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Benchmarking material removal rate, tool wear and surface topology in conventional and high efficiency pocket milling

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Abstract
Milling is still one of the most common, versatile and important machining methods in the manufacturing industry. Although CNC milling is well embedded within companies, digitalization allows for further optimization of cutting strategies that can decrease the machining cutting time, prolong tool life, and decrease energy consumption which will all reduce costs.
High efficiency milling (HEM) is a novel milling strategy where toolpaths are generated in a way the tool engagement angle does not exceed a certain value. Whereas conventional milling strategies do not take a maximal tool engagement angle into consideration. Thereby, the full length of the tool flank can be used during HEM, allowing higher removal rates.
This paper presents the performance comparison of HEM to traditional milling in terms of cutting time, tool wear and surface topology. Experiments with three different pocket sizes varying in width to length aspect ratios are conducted in 6063 aluminium and S275 steel. Cutting time are simulated for different radial tool engagements, suggesting that radial tool engagement increase is only meaningful up to a certain trade-off value of 10% to 12%, beyond this point the increase in material removal rate is neglectable and tool wear is expected to increase. Simulations as well as practical experiments show material removal rates for HEM twice as high compared to conventional milling. Significant differences in surface topology (surface waviness and roughness) are observed due to the specific material engagement and disengagement of the tool during HEM. Which could influence the strategy for following finishing operations, e.g.: sand blasting, grinding or polishing. Furthermore, tool wear is also significantly lower for the used HEM strategy. The combination of higher material removal rate and less tool wear during HEM are a double win (especially for companies), since cutting time decrease and less tools are worn per part.
Surface profile and dimensional accuracies of the workpiece, and tool wear were used as a measure of performance of the HEM and traditional milling strategies. The research identifies certain machining scenarios in which HEM is more advantageous over traditional milling.

Keywords: Tool wear, Surface finish, Surface profile, High efficiency milling

1. Introduction

CNC milling is a well-known method, used by many companies in the industry, for manufacturing metal and plastic parts in a flexible and cost efficient manner. It uses a rotating tool to cut away excess material from a rough shape, to create the intended part. The tool motion is typically controlled by a 3- to 5-axis motion system, and toolpaths are programmed beforehand by a Computer Aided Manufacturing (CAM) software.

Digitalisation and advancements in Computer Aided Design (CAD) and CAM have made this technology accessible to companies and even individuals. Although CNC milling has been available for over four decades. Nowadays, there are still many innovations which offer an increase in productivity.

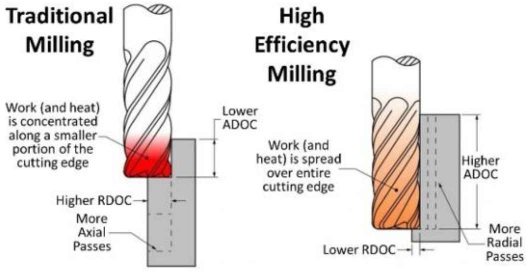


Figure 1. Traditional Milling vs. High Efficiency Milling [3]

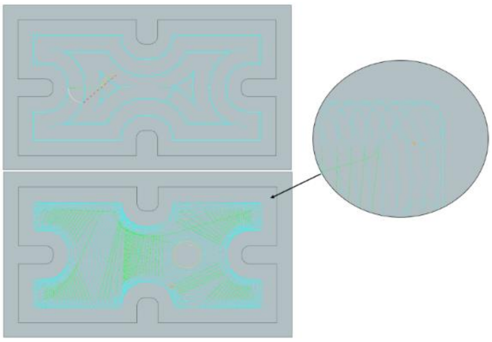


Figure 2. Top view of conventional (top) vs. HEM (bottom) milling

Though already adopted by some companies, few quantitative studies about HEM have been conducted, meaning limited knowledge concerning proper settings, CNC machine tool requirements, and scenario's in which HEM is preferred over more conventional strategies (potential drawbacks).

Liu et al. [1] performed a study investigating the influence of undeformed chip thickness on tool wear and chip morphology using dry trochoidal milling of titanium alloy Ti–6Al–4V. To improve machining efficiency and extend tool life, optimized cutting parameters with regard to radial depth of cut were developed. The results suggest that trochoidal milling can be superior compared to traditional strategies. This was concluded due to higher material removal rates (MRR) and longer tool life.

Uhlmann et al. [2] performed a comparative study between traditional and trochoidal milling strategies in terms of energy consumption and process time. The results of trochoidal milling demonstrated a 6% increase of average effective power consumption of the tool. However, the total amount of required energy decreased by 15% and process times by 35%. Uhlmann et al. concluded their paper with the fact that trochoidal milling still allows some margin regarding cutting parameters, while conventional milling is working at its tool load limit.

A study by Vavruska et al. [4] focuses on the contact point between the tool and workpiece to ensure optimal milling conditions. In case of conventional milling the angular velocity leads to changes in feed per tooth causing tool overload when machining inner arcs of the toolpath. Vavruska et al. avoids this by maintaining a constant feed per tooth.

These previous studies are certainly valuable in giving insights regarding cutting time, tool wear and even energy consumption. The machined volume is kept in a simple form, cutting away a certain rectangular shape to relatively simple slots. However, these volumes do not represent the shapes companies are creating and therefore the effect of the milled volume is not considered. In contrast to these studies, the goal of this research is to examine the effect of the shape of the milled volume, specifically for pockets.

2. Experiment setup

2.1. Workpiece

To include the effect of the shape of the milled volume, a test piece with three different pockets is designed. Exact pocket dimensions can be found in Table 1. Figure 3 shows a render of this design. In XY-plane, the aspect ratio of the pockets is varied, but depth and milled volume is kept constant for all pockets.

Table 1. Workpiece parameters

Pocket	Length /mm	Width /mm	Depth /mm	Volume /mm³
A	50..00	50.00	20.00	2500.00
B	75..00	33.33	20.00	2500.00
C	125..00	20.00	20.00	2500.00

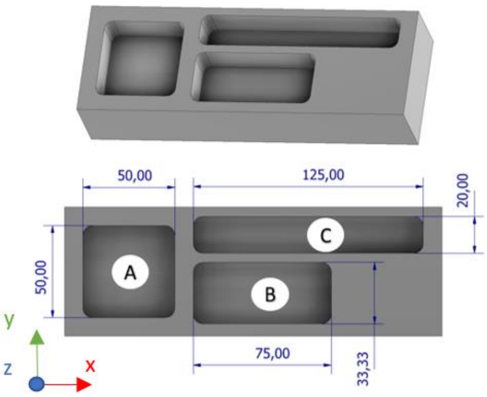


Figure 3. Workpiece dimensions

Two types of material, S275 steel and Al6061, are used as the workpieces. A survey conducted by machining companies in Flanders prior to this project revealed that the two aforementioned materials are the most commonly utilized. Tool wear tests are performed in S275 steel. For each test, a new unused tool is provided. As a comparison, each pocket is milled using a HEM- and a conventional strategy. This way, HEM results can be benchmarked to conventional milling. Furthermore, two more test pieces are milled in Al6061 to compare the surface topology of the HEM and conventional milled pockets.

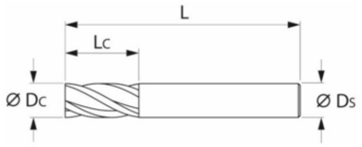
2.2. Apparatus and tool

For the milling experiment, the same CNC machine tool, a Mazak Variaxis J600/5X, is used. This machine tool has travel range in X-, Y- and Z- of 850 of 550 by 510 mm. Table 2 explains the technical data of the machine tool.

Table 2. Technical data of machine tool

	Parameters	Value
Capacity	Max workpiece diameter	730 mm
	Max workpiece height	460 mm
Spindle	Max speed	12 000 RPM
	Motor output	16 hp / 11 kW
Travels	X axis	850 mm
	Y axis	550 mm
	Z axis	510 mm

Tool wear is optically measured with a Hirox VH5000 microscope. Roughness measurements are executed on a Mitutoyo, SV-3000 CNC. The tool used during milling is an uncoated High Speed Steel endmill diameter 10 mm from Hoffmann Group (Figure 4). To facilitate the determination of tool wear, HSS was selected over carbide or coated tools.



Tool material	HSS Co 8
Coating	Uncoated
Standard	DIN 844 B
No. of teeth (Z)	3
Total length (L)	72 mm
Flute length (Lc)	22 mm
Cutting (Dc)	10 mm
Helix angle	42°

Figure 4. Technical data of cutting tool

3. Programming the toolpaths

Figure 5 shows a top view of the calculated toolpaths for both conventional and HEM milling. The toolpaths are programmed using Siemens NX CAD/CAM software. This software package also provides simulated machining times. When looking at the top views of the toolpaths, it might suggest that it takes more time to perform HEM. However, the HEM toolpath is used to mill the pocket at full depth (10 mm), while in the conventional method, the height is divided into four steps (2,5 mm step height). The cutting parameters (Table 3) - spindle speed (n), feed (v_f), axial depth of cut (ADOC) and radial depth of cut (RDOC) - are determined after consulting the virtual library of the cutting tool's manufacturer.

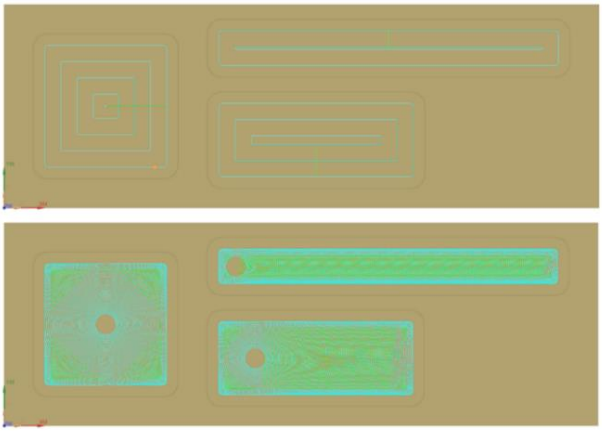


Figure 5. Toolpaths created in the commercial CAD/CAM software package (Siemens NX CAM). *Top*: traditional tool path strategy (Cavity mill). *Bottom*: HEM strategy (Adaptive Milling)

Table 3. Cutting parameters

	Steel (S275)		Aluminium (6061)	
	Traditional	**HEM**	**Traditional**	**HEM**
Spindle speed /rpm	891	891	4770	4770
Feed rate /mm .min^{-1}	38	123	369	519
Feed per tooth /mm	0.014	0.046	0.026	0.036
ADOC /mm	2.5	20.0	2.5	20.0
RDOC /mm	7.5	1.2	7.5	1.2

As previously discussed, traditional milling toolpaths are often calculated as an offset to the contour to be milled. This method is efficient, but results in unstable cutting conditions. As seen in Figure 6, there is an observable increase in the tool engagement angle (TEA) as the tool enters a corner. This sudden increase in TEA will result in an instantaneous spike in the load on the tool.

HEM toolpaths, on the other hand, are calculated to keep the TEA constant. This is important for maintaining a consistent load on the tool. A constant TEA is achieved through the use of adaptive toolpaths and a smaller radial depth of cut, which reduces chip thickness. To maintain a constant TEA, the feed rate can be increased considerably.

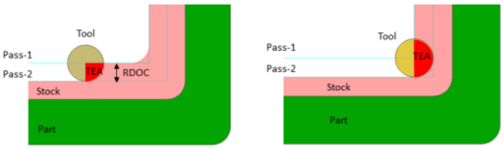


Figure 6. Increasing TEA in corners when using conventional milling

4. Results

4.1 Material Removal Rate

An initial parameter for benchmarking these two techniques is the execution times of various programs. However, this does not provide insight to the shape of the piece. Therefore, it is more efficient to consider the material removal volume. A more informative property is the material removal rate (MRR).

MRR is a widely used term in the field of manufacturing, referring to the volume of material that is removed from a workpiece per unit time [6]. It is a key performance indicator for many machining processes, and is typically used to evaluate the efficiency and productivity of a manufacturing process. [7]

MRR is usually defined mathematically as the product of the axial depth of cut (ADOC), radial depth of cut (RDOC) and feed rate (v_f). It is typically expressed in units of volume per time, such as cubic millimetres per minute [mm^3/min].

$$\mathrm{MRR} = \mathrm{ADOC} \cdot \mathrm{RDOC} \cdot v_f$$

MRR can be influenced by a number of factors, including cutting tool geometry, tool material, tool coating, type and condition of workpiece material, and cutting conditions such as spindle speed and feed rate [7]. The selection of the optimal machining parameters to achieve a desired MRR, is a key aspect of process planning and optimization in manufacturing.

When performing the described experiments in Section 2 and applying the toolpaths from Section 3, the MRR for both milling techniques and materials were calculated. As demonstrated in Figure 7, the MRR of HEM is found to be twice than that of traditional methods in Al6061. Furthermore, in case of S275, it is observed to be three times that of traditional milling methods.

The primary factor contributing to the increase in wear is the substantial enhancement in feed rate during HEM operations. This is a deliberate technique aimed at achieving consistency in chip thickness, as outlined in Section 4.

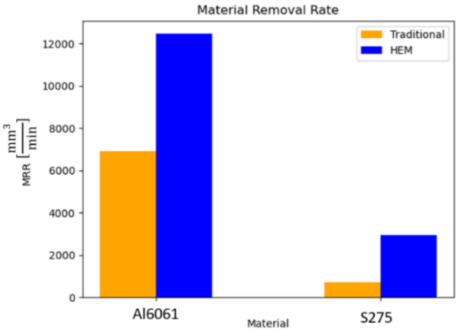


Figure 7. Material Removal Rate for Al6061 and S275

4.2 Tool wear

Endmill tool wear is a phenomenon that occurs during the machining process, characterized by the gradual degradation of the cutting edge and overall shape of the endmill tool [8]. It is caused by a combination of factors such as material removal, thermal stress, and mechanical stress [9]. Tool wear can lead to a decrease in tool performance, including an increase in cutting forces, as well as a reduction in MRR and surface finish [10].

There are several types of endmill tool wear, including flank wear, crater wear, and built-up edge (BUE). Flank wear occurs on the sides of the cutting edge and is caused by rubbing of workpiece material against tool [11]. Crater wear occurs on the tip of the cutting edge and is caused by impact of workpiece material against tool [12]. BUE is a build-up of workpiece material on the cutting edge, which can lead to a decrease in cutting performance [13].

During the microscopic observations conducted, the primary phenomenon observed was the formation of flank wear as illustrated in Figure 8. Notably, the width of the flank wear remained uniform throughout the entire axial depth of cut. The width of the wear was quantified by measuring it across three cutting edges and computing the average value.

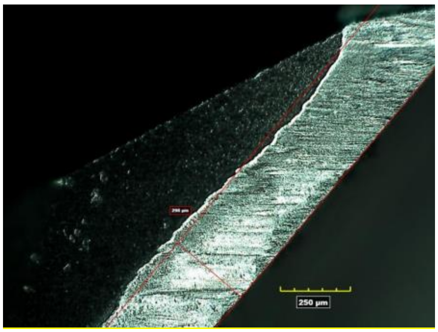


Figure 8. Flank wear measured for the traditional strategy

During the research, tool wear was microscopically investigated on the workpieces in S275 steel. The results of the average tool wear for each pocket can be found in Figure 9. It can be concluded that tool life can be extended when applying HEM.

Upon examination of the wear per pocket, a significant disparity in wear between traditional and HEM operations is observed to be most pronounced in pocket A. This phenomenon can be attributed to the distinct toolpaths utilized in traditional operations, as depicted in Figure 4. As evidenced in the figure, the tool in pocket A is subjected to three passes over each corner, in contrast to the two passes in pocket C, utilizing traditional methods. The repeated traversals of the tool over corners results in peak loads, leading to increased wear.

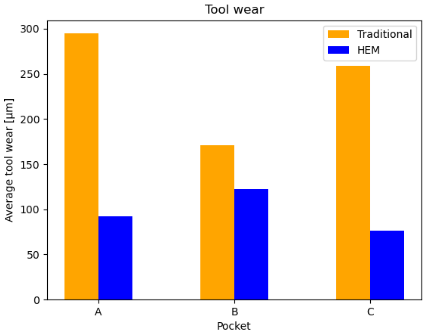


Figure 9. Comparison of the average tool wear per pocket using traditional milling and HEM in S275

4.3 Surface Topology

Surface topology refers to the geometrical shape, texture, and roughness of a surface. It is an important aspect of surface quality and is used to evaluate the performance of a machining process [14]. In the context of milling, surface topology is used to benchmark traditional milling against adaptive.

Traditional or conventional milling involves cutting material in a linear motion, with the tool cutting edge moving in a straight line. This method results in a rough surface finish with visible tool marks and a high level of surface roughness [15].

On the other hand, adaptive milling is a high-efficiency milling method that involves cutting material with a curved motion. The tool's cutting edge follows an adaptive path, which is a combination of circular and straight motions. This method results in a smoother surface finish with reduced tool marks and a low level of surface roughness [16].

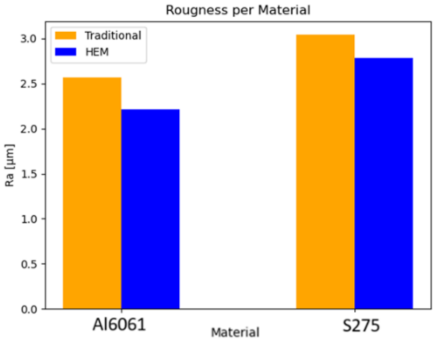


Figure 10. Comparison of the average roughness using traditional milling and HEM for both Al6061 and S275 steel

The surface roughness was quantified using a Mitutoyo Formtracer Avant FTA instrument, equipped with a probe radius of 2 µm and a corner angle of 60°. The measurements were specifically conducted on the pocket walls, from the bottom to the top along the Z axis (figure 3), since they exhibit the most discernible impact of the diverse machining strategies.

The results of the average roughness (Ra) per material group, as illustrated in Figure 10, indicate minimal deviation between traditional and HEM toolpaths. However, it is important to note that HEM utilizes shorter and more robust cutting movements, which may result in a less precise surface finish then predicted.

5. Conclusion

It can be concluded that the results of this study demonstrate that high efficiency milling (HEM) is a superior method for machining pockets in terms of cutting time and tool life. The material removal rate (MRR) for aluminium 6061 increased by 100%, and for steel S275 it was even up to 300%. Furthermore, HEM results in less wear on cutting tools, due to the distribution of heat input and forces over the entire cutting length of the cutter, and maintenance of a constant tool engagement angle (TEA), avoiding peak loads. This was particularly evident in pocket A due to the fact that multiple passes for traditional milling were required, resulting in increased tool wear. These advantages in terms of cutting time and tool life, make HEM a highly favourable option for machining pockets.

As future work, influence of clamping tools on vibrations caused by HEM and energy consumption per machined piece will be investigated to determine profitability of this method.

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