



Deep hole drilling

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ARTICLE INFO

Keywords:

Deep hole drilling

Machining

Surface

ABSTRACT

Deep hole drilling processes, which differ significantly from conventional drilling processes, are relevant for a lot of different applications where holes with high length-to-diameter-ratios and very good qualities are necessary. This paper gives an overview of different methods, which are established to produce bore holes with demanding aspects related to diameter, length-to-diameter-ratio, bore hole quality, workpiece materials and complex internal contours. Beside the detailed explanation of the deep hole drilling methods and tools also the fundamentals of the deep hole drilling principle are explained and completely new developed figures and tables summarize the state of the art. In addition for the most important areas the latest results of process and tool development are included.

1. Introduction

Drilling takes a key position in cutting technology whereby twist drilling is the most common drilling method [1]. In addition to enormous advantages, such as a simple and low cost application, there are some disadvantages making the classical twist drilling unsuitable for certain manufacturing tasks. The drilling diameter and the drilling length to be produced are the most important aspects for the use of deep hole drilling (DHD) processes [39,50]. Deep hole drilling is a metal-cutting method used for producing new as well as for an additional machining of existing bore holes. Fig. 1 shows, as a function of the diameter and the length-to-diameter ratio, the area of conventional drilling (grey) and the area of deep hole drilling (green). It clearly demonstrates that deep hole drilling methods dominate the whole field of drilling [189].

For the production of deep bore holes based on mechanical processes, two different tool designs are used: Tools with an asymmetrical single-edged design (Fig. 1/top left), which include drilling methods with single-lip deep hole drill heads (SLD), single-tube system (STS) drilling, also known as BTA (Boring and Trepanning Association) drilling, and double-tube system (DTS) drilling. On the other hand, there are tools with two symmetrically arranged cutting edges, which are used in the case of twist and double-lip drilling (Fig. 1/bottom left). Due to the realizable drilling depth, they can also be assigned to the deep hole drilling methods.

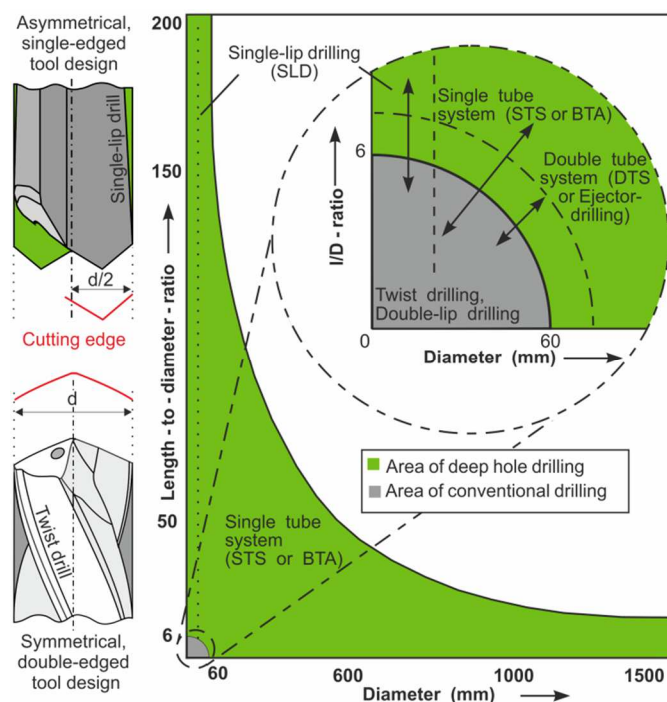


Fig. 1. Field of application of conventional and deep hole drilling [189]

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the so-called double tube system, can be used on universal machining centres.

In 1965, the DTS drilling was optimized by Faber, who integrated a special nozzle system in order to establish a slight vacuum. Therefore, a reduction of the pressure at the chip collecting opening was created to enable the return flow of the swarf through the main tube (ejector effect). Additionally, both pressure and volume flow differ from the STS drilling known values. This method leads to an increase of the application on conventional turning and milling machines.

1.4 Applications

The advantages of DHD lead to a large number of applications, which are described below. For SLD, industrial applications can be found in the manufacturing of holes with certain functions to supply lubricants in gear shafts, crank shafts and fuel supply in injectors for the automotive industry, the production of barrels of guns for the weapons industry, the fabrication of perforating dies for the food industry, the production of cooling holes in aero engines for the aerospace industry as well as the manufacturing of hollow implants and surgical instruments for the medical industry (Fig. 5). Furthermore, SLD with enhanced length-to-diameter-ratios is used to machine cooling holes in tools for the mold and die sector as well as bore holes in drill pipes for the oil industry. Further industrial applications can be found in general mechanical engineering, where, e. g., pneumatic and hydraulic supply bore holes are required [69,79,127,181,217].

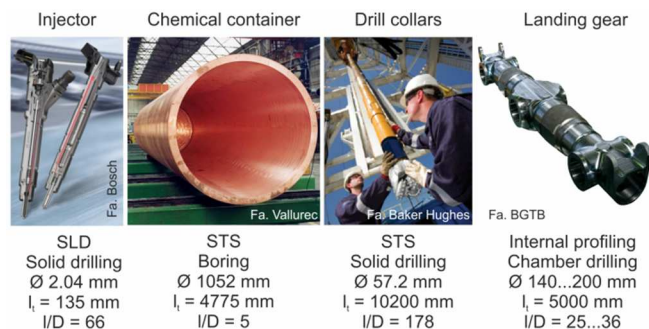


Fig. 5. Applications for DHD methods [3]

For STS drilling, important industrial applications can be found in the manufacturing of drill collars for the petrol industry, hydraulic cylinders, generator, gear and engine shafts, landing gears for the aerospace industry as well as single and double screw extruders for plastic injection moulding machines [213]. Due to its high productivity and the bore hole quality, which can be achieved, today deep hole drilling is increasingly used for manufacturing tasks where the ratio between the bore hole length and the bore hole diameter is less than 10 [189].

2. Fundamentals of deep hole drilling

2.1. Mechanical and thermal load on the tool

Numerous investigations deal with the mechanical load on the drilling tool [39,73,90,166,201]. The characteristic and asymmetrical cutting edge design of deep hole drilling tools is representative for all deep hole drilling processes shown at a single-edged STS drilling head including the acting forces and torques during the deep hole drilling process (Fig. 6).

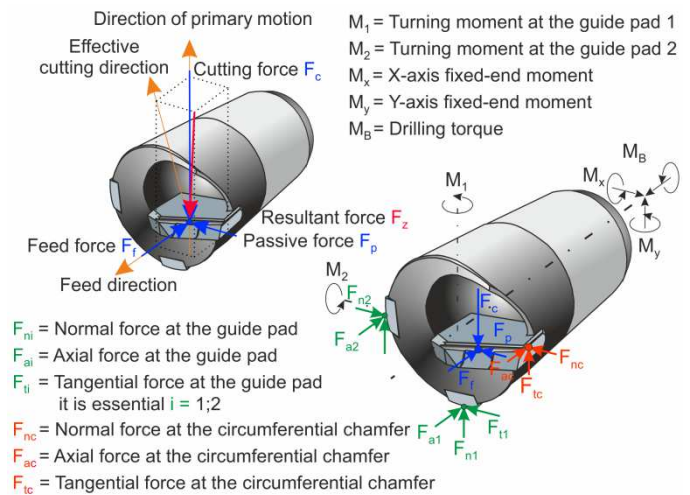


Fig. 6. Mechanical load at a STS-Tool [52,81,84,86,88,201]

In comparison to the acting process forces, the inertia forces of the drilling head and the cooling lubricant forces, which are generated by the cooling lubricant mass flow, have less impact and, therefore, will not be considered in detail. According to Bruchhaus, beside the acting feed force and the drilling torque, the clamping forces and torques are additionally acting in the area of the tool holder. The spatial acting cutting force is idealised in one point of the cutting edge. Thereby, the resultant force is built up of the three orthogonally orientated force components: Cutting force F_c , feed force F_f and passive force F_p . The cutting force F_c is determined by the feed rate f and the cutting depth a_p , the derived undeformed chip parameter and the specific cutting force k_c (also known as cutting coefficient). According to Hagemeyer, the mechanical load in passive and feed direction significantly depends on the cutting edge geometry [39,90].

Beside the twist and double-lip drills, the special characteristic of the remaining deep hole drilling tools includes the asymmetrical single-lipped tool design. Due to the acting cutting forces, the drill head with its guide pads is pushed against the generated bore hole wall [166]. The normal forces F_{nx} and the tangential forces F_{tx} at both the guide pads and the circumferential chamfer result from the asymmetrical tool design. This is in contrast to the double-lip drills, like the twisted ones, where the two passive force components of each cutting edge resolve each other. According to the distance between the cutting tip and the guide pad, the so-called guide pad recess, the resulting contact points are on different levels, whereby the different torques M_1 and M_2 are generated. With regard to the asymmetrical tool design, both the STS drilling and the single-lip drilling are very similar. Fundamental investigations on the mechanical load at single-lip drilling tools were carried out by many authors [70,71,87,127,140,141,144,168].

Due to the relevant literature, the mechanical load at the circumferential chamfer as well as the feed force of the guide pads are not taken into consideration because they are considered to be insignificant. For fundamental investigations of the effects of mechanism, especially when focusing on tool wear behavior, these mechanical loads should be carefully attentioned to [73].

Fig.7 illustrates the force and torque system of a single-edged STS drill head. The cutting torque does not only strain the guide pads but also generates the cutting torque M_c with the lever arm h . The whole drilling torque M_B , which strains the boring bar, consists of the cutting torque M_c and the friction torque M_f .

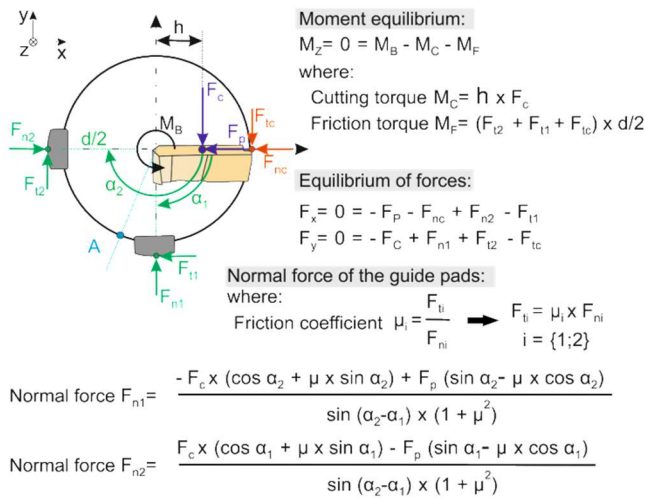


Fig. 7. STS drilling force and torque system [81,84,166]

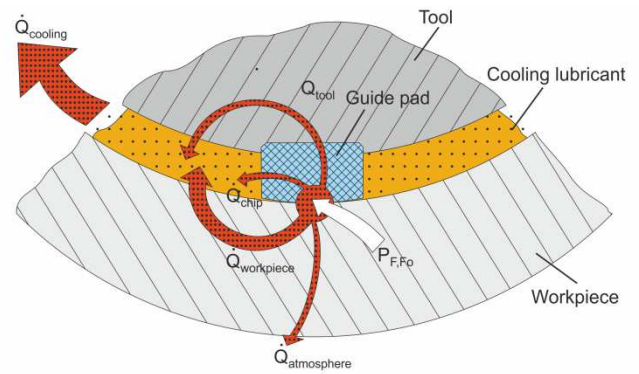
The orientation of the resultant cutting force depends on the cutting tip position and the cutting insert geometry and ends in the contact point A. The acting normal forces F_{nc} and the cutting and passive forces F_{tc} resulting from the machining process depend on both the guide pads angle position and the friction coefficient μ between the guide pads surface and the bore hole wall. For the friction coefficient the relation of the normal and the tangential force, named in the equation in Fig.7, is valid. The design of the cutting edge as well as the arrangement of the cutting edges significantly influence the value of the normal force. Therefore, various normal forces are possible, even if the bore hole diameter is kept constant. Pflgar investigated the mechanical load at a multi-edged STS drilling head in detail [143].

Beside the mechanical load of the tool, also the thermal load is very important. The resulting heat at the cutting tip is not directly transferred to the cooling lubricant. The major part of the heat is transferred to the chips, a lower percentage to the workpiece and the tool. The chip, workpiece and tool completely release heat in the case of an intensive cooling [194]. Investigations of Weinert et al. deal with the thermal load at the cutting insert. When using a STS drilling head with a diameter of $\varnothing 60$ mm and separated cutting edges, the measured temperature of $T_o = 1000$ °C at the outer cutting insert is much higher than the temperature at the inner cutting insert of $T_i = 160$ °C. According to Wittkop, who investigated the thermal load of the cutting edge when single-lip-drilling with a diameter of $\varnothing 15$ mm an austenitic-ferritic material with thermocouples, the temperature at the outer cutting edge of $T_o = 200$ °C is $T_A = 50$ °C higher than at the inner cutting edge [200,217].

Beside the thermal load of the cutting edge and due to the asymmetrical tool design, the thermal load of the guide pad is of particular importance. The dissipated friction power initiated by the relative motion between the guiding pad and the bore hole wall can be calculated as follows:

$$P_F = \mu \cdot F_N \cdot v_c$$

whereby μ is the friction coefficient, F_N is the normal force and v_c the cutting and sliding speed of the guide pad. In the contact zone of the guide pad, a heat zone occurs due to the friction and burnishing process. The guide pad is framed by the whole drilling head, therefore the direct heat emission to the cooling lubricant is more complicated compared with the cutting edge. The majority of the heat has to be given off by both the tool and the workpiece. Fig. 8 describes the heat flow schematically.



	Author	Guide Pad 1	Guide Pad 2	Parameter	Remarks
STS	Weber	600 °C	400 °C	D = 50 mm Material C60 $v_c = 150$ m/min $f = 0.14$ mm/U	Signals by thermocouple 1 mm below the guide pad surface
STS	Fuß	800 °C	500 °C	D = 60 mm Material C60 $v_c = 150$ m/min $f = 0.12$ mm/U	Signals by thermocouple 1 mm below the guide pad surface
SLD	Wittkop	180 °C		D = 15 mm Material 1.4462 $v_c = 60$ m/min $f = 0.03$ mm/U	Signals by thermocouple 0.2 mm below the guide pad surface

Fig. 8. Heat flow model in the guide pad contact zone with characteristic temperature measurements of guide pads [73,90,194,217]

The temperature in the contact zone between the bore hole wall and the guide pad was determined by direct measurements. Weber placed thermocouples in eroded bore holes with a distance of $s = 1$ mm from the guide pad's surface. According to his investigations, the increasing feed rate as well as the increasing cutting velocity raise the surface temperature. In addition, the temperature at guide pad 1 of the single-edged STS drilling head is significantly higher than at guide pad 2 [194]. Fuß integrated nine thermocouples in the front surface of each guide pad [73]. Similar to Weber the resulting values between guide pad 1 and guide pad 2 show an average deviation of 40 % [194]. Furthermore, the drop in temperature decreases with increasing distance from the front part of the guide pad. Generally, the temperature at the inlet is higher than at the outlet of a guide pad [73,194]. In contrast, Weinert investigated the thermal load of the guide pads when drilling with an single-edged STS drilling head with separated cutting edges and therefore two chip mouths and lower cutting velocities [208]. The substantially changed force and torque ratio results in significantly lower temperature loads. Beyond that, the thermal load of the guide pad 3, which is only necessary for the startphase of drilling and the bore through process, is less than the temperature at guide pads 1 and 2. Buse et al. mentioned that the chosen cutting speed has more impact on the thermal load than the chosen feed rate[44].

Wittkop investigated the thermal load for a single-lip drilling tool with a diameter of $D = 15$ mm when machining the austenitic-ferritic steel X20Cr13 [217]. Thereby he identifies a multistage process which is essentially attributable to the pilot drilling process (Fig. 9). When positioning the drilling tool (phase 1) directly in front of the workpiece the measured temperature is equal to the ambient temperature. Due to the feed movement the SLD tool enters the pilot hole resulting a temperature peak because of the frictional conditions between the rotating tool and the stationary workpiece (phase 2). After the of the whole SLD tool in the pilot hole the elastically recovery leads to decreasing temperature values and a uniform temperature level (phase 3). The second peak (phase 4) belongs to the current pilot drilling process. Due to the eccentric acting passive force triggered by the initial contact of the cutting edge with the bore hole bottom, the SLD drill-

ing head is pushed to the bore hole wall and generates an under-sized diameter. According to the gradual engagement of the inner and outer cutting edge, the temperature increases continuously. The engagement of the guide pad in the bore hole creates the third peak (phase 5). Reaching the quasi-stationary drilling process phase leads to an almost constant temperature level (phase 6) [217].

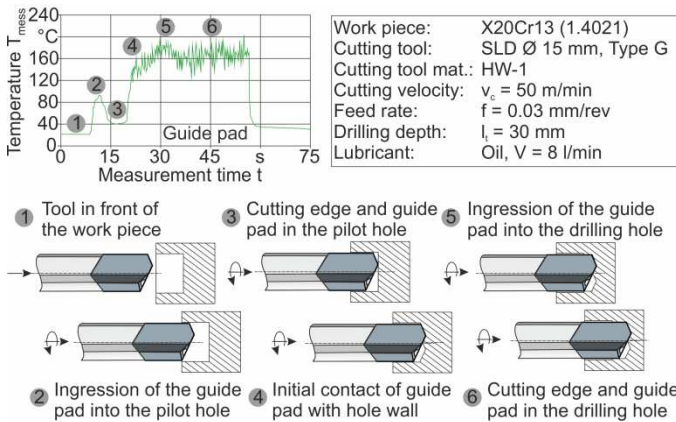


Fig. 9. Measured guide pad temperature during the drilling process [217]

The temperature fluctuations occurring in phase 6 can be caused by several reasons: the elastically twisting of the SLD tool on its own axis, the unstable lubrication film at the guide pad, the inhomogeneity of the workpiece material or the segmented and interrupted chip formation process. After the drilling process the temperature at the guide pads reaches the ambient temperature due to thermal transfer processes.

2.2. Process strategy

Due to the asymmetrical tool design, deep hole drilling tools require a guidance in the beginning of the drilling process. This guidance is usually realized by a drilling bush, described by different terms like boring bush or starting bush, or a drilled pilot bore hole (Fig. 10).

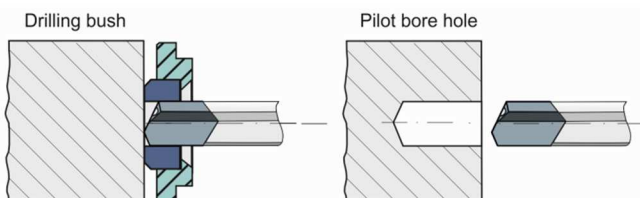


Fig. 10. Pilot drilling by drilling bush or pilot bore hole [172]

The implementation of the drilling bush is used on special deep hole drilling machines. For larger diameters, the drilling bush is hardened and grinded, whereby drilling bushes with smaller diameters are entirely made of cemented carbide. When deep hole drilling is applied on machining centres, pilot holes are frequently used. Drilling tools with an asymmetrical tool design create a resultant force which pushes the tool outside of the axial position. The centrifugal force enhances the tool's deviation when the tool is rotating. According to these reasons, the drilling bush has an important impact on the drilling process, therefore Eicheler et al. fundamentally investigated the startphase of drilling [64]. During the startphase of drilling unstable process situations are generated, which influence the further drilling process. Eicheler et al. investigated the influence on the bore hole quality, the tool wear behavior as well as the process reliability [64]. The tolerance of the guiding and the geometry of the pilot hole have a

significant influence on the resulting manufacturing quality as well as on the tool life [47,157,187]. Therefore, requirements of the pilot hole or the drilling bush should be accurately fulfilled. A maximum clearance of the guiding of 0.01 mm is recommended to achieve a precise geometrical manufacturing result and low tool wear [169,171,172,189]. Griffiths reported about the so-called bellmouthing. During the first few rotations of burnishing, the hole diameter is nearly equivalent to the drilling bush diameter. According to the larger diameter of the drilling bush, a lip is formed at the hole circumference [82].

According to Fig. 11 the whole deep hole drilling process can be divided into seven stages. The illustrated drilling torque curve is based on both constant cutting and feed velocity and the shown cutting tip design. The startphase of drilling can be subdivided into three different stages (B-D). When the drilling tool is guided in the drilling bush or the pilot hole (A), a minimal friction torque occurs which can be neglected. After the cutting tip hits the workpiece/bottom hole, the drilling torque increases continuously. For a moment (B), the drilling torque is almost constant according to the chip breaker. In (C), the whole cutting torque M_c is measured. Depending on the drilling bush oversize and its material characteristics, a friction torque is generated between the bush and the tool. The length of this stage is consistent with the guide pad recess (L1-L2). In (D), the guide pads engagement in the bore hole begins. According to the drilling bush oversize, the bore hole diameter in (C) is smaller than the drilling head diameter by twice the amount of the drilling bush oversize. Thus, the guide pads engagement in the bore hole starts. Therefore, the workpiece material is plastically deformed and forced to flow contrarily to the designated direction. That evokes the so-called bellmouthing. The engagement temporary increases the drilling torque until it reaches a nearly constant value during the whole drilling process. Fig. 11 exemplarily shows the ratio of the cutting torque M_c as well as the friction torque M_f for a drill head with a diameter of $d = 50$ mm. The ratio of the cutting torque M_c and the friction torque M_f is nearly independent of the bore hole diameter [157,167,194].

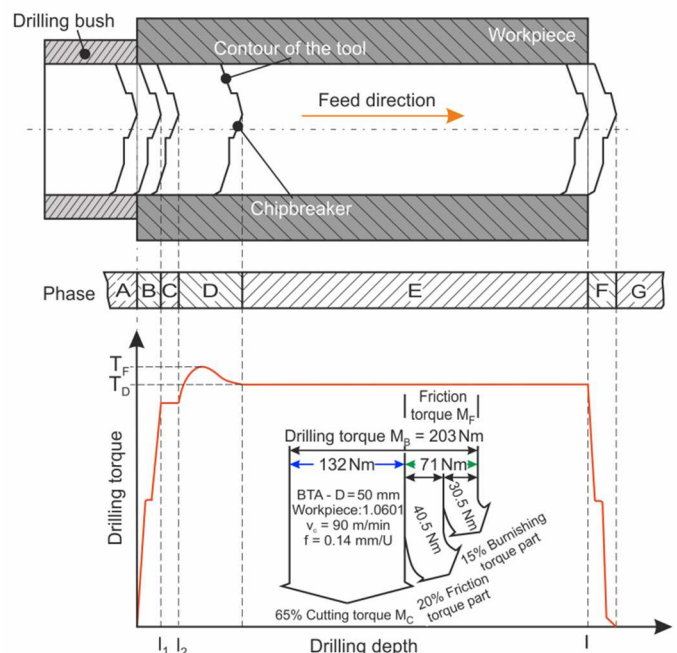


Fig. 11. Seven stages of the deep hole drilling process [81,82,166,194]

During the startphase of drilling, the drilling head, especially both the circumferential chamfer and the guide pad's front side chamfer are heavily loaded. Accordingly, the tool life depends on

the startphase of the drilling process. At (F), the bore through process, the drilling torque decreases due to the reduced cutting edge which is currently active in the workpiece material. Therefore, the value and the direction of the resultant cutting force has completely changed, whereby some drilling heads require support by providing a third guide pad. Frequently, the surface quality of the bore hole wall in stage F is getting worse. If the drilling head is not designed with a hurrying ahead but with a delayed cutting tip, the outer cutting edge penetrates the bottom material first whereas a so-called "Ausbohrteller" is generated. After the bore through process (G), there are different exit strategies to avoid damaging the tool by the tare weight of the free boring bar and the drilling head.

2.3. Cooling lubricant

Beside the machining centre, the cutting data, the tool and the workpiece, the cooling lubricant is one of the elementary influencing factors. High-quality lubricants, e.g. emulsion and deep hole drilling oils, lead to a higher efficiency when correctly applied [118,132,219]. In general, lubricants have to perform three important primary functions [179,189]:

- Lubrication – thereby reducing friction and wear at the cutting edge(s) and guide pads
- Flushing – thus providing continuous removal of chips
- Cooling – thereby removing heat from the tool and workpiece

By using suitable additives of the lubricant, the secondary functions, e.g. minimizing the tool wear, protection against corrosion and oxidation, reduction of the foaming tendency and a low oil mist formation, will be adjusted [117,179,191]. In case of machines were not being actually designed for a particular drilling task, the cooling lubricant flow rate and cooling lubricant pressure have to be adjusted to the diameter of the bore hole being drilled (Fig. 12).

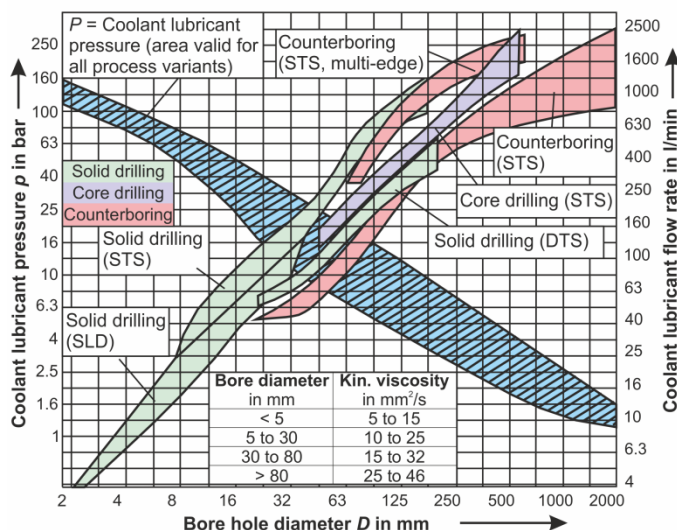


Fig. 12. Cooling lubricant flow rate and pressures for different deep hole drilling processes and the viscosity ranges as a function of the bore hole diameter [187]

Additionally, the cooling lubricant has a damping effect on the boring bar. In particular, it contributes to sound absorption. Normally, cooling lubricants used in deep hole drilling machines are water immiscible mineral and ester oils containing special additives like AW (anti-wear) and EP (extreme pressure) additives. Machines for other manufacturing processes, like machin-

ing centres, use water based cuttings fluids. Some deep hole drilling methods like single-lip, double-lip and twist drilling can also be used with MQL, which is described in Chapter 5.3..

2.4 Process dynamics

The deep hole drilling tool consisting of a drilling head and a boring bar, or in case of single-lip drilling consisting of a drilling head and a fluted shank has a tendency to vibrate, especially due to high length-to-diameter-ratios. The low dynamical torsional and flexural rigidity of the drilling tool leads to vibrations, occurring as radial chatter marks at the bottom of the bore hole or as a helical structure on the bore hole wall (Fig. 13) [193,206–209].

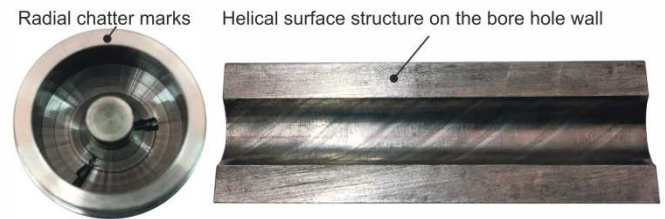


Fig. 13. Chatter marks and helical surface structure [193]

Flexural vibration is one kind of dynamic instability leading to a multi-lobe-shaped deviation of the cross section of the hole from absolute roundness. The pattern is helically propagated along the bore hole. The effect is known as spiraling [30,56,142,144,165,166,211]. According to Pfleghar the multi-lobe-shaped holes may result from a circular movement of the center of the rotating tool around the ideal centre of the bore hole [142,144]. The number of lobes of the cross section is related to the number of contact points of the rotating tool with the workpiece [206]. Three different types of spiraling depending on their occurrence are named by Stockert [166]: At the beginning of the process, reproducibly at the same drilling depth and seemingly random. Investigations of Gessesse et al. show a connection between the bending modes of the boring bar and spiraling for the second type of occurrence [77,78,166]. Additionally, Stockert mentioned three different categories as a cause [166]:

- The machine tool with an insufficient alignment of the machine axes
- The tool with its guide pad arrangement
- The inhomogeneity of the workpiece material

In contrast, the radial chatter marks are based on torsional vibrations, primarily influenced by the cutting data, especially the feed rate and the workpiece material [178,193]. The torsional vibrations are dominated by the eigenfrequencies of the boring bar. According to the STS deep hole drilling, the boring bar vibrates in the first or in the multiple of the first eigenfrequencies (Fig. 14).

The dynamical behavior of the boring bar changes with constant cutting data according to the increasing drilling depth. The main reason is the non-supported boring bar sections [193]. In contrast to the bending vibrations the torsional vibrations have no significant influence on the drilled surface quality due to the guide pad levelling. In contrast, the bottom of the bore hole is characterized by radial chatter marks (Fig. 13). The eigenfrequency of the boring bar depends on the material properties, the dimension and length of the boring bar [193]. According to the drilling method, Chapter 3 includes solutions to reduce the torsional and bending vibrations.

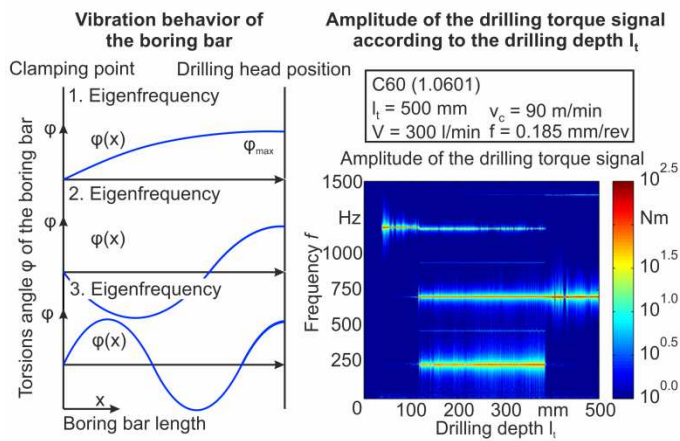


Fig. 14. Schematical illustration of the torsional eigenfrequencies of a boring bar [178,193,210]

2.5 Process variants

Fig. 15 shows the different process variants of deep hole drilling [189]. Solid drilling is the most frequently used drilling variant. Additionally, all deep hole drilling methods can also be used for counterboring and for core drilling (trepanning). Form-boring is designed to produce a specific bore hole bottom determined by the shape of the drilling head.

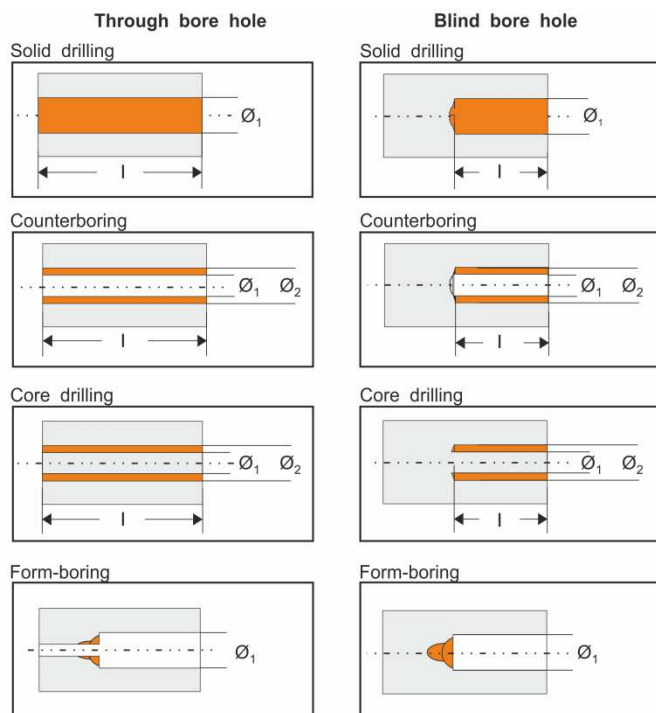


Fig. 15. Process variants of deep hole drilling [189]

Additionally, according to VDI3210, processes satisfying one or more of the following characteristics are denoted as assigned to deep hole drilling:

- Secondary machining of existing deep bore holes like centreless rough turning, roller burnishing, drilling-core cutting
- Tools of a similar design to deep hole drilling tools like single-edged reamer
- Use in deep hole drilling machines like internal profiling, roller burnishing

For machining workpieces using deep hole drilling and the associated methods, mostly deep hole drilling machines are applied. According to the type of the deep hole drilling machine, Fig. 16 shows the different modes of operation in order to machine workpieces.

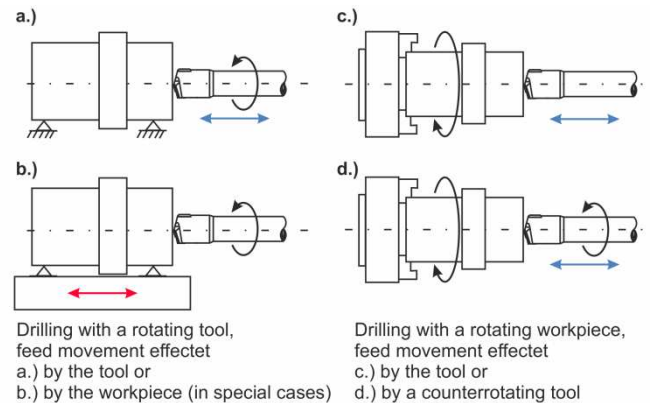


Fig. 16. Modes of operation [189]

This figure shows the possible combinations of cutting and feed movements when machining a cylindrical bore hole. Due to the mode of operation, some characteristic features exist: Type a and b should be used for workpieces which cannot be rotated in the machine. This is a typical application case for single-lip drilling and often used on machining centres. Type c is usually applied in cases of workpieces with a hole drilled at the axis of rotation and the most common method used on STS deep hole drilling machines. This constellation generates a minimized straightness deviation than deep hole drilling with a rotating tool. Type d usually has the lowest deviation and is often used for heavy or very long workpieces [113,172,182,189].

2.6 Quality characteristics

With regard to the guide pad recess and compared with the cutting tip and the circumferential chamfer, the guide pads are the last elements which are in contact with the bore hole wall. Therefore, the guide pads have the final impact on the emerging surface quality, which is schematically illustrated in Fig. 17.

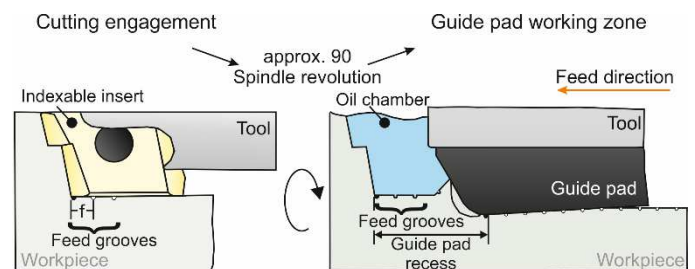
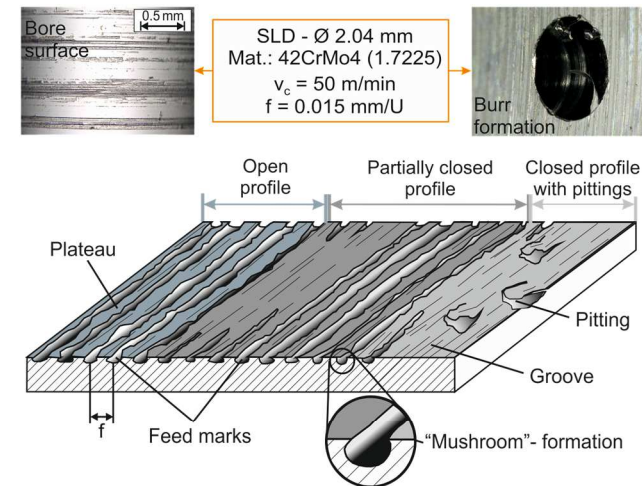


Fig. 17. Formation of the bore hole surface [73]

The left part of the Figure depicts the surface profile which is formed by the cutting insert. In the area of the guide pad recess and according to the slightly back tapered circumferential chamfer, feed grooves are determined. After a rotation of about 90°, guide pad 1 overruns the bore hole wall which was preformed by the circumferential chamfer. With regard to the illustrated different height levels, it becomes apparent that the guide pads predominantly are responsible for the resulting surface quality. At the moment of cutting, the bore hole diameter is smaller by approximately 0.02 mm than at the moment of smoothing and burnishing. During the deep hole drilling process, a material bulk in front of the guide pads occur, which is particularly machined by the circumferential chamfer. In addition, the remaining bulk will

be pushed into the generated feed grooves by another guide pad's overrun.

The surface roughness of a deep hole is mostly determined by the guide pads. According to the process principle, the surface quality of the drilled bore holes is very high. Nevertheless, the surface offers areas with characteristic feed marks and areas without. But all areas contain grooves being inconsistent and closer than the feed rate. As a consequence shown in Fig. 18, the surface typically consists of areas with plateaus and areas with grooves.



Drilling method [ref]	Universal limitations			Significant examples (Solid drilling)				
	Bore hole diameter D in mm	Drilling depth l in mm	Drilling tolerance	Work-piece material	Surface roughness Rz in µm	Straightness deviation		
SLD [96;117]	0.5 to 2	30-70 x D	IT10 to IT7	1.7911	0.4 to 0.1	2	30	120
SLD [117;93]	2 to 20	70-250 x D	IT10 to IT7	1.7225	0.91	5	30	390
SLD [96;216]	20 to 40	70-250 x D	IT10 to IT7	1.4021	10 to 8	15	20	900
Twist [11;69]	0.5 to 2	30-70 x D	IT14 to IT11	2.4668	1.5 to 1	1.3	30	50
Twist [105;216]	2 to 16	30-40 x D	IT14 to IT11	3.2163	9 to 3	10	30	260
STS [73;3]	6.3 to 180	100 x D	IT10 to IT7	1.3949	10	57.20	178	1500

Fig. 18. Characterisation of the bore hole surface and achievable bore hole qualities [3,69,73,93,96,105,117,216]

According to different normal forces at the guide pads and the guide pads number of overruns, depending on the feed rate f and the cutting speed v_c , the burnishing of the workpiece material in the feed marks occurs variously. With lower forces an open profile is generated (see also [45,89]). If a feed mark is not completely closed, it is called a partially closed profile. If the normal forces are too high, the burnished workpiece material connection is demolished and outbreaks and spallings are possible. This process is called pitting formation and especially occurs when smoothing. Therefore, in this case the surface pressure or the guide pad's number of overruns is too high [73].

The unevenly occurring grooves of a deep bore hole are formed due to partial outsourced workpiece elements which adhere to the guide pad's surface. The adhesion of these elements on the guide pad's surface is periodical, whereas the non-constant grooves in the bore hole surface are generated [39,73,91]. After the guide pad's contact with the bore hole wall and due to thermal procedures, the hole gets tighter and the grooves on the surface get a so-called mushroom-formed profile [73].

When machining bore holes with small length-to-diameter-ratios, the quality of the bore hole is characterized by diametral

accuracy, roundness or surface quality. In contrast to this, the longitudinal accuracy and form often are of secondary importance. By increasing the length-to-diameter-ratio of the bore hole, the longitudinal accuracy becomes more important [82–84,86,88]. Even if the straightness deviation is much lower than the conventional twist drilling and despite the self-centering character of the drilling tool, a mismatch of the ideal boring axis, especially when drilling with large length-to-diameter-ratios, is not completely avoidable [67,83,171,183]. The deviation of the drilling tool is described by different terms like run-out, straightness deviation or mismatch of the axis and always means a change of direction of the drilling head in relation to the ideal boring axis [63,67,169,182]. By using special coordinate measuring machines both the amount and the direction of the deviation can be measured, as shown in Fig. 19 [63,108].

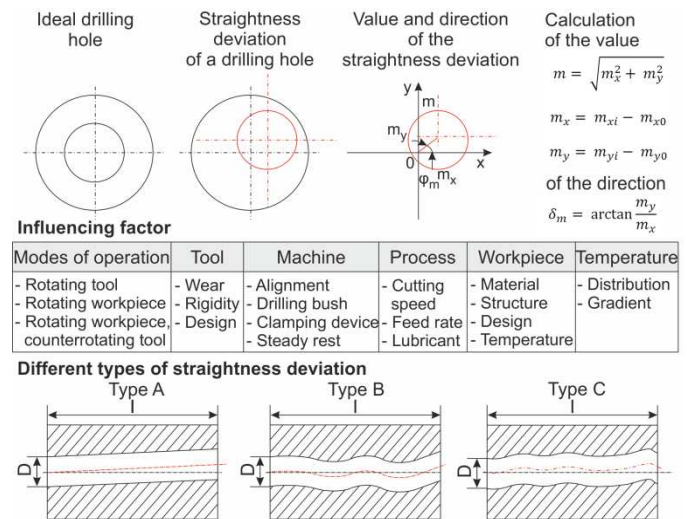


Fig. 19. Definition and different types of the straightness deviation [67,83,113,169,172]

Not only the amount and the direction of the deviation of the bore hole are of technological relevance, but also the deviation of the drilled bore hole along the whole drilling depth leads to additional evidence. Due to experimental investigations, Griffiths already noticed the various developments of the straightness deviation according to the drilling depth [83]. Enderle characterized the straightness deviation by different mathematical terms, whereby the exponential function seemed to be the most accurate description [67].

Numerous studies deal with the subject of straightness deviation of single-lip drilling as well as STS-drilling. Thereby, especially the mechanisms of action during the pilot drilling are analyzed in order to reach a fundamental understanding of the development of the tool deviation. According to Griffiths the factors machine, tool, workpiece and drilling process have a great influence on the straightness deviation [83,84]. With respect to the workpiece, especially the homogeneity, the workpiece accuracy, workpiece clamping and the cooling lubricant are of great significance [83,84]. Stürenburg enhances the fundamental understanding by carrying out fundamental investigations on the causes and mechanisms of the start of drilling [169,171]. According to Stürenburg, the pilot drilling and especially the oversize of the guiding bush influence the development of the straightness deviation. Weinert et al. expanded the influencing factors on the deviation by adding the factor temperature. Especially for the eccentric drilling or drilling of non-cylindrical workpieces, the existence of a thermal gradient influences the straightness deviation [199,203]. Additionally, Kessler et al. mention the axial guide pad recess to the tool tip, which provokes the dumping of the drilling head if the

drilling tool is not able to guide itself [57,113,157,169,182]. The straightness deviation of the tool during the pilot drilling depends on the existing inertia and cutting forces, wherefore the mode of operation has a significant influence on it [82,189,199]. Based on numerous experimental studies, the straightness deviation when using single-lip drilling tools is usually higher than using STS- or ejector drilling tools [57,110,145,157]. Furthermore, the deviation is mostly directed to the thin-walled part of the workpiece [109,110,157,217].

3. Deep hole drilling methods

The classic deep hole drilling processes are single-lip drilling, STS drilling and ejector drilling. These processes are all based on an asymmetrical tool design and differ predominantly in the supply of cooling lubricant and in the removal of the mixture of cooling lubricant and chips (swarf). Furthermore, twisted tools with a symmetrical tool design have recently been developed, i.e. deep hole drilling tools similar to the traditional twist drill, which allow bores to be produced whose length-to-diameter ratios lie in the range of deep hole drilling. Thus, today deep hole drilling is subdivided into five tool-specific processes which will be presented in the following sections. Additionally to the fundamental process principle, investigations and results based on the tool design, i.e. tool tip design, peripheral shape, coatings, cemented carbides and guide pad variations are presented.

3.1. Single-lip drilling (SLD)

3.1.1. Process principle

Single-lip deep hole drilling is typically used in the diameter range of $d = 0.5$ to 80 mm to realize bore holes with length-to-diameter-ratios up to $L/D = 900$. During the process the cooling lubricant is delivered through one or more holes which pass through the tool shank (Fig. 20). The mixture of chips and cooling lubrication is removed along a flute or longitudinal groove (bead) at the outside of the tool shank. The resulting surface quality of the bore hole can be decreased when the chip get in contact with the bore hole wall.

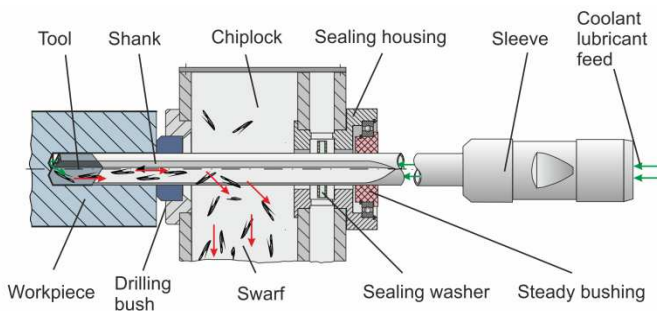


Fig. 20. Schematic process principle single-lip drilling [70,189]

Single-lip deep hole drilling is conducted on special purpose machines, machining centres or lathes. Because of the asymmetrical tool design, a guidance of the drill head during the start of the drilling is necessary. The guidance is realized by a drilling bush (special purpose machines) or a pilot hole (machining centres or lathes).

3.1.2 Tool design (tool tip design, peripheral shape, coatings, cemented carbide)

In general, the tool structure of single-lip deep hole drills consists of the three elements: drill head, tool shank and clamping

sleeve (Fig. 21). The drill head made of cemented carbide and the tool shank made of tool steel are connected by the straightening sleeve via solder joint. Special solutions for single-lip deep hole drilling with a tool diameter $d \geq 12$ mm can also feature replaceable inserts and guide pads soldered or screwed onto the drill head. In single-lip deep hole drilling with smallest tool diameters, the tool shank and the drill head are made of solid cemented carbide [96,187]. The tool clamping and the transmission of the drilling torque are acquired by the clamping sleeve.

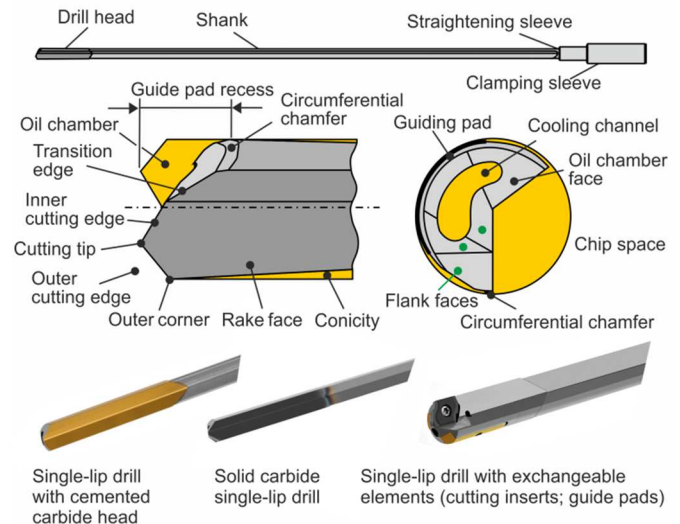


Fig. 21. Schematic tool design of single-lip deep hole drills [117,176,187]

The cooling lubricant is supplied through one or more cooling channels inside the tool shank. Single-lip deep hole drills with smallest diameters have kidney-shaped cross-section of cooling channels, while tools with diameters $d \geq 10$ mm are often characterized by two circular cooling channels [114]. The kidney-shaped cross sections of the cooling channels feature improved flow characteristics compared to two circular cross sections [94,107,136,137,217]. The cooling channels are implemented during the manufacturing of the carbide blanks by means of extrusion [116]. The evacuation of the mixture of cooling lubricant and produced chips takes place alongside the chip flute. The opening angle of the chip flute amount to 110° to 130° . Due to the alongside chip flute, the tool rigidity of single-lip deep hole drills is much lower compared to symmetrical twist deep hole drills. To reduce tool deflection and straightness deviation of long-shanked single-lip deep hole drills, steady rests are used for length-to-diameter-ratios of the tool shank larger than $L/D > 30$ to 50 [67,143,168,181,187].

The asymmetrical single-edged tool design and a rake angle of $\gamma = 0^\circ$ are characteristic for single-lip deep hole drilling. The common tool geometries with respect to the cutting edge design are defined in accordance with the standard VDI3208 [187]. The widespread point geometries consist of two cutting edges, the inner and outer cutting edge. The angles of incidence of the inner and outer cutting edge depend on the diameter and differ between $K2 = 105^\circ$ to 120° and $K1 = 50^\circ$ to 70° . To improve wear resistance as well as the chip formation several special point geometries has been developed. In this regard, the chip formation is of highest importance for the achievable process productivity and stability. The production of long and unfavorably formed chips involves the risk of chip congestion in the chip flute, sudden tool failure and marks on the bore hole wall. Beside the point geometry, a favorable chip formation mainly depends on the adjustment of cutting speed and feed rate [41]. Fig. 22 shows an

overview of the standard point geometries and selected special point geometries of single-lip deep hole drills.

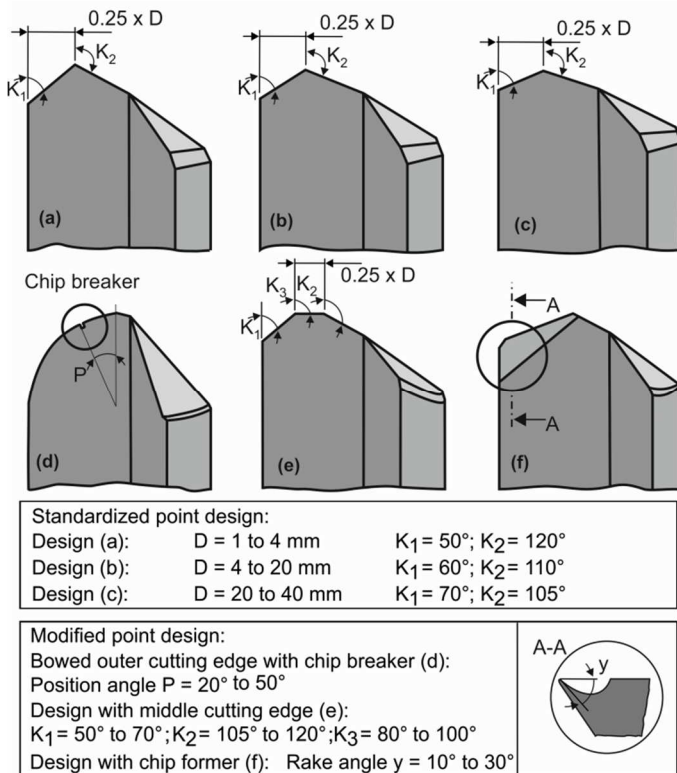


Fig. 22. Standard and special point geometries of single-lip deep hole drills [54,55,117,151,187]

The special point geometry (d) is characterized by a bowed outer cutting edge and a short inner cutting edge. The bowed outer cutting edge allows the machining of a rounded hole bottom. Furthermore, the bowed outer cutting edge is able to feature a chip breaker in the form of a notch to generate smaller chips, which can be removed easily and thus enable higher feed velocities [55]. The special point geometries (e) and (f) have been developed to increase process productivity in relation to the standard point geometries. Special point geometry (e) has an additional middle cutting edge with a length of 5 to 20 % of the tool diameter by an angle of incidence of typically K₃ = 90°. Thereby, stresses are induced into the chip and supports chip breakage [54]. The specialty of the point geometry (f) is a modified rake face geometry. By means of a chip former a positive rake angle is generated. The chip breakage takes place when the chip leaves the lead face and hits the breakage section, being designed in dependence of the workpiece material as well as the cutting parameters [151]. Additionally, the optimization of cutting parameters to achieve reliable deep hole drilling processes with respect to the chip formation was investigated by various authors (see also Chapter 4.) [8,101,102,134,135].

Within the stationary phase of the drilling process, the drill head of a single-lip deep hole drill is supported at the tool circumference by means of guide pads and a circular grinding chamfer. In Fig. 23 the standardised circumferential shapes of single-lip deep hole drills in accordance to the standard VDI3208 are shown. Beside the standardized circumferential shapes, a range of specific circumferential shapes adapted to the respective application exists [114,187,217].

Circumferential shape	Workpiece material	Remarks
	Steel	Good guiding, because the rear guiding pad still over d/2, usable for most processing tasks
	Steel, cast iron, aluminium	Rear guiding pad under d/2, normal drilling conditions, small drilling diameters, low tendency to clamp even with small conicity
	Grey cast iron, soft aluminium	Workpiece materials with good lubricity
	Aluminium, steel, brass	For unfavorable drilling conditions (e.g. interrupted bore holes, sloping surfaces)

Fig. 23. Circumferential shapes of single-lip deep hole drills [117,187]

The self-guiding by means of guide pads and a circular grinding chamfer allows the realization of bore holes with length-to-diameter-ratios up to l/D = 600 with low straightness deviations [87,157,166]. The choice of circumferential shape primarily depends on the workpiece material to be machined [187]. The arrangement and length of the guide pads have to be adjusted with the objectives of maximum process stability as well as an even contact pressure to obtain a favorable tool wear [143]. The deviations of diameter, roundness, surface quality and alteration of subsurface zone strongly correlate with the circumferential shape [9,23,64,143,214,216]. Extended drill heads with combinations of different circumferential shapes in a row are used in demanding applications to reduce the straightness deviation. In order to decrease the vibrations of the drilling process, the use of special damping elements between the drilling spindle and the clamping sleeve or damping adhesives between the shank and the clamping sleeve as well as the use of adpatronic tool holders were investigated [24,94,98,100,168,196]

3.2. STS (Single Tube System) Drilling

3.2.1. Process principle

In contrast to single-lip, double-lip and twisted drills, STS tools use two different designed tubes, onto which the cutting edge section referred to as the "drill head" is screwed. Fig. 24 schematically shows the typical process principle of STS drilling.

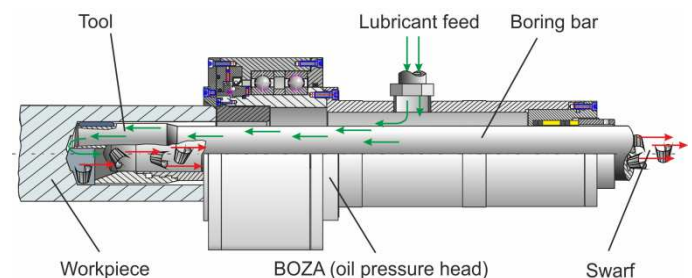


Fig. 24. Schematic process principle STS drilling [81,189]

In contrast to single-lip drilling, the cooling lubricant enters the annular gap between the drilling tube and the drill guide via

the oil pressure head and not through a coolant channel. For larger bore hole diameters, through the BOZA flow hundreds of liters per minute of cooling lubricant with a pressure of $p = 4$ to 10 bar. The cooling lubricant passes through the bore produced to the tool tip. There the cooling lubricant flows around the guide pads and cutting edges and flushes the chips inside the drilling tube out of the bore hole. The chips have no contact with the bore hole wall. Therefore, especially the surface quality is improved [61,62].

Using this type of deep hole drilling, the cooling lubricant requires a high-pressure seal between the oil pressure head and the workpiece. The mixture of cooling lubricant and chips is discharged at the end of the main spindle. In counterboring operations, when not drilling blind holes, the chips can also exceptionally be flushed out of the bore hole in the feed direction, and are then discharged in the area of the tailstock or workpiece headstock. Compared to the corrugated tube shaft of the single-lip drill, the cylindrical STS drilling tube has a higher rigidity. Therefore, steady rests to support the drilling tube are only necessary for unsupported lengths about of 80 to 100 times of the tool diameter.

3.2.2. Tool design (cutting edge layout, guide pad variations, guide pad coatings)

STS tools consist of a cylindrical drilling tube and a drill head screwed into or onto the drilling tube. Except for the lower diameters, they are normally equipped with exchangeable cutting inserts and exchangeable guide pads (Fig. 25). Similar to single-lip drills, the cutting tip of STS solid drilling tools is also located outside the rotation axis, calling for a drilling bush.

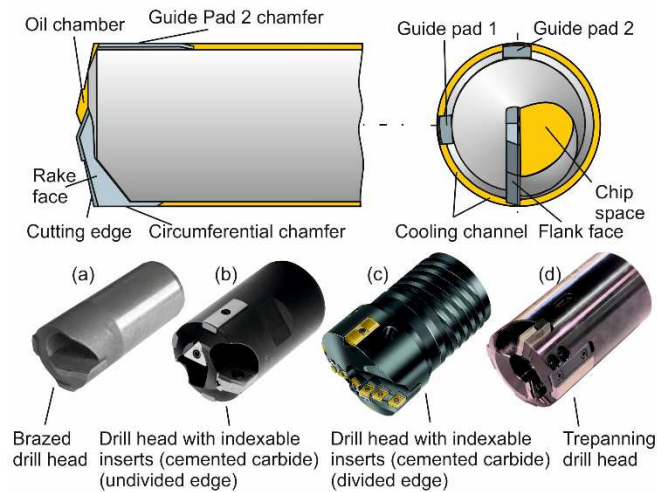


Fig. 25. Schematic tool design of STS drills [37,189]

Fig. 25 shows the four different drill head designs of STS solid drills. Brazed solid drill heads (a) are predominantly used for smaller bore hole diameters of $d = 6$ to 60 mm. The brazed single tip of the drill head is usually regrindable. Up to a bore hole diameter of $d = 12$ mm, brazed guide pads are applied. Larger diameters are drilled with indexable guide pads. Drill heads with both (b, c) indexable cuttings inserts and indexable guide pad inserts are available beginning of at a bore hole diameter of $d \geq 20$ mm. For bore hole diameters above $d \geq 40$ mm, the cutting edges are reciprocally distributed around the circumference of the tool (c). The whole cutting edge is divided into the three different parts outer, inner and intermediate cutting edge. The intermediate cutting edge is shifted by 180° degrees and positioned on the opposite side. The inner cutting edge is placed directly in the

drilling centre. All cuttings edges are oriented to fulfill a minimal overlap. Nevertheless, with larger diameters (b, c) the positioning results in the main cutting forces and passive forces to be absorbed by the guide pads 1 and 2 [152]. Biermann and Weinert optimized the STS drill head with respect to the structure topology as well as the chip mouths [27].

For drilling bore hole diameters larger than $d \geq 125$ mm, solid drilling with solid drill heads gets economically inefficient. Due to that, drilling with trepanning heads is established (d). According to Chapter 2.1., solid drilling as well as trepanning are single-edged tools because for each diameter position only one cutting edge is in contact with the workpiece.

According to the design of the cutting edge arrangement, the direction of the resulting main cutting force varies significantly during the start of drilling or bore through process in contrast to the stationary process. Therefore, the drill head requires support in those special process phases by providing a third guide pad.

Because of its relevance, the behavior of the guide pads during deep hole drilling and their influence on the bore hole formation was investigated [15,44,49,51,155,156,178]. According to the asymmetrical tool design the bore hole wall quality is mainly determined not by the cuttings edges but by the guide pads [87,157]. There is general consensus that due to higher normal forces guide pad 1 is pressed more powerful against the bore hole wall than guide pad 2, which results in higher tool wear of guide pad 1. Especially guide pad 1 shows an extensive damage in the front section while guide pad 2 is characterized by a larger support area [73,81,84]. Therefore, Greuner requires a fundamental adjustment of the guide pad positions for a more balanced utilization [81]. Hereby, the influence of the new guide pad position on the stability of the drilling process was not considered. According to Fuß, guide pad 1 takes responsibility for the support of the cutting force and therefore reacts to the dynamic behavior of the feed force while guide pad 2 is predominantly used for the smoothing part and therefore has an impact on the drilling torque [73].

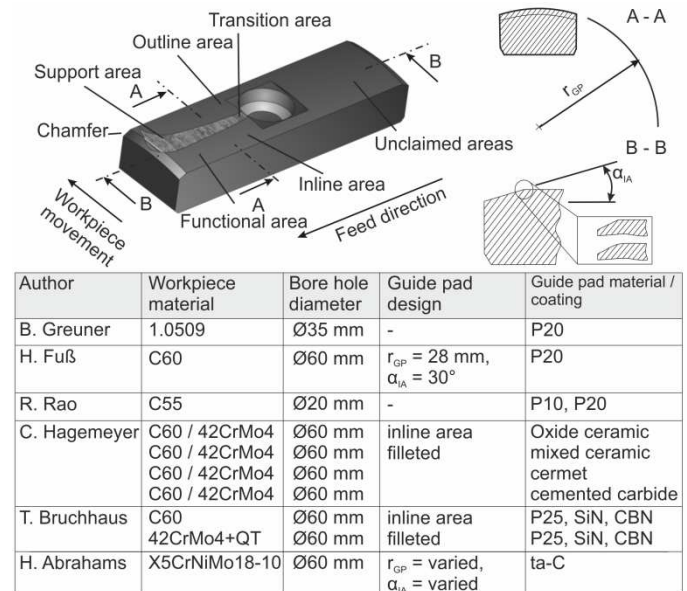
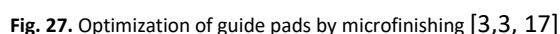


Fig. 26. Terms and design features of guide pads [3,39,73,81,90,150]

Further on, Fuß investigated the influence of different guide pad designs and varied the angles of guide pad 1 of $\alpha_1 = 178^\circ, 205^\circ, 223^\circ, 235^\circ$ and the guide pad 2 of $\alpha_2 = 276^\circ, 295^\circ, 277^\circ, 265^\circ$ [73]. Griffiths and Fuß described the

According to Wesling, the guide pad radius has to be smaller than the bore hole radius in order to reach an improved cooling and lubrication of the contact zone [213]. Bruchhaus proved via a FEM-Simulation that with filleted guide pads, both the maximum stress and the stress gradient in the contact zone are lower and the stress peaks are effectively reduced. This causes via lower local loads a reduction of tool wear in the inline area [39,197]. In order to reduce the guide pad's load the following aspects should be taken into account:

- If the back taper is missing or in an extreme case is negative, the drilling tool tends to spiral [166]. If the tool is spiraling, the supporting area takes place on the surface of the whole guide pad 2. Hagemeyer and Weinert investigated the guide pad wear behavior of different guide pad materials as cemented carbide, cermet, black mixed ceramics and silicon nitride ceramics. They did not determine any advantages of ceramic guide pads instead of cemented carbide guide pads [90,91,198]. The development of high temperatures at the guide pads creating insufficient conditions was proved by various authors. In order to avoid white layers by preventing the critical transition temperature, Griffiths proposes the installation of longitudinal grooves in the guide pads [86]. Abrahams and Biermann improved the guide pads for STS drilling of high alloyed steels by microfinishing and using an innovative amorphous and tetrahedral bonded (ta-C)-coating [3,4,28,29]. This coating has a hardness of about 7000 HV and in addition a reduced friction coefficient of 0.1 against steel (Fig. 27).



the lead-in-area is rounded which reduces the mechanical load at this specific area when machining X5-CrNiMo18-10. Due to the finishing process of the coated guide pads, the number of coating defects and the friction coefficient are reduced. In addition, the wear behavior of the guide pads is enhanced according to the better friction conditions when STS drilling high alloyed steels.

3.3.1. Process principle

This diagram illustrates the components and operation of a high-speed drill. The labels include: Drill head, Boring bar, Inner bar, Clamping Chuck, Coolant lubricant feed, Ejector-effect, Workpiece, Drilling bush, and Swarf. The diagram shows the drill assembly (drill head, boring bar, inner bar, and clamping chuck) positioned against a workpiece. A drilling bush is used to guide the drill. Coolant is fed into the drill through a coolant lubricant feed system. The ejector effect is shown as chips (swarf) are removed from the workpiece. The workpiece is shown with a hole being drilled.

The cooling lubricant flows through a second concentrically installed tube into the annular gap formed between the two tubes and up to the drill head where it emerges through bores, flows around the cutting edge area and flushes away the chips through the inner tube. One part of the cooling lubricant flows into the inner tube via an annular nozzle to the end of the main spindle. Therefore, a reduction of pressure at the chip mouth is created enabling the return flow of the chip-lubricant-mixture through the main spindle (ejector effect). The nominal bore diameter range lies between $d = 18 \text{ mm}$ to 65 mm . In traditional deep hole drilling machines, this process is only used where the high-pressure sealing required for STS-drilling between the oil pressure head and the workpiece is not possible, e.g. for machining workpieces with rough forging or casting contours.

The design of ejector drills is similar to the one of STS solid drilling tools (Fig. 29). Cooling lubricant outlets at the drill head are positioned in the backlash between the guide pads and the thread for connecting the drilling tube. Through these outlets, the cooling lubricant is transported from the annulus between the two tubes to the guide pads and cutting edges.

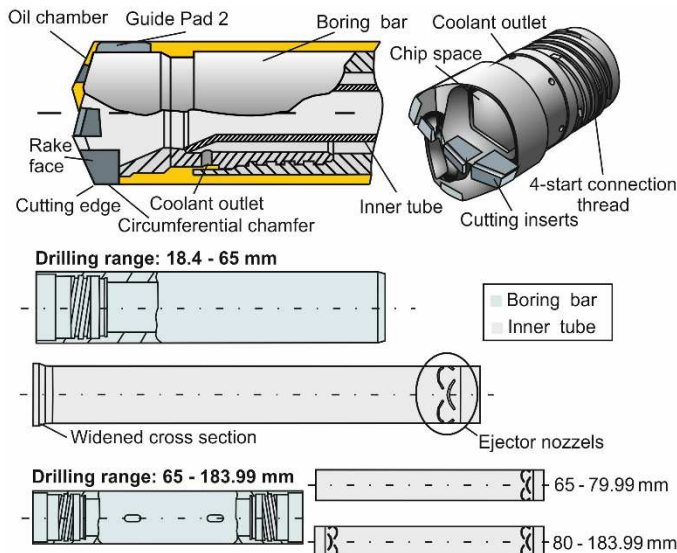


Fig. 29. Schematic tool and tube design of DTS drilling [7,158,189]

3.4. Twist drilling

3.4.1. Process principle

In the diameter range of $d \approx 0,5$ to 12 mm twist drills offer an alternative to the single-lip drilling concept for manufacturing deep holes with a length-to-diameter-ratio of up to $l/d \approx 30$ to 40 [190]. Due to the symmetric, commonly double-fluted design of the tools, the radial force resulting during twist drilling is very low to non-existent, which allows to use higher feed rates in comparison to the classic single-lip drilling. Although high speed steel is applicable as well, particularly in the lower range of length-to-diameter $l/D < 20$, solid carbide tools are commonly used to fully exploit the possible productivity enhancement. The helical shape of the flutes enables an additional advantage with regard to the chip evacuation, since the chip removal has been mechanically supported according to the principle of the Archimedean screw. Furthermore, the tools exhibit a sophisticated cutting edge design in order to ensure an appropriate chip shape for the reliable chip removal along the flutes. Therefore, the process control can usually be realised without feed interruption for chip breaking or tool retraction for chip removal.

Although twist drills exhibit a symmetric construction, slight unbalance and run-out error of the tool cannot be completely avoided. Hence, deep hole drilling with twist drills requires a pilot hole for the typical application on standard multi-purpose machine tools (machining centres and lathes).

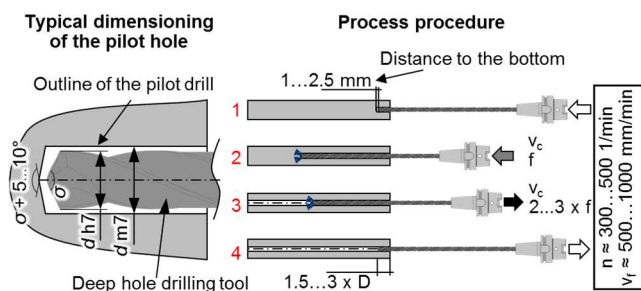


Fig. 30. Typical pilot hole design and process steps for deep hole drilling with twist drills [105,190]

The right part of Fig. 30 shows the process control of a common deep hole twist drilling operation. First, a pilot hole with high precision requirements regarding the shape and the dimensional accuracy has to be machined. Its diameter should be aligned to the diameter of the deep hole drilling tool (cf. left side of Fig. 30) to assure a good guidance of the tool avoiding a large diameter oversize of $\Delta d > 10$ to 15 μm , which could lead to an impaired drilling process, radial tool vibrations, tool breakage or high straightness deviations. Therefore, tool manufacturer usually recommend the use of special pilot twist drills, which provide the required diameter oversize of few microns and also exhibit an adapted point angle to produce a smooth entry of the chisel and the cutting edge into the material during the initial stage of the deep hole drilling process. In particular cases, length-to-diameter ratios of up to $l/D \approx 60$ to 70 can be achieved with special twist drills. Such tools are only available in the lower diameter range with a maximum diameter of $d_{\text{max}} \approx 6$ to 8 mm, since the total length of the drill is limited by today's grinding machines to a certain value of $l_{\text{max}} \approx 450$ to 500 mm. Due to missing tool support in common machining centres and the high aspect ratio of these tools, they cannot be directly applied after drilling the pilot hole, and a three-stage process using an intermediate step with a depth of approx. $l = 30 \times d$ has to be implemented to avoid buckling and breakage of the long tool.

3.4.2. Tool design

The tool design of a typical twist drill for deep hole drilling application is illustrated in Fig. 31. The tool consists of helical coolant channels for the internal supply of metal working fluid into the cutting zone. The flutes are manufactured by grinding between these coolant supply bores and usually exhibit sophisticated design as well as special surface finish to achieve a reliable chip evacuation even in a high drilling depth. Normally, a cylindrical clamping shank is used for a symmetric clamping of the tool to minimize the run-out error of the tool.

It is important to apply an appropriate combination of cutting speed and especially feed rate, which directly affects the frictional contact area at the flank face of the tool and therefore, the resulting process damping [160]. To reduce possible radial vibrations and to realise a better guidance in the bore, a four margin design is normally introduced in combination with a special chisel edge construction for decreasing the axial force and thus, the danger of buckling and breakage. Due to the high aspect ratio of the tools, their cross section weakened by coolant bores and the torsional-axial coupling of the helical design, twist drills are susceptible to vibrations.

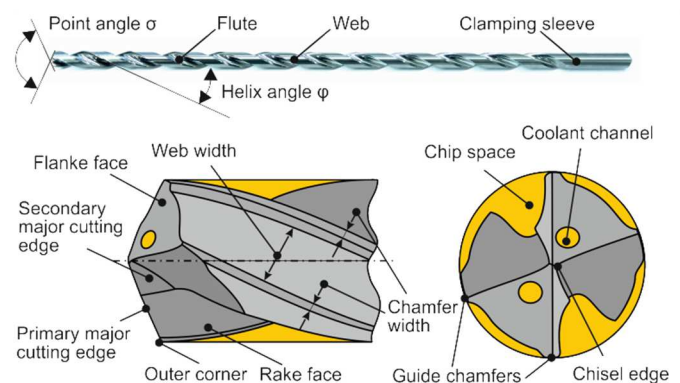


Fig. 31. Twist drill design for deep hole drilling applications [58–60]

In the case of double fluted tools, the coolant pressure can leak through the first flute and thus, no chip congestion in the second flute can be dispersed [105]. Despite the two cooling

channels, the flow resistance of the twist drills is significantly higher than that of single-lip tools, regardless of their design (brazed head or solid carbide) or shape (dual bore or kidney-shaped). Hence, the pressure needed to realise a predefined flow rate of the coolant is higher than in classic single-lip drilling. At the same time, the twist drill mechanically supports the chip evacuation by the helical design of its flutes and therefore, generally no higher coolant pressure is needed. The single-lip drill can provide higher process reliability, since, due to the single flute, there is only one way for the coolant and it is capable to dissolve a chip jam.

3.5. Double-lip drilling

3.5.1. Process principle

Double-lip deep hole drilling is used within the diameter range of $d = 2.8$ to 32 mm [22,190]. Like twist deep hole drills, double-lip deep hole drills have a symmetrical, double-lip tool design. Thereby, the cutting and passive forces arising at the opposing cutting edges are compensating each other. Consequently, a burnishing of the bore hole wall by the guide pads at the tool does not take place. Due to their tool design, double-lip deep hole drilling is predominantly used in machining short-chipping materials such as grey cast iron, free-cutting steels and aluminum cast alloys with high content of silicon [20,190]. In comparison to single-lip deep hole drilling on the one hand, higher feed rates can be reached by means of the higher number of cutting edges [20,217]. On the other hand, the cross sections of the chip flutes are smaller, which leads to a diminished process stability in machining steels [19,21,22]. Depending on the material to be drilled, higher length-to-diameter-ratios can be reached by means of a soldered tool design compared to twist deep hole drilling. Nevertheless, comparing single-lip and twist deep hole drilling, double-lip deep hole drilling has a relatively small market share [190].

3.5.2 Tool design

3.5.2. Tool design

The geometry of the chip flutes of double-lip deep hole drills differs from that of the twist deep hole drills by having straight flutes and thus a nominal rake angle of $\gamma = 0^\circ$. The cooling lubricant is supplied through two cylindrical channels inside the hollow tool shank. The mixture of chips and cooling lubricant is evacuated via the backlash between the longitudinal tool flutes and the bore hole wall. A high-pressure cooling lubricant supply is required to ensure that the lubricant reaches the operating zone and that the cooling lubricant functions such as cooling, lubricating and chip evacuation along the straight chip flutes are secured. The schematic tool design of double-lip deep hole drills is shown in Fig. 32.

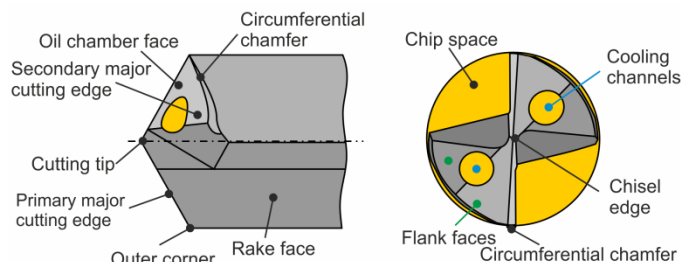


Fig. 32. Schematic tool design of double-lip deep hole drills [190]

Depending on the tool diameter, solid cemented carbide tools or tools with a drill head made of cemented carbide soldered onto a steel shank, are used [190].

4. Deep hole drilling of different workpiece materials

The following chapter deals with recent results and conclusions on deep hole drilling of different workpiece materials, as far as they have not yet been mentioned. The results for deep hole drilling shown in Table 1 are intended to provide a guideline for machining with modern cutting tool materials. Due to the fundamental investigations well-founded results, connections and conclusions have often been made with respect to the influence of cutting data, process parameters as well as tool designs.

Table 1: Overview of deep hole drilling of different workpiece materials [3,16,69,92,96,105,111–113,117,130,153,217]

Author	Drilling method	Bore hole diameter D in mm	Drilling depth L in mm	Workpiece material	Feed rate f in mm	Cutting velocity v_c in m/min	Drilling length l_f in m
Heilmann	SLD	0.5	30 x D	TiAl6V4	0.0005	50	~1
Kirschner	SLD	1.3	30 x D	Inconel718	0.005	30	0.78
	Twist	1.3	30 x D	Inconel718	0.01	20	0.78
Heilmann	SLD	1.5	30 x D	X2CrNiMo17-12-2	0.07	100	~5
	Twist	1.5	30 x D	X2CrNiMo17-12-2	0.05	30	~5
Kirschner	SLD	2	30 x D	20MnCrMo7	0.02	70	10
	Twist	2	30 x D	20MnCrMo7	0.05	80	10
Metzger	SLD	2	30 x D	C45***	0.04	80	~6
Keitzel	SLD	2	50 x D	50CrV4	0.01	78	10
Heilmann	SLD	2.04	66 x D	42CrMo4+QT	0.019	50	~10
Felderhoff	SLD	5	30 x D	42CrMo4+QT	0.2	80	30
	Twist	5	30 x D	42CrMo4+QT	0.2	80	30
Richarz	Twist	5	30 x D	42CrMo4+QT**	0.08	50	8.6
Hartmann	SLD	5	30 x D	20MnCrMo7	0.08	80	22.5
Bernreiter	SLD	6.35	90 x D	X33CrS16	0.03	60	-
Kersting	SLD	7	40 x D	34CrNiMo6	0.05	70	-
Iovkov	SLD*	10	30 x D	AlSi9Cu3	0.5	175	-
	Twist*	10	30 x D	AlSi9Cu3	4	175	-
Wittkop	SLD	15	20 x D	X20Cr13	0.08	70	~2
	Twist	15	20 x D	X20Cr13	0.15	70	~2
Kessler	STS	26	26 x D	C60	0.13	90	-
Abrahams	STS	60	50 x D	X5CrNi18-10	0.2	80	3

* = MQL

** = 50 ± 2 HRC

*** = lead free

Hartmann investigates the influence of the workpiece material related to the optimization of the cutting data for the machining of bainitic steels [92,93]. For reliable and efficient deep hole drilling processes, SLD tools with an improved cutting edge design, which generates a more stable cutting tip, were used. Compared to the quenched and tempered steel 50CrMo4+QT, high strength steels with a bainitic microstructure can be machined with higher feed rates and less tool wear. The improved machinability of the bainitic steels is shown in less mechanical tool loads during machining [92] (Fig. 33). Fig. 34 shows the dependence of the feed force and the drilling torque on material hardness during SLD deep hole drilling with small diameters a heat treated ledeburitic cold-working steel.

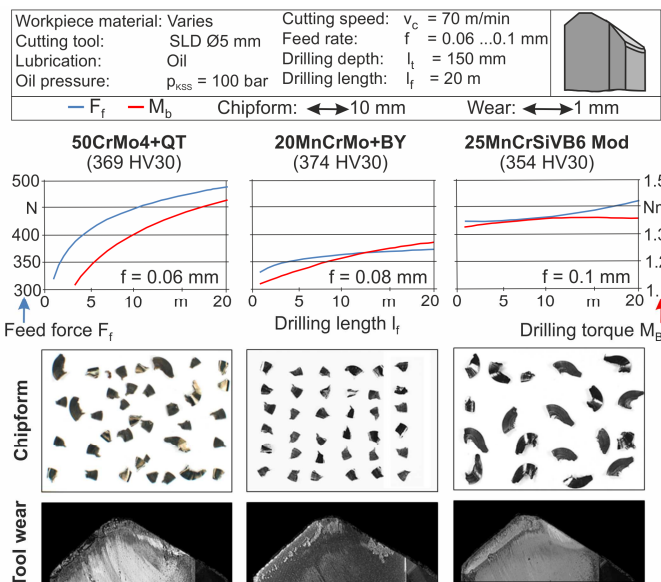


Fig. 33. Machining of high strength steels with bainitic microstructures [based on 92]

The cold-working steel hardness varies from 42 up to 61 HRC. According to the mechanical tool load, the influence of the microstructure at the same hardness of 58 HRC is illustrated by a comparatively high drilling torque when machining the secondary hardened material [66].

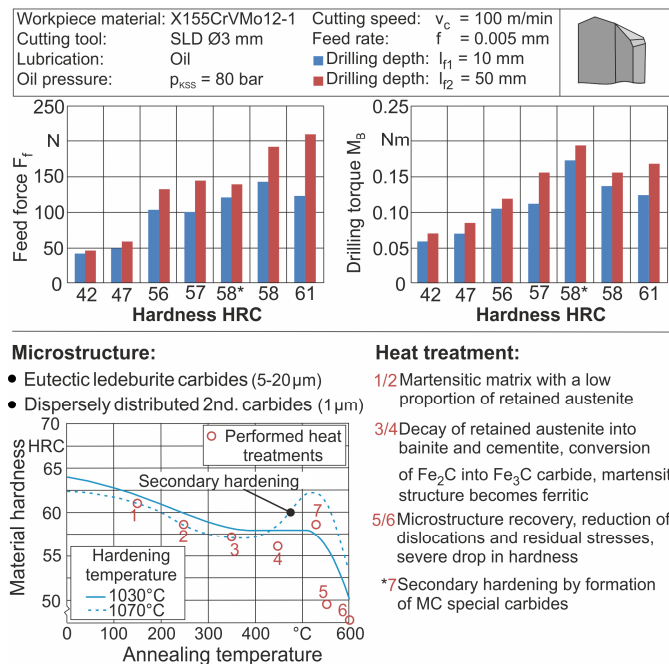


Fig. 34. Influence of the workpiece material microstructure on deep hole drilling [66]

In addition, Heilmann investigates the influence of the workpiece material under identical experimental set-ups (Fig. 35) [96,218]. The mechanical tool load occurring during the machining of stainless steel compared to the titanium alloy is considerably higher due to the material properties. The very high tendency to work-hardening of the steel in combination with low feed rates results in machining the solidified area in front of the cutting edge. Due to the low feed rates, this solidified area cannot be undercut, which results in a short tool life time [96].

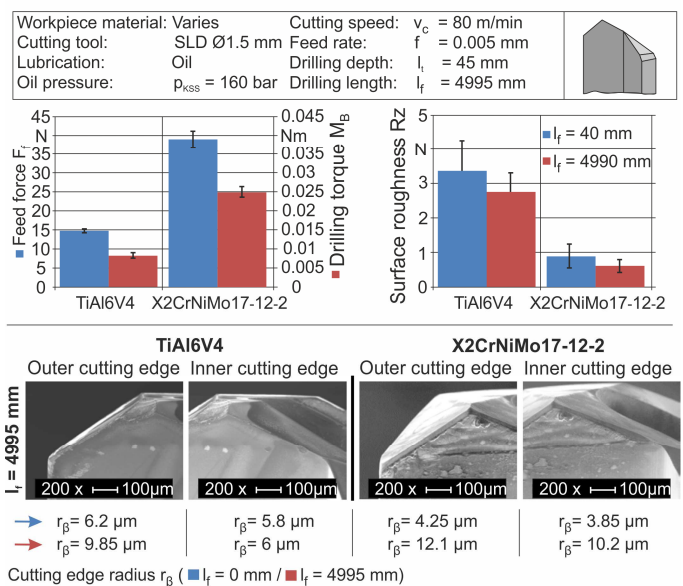


Fig. 35. Deep hole drilling of difficult-to-cut materials with smallest diameters [96]

According to the higher normal forces at the guide pads and the higher deformation capacity of the steel in the austenitic structure, an improved smoothing of the roughness peaks is achieved. The machining of the titanium alloy is characterized by a swelling load due to fluctuating compressive stresses and explains the significant damages in the cutting tip area [96].

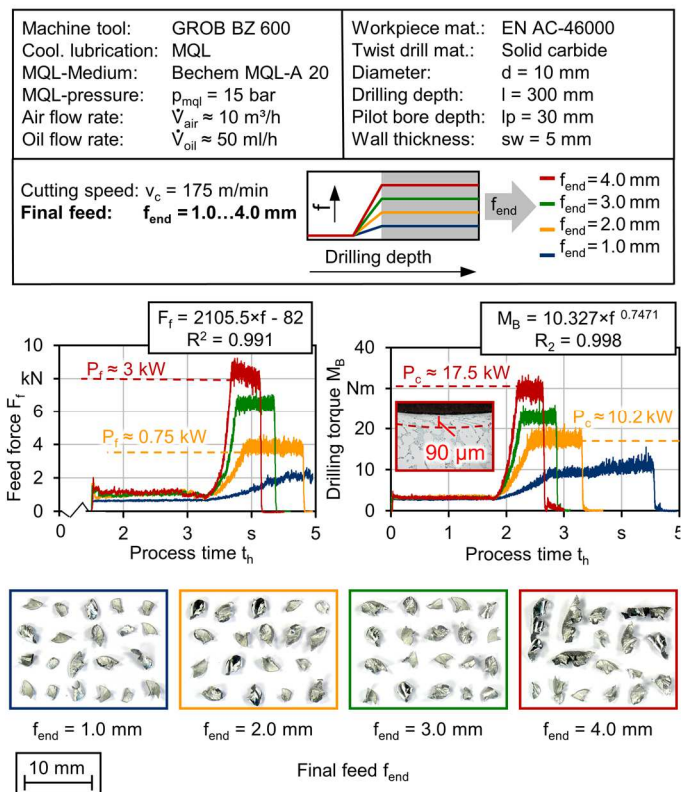


Fig. 36. Influence of the feed rate on the mechanical load and chip formation [105]

Iovkov investigated the deep hole drilling of aluminum cast alloy AISi9Cu3 (EN AC-46000) with MQL and achieved a high productivity enhancement by increasing the feed to extreme

values of up to $f = 4.0$ mm per revolution (Fig. 36) [105]. Thereby, a special tool design of the double-fluted solid carbide twist drills was implemented in addition to the high-pressure MQL device and the ramped feed increase strategy. At the highest parameters the tool load rises dramatically to a feed force of $F_f \approx 8000$ N and a drilling torque of approx. $M_d = 30$ Nm, which is untypically high for the aluminum machining, but still feasible with standard machine tools. The main advantage of the high-feed process is, apart of the increase in productivity, the significantly lower thermal load onto the workpiece (see chapter 5.3). From technological point of view, the feed rate should be limited to a max. of $f = 2$ mm/rev., since above this value, a strong plastic deformation of the material in the area of the bore hole wall occurs, the subsurface integrity can be impaired and the dimensional as well as form deviations increase [105].

For a comprehensive process analysis and improvement, well-founded insights on the chip formation in the closed operating zone are indispensable. For this purpose, quick-stop devices can be used to promptly separate tool and workpiece. Chip roots representing the frozen engagement situation and the defined material removal in front of the cutting edges are produced [85,120,163,204]. Afterwards, the mechanisms of chip formation in the different zones along the cutting edges are analyzed by metallographic preparation in sequential steps [10,120,177]. Nevertheless, the use of quick-stop devices is not feasible for analyzing smallest diameter deep hole drilling due to the impracticable demands on sudden acceleration and abrupt separation of tool and workpiece. A new methodology of analysis has been developed at the Institute of Machining Technology (ISF) to accomplish an in-depth chip formation analysis in smallest diameter deep hole drilling. The fundamental idea of the new analytical technique is the substitution of the surrounding, i.e. non-transparent bore hole wall by transparent acrylic glass [40,41].

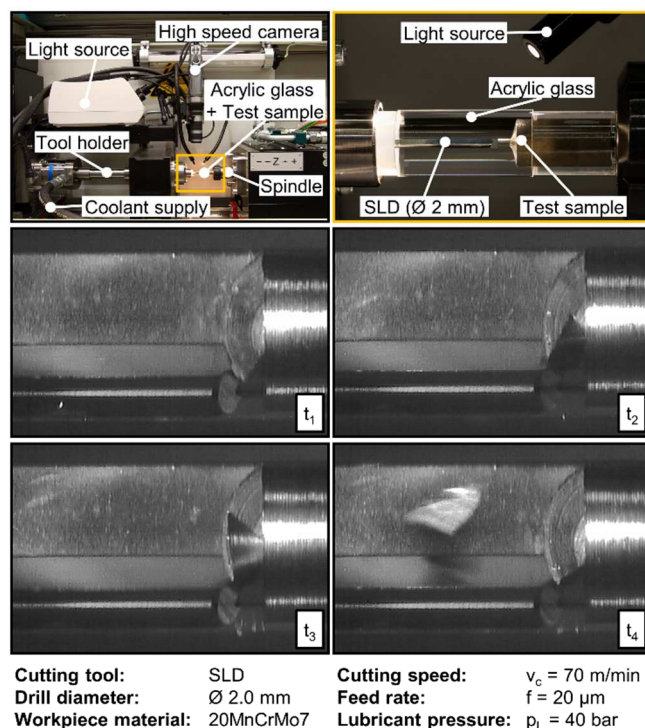


Fig. 37. Chip formation analysis by high-speed microscopy [117]

This approach facilitates the visualisation of the chip formation at the cutting edges as well as the chip removal along the chip flutes by means of high-speed microscopy. Fig. 37 shows the integration of the experimental setup into a conventional deep hole drilling machine as well as sequences of the chip formation

in smallest diameter single-lip deep hole drilling of high-strength bainitic steel 20MnCrMo7. To allow a constant observation of the chip formation, the experiments are conducted with stationary cutting tools and rotating material samples embedded into acrylic glass. Furthermore, laser diodes with specific wavelength instead of cold light sources are used for the illumination of the operating zone in order to avoid transparency problems in terms of flow turbulences while conducting analyses under enhanced lubricant pressures [29,117].

5. Special developments

5.1. Vibration assisted deep hole drilling

During the deep hole drilling process, chip formation and removal are critical factors for bore hole quality, process stability and can affect tool wear significantly. While the chip form can vary already by the methods of single-lip deep hole drilling, STS deep hole drilling or ejector deep hole drilling, process parameters like feed rate, cutting speed, workpiece material and lubrication also have a strong influence. Since tool engagement changes periodically during vibration assisted machining, this particular machining technology can induce several improvements especially for drilling applications of very deep bore holes [97,125].

While prior developments were mostly based on mechanical principles, new actuator systems in the field of vibration assisted drilling have been complementing these methods with a wide range such as piezoelectric, hydromechanical and electromagnetic principles to support the deep hole drilling process for a controlled chip breakage and evacuation (Fig. 38) [34]. Applications according to drilling with superimposed vibrations in the frequency ranges of sound and ultrasound have been discussed intensively [5,48,148,180].



Fig. 38. Actuator systems [33,139,146]

As vibration assisted machining in drilling is generally more common at high frequencies up to ultrasonic range (above 15 kHz) [11], research e.g. in [138,154] has found out that low frequencies (under 250 Hz) induce all the positive effects of vibration assistance, but with a more manageable stability. Especially the much higher amplitudes gained due to reduced inertia forces can achieve more favorable chip forms. Since vibrations are commonly generated at the tool, stroke losses over the tool length can be compensated much better at higher amplitudes. For deep hole drilling this was already proven by using a hydromechanical actuator system which can initiate strokes up to 1 mm to an air beared spindle rotor shaft in axial direction. Results showed reduced tool wear and higher possible feed rates (see below Fig. 39).

Heisel describes the machining of hard to cut materials such as martensitic steel, and, with respect to the chip formation, pure

aluminum and electrolytic copper with ultrasonic vibration assisted deep hole drilling [103].

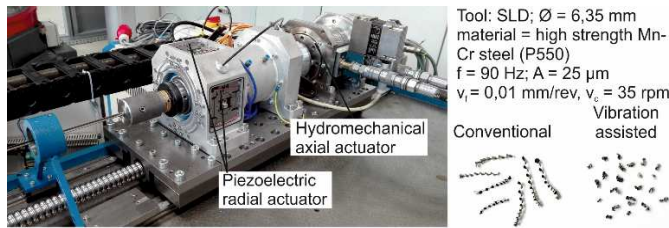


Fig. 39. Drilling spindle with a multidimensional oscillatory rotor shaft used for low frequency drilling applications [34]

The result shows that the machinability of all considered materials can be improved. For example, conventional machining of electrolytic copper Cu-ETP (C11000) is carried out at very low feed values, as the material tends to form very long and unfavourable chips. In addition, high frictional forces on the tool's guide rails cause high torsional strain on the deep hole drill.

Cutting tests show that the process parameters of drilling torque and feed force can be favourably influenced by means of ultrasonic vibration. In addition, it can be proved that, compared with conventional machining, a higher surface quality can be achieved in the case of an optimized combination between the feed rate and no-load amplitude of the actuator. Due to a simultaneously favourable chip form and length, a higher process stability can be established as well. Examinations of the surface zone, which were additionally carried out, indicate that vibration superposition influences the material properties of the workpiece [103].

5.2. Solutions to minimize the straightness deviation

The correction of straightness deviations in deep hole drilling at high l/D-ratios becomes more and more essential, e.g. in the oilfield industry. However, also in other metal machining applications, an increase of the straightness accuracy of deep bore holes is requested [73,172].

Using mechanical deflection of the drill head in combination with an ultrasonic measurement system is the most common method for controlling the drilling path in deep hole drilling applications. An influence on the tool path can be realized in STS deep hole drilling by the use of a radial adjustment mechanism for the cutting edges or the guide pads ([147] and Fig. 40).

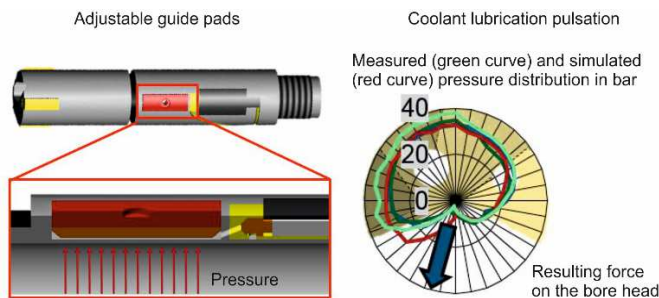


Fig. 40. Reducing straightness deviation in STS and SLD processes

Hydro- or piezo-mechanic actuator systems are integrated in these applications. Due to the restricted space in single-lip deep hole drilling tools, straightness deviation corrections cannot be achieved by implementing actuators in the tool itself. An influence on the drill head can be achieved mechanically with an external adjustment, where these effects are limited to reduced drilling depths. For example, by using an eccentric tap hole in

combination with a tiltable bore bushing, the bore path can be controlled by bending the tool [35]. In addition, at higher l/D-ratios and adequate tool diameters, eccentric bore bushings can be inserted into the borehole to correct the deviation. These applications result in increased labor and require experienced workers to handle. Thus the aim of recent research work in this field focuses on automatic operating systems which are fully integrated in deep hole drilling machines. Pulsation of the cooling lubricant has shown to be able to affect straightness deviations in the single-lip deep hole drilling process. The coolant pressure gradient on the drill head, due to a dynamic pressure overlap with the constant process lubrication flow, generates a radial force. When used synchronously to the tool's rotational movement, a repeated force impulse can be achieved in a particular angular section which is used to minimize or eliminate straightness deviations [36,99,149]. Consequently, this effect can be applied even to realize defined curved holes. Similar to the advantage of an oscillatory overlap of the feed for better chip formation, it has been shown in [65] that a feed pulsation in axial direction can have effect to reduce straightness deviations as well. However, these methods are induced together with an appropriate measurement system for determining the bore hole position, e.g. ultrasonic measurement devices, in order to realize a closed loop control.

Since mechanical methods are accompanied by greater complexity, non-mechanical solutions have been investigated as alternative process options. Local inductive heating of the workpiece has been found to have significant influences on bore hole straightness in STS deep hole drilling (Fig. 41). A temperature gradient is induced externally on one side of the workpiece for a local change of the material properties effecting the angular cutting force regime [31]. The use of complex actuating systems inside the bore head can be avoided. Besides the above mentioned technologies based on drilling processes with the aim of avoiding straightness deviations, applications by the use of electric discharge machining are investigated that consciously try to achieve a defined straightness deviation for drilling complex and curved holes [106,131].

Workpiece:	C60 (1.0601)	Feed rate:	$f = 0.13$ mm/rev
Tool:	STS $\varnothing 26$ mm	Drilling depth:	$l_t = 500$ mm
Cutting tool mat.:	HC-P25, TiN	Lubricant:	Oil, $V = 105$ l/min
Cutting velocity:	$v_c = 90$ m/min	Heating power:	$P_{th} = 2.5$ kW to 12.5 kW

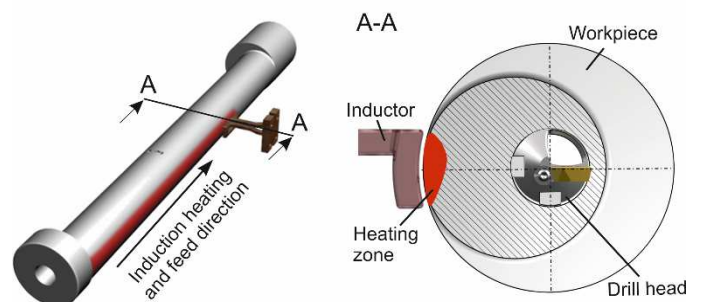


Fig. 41. Inductive heating in BTA deep hole drilling for straightness influence. [based on 113]

To minimize the systematic straightness deviation, resulting from the thermal workpiece distortion in MQL deep hole drilling with twist and single-lip drills (see section 5.3), Iovkov developed a new approach, based on a radial correction of the feed movement along the drilling depth [105]. Normally, drilling and deep hole drilling operations use one dimensional feed motion corresponding to the bore axis. Due to the heat input into the workpiece and its accompanying thermal expansion, the ideal bore axis and the front guided area of the deep hole drilling tool have been deflected in the direction of thermal workpiece distortion as

well. The bending of the tool effects a directional change of the drilling process and thus a high straightness deviation of the bore. Therefore, a small radial displacement of the machine tools spindle overlapping the axial feed movement during drilling can be used to move the tool in the direction, opposite to this of the initial straightness deviation. Results show that this approach is capable of changing the direction of systematic straightness errors and can be used for example to steer the deep hole drilling tool away from the thin-walled area of the component machined [24].

In order to determine an optimal radial compensation path for a specific process, a geometric-kinematic simulation was applied [18,105]. This approach unites a simple bending beam model of the tool and a finite-element-analysis (FEA) of the thermomechanical workpiece behavior during the process to geometrically calculate the resulting straightness deviation. In a second step, the same simulation has been used with modified boundary conditions, including preset position and angle values of the drill head for each depth position according to the current workpiece distortion from the FEA, to identify the radial spindle/tool clamping position, which is required to ensure the desired tool deflection and thus a minimal straightness deviation after the workpiece has cooled down to room/initial temperature again (Fig. 42).

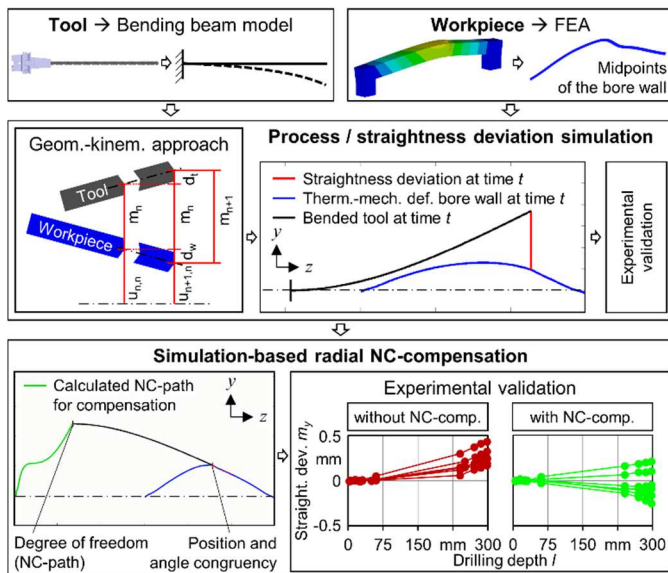


Fig. 42. Simulation-based procedure for the NC-based compensation of thermomechanically induced straightness deviations in MQL deep hole drilling using MQL and twist/single-lip drills

5.3 Minimum Quantity Lubrication

Dry cutting is not feasible in deep hole drilling operations, since a reliable chip evacuation and a sufficient lubrication of the cutting, but above all of the guiding elements, have to be provided by an cutting lubricant [119]. The only possibility for the realisation of semi-dry conditions is the introduction of MQL [202]. This coolant concept is not applicable in STS and DTS drilling because in these processes the chip removal makes a high flow rate of oil necessary. Therefore, the MQL is mainly used on standard machine tools or machining centres for single-lip, double-lip and twist drilling operations. The main advantage of MQL is the partly attainable longer tool life [202] and lower power consumption due to the avoidance of big cooling lubricant systems and pumps [2,38,126,161,185]. At the same time, the process technology, particularly including the tools, the MQL-supply and the cutting

parameters, has to be adapted to the semi-dry conditions, which is, based on the high process development efforts, only reasonable in series production and not meaningful for small, e.g. single-part production. In single-lip drilling, the sufficient supply of the radially loaded guide pad area is of crucial importance for the successful introduction of MQL, particularly when drilling adhesive materials, such as aluminum alloys [53,179,186,212].

Industrial applications of single-lip and deep hole drilling using twist drills with a length-to-diameter ratio of up to $l/D \approx 60$ to 70 are feasible under MQL conditions [25]. Thereby, the chip evacuation is supported by the significantly higher flow rate of the compressed air in comparison to the flow rate of classic high-pressure coolant supply [105,159]. Nevertheless, the high flow rate is not able to dissipate the process heat from the tool, the workpiece and the chips, since the low density and heat capacity of air lead to a high temperature increase of the MQL and thus to a significant heat input into the workpiece [26,104,105,173–175]. While modern cemented carbide tools can usually resist the high thermal load without any problems, the heat flow into the machined component causes thermal distortion, which has a negative effect on the accuracy of the current deep hole as well as on subsequent processes (Fig. 43) [105,175].

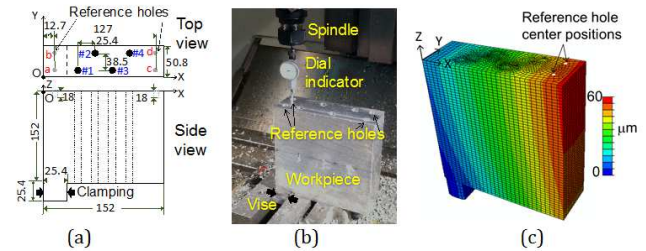


Fig. 43. The workpiece thermal expansion in deep hole drilling

A study on workpiece thermal distortion in deep hole drilling was conducted by Tai et al. [175]. Four 10 mm diameter and 152 mm deep holes were drilled in the aluminum workpiece with bottom side clamp (Fig. 43 (a) and (b)). To measure the workpiece thermal distortion, the accuracy of machine tool was utilized. Before drilling, two shallow reference holes (marked as a and b) were first drilled. After drilling four deep holes, the temperature of workpiece is raised to about 30 to 40°C and two other reference holes (marked as c and d) on the opposite side of the workpiece were immediately drilled. Due to workpiece thermal expansion, the distance between two reference holes across the workpiece is different from the 127 mm programmed in the tool path. The finite element model predicted workpiece thermal distribution (Fig. 43 (c)) showed this distance was increased by 51 μm. This value matched well with the 61 μm measured using the dial indicator (Fig. 43 (b)) and the laser interferometer. To decrease the thermal load of the workpiece, a high feed rate should be used, since the heat balance can be shifted more to the chips with increasing the undeformed chip thickness (Fig. 44).

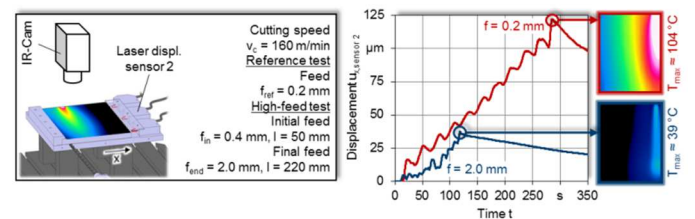


Fig. 44. Thermal load of the workpiece depending on the feed rate [105]

Using high performance twist drills for achieving feed values of up to $f = 2$ mm per revolution, Biermann and Iovkov were able

to drastically decrease the thermally induced workpiece deformations in MQL deep hole drilling of cast aluminum, apart from the enormous increase in productivity [18,24,105].

5.4 Process monitoring and control

An essential requirement for the development of process monitoring and control systems is the availability of sensors for the detection of relevant process conditions as well as suitable signal analysis methods for obtaining process information. This information can be used to evaluate the process or to adjust it by the implementation of a closed control loop. By identifying cause-effect relationships, process knowledge can be integrated in models. The implementation of models can be used to develop systems, such as model-based process monitoring or model-based controllers. In order to ensure tool protection, the deep hole drilling process is therefore commonly designed with conservative parameters in industrial practice. Process monitoring with sensors is a suitable instrument to assist the machine operator in the process evaluation and to operate the process with more economical parameters.

Sensors for monitoring the cutting forces

Commonly, a workpiece-side force and torque measurement based on piezoelectric dynamometers is used [79,96,170,215]. The tool-side measurement was carried out by Wessels [214] and Byrne et al. [46]. However, due to a limited number of manufacturers and sensors, suitable variants are not available for each tool holder. The measurement of the effective power of drive axes and the tool spindle belongs to the indirect measuring methods of the cutting forces and is carried out with external effective power modules or machine internal sensor system of the frequency converters [97,112,128].

Sensors for monitoring the chip transport

Process related and procedural related state variables can be used to assess the chip transport [12]. Wirtz used the axial force for the detection of chip jam and had been able to detect for small diameters that the system can identify the chip in time [215]. Following countermeasures for tool protection could be initiated. Furthermore, an identification of chip jams based on the absence of chip detection is possible. For this a deflector plate and a sensor are necessary. Baier uses an inductive sensor, Weinert et al. and Löbke an acceleration sensor and Wirtz an acoustic emission Sensor (AE sensor) [12,127,205,215].

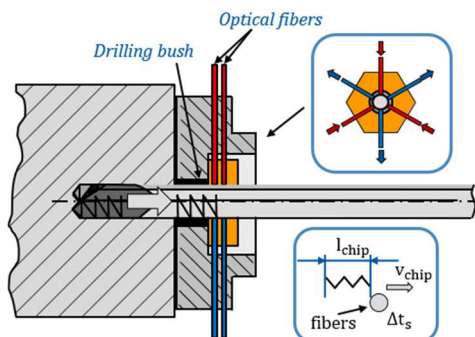


Fig. 45. Integrated sensor in drilling bush [111]

A different sensor concept was invented recently by Keitzel to increase the economic efficiency of the gun drilling process under the restriction of a safe chip removal. The principle can be seen in Fig. 45. The sensor consists of an extension of the drilling bush.

For the detection of chips, the sensor records infrared light beams with photodiodes that are arranged radial to the drill. If a chip passes the sensor, the reflection is disturbed and the length of the chip, the chip velocity and the chip-to-chip time can be calculated by knowing the cooling lubricant parameters. The relative velocity of the chip in comparison to the coolant is an application oriented key value that gives information about the friction of the chips at the surface of the chip flute and the bore hole [111].

6. Related deep hole drilling methods

In addition to the classic deep hole drilling methods, also a large number of further methods for the final machining of deep bore holes exists. Deep bore holes can be remachined with regard to their surface properties or can be used as the basis for machining complex and non-cylindrical shaped contours. Therefore, Fig. 46 shows an overview of the related deep hole drilling methods depending on the machining task and the bore hole contour to be created.

	Deep hole drilling methods					
	Machining of deep holes			Final machining of existing deep holes		
	Cylindrical deep holes			Non-cylindrical deep holes		
	Solid drilling	Core drilling	Boring	Finishing	Form-boring	Internal profiling
SLD	●	●	●		●	
STS	●	●	●		●	
DTS	●	●	●			
Twist drilling	●					
Skiving			●	●		
Roller burnishing				●		
Internal profiling						●
Single-edge reaming				●		

Fig. 46. Related deep hole drilling methods [189]

6.1. Internal profiling

For a lot of different reasons, there are components with deep bore holes whose inner contours may be rotationally symmetrical but not uniformly cylindrical. Such components can have contours without undercuts, such as centrifugal casting moulds or conical bores in extruder cylinders, as well as with undercuts, such as propeller shafts or landing gears. Such undercuts are often located where less material is held due to the mechanical load. To produce such chambered pockets, a pre-drilling of high quality is required (Fig. 47). If the radially extendable cutting tool is controlled by an NC (numerical control)-axis and connected to the NC bore slide of the deep hole drilling machine, it is almost possible to produce any bore wall contour in one cut over the entire contour length.

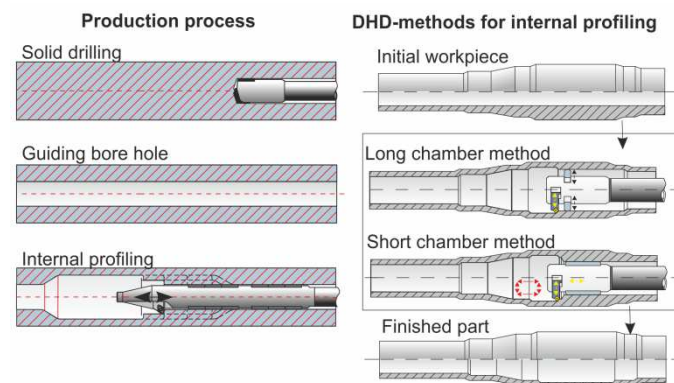


Fig. 47. Steps of internal profiling [43,74,189]

The position of the cutting edge can be modified by an axial displacement, e.g. by using an inner thrust tube. Additionally, the

guide pads can also be adjusted hydraulically. Since the guiding bore hole was already completely turned after the first cutting step with the so-called long chamber method, the guide pads must also be able to radially adjust in order to support the tool for larger chambers. As an alternative to this method, the so-called short chamber method does not require extendable guide pads because the tool is exclusively located in the pre-drilled guiding bore hole [43,74].

In addition to rotationally symmetrical internal profiling, two innovative contouring methods on deep hole drilling machines exist. Fig. 48 on the left side shows the blind hole bottom profiling. By synchronizing the tool feed rate f_t and the rotation of the cutting slider f_s variable bottom contours can be machined [75]. In contrast to form boring tools, the cutting speed value can be kept constant regardless of the contour radius due to changing rotational speed.

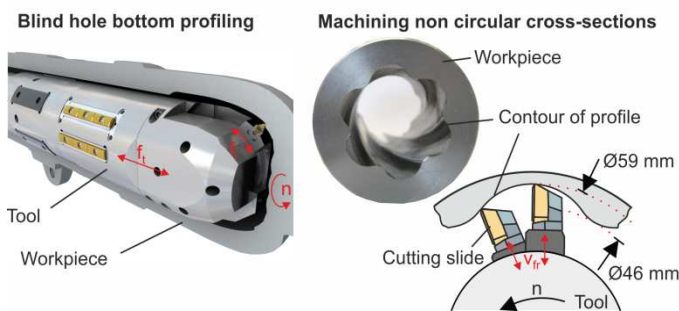


Fig. 48. Machining non-cylindrical and non-circular bore holes [based on 75]

The profiling system for non-circular cross-sections and a machined workpiece is shown in Fig. 48 (right) illustrating that it is possible to profile components not only in their drilling axis but also across. During the drilling process, one cutting slider is extended and retracted per revolution, depending on the contour to be produced. The process is being executed by pulling the tool through a precise pre-drilling. Due to a slight but continuous change in the temporal sequence per revolution, the contour turns in axial direction.

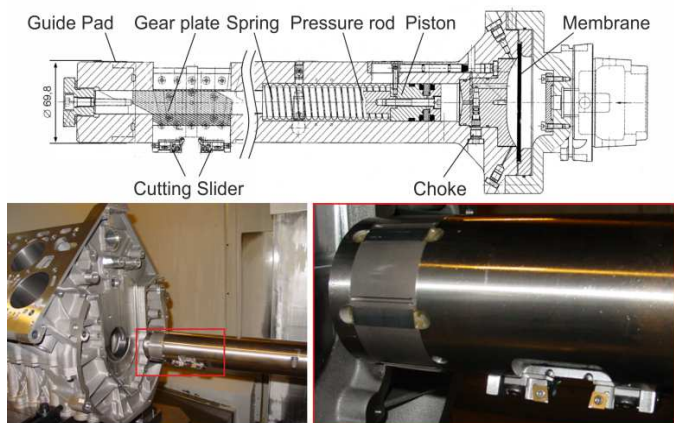


Fig. 49. Extendable cutting slider for machining an axial crankshaft bearing [based on 32]

Another possibility for moving a cutting slider along an additional axis is the use of coolant pressure. Such profiling tool concepts are often used on machining centres where the additional installation of a complete NC-axis does not economically make sense. An impressive example of the use of such extendable tool systems can be found in the fine machining of the crankshaft

bearing of the 16-cylinder Bugatti Veyron engine 16.4 (Fig. 49) [32].

6.2. Skiving and roller burnishing

Skiving improves the roundness and dimensional accuracy of the bore hole diameter. An open surface profile is produced close to the subsurface zone which is particularly suitable for following machining processes such as roller burnishing or honing. Since the tools are designed to follow the drilled bore hole axis, existing straightness deviation cannot be corrected [188]. In the field of machining hydraulic cylinders and cylinder liners, skiving and roller burnishing is considered to be a single, related manufacturing process, although it has a purely cutting and also forming component. The reason for this is the wide use of combined skiving and roller burnishing tools (Fig. 50). Although less attention has been paid to internal skiving than to internal roller burnishing, it is well-known how a smooth rolling surface can be achieved [42,68,80,115,122,133].

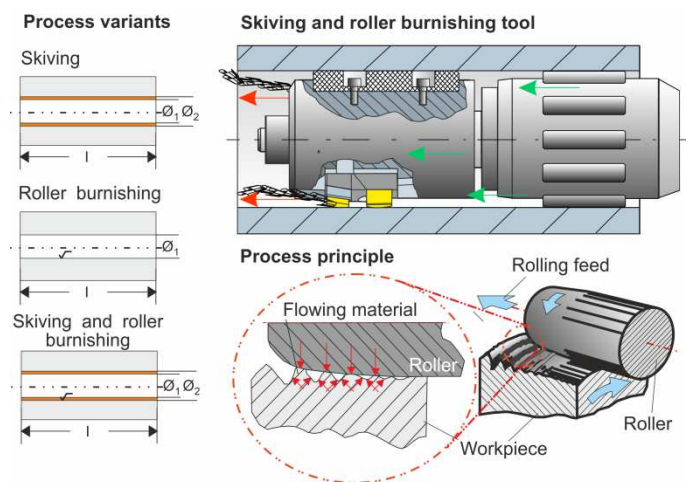


Fig. 50. Skiving and roller burnishing: variants, tool and principle [based on 189]

Hegewald created a modified Kienzle cutting force equation for a special-curved cutting edge in STS-internal skiving, taking into account the cutting depth [95]. This special form of internal skiving is characterized by the supply of cooling lubricant through the annular gap between the tool and the bore hole wall, which evacuates the chips in the feed direction. Therefore, the roller burnishing process is not negatively affected by the chips. In addition, the tool guides itself by the guide pads in the machined bore hole and thus represents a classic deep hole drilling method characteristic [42,95].

The burnishing rollers arranged at the circumference smooth the roughness caused by the skiving process. König already recognized that roller burnishing does not shift the roughness peaks. The roughness valleys rise to the same extent as the peaks of the machined surface are pressed into the workpiece material [121–123]. The roller burnishing process, that directly follows the skiving process, enormously depends on the skiving process quality. The specific microgeometry of the surface is considered to be a major factor influencing a successful roller burnishing process. According to Buse, the roundness of the skived bore hole, which is caused e.g. by the movement of the pendulum cassette, cannot be eliminated by roller burnishing as the elastic expansion causes the workpiece to spring back again. Therefore, in the case of combined machining, it is important to ensure that an ideal round skiving result is achieved as well as matched skiving feed rates and burnishing oversizes [42].

6.3. Single-edged reaming

Another machining process to increase the surface quality and the dimensional accuracy of a bore hole, is using single-edged reamers. Reaming is the counterboring of a pre-drilled bore hole with the tool supporting itself by the guide pads. Therefore, the tool geometry of these reamers is very similar to single-lip drills. An increasing number of reaming tools with internal supply are used for this purpose (Fig. 51) [124]. Different authors investigated the influence of the cutting data on the reamed bore hole quality [76, 129, 13, 192]. The difference to single-lip drilling with a small cutting depth is the usually missing circumferential chamfer, a long side cutting edge parallel to the reaming axis, as well as the low coolant quantities and pressures [189].

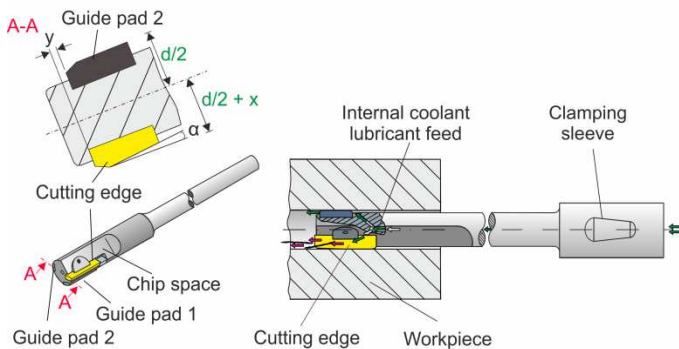


Fig. 51. Schematic tool design of a single-edged reamer [6,189]

In order to achieve high surface qualities at high cutting speeds, a double cut of the cutting edge is necessary dividing the machining process into a roughing and a finishing operation. The steep part of the insert is for the rough machining, the flat part for the finishing and counteracts the occurrence of vibrations [124,162].

7. Summary

The technological advantages of deep hole drilling processes and the varieties of application areas, such as the automotive and aerospace industries, demonstrate that deep hole drilling processes are of significant importance in metal-cutting machining technologies. Despite its use in both mass and individual production, it is often wrongly referred to as a niche process.

Especially with regard to the bore hole diameter as well as the drilling depth, classical deep hole drilling methods enable the efficient realization of incredible bore hole dimensions and accuracy. In addition, classical deep hole drilling methods are also used whenever the highest drilling quality is required. Due to a wide number of deep hole drilling methods, the possibilities for the manufacturing of complex and highly accurate components become possible.

In the present paper, the fundamentals of deep hole drilling like the asymmetrical cutting edge design and the use of cooling lubrication with high pressure and high volume flow and their impact on the deep hole drilling process are described. Illustrating classical deep hole drilling methods offer the difference to the conventional short drilling. Investigations of machining modern workpiece materials as well as the development of special solutions for almost impossible manufacturing tasks are presented. New related deep hole drilling methods enable the realization of complex and individual components and increase the field of application.

In the present paper the differences between deep hole drilling and conventional drilling become clear. Deep hole drilling methods are very often the enabler for realizing almost impossible manufacturing tasks.

8. Future Trends

It can also be assumed that all conventional deep hole drilling methods will continually be further developed in the future on the basis of their specific process advantages and characteristics. Due to the insufficient reachability of the deformed zone in often expensive and almost completely manufactured components, the desire for more process control is one of the priorities. The trend can already be observed that classical deep hole drilling tools will be significantly enhanced by the integration of sensor systems. Especially for tools with large diameters, there are enormous opportunities to create intelligent tool systems. One of the biggest challenges is the implementation of wireless, real time capable data transmission. Deep hole drilling machines and their peripherals will also be developed to be integrated into automated production systems and to be addressed by corresponding protocols. Due to the necessary components for complex and large tooling systems, integration becomes more difficult than for comparable machining processes.

In the area of developing deep hole drilling tools, two contrary trends can be identified. For tools with small and smallest diameters, it gets more and more important to select the appropriate tool design, cutting tool material, coating and cutting data using state-of-the-art analysis methods, due to the unstable cutting situation, when machining advanced high performance materials. Tools with large diameters offer more design possibilities to realize flexible and adaptable universal systems for machining small batch sizes with variable drilling requirements. The usage of new materials with damping material properties (e.g. for boring bars) and fluid-based tool designing are just a few of the possible innovations in the future.

Acknowledgments

The authors thank Y. Altintas and J. Sutherland as well as BGTB, boteK, BTA, US National Science Foundation, Sandvik and TBT for their contributions. For their valuable comments we thank R. Eisseler, I. Iovkov, M. Kirschner, C. Kumpf and T. Pullen. Special thanks are dedicated to M. Fuß and M. Metzger for the support in the preparation of this paper.

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