COMPARISON OF HIGH FEED MACHINING WITH CONVENTIONAL MILLING IN TERMS OF DIMENSION ACCURACY AND PRODUCTIVITY

Marcel Kuruc*, Marek Vozár, Vladimír Šimna, Tomáš Vopát, Róbert Hrušecký,
Ján Milde, Ivan Buranský, Martin Necpal & Jozef Peterka

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Abstract

Numerous industrial enterprises are forced to increase productivity if they want to stay competitive in the market. Therefore, there were performed many researches focused on possibilities of cost effective increasing the productivity. There were created advanced processes and new machining strategies, which could be improved by new cutting materials, advanced coatings and modified geometry. One of the cost effective methods to increase productivity is High Feed Machining (HFM). This method does not require high speed spindle (in contrast with High Speed Cutting – HSC). Moreover, it does not require any special devices or conditions. HFM can be performed on the modern machine tools. This article compares conventional milling and high feed machining of the reference steel materials – C45 by creating some basic shapes and features, such as horizontal and vertical surfaces, cylinders, grooves, etc. Results of the experiment could be applied to determine when HFM is advantageous and what advantages it brings about.

Keywords: high feed machining; dimension accuracy; productivity; reference steel; advanced machining

1. Introduction

High feed machining (HFM) is known as an effective roughing strategy with substantially higher material removal rate than conventional milling. With higher feed, the surface roughness is increasing as well [1]. This disadvantage is partially reduced by advanced tool geometry (Fig. 1). HFM in contrast with conventional milling is using much higher feeds (approx. 10 times higher). However, it can cause a significant increase in cutting force [2]. Therefore, in HFM, decreased depth of cut (DOC) is used along with the decreased lead angle of the milling cutter. This influences the section of the cut layer resulting in a change of direction of cutting force in a positive way, so that the cutting force is directed towards the spindle, decreasing machine load and reducing vibrations during the machining process. It also changes how the chip is formed during the milling process, causing a lower chip width than the feed per tooth.

This mechanism is called chip thinning [3, 4]. To achieve recommended feed per tooth, high enough feed rate is necessary. However, most of the modern machine tools offer the highest value of feed rate that equals to rapid traverse rate, which should be sufficient for most applications. Milling cutters for HFM are manufactured in different dimensions and forms, such as solid end mills or inserts (Fig. 2) [5, 8, 9].

The geometry of the cutting part of HFM tools is different from the tools used for conventional machining, and this could cause different accuracy of dimensions when machining features and surfaces of the workpiece. An assessment of how the high feed machining impacts the accuracy of the machined part when compared with the conventional machining method, and which method of machining is more accurate should be made. The possibility of using HFM not only for roughing but also for finishing operations in certain cases could increase the productivity of this method even more [6].

APMXS	Depth of cut maximum in feed direction side
DC	Cutting diameter
DCX	Maximum cutting diameter
RE	Radius
RP	Programmed radius
UTCN	Uncut thickness

Fig. 1. Geometry of high feed end mill [7]

Fig. 2. Cutting tools for high feed machining [8, 9]

The main advantage of HFM is productivity. It is achieved by a higher increase of feed than a decrease of depth of cut. Lower depth of cut also causes more uniform material additament, therefore semi-finishing is usually not needed, which decreases production time even more. However, rapid feed rate requires fast enough control system, otherwise, it will need to pause to read some lines of NC program in advance [10, 11, 12, 13]. The purpose of the experiment is to determine if finishing is always necessary after HFM.

2. Machining method

A machine tool for high-speed cutting (HSC) was applied in this experiment. This machine tool has a high-speed spindle (up to 42,000 rpm). During HSC most of the generated heat is drained by the chips. It causes reduction of workpiece material strength in the cutting zone. It also leads to a decrease of cutting force and allows to machine even quenched steel. Due to an increase of precision there was applied linear drives, which allows using feed rate (and rapid traverse) up to 40 m/min. This feed rate can be applied in high feed machining (HFM). Combination of high-speed cutting and high feed machining is often labelled as high-speed machining (HSM).

In this experiment, high-speed milling machine DMG Mori HSC 105 linear (Fig. 3) was used. This machine tool can operate continuously in five axes and it can operate as a conventional milling machine, high-speed cutting machine, and high feed milling machine. Therefore, it suits this, as well as further possible experiments [14].

Fig. 3. High speed machine tool DMG Mori HSC 105 linear [14]

As a cutting tool, milling cutter for general purpose JS 553 and high feed milling cutter JHF 980 were used (Fig. 4). Both tools were manufactured by Seco Tools Company. For both tools, cutting diameter is 10 mm and both contain 3 flutes. Their dimensions and other parameters are recorded in Tab. 1. Materials intended to be machined by these tools are shown in Tab. 2. A 3D model of the workpiece was created in CAD software Autodesk PowerShape Ultimate 2018 and then imported into CAM software Autodesk PowerMill Ultimate 2018 where two machining simulations using different strategies for conventional and HFM machining were run. After verification of the tool path, NC program for control system Heidenhain iTNC 530 was generated in this software as well. As a workpiece material, reference steel C45 (class of machinability – P4) was used.

Fig. 4. Milling cutters JS 553 (left) and JHF 980 (right) from Seco Tools

Milling cutter	Diameter [mm]	Number of teeth [-]	Maximum DOC [mm]	Overall length [mm]
JS 553	10	3	35	85
JHF 980	10	3	0.5	80

Table 1. Main dimensions of milling cutters [15]

	Produkt	Označeni	P1-8	P11	M1-3	M4-5	K1-7	N1	N2-3	N11	S1-3	S11-13	H3-31	TS1	TS2-3	TS4	TP1	TP2-3	TP4	Honeycomb	GR
JS ²	JS553	•	•	•	•	•	•	•	•	•	•	•	•			•				○
HFM	JHF980	•	•	•	•	•				•	•	○								

Table 2. Cutting tool applications according workpiece material [15]

3. Description of the experiment

Steel reference material C45 with dimensions 100x100x50 mm (two pieces) was used as a workpiece. It is medium carbon steel with tensile strength 700 MPa, yield strength 400 MPa, hardness 250 HB and fracture elongation 16% [15]. Its chemical composition is shown in Tab. 3. The workpiece was first machined by conventional milling and then high feed machining. Several different features meant to be used for high feed machining were designed on the workpiece, as shown in Fig. 5.

element	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
wt. %	0.46	0.4	0.65	0.045	0.045	0.2	0.03	0.4	bal.

Table 3. Chemical composition of C45 steel material [16]

Fig. 5. Model of component with obvious features

For each machining method (CM & HFM) different machining parameters were set – recommended conditions by tool manufacturer for the specific machining method. Therefore, there is a comparison of conventional milling (CM) with proper tool for CM and proper machining parameters for CM with high feed machining (HFM) with proper tool for HFM and proper machining parameters for HFM. Using a tool for HFM with machining condition for CM or with machining condition for HFM with just a fragment of recommended feed could not be considered as an equitable representant of conventional machining. Actual machining parameters used in the experiment are recorded in Tab. 4.

Milling method	Cutting speed [m.min ⁻¹]	Spindle speed [rpm]	Feed rate [mm.min ⁻¹]	Feed per tooth [mm]	Infeed [mm]	Depth of cut [mm]
CM	130	4138	870	0.07	10	1
HFM	250	7958	7162	0.3	5	0.25

Table 4. Machining parameters used in experiment [15]

Machining parameters and conditions, which are not labelled in Tab. 4, were constant, such as blast air as a coolant, and 0.5 mm additional material for finishing. However, vertical faces were not finished by HFM, because the design of the tool does not allow high enough depth of cut. These faces were only roughed without additional material for finishing in the radial direction [5]. During machining of the chamfer and upper fillet on the workpiece, an additional controlled axis was used.

After machining, machining time and dimensional accuracy were compared. Machining time was measured by a standard stopwatch. Dimensional accuracy was measured by coordinate measuring machine Zeiss Prismo Ultra using software Calypso. Because the probe is measuring only in specified points, this measuring was extended by measuring on optical 3D scanner GOM ATOS II TripleScan using software GOM Inspect. These devices are shown in Fig. 6.

Fig. 6. Coordinate measuring machine and optical 3D scanner used for measuring dimensional accuracy

Zeiss Prismo Ultra works in an air-conditioned room and utilizes different measuring probes. In the experiment probe with a ruby ball with diameter 3 mm was used. The accuracy of the device is affected by the measured dimension, but in this case, it was lesser than 0.7 μm [17]. Paths for measuring were generated by Calypso software automatically from the CAD model, therefore it could easily measure thousands of points. However, the touch probe cannot be used in corners (due to the natural radius of the tip).

GOM ATOS II TripleScan does not need an air-conditioned room. It utilizes a projector of light strips and two CCD cameras for digitalization of the object. This method can digitalize corners; however, it could have a problem with deep holes. During scanning, it captures millions of points, which are connected by polygonization into a 3D CAD model, which could be easily compared with the original CAD model used for machining. The precision of this device is 0.02 mm [18].

4. Results of the experiment

Two experimental samples were made. One sample was machined by conventional milling (CM) and the second one was machined by high feed machining (HFM) at above-mentioned machining condition. There were measured several dimensions, radii and angles. Due to the high amount of results, there are recorded only some of them. Results are recorded in Tab. 5. In order to avoid misunderstanding of labelling the dimensions, there was added a figure of measured dimension.

In the last row chamfer with dimensions $15 \times 45^\circ$ was evaluated, however, only the value of angle was measured. Measurement labelled in the table was provided only by the coordinate measuring machine (CMM).

Dimension	Value [mm]	Method	Measured value [mm]	Deviation [mm]
30	CM	30.0228	+0.0228
		HFM	30.0199	+0.0199
60	CM	60.0252	+0.0252
		HFM	60.1163	+0.1163
25	CM	25.0194	+0.0194
		HFM	24.9510	-0.0490
25	CM	25.0150	+0.0150
		HFM	24.9906	-0.0094
15	CM	15.0183	+0.0183
		HFM	15.0027	+0.0027
45°	CM	45.0051°	+0.0051°
		HFM	45.0045°	+0.0045°

Table 5. Selected results of the measurement

According to results recorded in Tab. 5 there can be seen that the worse results for HFM were obtained at measuring dimensions between pockets. It could be caused by machining without finishing – during roughing these faces were machined without leaving radial additional material for finishing (due to milling tool geometry).

Despite the similarity of left and right pocket, different results were obtained for each. At left pocket, the deviation caused by HFM is over twice as high as for the conventional machining. However, for the right pocket, the deviation caused by HFM was almost half of that in conventional milling. Deviation in conventional machining was in both cases similar; however, deviation in HFM was for left pocket five times higher than for right pocket. This could mean that HFM could provide better results than conventional milling, however, conventional milling can provide more stable and repeatable results.

The best results were obtained on the inner radius, paradoxically by HFM. There was a measured deviation of only $2.7\ \mu\text{m}$, which is value similar to the surface roughness. In this case, conventional machining achieved over six times higher deviation. However, according to the results of the pockets, there could be an issue with repeatability, despite the fact that measurement was repeated and utilized several hundreds of measuring points.

Sloped surface of the chamfer achieved good results in both methods. HFM achieved a little bit better results, which could be caused by more uniform additional material for finishing due to the lower depth of cut. Such uniform material could secure a more stable load of milling cutter and therefore lower vibration during the machining process.

Because the touch probe cannot be used in the inner corners and due to the evaluation of the whole surface instead of selected points, measurement on the optical 3D scanner was carried out as well. The results of digitalization and its evaluation can be seen in Fig. 7. There can be seen that HFM left material in inner corners, which is caused by the design of the tool. It is one of the reasons why is HFM used mostly for roughing only.

Fig. 7. Colour map of deviations of the samples machined by conventional milling (left) and HFM (right)

The main advantage of HFM should be a reduction of machining time. Real machining time for conventional milling and HFM is recorded in Tab. 6. Using of HFM substitute semi-finishing as well, but in the experiment, it was not used, not even for conventional machining. Both methods could be divided into roughing and finishing. However, for both methods, its own preferred machining strategies were used. Several different roughing strategies, as well as several finishing strategies, were used for each method according to machined features. They are summarized in Tab. 6. Term “Roughing” include all used roughing strategies for the specific method, as well as “Finishing” include all used finishing strategies for the specific method. Term “Machining time” is calculated as a time of all roughing and finishing strategies for the specific machining method.

Method	Roughing [h:min:s]	Finishing [h:min:s]	Machining time [h:min:s]
CM	1:14:00	0:16:20	1:30:20
HFM	1:01:55	0:03:45	1:05:40

Table 6. Machining time of conventional milling and HFM

As can be seen in Tab. 6, HFM provides time reduction in both roughing and finishing. Machining time of conventional machining is higher approximately by 50 %. Conventional machining had an advantage in double infeed and quadruple depth of cut, while HFM had an advantage in over four times higher feed per tooth. However, HFM works at higher cutting speed and therefore the resultant feed rate was over eight times higher.

It could achieve similar material removal rate, but conditions of HFM allow the use of certain machining strategies, which are not preferable for conventional milling. However, in terms of roughing, usually much bigger milling cutters with inserts are used for HFM which provide even higher time reduction. Due to the specific design of solid end mills for HFM, using of infeed with a value of half of the diameter is necessary. If there were compared tools according to the same infeed instead of the same shrink diameter, results of HFM (especially in terms of time reduction) could be even better.

5. Conclusion

The obtained results allow us to confirm that high feed machining (HFM) can achieve considerable machining time reduction and therefore it is suitable for roughing. The specific design of cutting tools for HFM allows to use higher feeds per tooth, as well as higher cutting speeds; however, this design prevents the use of higher depths of cut and infeed. The advanced design of the tool provides low surface roughness of machined workpiece; therefore, its value is comparable with surface roughness after conventional milling (despite a high difference in feed). After roughing, there can be seen that workpiece produced by HFM does not require additional semi-finishing. On the other hand, obvious steps remain on the workpiece after conventional milling. In some cases, there would be necessary to use additional semi-finishing.

Obtained dimensional measurements show that conventional milling achieves better accuracy in most of the cases (there were presented only selected results of measurement); however, the difference in precision between HFM and conventional machining is low and, in some cases, HFM achieved even better results than conventional machining. Therefore, HFM could be successfully applied even for finishing (due to achieving additional machining time reduction), especially in cases, where standard accuracy is sufficient. However, after machining with HFM there remains a small amount of material in inner corners, therefore it is more suitable for finishing flat surfaces.

Results of effects of the specific tool design could be applied in cutting-edge preparation. Further research will be focused on the influence of high-speed cutting (HSC) on the machining process and its comparison with conventional milling and HFM in their preferable machining condition; as well as determination of cutting edge difference between those tools for enhancement of the cutting edge preparation in order to compare both machining strategies from the standpoint of the tool wear.

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