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DISCONTINUOUS DRILLING OF INCONEL 718

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Abstract
Inconel 718 as one of the most common nickel-base alloys is mainly characterized by its high-temperature strength. Thus, in particular drilling is subject to high tool wear due to high thermomechanical loads on the cutting edges. To reduce those effects an alternative process design of discontinuous drilling was developed which contains a periodical interruption of the machining process with the aim of a targeted wetting and cooling of the tool at regular intervals. Thus, a significant reduction of the thermal load on the tool should provide a benefit to the drilling process and extend the tool life. Numerical and experimental investigations were used to analyze the introduced process strategy modification.

Keywords:
Inconel 718; drilling; thermal effects; simulation

1 INTRODUCTION

Due to their high strength and temperature resistance, nickel-base alloys are proven materials, especially in the aerospace industry. They are predestined for turbine blades, exhaust gas components, reactors and turbochargers [Steffens 2000, Bürgel 2011, Heubner 2012]. Furthermore, the corrosion resistance of nickel-base alloys in general enables these materials to be used in power plant construction as well as in the oil and chemical industries. Due to this high loading capacity, however, machining of the nickel-base alloy Inconel 718 also represents challenges, which are derived from its low thermal conductivity, simultaneously high toughness and good oxidation resistance [Wessels 2007, Donachie 2008]. Since the high thermal loads on the cutting edge accelerate the tool wear, the development of optimized strategies for the supply of coolant lubricant is increasingly in the focus of research.

1.1 Characteristics of Drilling of Inconel 718

As already mentioned, the nickel-base alloy Inconel 718 is characterized by its particularly pronounced high-temperature strength. In combination with high toughness and creep resistance, however, it is difficult to achieve productive and process-safe cutting parameters, especially in drilling due to its difficult-to-access cutting zone. These material characteristics favor high thermo-mechanical loads during drilling, which can lead to premature tool failure. Consequently, a sophisticated cooling strategy is essential for drilling processes. In this context, minimum quantity lubrication or dry machining are not suitable and cause almost direct tool failure [Wessels 2007]. Thermo-mechanical induced tool wear manifests itself on the one hand in an abrasive form, which is intensified by carbides as well as by strength-enhancing precipitations in the microstructure. On the other hand, the adhesion tendency of the material and the pronounced strain hardening promote the tool wear as well [Günther 1998, Veselovac 2013]. The mentioned thermal and mechanical effects and resulting wear also influence the workpiece quality by impairing the surface integrity and generating white layers. These base upon the alternating loads because of high thermal impact in the field of chip formation that has major influence on wear formation on the one hand and on workpiece quality on the other hand. Therefore, it is essential to remove the generated heat from the chip formation zone and to provide targeted cooling [Klocke 2011, Zhang 2013, Oezkaya 2019].

1.2 The research approach behind discontinuous drilling

Improving the chip breaking represents a possibility to counteract the described high thermal loads leading to high tool wear and reduced component quality concerning the machining of Inconel 718. Conventional drilling processes with pronounced ribbon chip formation often intensifies friction mechanisms at the secondary shear zone, resulting in increased process temperatures and affecting the tribological system. This aspect can be eliminated by obtaining short breaking chips, which can be done e.g. mechanically. Superimposing axial oscillation on the feed movement can lead to a process improvement, specifically in twist and single-lip deep hole drilling [Pecat 2014, Brinksmeier 2015, Bleicher 2019]. The periodically occurring interruption of the cutting process results in improved chip breaking behaviour for a large number of materials, but also in increased process forces compared to conventional drilling with the same material removal rate [Okamura 2006]. However, Pecat and Brinksmeier achieved in experiments on drilling under coolant lubricant a reduction of the cutting temperature $\Delta T \approx 43$ % [Pecat 2014, Brinksmeier 2015]. This result can be attributed to reduced friction between chip, tool and bore wall and, in addition, to the fact that the interruption of the cut enables the flush of the tool with cooling lubricant.

The central motivation behind discontinuous drilling is to consistently intensify the described positive effect of wetting the cutting edge and thus to guarantee an optimal coolant supply of the chip formation zone. The research of discontinuous drilling bases on Abele et al., as the authors proves that drilling tools experience a reduction of the achievable drilling path by up to 70 % when the length-to-diameter ratio l/d = 5 is increased to l/d = 30 [Abele 2007]. Apart from the increased tendency to oscillation, which is identified as the cause by the authors, an increased thermomechanical load associated with increasing cutting time without wetting and cooling the tool tip, can be suggested, too.

During investigations of discontinuous drilling of Inconel 718, the interdisciplinary integration of experimental and numerical investigations plays a decisive role in reducing the thermal load on tool and workpiece. As research will progress, the observation of the coolant lubricant supply will be fundamental, since it is responsible for the eduction of the process heat. In this context, numerical simulations are of great value for analyzing drilling processes, which is proven exemplary by the work of Biermann, Mieszczak, Oezkaya or Yang. Their research focused on the numerical examination of drilling to improve the machining process by predicting cutting forces or tool temperatures via thermo-mechanical finite element or CDF-models, investigating characteristics of fluids and heat input into the workpiece (Biermann 2013, Mieszczak 2010, Oezkaya 2016, Yang 2009).

2 EXPERIMENTS ON DISCONTINUOUS DRILLING OF INCONEL 718

The experiments were carried out on a special deep-hole drilling machine *tibo KTE 40-1000*. The cooling lubricant used is the cutting oil *Blaser Blasomill 10 D*, characterized by a viscosity of $v = 10$ mm²/s and a density of $\rho = 0.85$ g/cm^3.

2.1 Experimental setup

For the experimental analysis of drilling Inconel 718 a round, annealed and aged specimen with a diameter of d = 200 mm was used. The material's chemical composition is presented in **Tab. 1** and bases on the inspection certificate of the manufacturer. The material hardness was measured over the diameter and is an average of H = 490 HV30. The tensile strength of the material is $R_m \approx 1404$ MPa.

Tab. 1: Chemical composition of Inconel 718 (in wt-%)

Ni	Cr	Mo	Ti	Nb	Fe
52.66	18.48	3.06	0.97	5.35	18.43

Fig. 1 presents the experimental setup. Besides the workpiece and its clamping, the figure shows the tool used in the experiments that was clamped into a *Kistler 9170A* rotating dynamometer. This device measures the occurring feed force F_f and the drilling torque M_b during the machining process. Additionally, the figure contains an overview of the twist drill as well as its properties. Detailed microscope images of the twist drill's flank and rake faces in new condition were made (**Fig. 2**). The drilling tool used has a very stable design of the cutting edge due to its microgeometry and protective chamfer which is

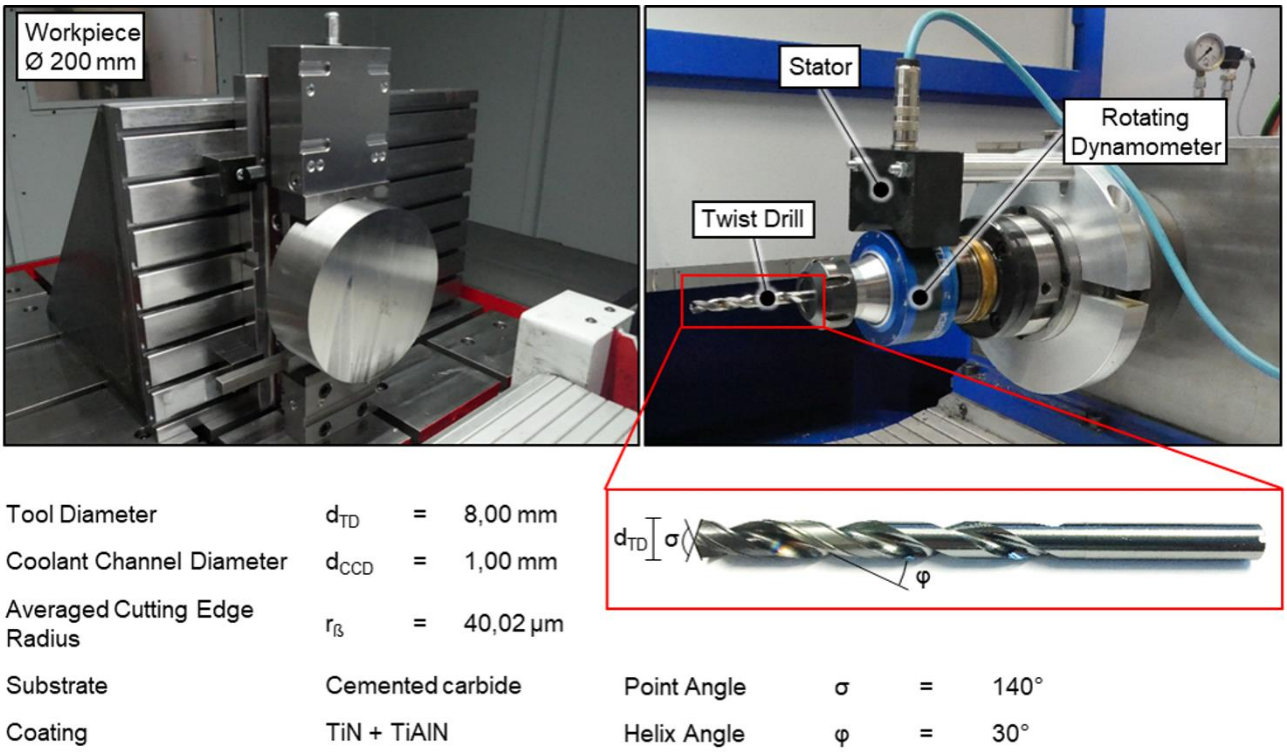

Fig. 1: Overview of the experimental setup and the properties of the twist drill

fundamental for its qualification for drilling of challenging materials.

The experiments focused on the comparison of continuous drilling (CD) with discontinuous drilling with three (DD-3) as well as seven interruptions (DD-7). Thereby, the total drilling depth was set to l_d = 64 mm.

The key aspect of the investigation on discontinuous drilling is the influence of the feed interruptions and the wetting of the cutting edges on the thermal load since the tool is flushed and can cool down in regular intervals.

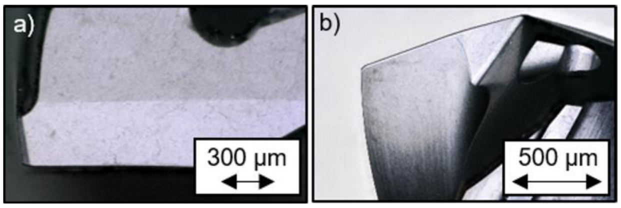

Fig. 2: Microscopies of the tool in new condition: a) flank face, b) rake face

According to this, the process parameters are fixed during the experiments to focus on the process strategies and their particular characteristics. An overview is given in **Tab. 2.**

Tab. 2: Overview of process parameters

v_c m/min	f mm	p_C bar	l_d mm	t_I s
25	0.1	40	64	2

The cooling lubricant supply was carried out through the internal coolant channels and kept at a constant pressure of p_C = 40 bar. In contrast to the conventional drilling, the alternative process design of discontinuous drilling contains interruptions of the tool's feed motion combined with a minor retraction movement from the chip formation zone of l = 2 mm. In this case, the time of each interruption was defined to be t_I = 2 s and is used to wet the cutting edges of the twist drill with cooling lubricant, in order to achieve beneficial tribological conditions and following reduced process temperatures. These parameters are chosen preliminary to guarantee a cooling effect of the cutting edge during the interruption of the tool's feed. In future research work these values have to be analyzed.

As described in **Tab. 3**, the drilling was periodically interrupted either three or seven times, so that the wetting of the cutting edges is renewed with varying frequencies.

Tab. 3: Design of experiments

Experimental approach	
Process kinematics	Interruption of feed after… of l_d = 64 mm
continuous	-
discontinuous	16- , 32- , 48- mm
discontinuous	8- , 16- , 24- , 32- , 40- , 48- , 56- mm

2.2 Experimental Results

Taking into account the parameters set, it can be stated as a result for all three process strategies examined that a drilling path of L_f = 2560 mm is achievable. **Fig. 3** shows the mechanical load on the twist drill, precisely the measured feed force F_f and the drilling torque M_b, occurring for continuous drilling, discontinuous drilling with three interruptions and seven interruptions, respectively. Apart from one outlier concerning the drilling torque M_b of continuous drilling at the stage of L_f = 768 mm the measured and averaged mechanical loads of the analyzed process strategies increase only slightly and are laying on the same level over the analyzed drilling path.

Since the process parameters of cutting speed v_c, feed f and drilling depth l_d are kept constant for analyzing the three process strategies, it is plausible that differences regarding the appearing mechanical load do not occur.

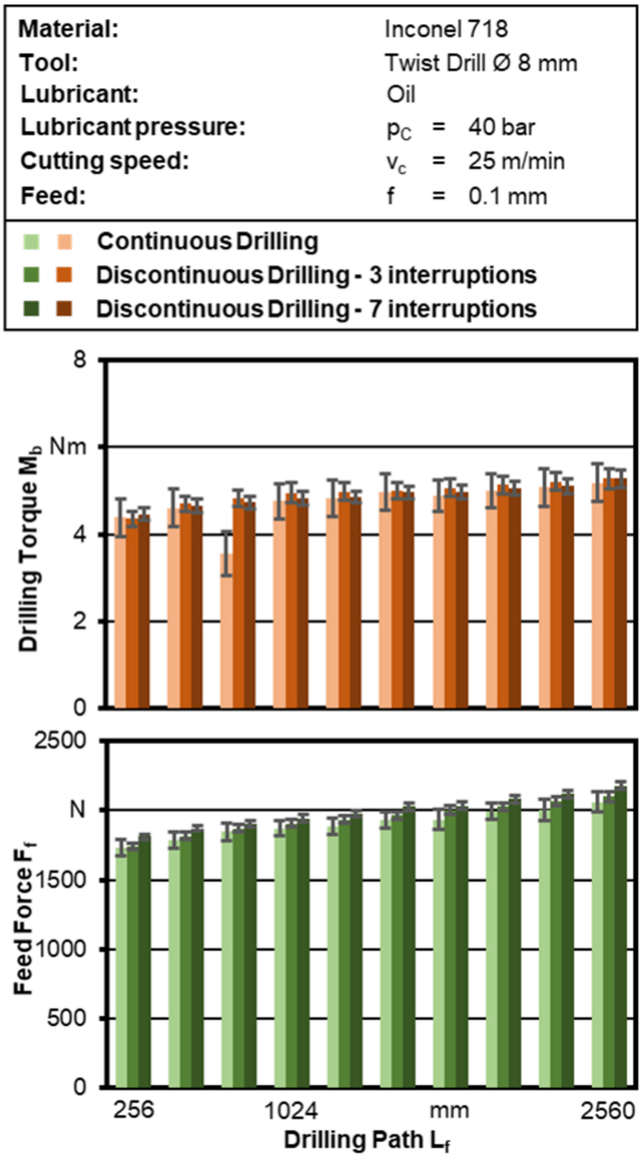

Fig. 3: Mechanical loads during drilling of Inconel 718

Additionally, as part of the experiments, the resulting chip form was analyzed in a defined and reiterating range of L_f = 256 mm. Firstly, it can be stated that drilling of Inconel 718 with the process strategies and parameters used results in beneficial chip formation and removal over the entire drilling path, as to be shown in **Fig. 4.**

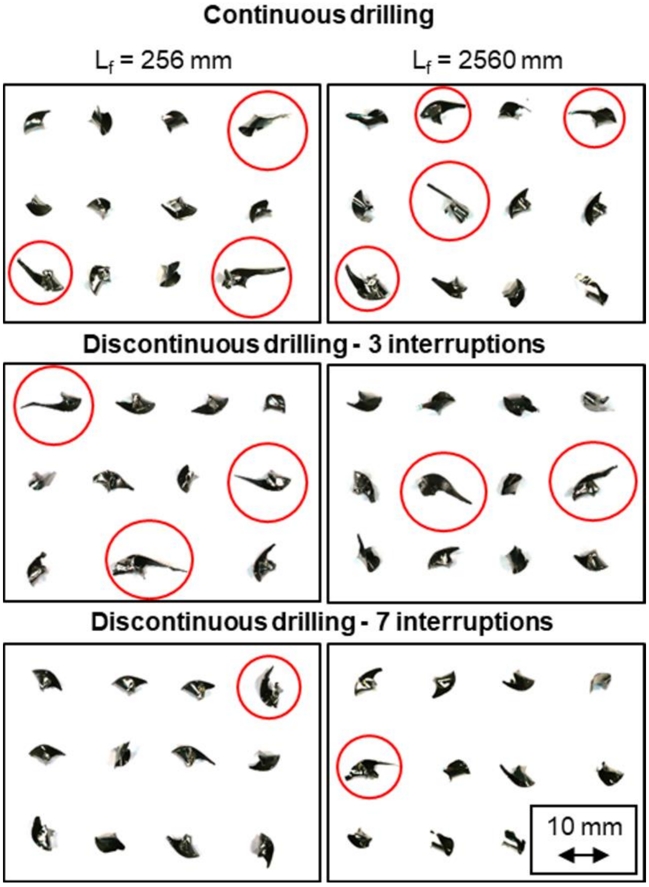

Fig. 4: Analysis of the resulting chip formation in continuous and discontinuous drilling of Inconel 718

However, seen over the drilling path, there is a recognizable further improvement in chip formation for discontinuous drilling, specifically for DD-7, which applied in particular to L_f = 2560 mm, while maintaining the same process parameters. In contrast to continuous drilling, the interruption of feed motion supports the chip breaking immediately. The subsequent cooling of the cutting edge by wetting the tool leads to reduced temperatures afterwards. When feed motion continues, this results in beneficial chip breaking over the drilling depth, in general. The figure emphasizes the improvement compared to continuous drilling by showing the amount of longer chips reminiscent of tails that is reduced with increasing insertion of interruptions. Since these kind of chips have a potential to stick to each other, it is desirable to prevent their formation.

An examination of the process specific flank wear shows further significant differences over the drilling path. As shown in **Fig. 5** at the beginning of the experiments the width of flank wear is nearly on the same level for all strategies. However, starting from a drilling path value of L_f = 512 mm the curves diverge. From L_f = 1536 mm the diagram shows a VB_{max} of continuous drilling that lays approximately 10 % above the one of discontinuous drilling with three interruptions, which also nearly corresponds with discontinuous drilling with seven interruptions.

Material:	Inconel 718
Tool:	Twist Drill Ø 8 mm
Lubricant:	Oil
Lubricant pressure:	p_C = 40 bar
Cutting speed:	v_c = 25 m/min
Feed:	f = 0.1 mm

Continuous drilling
Discontinuous drilling - 3 interruptions
Discontinuous drilling - 7 interruptions

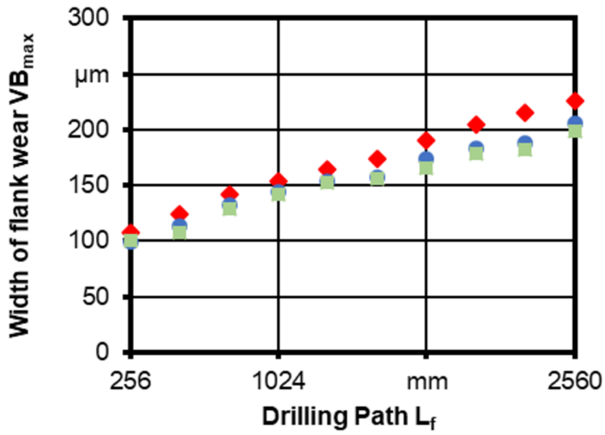

Fig. 5: Tool wear comparison between continuous and discontinuous drilling strategy

At the end of the investigations, corresponding to a drilling path of L_f = 2560 mm, the observed deviation between the conventional process strategy and the newly introduced discontinuous drilling still can be quantified to approx. 10 %. While measuring a maximum width of flank wear VB_{max} = 225,76 µm for a continuous feed at this point, the tools used in the experiments with three and seven feed interruptions show VB_{max} = 205,31 µm and VB_{max} = 198,68 µm respectively. From these results and the wear phenomena shown in **Fig. 6** can be assumed that the twist drills used can potentially achieve even higher drilling paths under the chosen standard process parameters, specifically if used for discontinuous drilling.

None of the twist drills exceeded the tool life criterion of VB_{max} = 300 µm and besides minor formation of built-up edge, mostly uniform and preferable flank wear occurs at the area of the cutting edge that faces the highest thermal load due to the highest cutting speed and thus friction at this position.

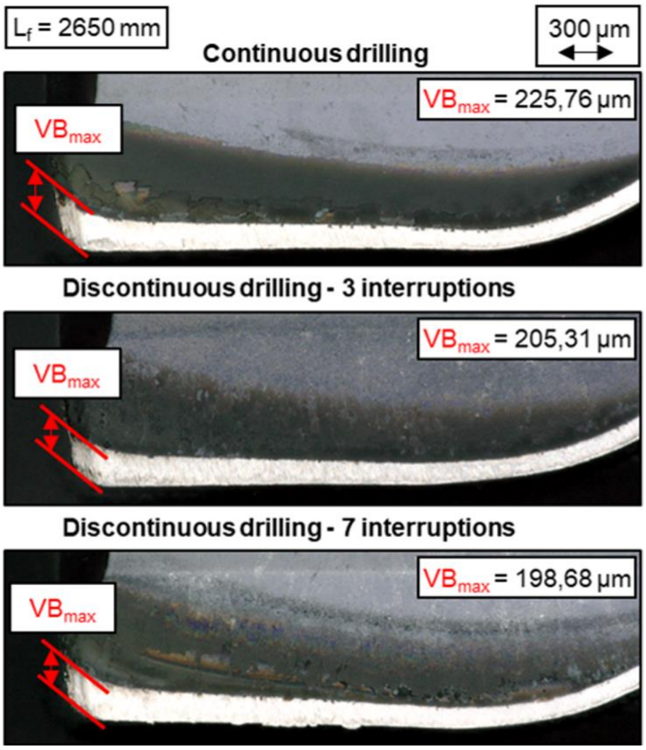

Fig. 6: Visual impressions of the tool's flank wear

The mentioned built-up edges and corresponding chipping are described in **Fig. 7** and occur due to the adhesion tendency of Inconel 718. Further, abrasive crater wear can be detected at the minor cutting edge that arise due to the contact with work-hardened material during the chip flow.

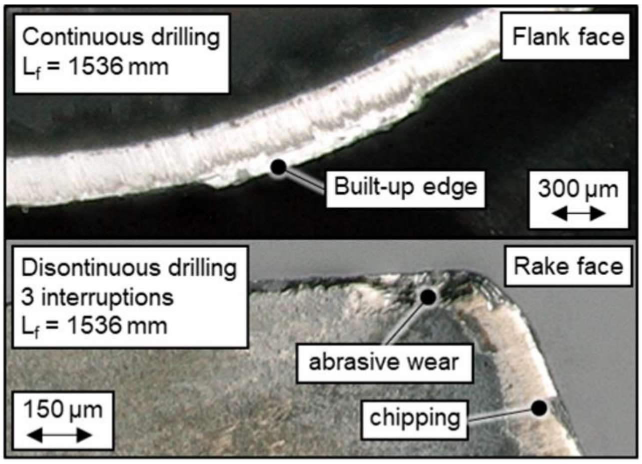

Fig. 7: Chipping at the minor and major cutting edge due to the effect of built-up edges

In consideration of the comparable mechanical loads that were measured for all examined process strategies, there are diverse widths of flank wear apparent. In this context, especially for drilling with seven interruptions, it can be assumed that the thermal load is reduced due to the periodical re-wetting and cooling of the cutting edge with cooling lubricant during the interruption intervals of $t_I = 2$ s. After the interruption, when the cutting process starts again, the cutting edge benefits from the lower temperature, the renewed lubrication and thus the reduced tribological action.

3 SIMULATION OF THE TOOL TEMPERATURE

In addition to the experiments on discontinuous drilling of Inconel 718, first simplified numerical studies were performed to review the thesis of reduced thermal loads and to obtain further impressions of the potential of the discontinuous process strategy in comparison to a conventional drilling process. For this numerical work, a thermal transient analysis was performed in *Ansys 2019 R3.* Based on the experimental process parameters, which are listed in **Tab. 2,** and used for both**,** continuous and discontinuous drilling, the process duration was calculated and transferred into a corresponding simulation time.

3.1 Definition of the parameters in the simulation

In the finite-element simulation, all of the settings made base on assumptions resulting from research work at the institute. The thermal loads affecting the tool during the cutting process are represented by a defined, linear increasing heat flow directly at the cutting edge where the chip formation takes place. This increase starts from an initial heat flow $\dot{Q}_{W,init} = 60$ W and reaches a stationary value $\dot{Q}_{W,stat} = 80$ W after $t_{inc} = 1.5$ s, which corresponds with the process heat from the experimental cutting parameters. This procedure represents the linearly decreasing cooling effect of the lubricant in the contact zone with proceeding drilling depth. At the same time, a convective heat exchange was applied to all the other surfaces of the drilling tool, at which the cutting fluid acts during feed motion. The corresponding surfaces are shown in the two top figures of **Fig. 8** and are valid for both process strategies analyzed. Additionally, for the simulation of discontinuous drilling, a further convective heat transfer of $v = 1500$ W/ m^2 · K has been applied to the cutting edge during the interruption time of $t_I = 2$ s. The comparative evaluation of the resulting temperatures is based on the maximum along the cutting edge. For the simulations, the CAD-model of the twist drill was imported to the software and was meshed with 163911 notes to ensure sufficient accuracy of the numerical results.

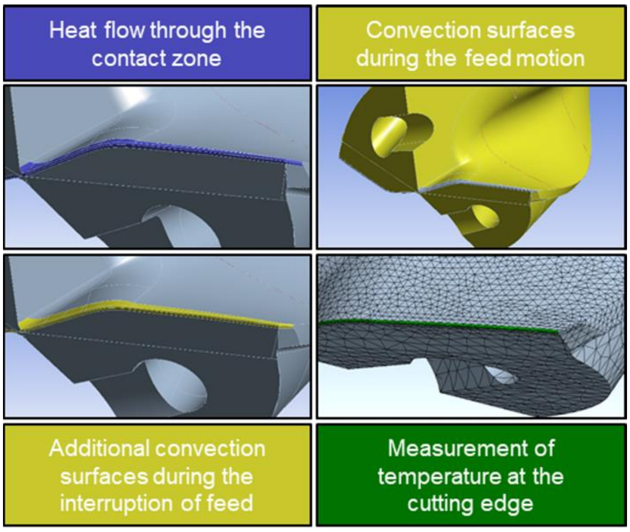

Fig. 8: Setting of input variables

3.2 Results of the simulations

The first simplified numerical simulations are offering first impressions of the resulting temperature curves depending on the different process strategies as shown in **Fig. 9**. Loading the cutting edges with a heat flow representing the increasing thermal load of continuous drilling leads to a constant temperature maximum of $T_C = 632$ °C over the whole drilling path. In contrast, it can be shown that a discontinuous process strategy could be able to reduce the proportion of feed motion where the maximum process temperature $T_C = 632$ °C is reached significantly. From inserting three or seven interruptions of heat flow and adding convection in this area simultaneously, it can be derived, that the thermal load of the tool is potentially reduced. Thus, decreased flank wear, as carved out in the experimental work, would be the consequence and indicating increasing tool life.

Cutting speed:	v_c	=	25 m/min
Feed:	f	=	0.1 mm
Heat flow:	$\dot{Q}_{W,init}$	=	60 W
	$\dot{Q}_{W,stat}$	=	80 W
Heat transfer coefficient:	v	=	$1500\ W/m^2 \cdot K$

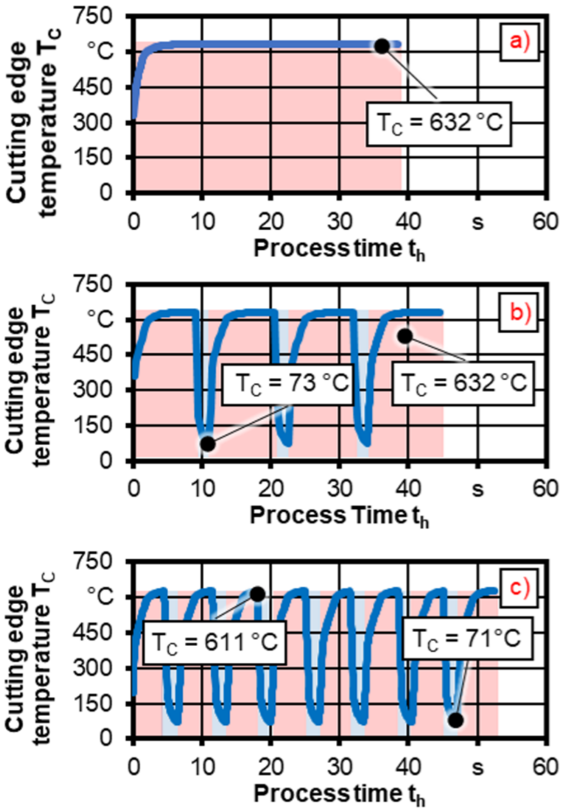

Fig. 9: Tool temperature simulations results. a) continuous, b) three interruptions, c) seven interruptions

By focusing on the curve for discontinuous drilling with seven interruptions this interpretation is emphasized and it can be concluded, that the process temperature maximum declines to T_C = 611°C. The higher number of interruptions that reduce the accumulated thermal load affecting the cutting edges during the drilling process could be a possible explanation.

4 SUMMARY

In conclusion, the first experimental and simulative research work gives good impression of the potential of a discontinuous machining process. It was pointed out that the flank wear at the twist drill benefits from adapting the feed motion to an interrupted process design by reducing thermal loading while the mechanical loading and the chip form remain nearly constant. Furthermore, a first numerical model was approximated to visualize the development of tool temperature in dependency of the process strategy and the results underline the demand of further research. Firstly, pyrometric measurements during continuous and discontinuous drilling will follow to detect the actual cutting temperatures while drilling Inconel 718. Additionally, high-speed recordings will help to detect characteristics of cutting fluid flow in front of the cutting edges. These experimental data will be included in the process model and will help to optimize it when connecting CFD-simulations with the simulation of chip formation. The final model can be used to increase productivity by analyzing process characteristics like the time of interruption and the feed.

Building on the presented experimental results, metallographic analyses of the bore holes to compare the particular surface integrity associated with the process strategies will be prepared. Another following and important part of the analysis will be the comparison between oil and emulsion for cooling lubrication to investigate the achievable effects under the different cooling performance of those fluids.

5 ACKNOWLEDGMENTS

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