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PROCESS ANALYSIS AND HOLE QUALITY OF CROSS-DRILLED HOLES

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Abstract:
Making cross-drilled holes differs significantly from the production of conventional holes. An analysis of the cross-drilling process explains the drill behaviour as well as the cutting forces while positioning cross-drilled holes. Using this information, the effects of misalignment as well as the width, number and position of the drill margins on the hole quality in cross-drilled holes are analyzed.

Key Words: Production Technology, Drilling, Cross-Drilled holes, Tools

1. INTRODUCTION

Drilling is amongst the most important operations of production technology. The aim of drilling is to place a hole on a specific location of the component with the least costs and as fast as possible while maintaining the required quality. Securing operability of highly loaded components such as common-rail-systems (component of the fuel-injection system of modern diesel engines) requires a continually increasing hole quality [1,2]. The hole quality is also one of the most important contributing factors to both the increase in productivity and the reduction of production costs for drill intensive procedures [3].

The requirements for the production of high quality machining are unfavourable for numerous part families, e.g. work pieces with cross-drilled holes. Cross-drilled holes are considered to be holes that cut or penetrate previously machined cross-holes in a component as well as precasted channels. Figure 1 (left) shows a cross-drilled hole, which centrically penetrates a cross-hole.

The qualitative requirements of cross-drilled holes are specific to the component. For example the surface quality as well as both the circular shape and the straightness of the drilling determines the lifetime and the maximum injection pressure of a common-rail-system [4]. Therefore the motor’s combustion efficiency as well as its fuel consumption are indirectly dependent on the quality of cross-drilled holes.

An additional example of use for cross-drilled holes are control units in mobile hydraulics, which are used to control excavator shovels (see Figure 1, right). In this case, high pressures as well as the demand for minimal amounts of leakage flow require a good seal between the plunger and the plunger hole. The liner can only be efficient if the cross section surface produced by the cross-drilled holes complies with the predetermined tolerance, which is in the single digit μm^2 area. The straight line stability of the boring tool significantly determines the compliance with the tolerance of the cross section surface.

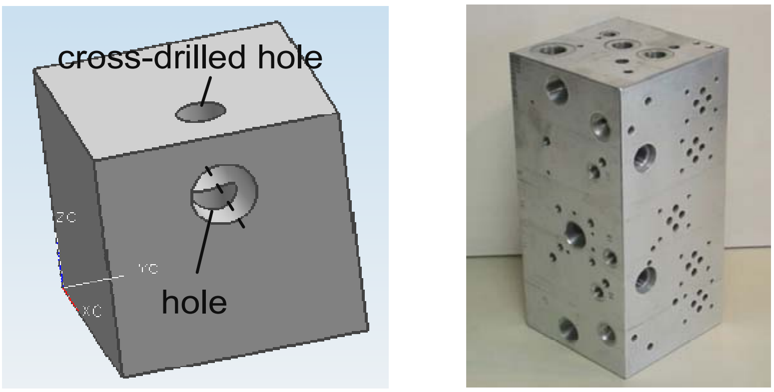


Figure 1: Cross-drilled hole (left); hydraulic control unit (right).

Malfunctions can arise, if the straightline stability does not comply with the specification, e.g. an uncontrolled movement of the excavator shovel can cause unpredictable consequences. Therefore the quality of the cross-drilled hole is of great importance, similar to the common-rail-systems.

The quantity of cross-drilled holes in components is expanding steadily through increasingly complex components and a trend towards a constant enhancement of the functional density [5]. In the future, the importance of creating high quality cross-drilled holes in large quantities will increase. Making cross-drilled holes to high quality standards requires specific process and tool optimisation. A fundamental understanding of the process is the precondition for the optimisation and the legally secure placement of cross-drilled holes. Often companies have special know-how on the topic of cross-drilled holes as well as on the achievable manufacturing quality. However, scientifically validated knowledge barely exists. This article addresses this issue through an analysis of the process of cross-drilled holes as well as investigating different effects on the quality of cross-drilled holes.

2 PROCESS ANALYSIS

2.1 Process phases in boring of cross-drilled holes

In comparison to drilling into a solid body, the drill procedure to make cross-drilled holes consists of seven process phases. Figure 2 shows the individual process phases based on a longitudinal cross section of a cross-drilled hole as well as a schematically indicated boring tool.

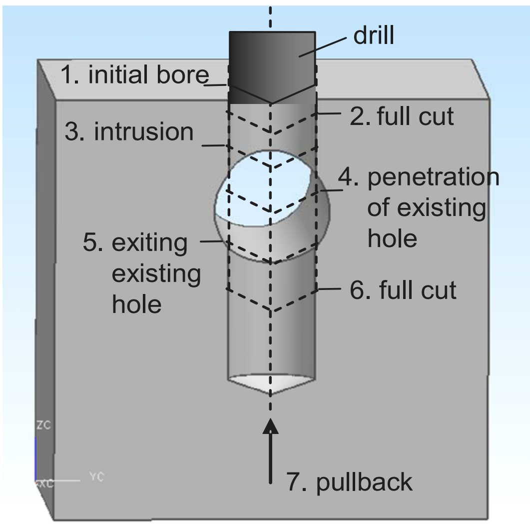


Figure 2: Process phases in the boring of cross-drilled holes.

The individual process phases differ mainly in the present contact conditions of the drill. Figure 3 shows the appropriate hole structure for the process phases 2, 3, and 5.

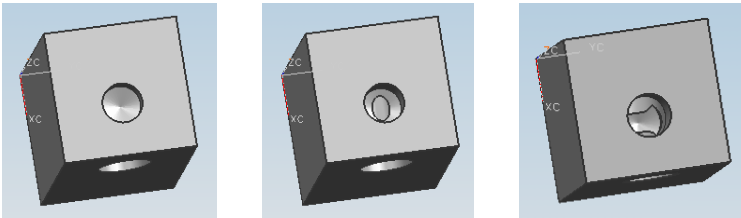


Figure 3: Hole structure in the process phases 2, 3, and 5.

2.2 Contact conditions and tool stresses in boring cross-drilled holes

In this section, both the contact conditions and tool stresses will be analysed for each of the process phases using experimentally acquired force and torque signals recorded during drilling. To demonstrate this, a penetration ratio DR (diameter ratio of cross-bore to cross-drilled hole) of 6 mm to 8 mm has been chosen for the cross-drilled holes. Figure 4 shows a typical feed force, radial force, and drill torque signal while boring through an existing cross-bore. The signal progress is organised into different process phases to comply with the previously determined convention.

The individual process phases differ greatly from each other according to the force and torque distribution in Figure 4. Process phases 1, 2, 6, and 7 correspond to the drilling of "conventional" holes. In contrast, phases 3 to 5 only occur when drilling cross-drilled holes and will therefore be analysed in the following section.

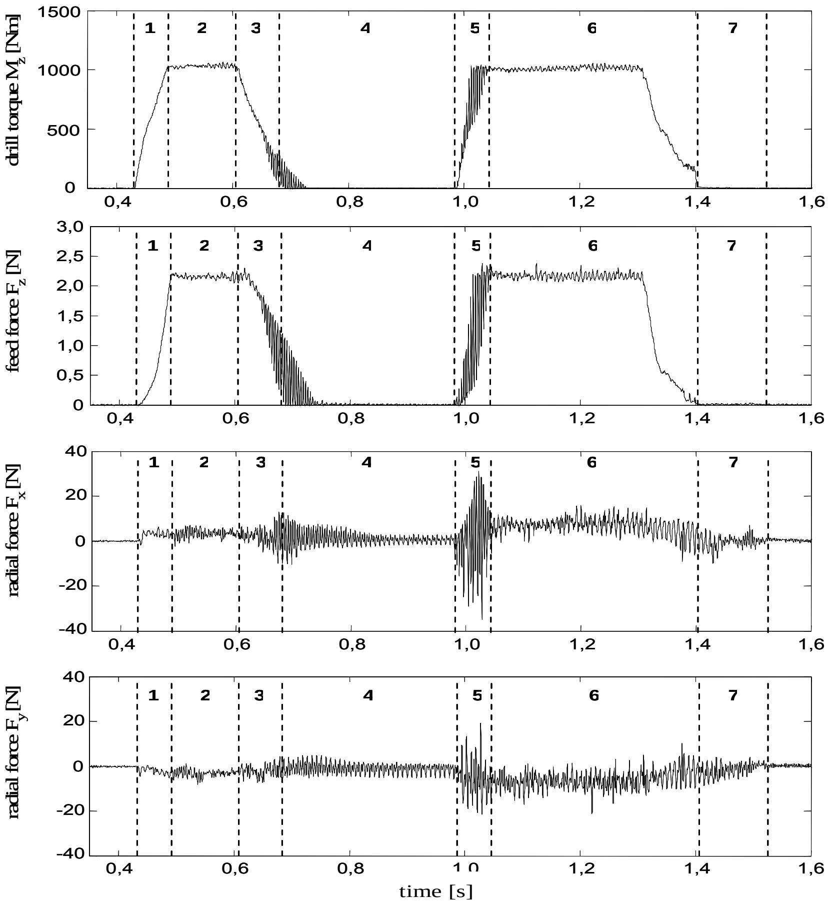


Figure 4: Radial force, feed force and torque progress during boring a cross-drilled hole.

Phase 1: Penetrating the cross-hole: The boring tool meets a convex surface during penetration of the cross- hole, which depending on the penetration ratio DV has a variable radius and is usually penetrated by the drill centre first. There is a reduction in feed force and torque after the breakthrough of the drill centre due to a reduction of the cross-section tension. Furthermore, it is a typical feature of the penetration process that feed force and torque respectively, show a maximum and minimum twice during one drill revolution. This can be explained by differences in the chip width. These differences occur because the geometry generated during the penetration process can be simplified by the superimposing of a cone and a cylinder. As a result a round rather than an elliptical entrance hole is formed. A continuous change of chip width and stress distribution results during one spindle revolution. As each cutting edge reaches the maximum and minimum chip width twice with each revolution, this results in the corresponding maximum and minimum in the feed force and torque signal.

The shape of the ellipse differs depending on the depth of penetration into the cross-hole. An almost round hole exists shortly after the penetration of the drill centre, so that the force path and the path of the torque show hardly any dynamics. The ellipse shape increases with the increasing depth of penetration, resulting in an increasing process dynamic.

The penetration of the cross-hole influences the radial force and its components Fx and Fy, respectively. An oscillation with a double spindle revolution frequency and increased amplitude (see Fig. 5, part b) occurs after a certain penetration depth, similar to feed force and torque.

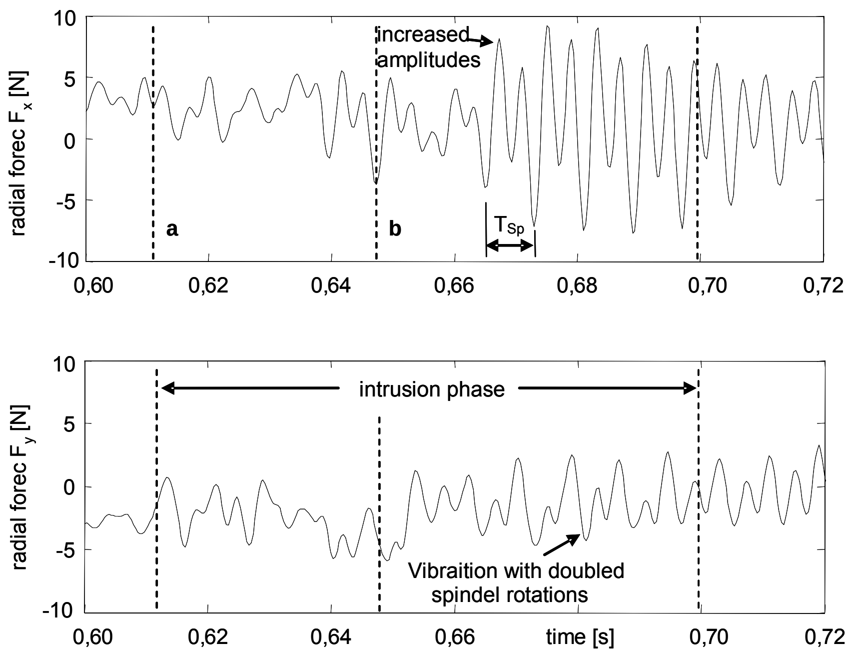


Figure 5: Radial force components F_x and F_y during the penetration of the cross-hole.

It is noticeable, that the oscillation amplitude of the F_x component in part b is considerably higher than that of F_y. This behaviour results from the chip width differences during one revolution, which are caused by the elliptic shape of the hole. The penetration phase is critical because the drilling tool encounters strong dynamic forces for the first time during the making of a cross-drilled hole. These forces can influence both the quality of the hole and the tool life.

Phase 2: Penetration of the cross-hole: The process phase “penetration of the cross-hole” follows directly after the penetration process and begins with the entry of the cutting edges into the cross-hole. At the beginning of the penetration phase using a penetration ratio of 6/8, an interrupted cut occurs which is untypical for drilling. This is due to the convex surface of the cross-hole. Fig. 6 shows the shape of the hole with an interrupted cut as well as the associated feed force F_z gradient. The amplitude of the feed force signal indicates the transition to an interrupted cut by periodically declining to zero. The drilling tool is subject to strong dynamic forces as well as alternating thermal loads during the penetration phase due to the interrupted cut. The chip width declines with increasing drilling depth until the boring tool changes from the interrupted cut to air cutting. In doing so both main cutting edges of the drilling tool get out of contact.

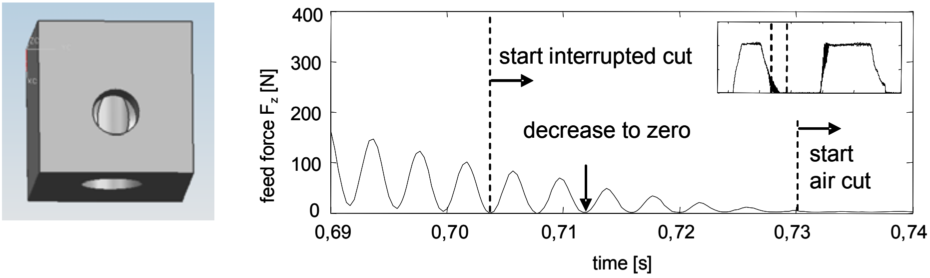


Figure 6: Shape of the hole an F_z gradient in phase 3 and 4.

It is a characteristic feature of air cutting that the feed force constantly remains at zero. The radial force components F_x and F_y behave similarly. However, Fig. 7 reveals, that a periodic oscillation with a double spindle revolution frequency occurs and persists throughout the entire penetration phase, despite air cutting.

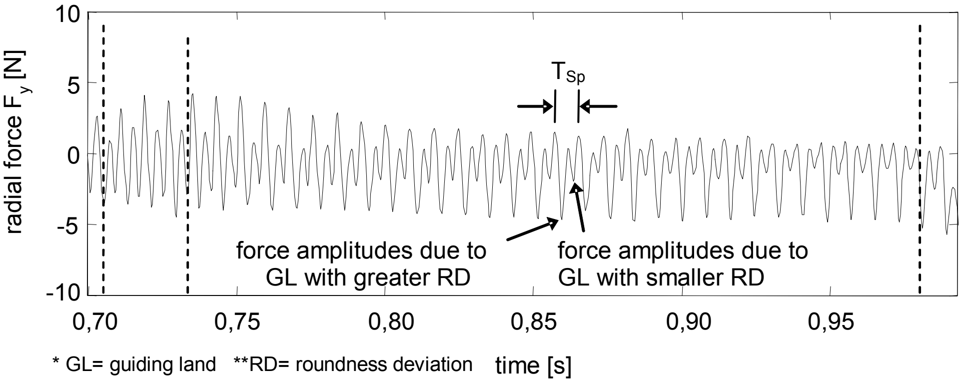


Figure 7: F_y gradient during penetration phase.

In order to explain this phenomenon the previous process phases must be taken into consideration, as they influence the penetration phase. In accordance with Figure 4, an inactive part in the radial force component F_y prevails during the full section in process phase 2. This inactive part results from the tool's curve in a positive y-direction, which is followed by a reset force in negative y-direction. The tool's curve persists during the intrusion phase as well as directly before and during transition into air cutting. On reaching the air cutting, the curve of the tool ceases to exist. Subsequently, the drilling tool touches the already generated hole edge with the margin of the drill due to the eliminated curve. A tool with two drill margin develops the force in negative y-direction twice per revolution. The differing amplitudes heights in the negative value range of the F_y signal in Figure 7 can be traced back to the different proportional penetration of the two margins of the drill. The drill margin with the greatest distance to the drill centre produces the higher energy levels.

It is a characteristic feature of the air cutting that the feed force constantly remains at the value zero. The radial force components F_x and F_y are believed to behave accordingly. However Figure 7 reveals that a periodic oscillation with a double frequency of a spindle revolution occurs in F_y, which persists throughout the entire penetration phase.

Phase 3: Exiting the cross-hole: Exiting the cross-hole, corresponds to drilling on a concave surface. At the penetration rate DV of 6/8 and a tool point angle of 140°, the cutting edges enter the concave surface first. When the cutting edges meet the concave surface, the feed force signal indicates a temporary slow increase in force, which repeats itself each half-revolution with a slight increase in amplitude (see Figure 8). The repetition of the force increase occurs since the cutting edges are only in contact every half revolution for a short period of time.

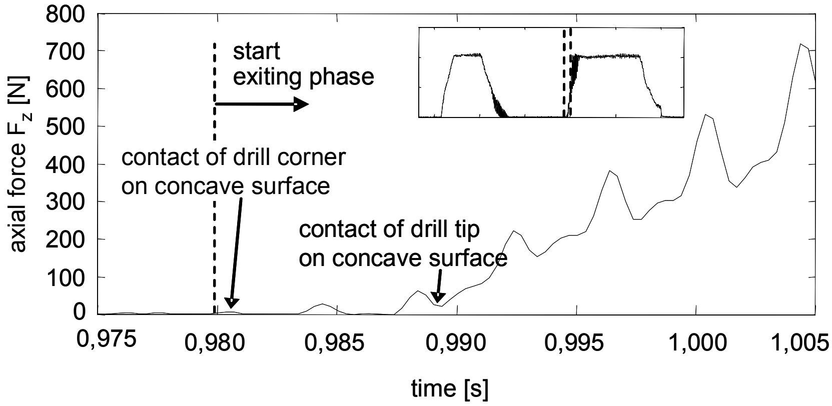


Figure 8: Feed force signal when drilling on the concave surface of the cross-hole.

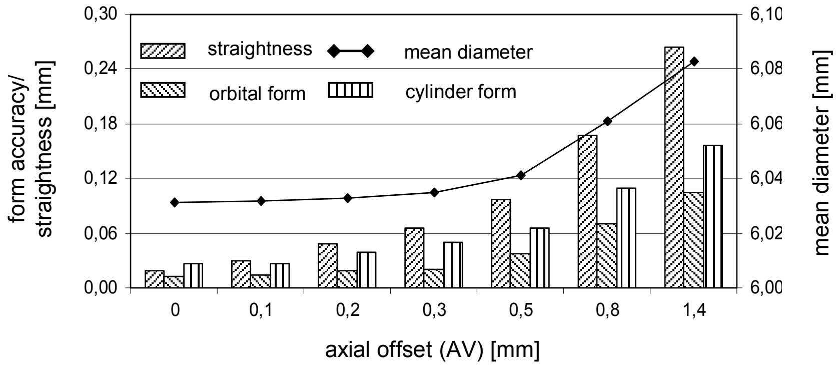
The feed force level increases steadily when the drill centre meets the concave surface. The temporary increase in feed force, which is superimposed by a rise in force level, continues to correspond to the contact of the cutting edge. As in the intrusion process, differences in the chip width also occur when exiting the cross-hole during one drill revolution. Contrary to the intrusion phase, the elliptic hole shapes are not responsible for the differences in the chip width when exiting the cross-hole. Due to the differences in chip width the boring tool is also subject to dynamic forces in the exit phase.

This dynamics appear as a periodic oscillation in the gradient of the radial force components F_x and F_y. As in the intrusion phase, the oscillation amplitudes of the radial force component F_x reach higher values than in F_y. Furthermore an inactive radial force fraction develops in the radial force components during the exiting of the cross-hole. Its direction corresponds to the direction of the inactive radial force fraction during the full section (process phase 2). This characteristic can be explained by a non centric spot drilling of the concave surface, so that the tool is pushed away and thus bends.

3. HOLE QUALITY IN BORING CROSS-DRILLED HOLES

3.1 Impact of an axial offset on the hole quality

The axial offset (AV) between the axis of the cross-drilled holes and cross-holes can occur constructively or uncontrolled due to tolerance fluctuations. Offsets due to tolerance fluctuations, as for example with cast parts, normally occur in the decimetre range, whereas the constructive bias occurs in millimetre range. Due to the industrial application, the hole quality of a range of different offsets are presented and discussed here. Figure 9 shows the achievable hole quality for a boring tool with two drill margins and seven different axial offsets. An increasing axial offset results in a decrease in quality value. Here, the straightness of the hole is influenced most significantly. For example, the straightness of the hole is approximately three times worse with an offset of 0.3 mm than with 0 mm, whereas the accuracy of the hole shape decreases by a factor of 1.5.



v_c [m/min] = 140; f [mm]= 0,175; D [mm] = 6; t [mm] = 18;
co [mm]= 0/0,1/0,2/0,3/0,5/0,8/1,4; KSS = IK, 5 % emulsion
50 bar; material = 1.7225; diameter ratio = 6/8

Figure 9: Drilling quality with different offsets.

The intense deflection of the boring tool during the intrusion and exit phase causes the strong influence of the offset on hole straightness. The strong chip width and thickness differences between both cutting edges are the reason for the deflection. The analysis of the chip width differences by using a chip width simulation reveals that the maximum chip width difference for the three offsets 0 mm, 0.2mm and 0.5 mm increases from 0 mm2, via 0.025 mm2 to 0.059 mm2 during the intrusion phase. The entire chip width that has to be detached by both cutting edges for a 0.5 mm offset amounts to 0.128 mm2 at the point of the maximum difference in stress area. This results in a 46 % chip width difference in the entire detached stress area. The increased change in drill behaviour with additional offset can be explained by this large percentage. Furthermore it is a typical feature that a force with a high amplitude in a negative x-direction arises with an increasing offset during the exit phase (see Fig. 10).

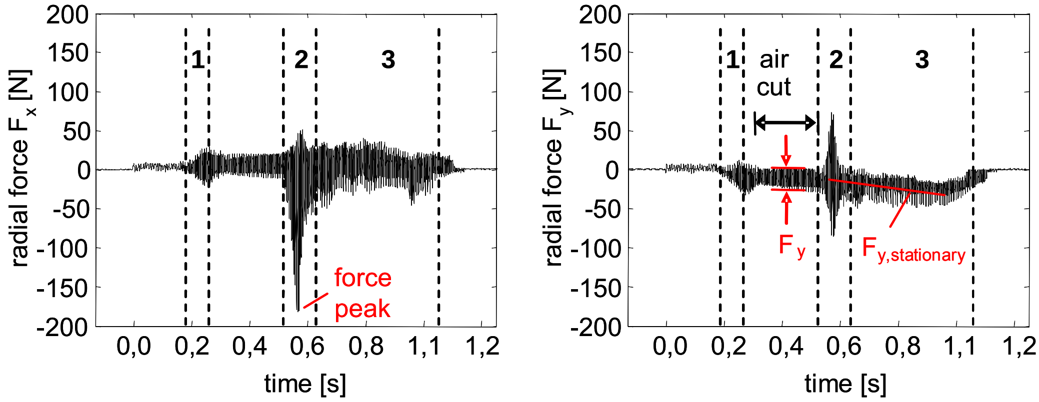


Figure 10: Radial force components F_x and F_y with a 0.5 mm offset.

The excessive force increase can be affiliated to the lack of self-centring during the off-centre drilling of the concave surface. The force amplitude during the exit phase also increases in the y-direction although without any preferred direction. The accuracy of the circular shape does not decrease in the same manner as the straightness however displays an anomaly that is mainly dependent on the offset. In comparison to the offsets 0.1 mm to 0.3 mm, a 0.5 mm offset causes a notable decrease in accuracy of the circular shape. Fig. 11 displays the measuring circuits of holes with a 0.2 mm and 0.5 mm offset respectively. Attention should be paid to the fact that the figures display abnormalities of the measured circles from an “ideal” round circle that match the middle diameter of the measured circle.

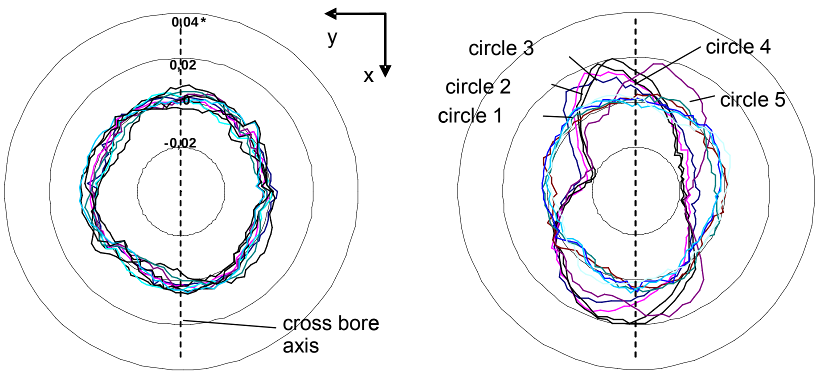


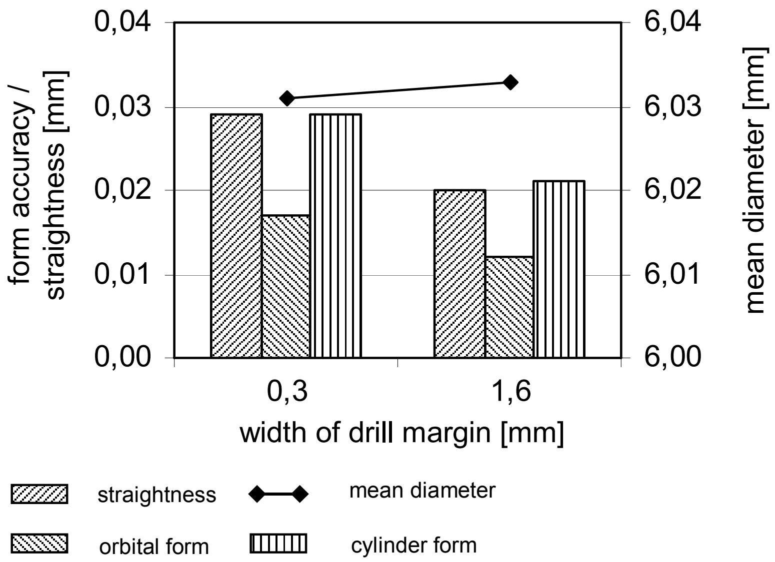
Figure 11: Measured circles at 0.2 mm and 0.5 mm axial offset.

While all measured circles of the hole with a 0.2 mm offset approach a good circular shape, the first five measuring areas of the hole with a 0.5 mm offset do not. The shape of the first five measuring circuits comply with an oval, which is slightly slanting towards the indicated axis of the cross-hole, thus taking into account the chosen form of representation in Figure 11. The oval hole shape can be explained by the strongly asymmetric stress on the drilling tool during the penetration phase. The stabilizing effect of the drill margins with one drill margin per cutting edge point in two opposite directions. Orthogonally to these there is no support, so that a deflection in the direction of the missing support occurs. A re-cutting of the accessory cutting edges during the air cutting is not responsible for the oval hole shape. Drillings, where the boring tool only creates the upper part of the cross-drilled hole without getting into the air cutting proof of this. This constellation also creates an oval hole shape in the upper part of the cross-drilled hole. With an increasing offset, not only the hole quality but also the hole shape decrease. For example an increased rubbing of the drill margins with the hole wall occurs due to the strong tool deflection in the penetration phase.

3.2 Influence of width, number and location of drill margins

A range of geometrical changes can influence the operation performance of a boring tool. These include among others drill margin geometry and the number of drill margins. In this section the effects on the hole quality are analysed for boring tools with different drill margin widths. Furthermore tools with four drill margins are used, where the position of the third and fourth drill margin were additionally varied.

1. Variation of the drill margin width: A point geometry with tetrahedral cut is used as the base micro-section for the variations of the drill margin width. The tools are available in 0.3 mm and 1.6 mm drill margins. Figure 12 shows the hole quality for drilling cross-drilled holes for the two drill margin widths 0.3 mm and 1.6 mm.



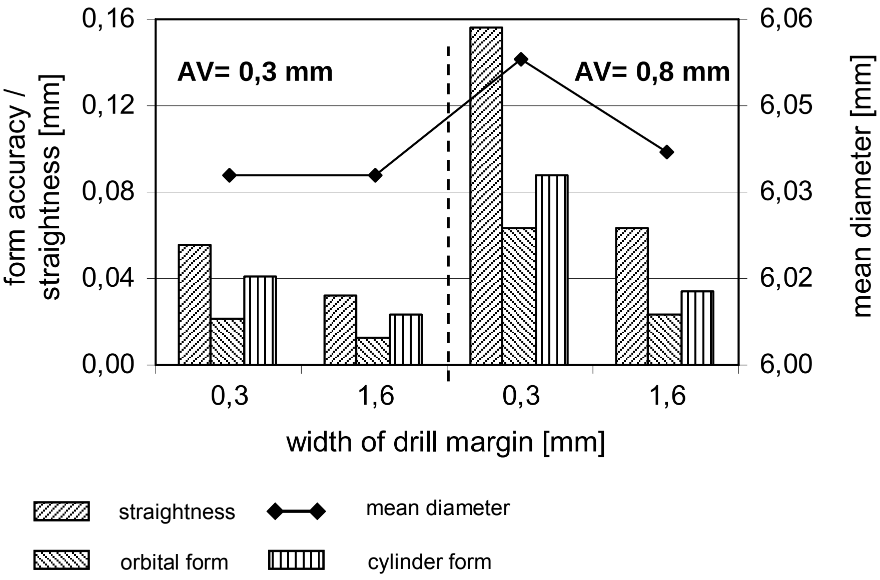
vc [m/min] = 140; f [mm]= 0,175; D [mm] = 6; t [mm] = 18; AV [mm]= 0;
KSS = IK, 5 % Emulsion, 50 bar; Material = 1.7225; DV = 6/8

Figure 12: Hole quality of different drill margin widths.

A broad drill margin improves the quality parameters straightness as well as circular shape / orbital form and cylinder shape accuracy considerably. The increase of the mean diameter can be explained by the slightly larger tool diameter of the boring tool with a 1.6 mm drill margin width. The improved stabilising effect during the penetration and exit phase is the reason for the improved straightness with a broad drill margin width. The deflection of the boring tool due to the occurring radial forces is reduced through the stabilising effect. The reduced circular shape accuracy results with a narrow drill margin due to the distinct dynamic in the radial force signal during the full section in the lower part of the cross-drilled hole. This is due to a revolving radial force with high amplitude. A comparable dynamic does not exist in the radial force signal with a broad drill margin because the excessive increase of radial forces which occur during the exit phase are reduced due to the support effect. The only excessive increases in broad drill margins result from chip clogging which however have no correlation with the width of the drill margins.

The width of the drill margin also influences the mean deviation of the arithmetic surface roughness value R_a measured at the wall of the cross-drilled hole. It is 40 % higher when using a tool with a narrow drill margin in comparison to a broad circular ground drill margin.

The quality differences between broader and narrower drill margins increase when drilling cross-drilled holes with axial offsets. Despite the strong asymmetric exposure, the boring tool with a broad drill margin of 0.8 mm offset achieves a good quality compared to a narrow circular grinding chamfer of 0.3 mm offset. This confirms the stabilising effect of a broad drill margin with cross-drilled holes.



vc [m/min] = 140; f [mm]= 0,175; D [mm] = 6; t [mm] = 18; AV [mm]= 0/ 0,8; KSS = IK, 5 % Emulsion, 50 bar; Material = 1.7225; DV = 6/8

Figure 13: Hole quality with different drill margin widths under axial offset (AV).

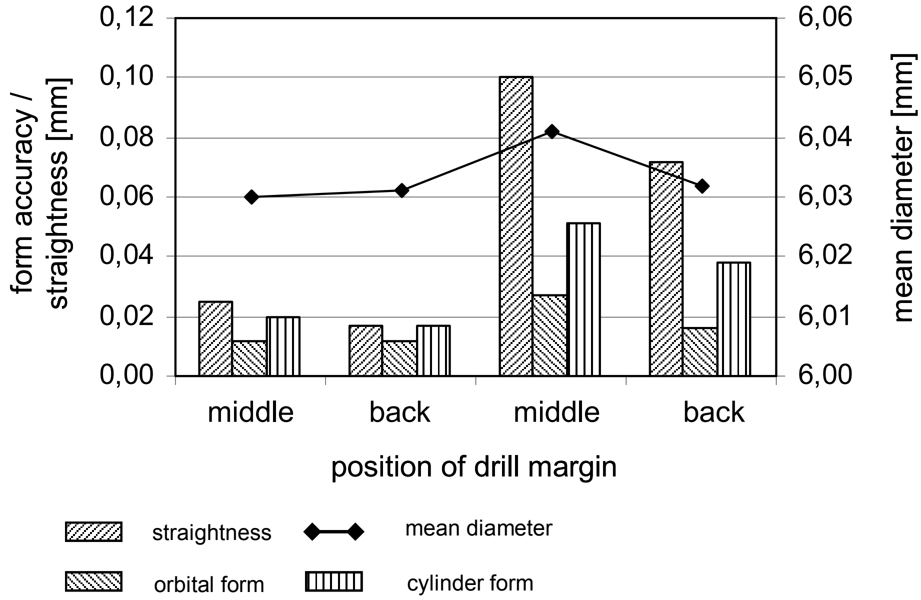
When using a tool with two drill margins and an offset of 0.8 mm, an oval drill shape develops in the upper part of the cross-drilled hole. The use of a boring tool with a broad drill margin inhibits the development of the oval drill shape so that high circular shape accuracy is guaranteed.

2. Variation of the number and position of the drill margins: In comparison to a broad drill margin, the use of four drill margins leads to an improved straightness as well as a higher circular and cylinder shape accuracy of the hole, regardless of the used axial offset. This is caused by the addition of the third and fourth drill margin respectively at the back of the drill, which leads to an additional support in two directions with a 90° difference. For a tool with two drill margins of 1.6 mm width the maximum angle between the directions of the support is only 31°. Therefore boring tools with a broad drill margin respond more sensitively to asymmetric stress than one with four drill margins. A variation of the position of the drill margins leads to two different drill geometries. For one of the two versions, the third and fourth drill margin is attached at the back of the drill (Figure 14, top). For the other drill version, the third and fourth drill margin is in the middle of the drill back (Figure 14, bottom).

3. resp. 4. drill marigins at the end of the drill back

3. resp. 4. drill margins in the middle of the drill back

Figure 14: Tool variations with four drill margins.



vc [m/min] = 140; f [mm]= 0,175; D [mm] = 6; t [mm] = 18; AV [mm]= 0/ 1,5; KSS = IK, 5 % Emulsion, 50 bar; Material = 1.7225; DV = 6/8

Figure 15: Hole quality dependent on the position of the third and fourth drill margin.

The tool with the positioning of the third and fourth drill margin respectively at the back of the drill achieves the better hole quality at both the 0 mm and 1.5 mm axial offset. The reason for the comparatively bad result of the tool with a centre positioning of the additional drill margins is the small angle difference between the two brace supports, which is only half as big as the angle at the alternative positioning. The advantage of the central positioning is that the additional drill margins can develop the support effect earlier because their distance Δz to the drill, seen in the direction of drill axis, is shorter. However for the tested tools, this advantage has no effect since the difference between the two tool types in the distances Δz only adds up to 1/10 mm.

4. CONCLUSIONS

The intervention measures and energy ratios as well as the interactions, which occur when making a cross-drilled hole were determined by an analysis of the processes using a penetration rate of DV 6/8 as an example. The process analysis shows, that the drilling process of cross-drilled holes is characterised by a high dynamic at the entry and exit points of the cross-hole. An additional typical feature of the boring cross-drilled holes is a re-cutting by the drill margins during the air cutting when penetrating the cross-hole as well as an increase in the radial force amplitude when exiting the cross-hole.

During the experimental inquiries concerning the hole quality of cross-drilled holes, the circular shape accuracy f_k, the straightness of the drill axis f_g, the cylinder shape accuracy f_z, the mean hole diameter d served as quality parameters. The studies show, that an offset between the axis of the cross-hole and cross-drilled hole leads to a distinct deterioration of the hole quality. Especially the straightness of cross-drilled holes is particularly affected, even with a small offset. From a 0.5 mm offset onwards, the quality parameters of the mean diameter, the circular and cylinder shape accuracy are highly affected since an oval hole shape develops in the upper part of the cross-drilled hole due to the asymmetric tool exposures.

The use of boring tools with a 1.6 mm drill margin width improves the hole quality considerably due to the increased support effect in comparison to 0.3 mm. An additional improvement can be achieved by the use of tools with four drill margins and 0.3 mm drill margin width. The best hole quality can be achieved by the use of a boring tool with four drill margins, where the third and fourth drill margin respectively are attached at the crossing of the drill back. The quality difference between tools with different drill margin widths and varying numbers of drill margins at an offset between the cross-drilled hole and cross-hole is particularly obvious.

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