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# Artificial Wear for the Assessment of Monitoring Performance

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**Abstract**

Various tool condition monitoring systems exist, that can increase machine availability and process reliability. Assessing and comparing their performance, however, requires high expenditure due to real process failures being scarce, too different or costly to reproduce. Hence, this paper investigates the reproducible simulation of flank wear. It introduces and validates a geometry for indexable inserts that results in process changes similar to those caused by natural flank wear. The validation considers turning processes with different feeds, depth of cut and cutting speeds in steel. Results demonstrate that the proposed geometry for indexable inserts affects process forces similar to natural flank wear.

*Keywords:* tool condition monitoring, flank wear, benchmark

## 1. Main text

Monitoring of tool wear and tool breakage is a prerequisite for unmanned production [1]. Corresponding systems are required to work reliably. Hence, extensive research exists aiming to design methods and systems that create few false alarms and feature a high failure detection rate as well as a precise wear prediction [2]. This is complex as systems and their parameters are highly specific to tools, processes and machines. Additionally, the trend towards individual parts and small series emphasizes the demand for monitoring systems with high flexibility and automatic parameterization. Consequently, various work in tool condition monitoring addresses methods that utilize monitoring knowledge across varying materials, tools, or process parameters. Despite progress, systems that are robust, sensitive and easy to parameterize remain a challenge.

Transferring knowledge for monitoring among machines has the potential to further reduce parameterization requirements and improve detection rates. For example, transferring a set of well-tuned parameters to a similar machine might allow the receiving machine to effectively monitor the first process. However, machines constitute a sophisticated system by themselves consisting of various components, such as different types of drives, guiding systems, controls and control parameters. Thus, a cutting process is a complex interaction involving materials, tools, and machines. In order to research the transfer of knowledge among different machines efficiently and reliably, it is beneficial to minimize the influences of materials, tools, and processes. This includes, for the scope of monitoring systems, a set of failures for detection.

**Nomenclature**

| | |
|---|---|
| $a_p$ | depth of cut |
| $f$ | feed |
| $F_c$ | cutting force |
| $F_f$ | feed force |
| $F_p$ | passive force |
| $VB_B$ | mean flank wear |
| $v_c$ | cutting speed |

While several works use artificial wear to standardize testing conditions, descriptions are often insufficient for

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reproduction. Another frequent shortcoming is the missing validation of artificial tool wear against naturally produced tool wear. This complicates the comparison of different results, the reproducibility of experiments and thereby the progress in the field of research for tool condition monitoring.

This work describes and validates an artificial failure to simulate flank wear. Thereby it provides a blueprint for efficient and reproducible testing across multiple machines, tools and research projects.

### *1.1. Assessing monitoring systems*

Monitoring systems, as within the scope of this review, comprise the monitoring of workpieces, processes, and tools. Setups and failures used to assess monitoring performance are specific to the monitoring target.

Simulated failures addressing the condition of workpieces are mostly local and include holes, inserted pins and material property modifications. Drilled holes simulate cavities in the workpiece material [3]. Inserted pins with a higher hardness than the workpiece material reproduce inclusions in the workpiece material [4]. Using an experimental design with aluminum and a high-speed steel drill increases the difference in material hardness and thereby reliability of detection [4].

A common monitoring target in processes is chatter. It is usually provoked by modifying cutting parameters. [5], for example, lowered the tool stiffness by changing the overhang of the tool. [6] varied the depth of cut and the revolutions per minute. The amount of publications and the consistency in which they provoke chatter demonstrates the reliability of this approach.

Modifying the process, workpiece or tool itself achieves the simulation of tool condition failures. [7] started the process without the workpiece mounted simulating the process behavior after a tool breakage. [8] introduced artificial flank wear of 300 µm and 500 µm to a milling cutter. Details about the cutter, the method of creating artificial flank wear, or the behavior in comparison to a naturally worn tool are unknown. [9] generated artificial wear on the flank face of an insert with a grinding machine. The artificial flank wear created was 140 µm, 210 µm and 280 µm. Details on the shape or the full size of the artificial wear are not given, nor is the artificial wear validated against a worn insert. [10] used cutting inserts with artificially ground flank wear ranging from 250 µm to 550 µm to generate data for a machine learning training data set. The creation process of the flank wear, the shape and size of the full flank wear are not detailed. The insert is validated against naturally worn inserts. [11] generated artificial wear on an indexable insert with a micro-electro-discharge machining process. The investigation comprises three types of wear: wear on the auxiliary flank, wear on the principle flank and crater wear on the flank face. Unlike real wear, the artificial wear covers selected spots only. It excludes the tip of the tool, for example, a region where wear is considerably high. Size of the artificial wear was systematically varied from 0 to 1 mm to determine its influence on cutting forces. While an unused tool was included in the experiments as a reference, a validation against a worn tool remains due.

The reviewed publications employ modified tools to simulate flank wear, but do not disclose the geometry of the modifications or lack validation with naturally worn tools. This paper investigates prepared cutting edges as an artificial failure to simulate worn indexable inserts. It describes the shape and size of the prepared edges. The validation is performed by comparing the cutting forces of the prepared indexable inserts with the cutting forces of naturally worn indexable inserts. The focus is on flank wear as it influences the dimensional accuracy, the surface finish and the stability of the machining process constituting a common tool life criterion [12].

## **2. Insert preparation and machining experiments**

Firstly, two indexable inserts were worn in longitudinal turning with an abrasive material (42CrMo4+QT, DIN EN 10025) to introduce wear (setup as in section 2.2 with feed $f = 0.2$ mm, depth of cut $a_p = 1.5$ mm and cutting speed $v_c = 300$ m/min). Additionally, two cutting edges of unused indexable inserts were prepared via laser ablation to resemble flank wear. The second step is a comparison of the process forces between the prepared indexable inserts and the naturally worn inserts in turning experiments. All indexable inserts used were of the ISO type CNMG 120408, model Walter Tiger Tec Silver MP5 WPP10S. The insert consists of a cemented carbide core coated with TiCN and $Al_2O_3$ via chemical vapor deposition.

### *2.1. Laser processing of indexable inserts*

A laser ablation process removed material from a previously unused tool to create a geometry that resembles flank wear. The initial step is the measurement of flank wear of the naturally worn indexable inserts. Mean flank wear of the worn inserts amounted to $VB_B = 301$ µm for tool no. 1 and $VB_B = 322$ µm for tool no. 2 after a machined volume $V_w = 190$ cm$^3$. Inserts further displayed crater wear and adhesion of workpiece material (Fig. 1).

A CAD model of the indexable insert defines the to-be removed material. It has the section of a wedge that is consistent along the cutting edge. One side of the wedge tilts 8° inwards, which equals the tilt of the flank wear area measured at the worn tools. The height of the wedge in the CAD model is higher than the actual wear to compensate for tolerances and positioning inaccuracies in the laser machining process. The height of the wedge amounts to 350 µm (Fig 2). The result section addresses the actual dimensions of the prepared area. The material was removed on an area of 2 mm wide to each side of the tip with a DMG SAUER Lasertec 40 machine via laser ablation. The used experimental ablation setup allowed to mount a new tool and to perform the material removal in less than 10 minutes.

### *2.2. Turning experiments for validation and data acquisition*

Longitudinal turning experiments took place on a Gildemeister CTX 420 linear universal lath. Workpieces were from S355JR structural steel (DIN EN10025-2, Mat.-No.: 1.0045, equivalent to ASTM A 573 M Grade 70). For each

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experimental condition, a length of 30 mm of the workpiece was machined without cutting fluid. Three different series were performed, varying the feed f, the cutting speed $v_c$, and depth of cut $a_p$ (Table 1). Every series was carried out twice, each with a previously unused insert, a worn insert and a prepared insert. Additionally, a series with fixed parameters was machined (setup 10) to assess tool life. Provided measurement uncertainties represent the standard deviation of the measurements divided by the square root of the number of measurements.

The measurement setup consisted of a dynamometer (type 9121 by Kistler) mounted to the turret of the machine tool. It recorded the process forces and acted as a tool holder (Fig. 3).

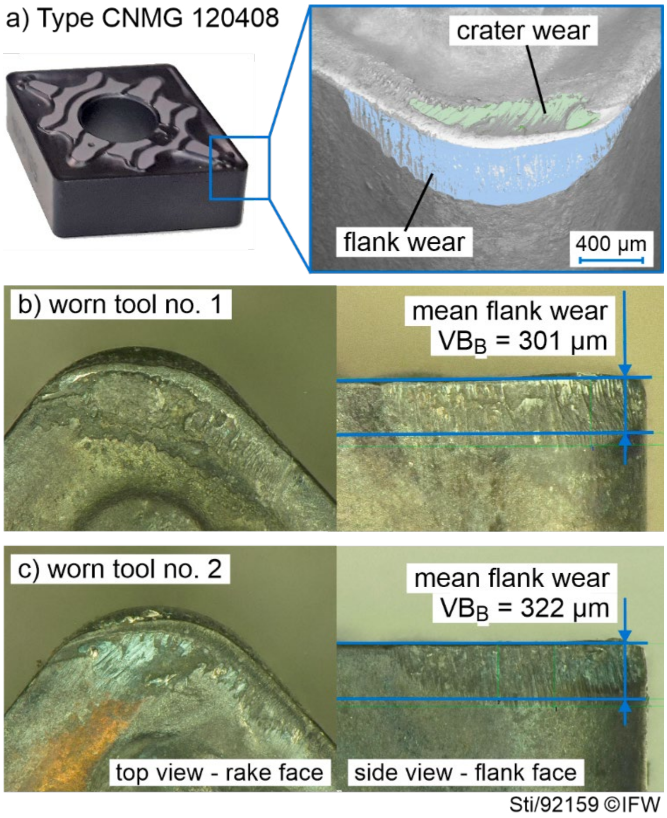

Fig. 1. Indexable inserts used for validation: (a) different types of wear, (b) top view with crater wear and side view with flank wear for tool no. 1 and (c) for tool no. 2

Table 1. Experimental setup for longitudinal turning

| setup | indexable insert | fixed parameters | varied parameter |
|---|---|---|---|
| 1 | unused | feed f = 0.3 mm, cutting speed $v_c$ = 300 m/min | depth of cut $a_p$:<br>0.5, 1, 1.5, 2 mm |
| 2 | worn | | |
| 3 | prepared | | |
| 4 | unused | depth of cut $a_p$ = 1 mm, cutting speed $v_c$ = 300 m/min | feed f:<br>0.2, 0.3, 0.4 mm |
| 5 | worn | | |
| 6 | prepared | | |
| 7 | unused | feed f = 0.3 mm, depth of cut $a_p$ = 1 mm | cutting speed $v_c$:<br>150, 200, 250, 300, 350 m/min |
| 8 | worn | | |
| 9 | prepared | | |
| 10 | prepared | f = 0.2 mm, $a_p$ = 1 mm, $v_c$ = 300 m/min | |

Force signals in all directions were low pass filtered by the amplifier with a cut-off frequency of 10 kHz. An analog-to-digital converter (ADC) of the type NI 9215 with BNC from National Instruments acquired the data at a rate of 25 kHz.

## 3. Results

### *3.1. Indexable inserts with artificial wear*

The prepared inserts feature a prepared area with a height of 320 μm ± 20 μm and a length of 2 mm (Fig. 4). The contour of the new, the worn and the prepared insert was measured in a plane 750 μm from the tip (Fig. 5). The position marks half of the depth of cut used in the wear out process. However, the height of the flank wear and the tilt of the surface vary along the cutting edge. Measurements were performed with a confocal sensor featuring a vertical resolution of 100 nm and lateral resolution of 1 μm (μScan CF by nanofocus AG). The elevated horizontal section of the naturally worn insert results from the adhesion of workpiece material. The prepared insert resembles the 8° tilt and the height of the natural wear. The tool radius of the prepared edge is larger than the one of the unused and naturally worn tool.

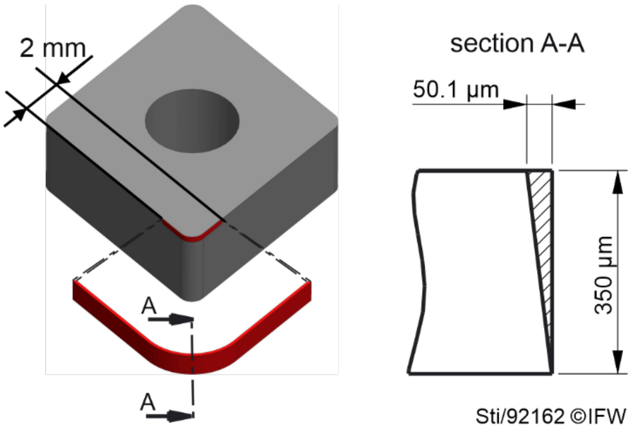

Fig. 2. CAD-model and its section for the material to be removed during the preparation process.

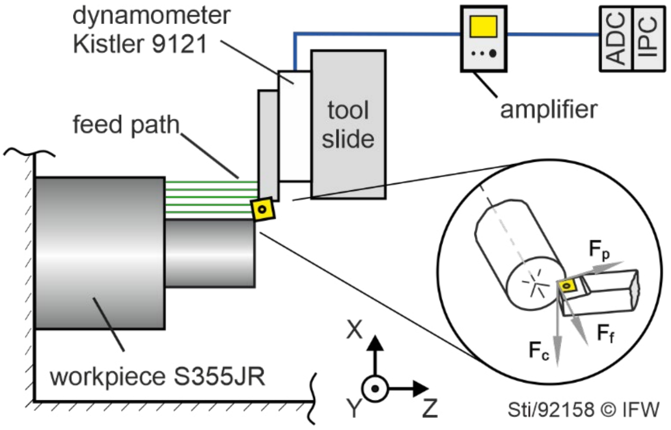

Fig. 3. Experimental setup with dynamometer and definition of cutting force $F_c$, feed force $F_f$ and passive force $F_p$.

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### *3.2. Characterizing machining behavior of indexable inserts*

On average across all measurements, the forces of the prepared tool and the naturally worn tool exceeded forces of the unused tool by 46 % and 48 %, respectively. Consequently, the prepared insert behaves more similar to the worn tool than to the unused tool with varying feed f, cutting speed $v_c$ and depth of cut $a_p$. The subsequent paragraph discusses the results for varying cutting speed (experimental series 7 to 9) as an example.

Cutting forces $F_c$ under varying cutting speeds from 150 m/min to 350 m/min were the most similar across all experiments for the worn and the prepared tool (Fig. 6 a). Throughout the experimental series 7 to 9 the cutting forces were at least 93 N higher for the worn tool than for the unused tool and at least 109 N higher for the prepared tool than for the unused tool. The highest difference between the worn and the prepared tool occurred at a cutting speed of 150 m/min and amounts to 31 N with the prepared tool causing higher forces. Compared to the unused tool, cutting forces $F_c$ were on average 108 N ± 1 N and 124 N ± 3 N higher for the worn and prepared tool, respectively.

Fig. 6 b depicts the passive forces $F_p$ for under varying cutting speed. The lowest difference between the prepared and the unused tool amounted to 30 N for a cutting speed of 150 m/min. For the worn tool, however, passive forces $F_p$ were at least 102 N higher than for the unused tool throughout all conditions. The highest difference between the worn tool and the prepared tool amounts to 87 N with the prepared tool causing the higher forces at a cutting speed $v_c$ = 350 m/min. With the unused tool as a reference, passive forces $F_p$ were on average 143 N ± 12 N higher for the worn tool and 152 N ± 34 N higher for the prepared tool.

While passive forces decrease with higher cutting speeds $v_c$ for the unused tool, they increase for the prepared and worn tools. This is accounted to the wear of the tools, which attenuates the effect of declining cutting forces due to thermal

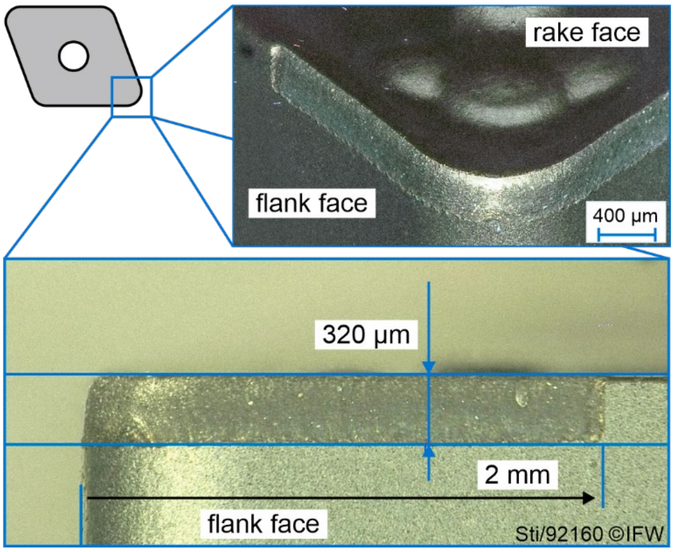

Fig.4. Contours of cutting edges in comparison (top) and side view of prepared indexable insert after laser machining (bottom)

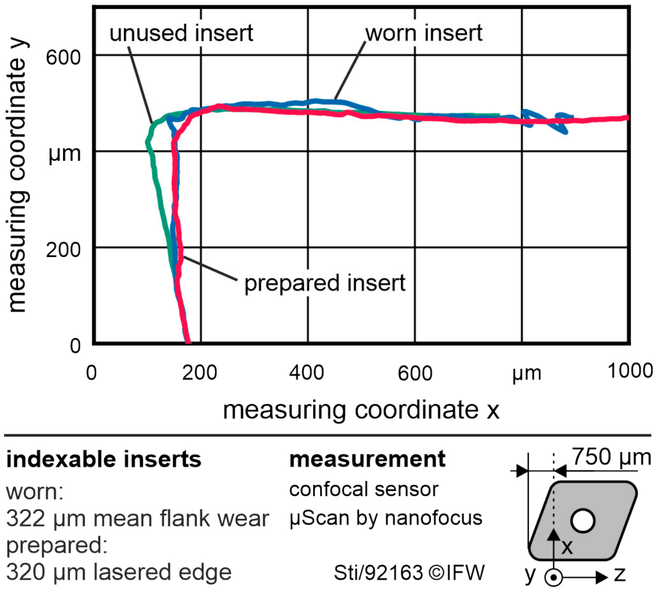

Fig.5. Contour scans of cutting edges of the unused, worn and prepared indexable insert

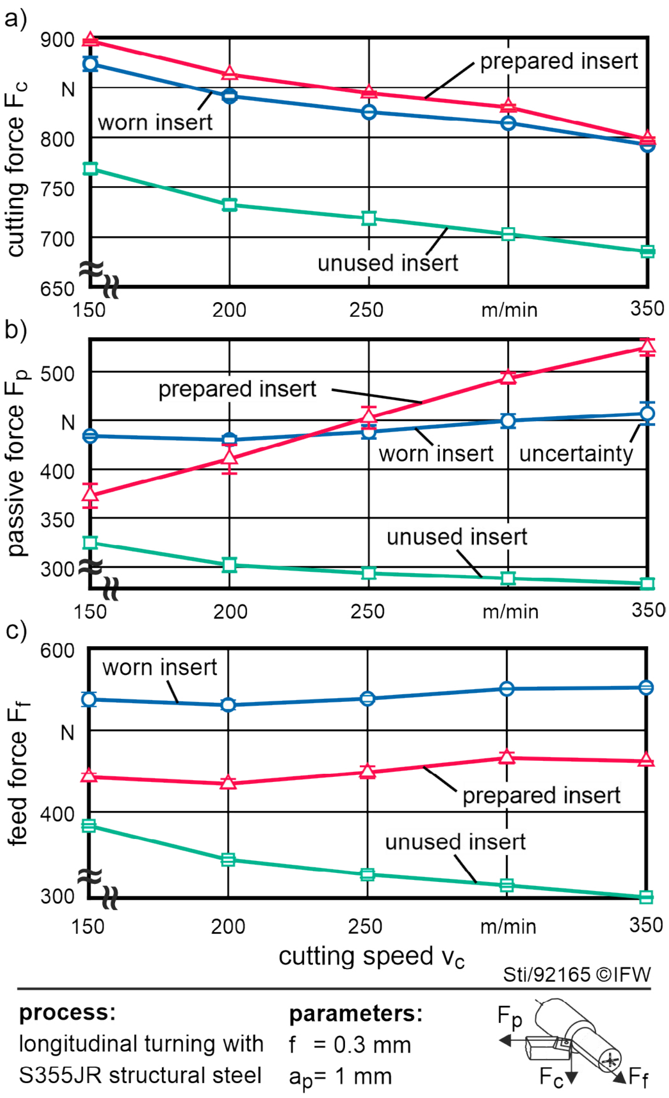

Fig.6. Comparison of a) cutting forces $F_c$ and b) passive forces $F_p$ and c) feed forces $F_f$ for unsued, worn and prepared indexable inserts under varying cutting speed

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softening of the workpiece material. This also applies to the feed forces $F_f$.

For the feed force $F_f$, the lowest difference between the prepared and the unused tool amounted to 56 N for a cutting speed of 150 m/min (Fig. 6 c). Striking is the average difference between the worn and the prepared tool, which amounts to 89 N. On average feed forces $F_f$ are 211 N ± 3 N higher for the worn tool and 120 N ± 3 N for the prepared tool. This is summarized, along with the results for the cutting force $F_c$ and the feed force $F_f$, in Fig. 7 c.

For both, the feed force $F_f$ and the passive force $F_p$, considerable differences exist between the prepared and naturally worn insert (Fig. 6 b and c). These possibly result from different micro geometries of the cutting edge, such a larger edge radius of the prepared insert or varying cross-sections of the naturally worn tool towards the corner of the insert. Additionally, the laser ablation process changes the surface and material properties. This surface behaves differently in an experimental series than the surface of a naturally worn tool that already has adhesions from its preparation process.

Fig. 7 depicts average differences of worn and prepared tools to unused tools grouped by the type of force and parameter varied. In general, increases in feed forces and passive force due to wear were higher than in cutting force. This matches common findings thereby supporting the validity of the employed wear [13]. In the majority of all test cases, the prepared tools caused on average higher forces than the worn tools. Exceptions are the passive forces under varying cutting speed, as addressed in the preceding paragraph, and the feed forces under varying feed as well as varying cutting speed. For latter only about half of the effect is caused by the prepared tool compared to the worn tool.

Further, variations in spread are to be considered. Small variations, as with the cutting force under variation of cutting speed, for example, indicate that the effects of wear are rather uncorrelated with the varied parameter (e.g. Fig. 6 a). Consequently, if the effect of wear varies with the independent parameter, spread increases. An example is the passive force under varying cutting speed for the prepared insert. Variation for both, the worn and prepared tools, are higher than average, due to the method of analysis employed. Accordingly, the approach is equally applicable. That is different in cases, where the spread is particularly high with only one of the tools. The preceding paragraph describes an example for the passive force under varying cutting speed (e.g. Fig. 6 b).

An established feature for the monitoring of wear, besides average process forces, is the frequency spectrum of forces [14]. Therefore, Fig. 8 depicts the periodogram of the cutting force $F_c$ for an unused, a worn, and a prepared tool. The most significant difference is located at about 6 kHz. At that frequency, the worn and prepared tools show a power density that is 9 dB lower than for the new tool. This drop at about 6 kHz is also the most prominent in the periodograms of the passive forces $F_p$ and the feed forces $F_f$ amounting to 9 dB ± 1 dB as well. In conclusion, the prepared indexable insert results in a frequency spectrum that is more similar to the one of the worn indexable insert than to the new insert.

Additionally, tool life was assessed with a series of repetitive turning operations (setup no. 10, Table 1). Cutting time accumulated to a total of 5 minutes. From the first cut to the last cut the forces changed in a linear manner by -10 N (-1.7 %), 16 N (1.8%) and 32 N (5.2 %) for the passive force, the cutting force and the feed force, respectively. Considering that the prepared inserts provoke an average force change of 46 %, the useful life of the prepared inserts exceed 5 minutes of cutting time under given process conditions.

## 4. Conclusion

The paper introduces a reproducible geometry to prepare indexable inserts to resemble flank wear. The cycle time of the laser ablation process to prepare an insert was less than 10 minutes, handling included. The prepared inserts were validated in longitudinal turning with steel. On average across all conditions, the forces of the prepared tool and the naturally

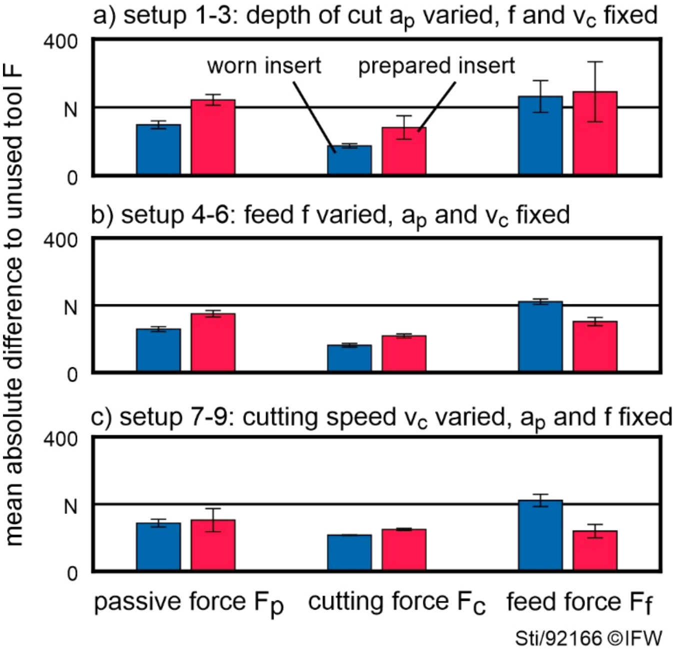

Fig.7: Comparison of passive forces $F_x$ for unsued, worn and prepared indexable inserts under varying cutting speed

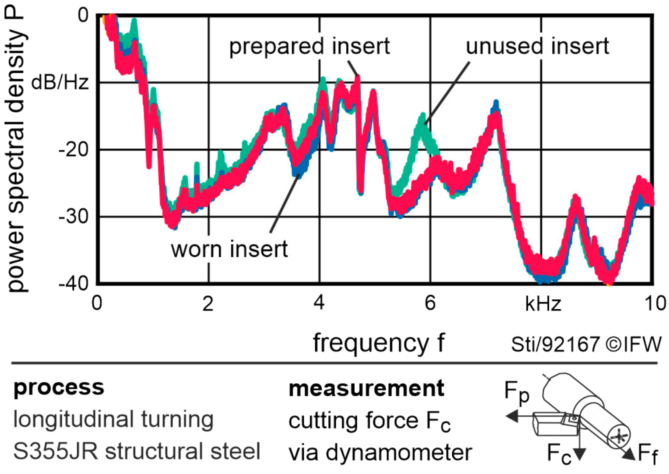

Fig. 8. Periodogram for the unused, prepared and naturally worn cutting inserts

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worn tool exceeded the forces of the unused tool by 46 % and 48 %, respectively. The highest similarity between the prepared and naturally worn tool occurred for cutting forces $F_c$. The prepared insert caused forces to increase at least by the amount that natural wear causes. Further, both conditions cause a drop in the frequency spectrum at 6 kHz. Consequently, the prepared insert resembles the patterns in the cutting force $F_c$ as caused by natural flank wear. For a system monitoring the amplitude or frequency spectrum of the cutting force, the prepared insert behaves more similar to the naturally worn tool than to the unused tool. The prepared insert is therefore considered suitable to assess monitoring systems.

Limitations apply for the feed force $F_f$ and the passive force $F_p$. Cutting speeds must be 200 m/min or higher in order for the prepared inserts to be more similar to natural wear than to unused inserts. For feed forces $F_f$, the increase in amplitude by the prepared insert might only be half of what natural wear introduces, in the worst case. Nevertheless, in all experiments the prepared inserts caused a change in process forces of the same sign as natural wear does. Further, the caused changes are always significant and well measurable with a dynamometer.

In summary, the proposed preparation for indexable inserts is suited to simulate flank wear within the assessment of a monitoring system. The prepared indexable insert is reproducible. It thereby fosters research that depends on constant process and failure conditions, such as transferring knowledge across multiple machines.

Future research might improve the proposed geometry to resemble effects of wear more closely, for example by fully reproducing the topology of a naturally worn insert, by adopting surface properties, or by optimizing the parameters of the laser ablation process. Further, other types of wear or shaping processes might be considered. Additional validation should focus on validating the geometry for a broader variety of process conditions, such as different materials, cutting fluids or tool geometries.

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