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Analysis of tool wear in face hobbing plunging manufacturing processes

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Abstract

For soft machining of bevel gears, multi-part tool systems consisting of a cutter head and stick blades are commonly used. In the past, experimental investigations regarding the tool wear in bevel gear milling have been carried out, aiming to optimize the process design and thus the process economic efficiency. However, the existing investigations refer only to face milling processes. In this paper, a tool wear study for an industrial application of the face hobbing plunging process is presented. Additionally an analogy trial of the process is designed. Based on the findings, it is concluded that the designed analogy trial is suitable for analyzing the tool wear development for face hobbing plunging processes.

Keywords: tool wear; bevel gears; face hobbing; analogy trial

1. Introduction and motivation

In manufacturing process design, it is important to consider tool wear, as the tool life and thus the economic efficiency of the process heavily depend on it. The relationships between tool geometry, process variables and tool wear in bevel gear manufacturing are highly complex [1]. Thus, tool wear is difficult to be described analytically.

The manufacturing processes for the soft machining of spiral bevel gears can be divided into continuous (face hobbing) and discontinuous processes (face milling) according to the principle of flank generation. In the literature, there are several tool wear studies on Face Milling by KLEIN [2], HARDJOSUWITO [3], HERZHOFF [4] and MAZAK [5]. However, the existing studies refer only to discontinuous bevel gear manufacturing processes.

In this paper, a tool wear study for an industrial face hobbing plunging (FH-P) application is presented. Furthermore, an analogy trial setup is introduced. Finally, the results of the analogy trial are compared to the ones of the tool wear study of the FH-P process and conclusions regarding the results' transferability are drawn.

Nomenclature

FEA	Finite Element Analysis
FH-P	Face Hobbing Plunging
EDX	Energy Dispersive X-Ray analysis
DIN	German Institute for Standardization
OB	Outside Blade
IB	Inside Blade
K	K-factor
r_β	Cutting edge radius
Ra	Average roughness
Rz	Roughness depth
v_c	Cutting speed
S_α	Section of the cutting edge – flank
S_γ	Section of the cutting edge – rake face
R_w	Tool radius
z_0	Number of stick blade groups
z_2	Number of workpiece teeth
m_{nm}	Mean normal module
$VB_{max,T}$	Maximum wear width on the tip

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2. State of the art

During the machining process, different wear mechanisms occur, depending on the type and duration of the tool load. Consequently, different wear forms result on the tool [4]. Fig. 1 shows typical forms of wear on the cutting wedge of the tool. Transverse cracks occur in the case of mechanical overloading. In contrast, ridge cracks are the result of thermal alternating load. During the cutting process, micro welding occurs due to high surface load and temperature in the contact zone between tool and workpiece material [6]. The adherence of the workpiece material to the tool cutting edge is referred to as adhesion [7].

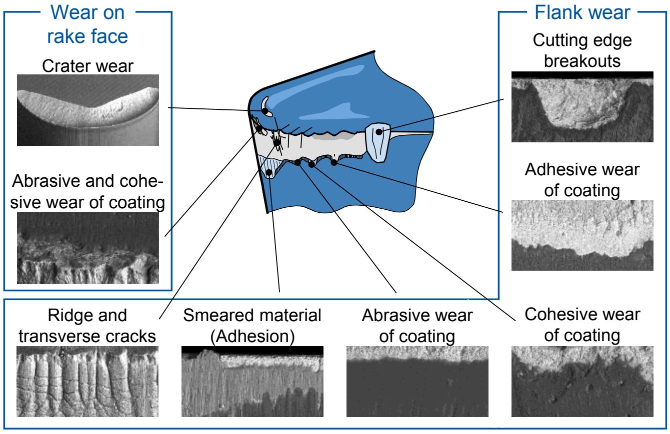

Fig. 1. Wear mechanisms on coated tools [8]

When the strength of the micro welds exceeds the strength of the material, layer failure occurs. In consequence, relative motion between the base and mating body results in shearing of the weld outside the original interface, which dislodges wear particles [6]. A distinction must be made between cohesive and adhesive coating wear on the coated tool. Cohesive coating wear occurs within the coating, while adhesive coating wear occurs at the interface between the coating and the substrate [4]. Cutting edge breakouts can occur when the wedge angle of the tool is too small. These can also be caused by local mechanical overloads due to hard, non-metallic inclusions or by chips being trapped between the tool cutting edge and the workpiece. Furthermore, damage to the cutting edge in the form of micro cracks can lead to breakouts [9]. Mechanical abrasion is also referred to as abrasive wear, since it is occurred by abrasion mechanisms. Wear on the rake face is referred as crater wear. Crater wear is caused by material removal resulting from thermal softening of the cutting material at high chip temperatures [10]. For cutting materials with higher heat resistance, diffusion is considered to be the cause of crater wear [11].

Experimental investigations on tool wear in bevel gear milling have already been carried out by KLEIN [2], HARDJOSUWITO [3], HERZHOFF [4], HOU [12] and MAZAK [5]. KLEIN varied the feed rate f, the cutting speed v_c, the cutting material and the coating of the tools in single-stick blade group experiments in discontinuous bevel gear milling and investigated the influence of the variations on the tool life [2]. The investigations of HARDJOSUWITO and HERZHOFF also dealt with the process of discontinuous bevel gear milling. Based on his investigations, HARDJOSUWITO developed a regression model to describe the tool wear on the cutting edge [3]. For validating the model HARDJOSUWITO performed bar turning tests as an analogy trial. In the works of KLEIN stick blades are used. HERZHOFF combined results of a FE-analysis with experimental results for the prognosis of the tool wear in bevel gear milling [4, 13]. HOU ET AL. compared the tool wear on face milling trials with the results of a FE-model [12]. ZHENG ET AL. proposed a semi-analytical model for cutting force prediction in face-milling, which was validated by both FEM simulation and cutting force experiments [14]. HABIBI ET AL. analyzed theoretically the chip formation using also FE analysis for face hobbing processes and proposed a new approach to blade design as well as a tool wear model [15, 16]. The works of HABIBI are based on the regression model developed by HARDJOSUWITO and regard face hobbing plunging processes. However the investigations are limited to simulative analysis and have not been validated through cutting trials. MAZAK studied the tool wear development on face milling processes and suggested a model for the prediction of the tool wear [5]. In addition to the work of HARDJOSUWITO where bar turning tests were used, the wear model of MAZAK was validated with the help of stick blade trials. EFSTATHIOU ET AL. introduced a CAD-based simulation model for manufacturing of spiral bevel gears by face milling [17].

3. Objective and approach

From the previous chapters, it is evident that the tool wear in face hobbing plunging processes has not been experimentally studied yet. The objective of this paper is to analyze the developed tool wear in FH-P on an industrial application. To achieve this objective, the procedure shown in Fig. 2 is applied.

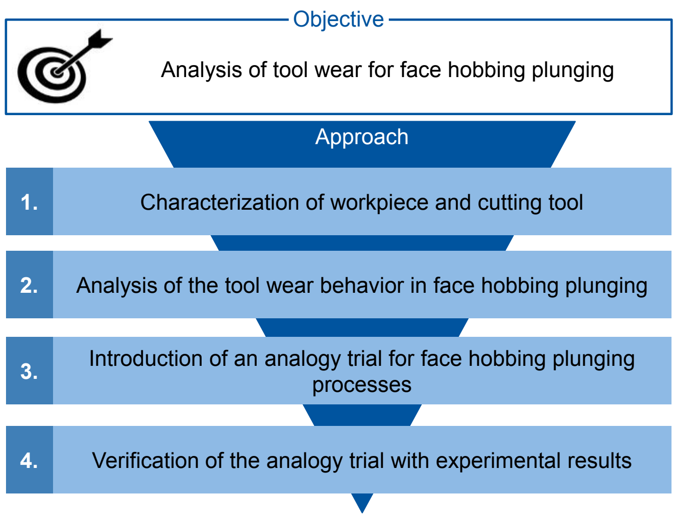

Fig. 2. Objective and approach

First, the cutting tool (stick blades) and the workpieces are characterized. Afterwards, experimental investigations of the tool wear behaviour are carried out for an industrially used process design on a fully loaded cutterhead. This is followed by an analogy trial with a reduced number of blades, where the tool wear is analyzed. Finally, the verification of the analogy trial takes place.

4. Experimental setup

In continuous bevel gear manufacturing processes, the stick blades are commonly arranged tangentially to a rolling circle in the cutter head in blade groups consisting each of inside and outside blades [18, 19]. During machining, both the cutter head and the workpiece rotate. The pitch movement is a result of the rotation of the workpiece. The pitch results from the translation between the number of blade groups and the number of workpiece teeth [7].

Experimental investigations were carried out on a KLINGELNBERG C30 bevel gear milling machine. The number of workpiece teeth was $z_2 = 45$ with a mean normal module of $m_{nm} = 3.65$ mm. The number of blade groups was $z_0 = 17$, which were positioned at the tool radius of $R_w = 88$ mm. The cutting speed was constant at $v_c = 240$ m/min for all trials, while the feed was given by a digressive feed ramp (Fig. 3). Through the feed ramp, the chip thickness was reduced as the plunging depth TA increased. The experiments were conducted without the use of cutting fluid.

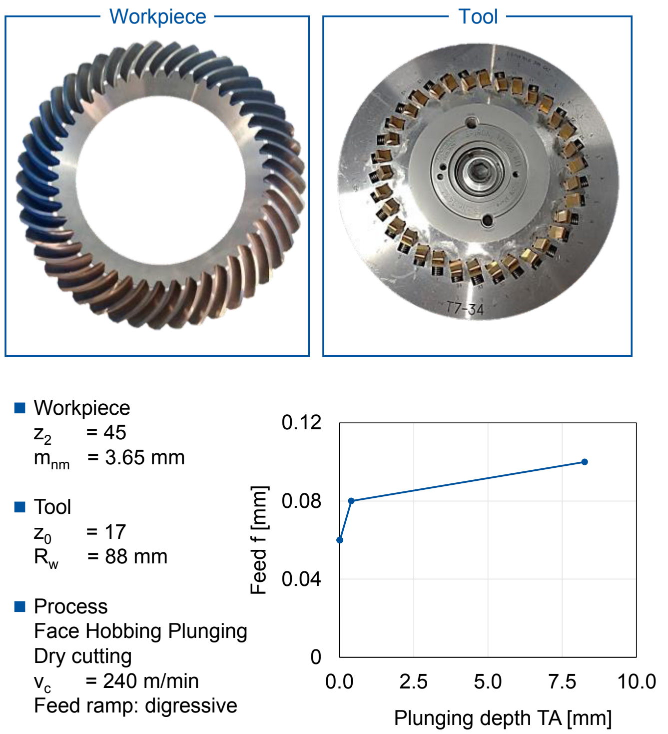

Fig. 3. Workpiece, tool and process data

For the analogy trials, only one group of blades was used. Carbide parts were clamped in the remaining pockets of the cutterhead to approximate the stiffness of a fully loaded one. The position of the stick blades is shown on the right side of Fig. 4. Two extra blades (presented in red, Fig. 4) were used for taking into account the influence of the reduced space between the stick blades of a fully loaded cutterhead on the chip formation. Those extra blades were positioned lower than the other ones and thus they were not involved in the machining process.

Since removing and reinstalling the stick blades would have resulted in a positional deviation, the wear was measured directly in the machine. To this end, a DINO-LITE digital microscope was used. With the aid of a software program, wear measurements were carried out based on the wear images of the blades after machining. The digital microscope was mounted on a fixture, which was clamped by the workpiece holder. The fixture consisted of a workpiece with an attachment that allowed the microscope to be mounted. To ensure a reproducible positioning of the microscope for each measurement, the machine axes were moved using a CNC program. Images of all stick blades were taken and evaluated.

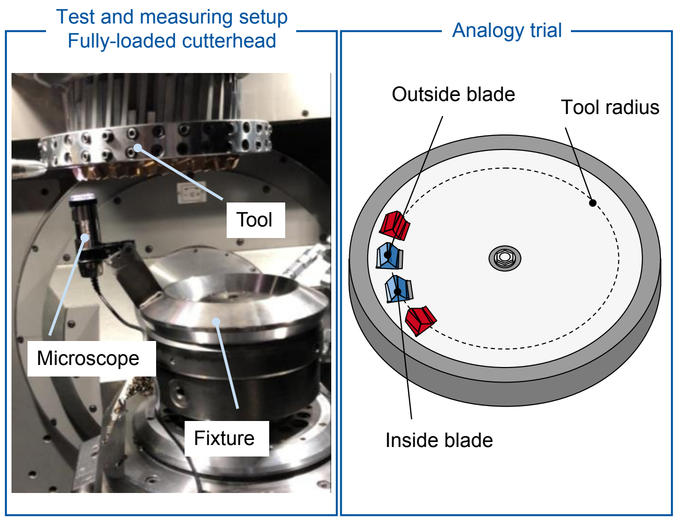

Fig. 4. Measuring and analogy trial setup

5. Characterization of workpiece and tool

Before the tests were carried out, the tools and the workpieces were characterized. The chemical element composition of the applied coating as well as of the cutting material were determined by an EDX analysis. For the characterization of the workpiece material, optical emission spectroscopy measurements were performed. Tungsten carbide cobalt was used as cutting material. All blades were coated in the same batch with six layers of AlTiN. The coating thickness was 6 µm in total. The tool material consisted of 98.4 % tungsten carbide and 1.6 % cobalt binder phase and the coating of 46.1 % Ti, 32.9 % Al and 21 % N.

The workpieces were manufactured from 16MnCr5 case-hardening steel. The chemical composition of the workpieces as well as the allowed tolerances given by DIN EN 10084 can be found in Table 1. The microstructure of the tool, coating and workpiece material is shown in Fig. 5. The tungsten carbide is depicted in white and enclosed by the black cobalt binder phase. The workpiece material had a fine-grained ferritic-pearlitic crystalline microstructure.

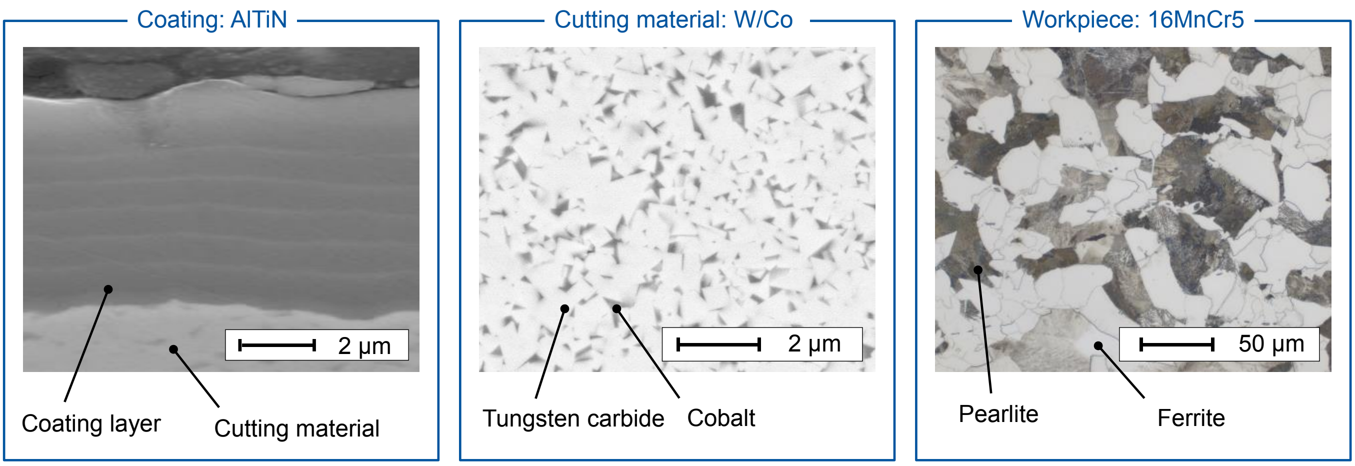

Fig. 5. Microstructure of coating, workpiece and cutting material

Table 1. Roughness and cutting edge radius values

m%	C	Si	Mn	P	S	Cr	Mo
DIN EN 10084 (min)	0.14	-	1.00	-	-	0.80	-
Measured value	0.18	0.11	1.34	0.01	0.03	1.10	0.05
DIN EN 10084 (max)	0.19	0.40	1.30	0.03	0.04	1.10	0.05

The initial condition of the blades was captured by tactile measurement of the roughness depth Rz and the average roughness value Ra of the rake face, the flank and the cutting edge (chipping). Moreover, the cutting edge radius and the K-factor were measured. The measuring positions are shown in Fig. 6 and the results are listed on Table 2.

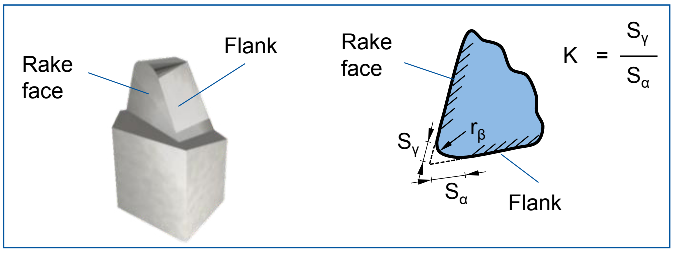

Fig. 6. Microgeometry of the cutting edge

Table 2. Roughness and cutting edge radius values

	unit	Mean value
Average roughness Ra (Rake face)	µm	0.09
Average roughness Ra (Flank)	µm	0.29
Roughness depth Rz (Rake face)	µm	1.05
Roughness depth Rz (Flank)	µm	1.73
Chipping Rz (OB)	µm	2.67
Chipping Rz (IB)	µm	3.01
Cutting edge radius r_β (OB)	µm	8.54
Cutting edge radius r_β (IB)	µm	6.11
K-Factor	-	0.94

The rake face had the lowest roughness (Ra = 0.09µm). The value of chipping on the outer blade (OB) was Rz_{OB} = 2.67 µm and on the inside blade (IB) Rz_{IB} = 3.01 µm. The cutting edge radius r_β varied from 6.11 µm on the inside blade to 8.54 µm on the outside blade. From the measured values of the K-factor, it can be concluded that the profile is symmetrical as $K \approx 1$. Finally, the condition of the blades was examined with a digital microscope, where no macroscopic damages were found. The presented values are the mean value of three measurements.

6. Evaluation of the wear investigations

In this chapter, the results of the wear investigations are presented and evaluated based on the maximum tool wear width (VB_{max}). In subsection 6.1 the experiments regarding the fully loaded cutterhead are discussed. Afterwards the results of the analogy trial are presented and compared to the ones of the fully loaded cutterhead.

6.1. Analysis of tool wear behavior in face hobbing plunging (fully loaded cutterhead)

For the investigation of the tool wear behavior in face hobbing plunging with a fully loaded cutter head, the maximum tool wear width VB_{max} was measured during the first three intervals on each stick blade. An interval consisted of the manufacturing of 20 workpieces. Then, the wear was evaluated on the three outside and inside stick blades, which exhibited the highest wear. Images were taken on the tip of the stick blade and clearance side (flanks) of the inside and outside blades.

By the evaluation it was found, that the tool wear on the tip was much higher than the flank wear. The wear curves for the maximum wear width on the tip $VB_{max,T}$ are shown in Fig. 7. The cumulated cutting length L has been calculated based on the number of cuts a single blade experiences during the manufacturing of one gear multiplied by the cutting length for a single cut and the number of parts, which have been manufactured. The calculation of the cumulated cutting length L is required for a direct comparison between the analogy process and the fully loaded cutterhead. The images of the blades after the manufacturing of the last interval are shown in Fig. 8.

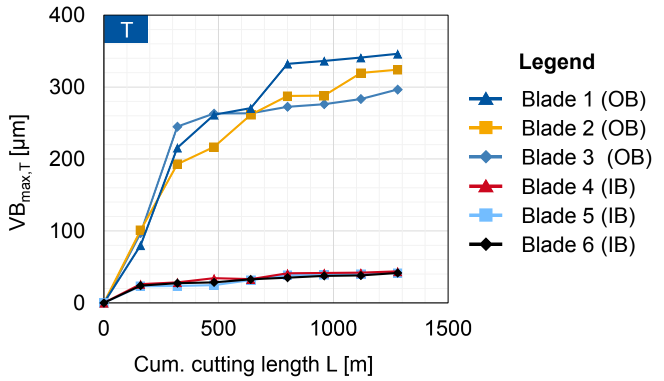

Fig. 7. Evaluation of tool wear in face hobbing plunging

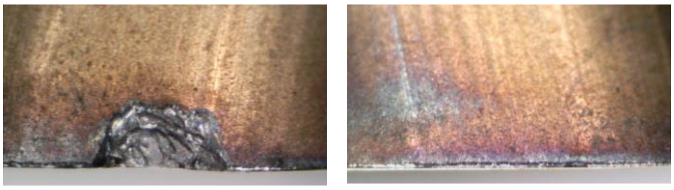

Fig. 8. Tool wear images of the tip of the outside blade (left) and the inside blade (right) by last machining cycle (L= 1280m)

Based on the images and the wear curves it can be concluded that the outside blade had a significantly larger maximum wear width on the tip $VB_{max,T}$ compared to the inside blade. The cause was a breakout, which became wider in the subsequent machining cycles. The flank wear of the outside blade was similar to the one of the inside blade. This effect was seen in 15 of 17 blade groups. This is consistent with the wear behavior of the blades for this specific process in the industrial environment. After the tests were carried out, selected stick blades were analyzed by means of a scanning electron microscope (SEM). The SEM micrographs of the rake face and the flanks are shown in Fig. 9.

With the help of the SEM micrographs, it was confirmed that a breakout had occurred at the tip of the outside blades and that the flanks were only slightly worn. In addition, the direction of the chip flow as well as white traces can be observed on the rake face. In a further EDX analysis, the chemical composition was measured at the positions a - f as shown in Fig. 9. The measurement results are presented in Table 3.

Increased Ti, Al and N contents were measured at the positions a and d. This was expected, as no chip traces or discoloration of this area was visible on the SEM images. The chemical elements Al and O observed at the positions b and e indicate the formation of Al_2O_3. For TiAlN coatings, it is known that high temperatures during dry machining lead to the formation of harder Al_2O_3 layers on the rake face, which contribute to the tool and process stability [20]. Additional measurements at the locations c and f revealed that the chemical composition in these areas is similar to that of the workpiece material. This could indicate that adhesion phenomena occurred between the rake face and the chips due to the high cutting temperatures. After the wear investigations on the fully loaded cutterhead were completed, the analogy trials took place.

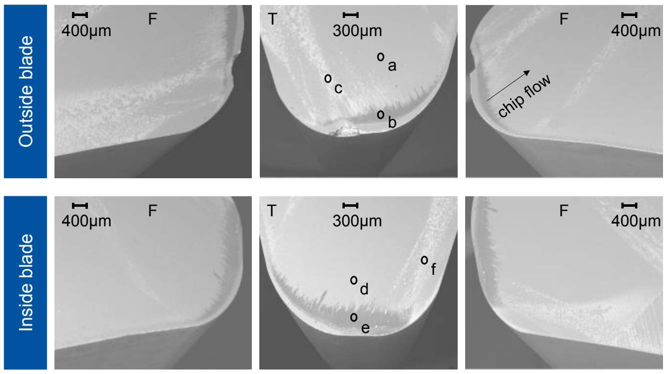

Fig. 9. SEM micrographs of the stick blades

Table 3. Chemical composition at the measured positions

m%	Fe	Mn	O	Cr	Ti	Al	N
Pos. a	0.80	-	7.30	-	**52.5**	**12.9**	**22.7**
Pos. b	5.30	3.20	**40.6**	-	-	**40**	-
Pos. c	**32.8**	**24.9**	23.5	**9.90**	3.20	0.40	-
Pos. d	-	-	3.9	-	**50.3**	**14.3**	**27.2**
Pos. e	-	0.50	**45.4**	-	-	**44.1**	-
Pos. f	**41.2**	**12.5**	28.8	**5.40**	5.80	0.70	-

6.2. Introduction of an analogy trial for face hobbing plunging processes

To ensure as identical machining conditions as possible between the process with a fully loaded cutter head and the analog trial, the feed ramp was reduced by a factor of 17, as only one group of stick blades was used. The number of manufactured parts was decreased by the same factor (17) in order to make a comparison between the two wear investigations on the same cutting length possible. Analogous to the prior investigation, images were taken on the tip of the cutting edge and flanks of the inside and outside blades and the maximum wear width VB_{max} was measured. The wear curves are presented in Fig. 10 and the images after the last machining cycle in Fig. 11.

Three trials with the same process parameters were carried out. By all of those three experiments, it was observed that breakouts occurred at the outside blade at the same region of the tip as by the experiments described in the subsection 6.1. The maximum wear width VB_{max} was measured at the tip of the outside blade and amounts on average VB_{max} = 405 µm. The abrasive wear at the tip of the inside blade was significantly lower with VB_{max} = 55 µm. The tool wear on the flanks was found to be similar to the experiment with the fully loaded cutterhead and was VB_{max} < 55 µm. According to the results, it can be concluded that the analogy test is validated and allows a good representation of the real machining process.

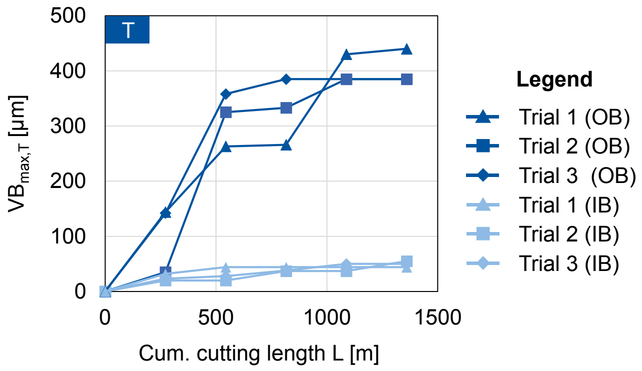

Fig. 10. Evaluation of tool wear in face hobbing plunging (analogy trial)

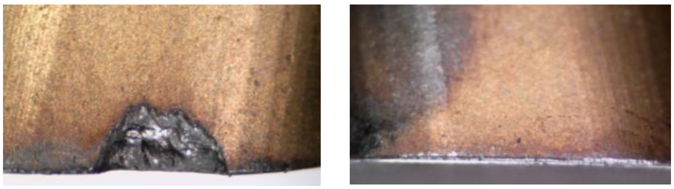

Fig. 11. Tool wear images of the tip of the outside blade (left) and the inside blade (right) by last machining cycle (L= 1360m)

7. Summary and Outlook

In this paper, experimental investigations of the tool wear behaviour were carried out for an industrially used process design on a fully loaded cutterhead. This was followed by an analogy trial with a reduced number of stick blades. Finally, the transferability of the results of the analogy test to face hobbing plunging with fully loaded cutterhead was examined.

It was found that the outside blade had a significantly larger maximum wear mark width VB_{max} on the tip compared to the inside blade. A breakout occurred at the tool tip, which increased in the subsequent machining cycles. On the inside blade no breakout was observed. The comparison of the tool wear development showed similarities between analogy trials and the fully loaded cutterhead. By the wear evaluation of the analogy trial it was shown, that the breakout occurred again at the tip of the outside blade and that the wear on the inside blade was significantly smaller. This effect was observed three times by the same setup of process parameters. The tool wear on the flanks was found to be similar to the experiment with the fully loaded cutterhead. Based on these findings, it can be concluded that the developed analogy trial is suitable for analyzing the tool wear development for face hobbing plunging processes. In future investigations, it can be used to analyze the influence of different process parameters on the tool life.

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