Wear and Tool Life Investigation of Carbide Inserts while Hard Machining of Armox 500 Steel

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Presented article deals about the experimental investigation of PVD coated cutting inserts of type SNHF 120408EN-SR-M1while hard face milling of steel Armox 500. This study was supported by the Slovak Research and Development Agency under the contract No. APVV-15-0710". All realized measurements and tests have been performed at Department of Engineering in Trencin. It also includes support and cooperation with the University of Defence in Brno, Department of mechanical engineering. The main aim of this experimental work is to focus measurement on the influence of the various values of feed rates per tooth during the hard machining experiments of steel Armox 500. All tested workpiece material is investigated with variable cutting conditions of feed rate per tooth, whereas the cutting speed and depth of cut were specified as the constant cutting parameters. Practical part of presented work also includes some figures of worn flank faces of carbide cutting inserts, microstructure of workpiece material and graphical dependences of tool wear and tool life curve in logarithm graph as the results of these realized experimental investigation.

Keywords: Hard face milling, Tool life, Wear, steel Armox 500, Mechanical properties

1 Introduction

Rough face milling technology of hard materials has become a great contribution for for the recent years. Especially hard finish milling can potentially be an alternative to planar grinding technology with the possibility to improve productivity, flexibility, wokpiece quality, capital expenses, and reduced environmental waste [11].

Planar grinding can be divided into the cutting processes which are always the final finishing operations of hardened steels. Some of the hard machining processes have been considered as the great alternative to traditional grinding operations. It is possible to say that hard machining process can reach the same surface quality as planar grinding while required cutting conditions, cutting temperature are defined [6].

Nowadays the hard machining presents a significant alternative instead of grinding for hard steels, because it can improves surface quality, reduces production costs, improves production efficiency and eliminates the environmental influenece of coolant. The main factors which can affect the reliability of hard machining processes are surface integrity and tool wear [2].

One of the existing problems in this hard machining process is early tool wear, and its influence on the machinability of hard steels. After the heat treatment application the final shape of workpiece has to be machined. Apart from abrasive technological processes, the face milling with geometrically defined cutting edges is established to machine hardened steel components as a substitution technology.

The benefits of hard machining with defined cutting edge compared to grinding technology are high level of material removal rates and reduced machining times. But aleready exists also the disadvantages of hard machining such as increased tool wear compared to machining materials in none hardened state [5].

The reason for that is the fact, that hardened steels are exposed to high loads, the surface quality and surface integrity already must present required characteristics. For that reason, the tool wear has a significant effect on the surface integrity. Face milling process of hardened steels has a important role for mould and die manufacturing sphere due to the high strength of machined material. One of the existing main disadvantages is the tool wear, which is a result of the high thermo-mechanical stress on the cutting tool. The flank wear rate can generally be impacted by the cutting edge geometry and surface coatings. This article investigates hard face milling of Armox 500 steel with milling cutter with regard to the flank wear.

Tool life is also an important factorr in investigating the cutting performance of coated carbide inserts. Flank wear significantly affects the shape of edge geometry of the cutting inserts and it is also one of the most important criteria in determining tool life [3].

When the cutting insert reaches tool wear criterion then the cutting edge fails and cannot be used further. Many machining investigations have been realized on hardened steel (with HRC = 48 and more) due to analyse the influence of flank wear onto tool life of the PVD coated carbide cutting tools. Current investigation aims to improve the tool life in hard face milling. In addition to the selection of the cutting insert and the machining conditions, can be said tehat the geometric shape of the cutting edge influences the behavior of the flank wear [6].

Generally the tool wear is a gradual process and wear rate depends on cutting tool and workpiece materials, tool geometr, coolant, process parameters and also machine-tool characteristics. Mainly flank wear in hard machining affects the tool life and it is one of the most important criterion in determining tool life. In addition to progressive tool wear, until gradual tool fracture or excessive chipping and surface roughness also significantly affect tool life. The tool wear criteria for face milling operations depends on the following values which are considered from ISO Standard 3685 for tool life testing [8, 11].

2 Materials and methods

From the point of view of the economy of machining, it is advantageous to machine with the cutting tool until its disastrous wear. The wear time of the cutting tool for selected wear criteria under particular cutting conditions is called the tool life T [min]. If the influence of the cutting parameters on the tool life of the cutting tool is analyzed, it can be delimited by the Taylor equation (1).

$$T = \frac{C_T^{'}}{v_c^m \cdot a_p^{xT} \cdot f_z^{yT}} \quad \text{[min]} \quad (1)$$

Where:
$C_T^{'}$...Constant [-],
T…Tool life [min].
m, x_T, y_T…Experimentally determined exponents of cutting parameters v_c [m.min^{-1}], a_p [mm], f_z [mm.tooth^{-1}].

In the process of realized experiments is monitored the dependence of $T = f(f_z)$. Then it can be used simplified Taylor equation (2).

$$T = \frac{C_T^{'}}{f_z^{yT}} \quad \text{[min]} \quad (2)$$

In this article, all realized experimental investigations were carried out by hard milling process. Machining tests are performed with the aim of study the performance of cutting parameter such as feed rate with consideration of multiple responses viz. volume of material removed, tool wear, tool life and flank face appearance to evaluate the performance of PVD coated carbide inserts and milling cutter. It has been observed through the Tescan Vega 5135 scanning electron microscope of type REM as the authors [4, 7]. Flank wear appearance of cutting insert can be seen in Fig. 3 and Fig. 4.

Armox steels are ultra high strength martensitic steel used as a armor material and protection for vehicles, mobile containers and other components in armament as well as civil applications. Ballistic resistances of these steels are given by combination of high hardness and strength with optimal value of toughness in a view of materials characteristics.

This type of steel is mainly used in a special production. Ttogether with the OCHN3MFA steel is mainly used to manufacture of the weapon systems which forms an integral part of the production of special technology. It was precisely investigated in the presented article of authers [13] and the main goal of this research was a experimental study and statistical monitoring of a precision machining of the OCHN3MFA steel.

Armox steel was used in Slovakia for construction of Aligator army vehicle body, demining system Bozena or mobile army containers for modular communication system Mokys. Scientific research and development in production of those steels allows to reduce active thickness of armor on 50 % with the same ballistic resistance.

Armox steels production process consists of few important steps to reach their required mechanical properties. First step is continuous casting of slab with using of ore with high chemical purity. The next step is the controlled rolling of the slabs at high temperature about 1250 °C to refine austenitic grains. Then the slabs are solution annealed at temperature about 850 °C. Most important for result high strength and hardness are two final steps – quenching and tempering. The slabs are quenched in continuous furnace from the temperature about 1000°C with very rapid cooling (Fig. 1) in water to harden the steels and finally low tempered at about 200 °C in order to make hardened steels tougher [2]. The microstructure resulting from this treatment is fine tempered martensite.

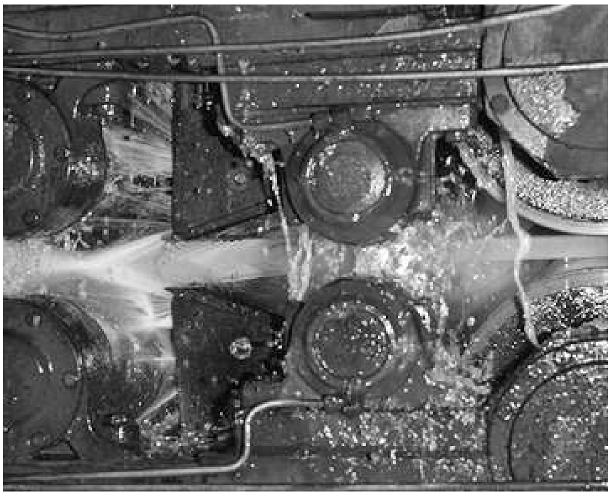

***Fig. 1** Rapid quenching of Armox steel by water [2]*

The producer of Armox steels recommend their secondary processing (machinig, cutting, welding etc.) at lower temperatures than tempering temperature due to accidental over tempering and degradation of mechanical properties in heat affected zone [1]. Specific properties of Armox steels require special tools for secondary processing of Armox steels by machining. Due to very high surface hardness, and therefore to high wear of used tool, the cutting edge made by cemented carbide and coated by PVD nano AlTiCN+TiN coating is required to mill the Armox steels.

Middle class of Armox high strength steels - Armox 500 was chosen as experimental material. Chemical composition is described in the Table 1. The basic mechanical characteristics are described in the Table 2. Showed mechanical properties were evaluated by standard tensile strength test (EN ISO 6892-1), Charpy impact test (EN ISO 148-1) and Brinell hardness test (EN ISO 6506-1). Chcemical composition was measured by spectral analyzer Spectrolab Jr CCD.

***Tab. 1** Chemical composition of examined steel Armox 500 [2]*

Chemical composition	C	Si	Mn	P	S	Cr	Ni	Mo	B
[wt. %]	0.27	0.23	1.10	0.014	0.009	0,81	1,58	0.7	0.004

***Tab. 2** Mechanical properties of examined steel Armox 500 [2]*

Mechanical properties	Tensile strength R_m [MPa]	Yield strength $R_{p0.2}$ [MPa]	Toughness KCU [J]	Hardness [HBW]	Elongation A_5 [%]
	1638	1422	25	516	9

Basic microstructure of this steel is shown in Fig. 2. The microstructure consists of tempered martensite with assumed small amount of retained austenite. There are observed some carbides which are product of tetragonal martensite transformation to cubic tempered martensite during tempering.

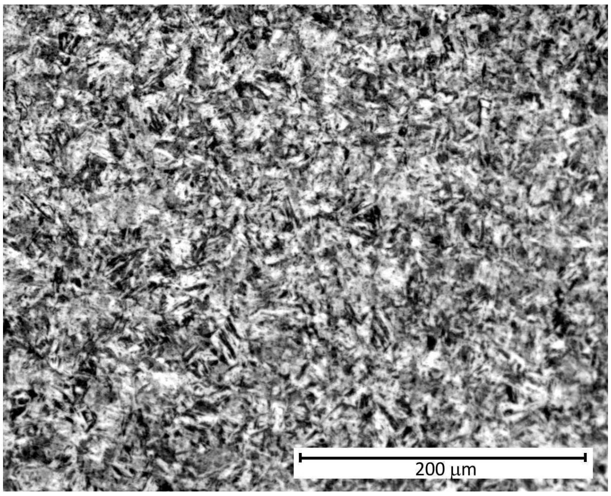

***Fig. 2** Microstructure of material Armox 500, etch. nital*

3 Experimental details

In the process of machining experiments were used PVD coated carbide cutting inserts for applying rough face milling process. Geometry of each cutting insert was SNHF 1204EN-SR-M1 and cutting material was cemented carbide type 8230 (P30 was tested) with PVD coating of TiAlCN + TiN type. These cutting inserts were used in the processes of all realized experimental tests of rough milling of the hard steel Armox 500. As proper type of cutting tool was selected milling cutter with the diameter of 50 mm. The geometry of its cutting edge is z = 4; χ_r = 75°; γ_o = -7°; α = 7°, λ_S = - 4°; (made by NAREX). Cutting tool geometry for this investigation was chosen according to ISO 3685 norm – Tool Life Testing of Cutting Tools [8, 12]. All types of changeable carbide cutting inserts, which are investigated, have a normalized shape which was mentioned above. All used cutting parameters were determined according the manufacturer recommendations, which was the DormerPramet Company. Numerical values of cutting parameters were chosen for testing these types of cutting materials and can be seen in Table 3.

***Tab. 3** Cutting parameters*

Cutting parameters				
Feed rate per tooth	f_z [mm.tooth^{-1}]	0.06	0.08	0.11
Spindle speed	n [min^{-1}]	500		
Cutting speed	v_c [m.min^{-1}]	78.5		
Depth of cut	a_p [mm]	2		

The processing of the individual values of the dependence of the tool life and feed rate per tooth can be realized by a graphical or analytical method. Each coordinate point is gradually drawn into the prepared diagram *of the* T_1-f_{z1} to T_3-f_{z3} (can be seen in Fig. 6). The value of the exponent y_T is determined as the tangent of the angle α, and the value of the constant Cv is substracted from the axis of the feed rate where the created line T-f_z intersect this axis (this is the feed rate value for the tool life T). The value of the C_T´ constant cannot be read from the graphical processing and therefore is calculated from the already determined values C_T´ and y_T, therefore $C_T = C_V^{yT}$.

During hard milling process realization, all these obtained values of machining times were achieved: t_{As1} = 6.3 min, t_{As2} = 4.5 min, t_{As3} = 3.2 min and averaged values of tool lives were as follows: T_1 = 118 min; T_2 = 83 min; T_3 = 59 min.

4 Results and discussion

Experimental dermination of dependence of tool life on feed rate T = f (f_z) at constant values of depth of cut a_p = 2 mm, and width of cut a_e = 40 mm, at determined wear criteria VB_k = 0,2 mm, without coolant (dry machining), with the constant value of cutting speed v_c = 78.5 m.min^{-1} and speindle speed n = 500 min^{-1}, were directly realized with high strength steel Armox 500 and with the milling cutter of type NAREX PN 222460.12 with number of teeth z = 4. All machining experiments were realized on the FA3V vertical milling machine tool (made by TOS Kuřim. The required values are calculated and processed in the Table 4. Graphical dependence of tool wear of used changeable cutting inserts is recorded in the Fig. 5.

***Tab. 4** The calculation table to the tool life T [min]determination*

N	T_i	f_{zi}	$\log T_i$	$\log f_{zi}$	$\log T_i \,.\, \log f_{zi}$	$\log^2 f_{zi}$
1	130.8	0.056	2.11661	-1.25181	-2.64959	1.56703
2	91.6	0.08	1.96190	-1.109691	-2.15202	1.20321
3	56.3	0.112	1.75051	-0.95078	-1.66435	0.90398
1	105.1	0.056	2.02113	-1.25181	-2.53007	1.56703
2	73.5	0.08	1.86629	-1.09691	-2.04715	1.20321
3	60.8	0.112	1.78390	-0.95078	-1.69609	0.90398
Σ	-	-	11.5003	-6.5990	-12.74008	7.3484

Note: where N is the number of all realized measuremens

$\sum \log^2 f_{zi} = -6.5990$ $\quad (\sum \log f_{zi})^2 = (-6.5990)^2 = 43.5468$

To determination of the specified $T = f(f_z)$ dependence not only with the conditions $v_{cmax} = 2{,}5$ and v_{cmin} [6] also tool wear criterion of $VB_k = 0{,}2$ mm is to be executed. Each research and investigation is conducted twice with the same cutting parameters and after modification of the position of each cutting, which also meets the general recommendations from the literature sources [9, 10]. As was mentioned above, the obtained results of flank wear and achieved tool life can be seen in Tab. 3 and in the resulting dependenc can be seen in Fig. 5. All realized face milling experiments were performed at these values of feed rates: $f_{z1} = 0.06$ mm.tooth^{-1}, $f_{z2} = 0.08$ mm.tooth^{-1}, and $f_{z3} = 0.11$ mm.tooth^{-1}. In this presented experimental work a criterion of average flank wear $VB_k = 0.2$ mm was selected for the tool life measurement. After each cutting tool path, tool wear measurements on applied cutting insert were executed to measure tool wear and then define the progress of flank wear.

By using the analytical method we express exponent y_T directly from the equation (2). Finally we get the form of equation (3) by means of the calculations. Replacing the competent values from Table 3 into Equation (3) for the exponent (y_T) then we obtain this type of equation:

$$y_T = \frac{N.(\sum \log T_i . \log f_{zi}) - \sum \log T_i . \sum \log f_{zi}}{N . \sum \log^2 f_{zi} - (\sum \log f_{zi})^2} \quad (3)$$

By plotting the measured and calculated values from Table 3 directly to Equation 3, the resulting value is as follows:

$$y_T = \frac{6.(-12{,}74008) - (-6{,}599.11{,}5003)}{6.7{,}3484 - 43{,}5468} = -1{,}011 = -b$$

The $C_T{}'$ constant can be determined by substituting the computed value for exponent y_T into the Equation (4) and than we obtained this following form and by fitting the values of this equation we get the following result:

$$\log C_T' = \frac{\sum \log T_i + y_T . \sum \log f_{zi}}{N} \quad (4)$$

Subsequently, by fitting the measured and calculated values from Table 3 directly to Equation 4, then we get:

$$\log C_T' = \frac{11{,}5003 + 1{,}011.(-6{,}5990)}{6} = 0{,}80478$$

Then: $C_T' = 10^{\log C_T} = 10^{\prime 1{,}011} = 10{,}25$

The obtained graphical dependence of $T = f(f_z)$, acquired from measurements and calculated through the method of least squares in logarithmic coordinate system is presented in Fig. 6. The final form for tool life equation $T = f(f_z)$ is represented by the: $y_T = 1{,}011 = \text{tg}\,\alpha$ $\alpha = \text{arctg}\, 1{,}011 = 45{,}33^{\circ} = 45^{\circ}\, 20'$ Accordingly the final version is: $T = \frac{C_T'}{f_z^{y_T}} = \frac{10{,}25}{f_z^{1{,}011}}$

In the process of realized investigations were selected three points of measurement in $T = f(f_z)$ according to the relevant equation, determining the profile of the obtained curves as linear in the logarithmic coordinates. Tool life dependence of the f_zT curve can be seen in Fig. 6.

The tool wear process is a very complicated phenomenon that depends on many factors (physical and mechanical properties of machined and tool material, type of machining operation, tool geometry, working conditions, cutting fluid, etc.), and in which many different physico-chemical phenomena (wear mechanisms). The most commonly used and quantified criterion is the flank wear VB which can be defined as the width of the wear on the flank face of cutting insert. In practice, methods of direct measurement of basic wear criteria are most commonly used for measuring the wear of the cutting tool. VB values are measured using a small workshop microscope so that the so-called crosshair is set to the base position at the line representing the rake face and then moves to the position where it meets the measured wear criterion. Measured values are taken into dependencies $VB = f$ (time). Worn flank faces appearance of used cutting inserts were investigated by REM microscopy of type Tescan Vega 5135 (can be seen in Fig. 3 and Fig. 4). Surface quality of the machined surfaces mainly depends on specified cutting parameters and maintained a significant task in the fatigue life and functionality of the machined surfaces. The monitoring of flank wear was realized after 12 min; 18 min; 24 min; 30 min; 40 min; 50 min; 70 min; 90 min; 100 min; 115 min; 125 when setting values of feed rates f_{z1} to f_{z3}.

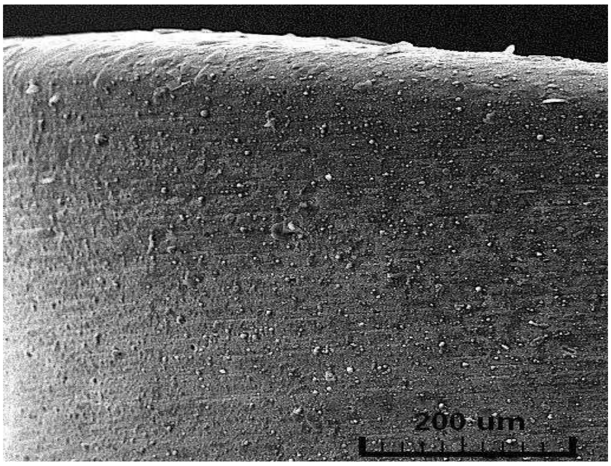

***Fig. 3** REM image of cutting edge before hard milling (exp. 250x).*

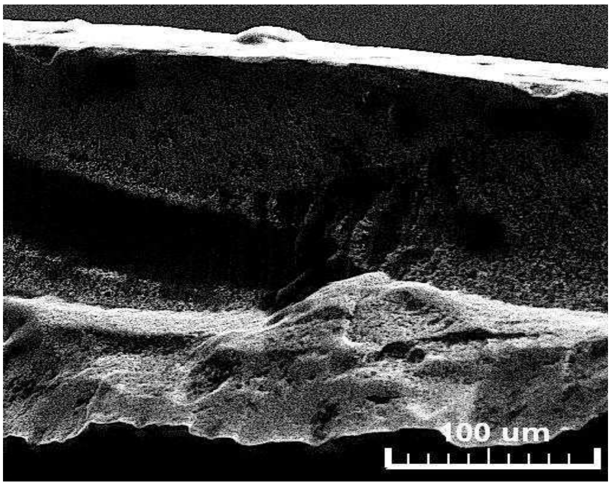

***Fig. 4** REM image of surface morphology of worn cutting edge atT = 91,6 min and fz = 0.08 mm.tooth-1(exp. 500x)*

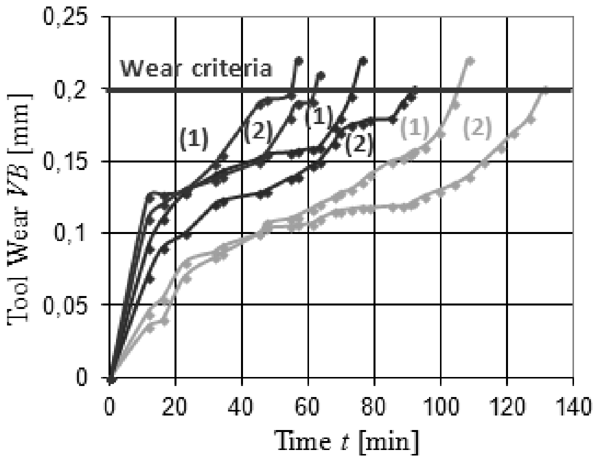

***Fig. 5** Graphical presentation of dependence of tool wear in hard milling of Armox 500 steel to determine the dependence of T = f (fz) while feed rates are determined of fz1 =0.06 mm.tooth-1, fz2 = 0.08 mm.tooth-1 fz3 = 0.11 mm.tooth-1 and (numbers 1, 2 placed at the acquired curves in the graph) means the number of realized measurement at determined feed rate per tooth*

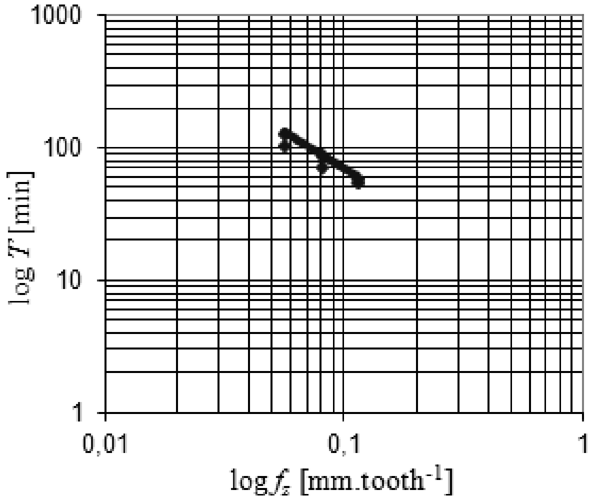

***Fig. 6** Tool life testing of f_zT curve in hard face milling of Armox 500 steel*

5 Conclusion

All realized experimental investigation in authors presented article is focused on the fundamental relations between tool wear and tool life. In the process of experiments also deals about the cutting inserts and workpiece material Armox 500 and its mechanical properties. The acquired results and findings are summarized in the following points:

- The main aim of this presented study is the investigation and measurement of the tool life depending on the feed rate per tooth according to Taylor equation when hard face milling of steel Armox 500.
- Feed rate per tooth f_z (selected machining parameter) also has comparatively significant influence on the flank wear (as well as cutting speed v_c).
- The investigated and obtained results were statistically processed by the linear regression analysis according to the method of the least squares.
- In the process of realized experiments authors also evaluated chemical composition of worpiece material measured by spectral analyzer Spectrolab Jr CCD.
- In the microstructure study, authors realized production of metallographic samples. Based on her assessment, the authors state that the observed microstructure consists of tempered martensite with assumed small amount of retained austenite. There are also observed some carbides as a product of tetragonal martensite transformation to cubic tempered martensite during tempering.
- The study of the size and location of the flank

wear in worn cutting carbide inserts has been also observed through the REM type Tescan Vega 5135 scanning electron microscope. Changes on substrate material were widened during machining, and can be said that was caused by the increase of cutting temperature. Analysis of the worn area also confirmed that there is high dependance of the workpiece sample on the cutting inserts face in concerning the temperature growth, causing the formation of seizure areas on the rake and flank faces of carbide inserts.

As for the used cemented carbide cutting material with AlTiCN+TiN PVD coating, the carbide insert wear started with the delamination of the coat onto the flank zone in addition to abrasion, adhesion oxidation. The composition of cutting edge of carbide inserts changed entirely. Due to the high temperature in machining area within the hard face milling process, thermal cracks also exist on the worn area.

In terms of past researches, authors note that the most significant impacts have cutting speed v_c, and then the feed rate f_z. However some other parameters of tool life as for example $T = f(a_p)$, have not yet been studied, which gives a new opportunity for further experimental investigation. Further experiments with respect to the dependence $T = f(a_p)$ on different cutting parameters with respect to wear behaviour and surface integrity will be conducted in the future.

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