



Simulation-based design of flank face modification for the milling of Ti-6Al-4V and Inconel 718

Berend Denkena¹ · Benjamin Bergmann¹ · Sebastian Worpenberg¹

Received: 28 October 2021 / Accepted: 5 March 2022 / Published online: 24 March 2022
© The Author(s) 2022

Abstract

The milling of titanium and nickel-based alloys leads to high tool wear due to the high thermomechanical load on the tool. By modifying the flank face on end mills, it is possible to limit the increase in the width of flank wear land, thus increasing tool life, component quality and increasing the allowable productivity of the tools. The flank face modification is characterized by the width and depth of the undercut and the rounding in the undercut of the modification. Through a simulation-based approach, a method is created to design the flank face modification in a load-optimized way and thus to use the full potential in the respective application cases.

Keywords Ti-6Al-4V · Inconel 718 · Milling · Flank face modification

1 Introduction

Titanium and nickel-based materials are used as construction materials for highly stressed and safety-relevant components, for example in aviation or medical technology or in contact with corrosive media. While titanium-based materials are used primarily because of their low density, specific strength, and good corrosion resistance, nickel-based materials are mainly used for their high temperature strength and the likewise very good corrosion resistance. Due to their properties, the mechanical processing of titanium and nickel-based alloys leads to an increased tool load compared to ferrous metals [1–3]. The high thermomechanical load at the cutting edge causes a high resulting tool wear, which leads to unfavorable surface properties in the machined component [4–6]. In order to maintain favorable surface properties and to avoid tool breakage and resulting component damage, the operating time of the tools is limited when machining

titanium and nickel-based alloys. High-quality cutting materials, together with the required number of tools, therefore cause high costs in machining of titanium and nickel-based alloys, which are multiple times higher than those required for machining steel.

One approach to reduce wear in machining is the use of a flank face modifications. The flank face modification is inserted on the flank face of the tool. Thereby, the flank face is shifted in the direction of the milling tool axis at a defined distance from the cutting edge compared to the original flank face. This undercut geometry is described with the width S_b , the depth S_v , and the rounding of the undercut r (Fig. 1). The depth of the undercut provides a wear reserve, whereas the width defines the maximum contact between tool and workpiece at the flank face. The advantage is that the contact conditions and thus the load on the component's surface remain approximately the same, while the cutting material in the undercut is subject to continuous wear. The stability of the modification against fracture is determined to a large extent by the geometric parameters, in particular by the depth and the radius that is formed during the grinding process. Ideally, the width of the modification is very small combined with a high depth, resulting in low tool-workpiece contact length and high wear reserve. However, due to the high mechanical load, such a modification is unstable and tends to break out. Furthermore, the smallest possible radius leads to constant contact conditions over the tool life. Due to the grinding process, however, the radius cannot be chosen

✉ Sebastian Worpenberg
worpenberg@ifw.uni-hannover.de

Berend Denkena
denkena@ifw.uni-hannover.de

Benjamin Bergmann
bergmann@ifw.uni-hannover.de

¹ Institute of Production Engineering and Machine Tools,
Leibniz University Hannover, An der Universität 2,
Garbsen 30823, Germany

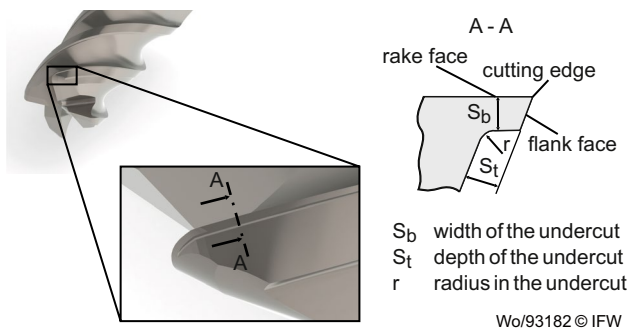


Fig. 1 Modelling and geometric parameters of the flank face modification

directly, but is determined by the edge radius of the grinding wheel and the process kinematics. Furthermore, small radii lead to an increase in stress and favor breaking of the cutting edge. With a suitable design, the operating time of the tools can be increased and the workpiece quality can be improved simultaneously.

The use of flank face modifications has already been successfully demonstrated in numerous studies. Denkena [7] showed tool life increases of up to 480% in hard turning with modified CBN tools compared to non-modified tools.

Bücker et al. [8] showed an increase in tool life during drilling experiments of Inconel 718 of more than 75% when using solid carbide drills with flank face modification. In further work by Bücker et al. [9], the flank face modification was used to achieve an improved supply of cooling lubricant to the flank face when drilling Inconel 718. This led to a further increase of the possible drilling length until the wear criterion was reached by more than 500%.

Denkena et al. [10] investigated the use of flank face modifications in hard milling and were able to achieve an 86% increase in tool life. The modification was applied to circular indexable inserts for face milling in areas of small chip thickness, resulting in low mechanical stress. In addition, Denkena et al. [11] transferred the use of the flank face modification to the turning of titanium and nickel-based alloys.

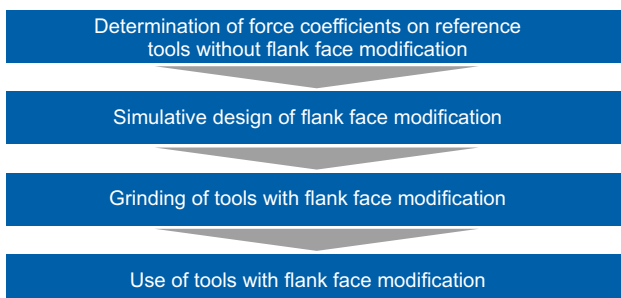


Fig. 2 Procedure for designing and manufacturing milling tools with flank face modification

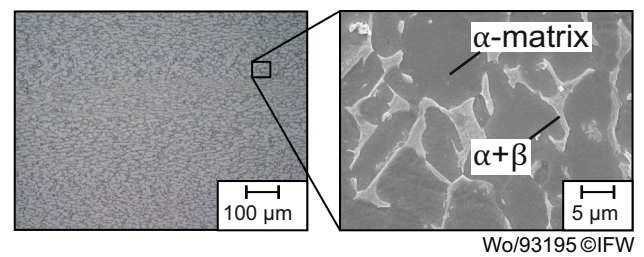


Fig. 3 Microstructure of Ti-6Al-4V annealed

The achieved increase in tool life amounts up to 150% and the process of grinding could be qualified as an economical method for the production of the modification. The design of the modification was carried out using a static finite element (FE) simulation, which reduced the calculation time for determining the tool load significantly compared to the previously used chip formation simulation. The design was based on the maximum compressive strength of the carbide.

There is still no knowledge available on the design of the flank face modification for milling of difficult to cut materials with solid carbide end mills. Due to the interruption of the cut, the tool substrate is subject to alternating mechanical stress. Therefore, it has to be investigated whether the compressive strength of the carbide is suitable as a failure criterion. The present work addresses the design and the operating behavior of solid carbide end mills with flank face modification for milling the titanium alloy Ti-6Al-4V and the nickel-based alloy Inconel 718.

2 Experimental setup

The procedure for the design, the manufacturing, and the use of milling tools with flank face modification within this work are shown in Fig. 2. In a first step, the mechanical load for the design of the flank face modification is determined on reference tools. The mechanical load is used to calculate force coefficients. Then the simulative design of the flank face modification was carried out using the finite element method (FEM). Tools with flank face modification

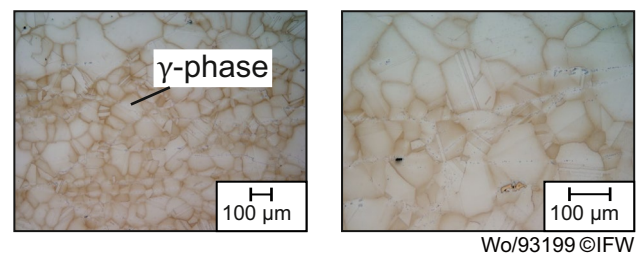


Fig. 4 Microstructure of Inconel 718 solution annealed

Table 1 Chemical composition of the alloy Ti-6Al-4V

Element	Al	V	Fe	C	N	Ti
wt%	6.44	4.31	0.21	0.021	0.005	bal.

were manufactured on the basis of the simulation results. Subsequently, the design methodology was validated and wear tests were carried out on tools with and without flank face modification.

2.1 Material

Within the present work, the titanium alloy Ti-6Al-4V and the nickel-based alloy Inconel 718 were investigated. The titanium alloy is in the annealed condition. The microstructure as a scanning electron microscope (SEM) image is shown in Fig. 3. The sample was polished in the final step with a diamond suspension with a diamond grain size of 1 μm . The etching was carried out with Kroll reagent. The microstructure consists of globular α grains with lamellar $\beta + \alpha$ phase. In the SEM image, the α phase appears dark. According to Grove [12], the tensile strength of Ti-6Al-4V with globular microstructure is in the range of 1000 MPa to 1200 MPa, whereas the bimodal microstructure presented here has a tensile strength in the range of 900 to 1000 MPa. The higher strength of microstructures with a high proportion of α -titanium is due to fewer slip systems in the hexagonally closest packed elementary cell compared to the body-centered cubic elementary cell of β -titanium. In relation to the mechanical tool load, this microstructure modification resulted in the maximum effective cutting forces in the cutting speed to range between 40 and 80 m/min [12].

The investigations on the nickel-based alloy were carried out in a solution-annealed condition. The microstructure consisting of the austenitic γ -matrix is shown as a light microscope image in Fig. 4. The sample was polished with diamond suspension with a grain size of 1 μm in a final step. The etching was carried out with V2A etchant. According to Haynes International, the tensile strength of the alloy in solution heat-treated condition is 871 MPa [13]. Through a double-stage aging process, the tensile strength of this alloy can be increased up to 1400 MPa at room temperature. This effect is due to the precipitation of the coherent phases γ'' and γ' , which have a volume share of 20 and 5% respectively [14].

Table 2 Chemical composition of the alloy Inconel 718

Element	Al	Si	Ti	Cr	Mn	Fe	Co	Cu	Nb	Mo	Ni
wt%	0.44	0.06	0.93	19.31	0.21	17.89	0.27	0.17	5.29	2.97	bal.

Table 3 Hardness of workpiece materials

Workpiece material	Hardness [HV1]
Ti-6Al-4V	348 \pm 15
Inconel 718	418 \pm 15

The chemical composition of both materials in weight percent (wt%) is shown in Tables 1 and 2. The hardness of all investigated materials is shown in Table 3.

2.2 Milling tests

The mechanical tool load is investigated in milling tests on the alloys Ti-6Al-4V and Inconel 718. The experimental investigations have been carried out on a Heller H5000 4-axis machine tool using fluted end mills type Seco JHP770120E2R100.0Z4A-SIRA for machining of Ti-6Al-4V and JHP780120E2R080.0Z4A-M64 for the machining of Inconel 718 without a modification of the flank face. Both tools have four teeth and a diameter of 12 mm. The tool JHP770 is coated with a PVD-AlCrN coating, whereas the tool JHP780 is coated with a PVD-AlTiN coating. To keep vibrations low during machining, a short hydraulic expansion toolholder of type Schunk Tendo E compact is used. The process forces are measured on a Kistler 3-component-dynamometer of the type 9255C. The milling tests on the alloy Ti-6Al-4V were carried out with a cutting speed of 60 m/min and a feed per tooth of 0.096 mm. In the further process of this work when carrying out wear tests, the cutting speed was increased to 80 m/min. For the alloy Inconel 718, a cutting speed of 30 m/min and a feed per tooth of 0.072 mm was used. The values mentioned are based on recommendations from the company Seco Tools for machining the two alloys with the specific tools.

2.3 Grinding process

The milling tools were manufactured on a Helitronic Vision 400 L tool grinding machine from Walter Maschinenbau GmbH. The grinding of the flank face modification was integrated into the grinding process as an additional process step. This process step is based on the grinding of the first flank face of the milling tool. By offsetting the grinding point in x, y, and z directions, the desired modifications can be produced. For the production of the flank face modification, resin-bonded grinding wheels from Saint-Gobain

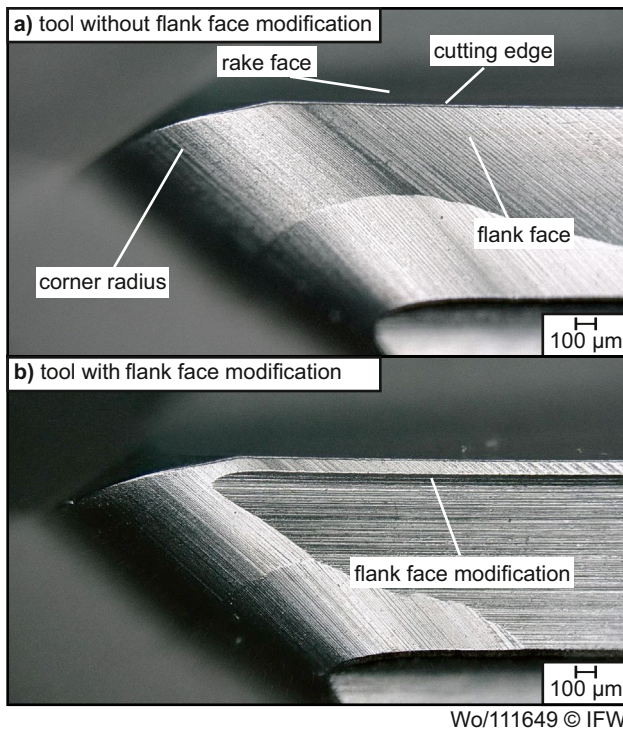


Fig. 5 Comparison of a tool **a)** without flank face modification and **b)** with flank face modification

Diamantwerkzeuge GmbH of shape 1A1 were used. The grinding wheels have a diamond grain size of D54. The cutting speed of the grinding process is 25 m/s and the feed rate 120 mm/min. Subsequently, the milling tools are reworked by drag finishing followed by a coating process. Figure 5 shows milling tools with and without flank face modification subsequent to the finishing process.

3 Simulation model

In order to develop a methodology for the design of the flank face modification, knowledge of the mechanical tool load is important. The measured process forces are used to calculate the force coefficients according to the empirical force model of Altintas [15] as input parameters for the simulation. The force coefficients are applied to a three-dimensional tool model provided by Seco Tools. Using the software

Solidworks, the flank face modification was designed and the geometric parameters of the modification were set as degrees of freedom. With the help of the software Ansys a parameter study under variation of the degrees of freedom of the modification was constructed and the minimum principal stresses in the undercut of the modification were calculated. Subsequently, a selection of milling tools with flank face modification was produced by grinding (Fig. 12). The selection includes milling tools for which there should be a failure of the cutting edge due to cutting edge fracture based on the simulation results and milling tools that should form a stable modification based on the simulation results. In order to validate the model for the design of the flank face modification, application tests of the tools are carried out.

3.1 Determination of mechanical load

The measured force values of the milling process in x, y, and z directions can be transformed to the local tool coordinate system using the transformation matrix in Eq. (1) [15].

$$\begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} = \begin{bmatrix} \sin(\varphi) & \cos(\varphi) & 0 \\ \cos(\varphi) & -\sin(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad (1)$$

With the help of a geometric material removal simulation, the contact conditions during the milling process were calculated under the corresponding process conditions. This approach is similar to proceeding of Denkena et al. [16, 17]. The simulation consists of the modules workpiece, tool and process parameters. The assembly of the simulation is shown in Fig. 6. To implement the real tool geometry, the cutting edges as well as the flank and rake face of the milling tools used were extracted from an existing CAD model. The geometry of the workpiece is discretized as a multi-dexel grid. For each time step of the simulation, the tool rotates by a defined angular step and moves at feed rate in the feed direction. By intersecting the individual cutting edges and rake faces with the workpiece, the chip thickness h , the length of the engaged cutting edge section S , and the chip cross-section A are calculated for each time step. The calculated values are used to solve the force model described in [15] (Eq. (2)). The cutting force is divided into tangential, radial, and axial forces. The force components are further

Table 4 Process parameters

Workpiece material	Cutting speed v_c [m/min]	Feed per tooth f_z [mm]	Depth of cut a_p [mm]	Width of cut a_e [mm]
Ti-6Al-4V	60	0.038, 0.058, 0.077, 0.096, 0.112	4	3
Inconel 718	30	0.029, 0.043, 0.058, 0.072, 0.084	4	3

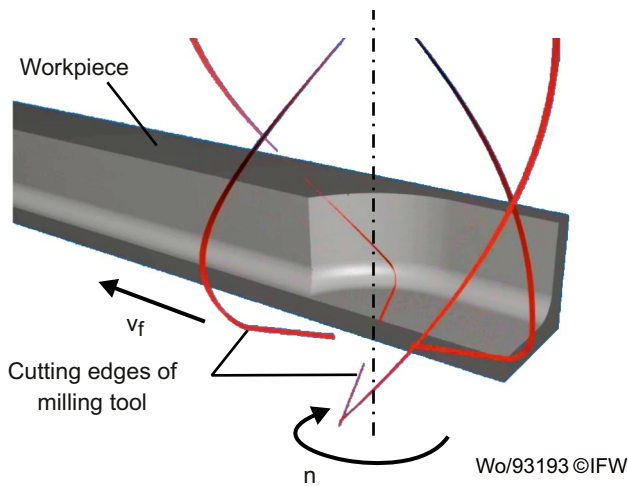


Fig. 6 Assembly of the geometric material removal simulation with the modules’ workpiece, toll, and process parameters

divided into cutting force components K_{ic} proportional to the chip cross-section and friction force components K_{ie} proportional to the length of the cutting edge which is in contact with the workpiece.

$$\begin{bmatrix} dF_t \\ dF_r \\ dF_a \end{bmatrix} = \begin{bmatrix} K_{tc} \cdot dA + K_{te} \cdot dS \\ K_{rc} \cdot dA + K_{re} \cdot dS \\ K_{ac} \cdot dA + K_{ae} \cdot dS \end{bmatrix} \quad (2)$$

For the identification of the force coefficients, milling tests were carried out under variation of the feed rate. The process parameters used to determine the force coefficients are shown in Table 4. By means of a linear regression of the least squares of error, the simulated chip cross sections and the associated specific process forces can be compared with the experimentally determined cutting forces and the coefficients of cutting force and friction can be calculated by solving the systems of equations.

The calculated coefficients of cutting force and friction force are shown in Table 5. The experiments in machining Ti-6Al-4V were carried out at a cutting speed v_c of 60 m/min. The feed per tooth f_z was varied in the range between 0.038 and 0.112 mm on five levels. When machining Inconel 718, a lower cutting speed of 30 m/min was selected. In addition, the feed per tooth for machining Inconel 718 is 25% lower in each case, so that it was varied in the range between 0.029 and 0.084 mm on five levels. In both cases,

a cutting depth a_p of 4 mm and an engagement width a_e of 3 mm were used. The selected cutting speed corresponds to the manufacturer’s specifications for an optimal machining result with the respective tools when machining the materials. The reference feed rate which is also used for machining tests with tools with flank face modification is always located in the fourth position. Based on these values, the feed rate was reduced by 20, 40, and 60% respectively and in one case increased by 20%.

3.2 Determination of thermal load

It is known that the compressive strength of tungsten carbide decreases due to temperature rise during cutting. Therefore, knowledge of the existing temperatures in the area of flank face modification is important for the design of the flank face modification. Due to the difficult accessibility of the measuring section of a rotating tool, temperature measurements were carried out in the external longitudinal turning of the respective materials. For this purpose, the cutting conditions of the milling process were transferred to the external longitudinal turning with regard to engagement times and cooling times of the tool. For this purpose, a shaft was prepared accordingly in order to map the engagement times and cooling times (Fig. 7a). The machined shaft has bars whose width corresponds to the cutting arc of the milling process. The distances between the bars, where the tool is not engaged during the turning process, correspond to the length of the arc in which a single cutting edge of the milling tool is also not engaged during the milling process. The tools for temperature measurement were made from the same carbide substrate used for the end mills. The temperature measurements were carried out with a single-color pyrometer from IMPAC, type IP 140-LO, with a measuring range between 110 and 670°C. For the measurement, an emission coefficient of the measuring point was determined in advance. The coefficient has been evaluated by heating an indexable insert on a heating plate in the range $T = 150\text{ °C}$ to 300 °C . Through parallel measurement with the single-color pyrometer and a calibrated contact thermometer, the emission coefficient is defined. An emission coefficient $\epsilon = 0.2$ was used for the measurements. For the temperature measurements, the manufactured inserts were prepared with grooves in the area of the corner radius using laser ablation. The grooves are located at a distance of $200\text{ }\mu\text{m}$ from the cutting edge.

Table 5 Cutting force and friction coefficients

	Cutting force coef. K_{ic} [N/mm ²]			Friction coef. K_{ie} [N/mm]		
	K_{tc}	K_{rc}	K_{ac}	K_{te}	K_{re}	K_{ae}
Ti-6Al-4V	1,790	527	103	7	43	21
Inconel 718	2,470	1,370	774	32	60	26

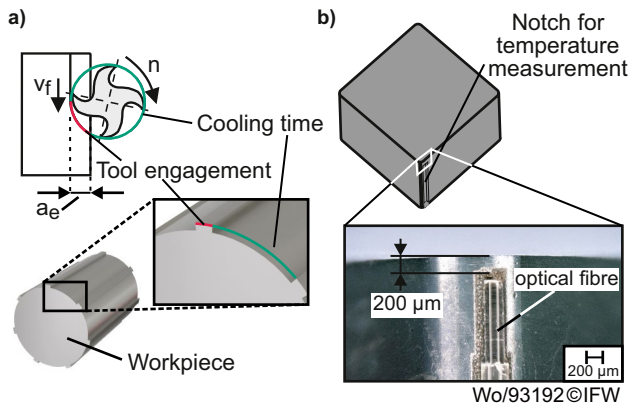
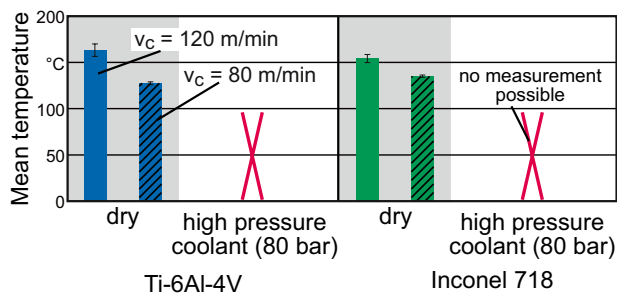


Fig. 7 Temperature measurement. **a)** Transfer of cutting conditions of milling to external longitudinal turning. **b)** Position of the optical fiber in the tool

The temperature was measured via optical fibers which were placed within these grooves.

Analogous to the investigations of Denkena et al. [10], the influence of the temperature is expected to be rather low due to the high-pressure cooling and coolant pressure of 80 bar. For this reason, cutting experiments are carried out under increased process parameters without cooling lubricant. After these investigations, the temperature measurement is carried out with the target process parameters using high-pressure cooling.

The results of the temperature measurement for both materials are shown in Fig. 8. At a cutting speed of 120 m/min in dry machining, the temperatures at the measuring location during machining of both materials are in the range between 150 and 170 °C. When the cutting speed is reduced, the temperatures decrease to values of 130 °C. It should be noted that the measuring point is in a distance of 200 µm from the cutting edge in the direction of the flank face. The



material Ti-6Al-4V/Inconel 718	process parameters $v_c = 120, 80, 60$ m/min $a_p = 0.1$ $f = 0.08$ mm	
process External longitudinal turning		Wo/93191 ©IFW

Fig. 8 Results of the temperature measurement

measuring point is therefore close to the area that is important for the later design of the flank face modification but distant from the range of maximum temperatures of the cutting process. Taking into account the measuring point, the results of the temperature measurement are comparable with the results of other authors under comparable process parameters [18, 19].

Following the dry machining investigations, experiments were carried out using high-pressure cooling with a coolant pressure of 80 bar and a cutting speed of 60 m/min. In this case, temperatures < 110 °C are present at the measuring point. This means that the temperature is below the measuring range of the single-color pyrometer used. In summary, however, the results show that the thermal stress in the area of the flank face modification can be considered to be rather low with the selected process parameters. It is expected that the thermal stress will not lead to a significant decrease in the strength of the carbide. For this reason, the thermal influence is not considered further in the design of the flank face modification.

3.3 Simulation-based design of flank face modification

The simulation-based design of the flank face modification was performed with a coupled parameter study with the computer-aided design (CAD) software SolidWorks and the FEM-software Ansys. The flank face modification was modelled in a given CAD model of the used end mills. Thereby, the geometric parameters of the flank face modification width S_b , depth S_t , and radius in the undercut r were set as degrees of freedom as shown in Fig. 1. Within the FEM simulation, the geometric parameters were varied according to Table 6. This results in a total of 485 simulation results as data points for a regression model.

In order to apply the determined mechanical load in the FEM analysis to the tool, the maximum chip cross section at the given process parameters was projected onto the rake face of the CAD model. To minimize the error in the force direction along the cutting edge, it was divided into sections. In the area of the radius of the milling tool, segment sizes of 0.3 mm were used whereas in the area of the peripheral cutting edge, the segment size is 0.6 mm. Fig. 9 shows the segmentation of the cutting edge. On the respective sections the cutting force coefficients are applied as

Table 6 Variation of parameters for FEM-based modelling

Geometrical parameter		Dimension [μ m]
Width of the undercut	S_b	50, 60, 70, 80, 90, 100
Depth of the undercut	S_t	50, 60, 70, 80, 90, 100
Radius in the undercut	r	160, 170, 180, 190

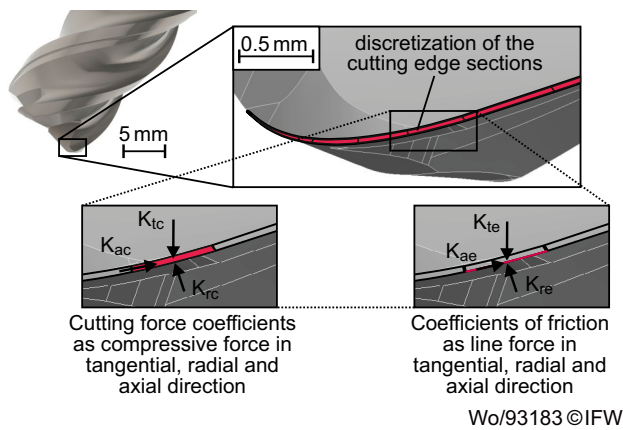


Fig. 9 Force introduction through cutting and friction coefficients

surface load and the friction coefficients as line load at the cutting edge. Subsequently, the FEM model was meshed. In order to obtain a good compromise between the required computing time and mesh quality, a second-order tetrahedral mesh was used. In the area of the flank face modification, where the greatest stresses are to be expected, a mesh refinement was carried out until convergence was achieved. The criterion for achieving convergence was a change in the result value of 0.2%. In this area, the average characteristic length of the elements is $6\mu\text{m}$. Using FEM analysis, the maximum compressive stresses in the undercut of the modification were simulated and evaluated. The evaluated area is shown in Fig. 10. The maximum stresses occur in the area close to the maximum depth of cut a_p , therefore this area is considered critical for the application behavior of tools with flank face modification.

Taking into account the variation of the geometric parameters, regression models of the maximum compressive stress as a function of depth and width of the undercut could be generated for each radius in the undercut. Such a regression model for a radius of the modification of $160\mu\text{m}$ when machining the material Ti-6Al-4V is shown

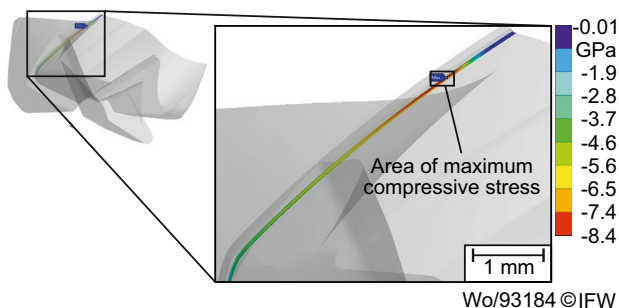


Fig. 10 Area of maximum compressive stress in the undercut of the modification

in Fig. 11. Figure 11a shows the regression model with a coefficient of determination of $R^2 = 0.99$. Figure 11b shows the iso-lines of constant compressive stress as a function of width and depth. In addition, the curve for a constant compressive stress of 6.6 GPa is drawn. This value corresponds to the maximum compressive strength of the carbide substrate used and serves as a failure criterion in this study. Modifications with parameter combinations on the left side of this line should lead to an unstable modification and promote the occurrence of cutting edge breakout. Modifications with parameter combinations on the right side of this line are supposed to result in stresses low enough to prevent substrate failure.

4 Results and discussion

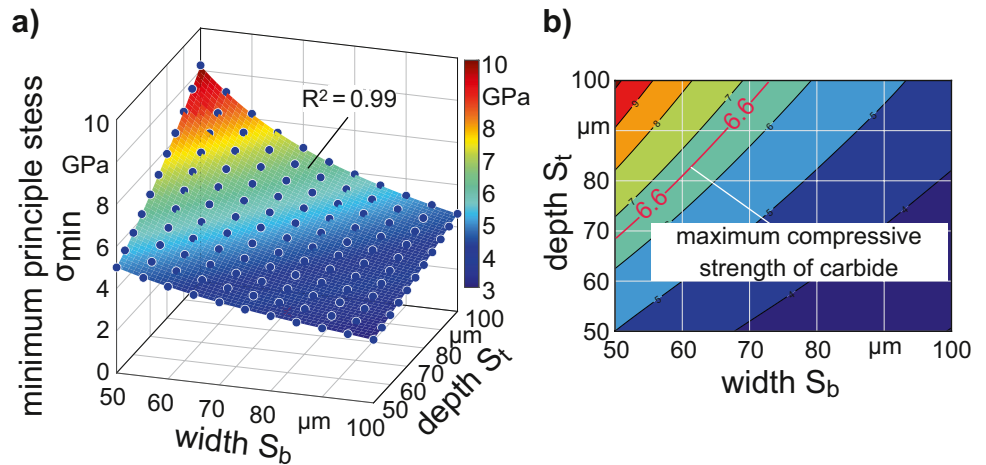
4.1 Validation of the simulation model

A comparison of all isolines for 6.6 GPa of the corresponding radii is shown in Fig. 12. It is noticeable that the possible parameter range for a stable modification is larger when machining the alloy Ti-6Al-4V due to the higher mechanical load when machining Inconel 718 despite reduced process parameters. A selection of milling tools with different geometric parameters regarding the undercut was ground for the machining of Ti-6Al-4V and Inconel 718 respectively. Following the grinding process, the end mills were reworked by drag finishing and then coated. Each dot in Fig. 12 corresponds to one milling tool. The color of each dot indicates the radius r in the undercut.

Machining tests were carried out to verify the model. Figure 13 shows microscopy images of the milling tools 1 and 2 after an operating time of 8:30 min and 0:50 min respectively from the tip of the milling tool and from the area of the maximum cutting depth. The position of the tools in the parameter field of the simulation can be seen in Fig. 12. Even after an operating time of 8:30 min, there is still an intact cutting edge for tool 1. On the other hand, tool 2 shows a breakout of the cutting edge in the area of the maximum cutting depth. According to the simulation, this is the area where the highest stresses appear. However, when considering the isolines in Fig. 12, it is noticeable that according to the simulation, both tools lie in an area with unstable flank face modification. Accordingly, the true fracture limits of the flank face modification are located further in the range of lower widths and greater depths of the undercut than calculated by the simulation.

Similarly, Fig. 14 shows tools that were used in the machining of Inconel 718 after an operation time of 8:00 min and 1:30 min respectively. Again tool 3 shows an intact cutting edge even after extended operating time, whereas tool

Fig. 11 Results of the FEM analysis of the stress in the undercut when machining the alloy Ti-6Al-4V with a radius of modification of $r = 160 \mu\text{m}$. (a) Regression model. (b) Isolines of constant stresses



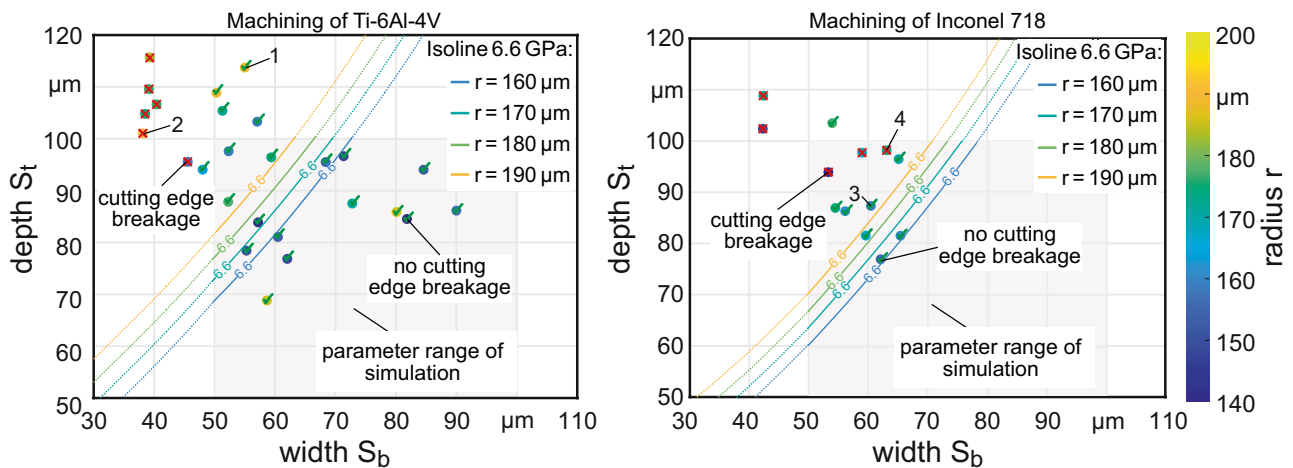
Wo/93188 ©IFW

4 shows chipping along the whole length of the cutting edge after an operating time of 1:30 min. In this case, both tools are located near the calculated fracture limits. However, there is still a slight shift in the real fracture limits compared to the calculated fracture limits in the direction of smaller widths and larger depths, although much smaller than is the case with the tools for machining Ti-6Al-4V.

The investigations presented show that milling tools with flank face modification can be used successfully when machining difficult to cut materials. It is also evident that the chosen design methodology is in principle suitable for the design of the flank face modification even though there is a shift between the real and the simulated fracture limits. Since in both cases there is a shift of the real fracture limits towards smaller widths and larger depths of the undercut, the simulated fracture limits represent parameter combinations that reliably prevent catastrophic failure of the cutting

edge. For a validated design, however, it is still important to know the cause of these deviations. One difference can be attributed to an overestimation of the stresses in the simulation. The simulation represents the critical case in which the chip cross section along the cutting edge corresponds to a constant value. In this case, this value is equal to the maximum chip cross section at the selected process parameters. In the real process, however, varying chip cross sections occur along the cutting edge due to the helix angle of the milling tool. This fact was not taken into account in the simulation. The assumption of constant chip cross sections along the cutting edge can thus be considered a safety factor in the design of the flank modification.

Another factor that can lead to deviations between simulation and experimental results is the elastic material springback at the flank face. According to Bergmann [20], elastic chip thickness springback is particularly pronounced in



Wo/106485©IFW

Fig. 12 Isolines for 6.6 GPa for the corresponding radii for Ti-6Al-4V an Inconel 718

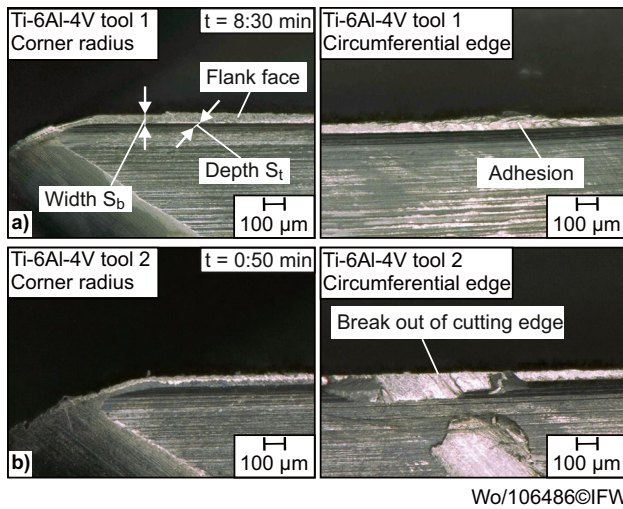


Fig. 13 Milling tools with flank face modification after an operating time of 8:30 min for tool 1 and 0:50 min for tool 2 for the material Ti-6Al-4V; (a) tool 1, (b) tool 2

materials with a higher ratio of tensile strength R_m to modulus of elasticity E . Due to the higher material springback, an increasing proportion of the minimum chip thickness is elastically deformed. This results in increased contact with the flank face. In this case, the forces acting on the flank face can contribute to a stabilization of the flank face modification. In subsequent investigations, the tangential and normal stresses in the area of the cutting edge in the direction of the flank face are determined according to Bergmann [20] and integrated into the simulation.

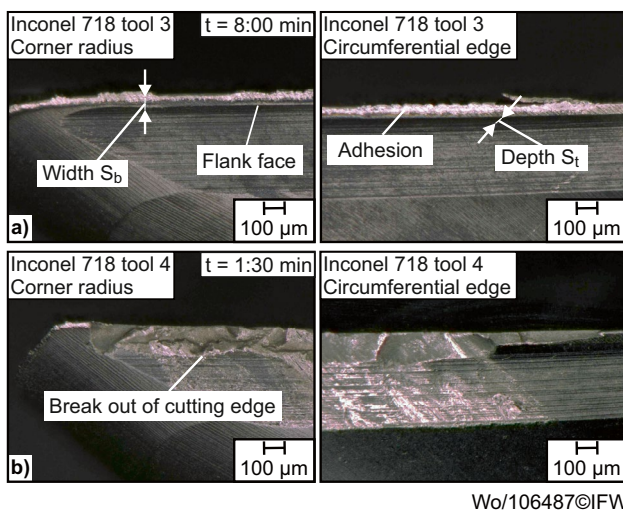


Fig. 14 Milling tools with flank face modification after an operating time of 8:00 min for the tool 3 and 1:30 min for tool 4 for the material Inconel 718; (a) tool 3, (b) tool 4

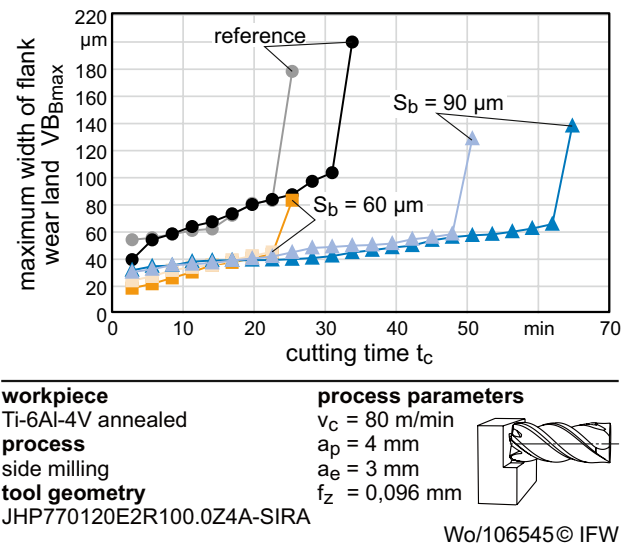


Fig. 15 Results of the wear tests on Ti-6Al-4V

4.2 Investigations on the performance of tools with flank face modification

Solid carbide end mills with different flank face modifications were produced using the design methodology. In addition to the milling tools with flank face modification, the reference tools without flank face modification were also manufactured within this work. In this way, possible influences from the grinding process are kept constant for all tools used. Figure 15 shows the results of the wear tests for the alloy Ti-6Al-4V. The experiments were carried out with increased process parameters compared to the design methodology. In this context, the cutting speed was increased from 60 to 80 m/min. For all tools, the wear criterion was reached in the form of chipping along the cutting edge. In the case of the reference tools, the end of tool life occurred after a maximum of 33 min of cutting time due to the occurrence of chipping on the cutting edge in the area of the maximum depth of cut a_p . For the wear tests of the tools with flank face modification, two tool groups were selected that differ primarily with regard to the width of the flank face modification S_b . The first group of these tools have a width of the flank face modification S_b of 60 μm . These tools did not show any increase in tool life compared to the reference tools. The end of tool life was reached after a maximum operating time of 25 min. One of the tools is shown in Figure 16. In this tool, a chipping of the flank face modification occurred below the cutting edge in the area of the corner radius of the milling tool. With the second tool, a shaft fracture occurred within the cutting time. One reason for the failure of both tools may be the increase in mechanical stress on the tools with progressive tool wear. Due to the wear, there

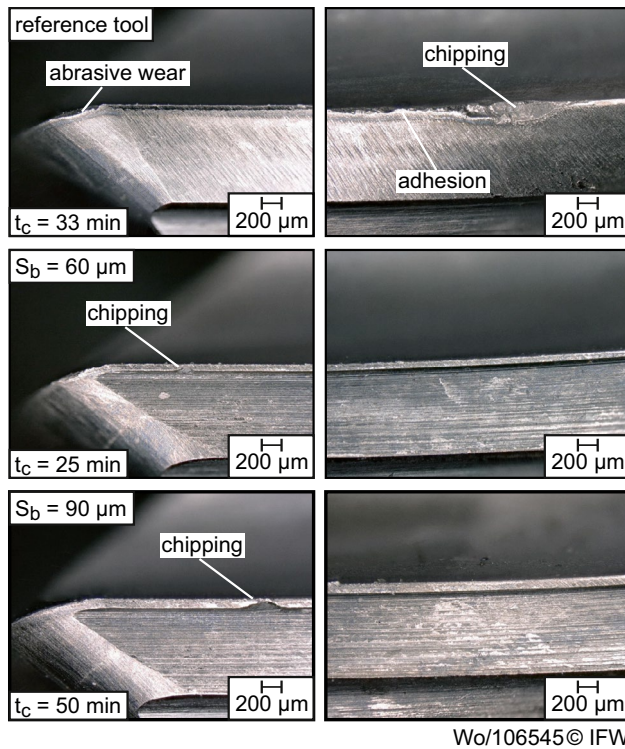


Fig. 16 Microscopy images of the worn tools after milling of Ti-6Al-4V

is an overload in the area of the flank face modification and thus tool failure occurs. In contrast, the use of tools with a width of $S_b = 90 \mu m$ leads to an average tool life increase of 108%. The operating time until the end of tool life is larger than 50 min for both tools. For these tools, the end of tool life is also determined by chipping on the flank face below the cutting edge.

Figure 17 shows the results of the wear tests on the alloy Inconel 718. Analogous to the procedure for machining the alloy Ti-6Al-4V, four tools with flank face modification were used in addition to the reference tools. These tools differ in terms of the width of the modification on two levels. The wear criterion in these experiments was also achieved in the form of chipping on the cutting edge or the flank face modification. For both reference tools, the end of tool life is reached after a cutting time of $t_c = 29$ min. The tools show adhesions on the cutting edge during the entire tool life. As the time in use progresses, these adhesions eventually lead to the formation of microchipping and finally to the formation of larger chipping due to continuous removal of cutting material from the cutting edge. These lead to the end of tool life. Subsequently, the tools with flank face modification were used. Neglecting tool number 26, an average tool life increase of 22.5% was achieved. Tool 26 showed an early chipping in the area of the maximum depth of cut a_p , which led to the

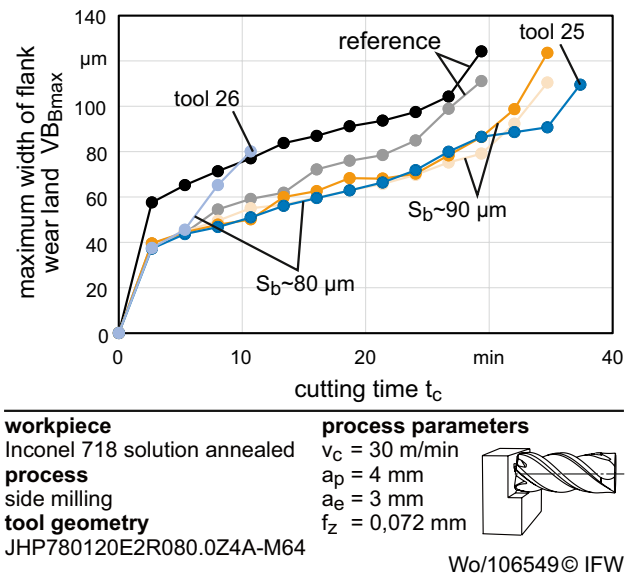


Fig. 17 Results of the wear tests on Inconel 718

end of the tool life after a short time. It is noticeable that this chipping only occurred on the second cutting edge. However, by examining the geometries of each individual cutting edge, manufacturing deviations could be excluded. Therefore, it is assumed that this cutting edge had a previously unnoticed damage that led to the unfavorable fracture behavior. Apart from this fact, the wear behavior of the other tools with flank face modification corresponds to the behavior of the reference tools. Here, too, the wear process is characterized by adhesion, which favors the occurrence of micro-chipping and later larger chipping due to the continuous removal of cutting material from the cutting edge. As the experimental investigations show, however, this behavior is delayed compared to the reference tools and finally leads to an increase in tool life, although less pronounced than when machining the alloy Ti-6Al-4V (see Fig. 18).

4.3 Design guideline for tools with flank face modification

Through the experimental investigations carried out for this work, the following desing guideline can be applied based on experiments.

- As expected, the radius in the area of the flank face modification of the milling tool has a great influence on the formation of stresses in the radius of the flank face modification. Therefore, the selected radius in the modification area should tend to be larger. Within this work, grinding wheels of geometry 1A1 with a diamond grain size of D54 were used for grinding the flank face

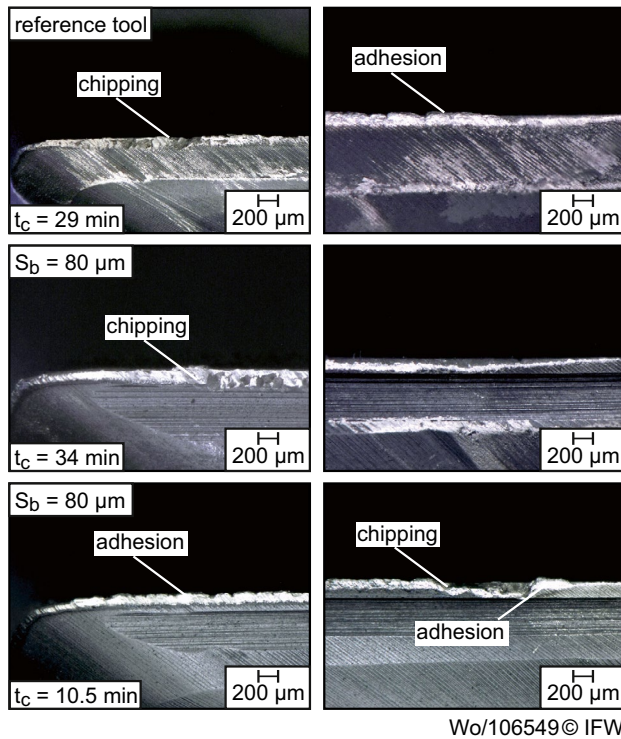


Fig. 18 Microscopy images of the worn tools after milling of Inconel 718

modification, where the radius was trued as sharply as possible which resulted in a radius $r = 90 \mu\text{m}$. The radius on the used grinding wheel created in this way still shows sufficient geometric accuracy even with an increasing number of ground milling tools. When using grinding wheels with a smaller diamond grain size of D46 or D33, a smaller radius of 55 to $70 \mu\text{m}$ can be trued on the grinding wheel. Therefore, smaller radii can be ground in the modification area. However, with an increasing number of ground tools, the geometry changes rapidly. This means that the grinding wheel has to be trued at short intervals when using smaller diamond grain sizes.

- As tool wear on the milling tool progresses, mechanical stress on the tool increases. This can lead to a failure of the tool with flank face modification because the maximum compressive strength of the carbide substrate is exceeded. The depth of the flank face modification S_t should not be chosen larger than the width of the flank face modification S_b to prevent tool breakage with increasing tool wear.
- In general, the depth of the flank face modification S_t has a greater influence on the formation of stresses than the width of the flank face modification S_b . For radii $r > S_t$, it is recommended to use a ratio of S_t/S_b of 1:1, whereas for radii $r < S_t$ the ratio of S_t/S_b should be at least 1:1.2.

5 Conclusion and outlook

In this work, the design and application of flank face modifications on solid carbide end mills for machining difficult-to-machine materials were investigated. Based on the results presented, the following conclusions can be drawn:

1. The design of the flank face modifications was successfully carried out using FEM analyses.
2. When designing the flank face modifications, the temperature influence can be neglected due to the distance to the contact area between tool and workpiece.
3. The results of the application tests show that the use of tools with flank face modification is possible in principle for milling difficult-to-machine materials. Contrary to the simulation results, however, the fracture limit for the flank face modification is shifted to smaller width and greater depth of the undercut. This can be traced back to the elastic material springback at the flank face which can contribute to stabilizing the modification. This has not been taken into account in the simulation so far and is the subject of further investigation.
4. In all tests, the end of tool life was reached by chipping at the cutting edge.
5. The use of tools with flank face modifications can increase the tool life when machining the alloy Ti-6Al-4V by an average of 108% within these experiments. When machining the alloy Inconel 718, the average increase in tool life is 22.5%.

Flank face modification can be used to effectively limit the contact between the flank face of the tool and the workpiece. It is assumed that in this way the thermomechanical load on the surface can be limited as well. This will be investigated in subsequent work. By reducing the thermomechanical load through the machining process, the occurrence of tensile residual stresses in the component surface can be reduced. This can contribute to an increase in the service life of the component. This aspect is also the subject of further investigations.

Author Contributions All the authors contributed to the study conception and design. The experimental work and the theoretical analysis were performed by Sebastian Worpenberg. The manuscript was written by Sebastian Worpenberg. Berend Denkena acquired the funding for the project leading to this publication. Berend Denkena and Benjamin Bergmann reviewed the manuscript. All the authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. Research project 20765 N is supported by the AiF-Forschungsgemeinschaft Werkzeuge und Werkstoffe e.V., Remscheid (FGW) as an AiF research association. Funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a resolution of the German Bundestag.

Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication The manuscript is approved by all the authors for publication; all the authors listed have approved the manuscript that is enclosed.

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Klocke F, Krämer A, Sangermann H, Lung D (2012) Thermo-mechanical tool load during high performance cutting of hard-to-cut materials. *Procedia CIRP* 1:295–300
- Lütjering G, Williams JC (2007) *Titanium*, 2nd edn. Engineering Materials and Processes, Berlin and New York
- Rahman M, Wong YS, Zareena AR (2003) Machinability of titanium alloys. *JSME Int J Ser C* 46(1):107–115
- Wyen, C-F, Wegener, K (2010) Influence of cutting edge radius on cutting forces in machining titanium. *CIRP Annals* 59(1), 93–96
- Köhler J, Grove T, Maiß O, Denkena B (2012) Residual stresses in milled titanium parts. *Procedia CIRP* 2:79–82
- Dudzinski D, Devillez A, Moufki A, Larrouquère D, Zerrouki V, Vigneau J (2004) A review of developments towards dry and high speed machining of inconel 718 alloy. *Int J Mach Tools Manuf* 44(4):439–456
- Denkena B, Köhler J, Meyer R, Stiffel JH (2011) Modification of the tool-workpiece contact conditions to influence the tool wear and workpiece loading during hard turning. *Int J Automot Technol* 5(3):353–361
- Bücker M, Oezkaya E, Zimon M, Biermann D (2018) Investigations on the effects of an innovative flank face modification for the drilling of nickel-base alloys. *Procedia Manufacturing* 18:20–26
- Bücker M, Oezkaya E, Hensler U, Biermann D (2020) A new flank face design leading to an improved process performance when drilling high-temperature nickel-base alloys. *SSRN Electron J*
- Denkena B, Köhler J, Bergmann B (2015) Development of cutting edge geometries for hard milling operations. *CIRP J Manuf Sci Technol* 8:43–52
- Denkena B, Bergmann B, Grove T, Pape O (2017) Increasing productivity in turning of hard-to-cut materials by means of modified flank faces. *Procedia Manufacturing* (14):97–104
- Grove T (2015) *Hochleistungszerspannung von Titan: Zugl.: Hannover, Univ., PhD-Thesis, 2015, Berichte aus dem IFW, vol 2015.4. Garbsen*
- Haynes International (2020) *Haynes 718 alloy*
- Slama C, Abdellaoui M (2000) Structural characterization of the aged inconel 718. *J Alloys Compd* 306(1–2):277–284
- Engin S, Altintas Y (2001) Mechanics and dynamics of general milling cutters Part i helical end mills. *Int J Mach Tools Manuf* 41(15):2195–2212
- Denkena B, Pape O, Grove T, Mücke A (2019) Advanced process design for re-contouring using a time-domain dynamic material removal simulation. *Procedia CIRP* 79:21–26
- Denkena B, Mücke A, Schumacher T, Langen D, Hassel T (2018) Technology-based re-contouring of blade integrated disks after weld repair. In: *Proceedings of the ASME Turbo Expo: Turbomachinery Technical Conference and Exposition - 2018, The American Society of Mechanical Engineers, New York, N.Y*
- Birmingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New observations on tool life, cutting forces and chip morphology in cryogenic machining ti-6al-4v. *Int J Mach Tools Manuf* 51:500–511
- Armendia M, Garay A, Villar A, Davies MA, Arrazola PJ (2010) High bandwidth temperature measurement in interrupted cutting of difficult to machine materials. *CIRP Ann Manuf Technol* 59(1):97–100
- Bergmann B, Grove T (2018) Basic principles for the design of cutting edge roundings. *CIRP Annals* 67(1), 73–78