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RESEARCH

Prediction of Coated Tools Performance in Milling Based on the Film Fatigue at Different Strain Rates

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A B S T R A C T

The knowledge of coated tool wear mechanisms in milling is pivotal for explaining the film failure and selecting the appropriate cutting strategy and conditions. In this paper, tool wear experiments were carried out in milling of four different steels using coated cemented carbide inserts. The variable stress, strain and strain rate fields developed in the tool during cutting affect the film-substrate deformations and in this way the resulting coatings loads and its fatigue failure. For investigating the influence of cyclic impact loads magnitude and duration on the films' fatigue of coated specimens, an impact tester was employed which facilitates the modulation of the force signal. The attained tool life up to the films' fatigue failure was associated to a critical force for the film fatigue endurance and to the cutting edge entry impact duration. These factors converge sufficiently to the tool life in all examined milling kinematics and workpiece material cases.

1. INTRODUCTION

Milling operations are often associated with complicated cutting edge-workpiece contact and intensive tool impact loads. These facts render the prediction of the tool wear development a difficult to be achieved task [1,2]. Recent investigations with coated cemented carbide inserts revealed that the milling up or down kinematic, as well as the cutting parameters, significantly affect the stress field developed in the cutting edge during the material removal and consequently the cutting performance [3,4].

The present paper introduces a method for calculating the coated tool wear evolution in milling. In such cutting procedures, repetitive impact loads with variable duration and magnitudes are exerted on the coated cutting edge, caused by the interrupted material removal. Hence, it was necessary to quantify the effect of the cutting edge entry impact duration on the coated tool fatigue failure at various cutting loads. This was enabled by a developed impact tester, facilitating the applied impact force modulation [5].

2. EXPERIMENTAL DETAILS

In the conducted investigations, peripheral and face milling experiments were conducted by a 3-axis numerically controlled milling center applying milling cutters of 17, 35, 57 and 90 mm effective diameters. The geometry of the cutters and the employed cutting inserts is exhibited in Fig. 1. The cemented carbide inserts are coated by a TiAlN PVD film of ca. 3 μm thickness.

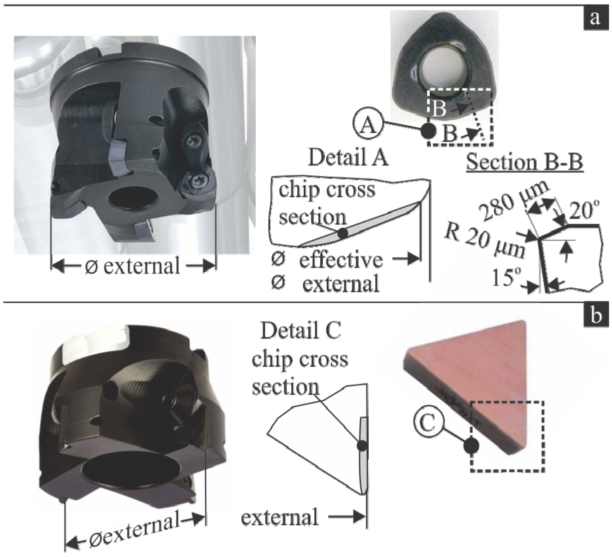
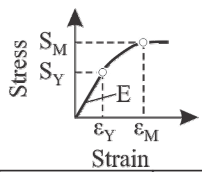


Fig. 1. The employed milling cutters.



		IMPAX (AISI P20 modified)	AISI 304 L
E	GPa	205	205
S_Y/ε_Y	GPa/-	0.9/0.00439	0.24/0.00117
S_M/ε_M	GPa/-	1.2/0.13	0.58/0.55
C/Si/Mn/Cr/Ni /S/Mo/P	%	0.37/0.3/1.4/2.0/ 2.0/0.01/0.2/-	0.03/1/2/18/8 /0.03/-/0.045
Thermal conductivity	W/(m K)	21	17
Specific heat	J/(kg K)	460	500
Hardness	HB	290-330	88 (max)

		NIMAX	EN 42CrMo4 QT
E	GPa	205	210
S_Y/ε_Y	GPa/-	0.785/-	0.75/-
S_M/ε_M	GPa/-	1.265/-	1.1/-
C/Si/Mn/Cr/Ni /S/Mo/P	%	0.1/0.3/2.5/3/1 /-/0.3/-	0.42/0.25/0.8/1.05/- /0.02/0.2/-
Thermal conductivity	W/(m K)	28	41.7
Specific heat	J/(kg K)	460	480
Hardness	HB	360-400	280

Fig. 2. The employed workpiece material properties.

The chamfer of ca. 280 μm and edge radius 20 μm respectively (see Fig. 1) contribute to cutting edge stabilization especially at elevated dynamic loads. This may lead to an effective avoidance of cutting edge micro breakages, especially when the chip formation is not stable, as for example at the cutting edge entry into the workpiece material during up milling [3].

The specifications of the applied workpiece material are displayed in Fig. 2. Four different steels were used; the hardened steel IMPAX, the stainless steel 304 L and the hardened steels NIMAX and 42CrMo4.

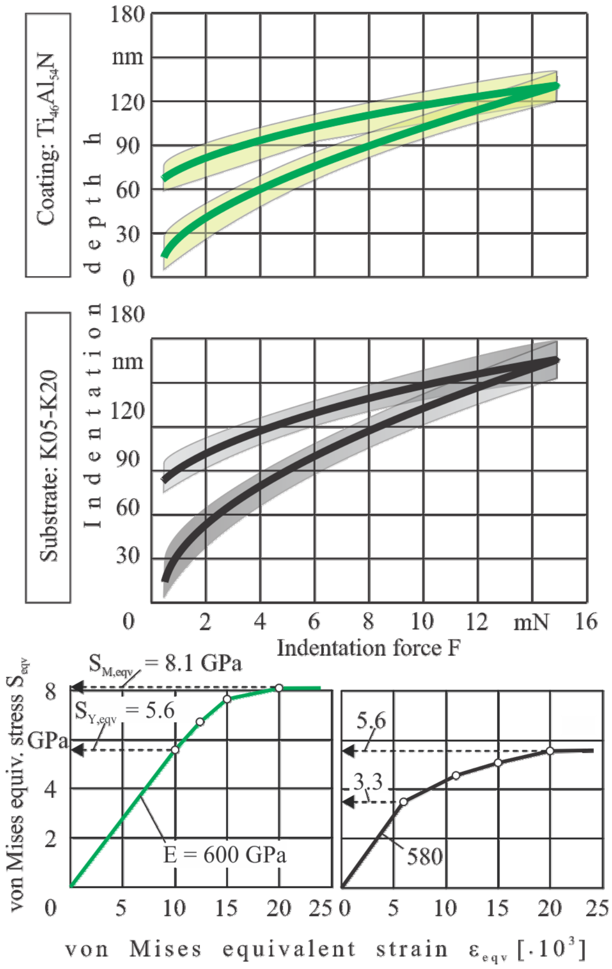


Fig. 3. The employed coatings and substrate properties.

The mechanical properties of the applied coating and substrate materials were detected by nanoindentations and a FEM-based algorithm, facilitating the determination of related stress-strain curves [6]. The elastoplastic film material laws are demonstrated in Fig. 3.

For rendering possible the modulation of the impact force characteristics such as of frequency, impact duration and force signal pattern, an impact tester has been employed, in which a piezoelectric actuator is applied for the force generation [5]. By this device, the fatigue behaviour of thin hard coatings at different impact force patterns amplitudes and durations can be investigated.

3. IMPACT FORCE AMPLITUDE AND DURATION EFFECT ON COATINGS' FATIGUE FAILURE

For detecting the effect of the cutting edge entry impact duration on the film fatigue failure, impact tests at forces of various durations and amplitudes were carried out on the used coated inserts (see Fig. 4a).

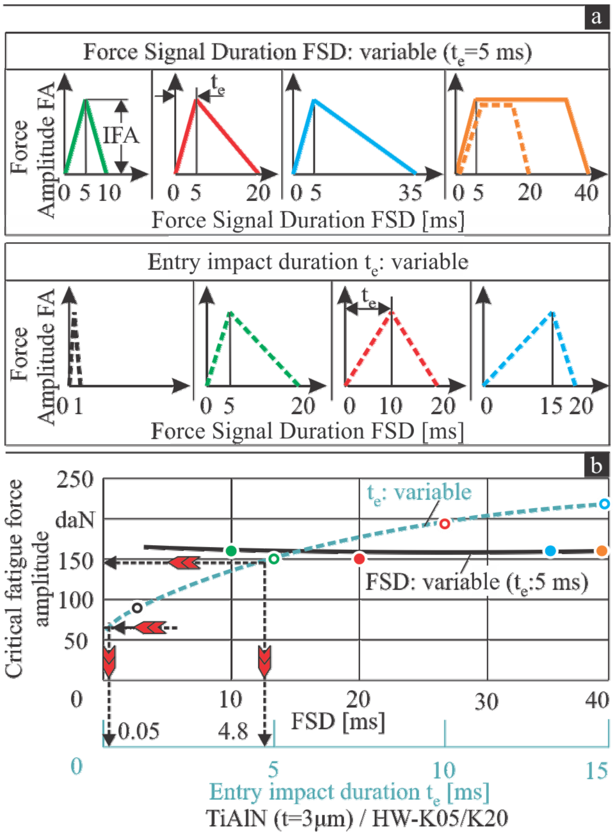


Fig. 4. a) Triangular and trapezoidal impact force signals b) Effect of impact signal and entry impact durations on the critical force amplitude.

All applied triangular force signals with durations (FSD) of 10 ms, 20 ms and 35 ms and the trapezoidal ones of 20 ms and 40 ms, which are presented at the upper Figure 4a part, had a constant signal growth time t_e of 5 ms (entry impact duration t_e). In contrast, the displayed force signals at the bottom of Fig. 4a possess different entry impact durations t_e from about 0.5 ms up to 15 ms. These force signals are created by the piezoelectric actuator and measured by the piezoelectric force transducer.

The effect of the force pattern on the critical force amplitude, which induces coating fatigue failure after one million impacts, is monitored in Fig. 4b. According to these results, the critical fatigue force amplitude remains practically invariable versus the force signal duration at constant t_e. On the other hand, t_e affects significantly the film fatigue behaviour, as it is exhibited in the same diagram. An increase of the impact entry duration t_e from 0.05 ms up to 15 ms results in a significant critical fatigue impact force amplitude augmentation from about 60 daN up to 220 daN respectively. The cutting load signal, i.e. the stress course versus the cutting length, when a chamfered cutting edge is used, resembles to a triangular force signal at entry impact duration of 3.6 ms [3]. Moreover, the stress course on a cutting edge without chamfer and smaller radius, versus the cutting length corresponds to a trapezoidal force pattern at significantly lower entry impact duration of 0.036 ms.

Considering these facts and the results exhibited in Fig. 4b, the chamfered coated cutting edges can withstand to fatigue failure approximately a two and half times higher entry impact force amplitude. In this way, at the same stress level, the film failure of a chamfered cutting edge may appear in up milling after a longer cutting time compared to an insert without chamfer. The temperature developed close to the transient region of the cutting edge between flank and rake amounts to about 200 °C at a cutting speed of 200 m/min and chip tool contact time up to roughly 15 ms [4]. Thus, in this cutting edge region, the crystalline structure of the investigated TiAlN film remains stable, no diffusion or oxidation takes place and the film fatigue, which can be investigated by the impact test, is the prevailing factor.

4. FLANK WEAR DEVELOPMENT VERSUS THE CUTTING EDGE ENTRY IMPACT DURATION

The contact conditions at the tool entry into the material in milling are pivotal for the tool wear [1,2,4,7,8]. The impact load on the cutting edge at the tool entrance into the workpiece material depends on the milling kinematic (up or down, peripheral or face), since these factors affect the developed chip geometry and thus the stress fields of the coating versus the tool rotation. The entry impact duration corresponds to the cutting time, up to the development of the maximum equivalent stress in the coating.

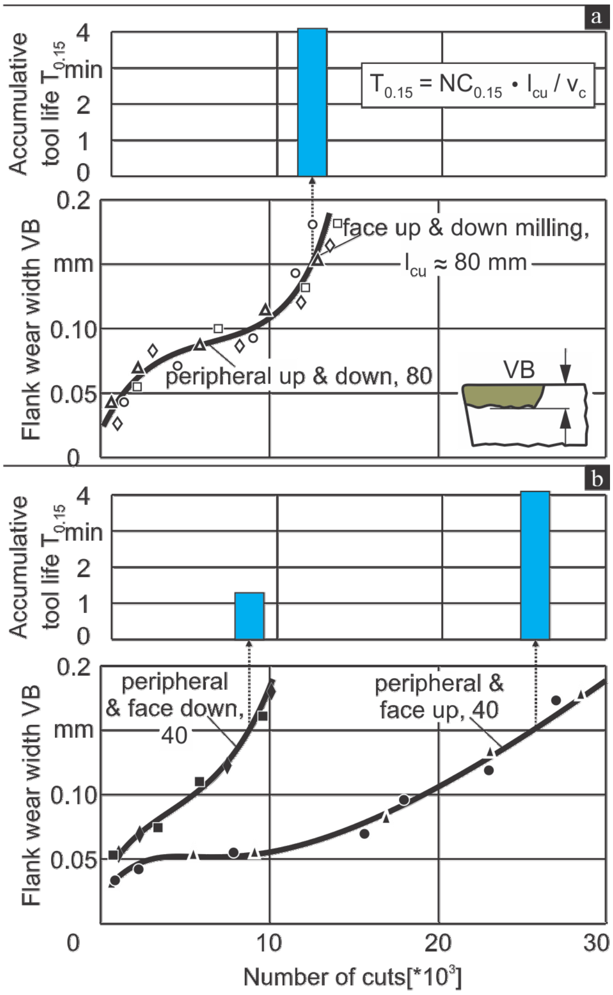


Fig. 5. Flank wear land width versus number of cuts in various cases of face and peripheral milling.

For describing the effect of the entry impact duration on the tool wear in milling with coated tools, the accumulated tool life is introduced. The latter parameter refers to a flank wear land width VB of 0.15 mm. This parameter can be calculated considering the undeformed chip length l_{cu}, the cutting speed v and the attained number of cuts $NC_{0.15}$ up to the same VB according to the equation shown in the upper part of Fig. 5a. In Fig. 5a and 5b characteristic examples concerning the effect of the entry impact duration on the tool life are exhibited. These examples refer to peripheral and face milling of different undeformed chip lengths. Further examples in milling at various conditions, kinematics and materials are presented in [3,9,10,11]. As it can be observed in Fig. 5a, at an undeformed chip length of roughly 80 mm, a similar tool wear evolution in up and down, face or peripheral milling develops, leading to almost the same accumulative tool life.

Moreover, as it is demonstrated in Fig. 5b, when up milling is applied, the flank wear development is less intense compared to down peripheral or face milling at a chip length of about 40 mm. The attained accumulative tool life in up milling is approximately three times higher compared to those ones in down milling. This behaviour can be explained, based on the developed cutting edge entry impact duration in the previously described cases.

To highlight this effect, in Fig. 6, the obtained accumulative tool life in the investigated peripheral and face milling cases is displayed versus the cutting edge entry impact duration t_e. The curve in this chart describes the effect of the cutting entry impact duration on the accumulated tool life. The relevant results were obtained in milling, at various tool geometries, cutting kinematics and conditions [3,9,10,11].

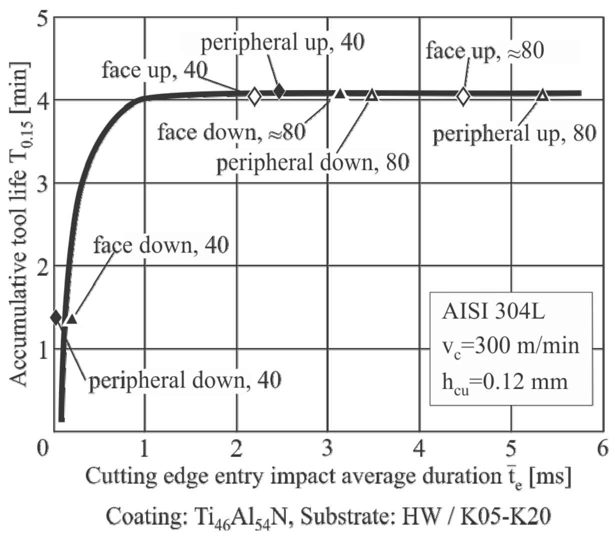


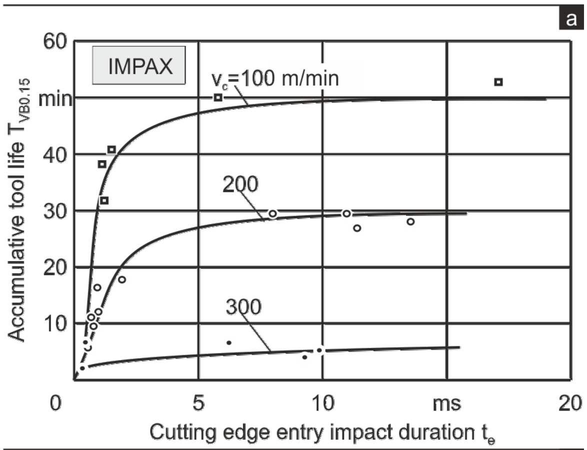
Fig. 6. Accumulated tool life in milling versus the entry impact duration.

In down milling, face or peripheral, at undeformed chip lengths l_{cu} of ca. 40 mm, the cutting edge entry impact durations t_e amount to approximately 0.1 ms leading to the accumulative tool life diminishing.

Furthermore, in up milling at an undeformed chip length l_{cu} of ca. 40 mm, due to the smoother chip thickness growth at chip formation start, the cutting edge entry impact duration t_e is approximately 2.2 ms and the accumulative tool life increases significantly compared to the corresponding one in down milling.

In contrary, in down and up milling, face or peripheral, at undeformed chip lengths l_{cu} of about 80 mm, the entry impact duration varies from 3.1 to 5.4 ms and the accumulative life remains almost on the same level.

Considering Fig. 6, it can be concluded that entry impact duration larger than 2 ms lead practically to almost the same accumulative tool life. Furthermore, it is obvious, that short entry impact durations correspond to comparably lower coating fatigue critical forces (see Fig. 4) and diminishes the coated tool life. Longer entry durations improve the film fatigue behaviour, thus enhancing the coated tool life.



b

v_c=100 m/min	$T_{VB0.15} = -\frac{2000}{e^{(0.8t_e + 3.7)}} + 50$
200	$T_{VB0.15} = -\frac{800}{e^{(0.3t_e + 3.3)}} + 30$
300	$T_{VB0.15} = -\frac{80}{e^{(0.15t_e + 2.9)}} + 6$

Fig. 7. Accumulated tool life in milling of the employed hardened steel IMPAX versus the entry impact duration at various cutting speeds.

The accumulated tool life in milling of the employed hardened steel IMPAX versus the entry impact duration at various cutting speeds is displayed in Fig. 7. The accumulated tool life in milling of the employed hardened steel IMPAX versus the entry impact duration, displayed in Fig. 7, can be described by the equations, displayed in Fig. 7b, for the cutting speeds of 100, 200 and 300 m/min.

Similar experiments were conducted for all employed hardened steels. Figure 8 illustrates the accumulated tool life in milling of NIMAX, AISI 304 L and the 42CrMo4 versus the entry impact duration at various cutting speeds. The obtained accumulated tool life of NIMAX is substantially lower than the corresponding of IMPAX at the same cutting speed and almost equal to 1/3 of that.

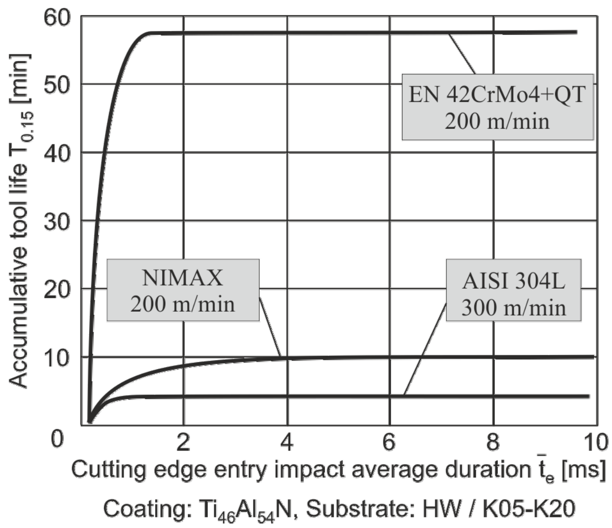


Fig. 8. Accumulated tool life in milling of the employed hardened steels versus the entry impact duration at various cutting speeds.

This is due to comparatively higher hardness of NIMAX. Moreover, it is obvious that due to reasons described in [11-14] stainless steel is difficult to cut.

5. THE DEVELOPED MODEL FOR DESCRIBING THE WEAR EVOLUTION ON COATED TOOLS IN MILLING BASED ON CUTTING EDGE ENTRY IMPACT DURATION

The general form of the equations, shown in Fig. 7, describing the accumulated tool life as a function of the cutting speed and the entry impact duration is:

$$T_{0.15}(v, t_e) = -\frac{C_3}{e^{(C_1 \times t_e + C_2)}} + C_4 \qquad (1)$$

The parameters C_1, C_2, C_3 and C_4 depend on the cutting tool and workpiece material data. Moreover, these parameters are functions of the cutting speed and the entry impact duration.

Considering the entry impact duration, using equation (1), the cutting tool life $T_{0.15}$ up to a flank wear land width VB equal to 0.15 mm can be estimated. Moreover, the number of cuts $NC_{0.15}$ corresponding to a flank wear land width VB equal to 0.15 mm can be calculated based on the undeformed chip length and the cutting speed using the relation (2).

$$T_{0.15} = NC_{0.15} * l_{cu} / v \tag{2}$$

Bearing in mind that a number of cuts equal to zero correspond to a tool wear VB also equal to zero and the number of cuts $NC_{0.15}$ is associated to VB equal to 0.15 mm, the evolution of the tool wear during milling can be calculated as described in [9].

6. COMPUTATION OF THE TOOL WEAR IN MILLING AT CHANGEABLE CUTTING CONDITIONS

During milling a workpiece, the values of parameters influencing the tool wear development such as chip length, chip thickness, entry impact duration etc. may vary in the successive tool paths. Considering these circumstances, for computing the tool wear developed during milling, the methodology explained in Fig. 9, is applied [15,16].

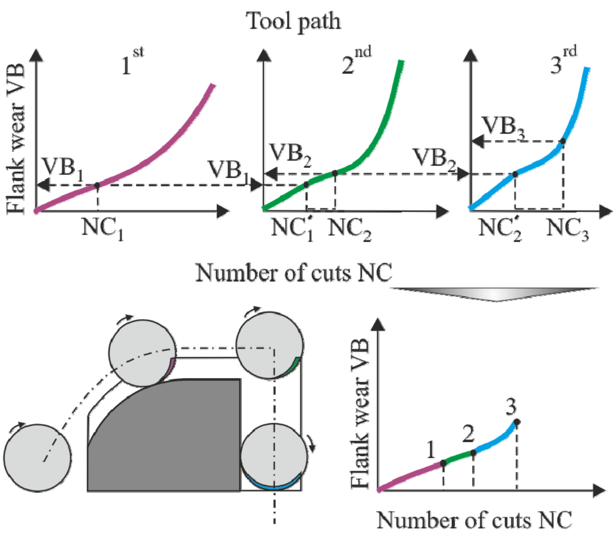
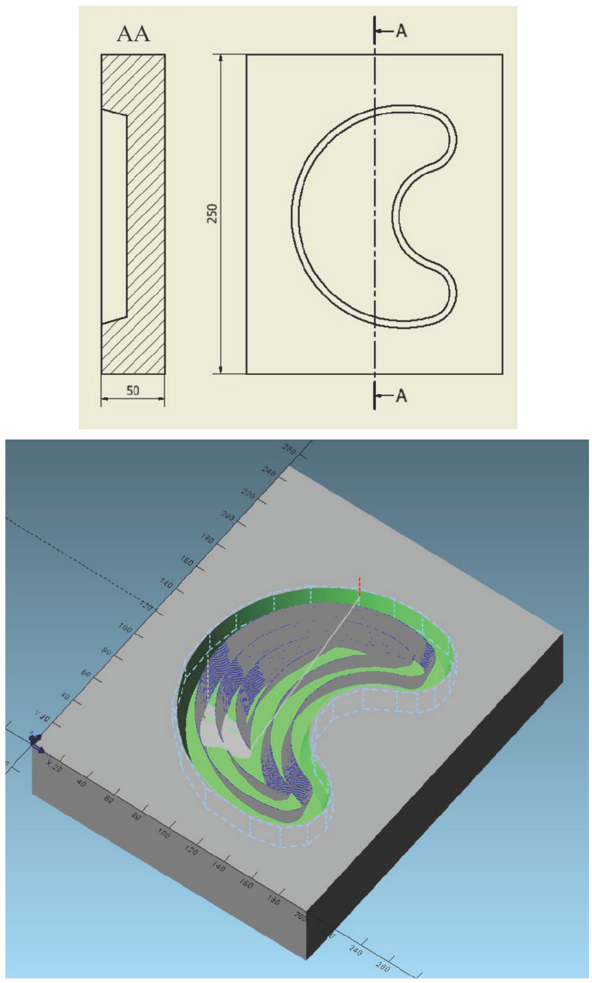


Fig. 9. Determination of tool wears evolution in milling at various cutting conditions.

Based on the cutting data of every tool path, the number of cuts NC_i and furthermore the tool wear VB_i at the end of a tool path (i) can be calculated, as demonstrated in this figure. The flank wear VB_{i-1} developed in the previous tool path (i-1), is related to a number of cuts NC_{i-1} considering the cutting data of the actual tool path. The number of cuts NC_i data of the actual tool path is added to the NC_{i-1} and thus the flank wear VB_i at the tool path (i) can be determined. By this method the flank wear development can be effectively predicted in all successive cutting tool paths.

7. AN APPLICATION EXAMPLE OF THE DEVELOPED METHODOLOGY

The analytical method for estimating the tool wear is applied in the case of a test part presented in Fig. 10. Considering the initial and final workpiece's geometry, the tool paths required to remove the raw material volume were defined using the commercial "OPUS-CAM" system [17].



Workpiece material: AISI P20 modified (IMPAX)
Tool path created by OPUS

Fig. 10. The employed test part and the tool paths required for the material removal.

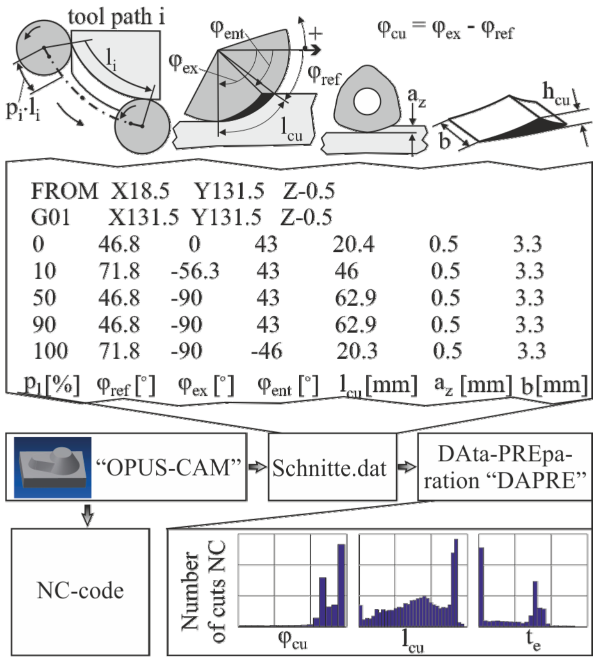


Fig. 11. Determination of chip data along the tool paths by a CAD/ CAM system.

The determined tool paths are presented in the lower part of Fig. 10 too. The machining took place in forty z-levels. The raw material removal was accomplished using up milling and down milling as well. Both operations lead to the same final workpiece shape, but the tool wear behaviour in each case may be different.

After the tool paths have been determined, the "Schnitte.dat" file is generated by OPUS, as shown in Fig. 11. This file contains geometrical data related to the chips formed in each tool path. More specifically, the parameters illustrated in Fig. 10, determined at certain distances from every tool path initial point are stored into the "Schnitte.dat" file. In the first column of the file, the tool position is defined as a percentage p of the actual tool path length l_i, whereas i is the number of the tool path. At every tool position, the angle φ_{ref} of the first tool rake – workpiece contact, the corresponding entry angle φ_{ent} at the maximum cutting edge penetration into the part material and the exit angle φ_{ex} are stored. Moreover, in the following columns, the undeformed chip length l_{cu}, the axial depth of cut a_z and the chip width b are accumulated. The data of the "Schnitte.dat" file are further processed by the developed Data - PREparation (DAPRE) software.

Thus, various data, as for instance the entry impact time per chip, the undeformed chip lengths, the tool –workpiece contact angle etc. can be provided. Considering these data the coated tool wear evolution versus the number of cuts is described and in this way, the conduct of algorithms for an analytical optimization of milling process towards attaining set targets is facilitated.

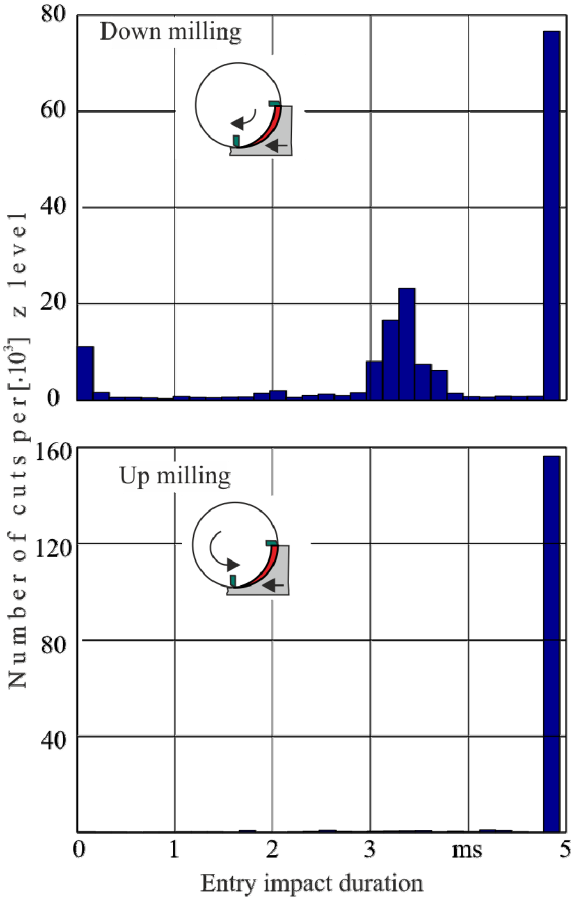


Fig. 12. Histograms of the entry impact duration along the tool paths.

Characteristic results of this methodology are displayed in Fig. 12, where histograms of the entry impact time of the removed chips in both up and down milling kinematics are illustrated.

In up milling almost all chips were cut at impact duration of approximately 4,8 ms. In contrary, when down milling is applied almost half chips possess entry impact durations of less than 4 ms, while some of them are associated with impact durations less than 1 ms. In this way, it is expected a more intense wear evolution in down milling compared to up one.

It is has to be pointed out, that the more intense tool wear evolution in down milling of this particular test part compared to the up one, cannot stand for every milling case and depends on the workpiece and the tool edge geometry and material data.

For calculating the tool wear developed during milling of the test part, the introduced method in previous paragraph was used. The flank wear land width VB versus the number of cuts NC was calculated and experimentally detected. The measured and the calculated values of the tool wear evolution in both milling kinematics are presented in Fig. 13. The experimental results converge sufficiently with the calculated ones.

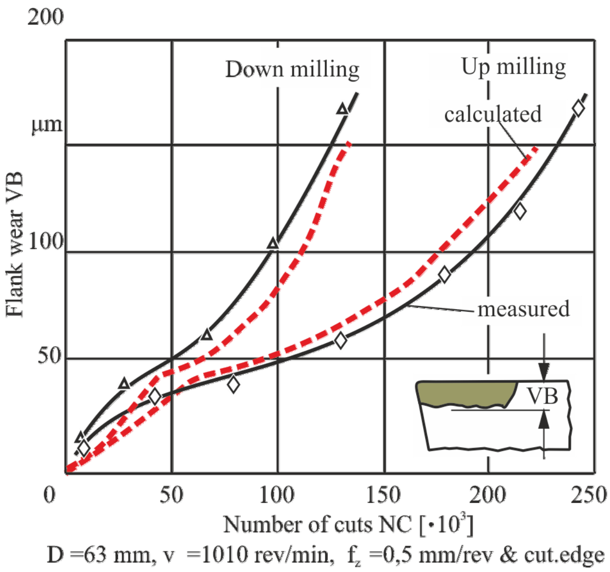


Fig. 13. Calculated and measured flank wear development versus the number of cuts.

8. CONCLUSIONS

The results described in this paper show the significant effect of the cutting edge entry impact duration on the coated tools wear evolution in peripheral and face milling. The effect of cutting edge entry impact duration on the coated tool fatigue failure was investigated via an impact tester with force signal modulation facilities. Moreover, based on the cutting edge impact duration, a calculation of the expected tool wear development can be carried out. In this way, the selection of optimum cutting conditions and strategies in milling with coated tools can be achieved.

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