Comparison between milling roughing operations in full slotting manufacturing: trochoidal, plunge and conventional milling

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Abstract: Manufacturing improvements in terms of manufacturing-chain costs and times reduction are becoming a real need in the industry, especially for roughing operations. To satisfy these industrial requirements, more efficient machining processes have been developed, such as High Efficiency Milling (HEM). According to the above mentioned direction, trochoidal milling appears as an efficient method for roughing operations of full slots. This work presents an analysis in terms of production time between conventional, plunge and trochoidal milling to determine which process configuration is more productive.

Keywords: Trochoidal milling, High Efficiency Milling (HEM), Slot roughing.

1. Introduction

Technological advances in the development of new materials have allowed the evolution of the cutting tools to a new level, increasing their performance and their useful life. Currently, each operation and material workpiece have a specific working tool to ensure optimal process performance.

Nevertheless, not only does the substrate determine the tool's outputs, but to continue progressing, in the same way, and to take performance to the next level, is necessary to enhance other aspects of the machining operation such as toolpath generation. For example, in the case of milling operations, the programming of the toolpath is a critical factor to be able to extract the maximum potential from the tool since the death times depends exclusively on the trajectory generations of CAM software.

In this line, the "High Efficiency Milling" concept has been developed, which explores how to improve the path in order to reduce the time wasted in tool repositioning. As a result, a strategy called trochoidal milling was created, which allows to deal with the needs demanded by the market. This technique consists of producing a circular chain toolpath that enables a continuous cutting of the material, saving time in machining. Furthermore, due to the nature of the process that works with a reduced radial depth of cut (aₐ) and an increased axial depth of cut (aₐ), the tool cutting edge works entirely leading to a reduction in cutting forces and consequently in the tool wear, lengthening the tool life.

In order to analyse in detail the advantages of this method, a comparative study is carried out between other existing options, which are conventional and plunge milling. In this case, slotting machining will be analysed to justify whether or not trochoidal milling is more advantageous.
2. Slotting technologies

At the present time, there is a real necessity for reducing machining times in order to be more productive. This is the case of manufacturing sectors such as the aircraft and automotive industry, in which the requirements are becoming increasingly more demanding. In that line, in recent years have appeared some new terms related to milling processes, some of them are old, like High Speed Machining (HSM), and others are new, like High Efficiency Milling (HEM).

On the one hand, High Speed Machining have been used and studied throughout years. HSM is a term typically attribute to small-diameter tools (around 10 mm or below) at high rotational speeds (10,000-100,000 rpm) [1]. Currently, HSM is mainly used in three sectors: manufacturing of aluminium components for the automotive sector, manufacturing of thin-walled long aluminium components for the aircraft industry and in the die and mould industry for finishing operations [2]. There have been many studies that have been carried out on this subject that have proved a large amount of benefits: reduced lead times, low cutting forces and capacity to manufacture thin-walled workpieces, obtaining high quality surfaces and great accuracy, better dissipation of heat, etc. But this technique also has some disadvantages, which involve the excessive tool wear and the need of high rotational speed of the spindle. One critical aspect that has influence in the rest of parameters (cutting forces, surface integrity, surface roughness, chip formation and tool wear) involved in the process is the cutting speed. This parameter has been commonly studied by experimental, analytical and numerical methods [3].

On the other hand, High Efficiency Milling (HEM) process is a more modern term which reflects the necessity of improvement in milling in order to be more productive. Specifically, it is a roughing method in which heat generation is more controlled during machining. This method uses the idea of Chip Thinning theory, which consists on programming small radial depth of cut (RDOC) and large axial depth of cut (ADOC), see figure 1. In other words, the HEM technique uses similar cutting parameters to milling finishing operation, concretely RDOC and ADOC, but with significant differences, that are the use of higher feeds and speeds. This allows to achieve higher Material Removal Rates (MRR), which can translate into higher productivity. Moreover, in the literature many researchers state that this method provides many benefits apart from those already mentioned, and they are very similar to the ones obtained with HSM processes, such as, reduced cutting forces [4] and capacity to manufacture thin-walled pieces among others [5]. These are the reasons why this milling method is used to remove large amount of material, especially in roughing and slotting operations.

![Figure 1. Conventional milling vs HEM.](image)

The phenomenon of Chip Thinning is related to two parameters, chip thickness and feed per tooth, and it occurs when there is a variation in the radial depth value. Nevertheless, it is a very dependent operation on how well it is programmed in terms of heat generation. In other words, if it is not well programmed, HEM can cause an exponential increase of heat due to high speeds and feeds of tool movements, especially if the machine tool is not capable to achieve those velocities, because it will
cause rubbing issues between tool and workpiece material. This interaction can induce deformations into the workpiece and overheating in the tool. However, if the programming is correctly done, it will have many benefits in the manufacturing. For that, it should not have to fall below the line of reduced step-over without high feeds and speeds.

Currently, HEM is an increasingly used method in the manufacturing sector, where the most outstanding characteristic is the used of most of the effective length of cut in order to extract all the potential performance of the mill, which includes productivity and tool life. It must be considered that this method implies more radial passes, but the heat generated during the process will be evenly spread through the whole effective cutting length, reducing the appearance of an early failure and breakage.

2.1. Conventional Milling

Conventional groove milling or slotting has been one of the first manufacturing strategies used by machine operators since the appearance of milling technology due to its simplicity of programming, concretely in full slotting applications programmed in 3 axes machines. This process consists of making slots in the workpiece by integrating two movements: one of rotation, inherent in the rotation of the tool; and another of translation, indicated by the geometry of the cavity to be machined, without the need of programming a complex trajectory.

For this purpose, the market offers different tools in the creation of full slots with conventional methods. The most widely used in the industry are conventional shank milling cutters since, in addition to being used for grooving, they serve for many other types of milling operations. Another type of tool widely used are side and face milling cutters, since thanks to its geometry, they allow defining both the floor and the groove walls. Last but not least, there are other tools options called form tools such as T slot milling cutters or dovetail milling cutter. These tools allow us to make T or dovetail slots rather easily, which would be very difficult to obtain with other methods.

The use of one or another tool depends on the kinematics of the machine, and in turn, on the orientation of the part. For three-edged tools, the normal vector of the groove floor is perpendicular to the axis of rotation of the tool. As for the conventional shank milling cutters, that normal is parallel to the axis of rotation of the tool.

Likewise, the geometry of the groove also influences the choice of the tool. In the case of rectangular grooves, both the side and face and shank cutters would be useful. However, in the case of grooves that are not rectilinear, the use of side and face cutters is not feasible due to geometric and shape limitations. Before starting machining, it is of utmost importance to analyses which tool fits better to the workpiece.

In the following, shank tools will be delved into further, due to their extensive use in industry as well as their advantageous features over side and faced ones. The main feature of conventional grooving with shank cutters is that the diameter of the tool to be used is the same as the width of the groove. Due to the radial pass depth (a_r) in machining, there is a large contact surface between the cutter and the workpiece. In turn, for this reason, the cutting forces generated in the radial direction of the tool increase. Besides, a negative aspect related to what was previously described is the evacuation of the heat generated during the process. Since the tool is confined between the walls of the slot, making it very difficult to influence the cutting area with a coolant.

Chip evacuation is another problem to consider. The main reason is that the chip is caught between the edges. If the material to be machined is fragile, the tool does not have problems to evacuate the chip because it breaks into small fragments. In the case of materials with a ductile character, the chip is longer and more tenacious, so the tooth suffers an overload to deform the chip. In these cases, it is preferable to choose an inclined or helical tooth, to be able to evacuate the generated chip more easily.

The cutting forces make the grooving operation to have limitations. As is the case of the vibrations generated during machining. These make the milling unable to reach the depth of the groove in a single pass. Therefore, it is crucial to choose well the tool to use, since the depth of the grooving will be defined by the tool. At a greater axial depth of cut, the radial forces will be higher. Stair grooving can be advantageous on these occasions. That is, machining the groove in multiple passes, thus decreasing the axial depth of cut in each cycle.
2.2. Trochoidal Milling

The trochoidal milling method was originally developed for roughing cavities of difficult-to-machine materials, such as hard steels, and heat-resistant superalloy materials. It is also a technique used to machine other materials, especially in applications sensitive to vibrations. Trochoidal milling is widely used when it is necessary to create grooves wider than the diameter of the cutting tool. In the last years, trochoidal milling has appeared as an alternative for conventional roughing techniques. Moreover, it is considered both a HSM and a HEM process.

First of all, the definition of trochoidal milling should be defined. The essential characteristic of trochoidal milling resides in its toolpaths, which are described by a series of overlapping circular forward movements in radial direction, together with a high axial depth, in general [6]. It is a combination of a uniform linear path with a uniform circular path, as can be seen in figure 2. Within trochoidal milling classification, there are two different types, circular trochoidal and true trochoidal.

![Figure 2. Trochoidal path classification: (a) Circular trochoidal. (b) True trochoidal.](image)

Unlike a completely linear radial tool path, as in conventional groove machining, trochoidal milling takes advantage of a spiral tool path with a low radial depth of cut to reduce tool load and wear. Due to these characteristics, trochoidal milling can be very advantageous in certain applications, since the reduced radial overlapping of passes during the path reduces the amount of heat generation. Furthermore, in turn, both the cutting forces and the load applied to the spindle are decreased. This means that the reduced radial forces allow greater precision during production, and therefore, allow more complex details to be machined without reducing their precision. Another important characteristic of trochoidal milling is that due to the lower radial cutting depth of cut it allows a higher axial cutting depth of cut, which means that the entire length of the cutting edge can be used. This ensures that heat and cutting forces are distributed across the edge of the tool, rather than being concentrated in one section. Reduced heat and wear, combined with its uniform extension on the cutting edge, result in significantly improved tool life in comparison with conventional grooving methods. Another very relevant consideration in trochoidal milling is that due to the reduced cutting forces generated, the cutting speeds of the tool can be increased. Since the entire cutting length is used, this type of milling eliminates the need for multiple axial cutting passes at different depths when machining. This supposes a reduction of the machining time.

As mentioned before, trochoidal milling is increasingly used, owing to its characteristic of avoiding heat accumulation and reducing cutting efforts, which are essential qualities for an optimized manufacturing with reduced tool wear [7]. As already described, trochoidal paths are described by the union of circular and linear movements, resulting in circular trochoidal or true trochoidal. This second one has emerged as a significant alternative in rouging operations, since it allows more stable kinematics conditions due to its toolpath follows continuous tangency and not a circle [8]. With this trochoidal path, true trochodal, is possible to avoid a full tool immersion angle, which is one of the most concerning issues in slotting operations. Some researchers have proved that cutting forces can be restricted modifying the value of two adjacent trochoidal circles [9]. To be able to incorporate this milling
technique to a milling centre, the following requirement must be fulfilled: it has to have fast X and Y axes accelerations in achieve smooth trajectories.

A considerable amount of studies have been carried in the field of trochoidal milling in recent years. On the one hand, many of them are focused on the calculation of cutting forces and on the engagement between the tool and the workpiece, which is a very important aspect of this milling strategy [10], or related to the optimization of trajectories in search of stability [11]. On the other hand, other researchers focused on the calculation of mechanical and dynamic properties, including both vibration and chatter stability, as for example in [12]. Furthermore, there are researches that focused on the calculation of trochoidal trajectories for complex geometry pockets [13].

2.3. Plunge Milling

The third method used for roughing operations is plunge milling, also known as axial milling or Z-axis milling. The principal characteristic of this milling technique is that the feed movement is in the direction of tool axis during the toolpaths, which has the highest structural rigidity of the spindle, and therefore of the machine. That is the main reason why this process tends to have less vibrations than conventional milling techniques. In figure 3 are illustrated the different types of plunge milling, which can be used for enlarge small holes, roughing operations or slotting large holes.

![Figure 3. Plunge milling different types](image)

(a) Plunge Milling for roughing operations. (b) Plunge Milling to enlarge holes. (c) Plunge Milling to slot large holes.

It should be noted that in plunge milling the tool is performing drilling and milling operations at the same time during the process. Thus, the greatest forces of the process occur axially to the detriment of radial forces of conventional milling. This exchange between magnitude of forces results in greater stability of the process. As seen, in conventional milling excessive radial forces make the process unstable due to the vibrations generated. However, in the plunge milling the radial forces are much lower and, therefore, the possibility of the tool flexing is less, thus reducing vibrations. This also allows a greater tool overhang, which is the reason why accessibility is gained. That is, the plunge milling allows to reach a greater depth.

In general, the feed per tooth in plunge milling is lower than in conventional milling. That, added to the amount of traverse movements due to the repositioning of the tool, makes this technique not usually the first alternative for roughing. However, the reduction of radial forces and feed implies a lower power consumption, so this technique is also an alternative for when the power and torque of the machine are a limitation.

The surface finish of the walls is generally poor, the worse the greater the radial depth of cut, $a_r$. This is represented in the case of slotting in figure 4, where the walls are left with a profile characterized by circular grooves, due to the radial depth of cut of the process. This profile becomes more noticeable the higher the radial depth of cut. On the other hand, the greater the radial depth of cut, the greater the evacuated chip flow and, therefore, the more efficient the process will be. In addition, in plunge milling the limitation is not determined by power or stability (as it could happen with the depth of pass $a_p$ in
conventional milling), but rather the axial depth of cut is limited by the length of the cutting edge. For all these reasons, plunge milling is a technique geared towards roughing operations. Consequently, in the case of slotting, an additional finishing operation is necessary.

Figure 4. Representation of plunge milling process.

Plunge milling process is extensively used across many sectors, for example in the manufacturing of wall and cavities in the moulds and die sector or in the aerospace industry in order to be more productive during roughing stages. An interesting application of plunge milling is the roughing of integral turbine discs or blisks. The blades of these components are high in relation to the space between each other, so they can be considered as narrow and deep grooves [14]. Plunge milling is also used in the machining thermo resistant superalloys such as Inconel® 718 [15]. Nevertheless, some aspects that should be taken into account are the thrust loads and torque generation for each combination of tool-material in order to design spindles and motors capabilities.

The literature about plunge milling is not very abundant, and most of works focused on design of cutting tool geometry. In that sense, [16] investigated the intermittent plunge milling operation, in which the main objective was the manufacturing of vertical walls with high dimensional accuracy analysing tool motion and geometry. Other researchers [17], used plunge milling as a technique to manufacture complex chamfers and also estimated cutting efforts of the process.

Moreover, there has also been other researchers that carried out some investigations related to mechanics and dynamics of plunge milling with the purpose of predicting cutting efforts, vibrations and torque among others [18]. And other ones focused on the calculation of the stability of chatter in plunge milling operations [19].

3. Methodology

This work presents a comparison between three machining strategies to produce a groove, specifically the conventional milling, trochoidal milling and plunge milling strategies have been analysed. When carrying out these machining operations, blades with small spaces between them have been selected as demonstration parts. The volume of material to be removed in the roughing operation between each blade is 180 cubic millimetres, and this process has been performed 30 times for each of the operations. A new tool was used for each operation. In the case of plunge milling, a 2-flute centre mill was used, while a 4-flute grooving mill was used for the other operations. The aim is to find out which of the three strategies is more productive, and to do so a series of machining operations have been carried out varying the cutting parameters of the operations obtaining the total machining time for each strategy.

For the test, a series of small-sized blades have been designed (10 mm of height), with small inter-wall spaces (180 mm²). Specifically, in each demonstration piece, 6 cavities have been machined for each operation with different cutting parameters, see figure 5, and this demonstration part has been manufactured 5 times. The parameters that have been varied for each one are specified below.
• **Conventional Milling:** in this operation both lateral and vertical depth of cut and machining strategy have been varied. RDOC of 35% and 65% of the diameter were tested, while the ADOC have been 25% and 50%. The grooving strategy has varied between zig and zigzag.

• **Trochoidal Milling:** in this case, only the step-over between each pass was varied, starting at 2.5% of the diameter and ending at 15%, increasing by 2.5% in each operation.

• **Plunge Milling:** as in trochoidal milling, only the step-over between each consecutive pass was varied, in this case starting at 20% and ending at 45%, increasing by 5% in each operation.

4. **Results**
This work has focused on the comparison of both machining times and surface roughness for 3 different roughing strategies. The machining time gives an insight into which operation is more productive, while the roughness quality allows us to promote smoother and more consistent semi-finishing and finishing operations. For that, several combinations of manufacturing strategies parameters were applied to analyse the total machining time of each strategy in each case. The results of machining time are presented in table 1, being the average of the 5 operations for each of the different combinations of cutting parameters.

![Figure 5. (a) Machined demonstrator piece. (b) Resulting stock visualisation.](image)

| Vc* | a_p | a_c | Strategy | Time | a_p | Step-over | Time | a_p | Step-over | Time |
|-----|-----|-----|----------|------|-----|-----------|------|-----|-----------|------|
| 187.5 | 1 | 35% | ZIGZAG | 0:02:06 | 5 | 15,0% | 0:01:24 | 5 | 20% | 0:03:47 |
| 187.5 | 1 | 65% | ZIGZAG | 0:02:03 | 5 | 12,5% | 0:01:34 | 5 | 25% | 0:04:04 |
| 187.5 | 2 | 35% | ZIGZAG | 0:01:32 | 5 | 10,0% | 0:01:57 | 5 | 30% | 0:04:44 |
| 187.5 | 1 | 35% | ZAG | 0:04:58 | 5 | 7,5% | 0:02:24 | 5 | 35% | 0:05:16 |
| 187.5 | 1 | 65% | ZAG | 0:03:16 | 5 | 5,0% | 0:03:22 | 5 | 40% | 0:06:05 |
| 187.5 | 2 | 35% | ZAG | 0:02:32 | 5 | 2,5% | 0:06:26 | 5 | 45% | 0:07:17 |

* The same cutting speed was used in all operations

As for the surface roughness results, only those relating to conventional milling and trochoidal milling are shown in figure 6, as those obtained in plunge milling are much worse than in the others, due to the undulations of the remaining material left behind due to the process itself. The values were of a higher order, so they have been discarded in the comparison. Specifically, a topographical analysis of the machined surface was carried out and the surface roughness parameters were analysed. In addition, a series of profiles have been obtained in the most unfavourable direction and roughness parameters have been measured on them as well. The values shown are representative of the averages of all the measurements taken.
5. Conclusion

The focus of this work concerned the manufacturing of slots via different milling strategies. Major conclusions from this work can be summarized as follows:

- With regard to the object of study in this work, which is to see which operation is the most productive, in most of the cases, the following conclusion can be drawn: trochoidal milling allows slightly higher stock removal rates in comparison with conventional milling, and much better in comparison with plunge milling. In cases where conventional milling is faster, it happens that the tool is subjected to excessive loads, which cause quick wear and possibilities of fragile breakage.

- With regard to the finish of the walls after roughing, which is an aspect that affects the subsequent operations, it can be seen in figure 6 that trochoidal milling is the one that leaves the best result, where both surface roughness and profile values are better. The plunge milling, on the other hand, leaves this excess but with inherent undulations due to the process configuration and the conventional milling leaves too much excess due to the fact that the slotting is done in 3 axes and cannot adapt to the curvature of the blades.

- Another aspect to take into account is what the tool suffers in each of the operations. Here, trochoidal milling is also better, since by using the whole flank of the tool in the cut, the heat generated in the cut is better distributed without having areas of heat concentration, as in the case of conventional milling. While in plunge milling, special tools with a centre-edge cut are required.

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