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The Influence of the Choice of Machining Strategy on Production Technology

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This paper deals with the issue of selecting different machining parameters in the CAM system Siemens NX 1946. The issue of choosing between a solid end mill, milling cutter, and a high-feed tool when machining simple rectangular and rugged cavities concerning time and residual material is solved here. The chosen material was 1.1730, which is a basic material for the production of moulds without heat treatment. The paper deals with the issue of choosing the size of tool feed into the cut and its influence on the formation of the machining path depending on the depth of the cavity. The size of the residual material depends on the machining strategy and the choice of the plunge method into the material with regard to the total machining time. Performed simulations and experiments have shown a significant impact in individual settings and, thus, on the cost of machining components of such shapes.

Keywords: CAM system, Strategies, Cutting time, High-Speed Cutting

1 Introduction

The programming options, choice of various tools, and machining methods, which are enabled by today's programs, represent a wide range of options for generating tool trajectory and guidance of the tool during machining. In today's market, countless CAM programs are available, each providing users with different machining methods. These methods are primarily determined by the machining tool and geometry. Of the basic types of machining, such as milling, face milling, and side milling, modern programs also provide the use of other machining methods, such as high-pitching, plunging, planning, and trochoidal milling. The basic principle of these machining methods is very well known, but the algorithms used for calculating individual drags may differ depending on the shape of the machined part. Another factor that significantly influences the selected machining strategy is the machining tool. As was mentioned, the choice of the tool and its geometry significantly affect methods that can be used during machining and, thus, affect the lifetime of the tool. Each manufacturer solves this issue as part of its testing and optimizes the tool for the most efficient machining, i.e., material removal, surface quality, and tool lifespan. The machined material, like steel, dural, or stainless steel, is another parameter that affects the machining strategy. However, it is not a critical parameter. The importance of the decision is in the coating of the tool. The coating also significantly affects the chips' formation and evacuation from the cutting site, especially during drilling. Perez et al. [1] devoted themselves to the analyzing machining strategies for circumferential milling. They concluded using the roll-in technique because the cutting forces gradually increase until the cutter achieves a uniform cut. Conversely, with the direct method, the cutter is very quickly under the highest pressure. Others who focused on strategies were Izol et al. [2]. Their research showed the importance of selecting areas from the shape surface. According to them, the main shape marks must completely characterize the sample. Vakomdios and his team [3] investigated the influence of the milling strategy on the surface roughness during ball mill machining of an aluminum alloy. Sadílek et al. [4] concentrated on the analysis of machined surfaces and their roughness after 3axis and 5axis milling. They compared two machining strategies used for shaped surfaces. Their results show that the strategy of milling can significantly affect roughness. Józwik and his team [5] found out that trochoidal milling is much more favour-bale compared to conventional milling because of the shorter machining time. Similarly Slebejová et al.[6] came to the same conclusion regarding trochoidal milling. They added that the effect of the depth of cut and angle of engagement had the biggest effect on the surface quality. Matras et al. [7] focused on the accuracy of milling strategies when machining free surfaces. Varga et al. [8] performed a comparative study of machining strategies for shaped surfaces. Like many others, they emphasize the importance of developing an appropriate machining strategy to save cost and time. In his subsequent work, Varga [9] assessed surface qualities for selected milling strategies in the production of relief surfaces. Grešová et al. [10], in their article The influence of the machining strategy with a ball mill on the roughness of free surfaces state that the suitability of the machining strategy cannot be determined only with the help of

CAM software because the different mathematical models of CAM systems and also influences that cannot be included in the simulation e.g. clamping force. Another research was conducted by Dobrzynski and his team [11], who investigated the strategy's effect on the surface's evenness. Choy [12] focused on appropriate strategies for corner milling. When choosing a strategy, it is not necessarily only about the qualitative parameters of the surface. Ma [13] optimized strategies for optimal energy consumption of a CNC machine.

2 Experimental conditions

2.1 Materials

A block of 1.1730 material was selected to verify the suitability and applicability of machining strategies and methods. This material is used to produce parts of moulds that are not highly stressed and, therefore, do not require further heat treatment. However, if necessary, it can be hardened to a hardness of 58 HRC.

Tab. 1 *Chemical composition of the material*

Element content in %		
Element	**Value**	**Limit values**
C	0.45	0.40 – 0.50
Mn	0.70	0.60 – 0.80
Si	0.30	0.15 – 0.40
P	0.029	≤ 0.035
S	0.027	≤ 0.035

2.2 Cutting tools

A high-feed milling holder R217.21-0816.RE-LP06.2A from seco tools was chosen as the machining tool.

This holder was subsequently fitted with LPHT060310TR-M06 MP2050 inserts also from seco tools.

Based on these shape and geometry parameters, the entire tool was modeled in the Siemens NX 1946 program, a sample of which can be seen in Fig. 1.

The second tool selected was the R217.69-0816.RE-10-2A holder, also from Seco Tools, with parameters listed in Table 4.

This cutter was equipped with inserts also from the Seco Tools company, concretely XOMX10T308TR-ME07 MS2050.

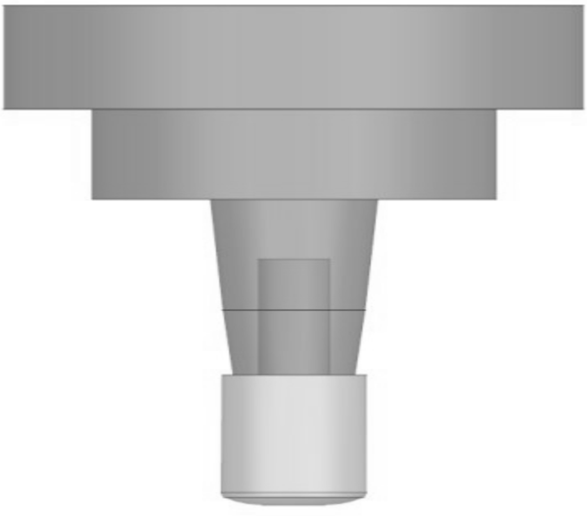

Fig. 1 *Model of the high-feed milling tool*

Tab. 2 *Parameters of the high-feed milling cutter*

Name	Description	Value
APMXE	Depth of cut maximum in feed direction end	4.5 mm
APMXS	Depth of cut maximum in feed direction side	0.8 mm
DCX	Cutting diameter maximum	16 mm
DC	Cutting diameter	7.5 mm
DCSFMS	Contact surface diameter machine side	13.5 mm
LF	Functional length	20 mm
RMPX	Ramping angle maximum	5°
RPMX	Rotational speed maximum	39 000 min^{-1}
TDZ	Thread diameter size	M8
Weight	Net weight	58 g
ZEFP	Peripheral effective cutting edge count	2

Tab. 3 *Parameters of a high-feed insert*

Atribute	Description	Value
CCER	Curved cutting edge radius	8 mm
CEDC	Cutting edge count	2 edges
GAN	Insert rake angle	11°
-	Grade type	Carbide PVD
RE	Corner radius	1 mm
S	Insert thickness	3.18 mm
W1	Insert width	6.4 mm
Weight	Net weight	2 g

Tab. 4 *Parameters of the milling holder R217.69-0816.RE-10-2A*

Attribute	Description	Value
APMXE	Depth of cut maximum in feed direction end	6 mm
APMXS	Depth of cut maximum in feed direction side	9 mm
DC	Cutting diameter	16 mm
DCSFMS	Contact surface diameter machine side	14 mm
LF	Functional length	23 mm
RMPX	Ramping angle maximum	7.5°
RPMX	Rotational speed maximum	29 400 min^{-1}
TDZ	Thread diameter size	M8
Weight	Net weight	58 g
ZEFP	Peripheral effective cutting edge count	2

Tab. 5 *Parameters of XOMX10T308TR-ME07 MS2050 insert*

Attribute	Description	Value
LE	Cutting edge effective length	9.3 mm
BS	Wiper edge length	1.3 mm
CEDC	Cutting edge count	2
GAN	Insert rake angle	20.4°
-	Gradetype	Carbide PVD
RE	Corner radius	0.8 mm
S	Insert thickness	3.83 mm
W1	Insert width	6.9 mm
Weight	Net weight	3 g

2.3 Machining geometry

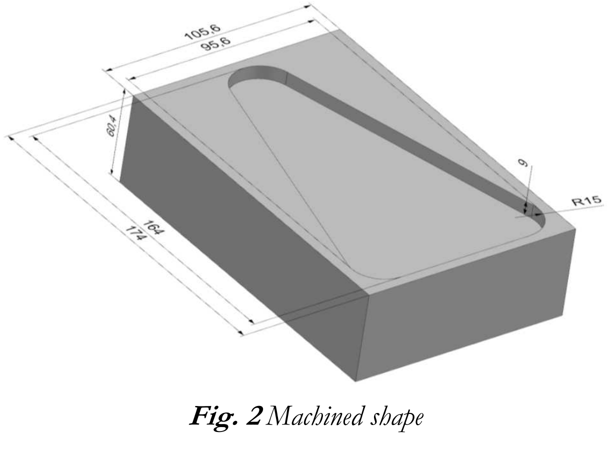

Fig. 2 *Machined shape*

The first testing cavity, shown in Fig. 2, consists of a pocket with a depth of 9, 19 and 29 mm with basic dimensions of 174x105.6x60.4 mm (LxWxH). The inner radii have a radius of 15 mm, so they are adapted in a sufficient way for the diameters of the tools used. The part is machined with an allowance of 0.5 mm for finishing.

3 Effect of depth of cut and size of feed on machining path

In order to use optimal machining parameters, the Seco Tools database was used with regard to the selected material and machining method.

Tab. 6 *Machining parameters*

Attribute	LPHT060310TR-M06 MP2050	XOMX10T308TR-ME07 MS2050
Depth of cut [mm]	0.7 / 0.4	4.5 / 2
Cutting speed [m/min]	343 / 371	240 / 235
feed per tooth [mm/tooth]	0.65 / 0.91	0.095 / 0.12
RPM [rev/min]	6 824 / 7 400	4 775 / 4 675
Feed speed [mm/min]	8 880 / 13 500	907 / 1 120
Machining time [s]	173 / 197	165 / 329

The expected result would be that an insert with a smaller depth of cut would be faster for shallow pockets. However, with a cavity depth of 9 mm, a 4.5 mm depth of cut insert only needs two axial cuts to finish. It is, therefore, always necessary to consider how much material will be removed during the last cut and to adapt the general depth of the cut to this. As can be seen from Tab. 6, decreasing the depth of cut causes the feed rate to increase along with the feed per tooth. A comparison of the tool path during machining with different cutting conditions can be seen in Fig. 3. It shows that the CAVITY MILL method with a depth of cut of 0.7 mm differs from the one with a depth of 0.4 mm, mainly in the amount of unproductive movements of the tool. Differences can also be observed in the case of productive movements as the CAVITY MILL, with a higher feed per tooth, performs more of these movements. The most significant difference is visible in rounding formation in the detailed view from Fig. 3.

The machining paths were also investigated for a cut width of 4.5 mm and 2 mm. Here, the difference in the paths in the section was not confirmed, as we can see in Fig. 4, only a slight change in the path of the tool entering the engagement occurred.

In addition to the stated machining depth of 9 mm, other depths were investigated, namely 19 mm and 29 mm. Here, the machining paths no longer showed any differences and only copied the previous paths at different depths of engagement, reflecting the pocket's chosen depth. The total machining time is also related to the correct choice of tool paths. It has a significant effect on the machining price. Both individual machining methods and selected machining depths were compared here.

Fig. 5 shows the influence of the machined depth (9 mm, 19 mm and 29 mm) as well as the machining operation in dependence on time. It can be noticed that in the case of manufacturing one piece at a depth of 9 mm, the technology with a higher depth of cut of 4.5 mm achieves a shorter machining time. However, if the pocket is deepened to the already mentioned 19 mm or 29 mm, faster machining will occur with the help of HFM technology, with a cut depth of 0.7 mm. Another finding is that when the manufacturing cutting conditions are recalculated, in this case with a change in the depth of cut from 0.7 mm to 0.4 mm and from 4.5 mm to 2 mm, there is a very significant increase in machining time in the case of 9 mm deep pocket to almost double. The manufacturer's recommended cutting conditions appear to be the most suitable. However, modified cutting conditions can also be used in practice, for example, when there is reduced rigidity of the tool, clamping force of the workpiece, or rigidity of the machined part itself.

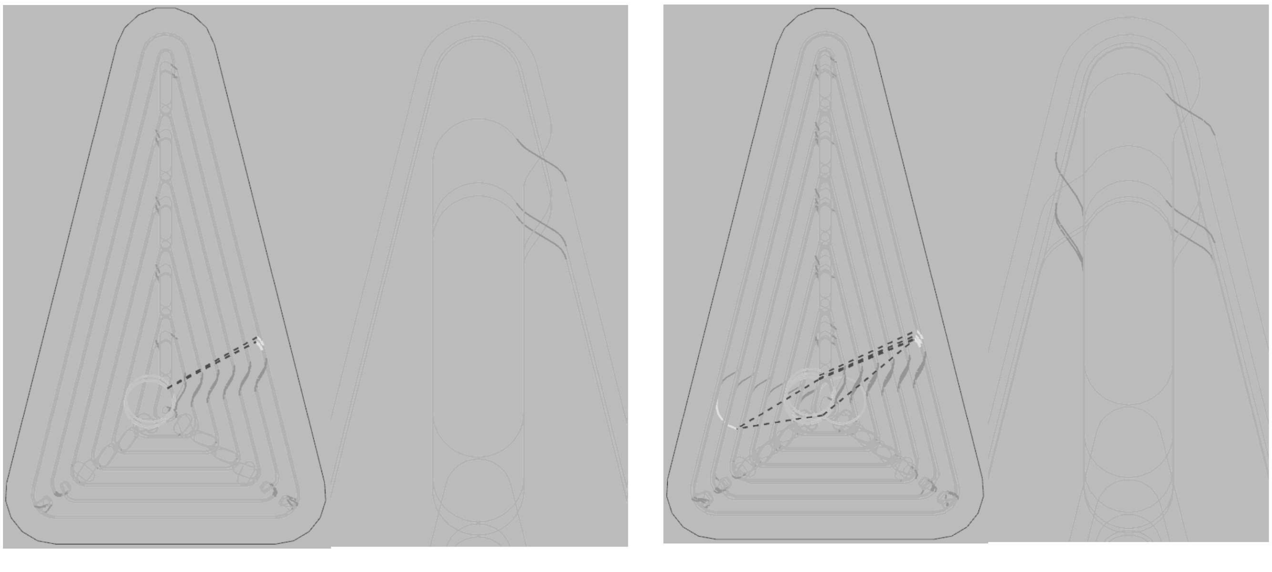

Fig. 3 *The path difference for the depth of cut is 0.7 mm on the left and 0.4 mm on the right*

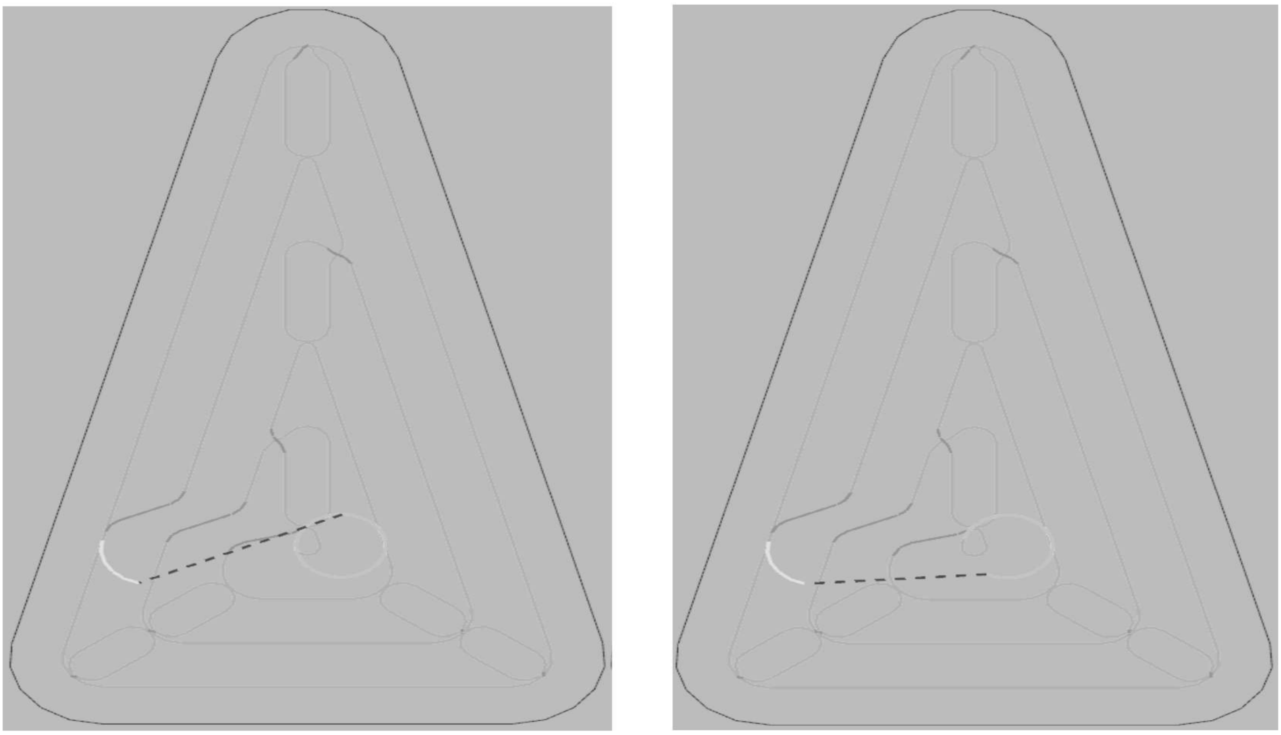

Fig. 4 *Path difference for a depth of cut 4.5 mm on the left and 2 mm on the right*

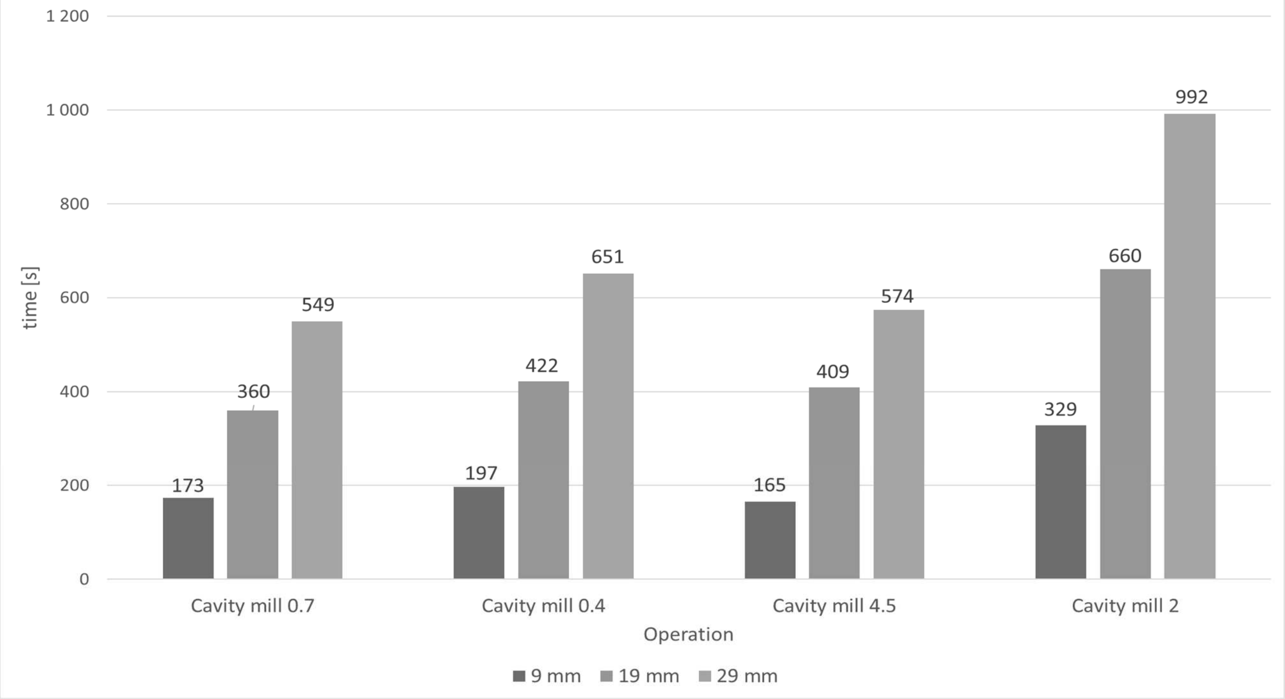

Fig. 5 *Machining time in dependence on depth and selected operation*

4 Influence of the lifespan of the tool on the cost of machining

In business, however, the total price of machining and the total price of the product is what matters. It consists of various factors, and it is not always possible to calculate them precisely. In general, the total costs consist of the price of materials, tools, machine deduction, energy, worker's wages, and more. For cost compression, a graph was created (Fig. 6), which represents relative cost changes for individual machining areas. The introductory price of machining with a high-feed insert was set for comparison. This represented 100% of the machining costs. All costs include the same items: tool price, machine cost, service, and other overheads. They are expressed as a proportional change in price to the basic operation and input.

As already mentioned, in the case of a pocket with a depth of 9 mm, a method with a depth of cut set to 4.5 mm is more effective than 0.7 mm. However, from Fig. 6, it is clear that even in the case of faster machining, the price advantage is not ensured, which is the primary decisive criterion. Although the method using a depth of cut of 0.7 mm consumes more time, the significant difference in the price of the insert and the very similar service life make the CAVITY MILL_0.7 technology the most suitable choice for machining the given pocket.

The price is even more favourable for deeper pockets. Considering the shape of the LPHT060310TR-M06 MP2050 insert (Fig. 1), unmilled material remains, negatively affecting the machining time required during finishing operations, and can locally excessively load the tool. The raw amount of material for individual operations is shown in Fig. 7 and Fig. 8, using the most accurate, fine-grained IPW analysis in the Siemens NX program.

The visual representation reveals a significant difference in the unmilled aries – corners, which in the case of CAVITY MILL_0.7 is 1.373 mm compared to CAVITY MILL_4.5 with a value of 0.736 mm. In both cases, a finish allowance of 0.5 mm was set even though an XOMX10T308TR-ME07 MS2050 insert was used with a rounding value of 0.8 mm. Unmilled material is only 0.236 mm from the finishing allowance. Due to the identical shape of the LPHT060310TR-M06 MP2050 insert used in the CAVITY MILL_0.7 and CAVITY MILL_0.4 operations, it is unnecessary to show the results of the second operation. The same applies to the XOMX10T308TR-ME07 MS2050 insert.

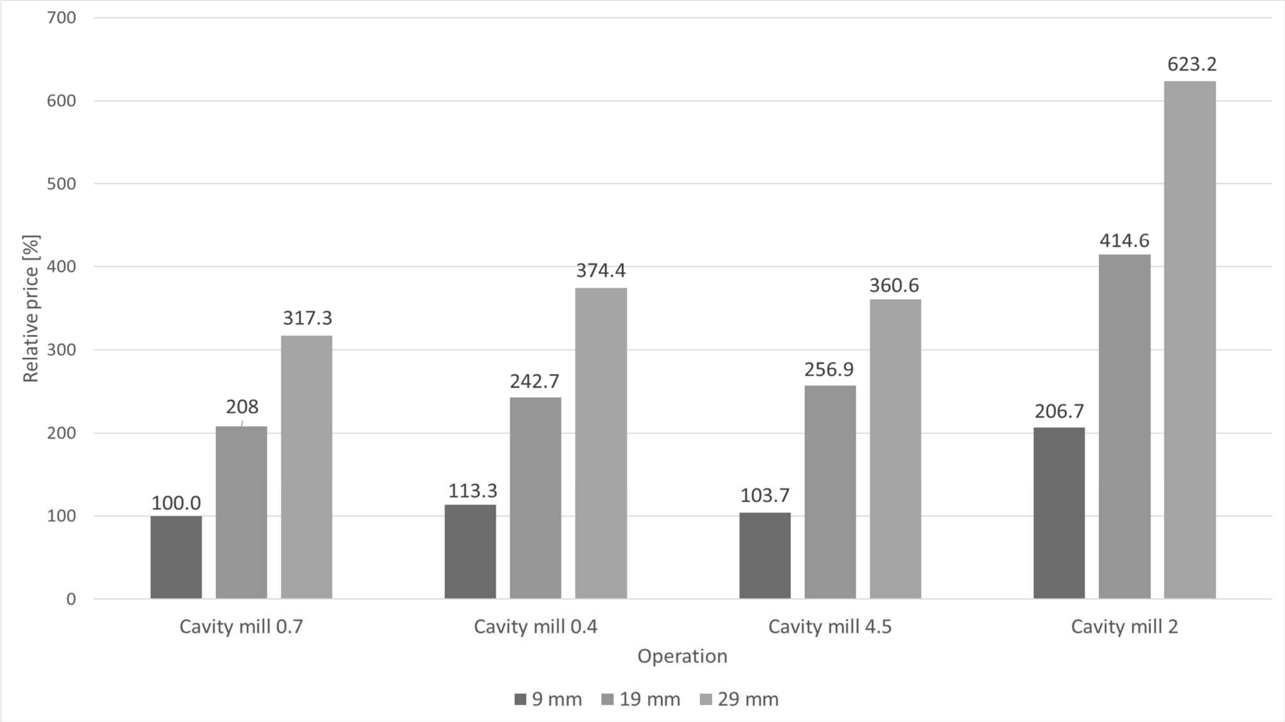

Fig. 6 *Machining cost comparison*

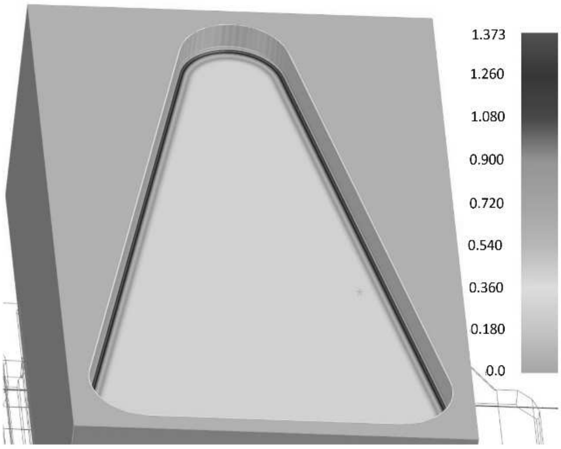

Fig. 7 *Unmilled material from Cavity mill_0.7*

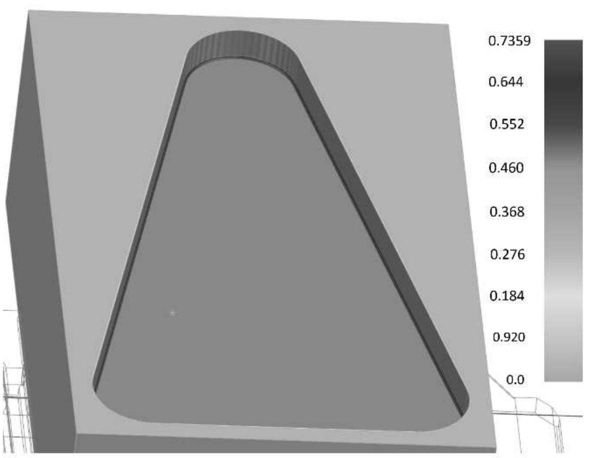

Fig. 8 *Unmilled material from Cavity mill_4.5*

5 Effect of the engage method on machining time

The appropriate, engaging method is another critical factor ensuring a longer tool life. A tool with LPHT060310TR-M06 MP2050 inserts was used with the manufacturer's predefined cutting conditions. The Siemens NX software offers four types of engage:

- HELICAL
- RAMP
- PLUNGE
- NONE

In the case of the tool with inserts, only engages RAMP or HELICAL(Fig. 9 and Fig. 10) are suitable. The manufacturer's parameters can also be used for these two types, which recommend a maximum milling angle of 5° for the LPHT060310TR-M06 MP2050 insert.

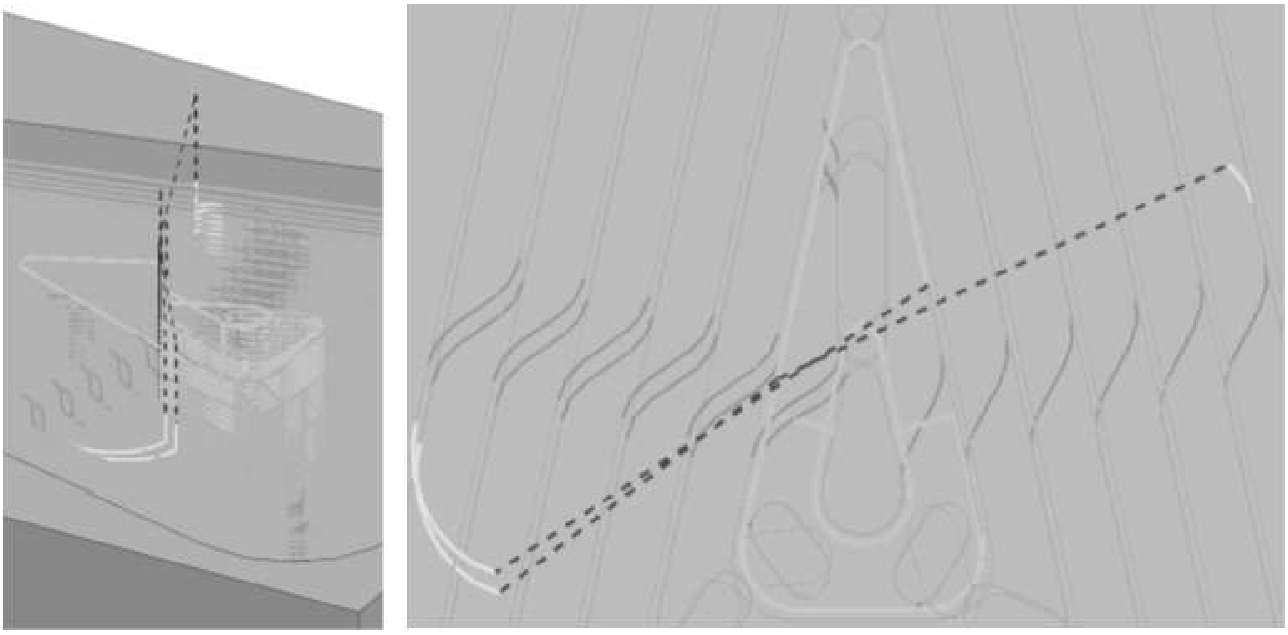

Fig. 9 *RAMP engage*

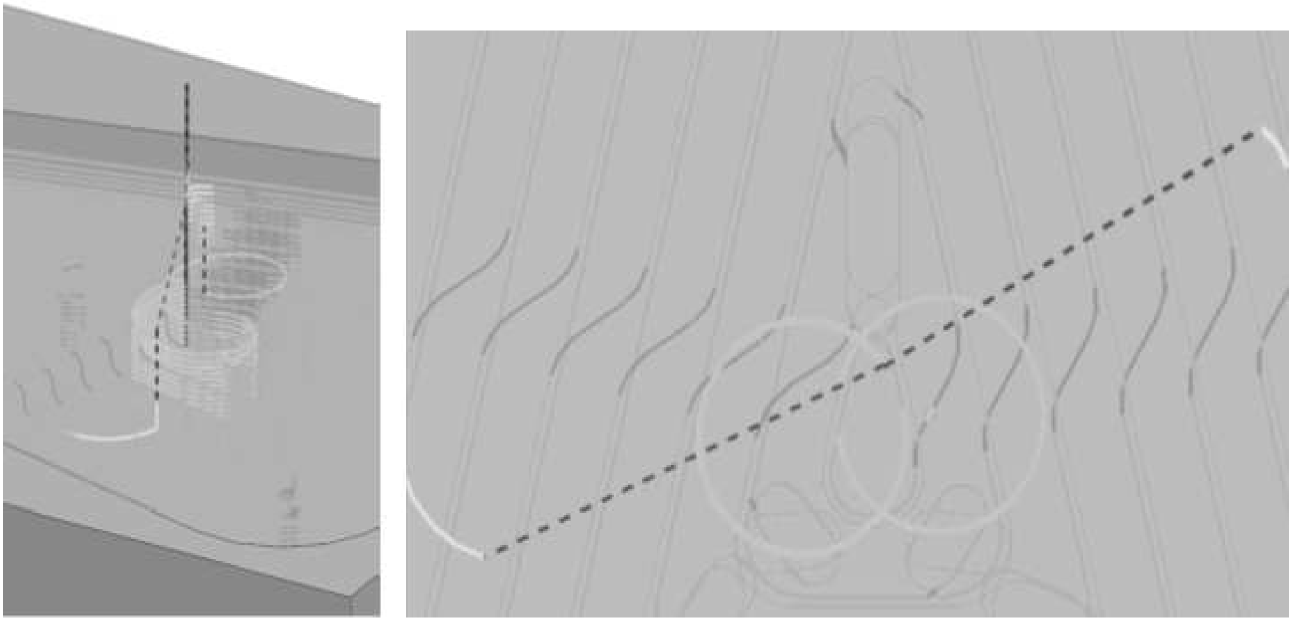

Fig. 10 *HELICAL engage*

PLUNGE engage type, shown in Fig. 11, can only be used if the tool is adapted to this method. In this case, the strategy cannot be used because the tool with the cutting edge plate is not adapted, mainly due to the tool diameter of 16 mm and the cutting edge width of 6.4 mm. Nevertheless, for completeness, both types of raids are found in the article, primarily to detect time differences.

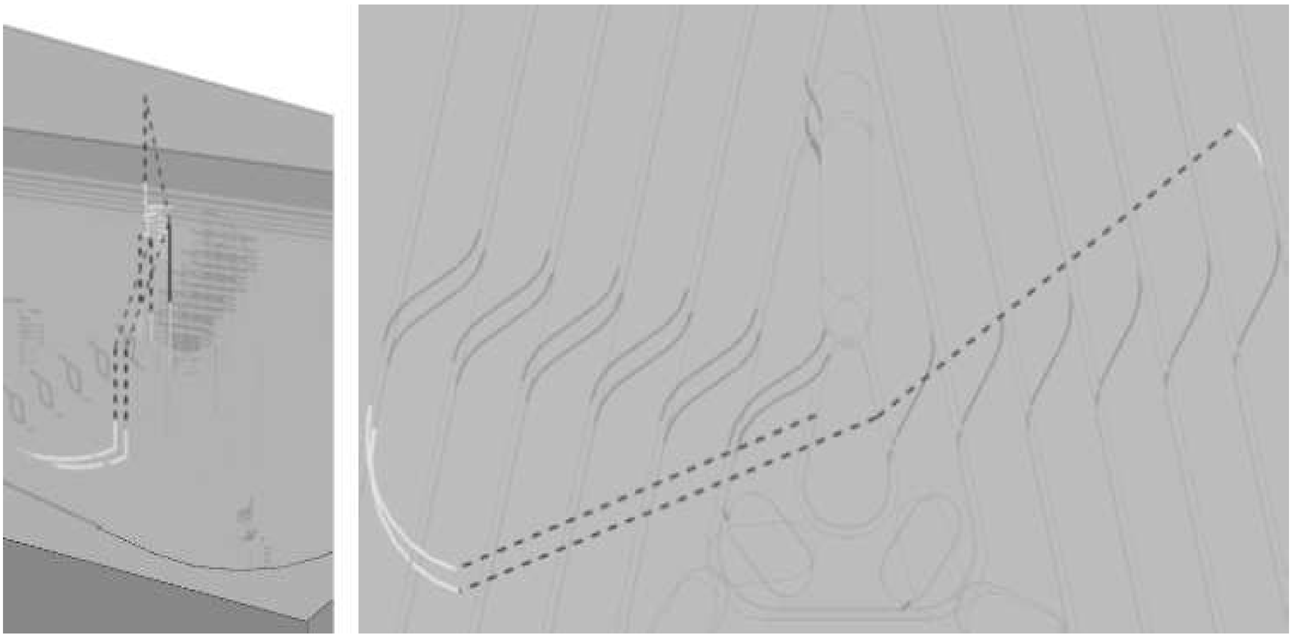

Fig. 11 *PLUNGE engage*

Fig. 12 illustrates that the difference between Helical engage and RAMP is insignificant. At a pocket depth of 9 mm, the result is identical. At depths of 19 mm and 29 mm, there is a two-second difference in favour of the HELICAL. In reality, however, it can be said that both types are very similar in terms of time requirements. Interestingly, the method without a run-in (NONE) is only 5 seconds faster than the other two at a pocket depth of 9 mm. With this, it is possible to determine how long the runs into the material last, which in the case of a cavity depth of 19 mm is only 10 s with a HELICAL run and 12 s in the case of a RAMP. With a pocket depth of 29 mm, the HELICAL takes 16 s; RAMP takes 18 s. By calculation, it can be determined that the approaches take approximately 3% of the total machining time.

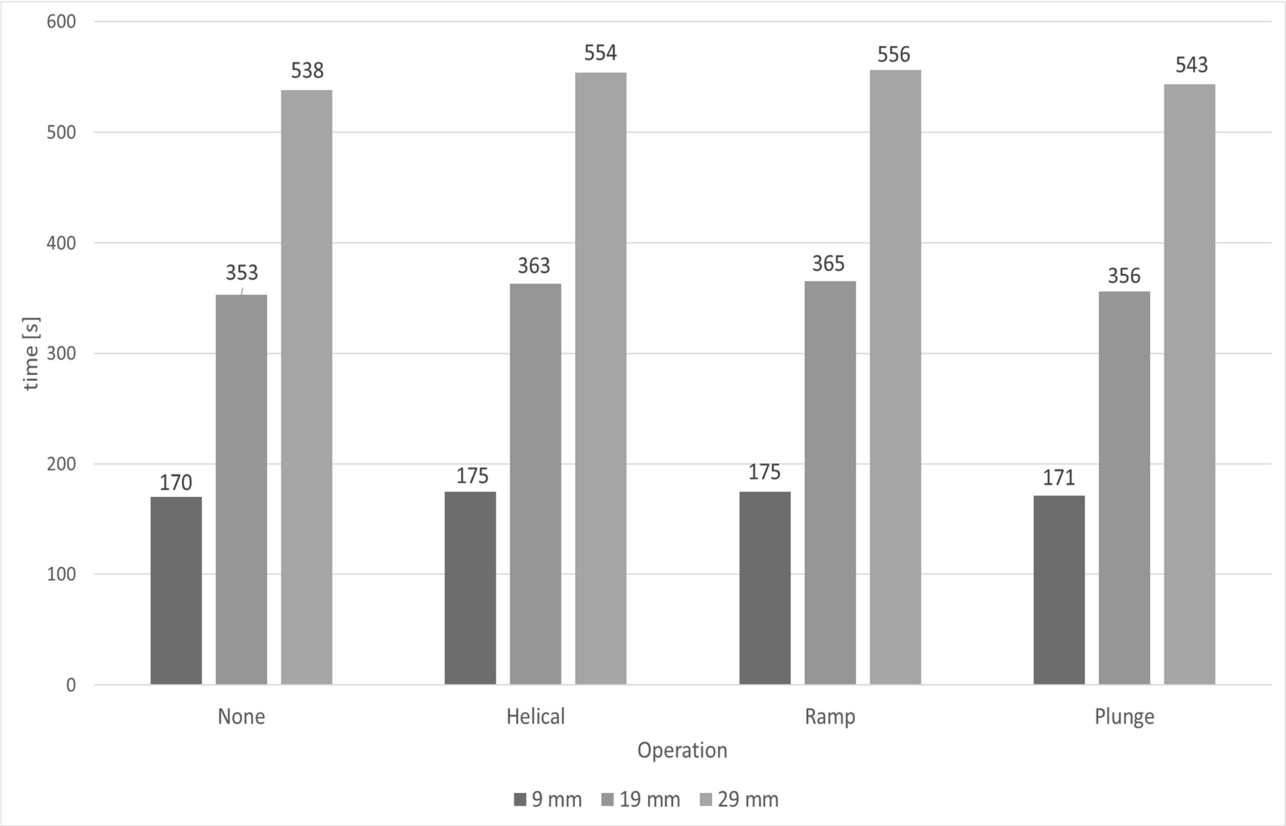

Fig. 12 *Comparison of engage on machining time*

6 Influence of the choice of cut pattern during pocket machining

The cut pattern is another critical parameter. An inappropriate pattern choice can significantly increase time or unmill material parts. The original cutting conditions of the LPHT060310TR-M06 MP2050 cutting edge are used for comparison. The approach takes place along a helix with a descent angle of 5°, and the percentage representation of the tool in the formation of rounding is 40 %.

The ZIG, ZIG ZAG, and ZIG WITH CONTOUR cutting patterns are based on a similar principle, yet they differ significantly. The ZIG cut pattern uses unidirectional material removal. After completing the cutting path, the tool is forced to return to the line of the beginning with a secondary, non-productive movement, although with a shift, as seen in Fig. 13. Due to this unproductive movement, there is a significant increase in machining time. It is mainly used where it is necessary to cool the tool before the next cut or where emphasis on the surface is required.

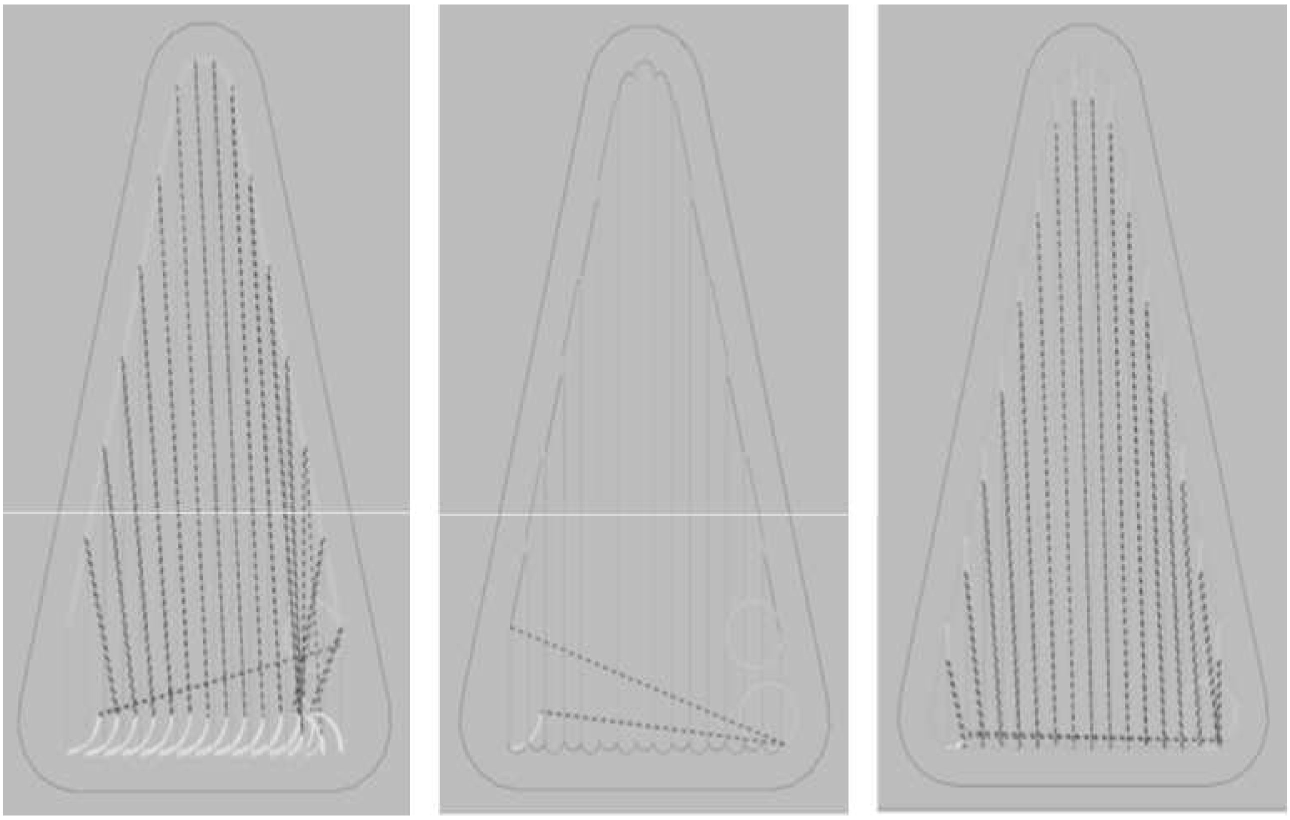

Fig. 13 *Tool path display Zig (left) Zig Zag (centre) Zig with contour (right)*

The ZIG ZAG pattern is similar, but a productive one replaces the non-productive movement, so chip removal occurs in both directions of the movement. This ensures significantly higher productivity. The last cut pattern also with a principle similar to the previous ones, is ZIG WITH CONTOUR from Fig. 13. The wall material is initially removed, followed by one-way machining, including unproductive reciprocating motion, as in the case of the ZIG method. This causes a smaller value of the unmill material, which is close to the FOLLOW PART variant pattern. However, due to the secondary movement, it is the most time-consuming of all variants.

The ZIG ZAG method leaves most remaining material of all available variants, except for the PROFILE cut pattern, which is unsuitable for roughing operations. ZIG and ZIG WITH CONTOUR are very time-consuming. Due to the unmachined remains, the variant with the contour works better because the time to complete the machining of the part without the remains will be much shorter. Nevertheless, ZIG WITH CONTOUR operation is two times slower than the FOLLOW PART variant and has a lower quality machined surface.

Considering part shape, FOLLOW PART and FOLLOW PERIPHERY variants are considered. The ZIG, ZIG ZAG, and ZIG WITH CONTOUR cut patterns are unsatisfactory choices., In this case, rectangular or square-shaped pockets would ensure a superior surface. Fig. 14 shows this comparison of the effect of cutting patterns on machining time.

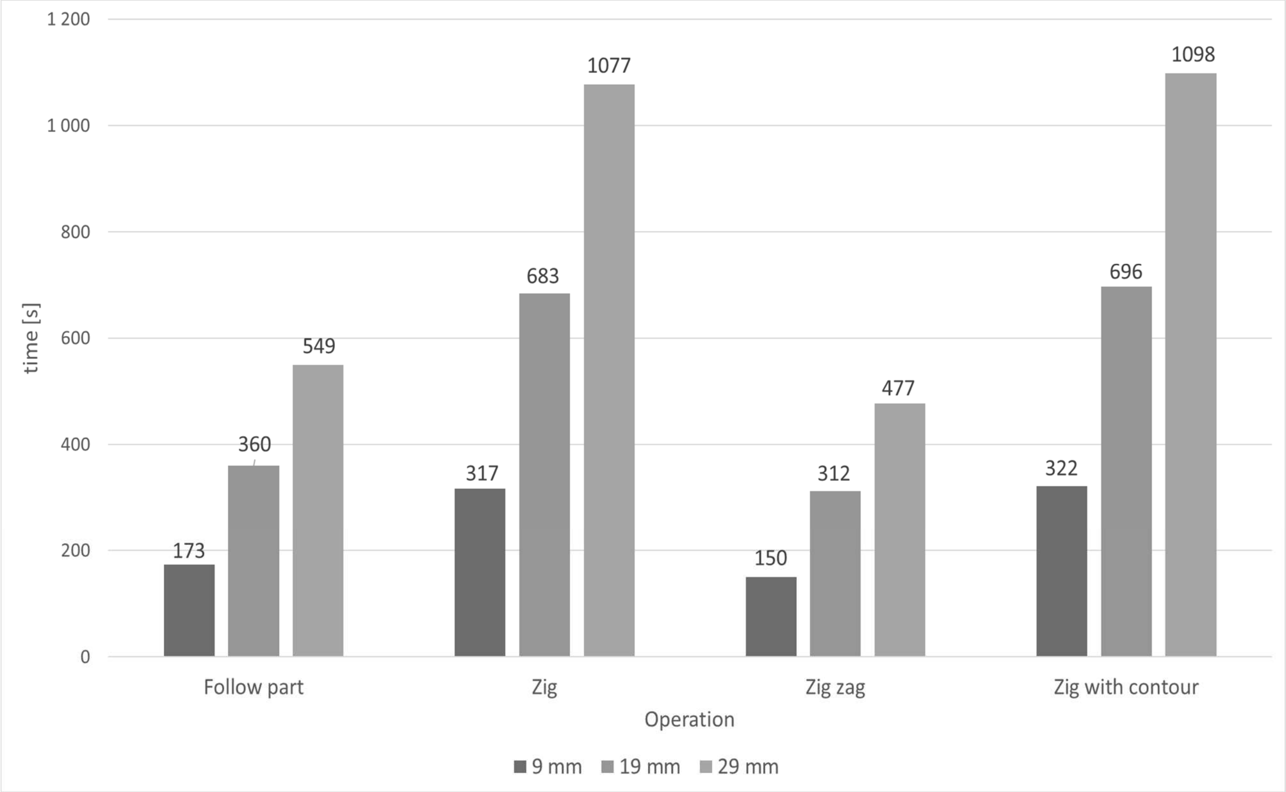

Fig. 14 *Effect of cut patterns on machining time*

7 Machining simulation verification

To verify the obtained data, the machining process of the proposed geometries was designed and carried out. Used geometry was already mentioned: a basic triangle shape up to 29 mm of depth and a more complex cavity that better represents actual cavities.

7.1 Basic shape machining

R217.21-0816.RE-LP06.2A mill with LPHT060310TR-M06 MP2050 inserts was used for machining the basic shape. The simulated machining time was 6 minutes and 4 seconds. However, the measured time was 14 minutes and 16 seconds during machining. When examining this significant difference between the times, it was found that the required tool feed rate was not being achieved. Due to the small to negligible paths of tool approaches, the average feed speed was determined as an indicator of the feed rate. This theoretical value is based on the basic values: speed, time, and distance.

$$v = \frac{s}{t} \rightarrow s = v \cdot t [mm] \quad (1)$$

$$s_1 = s_2 \quad (2)$$

$$v_1 \cdot t_1 = v_2 \cdot t_2 \quad (3)$$

$$\overline{v_1} = \frac{v_2 \cdot t_2}{t_1} = \frac{8\,880 \cdot 364}{859} = 3\,763\ [mm/min] \quad (4)$$

Where:
v...speed [mm/s],
s…path [mm],
t…time [s].

As can be seen from the simple calculation above, the theoretical average feed speed ($\overline{v_1}$) is 3763 mm.min^{-1}, less than the set value. In the theoretical case, this value would correspond to the set value of 8,880 mm.min^{-1}. The range of these values is influenced mainly by the machine's kinematics and, in advance, the possibility of acceleration and deceleration of moving masses. The very result of machining and wear of the tool can then be seen in Fig. 15.

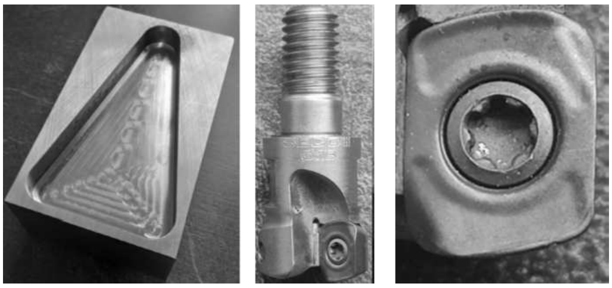

Fig. 15 *Basic machined shape and used tool with insert*

7.2 Complex shape machining

The complex part was also set to a general depth of 29 mm, but contours were set in different depths to verify the possibility of comparison with the more realistic shape of the part. The machining time for the second part was 16 minutes and 12 seconds. This differs only negligibly from the simulated time, which was 7 seconds shorter. During machining, there was a problem with an accumulation of chips in the cavity, which was necessary to solve because it caused excessive heating of the mill and wear of the insert itself, which can be seen in Fig. 16.

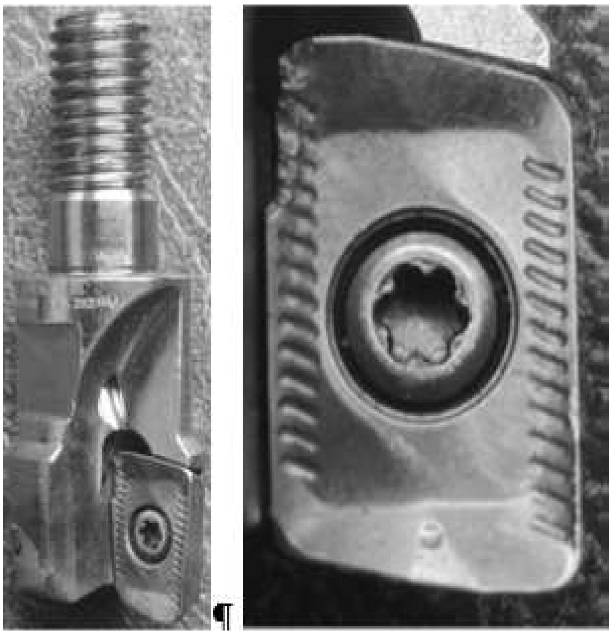

Fig. 16 *Worn insert after machining*

The machining result is shown in Fig. 17. A detailed examination revealed a deterioration in the machined surface quality and more extensive unmilled areas compared to the previous machining.

Fig. 17 *Machined complex shape*

Due to the quality of the surface and the observed deviations of the simulated and machined surface, a comparison of the two was made. This comparison can be seen in Fig. 18, where the simulation result is almost identical to the machining, but the machined surface has an unmilled area, highlighted by a black rectangle.

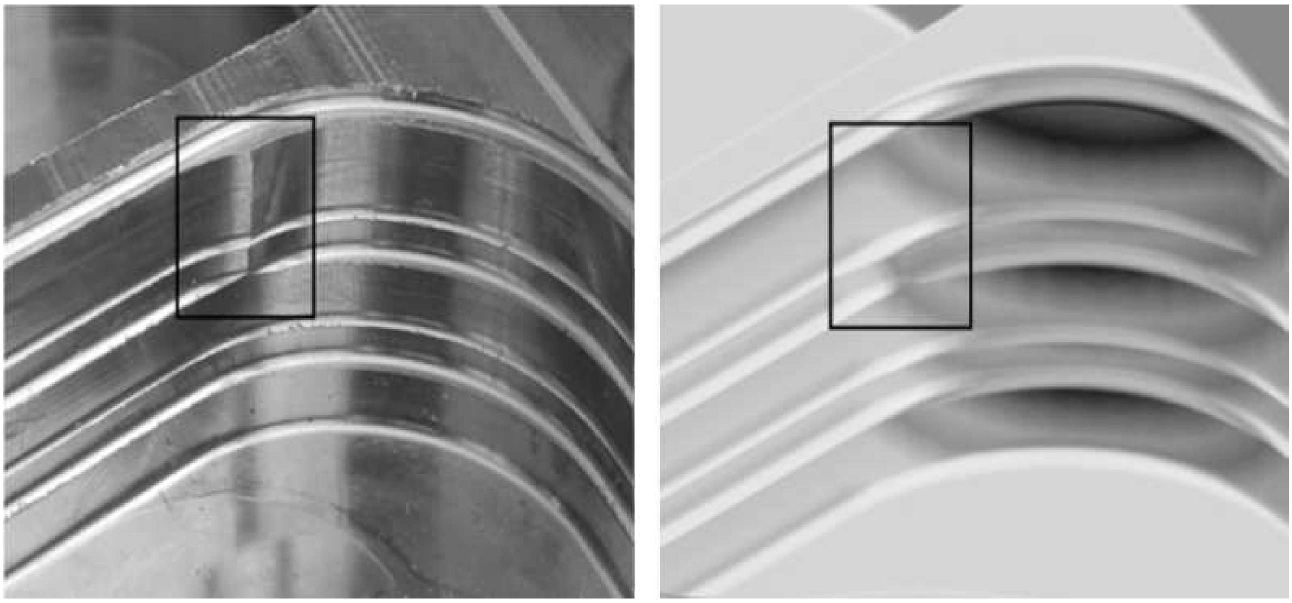

Fig. 18 *Unmilled shape of the raw material in the radish*

Fig. 19 shows an entry point of the tool, where an unmilled stump on a straight wall is apparent. These relatively small deviations can cause a short-term overload of the finishing tool and result in excessive dulling or local deterioration of the surface quality caused by tool vibration.

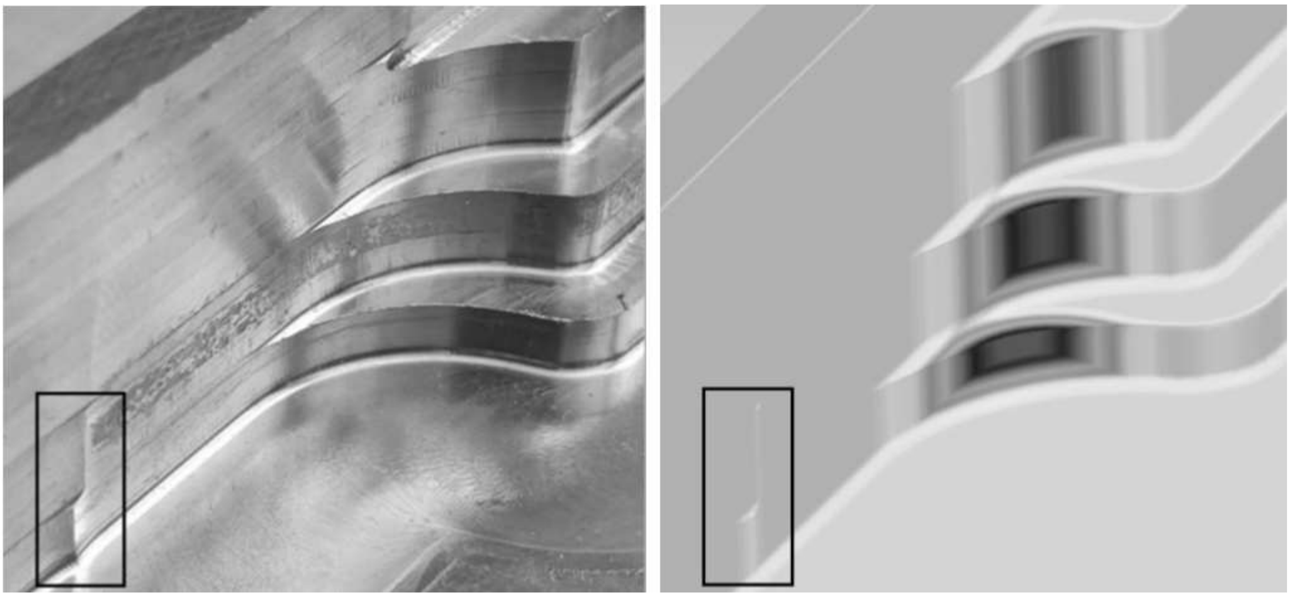

Fig. 19 Unmilled stump on a straight wall

7.3 Productive machining shape

Based on the simulations and experiments, an effort to achieve maximum productivity when machining with a high-feed milling cutter arose. Previous data indicated a short travel distance during machining when the tool cannot reach the required feed rate. This negative effect was intended to be eliminated by the cavity size shown in Fig. 20. The smaller cavity on the left (102.1 x 102.1) and the larger one on the right (143.7 x 143.7) were intended to provide sufficient paths for acceleration and deceleration during machining.

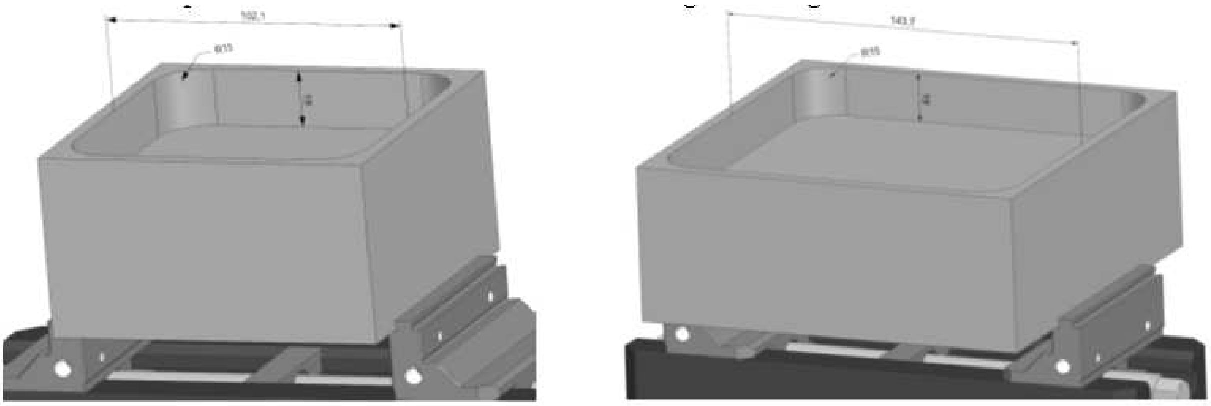

Fig. 20 Productive machining shapes

For a cavity 102.1 x 102.1 mm, the simulation determined that the machining time is 5 minutes and 14 seconds, compared to the actual time of 9 minutes and 31 seconds, which resulted in a theoretical average feed speed of 4,883 mm/min. For a 143.7 x 143.7 mm cavity, the theoretical machining time was 10 minutes and 55 seconds, a 159% increase over the actual 17 minutes and 20 seconds at a theoretical feed rate of 5.593mm/min.

8 Discussion

Fig. 3 compares tool paths of 0.7 and 0.4 mm depths of cuts. Interestingly, individual machining trajectories change over the height of the cavity. In general, it can be assumed that the depth of cut (ap) will not affect the individual trajectories of this cavity, especially the constant cross-section in all cuts. However, the software algorithm approaches these machining parameters differently, and changing them can either intentionally or unintentionally affect the paths. In Fig. 4, however, the opposite can be observed when the paths do not change. However, a different type of tool is used here, which also affects the path calculation algorithm. The unmilled material after machining will undoubtedly be an essential and non-negligible factor here.

The increasing trend of machining time between individual machining depths of 9, 19, and 29 mm observed in Fig. 5 is expected and logical as the amount of material removal increases, so does the machining time. More interesting, however, is the machining time indicator for individual depths of cut. Differences are observed here, but despite the longer machining time, it can positively affect the tool's lifetime and, thus, the overall machining cost. This effect can then be observed in Fig. 6 at a machining depth of 19 mm for Cavity mill 0.4 mm and Cavity mill 4.5 mm. Here, the difference of 14.3% of the price can have a significant share, especially in small production series.

The influence of unmilled material in Fig. 7 and Fig. 8 affects the choice of tool shape, machining depth, and machining strategy.

The influence of the engage method (Fig. 9, Fig. 10 and Fig. 11) significantly affects the machining cost. This parameter is determined by the used tool and its geometry, which allows immersion. The path of the tool, referred to as plunge, can be characterized partly as the main machining time and partly as secondary, from the perspective of tool speed. This path usually does not have an entire cutting movement, although it already removes the material of the semi-finished product, which is governed by a separate machining parameter. The engage method has an increasing influence on the machining depth, as we can see in Fig. 12. From the most significant difference of 4 seconds for a depth of 9 mm, the machining time increases to 18 seconds for a depth of 29 mm.

Cut pattern choice is most influenced by the requirement for unmilled material on the cavity wall, which was a critical factor in the machining time. Fig. 14. demonstrates this: the ZIG and ZIG WITH CONTOUR methods show approximately twice the machining times compared to the ZIG ZAG method, which leaves relatively significant tool marks on vertical walls, which may not be desirable.

Machining verification can then show differences between simulation and actual machining times. It is mainly the possibilities of acceleration and deceleration of moving parts of the machine that do not reach the required displacement values on the selected tracks. Also, there are differences in the size of the unmilled material in the simulation and reality.

9 Conclusion

This article deals with the issue of machining programming from different points of view. After the introductory part, the methods, their conditions, and individual tests and simulations are defined, which have proven the non-negligible influence of the programmer on the total machining time thus, production cost. Upon closer examination, different degrees of influence on these indicators can be seen. Their influence is insignificant for small batch production, representing savings in units to tens of seconds on the machining cycle. It finds application mainly in serial production, where the total cycle time, the cost of the machine, tool, and other accessories in the required volume represents the possibility of profit increase or price reduction against the competition.

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