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OPTIMAL TOOL PATH STRATEGIES FOR DECREASING THE MANUFACTURING TIME OF ONE THERMOFORMING MOLD

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Abstract: *In this paper it is analyzed one thermoforming mold product that was machined at the S.C. ULMA PACKAGING S.A. company, and was used for plastic containers in which the food or non-food products are packed. Manufacturing of thermoforming products are made using thermoforming machine called TFS 200. Two different manufacturing methods will be presented using the same tools, the same technological parameters but using different tool path strategies in order to analyze the machining time in both cases. In this paper are determined the optimal technological parameters and the optimal tool path strategy usage on manufacturing time of one thermoforming mold. The obtained results will demonstrate the beneficial effect of the optimal tool path selection on manufacturing time.*

Key words: *manufacturing, Design for Manufacturing (DFM), technological parameters, tool path, thermoforming mold.*

1. INTRODUCTION

The main role of the mechanical engineer in the continued development of industry is to be a creator by applying knowledge and experience to solve technical problems and to optimize manufacturing processes. The manufacturing time can be optimized by statistical optimization techniques making breakthrough improvements to a product or a process from productivity point of view.

The goal of the mechanical engineer is to optimize the manufacturing operations, as well as their economic impact while making a product, by minimizing the manufacturing time. In order to optimize the machining method and to minimize the manufacturing time, within companies there are used certain types of cutting tools and machines characterized by optimal technological parameters. It is important to realize a design for manufacturing (DFM) of the product which must provide an easy machining, assembling to decrease the manufacturing costs without having a negative impact on the quality requirements of products. About 70% of manufacturing costs of a product: cost of materials, processing and assembly are determined by design decisions. [2]

DFM principles and methods can be used within the designing process and manufacturing costs can be estimated with a significant impact on the production cost at the end. DFM principles and guidelines is a useful tool for designers to sort out manufacturing issues with significant influence on the final cost. There are several rules that can be specified in this sense, such as eliminating the intricate shapes and peculiarities of one part, applying and using of standardized methods and tools, comprising of different technological operations that are applied in the case of manufacturing of a part into a single operation / manufacturing process on a machine, etc. [3] Selecting of an adequate material, in close connection with the designed shape and features of one specific part to be manufactured, selections of tools that are adequate to machine the specific part, with minimized costs, setting of adequate tolerances that are in concordance with the product design and manufacturing process are also few important principles that are considered in the DFM process. Material characteristics as well as machinability of the material are two of the most important issues that must be considered in the process of selecting the adequate material for one particular product to be manufactured.[4] Selecting of adequate cutting tools is highly important since it has a decisive influence on the final cost if a product at the end. Few of the most important characteristics to be considered in the case of tools for minimizing the manufacturing costs are their strength, their stiffness and their manufacturing costs. Therefore, the product must be designed so as to avoid using of specialized, complex cutting tools. By using these principles together with Computer Aided Design (CAD), Finite Element Analysis (FEA) and Computer Aided Manufacturing (CAM), designing engineers must find alternative solutions manufacturing of a product, taking into consideration the designing shape of a product or process which assures a minimal machining time and low manufacturing cost at the end.

Several statistical optimization methods can be used for optimizing the technological parameters that are used in the cutting process, with a high impact on the time manufacturing minimization and increase of the economic impact of the entire manufacturing process of one product at the end. [1]

Finding of optimal technological parameters in close correlation with the finding of optima tool path are also few ways of minimizing the machining time of a product at the end. [7] Decreasing of cutting forces, decreasing of the tool wear, minimizing of surface roughness level, as well as minimizing the work piece deformations are few of the main advantages that are foreseen to be reached by applying tool path optimization methods. For instance, in the process of pocket milling: contour-parallel, one-way direction-parallel and zig-zag direction-parallel tool paths are few of the most important commercial tool path optimizing strategies that are well-known and applied on a large scale by the researchers in the milling process of complex parts that are machined by CNC. [6]

2. Description of the analyzed part

The designing process of the thermoforming mold (figure 1) was realized using Solid Edge software. To obtain plastic containers in which the food or non-food product is packed, Figure 2, it is used a thermoforming mold, which is part of a thermoforming machine TFS 200, presented in Figure 3. In order to obtain the 3D model the following steps were needed: sketching, constructing base features, creating the details of the part, analyzing section views.

Fig. 1. The analyzed mold

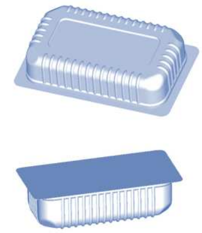


Fig. 2. The plastic food-container after the process

Fig. 3. TFS 200 Thermoforming machine

The analyzed part is made of aluminum alloy EN-AW-5083 H111. This material it is highly resistant to the chemical attack that might occur in industrial chemical environments, because of its exceptional performance in extreme environments, figure 4.

Property	Value
Density	265 g/cm³
Melting Point	570 °C
Thermal Expansion	25 x10^{-6} /K
Modulus of Elasticity	72 GPa
Thermal Conductivity	121 W/m.K
Electrical Resistivity	0.058 x10^{-6} Ω .m

BS EN 485-2:2008 Plate 6.3mm to 80mm	
Property	Value
Proof Stress	115 Min MPa
Tensile Strength	270 - 345 MPa
Hardness Brinell	75 HB

Fig. 4. Physical and mechanical properties of the EN-AW-5083 H111 aluminum alloy [4]

2. Computer Aided Manufacturing for the thermoforming mold using EdgeCam

EdgeCam is a computer aided manufacturing program that allows the generating of the machining strategies and CNC codes for CAD models. The main stages to be followed in EdgeCam in order to obtain the final CNC code for the considered model are presented in Figure 5 and the CAM steps in the Table 1.

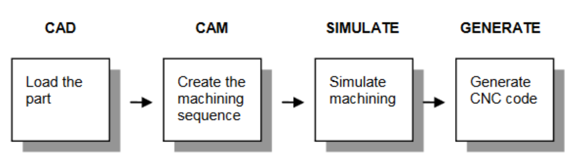
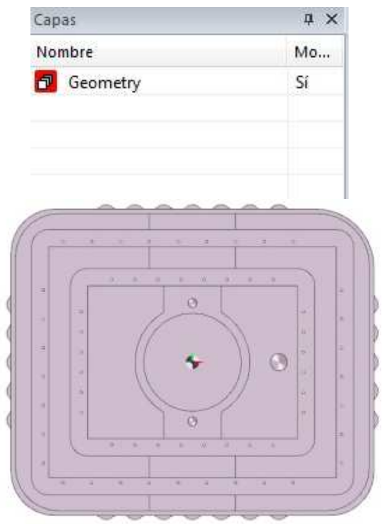
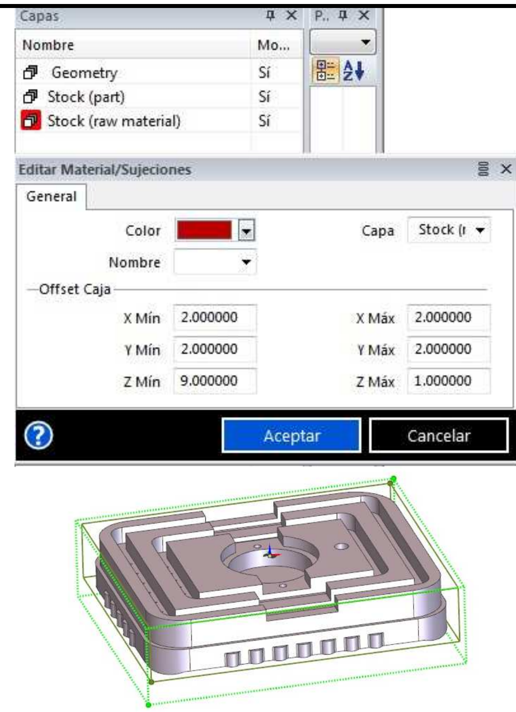
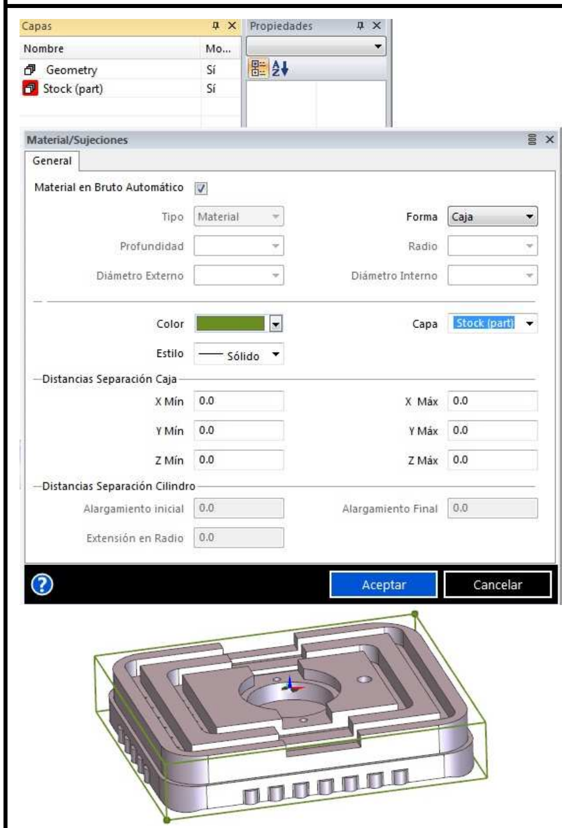
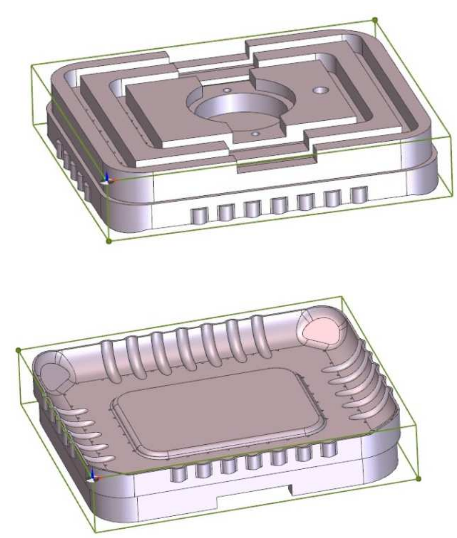
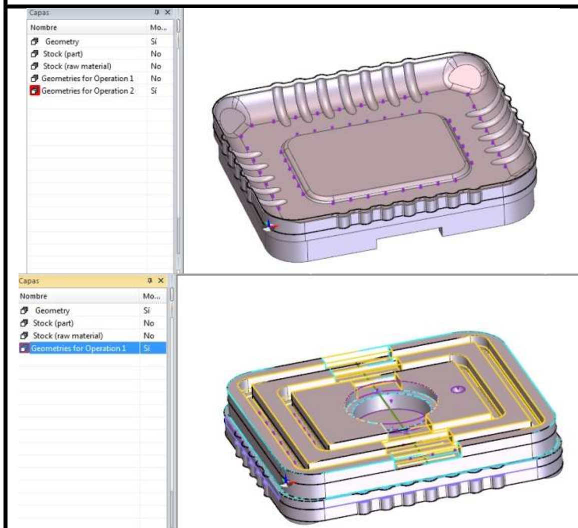
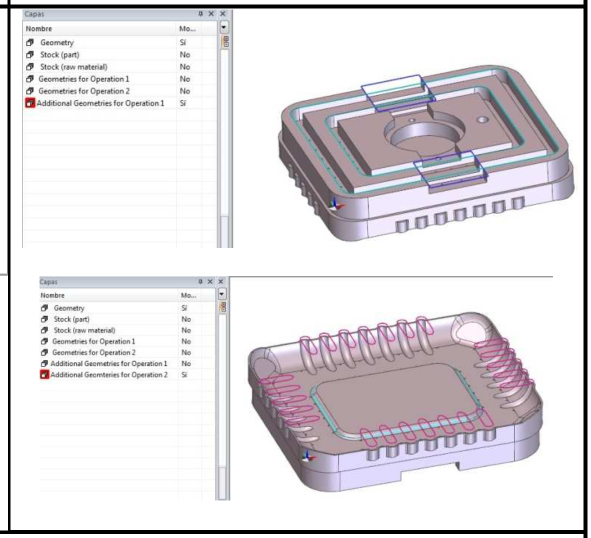


Fig. 5. The main stages in EdgeCam [5]

Table 1

Computer Aided Manufacturing (CAM) steps

1.Loading the 3D model	3.Defining of the Raw Material
	
2.Creating the Stock around the 3D model	**4. Defining of the Coordinate Systems**
	

5.Selecting the necessary Geometries	6.Creating of the Additional Geometries
	
7.Creating of the Machining Sequences	
8.Simulating the machining operations	
9.Generating the CNC Code	

In order to calculate and decrease the manufacturing time of the thermoforming mold it is necessary to obtain the CNC program. In the Design Mode of the software used, the necessary stock was created around the 3D model and the two different coordinate systems were created for the two fixings. By using the Automatic Feature Finder tool all the necessary geometries were selected. In the Manufacture Mode of the software, two Machining Sequences were defined for each of the fixings, by using the previously defined coordinate systems. Before making any operation, it is necessary to select the suitable tool from the Tool Store. After finishing the computer aided manufacturing, the machining sequences can be simulated and the CNC codes are generated. By using further on these CNC codes the thermoforming mold can be machined on Mazak VTC 200C Vertical Machining Center. For the machining processes of the thermoforming mold there are used indexable milling cutters from Walter, solid carbide end-mills, solid carbide torus end-mills, solid carbide ball nose end-mills from Hoffmann and OSG companies, solid carbide drills and HSS drills from Guhring.

2.1. The technological parameters for the necessary tools

In the following, all the milling and drilling tools will be analyzed and the necessary technological parameters will be calculated taking into consideration the equations (1) and (2) [8] for spindle speed *(n)* and for feed rate (v_f):

$$n = \frac{1000 \cdot v_c}{\pi \cdot D} \text{ [rev/min]} \quad (1)$$

$$v_f = n \cdot f_z \cdot z \text{ [mm/min]} \quad (2)$$

In order to calculate the necessary technological parameters by using the above mentioned equations, the recommended values of the cutting speed (v_c) and the feed per tooth (f_z) or feed per revolution (f_{rev}) will be used, according to Table 2.

By taking into account the above technological parameters for all of the used tools, it was possible to start the computer aided manufacturing of the thermoforming mold, by using the EdgeCam software.

Table 2

Spindle speed and feed rate calculation for the used machining tools

	Spindle speed [rev/min]	*Feed rate [mm/min]*
Indexable milling cutter ϕ80	5800	1450

Solid carbide end-mill ϕ6	7500	450
Solid carbide end-mill ϕ13	3500	560
Solid carbide end-mill ϕ16	3000	600
Solid carbide end-mill ϕ1	9800	120
Solid carbide end-mill ϕ2	5200	120
Solid carbide torus cutter ϕ10 R1.5	5000	500
Solid carbide torus cutter ϕ4 R1	10000	500
Solid carbide ball nose end-mill ϕ4	10000	460
Solid carbide drill-reamer 6 H7	4000	760
Solid carbide drill ϕ3.7	10000	2540
HSS drill ϕ1	10000	410
M4 form tap	1000	-

2.2. Computer aided manufacturing stages

The first stage (loading the part, creating stocks, defining coordinate systems, selecting necessary geometries) continues with the CAM stage which includes the creation of the machining sequences (tool selection and definition of the machining operations) and also the machining simulation. It is necessary to create two different machining sequences for the two different fixtures, as shown in Figure 6.

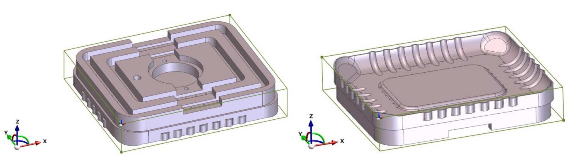


Fig. 6. Fixture I and II of the thermoforming mold

The definition of the machining sequences assumes the selection of the suitable machining center, which in this case will be the Mazak VTC 200C Vertical Machining Center, shown in figure 7. After selecting the necessary tool, the necessary machining cycle will be selected from the Operations menu (Face Milling, Hole, Roughing, Profiling, Slotting, Chamfer, etc.).

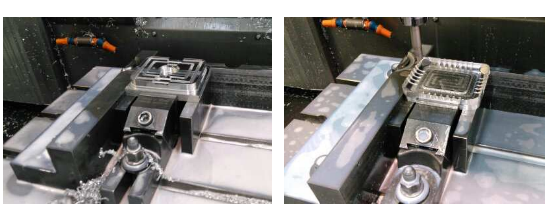


Fig. 7. The thermoforming mold fixed on the Mazak VTC 200 C Vertical Machining Center's table

After creating the first machining sequence, the next step of the computer aided manufacturing process was the machining simulation. In Figures 8 and 9 the machining simulation after each machining cycle is presented, for the fixtures I and fixture II.

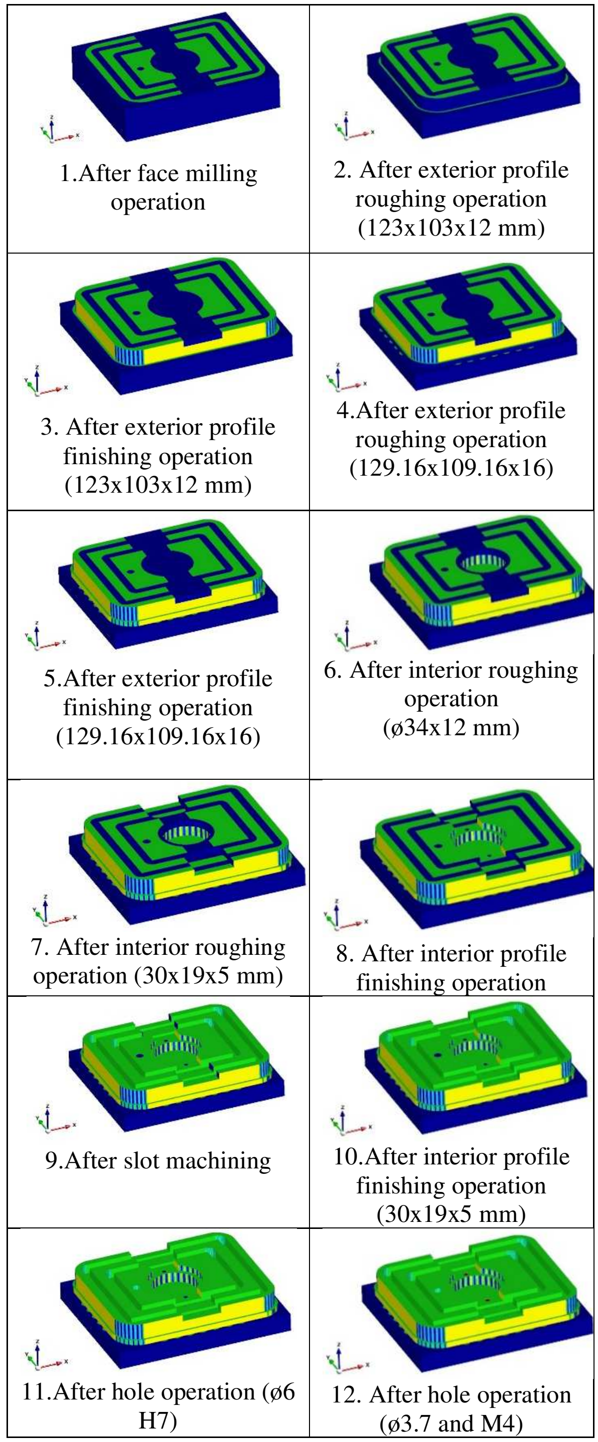


Fig. 8. Machining cycles simulation (Fixture I)

By using the View Comparison option, a comparison between the stock and the final part was made after each machining cycle. Green, yellow and orange colors refer to fully machined surfaces, blue color refers to surfaces with left over material and red color refers to threaded holes. For the second fixture a new sequence was created.

EdgeCam calculates the machining cycle time and provides this information for the overall machining time, as well as the specific machining events. The Time Line window displays the entire machining sequence graphically, allowing the users to quickly identify which machining events consume the longest amount of time from the overall machining cycle time.

From Figure 10 is possible to notice that the first sequence lasts for 17 minutes and 38 seconds, and the longest amount of the overall machining cycle time is consumed by the solid carbide end-mill ϕ16. In Figure 11, the Time Line window is presented for the second fixture of the thermoforming mold. The overall machining time for this sequence is 3 hours, 8 minutes and 35 seconds.

The longest amount of the overall machining cycle time is consumed by the solid carbide end-mill ϕ2 and the solid carbide ball nose end-mill ϕ4. These two tools are used in the machining process for approximately the same amount of time, 50 – 60 minutes. By analyzing these values regarding the machining time, it is obvious that the second sequence takes too long for this relatively small work piece. Therefore, the machining time is needed to be reduced in order to decrease the manufacturing costs. In the following, the optimization of the machining time was realized by applying a more suitable tool path strategy, which assures the same roughness of the machined surfaces.

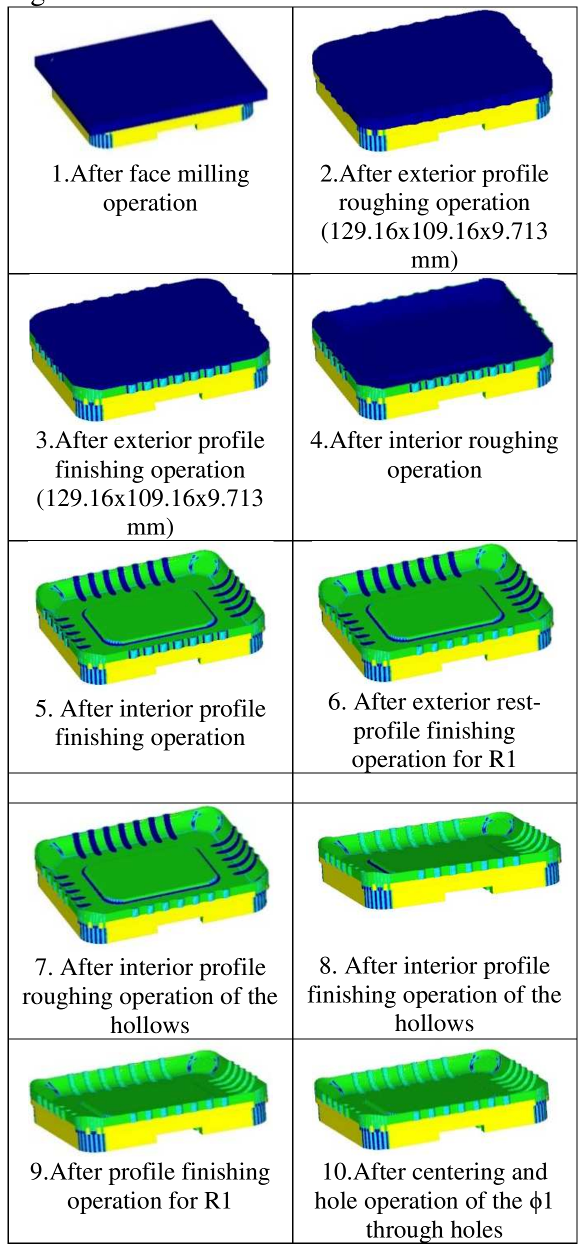


Fig. 9. Machining cycles simulation (Fixture II)

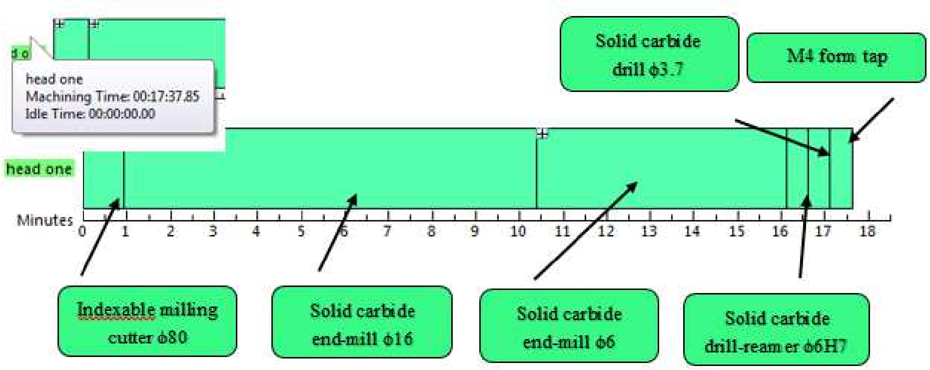
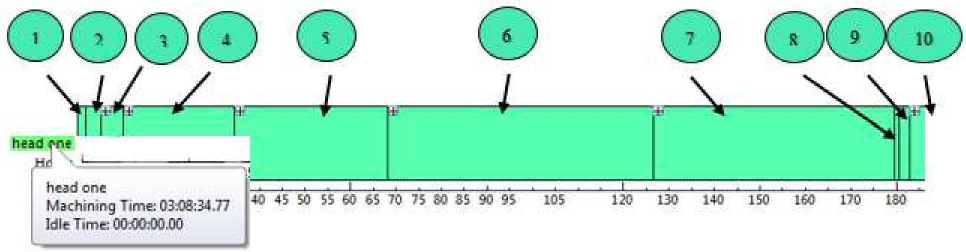


Fig. 10. Time Line window for the first fixture of the thermoforming mold

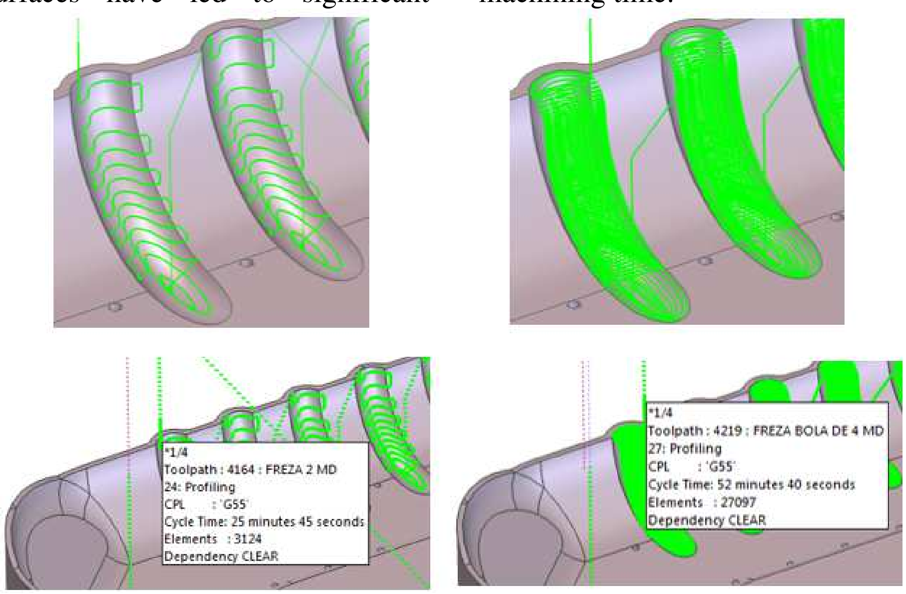


1-Indexable milling cutter ϕ80
2-Solid carbide end-mill ϕ16
3- Solid carbide end-mill ϕ6
4-Solid carbide end-mill ϕ13
5-Solid carbide torus cutter ϕ10 R1.5
6-Solid carbide end-mill ϕ2
7-Solid carbide ball nose end-mill ϕ4
8-Solid carbide torus end-mill ϕ4 R1
9-Solid carbide end-mill ϕ1
10-HSS drill ϕ1

Fig. 11. Time Line window for the second fixture of the thermoforming mold

3. Decreasing of the manufacturing time for the thermoforming mold by using the optimal tool path strategy

Decreasing the machining time in a milling process is one of the important criteria to improve the overall efficiency of the machining process. The paper presents a research regarding the decreasing of the machining time, focusing on flow surface machining method to increase the efficiency and performance during the machining process. Freeform surfaces have been widely used in various engineering applications. Increasing requirements for the accuracy of the freeform surfaces have led to significant challenges for the manufacturing of these surfaces. The machining of the thermoforming mold’s hollows will be analyzed taking into consideration the fact that the longest amount of the overall machining cycle time is consumed by the machining of these freeform surfaces. The Profiling cycle was used in order to generate a connected series of Z level profiles, by taking into account the shape of the tool and the selected boundaries to keep the tool in contact with the part. Therefore a standard Z-level tool path was obtained, which assured the desired accuracy and roughness of the hollows due to the set Cusp Height value but also guaranteed a long machining time.



a) b)

Fig. 12. The contour-parallel tool path of the (a) ϕ2 solid carbide end-mill and (b) ϕ4 solid carbide ball nose end-mill

In Figure 12 the contour-parallel tool path of the ϕ2 solid carbide end-mill (which is used for realizing the interior profile roughing) and the ϕ4 solid carbide ball nose end-mill (which is used for realizing the interior profile finishing) are presented. The interior profile roughing cycle takes 25 minutes and 45 seconds and the interior profile finishing operation of the hollows takes 52 minutes and 40 second when this standard, contour-parallel, Z-level tool path strategy is applied.

In the following, another tool path strategy was applied for the finishing machining operation of the hollows in order to reduce their machining. Therefore, the interior profile roughing cycle remains the same; only the interior profile finishing cycle was modified.

Instead of applying a Profiling cycle for the finishing machining of the hollows, a 3D surface milling cycle was applied, called Flow Surface which generates tool paths following the flow of the freeform surfaces. After the interior profile roughing operation was realized by the ϕ2 solid carbide end-mill, the left over material needs to be eliminated by the ϕ4 solid carbide ball nose end-mill. Due to the fact that a 3D finishing tool path was applied, which is characterized by a tangential movement to the hollows' surfaces, the remained material is too much for the considered tool in these circumstances, therefore the previously presented interior profile finishing operation was replaced with two operations: one semi-finishing and one finishing flow surface operation.

The Flow Surface Cycle was used both for semi-finishing (Figure 13) and finishing operation (Figure 14).

In the General tab, the Strategy was set to Blend between Two Curves and the edges of the hollows were selected for these two requested curves. The Mill Type was set to Climb. The distance between cuts is determined by the Stepover (10%) setting, but due to the fact that the Number of Cuts was specified, the cutting stops when this value is reached. The 3D Offset for the tool path from the surface was set to 0.2 mm. The Tolerance which controls the accuracy of the fit between the geometry (surfaces) and tool path, was set to 0.01 mm. The feed rate used in this case was set to 460 mm/min, the spindle speed to 10000 rev/min and the plunge feed to 300 mm/min.

The Flow Surface Cycle stops at the bottom of the hollows due to the fact that the Associative is checked in the Depth tab, therefore the depth's value is automatically calculated by the software. After the Flow Surface Cycle was created, the tool path of the solid carbide ball nose end-mill appeared in the graphics area. This tool path is presented in Figure 13.

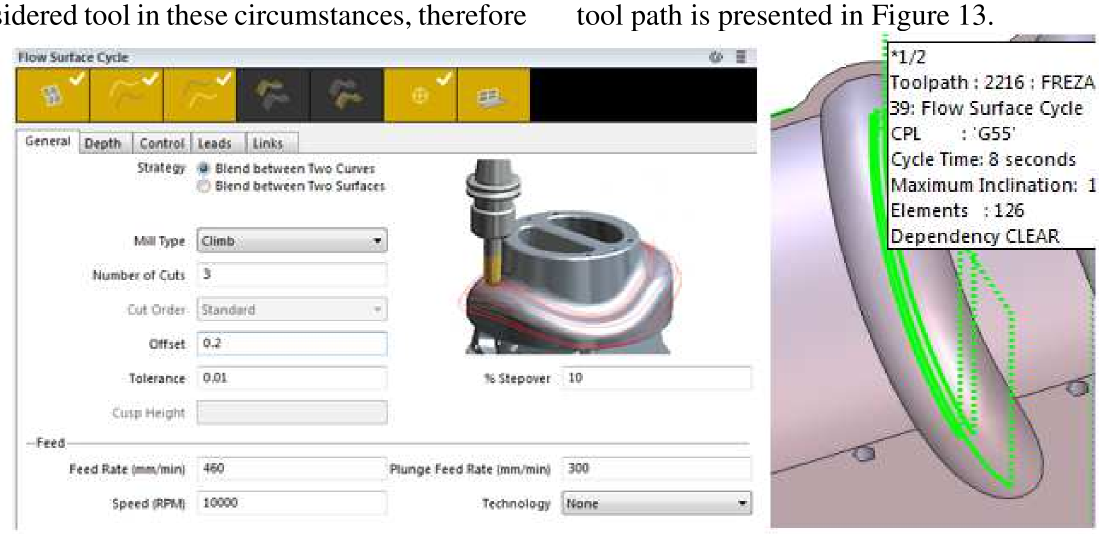


Fig. 13. Definition of the Flow Surface Cycle for the semi-finishing of the hollows and the ϕ4 solid carbide ball nose end-mill's tool path in this case

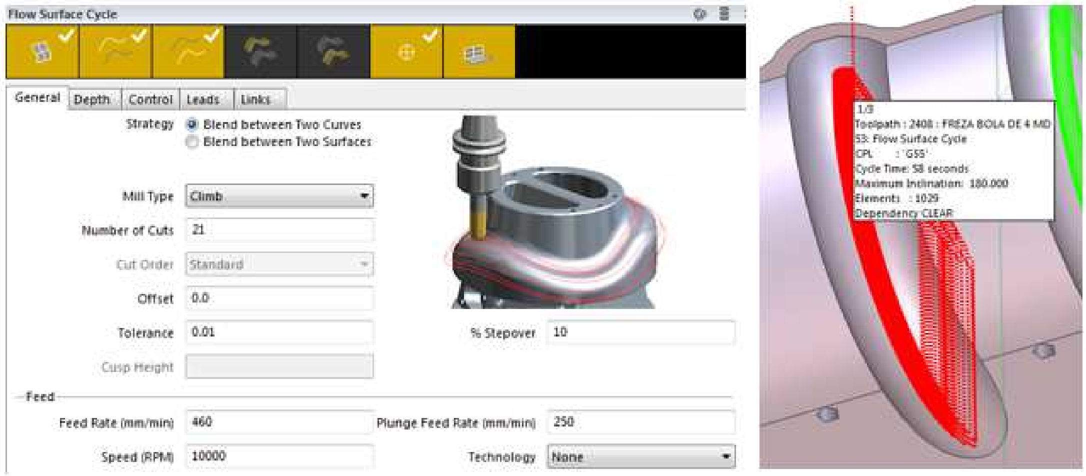


Fig. 14. Definition of the Flow Surface Cycle for the finishing of the hollows and the ϕ4 solid carbide ball nose end-mill's tool path in this case

After this semi-finishing cycle it was necessary to define a finishing cycle using again the Flow Surface Cycle (Figure 14). In this case, the Number of Cuts was increased to 21 in order to obtain a well finished surface, and the Offset was set to 0 mm.

After the Flow Surface Cycle was created, the tool path of the solid carbide ball nose end-mill appeared in the graphics area. This tool path is presented in Figure 14.

By analyzing Figures 13 and 14, it can be observed that the semi-finishing cycle for one hollow takes 8 seconds, while the finishing cycle of one hollow takes 58 second. Knowing that the thermoforming mold has 24 hollows, which are similar to each other, it means that the whole semi-finishing cycle takes 3 minutes and 12 seconds and the whole finishing cycle takes 23 minutes and 12 seconds. By using only the contour-parallel tool path strategies, the total machining time of the hollows will be 78 minutes and 25 seconds. As it is presented in Table 3, by simply changing the tool path for the finishing of the hollows, it is possible to reduce the machining time of these surfaces.

Table 3

The influence of the tool path strategy on to the machining time

	Roughing (Profiling Cyle)	**Finishing (Profiling Cyle)**	**Semi-finishing (Flow Surface Cycle)**	**Finishing (Flow Surface Cycle)**	**Total time**
Using contour-parallel tool path	25 min 45 sec	52 min 40 sec	-	-	**78 min 25 sec**
Using 3D tool path	25 min 45 sec	-	3 min 12 sec	23 min 12 sec	**52 min 9 sec**

Therefore the standard Z-level tool path was modified into tangential movement to the hollows' surfaces by using the Flow Surface Cycle thus obtaining a reduced machining time of 52 minutes and 9 seconds.

4. CONCLUSIONS

Due to the fact that the EdgeCam calculates the machining cycle time and provides this information for the overall machining time, as well as the specific machining events, by analyzing the Time Line window for the second fixture of the thermoforming mold, it was obvious that the longest amount of the overall machining cycle time was consumed by the ϕ2 solid carbide end-mill and the ϕ4 solid carbide ball nose end-mill, these two tools being used in the machining process for approximately the same amount of time, 50 – 60 minutes. By analyzing these values regarding the machining time, the second sequence takes too long for this relatively small work piece. Therefore, the machining time was needed to be reduced in order to decrease the manufacturing costs.

The machining of the thermoforming mold's hollows was analyzed taking into consideration the fact that the longest amount of the overall machining cycle time was consumed by the machining of the freeform surfaces.

The optimization of the machining time was realized by applying a more suitable tool path strategy, which assured the same roughness of the machined surfaces. By simply changing the tool path for the finishing of the hollows, it was possible to reduce the machining time of these surfaces.

In conclusion, it means that the overall machining time was reduced with approximately 26 minutes for one part.

By taking into consideration the fact that the Company is represented by low volume production, the required quantity of this thermoforming mold is 25 parts. It means that the machining time was reduced with 650 minutes (approximately 11 hours) for the whole quantity of parts required to be manufactured. The manufacturing cost for one hour is equal to 28 euros, therefore the manufacturing costs were also reduced with 308 euros in total in this case.

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Strategii optime ale traiectoriilor sculelor așchietoare pentru reducerea timpului de fabricație a unei matrițe de termoformare

Abstract: *În această lucrare se analizează o matriță de termoformare care a fost prelucrată la compania S.C. ULMA PACKAGING S.A. utilizată pentru obținerea unor recipiente de plastic în care sunt ambalate produsele alimentare sau nealimentare. Fabricarea produselor se face folosind o maşină de termoformare numită TFS 200. Două metode de fabricație diferite vor fi prezentate folosind aceleași scule aşchietoare, aceiaşi parametri tehnologici, dar folosind diferite traiectorii ale sculelor aşchietoare pentru a analiza timpul de prelucrare în ambele cazuri. Rezultatele obținute vor demonstra beneficiile selectării unor traiectorii ale sculelor aşchietoare optime asupra timpului de fabricație a matriței. Scopul acestei lucrări este de a determina parametrii tehnologici optimi, respectiv de a determina traiectoria optimă a sculelor aşchietoare în timpul procesului de fabricație a „matriței de termoformare".*

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