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METROLOGICAL QUANTIFICATION OF TOOL WEAR BEHAVIOR OVER TIME

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Abstract
Tool wear, caused by high machining temperatures, cutting speed or mechanical load, can have various characteristics. Current solutions for metrological quantification are limited with respect to their viewing dependency and user influence. Here, a measurement solution which is based on 3D focus variation measurements is presented. The quantification is carried out by the automatic evaluation of flank wear parameters (ISO 3685:1993, ISO 8688-1:1989) and plastic deformation impression and depression parameters on 3D dataset series. This allows the visualization and assessment of wear over a period of time and provides crucial information for the manufacturing and machining process.

Keywords:
Wear measurement, flank wear, plastic deformation, focus variation

1 INTRODUCTION

In production, the focus is on economic efficiency and thus tool performance and tool life are important factors in manufacturing processes. Tool wear is one of the most common problems in terms of tool life. During the machining process high temperature, high cutting speeds and high stresses usually occur, which lead to wear of the cutting edge in various ways. The wear behavior of cutting tools is influenced by many different factors as e.g., tool macro and micro geometry, material properties of tool and workpiece, and manufacturing process parameters. Investigations of tool wear behavior can help to understand and to change these influence factors. Therefore, the metrological quantification is essential in development of cutting tools and in manufacturing processes.

In the last ten to twenty years much research has been done with respect to the metrological quantification of the micro geometry of cutting tools. Different methods and parameters have been developed and standardized for characterizing the cutting edge rounding e.g. [Denkena 2014] [Wyen 2012] [VDI/VDE 2654-2 2020]. The metrological quantification of cutting edge rounding is no longer indispensable in development of high performance cutting tools e.g. [Zangl 2021] [Scherer 2012].

The importance of wear behavior has been carried out very early – different wear types and parameters have been published and standardized in [ISO 3685 1993] [ISO 8688-1 1989] [ISO 8688-2 1989]. While some parameters have been defined for flank wear and for crater wear, the description of the plastic deformation behavior is limited to the definition of the term. Therefore, this paper aims to give a solution for the metrological quantification of this wear type.

Current wear measurement solutions are mainly based on 2D images or scanning electron microscopes, focusing on crater and flank wear e.g. [Chen 2019]. Limitations of these measurement solutions are on the one hand the viewing dependency and on the other hand the user influence due to the manual inspection [Daicu 2022]. Recently, some investigations based on 3D datasets have been published with focus on difference analysis e.g. [Boing 2019].

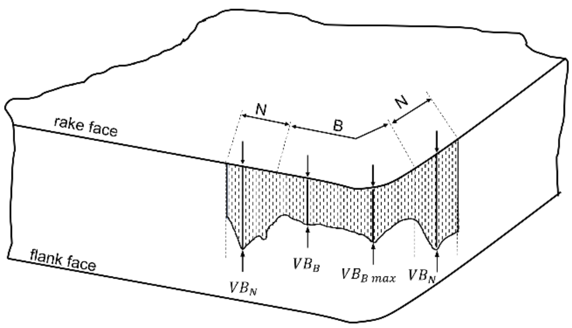
As continuous increasing wear on flank and rake face leads finally to the end of tool life, the investigation of the wear behavior over time is essential. The proposed solution allows the calculation of flank and notch wear parameters according to existing ISO standards (see [ISO 3685 1993] [ISO 8688-1 1989] [ISO 8688-2 1989]), the possibility to characterize plastic deformation depression and impression by a set of newly defined parameters as well as the automatic calculation of the wear evolution over a period of time.

In the following sections, first the existing wear parameters on the flank face as well as plastic deformation parameters are defined. Afterwards the measurement solution based on 3D focus variation measurements is described in detail. Finally, the wear inspection is demonstrated and discussed on several 3D datasets series.

2 METROLOGICAL QUANTIFICATION

2.1 Wear parameters

Tool wear typically can be distinguished in wear types which affect the flank face as e.g., flank wear and notch wear and wear occurring on the rake face as e.g., crater wear. This paper mainly focuses on the wear types which occur on the flank face. The most common wear type is flank wear which is caused by abrasion. It can be described by the width of the flank wear land VB_B at one position and $VB_{B\ max}$ which is the maximum flank wear land in region B. A special form of flank wear is notch wear occurring at the notch regions N on the major flank near the work surface. Both types are defined and described in detail in *ISO* 3685:1993. Fig. 1 gives a schematic representation of these wear types and its parameters.



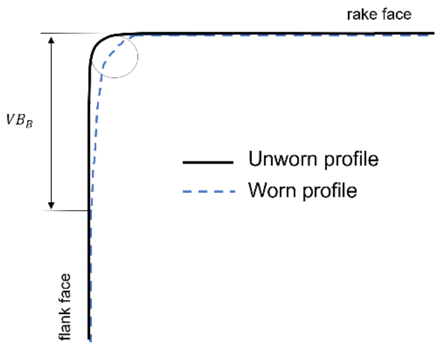


Fig. 1: Top: Schematic illustration of flank wear and notch wear according to ISO 3685:1993. Bottom: The parameter VB_B describes the width of flank wear land on the worn profile.

Plastic deformation describes a shape deformation without material removal (see [ISO 8688-1] for an exact definition) which is mainly caused by to high cutting temperatures. The wear type can be divided into a downward and outward deformation of the flank face called depression, and an inward deformation of the flank face called impression. In contrast to flank wear, there are hardly any standardized parameters for characterizing plastic deformation.

The present approach described in this paper characterized depression and impression on the basis of different parameters calculated on surface profiles which has been generated by intersections of an orthogonal plane with the cutting edge. The following parameters are defined to characterize the plastic deformation depression (PDD) (see *Fig. 2*):

- $LPDD_{D1}$, $LPDD_{D2}$: Plastic deformation depression depths characterizing the downward deformation.
- $LPDD_H$ and $LPDD_W$: Plastic deformation depression width and height describing the outward deformation on the flank face.

The following parameters are defined to characterize the plastic deformation impression (PDI) (see Fig. 3):

- $LPDI_D$: Plastic deformation impression depth characterizing the inward deformation on the flank face.
- $LPDR_R$: Plastic deformation impression retreat characterizing the flank face retreat till the resulting outward deformation on the rake face.

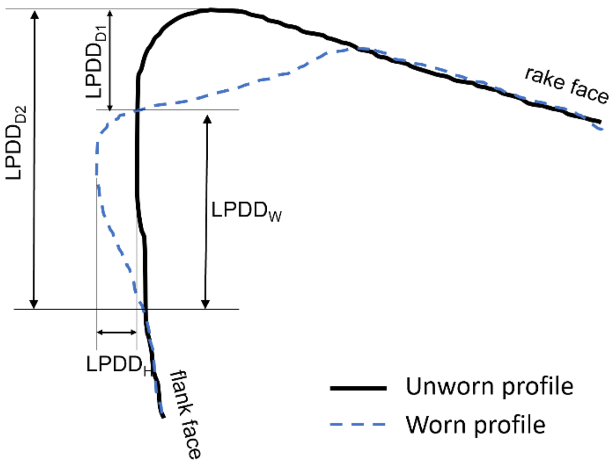


Fig. 2: Plastic deformation depression parameters defined on a profile.

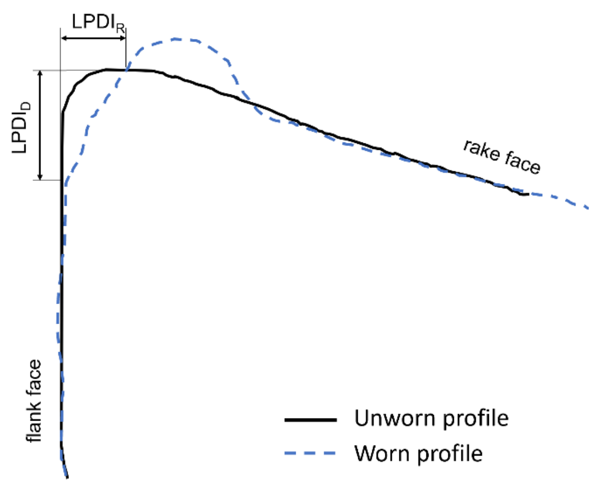


Fig. 3 *Plastic deformation impression parameters defined on a profile.*

2.2 Description of the wear parameter calculation

As mentioned before, much research has been done for the metrological quantification of the cutting edge microgeometry. In the industry, methods that calculate the parameters on the basis of profiles are the most popular. In the measurement solution presented in this paper this idea was taken up (see Fig. 4).

All wear parameters for flank wear and plastic deformation are calculated in relation to a reference dataset defined by the first dataset in the timeline. In general, such a timeline consists of one dataset of an unworn cutting edge, measured before it is used and a set of worn cutting edges measured at several stages of the wear process. This is necessary to evaluate the wear behavior over a period of time. Consequently, the first dataset is the reference dataset. First all measured datasets are aligned to each other. Afterwards, a defined number of profiles is extracted from each 3D dataset. The extraction is performed by the use of a cutting plane orthogonal to the main cutting edge. Subsequently, an iterative threshold-based searching algorithm is used to calculate the wear parameters starting from the unworn profiles which are the reference profiles to the worn profiles. The threshold is used to define the range in which a deformation is identified as wear e.g., deviations smaller than the threshold are not identified as wear. Additional to the parameters calculated per profile a parameter statistic (mean, max) over all profiles and the evaluation over time per profile are calculated.

instrument or e.g., in an in-process and in-line measurement solution where a high-resolution focus variation sensor is mounted on the collaborative robot. Focus variation (FV) is an optical area-based measurement principle which uses the small depth of focus of an optical system to provide topographical and color information through the variation of focus during a vertical scanning process. Details about focus variation can be found elsewhere [Danzl et al. 2011] [ISO 25178-606: 2015] [Repitsch et al.]. Focus variation is well known for measuring high slopes which frequently occur on cutting tools. Thereby, it has some advantages with respect to other optical measurement principles which are restricted with respect to measurable slopes as it mainly depends on the numerical aperture of the objective.

The datasets were measured using an 10x objective and by the use of a ringlight which allows an individual illumination for cutting edge measurements.

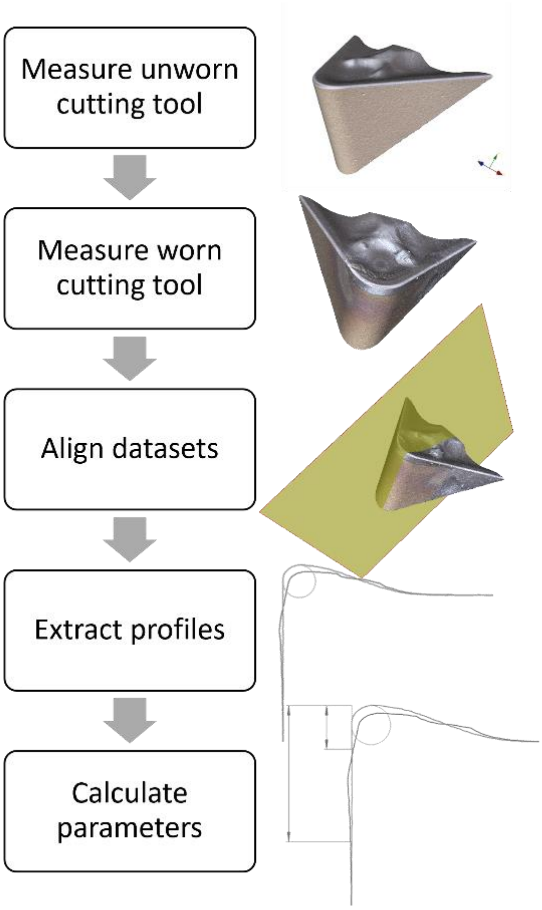


Fig. 4*: Several steps for the automatic calculation of flank wear and plastic deformation parameters.*

Fig. 5 : The used measurement setup (c) Bruker Alicona

3 RESULTS

3.1 Measurement setup

The basis for the measurement builds a six-axis collaborative robot (see *Fig. **5***) which can either be used e.g.in an in-line and off-machine situation in a pick and place measurement solution where the collaborative robot presents the workpieces to the focus-variation measurement sensor on a benchtop measurement

3.2 Evaluation

The evaluation in this section has been done by a wear software module developed by Bruker Alicona in cooperation with Sandvik Coromat. This module allows the automatic wear calculation on a timeline of wear datasets as it is described above.

In this section the presented measurement solution is evaluated on cutting tools representing different wear types: flank wear, plastic deformation depression and plastic deformation impression. Since flank wear is already very present in literature, the investigations in this paper mainly focus on plastic deformation, results on flank wear are discussed only briefly.

The first timeline, which was evaluated is a dataset series with occurring plastic deformation depression. The depression dataset series consists of 7 datasets where the first dataset M_0 is a focus variation measurement of the unused and thus unworn cutting edge, the other six FV measurements ($M_1 \dots M_6$) represent the cutting edge at several wear stages. For the evaluation 50 profiles are extracted. Consequently, for the timeline the following results are available using the algorithm above:

- $LPDD_{D1}$, $LPDD_{D2}$, $LPDD_W$, $LPDD_H$ at each position in each wear stage W_i where W_i is a pair of measurements M_0M_i with i = 1,…,6.
- The mean and max value of each parameter at one wear stage. $LPDD_{D1\ max}$, $LPDD_{D1\ mean}$, $LPDD_{D2\ max}$, $LPDD_{D2\ mean}$, $LPDD_{W\ max}$, $LPDD_{W\ mean}$, $LPDD_{H\ max}$, $LPDD_{H\ mean}$
- For each parameter its evaluation over time

Fig. 6 shows two example datasets, the first and the last dataset in the timeline, consequently the unworn and most worn cutting edge. In the difference dataset on the right side the plastic deformation depression is clearly visible. The pink area visualizes the downward deformation, the green gradient on the flank face the outward deformation.

A typical wear evaluation result can be seen in Fig. 7 showing the 3D dataset, the cutting plane specifying the position, the resulting profiles, the calculated parameters, and the timeline. The zoomed-out section shows a detailed view of the extracted profiles at the cutting plane position and the calculated parameters. The associated values can be found in Tab. 1.

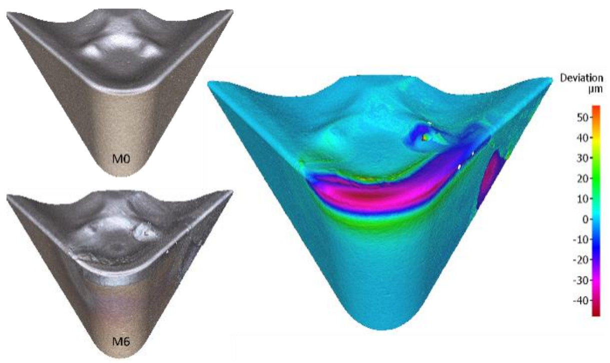


Fig. 6 : Left: Dataset of the unworn cutting edge M_0 and the worn cutting edge M_6. Right: Difference dataset visualizing the plastic deformation depression along the main cutting edge.

Fig. 8 shows an evaluation over a whole timeline. On the top of the figure the whole timeline of seven datasets is shown. The diagrams on the bottom show the evaluation of the depression parameters $LPDD_{D1}$, $LPDD_W$, and $LPDD_H$, at the specified position at different wear stages of the timeline.

The same evaluation has been done on a PDI dataset series consisting of 7 dataset M_0 to M_6. *Fig. 9* shows the difference dataset calculated between M_0 and M_6. Fig. 10 and Tab. 2 shows the results of the PDI calculation. The cutting plane position is chosen to be the position of the maximum depth of deformation. As it can be seen the impression clearly can be identified.

Tab. 1. Plastic deformation parameters calculated on the wear profile in Fig. 7

Depression parameter	Value [mm]
$LPDD_{D1}$	0,199
$LPDD_{D2}$	0,695
$LPDD_W$	0,496
$LPDD_H$	0,014
$LPDD_{D1\ max}$	0.225
$LPDD_{D1\ mean}$	0,181
$LPDD_{D2\ max}$	0,695
$LPDD_{D2\ mean}$	0,534
$LPDD_{W\ max}$	0,496
$LPDD_{W\ mean}$	0,353
$LPDD_{H\ max}$	0,018
$LPDD_{H\ mean}$	0,010

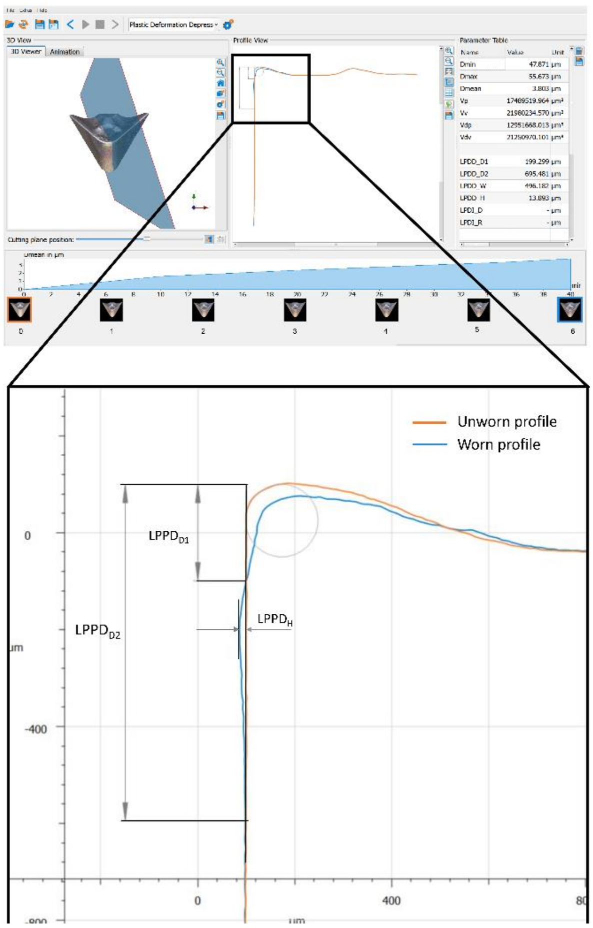


Fig. 7 : Result of the PDD evaluation on the whole timeline. Zoomed out is a detailed view of the worn profile of M_6 compared to the unworn profile of M_0 at the cutting plane position ($LPDD_{D1\ max}$ position)

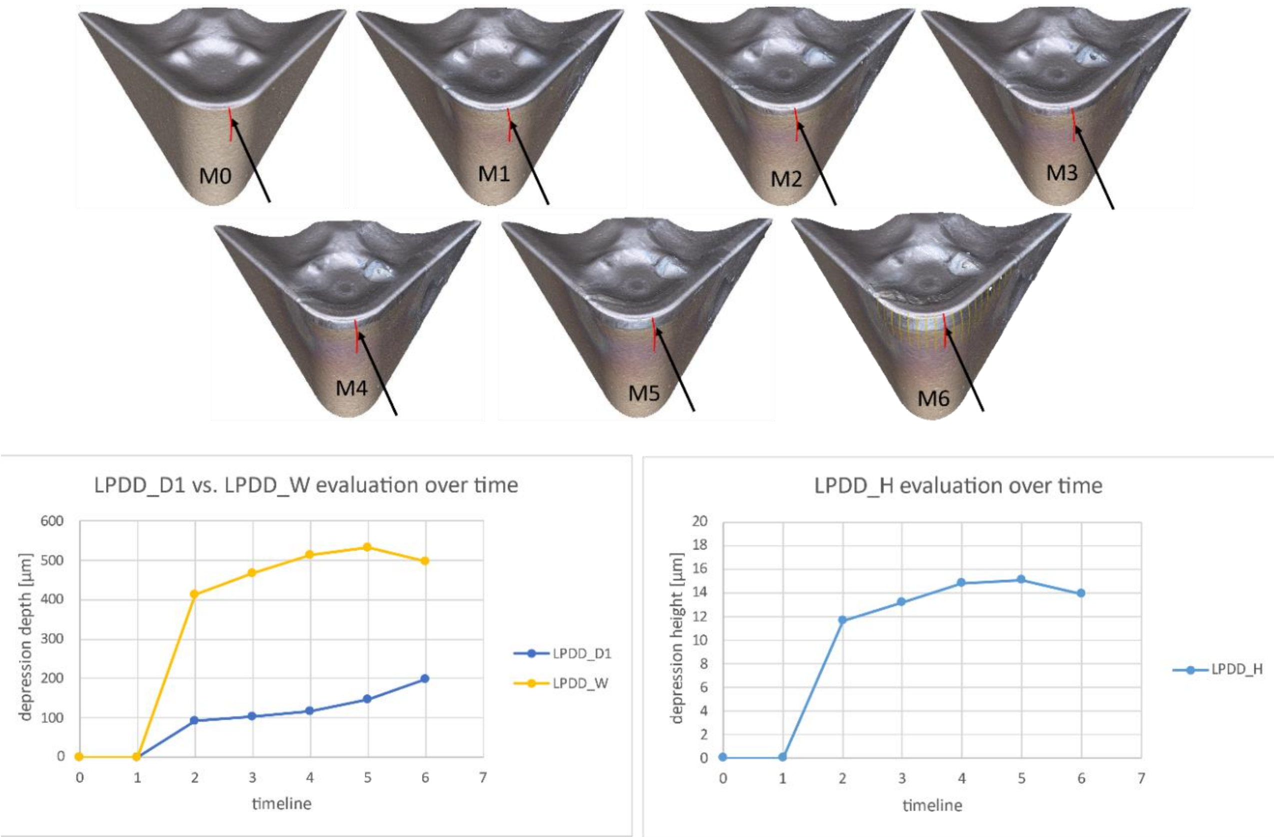


Fig. 8 : Plastic deformation depression evaluation for the whole timeline.

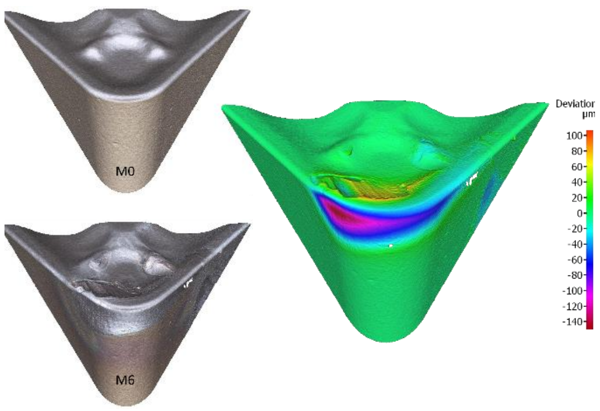


Fig. 9 : PDI difference view. Left: Dataset of the unworn cutting edge M_0 and the worn cutting edge M_6. Right: Difference dataset visualizing PDI along the main cutting edge.

Tab. 2 : Plastic deformation impression parameters calculated on the wear profile in Fig. 10

Impression parameter	Value [mm]
$LPDI_D$	0,527
$LPDI_R$	0,162
$LPDI_{D\ max}$	0,527
$LPDI_{D\ mean}$	0,350
$LPDI_{R\ max}$	0,331
$LPDI_{R\ mean}$	0,218

Finally, Fig. 11 shows a typical flank wear measurement result automatically calculated by the software module. VB_B at that position is 0,396 mm.

Due to the automatic calculation of the alignment, profile extraction, and parameter calculation the whole user influence can be avoided. By the calculation on the basis of 3D datasets, not only a 2D based view-based distance can be calculated, but the whole 3D geometry can be exploited.

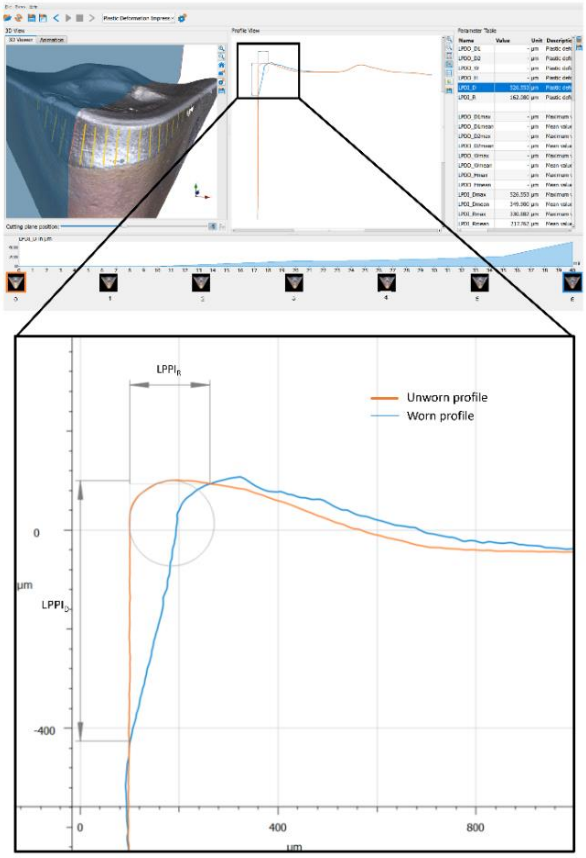


Fig. 10 : Result of the PDI evaluation on the timeline. Zoomed out is a detailed view of the worn profile of M_6 compared to the unworn profile of M_0 at the specified cutting plane position – ($LPDI_{D\ max}$ position).

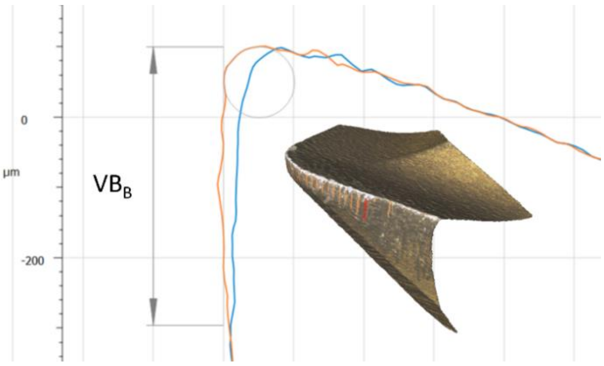


Fig. 11 Result of the flank wear measurement

4 SUMMARY

In this paper, a method for metrological quantification of flank wear types, especially plastic deformation has been presented. A set of parameters characterizing plastic deformation depression and impression has been defined and an automatic measurement solution based on a timeline of 3D datasets has been shown. It could be demonstrated that the visualization and assessment of wear over a period of time provides crucial information which can further be used for the manufacturing and machining process avoiding the main influence factors as viewing dependency and human influence. An interested point for the future is the further development with respect to other wear types as e.g., crater wear.

5 ACKNOWLEDGMENTS

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