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TOOL WEAR INVESTIGATIONS BY DIRECT AND INDIRECT METHODS IN END MILLING

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Abstract: *Milling is a versatile manufacturing technology. Depending on the situation, coating on the cutting tool can have significant influence to quality and cost of the process.*
In this study an attempt is made to develop methodology for relatively simple but effective means for evaluating the quality and suitability of a coating for a particular milling operation. Flank wear width is generally recognized as the key indicator for tool life criteria. In practice several other indication of worn tool are used: shape and colour of the chip, quality of the manufactured surface etc. Measurements by optical measurements are analysed. Cutting forces are measured in comparison. Three coatings were tested.
Key words: tool wear, tool life, flank wear, PVD coatings, end milling.

1. INTRODUCTION

Gradual search and evolution towards more cost effective solutions is a natural way to progress in the manufacturing industry. The question of a production cost is affected by many variables. Volumetric chip removal rate is common parameter for describing and quantifying productivity in the cutting industry [1]. Formally it stands for the product of the cutting speed with the area of engagement between tool and workpiece. Referring to metal machining operations, the cost of cutting tool exchange can be of considerable interest to the manufacturer. Variety of tools available to the machinist today is wide and expanding continuously. Often it is matter of personal preferences and previous experience that lead in the decision making process, while choosing between tools for different operations in either milling or turning. Already several production technology laboratories are offering commercial services for conducting machinability tests for machining companies. General recommendations for specific milling, turning operations for several workpiece material classes are available from handbooks and in the information from the tool manufacturers. Due to the specific nature of the cutting operation generalisations are difficult to do and extrapolation and interpolation tend not to give reliable results [2]. Meaning that different tool-operation-material combinations lead to different conditions at hand.
Current research project aims to bridge the gap between academic laboratory research and practical questions originating from machining industry. In particular an experimental method for tool life estimations in end milling operation is suggested, tested and discussed. Flank wear together with cutting forces are determined and reasoned. It is a straightforward approach designed from the perspective of simplicity and usefulness for practical machining situations.
From the previous works published on the subject following information is of a concern in the contest of the current project. Rihova et al [3] have studied the wear of turning inserts from the perspective of implementing changes in the composition of the workpiece material. While Kennedy&Hashimi [4] have proposed methods for testing coatings

under controlled conditions other than those of direct machining. Relatively similar approach as presented here was taken by Narashimha et al [5]. Where a set of turning inserts with different coatings were tested during finish turning of AISI 1018 steel under dry conditions. Their goal was to prove the positive effect of a hard coating on a tool life extent. Bouzakis et al [6] have shown that wear resistance of a coating can be related to the results of a dedicated impact test performed on a coating. Recently there have been reports on attempts for using flank wear measurements for on-line monitoring of the cutting conditions [7].

1.1. Cutting tool wear

Tool wear is an intrinsic phenomenon related to the principle of cutting operation. When referring to metal cutting, the conditions in the cutting zone are severe. Contact stresses present are those in the range of tensile strength of the workpiece material. Temperature values near the cutting wedge can rise up to around 1000 ºC. These thermo-mechanical circumstances result in the wear of the cutting tool.

Tool life definition is not an absolute term, instead users are given flexibility in setting the limits depending on the particular circumstances. Narashimha et al [5] have provided with an effective explanation stating that tool should be considered to be worn when the replacement costs are is less than the cost for not changing the tool.

Commonly recognized types of cutting tool deteriorations are wear, chipping, plastic deformation and diffusion. In principle another division can be made into two groups, where in the first wear and diffusion related types are considered to be of gradual increase in time. The second group consisting of chipping and microcracking is more abrupt and difficult to predict. Rough description of types of wear and their classification is summarized in figure 1.

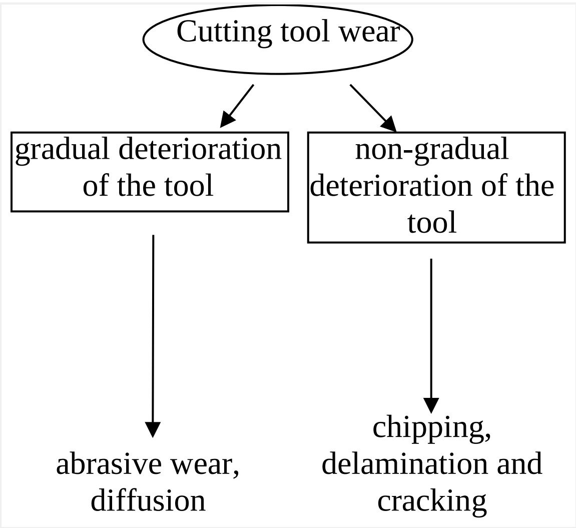

Fig. 1. Simplified overall chart of tool wear types.

When focusing on the practical side of tool life estimations, essentially two main approaches can be distinguished.

1) Establishing tool life criteria based on the value of the flank or clearance face of the cutter. This method is also used by current standards ISO 8688 Tool life testing in milling [8] and ISO 3685 Tool-life testing with single-point turning tools [9]. One of the most considerable effects due to flank wear is the decrease of the diameter of the mill. This can lead to dimensional inaccuracies and out-of shape geometrical tolerances of the workpiece.

2) Recent research results promote the wider usage of rake face wear. It has been argued that the later has pronounced influence on the fatal breakdown of the tool. Increase in the cutting force values is commonly related to the crater wear scar developments on the rake face of the cutter.

Two mentioned wear types and additionally the change of cutting edge radius could end up in the premature and unexpected fracture of the tool bit.

2. EXPERIMENTS

2.1 Tested end mills Machining operation

Milling, more specifically contouring with end mills was chosen as the machining operation to be investigated. End milling is a common material removal process. It is universal and wide spread, thus potential ways of cost reduction are of interests to manufactures and toolmakers.

Information about the end mills used in the current study is presented in Table 1. All three tested cutters were identical in geometry having a diameter of 8 mm and flute angle of 35°/38°. Commercial monolayer (Ti1-xAlx)N, nanocomposite (nc-Ti1-xAlxN)/(a-Si3N4) (nACo®) and (nc-Cr1-xAlxN)/(a-Si3N4) (nACro®) coatings were deposited in the arc plating PVD-unit PLATIT-π80. Deposition temperature was 450 °C. Coating thickness was measured using the kalotest method with a kaloMAX® tester and is shown in table 1. Hard coating and its influence to the tool life was the primary subject of study.

Coating:	Coating thickness	Adhesion
nACo	1.4 µm	HF 3
TiAlN	1.71 µm	HF 3
nACro	20.1 µm	HF 3

Table 1. Properties of coatings deposited on the tested end mills

2.2 Cutting conditions

Milling experiment was designed to ensure and retain constant cutting conditions throughout testing. HAAS SMM-HE vertical CNC machining center was used.

High-speed machining concept was adapted to current specific test run. Cutting parameters used in milling tests are given in table 2.

Tested tools were periodically checked for tool wear by flank wear measuring after cutting two layers of material. The volume of the material removed by cutting one layer was 113,5 cm^3, the tool wear was recorded periodically after cutting of 227 cm^3 of material, which corresponds to 36 m of cutting length. For the estimation of the tool wear an optical ZEISS Discovery V12 stereomicroscope with software ZEN was utilized. Every end mill was tested for 252 m of cutting length (1589 cm^3 of removed material).

Cutting speed v_C, m/min:	238
Width of cut, a_E , mm	1.6
Depth of cut, a_P , mm	4
Feed per tooth, mm/Z	0.08
Material removal rate, cm^3/min	19.2
Coolant	dry air

Table 2. Cutting parameters for testing end mills testing.

2.3 Workpiece material

HYDAX 25 was chosen as test material due to its widespread usage and relatively good machinability characteristics. Testing was conducted using material in as-received state, hot-rolled bars with rectangular cross section of 105 mm in side length, test billets were cut into pieces of 300 mm in length. The nominal chemical composition and values of mechanical properties are given in table 3

Cast analyses		Tensile test	
Element	wt. %	Measure	Value
C	0.21	Rp0.2	340 MPa
Si	0.20	Rm	552 MPa
Mn	1.04	A5	26.4 %
P	0.012	Z	56 %
S	0.106	HBW	144.7

Table 3. Workpiece material characteristics

2.4 Cutting force measurements

Difference of cutting forces for a new, unused end mill and worn end mills used in experiment was measured. Cutting force measurement system included KISTLER piezoelectric dynamometer 9257B, charge amplifier 5070 and Dynoware 2825A software. Workpiece of Hydax 25 was bolted directly onto the dynamometer, force values for three orthogonal directions were measured. System setup is pictured in figure 2. The dynamometer was aligned and clamped onto the table of the machining centre in a way the dynamometer force measurement axes direction is parallel to the axes of the milling centre. Cutting forces were measured during the direct motion of the end mill along the X axis of the machining centre toward negative direction of the machining centre's X axis direction (from right to left as seen from machining centre's operator standpoint).

In the contexts of the study the absolute values of the cutting forces were not of primary interest. Instead, the difference of cutting forces between tested end mills was of utmost importance.

Fig 2. Setup for cutting force measurements: A) machine tool spindle with tested end mill; B) workpiece; C) dynamometer and D) table of machining centre.

3. RESULTS

From the optical and scanning electron microscopy (SEM) inspections visual proof of differences in wear resistance of compared coated end mills were found. The results of the flank wear mark size for each worn tool with different coatings is summarized in figure 3.

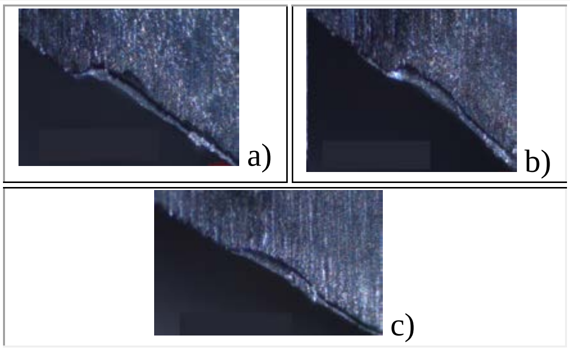

Fig. 3. Flank wear scars determined from end mills with three different coatings. a) naCo, b) TiAlN and c) nACro.

To minimize potential random errors, flank wear measurements were constantly made at the vicinity of the primary groove i.e. the theoretical line on the clearance face that is equal in height with the depth of cut. Numerical values at the end of the cutting tests i.e. after cutting 252 m are summarized in table 4.

Coating type:	Flank wear width, mm
nACo	0.120
TiAlN	0.087
nACro	0.067

Table 4. Flank wear values.

Milling as an interrupted cutting process with constantly changing theoretical chip thickness generates fluctuating cutting forces. The cutters teeth passing frequency into and out of the cut in milling depends on the rotating speed and number of teeth of the cutter, being about 633 Hz in tests carried out during this work. Nevertheless, the detailed cutting force fluctuations can still be measured by help of high sensitivity and measuring frequency piezoelectric dynamometers. An example of measured cutting forces for worn end mill with naCo coating is shown in figure 4.

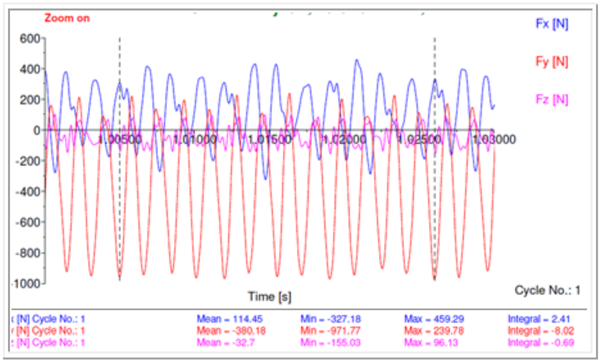

Fig.4. Cutting forces (N) for worn nACo end mill, measuring frequency 30000 Hz.

Cutting force components shown on figure 4 are directed as follows:

- F_x is directed along the feed direction of end mill (along X axis of machining centre). Positive value of F_x shows that end mill is climb milling, i.e. trying to pull the material toward itself in X axis direction.
- F_y is directed perpendicular to feed direction (along the Y axis of machining centre). Negative value of F_y means that end mill is pushing the material away of itself in Y axis direction.
- F_z is directed along the end mill rotational axis (along the Z axis of machining centre). Negative value of F_z means that end mill is pushing the material up from the table (toward itself).

Although detailed plots of milling forces can be acquired as one shown on figure 4, it is not yet sure how adequate the obtained results are. The properties of the measurement system, inertia of the workpiece etc. are likely to influence the outcome. Therefore the aim of this work was not to investigate the fluctuation of the cutting forces in detail but rather to compare the mean values of measured forces. As several tests conducted on various frequencies revealed, the mean values of cutting forces can be acquired even on low frequencies (below tooth passing frequency) without remarkable differences in calculated mean values. For comparing the mean values of cutting forces the measurements were conducted at frequency of 200 Hz. For graph plotting the results were smoothed by Dynoware computer software, the mean values of cutting forces were also calculated by Dynoware. Graphs of mean cutting forces for worn end mills after cutting the toolpath of 252 m length and for a new end mill can are presented in figure 5. Measured force values indicate that tool wear in used, specific cutting conditions leads to remarkable growth of cutting force component F_y, forcing the tool to bend away from cut surface, therefore being partly responsible in change of part dimensions. The mean values for all measured cutting force components are presented in table 5. As with the visual inspections naCo had the highest amount of wear, naCro and TiAlN coated tools were performing better in that sense with a slight advance to naCro.

	F_x	F_y	F_z
Unused tool	103.1	-138.1	-43.3
TiAlN	105.7	-277.5	-46.0
nACro	103.7	-242.1	-46.0
naCo	115.6	-365.3	-35.7

Table 5. Mean values of measured force components, N.

4. CONCLUSION

In this paper, the wear behaviour of 8 mm diameter end mills during dry machining of the HYDAX 25 construction steel was investigated. Based on the results found the following conclusions can be drawn. Two methods of tool wear estimations give consistent results. As both of them indicate the preferable coating solution at particular situation. Nevertheless it is important to stress that method discussed here should be considered as a rough reference for a specific industrial machining application. In the future work sample size needs to be raised for raising the confidence level of the results. For practical importance the tool life end condition needs to be defined by some reasoned way.

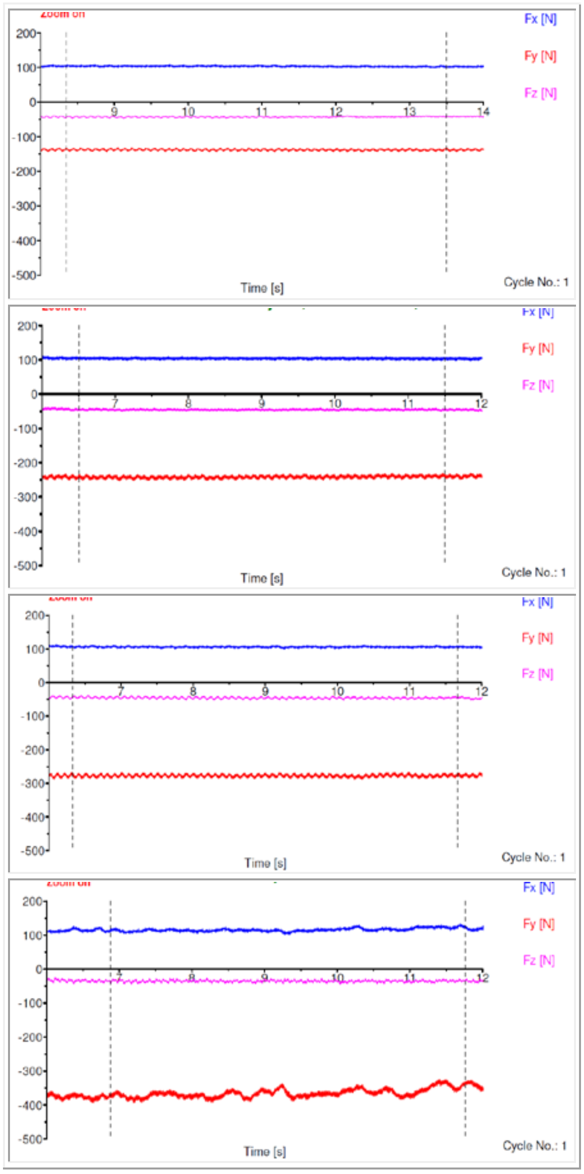

Figure 5. Smoothed graphs of measured cutting force components, from top: a) new end mill; b) worn naCro coated endmill; c) worn TiAlN coated end mill; d) worn naCo coated endmill.

5. ACKNOWLEDGEMENTS

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