PRODUCTION PROCESS

A novel method for chip formation analyses in deep hole drilling with small diameters

D. Biermann · M. Kirschner · D. Eberhardt

Abstract Recent trends of downsizing and miniaturization of components, e.g. in the automotive industry for the manufacturing of fuel injectors or in the medical industry for the production of bone screws or surgical instruments, increase the importance of mechanical deep hole drilling with small diameters. Unfortunately, there are still some open challenges regarding this process. In addition to the unfavorable ratio of the cutting edge rounding to the achievable feed rates and undeformed chip thicknesses which results in significant mechanical tool loads, the control of the chip formation and the removal constitutes a major difficulty. The slender tool dimensions, especially the small cross sections of the chip flutes, necessitate a favorable chip formation to achieve the required process safety and productivity. Therefore, analyses of the chip formation, when machining difficult-to-cut materials provide the means for an effective process design. This analysis, however, is particularly difficult due to the closed operating zone. Quick-stop devices used for the chip formation analyses so far are limited in the tool diameter respectively the revolution speed. Furthermore the informative value is limited, because a quick-stop test takes a significant time to stop and thus the instantaneous cutting conditions during the tool retraction are altered. To overcome these restrictions, a new method for the analysis of the chip formation in small diameter deep hole drilling is presented in this paper. It is based on the utilization of a high-speed camera and tailored material samples. The experimental set-up and the results of first analyses conducted under minimum quantity lubrication are presented. The chip formation process is analyzed for the single-lip gun drilling of the nickel-based alloy Inconel718 and the bainitic steel 20MnCrMo7.

Keywords Gun drilling · Small diameter machining · Chip formation · High-speed analysis · Nickel-based alloy · Bainitic steel

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1 Introduction

Regarding conventional deep hole drilling processes, single-lip deep hole drilling, ejector and BTA deep hole drilling are distinguished. Whereas single-lip deep hole drilling (SLD) is used for small diameter machining in the range of d = 0.5…40 mm, ejector- and BTA-drilling are used for applications in the diameter range of d = 18…250 mm respectively d = 6…2,000 mm. Under favorable conditions, bore holes with a length-to-diameter-ratio up to 250 can be produced [1, 2]. Conventional deep hole drilling processes are characterized by an asymmetrical tool design that requires a tool guiding during the initial work piece penetration. In the stationary drilling phase, cutting and passive forces are transferred as normal forces by the guide pads to the bore hole wall. The burnishing of the bore hole wall supports the production of high manufacturing qualities [2, 3]. In addition, twist drilling and double-lip gun drilling, featuring a symmetrical tool design, are also used for deep hole drilling. However, these processes are limited in the feasible length-to-diameter-ratio and the achievable manufacturing quality.

For small diameter machining, single-lip gun drilling and twist drilling are predominately used. Typical areas of applications in the range of d ≤ 2 mm can be found in the automotive industry for the production of fuel injectors and in the medical and biomedical industry, where holes in bone nails and screws have to be drilled for specific functional purposes [4, 5]. Due to the trends of downsizing and to improve the resource efficiency, e. g. in the automotive, rail traffic and power industry, the machining of high-strength steels, including small diameter deep hole drilling, becomes more and more relevant [6, 7]. Moreover, the small diameter machining of difficult-to-cut materials like nickel-based alloys is of utmost importance in the aerospace industry, e. g. for the production of turbine and compressor disks [8]. With regard to the number of possible application fields, it is surprising that scientific publications are limited to fundamental investigations for small diameter twist drilling with restricted length-to-diameter-ratios [9–13].

Particularly in deep hole drilling of high-strength and difficult-to-cut materials, the unfavorable ratio of the adjustable undeformed chip thickness to the cutting edge rounding results in an excessive tool load. The material removal takes place in the area of the cutting edge rounding under negative effective rake angles. Consequently, if the minimum undeformed chip thickness is not reached, the so called ploughing effect is predominant in front of the cutting edge [14].

Besides the consequences of the limited tool rigidity, a major challenge in small diameter deep hole drilling is the chip removal [5, 15, 16]. The production of unfavorable chip forms and long chips causes a rapid tool failure due to chip jamming. In twist drilling, the chip removal is supported by the curling of the chip flutes and the coolant pressure. In contrast, in SLD is the only mechanism supporting the chip removal, the coolant flow. To guarantee a residue-free chip removal, the coolant is fed under high pressure through the cooling channels inside the tool shank. The cross sections of the chip flutes in small diameter deep hole drilling, however, are extremely limited, which increases the importance of a favorable chip formation. In Fig. 1 the conventional theory of chip formation in single-lip deep hole drilling is shown.

According to the conventional theory of Fink [17], two separate chips are produced at the inner and outer cutting edge. The two chips are running off in opposed directions and thus interfere each other. The faster flowing chip at the outer cutting edge is frequently ripping the simultaneously produced chip at the inner cutting edge. In contrast to this conventional theory, Heilmann made different observations for small diameter single-lip drilling of stainless steel AISI316L (Fig. 2).

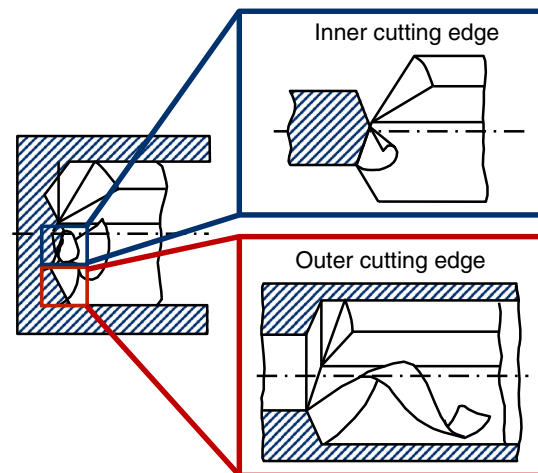**Conventional theory of the chip formation process in SLD by Fink**

Fig. 1 Chip formation in single-lip deep hole drilling [17]

Observations of Heilmann for small diameter SLD of stainless steel AISI316L
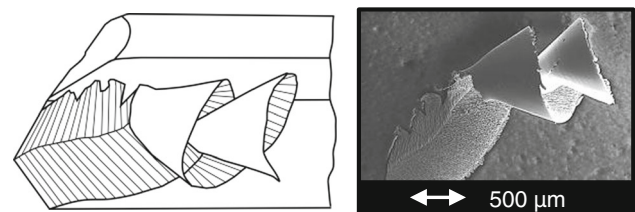

Fig. 2 Chip formation in small diameter deep hole drilling of AISI316L [5, 16]

Using the standard tool tip geometry, only one connected chip has been produced at the inner and outer cutting edge. Due to the low cutting speed in the tool axis area the chip tends to ripping in the respective zone. As shown in Fig. 2, a helical chip of a medium length has been formed. Furthermore, the tip of the gun drill is formed on the tail end of the chip. The chip removal becomes a particular challenge as a result of the width of the chip, a higher friction between chip and bore hole wall, as well as a tendency to chip clogging [5, 16]. To ensure high process stability and to realize the best possible productivity in small diameter drilling, the chip formation, as a crucial factor, needs to be investigated in more depth.

To generate a better understanding of the chip formation in drilling processes, a range of quick-stop devices has been developed by different researchers [18–23]. By the use of these quick-stop devices, chip roots are produced in the closed operating zone, which allow a detailed analysis of the chip formation and the material behavior in the operating zone to be performed. Nevertheless, the use of these quick-stop devices is restricted in the tool diameter,

respectively in the achievable revolution speed. A quick-stop test for small diameter deep hole drilling under application relevant cutting speeds, however, requires extreme revolution speeds and accelerations. In addition, a quick-stop test takes a significant time to stop and thus the instantaneous cutting conditions during the tool retraction are altered. An alternative to analyze the chip formation in detail is given by the use of high-speed cameras. By these means, the chip formation process has already been recorded for different machining processes, e. g. turning and reaming [24–27]. Due to the closed operating zone, the use of high-speed analysis in deep hole drilling has not been examined scientifically yet and requires a specific experimental set-up. This is an important contribution of this paper and is reported in the following.

2 Experimental set-up and procedure

The experimental analyses on single-lip deep gun drilling with a tool diameter of d = 2.0 mm were conducted on a Chiron 3-axis vertical machining center of type FZ12S. This machine offers a good accessibility of the operation zone and allows a high spindle rotation speeds up to n_{max} = 15,000 rpm, to be applied to the samples. The model of the test set-up in the working area is shown in Fig. 3.

The chip formation analysis was conducted for a stationary gun drill and a rotating sample. This setup allows a continuous focus on the cutting edge as well as on the rake face to observe the chip formation during the drilling process. The test samples were clamped via the collet chuck of the machine tool spindle. As the working zone in drilling processes is closed, a specific design of the test samples was required to allow the chip formation to be filmed. The design of the respective test samples used for

the high-speed chip formation analysis is presented in Fig. 4.

The test samples are made of a transparent acryl glass and specifically designed material samples, which were fixed inside the acryl glass rod by a frontal fixing screw. Both, the material samples and the rods made of acryl glass are manufactured by turning as well as turning and drilling. The machining was carried out on a CNC-turning lathe Monforts RNC 200A. A hole with a diameter of d = 2.0 mm and a length of 14 mm in front of the acryl glass rod is machined. This hole was used for the front shoulder of the work piece material sample and served as pilot hole during the run-in stage of the gun drill. The front shoulder of the material samples had a diameter of d = 1.95 mm and a length of l = 8 mm. Thus drilling of hulls is avoided as a result of the small undersize compared to the nominal diameter of the gun drills used. After inserting the material sample in the acryl glass a pilot hole of l_p = 6 mm (3×D) is left at the front side to guide the gun drill during the start of drilling.

The gun drill is clamped via a tool holding fixture on a multi-component load cell. The fixture is enhanced by an adapter for providing the lubricant supply. The load cell is triggered with the high-speed camera to allow a synchronized recording of the chip formation and the occurring mechanical tool loads. The load cell is stationary positioned on the machine table.

The chip formation process was recorded using a Keyence high-speed camera of type VW-9000. The recordings were made in a resolution of 256 × 128 pixel, with a 20-times magnification and a frame rate of 33,800 fps. The experimental analyses were conducted under minimum quantity lubrication (MQL) with a flow rate of approx. V_{MQL} = 50 ml/h and an air pressure of p_{MQL} = 16 bar. The feeding and use of MQL guarantees a no interference
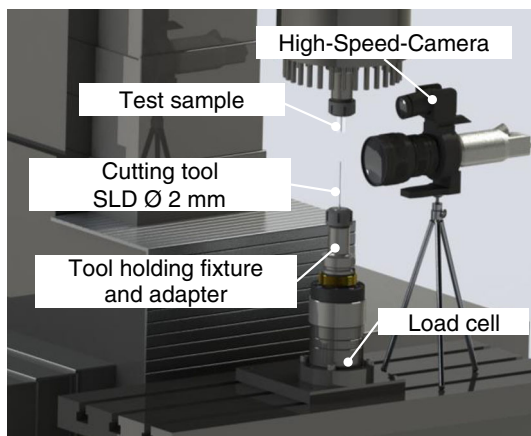

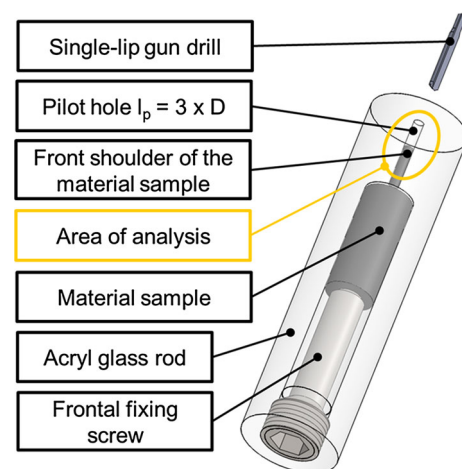**Fig. 3** Experimental set-up for the high-speed analysis

Fig. 4 Design of the test samples

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with the recordings of the chip formation process. Even though the industrial gun drilling of the focused materials is usually not running under MQL it allows to prove the validity of the novel method for chip formation analyses. Analyses under conventional flood cooling require further effort to record the chip formation and are planned in subsequent investigations.

The experimental analyses were focused on single-lip gun drilling with a diameter of d = 2.0 m. With respect to the single-lip gun drills a standard geometry, which is widely recommended for applications in this diameter range, was used [1]. In Table 1 a SEM-picture and selected specifications of the applied uncoated gun drills are shown.

The tool tip is characterized by angles of incidence of $\kappa_1 = 50°$ at the outer cutting edge and of $\kappa_2 = 120°$ at the inner cutting edge. The tools are made of cemented carbide grade K15 and have a circumferential shape G, which means that the gun drill is supported by one guide pad at the bore hole wall over an angle of approx. 115°. The initial cutting edge radii of the gun drills were about r = 6 μm.

As work piece materials, the nickel-based alloy Inconel718 and the high-strength, bainitic steel 20MnCrMo7 were analyzed. The difficult-to-cut super alloy is characterized by an austenitic microstructure and superior elevated-temperature and corrosion properties. Thus, the Inconel718 is often used in aerospace applications, for instance for turbine components. The material properties of Inconel718 are summarized in Table 2.

The bainitic steel 20MnCrMo7 offers high strength in combination with high toughness (Table 3). These material properties are obtained by a defined cooling phase after heating the material within forging or hot rolling processes. Consequently, a subsequent energy and cost intensive heat treatment is saved in comparison to usual heat-treatable steals. Potential applications can be found in the automotive industry, e.g. in the manufacturing of fuel injectors. Hence small diameter deep hole drilling of this material is a practically relevant process.

3 Validation of the experimental method

In preliminary tests, the validity of the new proposed method for analyzing the chip formation process in small diameter gun drilling processes was verified. Because the chip formation takes place along the tool tip the validation was concentrated on the chip formation and additionally the feed forces. The influence of the circumferential side-walls will be discussed in following analyzes regarding the wetting of the guide pads in single-lip deep hole drilling. In these tests, samples made of solid quenched and tempered steel 42CrMo4 and samples made of the same work piece

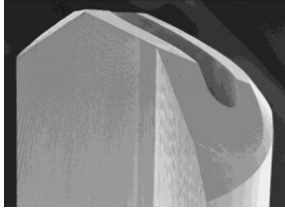**Table 1** Geometrical tool design of the gun drills used

Tool	Geometry
	$\varnothing$ = 2.0 mm K_1 = 50°; K_2 = 120° a_s = d/4 K15 Circumferential shape G

Table 2 Material properties of Inconel718 for room temperature

Work piece material	Inconel718
Tensile strength R_m	1,429 N/mm^2
Yield strength $R_{p0.2}$	1,227 N/mm^2
Hardness H_m	428 HB
Contraction of area Z	23 %
Breaking elongation A	17 %

Table 3 Material properties of the 20MnCrMo7 for room temperature

Work piece material	20MnCrMo7
Tensile strength R_m	1,253 N/mm^2
Yield strength $R_{p0.2}$	860 N/mm^2
Hardness H_m	388 HB
Contraction of area Z	47.8 %
Breaking elongation A	15 %

material, inserted in acryl glass, were machined under identical boundary conditions. The mechanical loads and the resulting chips were compared in order to ensure the comparability of both processes (Fig. 5).

The results of these preliminary tests are shown in Fig. 5. A similar chip form was produced in both tests. The difference in the mean value of the feed force is negligible. The slight deviation is caused by a marginal undersize of the material samples inside the acryl glass with respect to the nominal diameter of the gun drill. Consequently, the cross section of the undeformed chip is slightly reduced.

4 Analyses of the chip formation process in small diameter gun drilling

The analyses of the chip formation are divided into two parts. In the first part, the chip formation during the start of drilling and the obligatory phases are visualized for gun drilling Inconel718. In the second part the stationary chip formation process for the machining of both materials is considered.
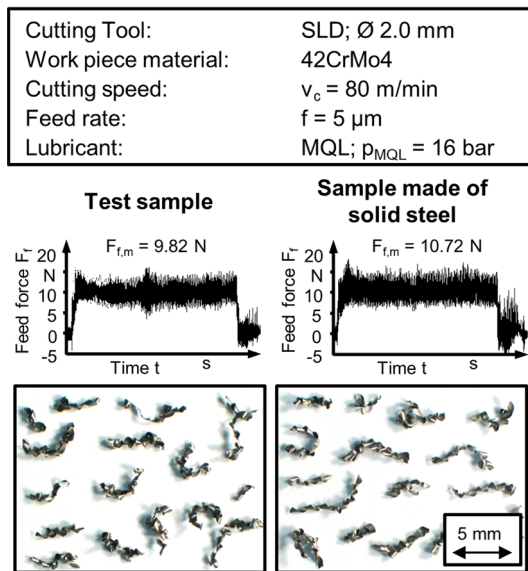
Fig. 5 Validation of the experimental methodology

In Fig. 6, the measurement of the axial force and a sequence of chip formation images taken in the different phases are shown for Inconel718. The experimental tests were conducted with a cutting speed $v_c = 30$ m/min and a feed rate f = 5 μm.

At time t_0, the tip starts to penetrate the material. This point in time is indicated by an increase of the feed force. This initial phase is characterized by a further increase of the feed force and a thin and straight chip flowing along the rake face. The influence of the cutting speed gradient between the tool center and the corner edge on the chip formation is negligible until the next process phase starts at time t_1. From this point in time, a folded chip with increasing chip width is produced. As a consequence, the axial force becomes almost constant. From time t_2, the complete inner cutting edge is engaged. At time t_3, the corner edge and the circular grinding chamfer penetrates the material surface. Nevertheless, this is a theoretical point in time due to manufacturing-caused small undersize of the material samples inside the acryl glass. A further characteristic point of time in single-lip gun drilling, t_4, represents the first contact of the guide pads with the bore hole wall. In this experiment, this ingression would occur after $t_4 = 3.22$ s. However, no changes in the feed forces are measured. The hole in the acryl glass and the gun drill used both have the identical diameter. The chip formation is stationary within the interval $[t_2, t_3]$. In the following, this stationary phase of chip formation while gun drilling Inconel718 is analyzed in more detail. In Fig. 7, a sequence of video images and a SEM-picture of the chip formation are shown.
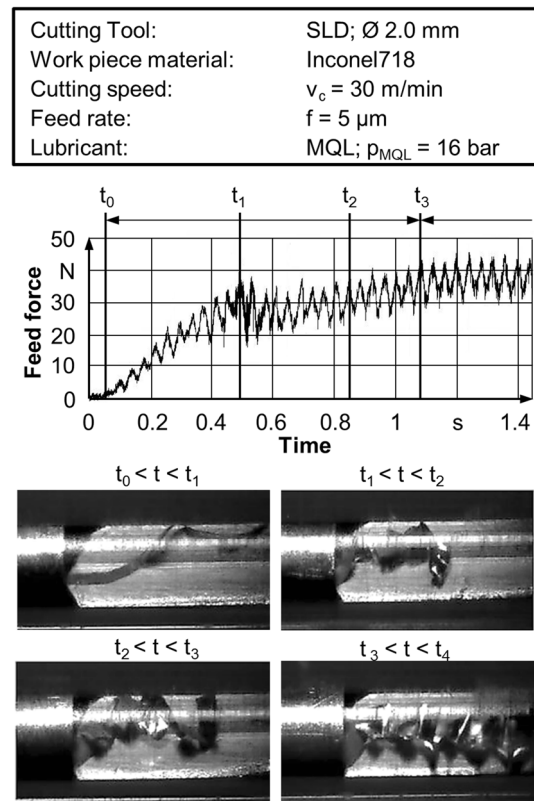

Fig. 6 Start of drilling in small diameter gun drilling of Inconel718

The sequence of images shows that, based on the cutting speed gradient, the chip formed at the outer cutting edge is retained by the more slowly formed chip at the inner cutting edge. These differences in the material flow result in a folding of the chip (green circles) further enforced by the mutual contact on the shoulder of the chip flute. The chips have no tendency to curling, however, even after a contact with the bore hole wall occurs some rips of the chips can be observed close to the inner cutting edge (red circles) due to the low local undeformed chip thickness, as well as the tendency of low cutting speeds to enforce a segmented chip formation. After a certain chip length has been formed, a separation of the chip occurs and a new chip is formed following the same principles.

In addition, analyses on the chip formation of the high-strength, bainitic steel 20MnCrMo7 were performed. In Fig. 8, the results for gun drilling 20MnCrMo7 with a cutting speed $v_c = 80$ m/min and a feed rate f = 5 μm are presented.

In contrast to the findings for gun drilling Inconel718, the chip formed at the outer cutting edge curls immediately. The chip formed at the inner cutting edge is running in the opposite direction, but tends to curling as well. Subsequently, both chips entangle each other and separate after some rotations of the work piece. However, the chip formation is quite irregular due to the small undeformed
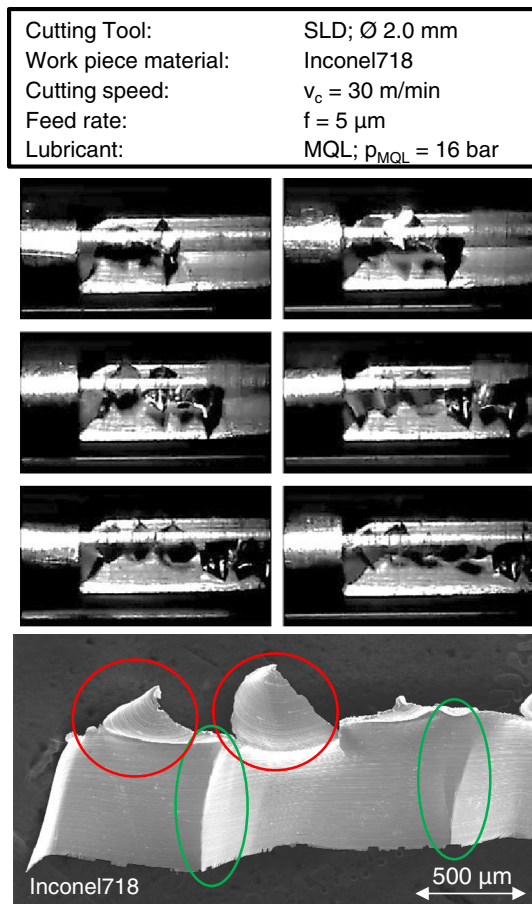
Cutting Tool:	SLD; Ø 2.0 mm
Work piece material:	Inconel718
Cutting speed:	v_c = 30 m/min
Feed rate:	f = 5 µm
Lubricant:	MQL; p_{MQL} = 16 bar

Fig. 7 Chip formation obtained by gun drilling Inconel718

Cutting Tool:	SLD; Ø 2.0 mm
Work piece material:	20MnCrMo7
Cutting speed:	v_c = 80 m/min
Feed rate:	f = 5 µm
Lubricant:	MQL; p_{MQL} = 16 bar

Fig. 8 Chip formation obtained by gun drilling 20MnCrMo7

chip thickness, which does not cover the entire cutting edge rounding of r = 6 µm. The SEM-picture depicts the separated chip formation at the inner and outer cutting edge, as well as the tendency to curling. As marked by the red circle in the SEM-picture, in some cases the chip formed at the inner cutting edge sticks to the chip formed at the outer cutting edge. Overall, the chip length is much shorter compared to the chips formed in gun drilling Inconel718. This is caused by the lower tensile strength of the bainitic steel.

5 Conclusions and outlook

In this paper a new approach to analyze the chip formation in small diameter deep hole drilling processes was presented. The use of material samples fixed in acryl glass and the utilization of a high-speed camera allowed the chip formation at the inner and outer cutting edge, as well as on the rake face to be visualized. In addition, this method enabled the evaluation of the chip removal process along the chip flute as a supplement to already existing quick-stop tests. The experiments on gun drilling
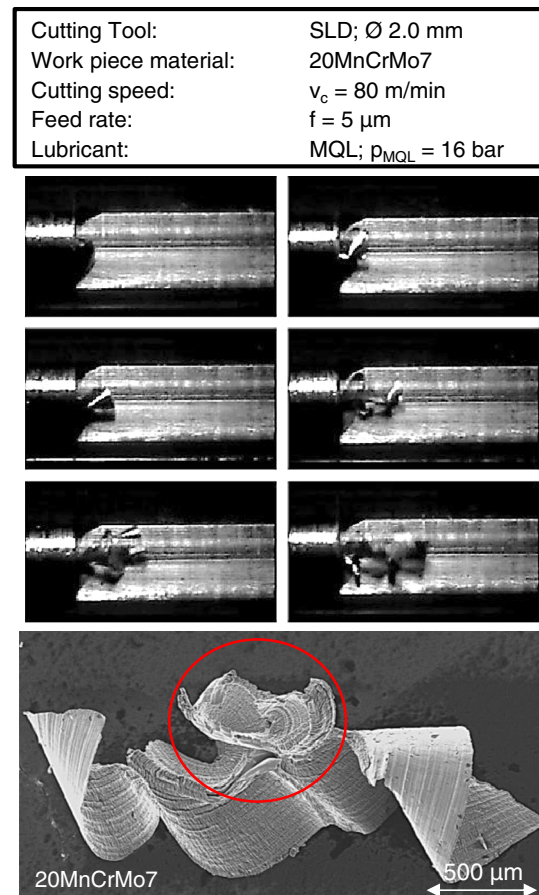
under minimum quantity lubrication proved significant differences in the chip formation of the nickel-based alloy Inconel718 and of the bainitic steel 20MnCrMo7. Due to the high tensile strength, the nickel-based alloy Inconel718 presented chip curling and produced much longer chips. In contrast, the bainitic steel 20MnCroMo7 tend to chip curling and separation at the tool tip. In conclusion, the first results demonstrated that the proposed method allows the chip formation process in small diameter deep hole drilling to be analyzed and understood. In subsequent experimental investigations, the influence of the tool geometry, e. g. the cutting tip design, and the wear state of the cutting edges will be analyzed. Moreover, also analyzes on small diameter gun drilling under conventional flood cooling will be realized. A high-resolution lens will be used to highlight further details of the chip formation process.

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