nodes set (B)	Visited node	Set of distance (D)						Perviosly					
		12	10	8	6	4	2	12	10	8	6	4	2
12		0	∞	∞	∞	∞	∞	0	0	0	0	0	0
10,8,6	12	0	1,91	4,25	7,34	∞	∞	0	12	12	12	0	0
8,6,4	10	0	1,91	4,25	7,29	11,34	∞	0	12	12	10	10	0
6,4,2	8	0	1,91	4,25	7,18	10,67	17,24	0	12	12	8	8	8

4	6	0	1,91	4,25	7,18	10,63	15,94	0	12	12	8	6	6
2	4	0	1,91	4,25	7,18	10,63	15,21	0	12	12	8	6	4
	2		1,91	4,25	7,18	10,63	15,21	0	12	12	8	6	4

The method presented in this paper enables the creation of rest machining process stage optimally, based on the algorithmic graph theory. With the help of the results it can be ascertain that the optimal process sequence in rest machining stage depends on

- fillet radii,
- dimension of residual material area,
- tool changing time,
- average feed speed, which is determined by acceleration of the machine feed drive,
- demanded roughness and
- material properties.

The application of the Dijkstra-Algorithm offers the possibility to select an optimal combination from the milling tool-set for rest machining. Algorithm computes the shortest path between the starting node and end node of graph tree, which represent possible milling sequences taking into account the boundary conditions.

VII. Conclusion

During the optimization, the demanded surface quality is assured by means of a restriction model, which is developed on the basis of connections between the surface roughness, tool radius and stepover distance. The computation of machining time makes clear, that by using the tools with nearby radii ($R_{foll.}/R_{prev.}$ >0,5), the residual material areas can be removed faster as the tools with large radius difference. Represented here restriction model is limited not only to roughness, but can be extended by other technological process characteristics.
Developed method supports the programmer when planning the HSC milling process of complex geometry and the NC-program generation.

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NOMENCLATURE

B – node of graph, that equates to the rest machining tool
D- set of distance , which describes the milling time between the milling stages
d-depth of cut
b- stepover distance
r- radius of rest machining tool
R- radius of finishing tool
R_z- theoretical roughness corresponds to scallop height at the machined surface
$R_{prev.}$- radius of previous tool
$R_{foll.}$- radius of the following tool
V_f - obtained average feed speed
L- total length of fillet
t_s - machining time
t_a - auxiliary time

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