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Analysis of the Influence of Tool Geometry on Surface Integrity in Single-lip Deep Hole Drilling with Small Diameters

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Abstract

The industrial relevance of bore holes with small diameters and high length-to-diameter ratios rises with the growing requirements on parts and the tendency of components for downsizing. Examples for components requiring deep holes with small diameters exist in the automotive industry; for the production of injectors for fuel injection as well as for medical and biomedical parts. Based on growing functional requirements, for example with the increase in injection pressure to improve the efficiency of the combustion process in diesel engines, the requirements on the surface integrity of bore holes also increase. To meet these requirements, an adaption of the deep hole drilling process is necessary. In this paper the influence of tool geometry, coating and cutting data on the bore hole quality and tool wear will be presented.

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Keywords: Deep hole drilling, Tool geometry, Surface integrity

1. Introduction

Single-lip deep hole drilling (SLD) is frequently used in various industrial applications. For example, this process is used in the automotive industry for the production of injectors used in fuel injection. Due to the downsizing and the increasing power density, the diameters of the injection bore holes diminish in size. Furthermore, the requirements concerning surface quality increase. This is founded in the higher

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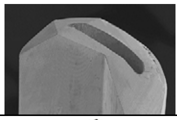
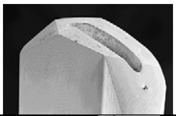
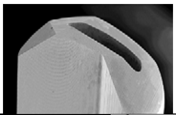
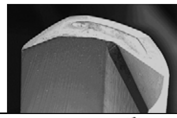
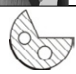
injection pressure used. Surface defects can lead to cracks and breakages of the parts that affect the breakdown of the car in use. Another field of application are medical and biomedical products. For example bone nails and bone screws are drilled due to functional reasons. Based on the tool design using these tools a high bore hole quality and low surface defects can be produced [1].

2. Experimental Setup

For the experimental investigations, a single-lip deep hole drilling machine tool of the type TBT ML-200 was used. This machine tool is designed for SLD with small tool diameters in the range of d = 0.5…6 mm. Due to the tool diameter range, a spindle with a maximum number of revolutions of 36,000 rpm was integrated. Furthermore, a very high coolant pressure of maximum p = 250 bar can be realized.

Before the adaption of the deep hole drilling process, a variation in tool geometry, coating and cutting data was done. In this context, the influence of the number and position of the guiding pads, the conicity of the drill head and the influence of a coated tool with an adapted tool geometry for high cutting data will be analyzed, and compared to a tool with the conventional design. Main characteristics of the tools used in the machining tests are listed in Table 1.

Table 1. Tools used in the experiments

Tool	A	B	C	D
				
Peripheral contour:	G 	C 	G 	G 
	1 guiding pad	2 guiding pads	1 guiding pad	1 guiding pad
Conicity:	1/800	1/800	1/400	1/800
Tip geometry:	$\chi_1 = 50°$, $\chi_2 = 120°$	$\chi_1 = 50°$, $\chi_2 = 120°$	$\chi_1 = 50°$, $\chi_2 = 120°$	$\chi_1 = 60°$, $\chi_2 = 110°$ protective chamfer s = 330 μm
Cutting material:	K15	K15	K15	K25
Coating:	-	-	-	AlTiN

The tools A, C and D have one guiding pad at their circumference. In difference, tool B has two guiding pads. These are smaller than the guiding pad of the other tools. Another variation in the tool geometry is the conicity of the drill head. All SLD tools have a conicity to avoid high tool loads by reducing friction at the guiding pad and the circular grinding chamfer. In comparison to tool A, tool C matches in its properties of tool A except for the conicity. The conicity of tool C is twice the value of the conicity of tool A. Tool D has a newly developed design. The tip geometry of the tool is characterized by a chamfer instead of the tip. Furthermore, it has other tool cutting edge angles. In combination, both factors stabilize the tool tip area with respect to tool breakage. These changes in tool design allow a higher productivity. Furthermore, a more ductile cutting material in combination with a coating for wear protection was utilized to realize higher feed velocities.

The cutting parameters used for tools A-C as well as for tool D were identified in preliminary machining tests. With these cutting parameters, the tool life time criterion of a drilling length of $l_f = 4995$ mm was achieved and, in comparison to the results coming from machining test with other cutting parameters, the best process behavior concerning tool wear, chip form and bore hole quality was reached. For tool A-C a cutting speed of $v_c = 100$ m/min and a feed rate of $f = 0.007$ mm/rev was selected. Because of the optimization in its design with tool D, a feed rate of $f = 0.015$ mm/rev when using the identical cutting speed similar to the other tools was realized. The cooling lubrication concept was an internal oil supply using a high oil pressure of $p = 160$ bar. As workpiece material, the stainless steel AISI 316L was used. This material is characterized by an austenitic microstructure, a high ductility, a high tendency to adhesion and to work hardening.

3. Results

The properties and the quality of manufactured surfaces often affect directly the function of the component. Compared to deep holes produced by twist drilling, SLD enables an improved productivity and better bore hole qualities. Nevertheless, the surface quality of holes produced by SLD depends on several process variables. A main variable is the tool geometry. To evaluate its influence on the surface integrity, the surface quality as well as the impact of the drilling process on the sub-surface zone, depicted by microhardness measurements in longitudinal cross-sections of the bore holes, will be analyzed. Basically, the surface integrity in deep hole drilling is mainly influenced by the mechanical loads and the tool wear. For the evaluation of the impact of the tool geometry on the surface integrity, these factors will be used.

In deep hole drilling, the bore hole quality is generated by the guiding pad or guiding pads at the circumference of the tool. Due to the asymmetrical design of deep hole drilling tools, at the guiding pad / pads the radial forces occurring in the machining process are supported at the bore hole wall. In difference to conventional drilling processes, this contact between the tool and the bore hole wall leads to a smoothening of the surface roughness [2, 3]. The value of the radial forces supported at the bore hole wall can be influenced by the tool geometry. Because of that, in Fig. 1 the influence of the tool geometry on the surface quality is presented.

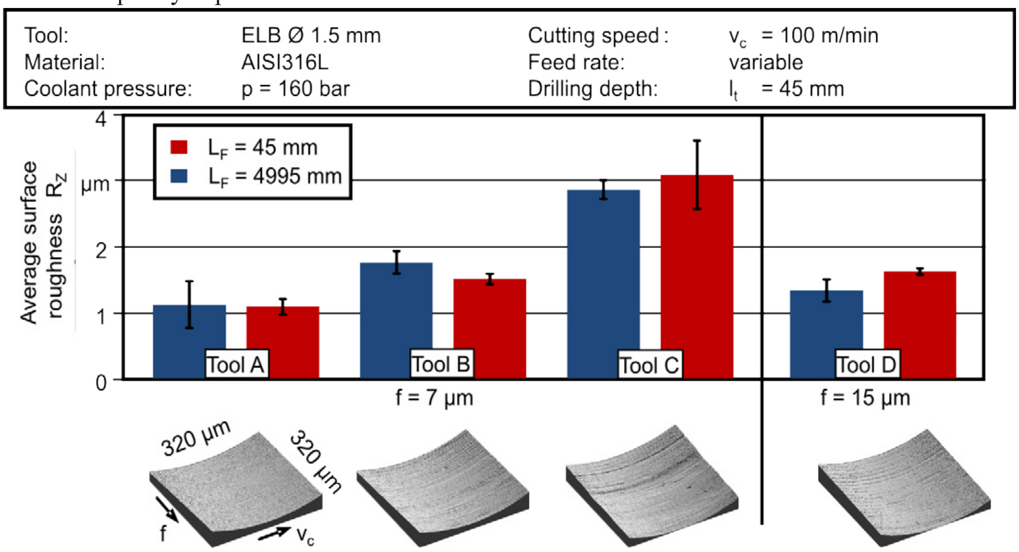


Fig. 1: Average surface roughness

In the experiments conducted, high surfaces qualities were reached. The average surface roughness is between $Rz = 1.1 \ldots 3.1$ µm. In this comparison, the tool with the standard geometry (tool A) produces the surfaces with the highest quality. In difference, the use of tool B leads to a degradation in surface quality. Due to the smaller contact area, a higher pressure per area unit and a deeper guide pad ingression into the bore hole surface of the SLD with peripheral contour C benefits adhesion and welding effects. These effects lead to a reduction in surface quality. An increased drill head conicity reduces the contact zone in axial direction and impairs the surface quality significantly. This construction abets the prone to tool movement and oscillation. Despite the increased feed rate for the use of tool D, the average surface roughness is very low. The increased mechanical loads and the asymmetric cutting part enforce the surface smoothening.

Due to differences in the mechanical loads, an influence of the tool geometry on the peripheral zone can occur. Here, different effects leading to a hardening of the peripheral zone can happen. The stainless steel AISI316L has a high tendency to work hardening. Furthermore, martensite layers can be generated by high stresses. In Fig. 2 the influence of the peripheral zone for tool A and tool D is shown.

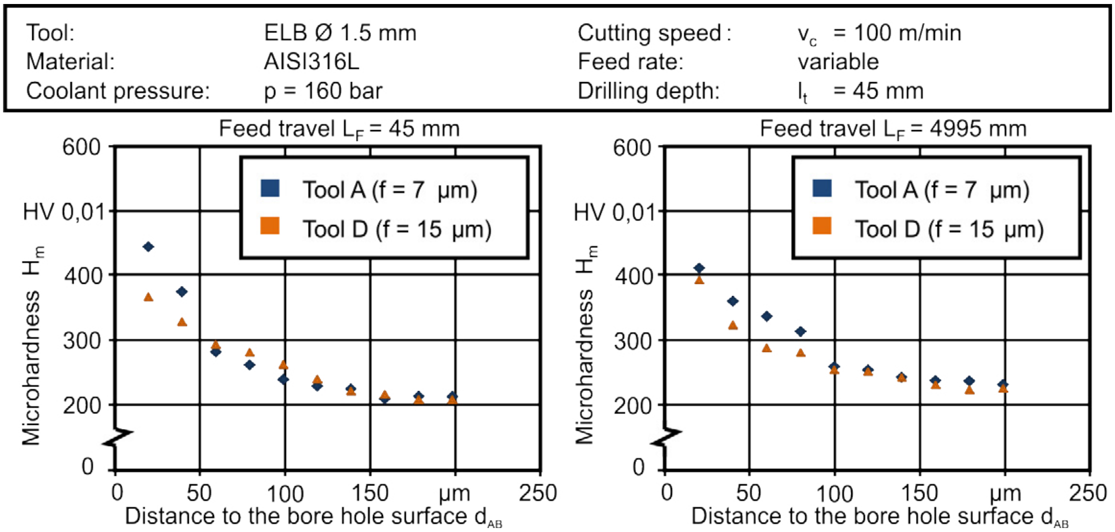


Fig. 2: Influence of the tool design on the peripheral zone

For both tools, a significant influence of the peripheral zone is up to a certain distance to the bore hole of round about d_{AB} = 150 µm. The maximum microhardness of approximately H_m = 400 … 450 HV0.01 is measured in a distance of d_{AB} = 20 µm. Although the feed rate and the corresponding mechanical loads when using tool D are significantly higher than the feed rate of tool A, the differences developed in microhardness are negligible. The friction-reducing coating as well as the abbreviated contact time compensates the effects of the higher loads. Furthermore, the material capacity for hardening effects is utilized. A further increase in hardness of the peripheral zone cannot be reached by higher loads.

4. Evaluation

The differences in surface integrity when using tools with varying geometries can be explained by the occurring mechanical loads and the tool wear. In the following, the influence of the tool geometry on these factors will be discussed and their influence on the surface roughness and on the peripheral zone will be pointed out. The mechanical loads in machining operations result from friction, shear and deformation processes. In SLD with small tool diameters, the ratio between low feed rates and high cutting edge rounding is responsible for high compressive stresses at the inner and outer cutting edge

[4, 5]. In the following, the measured mechanical loads as well as the resulting tool wear occurring in the viewed deep hole drilling processes using different tool types are presented in Fig. 3.

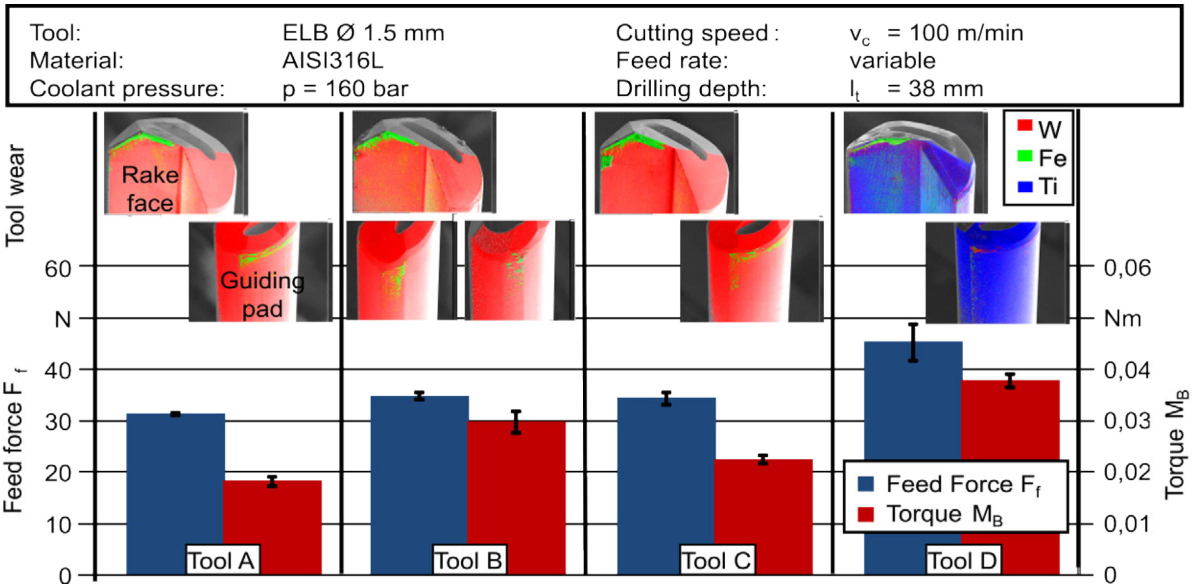


Fig. 3: Mechanical loads and tool wear

The tool design influences the mechanical loads. Using tool A, the lowest feed force and torque occurs. A variation of the number and form of the guiding pads lead to an increase of mechanical loads, especially of the torque. Due to the smaller contact zone, the pressure between guiding pad and bore hole wall increases. This leads to a deeper penetration of the guiding pads into the bore hole wall when using tool B [6]. Due to this effect, higher loads, especially a higher torque, occurs. Material deposits at the guiding pads lead to a furrowing of the bore hole wall resulting in a low surface quality. Compared to tool A, a variation in the conicity of the drill head also leads to higher tool loads. Here, a similar effect like in the experiments with tool B occurs. Because of the lower shoring range along the guiding pad, a higher pressure in the contact area occurs. The guiding pads ingress deeper into the bore surface and impede an axial movement and tool rotation. The lower shoring range assists the development of flexural vibrations. The bore head is more vulnerable to dump and produces worst surface qualities. Moreover, the higher boring head conicity simplifies it for produced chips to get into the gap between the tool and the manufactured surface. The chips get jammed and increase the mechanical tool loads. The highest mechanical tool loads were measured using tool D. This is due to the increase in the cross section of undeformed chip thickness based on the higher feed rate. In addition, based on the AlTiN-coating, this tool has a higher cutting edge rounding that influences also the mechanical tool loads. With increasing mechanical loads, the radial force which is supported at the bore hole wall also increases.

The solitary view of the mechanical loads cannot explain all results. Because of that, the tool wear is also analyzed. Single-lip drills mainly wear at the rake and flank face near the inner and outer cutting edge, the corner and the guiding pad. For the machining with tools with small diameters, the chips are formed at the cutting edge rounding in consequence of the limited undeformed chip thickness. Therefore, the produced chips just partially contact the rake face, so that crater wear is negligible. The development of tool wear can affect the process stability. A corner wear and an increasing cutting edge rounding change the mechanical loads. As a result of higher process forces, the radial loads grow up and lead to a smoothening of the surface. On the other hand, chippings and adhesive wear can impair the topography.

The uncoated tools (tool A, B, C) show adhesive wear at the cutting edge. Noticeable is the clustered adhesive tool wear under the corner of tool C. This indicates that the drill head of this tool benefits tool movements and instability. Moreover, it is observable that tool B und C have a larger-scaled axial guiding pad wear compared to the reference tool A. This affects the surface quality negatively by furrowing the surface. In difference, the coated tool D shows the lowest adhesive wear at the guiding pad. This is due to the high chemical stability and the low tendency to adhesion and welding. Using the coating, a reduction in furrowing and grooving loads of the bore hole wall occur.

5. Conclusions

The experiments have shown that the surface integrity in deep hole drilling can be affected by the tool geometry. Main variables on the surface quality are the occurring radial forces, the size of the contact area between the guiding pad / pads, and the wear at the guiding pad / pads. Using the conventional design, the highest bore hole quality can be reached. The variation of the peripheral contour and the conicity of the drill head are not appropriate to increase the surface quality. Furthermore, these variations decrease the process stability. An improvement can be achieved using a tool with a newly developed tool design marked by a protective chamfer at the tool tip, other cutting edge angles, a tool coating and a more ductile cutting material. With this tool, higher feed rates can be realized. Although the mechanical loads are on a higher level, the impact on the peripheral zone is comparable to the results coming from experiments using the standard tool.

Acknowledgements

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