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Experimental investigations of a helical laser drilling process for pilot holes on complex surfaces

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Abstract

Increasing requirements and a high degree of freedom in design increasingly demand the manufacturing of bore holes with small diameters and high length-to-diameter ratios on complex shaped surfaces. Injection nozzles, medical tools and implants, cooling holes or oil channels are just a few examples. Unlike mechanical drilling tools, the laser beam is not deflected on inclined or curved surfaces and can therefore be used to create pilot holes for a subsequent mechanical drilling process. In this paper, the generation of pilot holes on flat and inclined surfaces using a Nd:YAG laser is investigated. A helical laser drilling process is used to drill holes with a diameter of 1.5 mm in X2CrNiMo17-12-2 stainless steel. Hole depth, diameter, roundness and conicity are evaluated. Application tests with single-lip drilling tools prove the potential of the laser holes to serve as a drilling guide for the mechanical deep hole drilling process.

Keywords: laser drilling; manufacturing technology; laser assisted processes; process combination; deep hole drilling

1. Introduction

Due to the increasing demands on components in terms of their specific properties and their manufacturing process, e.g. weight and cost reduction, sustainability or increasing power density, nowadays component sizes are constantly diminishing. Small-diameter, high length-to-diameter ratio bore holes have become very important in many industries, such as medical and biomedical, as well as aerospace and automotive (Michel, 2018). Typical applications in the medical industry include the machining of widely varying and complex contoured implants, medical instruments or the production of bone nails. In the aerospace or automotive industry, these bore holes are used, for example, for injection nozzles, cooling

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holes in turbine blades or lubricant holes in bearings or gear shafts (Hyacinth, 2015). Manufacturing these bore holes on complex shaped parts, requires a challenging machining process that can take up a large part of the production time.

Various manufacturing processes are used to produce deep holes with small diameters. In this context, single-lip deep hole drilling (SLD), laser drilling, electrical discharge machining (EDM), electron beam machining (EBM) and electrochemical machining (ECM) should be mentioned (Zabel, 2012). Since all processes differ in their specific properties and thus have different advantages and disadvantages when machining bore holes, synergy effects can be realized by combining different processes, which contribute to a more efficient production. Single-lip deep hole drilling is characterized by high length-to-diameter ratios with particularly high bore hole qualities (VDI3210). Due to the asymmetric tool design, however, the drill must be guided through pilot holes or drill bushes at the beginning of the drilling process. Especially complex surfaces increase the manufacturing effort and thus the production costs, as special drill bushes must be used, or a preliminary face milling process is required (Biermann, 2012). By combining laser drilling with subsequent single-lip deep hole drilling Heilmann showed in 2012 that the advantages of both mechanical drilling and laser drilling can be merged. Since the laser beam is not deflected by inclined or curved surfaces, it is possible to manufacture pilot holes with a laser to guide the single-lip drill in the beginning of the drilling process. However, due to the fact, that the maximum pilot hole tolerance for suitable pilot holes with a diameter of $D = 0.6$ - 2.5 mm shouldn`t exceed 10 µm, laser drilling of such holes is very demanding (VDI3208). There are several different techniques for producing laser bore holes, which differ in terms of their production times and their achievable bore hole quality. In this context, a difference is made between single-pulse, percussion, trepanning and helical drilling (Fornaroli, 2013). The helical drilling can be further subdivided into the classic helical drilling, the helical contour cutting and the helical trepanning (He, 2020). In contrast to mechanical drilling, laser drilling combines the advantages of very short process times with a high degree of flexibility and automation as well as wearless machinability of almost all materials (Dausinger, 2004). However, the disadvantages include a limited drilling depth of approximately $l_t = 30\ mm$ and the occurrence of recast layers on the surface of the bore hole (Lehner, 2003). In Addition to a hardening of the microstructure and a negative influence on the quality of the borehole, in particular the surface quality and the roundness, micro-cracks can occur, which can reduce the lifetime of the components significantly (Zabel, 2012).

In previous investigations at the Institute of Machining Technology, it was already shown that a millisecond Nd:YAG laser was able to produce laser pilot holes with a diameter of $D = 0.5\ mm$ and a drilling depth of $l_t = 3\ mm$ using the single pulse strategy. For both laser pilot hole drilling and mechanical pilot drilling, it was demonstrated that the realized tool life of the subsequent single-lip deep hole drilling process is comparable (Heilmann, 2012 and Michel, 2018). Motivated by the limitation of the hole diameter using the single pulse strategy, this paper focuses on the realization of larger pilot holes, with a diameter of $D = 1.5\ mm$. By using a CNC controlled circular movement of the machine cross-table, a relative movement between the workpiece and the laser could be realized. Thus, it was possible to use the two laser drilling strategies trepanning and helical trepanning. The evaluation whether these boreholes are suitable as a drilling guide for the single-lip deep hole drilling process was carried out based on a detailed analysis of the realized bore hole diameters and depths as well as the analysis of bore hole shape and conicity in cross sectional images. After the determination of suitable laser drilling parameters, the process combination was carried out using the laser pilot holes for guiding the single-lip drilling tool. The tests were conducted with an in-process force measurement of feed force and drilling torque. The process was analyzed based on tool wear, surface roughness and straightness deviation.

2. Experimental set-up

The investigations are carried out on a specially designed TBT ML 200 micro deep hole drilling machine. In addition to the working area for mechanical deep hole drilling, the machine has an area for laser machining separated by a safety door. A movable cross table connects the two working areas and enables laser machining and mechanical machining in one clamping, see Fig. 1. The laser is an HL 101P Nd:YAG laser from Trumpf with a D70 focusing optic. The optic is fixed with the axis of the laser parallel to the axis of the drilling spindle. The movement of the laser beam on the workpiece is realized only by the cross-table. The laser system has a maximum power of $P_L = 80\ W$ with a pulse power of $P_P = 0.5 - 8\ kW$ and a pulse duration of $\tau = 0.08 - 1\ ms$. The laser beam has a focus diameter of $d_f = 150\ \mu m$ and is directed onto the component via a lens with a focal length of $f_L = 200\ mm$. Compressed air, argon or oxygen with a pressure of $p = 6\ bar$ can be used as the process gas. The laser system is deliberately equipped with a millisecond laser to generate a high material removal rate as well as to ensure a robust system for the integration into the working environment of a conventional deep hole drilling machine, which is subject to vibrations, chips and cooling lubricant.

Single-lip drills with a diameter of $d = 1.5\ mm$ are used for the mechanical single-lip deep hole drilling process. The asymmetrically designed tools have angles of incidence of $K_1 = 50°$ at the outer and $K_2 = 120°$ at the inner cutting edge. The bore holes have a length-to-diameter ratio of $l/D \approx 40$ with a drilling depth of $l_t = 59\ mm$. The cutting speed is $v_c = 30\ m/min$ at a feed velocity of $v_f = 19.11\ m/min$ ($f = 0.003\ mm$) and a coolant pressure of $p = 130\ bar$. The pilot hole required for the process should have a diameter of $D = 1.5^{+0.01}\ mm$ and a cylindrical area with a depth of at least $l_t = 3\ mm$ for optimum guidance of the tool. The workpieces used in the tests are made of the austenitic stainless steel X2CrNiMo17-12-2 (AISI 316L) with turned or milled surfaces. In addition to a flat surface perpendicular to the bore axis, specimens with an angle of $\gamma = 30°$ and an angle of $\gamma = 45°$ are used as an example for complex surfaces.

Deep hole drilling machine TBT ML-200

Bore hole diameter.:	$D = 0.5 - 6$ mm
Spindle power:	$P = 4$ kW
Number of rev.:	$n_{max} = 36.000\ min^{-1}$
Feed velocity.:	$v_{f,max} = 15.000$ mm/min
Drilling depth:	$l_{t,max} = 450$ mm
Cooling lubricant:	Motorex Ortho NF-X
Pressure:	$p_{max} = 230$ bar

Trumpf Laser HL 101P

Laser type:	Nd:YAG
Laser power:	$P_L = 80$ W
Peak power:	$P_P = 0.5 - 8$ kW
Peak energy:	$E_P = 0.04 - 8$ J
Pulse duration:	$\tau = 0.08 - 1$ ms
Focal length:	$f_L = 200$ mm

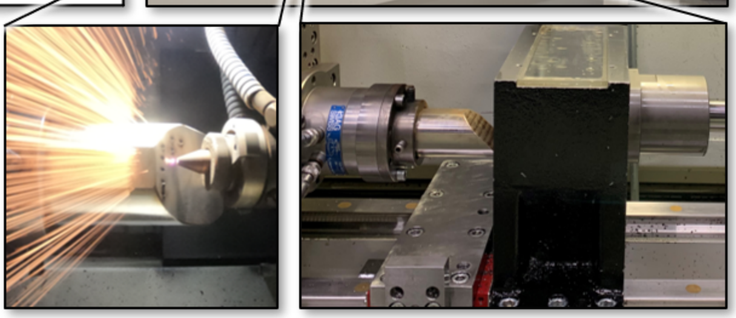

Fig. 1. TBT ML 200 Micro deep hole drilling machine with integrated Trumpf HL 101P Nd:YAG laser

3. Laser pilot hole drilling

Based on the experience gained with single-pulse laser drilling, first a suitable laser drilling strategy for the realization of laser pilot holes with larger diameters was developed. Since the optics of the laser drilling unit are spatially fixed in the working area of the machine and the laser beam cannot be manipulated via scanning optics, the relative movement between laser and workpiece takes place exclusively via the cross-table of the deep hole drilling machine. The cross table has a theoretical maximum feed rate of $v_f = 15\ m/min$. However, when implementing circular movements with smallest diameters, the system is limited in terms of the required dynamics and the required acceleration of the axes.

According to preliminary investigations, a pulse power of $P_P = 8\ kW$, a pulse duration of $\tau = 0.4\ ms$ and a pulse frequency of $f_L = 24\ Hz$ were chosen for the comparison of the laser strategies. The focal distance was set to $s_F = 0\ mm$ with a nozzle distance of $s_N = 2\ mm$. The feed velocity of the cross table and thus the feed velocity of the laser on the circular paths was $v_{fL} = 72\ mm/min$. In the trepanning laser drilling strategy, laser drilling was performed along concentric circular movements. Starting from the drilling center, the first circular motion with a circular diameter of $d = 0.2\ mm$ was first repeated 20 times to realize the required drilling depth. To achieve the desired bore hole diameter, the diameter of the circular path was increased incrementally by $\Delta d = 0.2\ mm$ in each case repeating the circular path 20 times. In the laser drilling strategy helical trepanning, the same circular movements were used. However, each circle was initially machined only once. To realize the drilling depth, the complete pattern of all circles then was repeated 20 times. In contrast to conventional helical laser drilling, however, the laser focus point was not advanced. Figure 2 schematically shows the laser drilling strategies on the left and the resulting laser holes on the right. It can be clearly seen that the helical trepanning laser drilling strategy achieves a significantly better drilling quality. Here, the material is removed evenly and layer by layer, resulting in good cylindricity of the hole. With the trepanning strategy, the material removal from the bore hole is difficulty. Particularly in the center of the bore hole, significantly less material is removed due to the small diameter of the first circular movements and the resulting high aspect ratio between diameter and machining depth. In addition, less material solidifies on the bore hole wall when drilling with laser helical trepanning, which results in a significantly better roundness of the bore hole. Therefore, the laser drilling strategy helical trepanning was selected for further investigations.

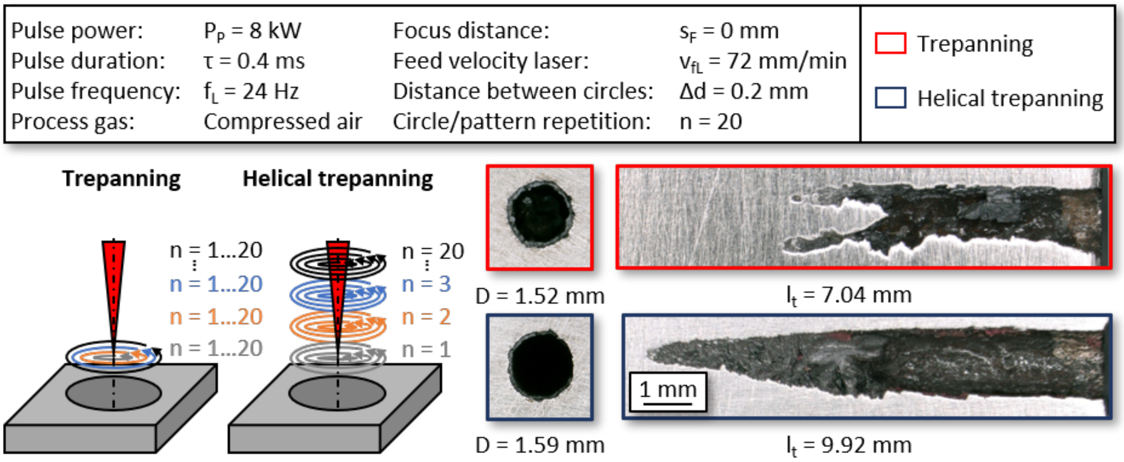

Fig. 2. Comparison of the two used laser strategies (trepanning and helical trepanning)

In addition to a suitable laser strategy, the process gas can also have a significant influence in laser drilling. With identical laser parameters, there can be significant differences in terms of material behavior and thus drilling depth and bore hole quality. In addition to bore hole quality, productivity during machining also represents a decisive factor for the benefits of a process. With regard to laser machining, the use of pure oxygen has the potential to release additional energy during laser machining through exothermic oxidation reactions and thus accelerate material removal. In a further series of tests, therefore, the process gases compressed air, oxygen and the inert gas argon were compared. Fig. 3 shows the resulting bore hole diameters and bore hole depths. The measurements of the diameter on the component surface and the depth in the cross sections of the bore holes were carried out using a Keyence VHX5000 light microscope. The results show the averaged values of 3 boreholes. The standard deviation of the measurements was minimal indicating very stable laser drilling processes. While there are only minor deviations regarding the diameter, there are large differences between the process gases with respect to the drilling depth. The use of argon leads to both a lower drilling depth and a smaller diameter. There is also greater adhesion of solidified material to the surface. The lack of exothermic reactions when using argon results in lower temperatures during the laser process. The heat-affected zone is smaller, and less material is melted or vaporized per pulse, resulting in smaller diameters and lower drilling depths. The melted material can also solidify more quickly on the bore hole wall and on the component surface. When using compressed air and pure oxygen, the oxygen contained leads to an exothermic reaction of the material and increases the temperature in the machining zone. Thus, significantly more material can be melted and removed from the bore hole. The slightly lower drilling depth with pure oxygen can probably be attributed to a different pressure of the process gas. While the gas pressure for compressed air was set via a pressure control valve next of the optics, the gas pressure for oxygen and argon was set via the pressure reducers on the gas cylinders. The uncalibrated pressure reducers of the gas cylinders as well as the pressure loss over the longer supply hose could explain the differences between compressed air and oxygen. Since it was possible to drill holes with sufficient depth and diameter with all process gases, but the material removal rate was highest with compressed air, compressed air was used as the process gas for the further tests.

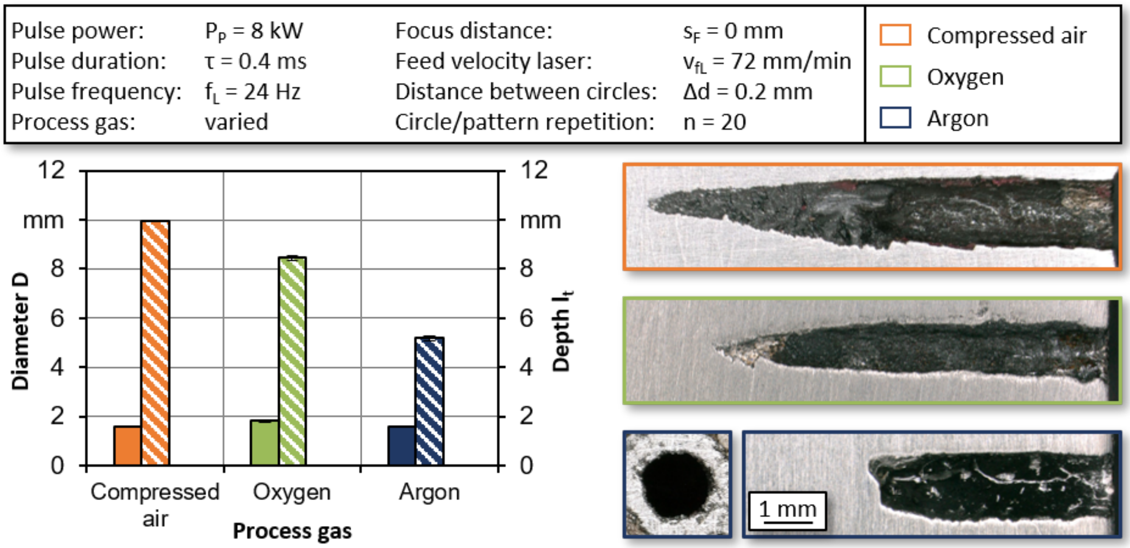

Fig. 3. Influence of the process gas on diameter D and depth l_t

After the identification of a suitable laser strategy and the determination of the process gas, the optimization of the laser parameters pulse power, pulse duration, pulse frequency and feed rate is carried out to generate suitable laser pilot holes for the single-lip drill with a diameter of *d = 1.5 mm*. It should be noted that the parameter range is limited on the one hand by the dynamics of the cross table and on the other hand by the maximum power of the laser system of $P_L = 80\ W$. The power results from the parameters pulse power, pulse duration and pulse frequency. During extensive investigations, a pulse power of $P_P = 4\ kW$, a pulse duration of $\tau = 0.175\ ms$, a pulse frequency of $f_L = 100\ Hz$ and a feed rate of $v_{fL} = 200\ mm/min$ with flat specimen geometry could be determined as suitable parameters with respect to the resulting bore hole diameter, the bore hole depth, the roundness and the conicity. When transferring the process from the flat workpiece geometry to components with an angle of $\gamma = 30°$ and $\gamma = 45°$, it was necessary to superimpose an additional linear motion of the cross table in the laser axis in addition to the pure circular motion to keep the focus distance constant to the surface. Otherwise, a pure circular motion would result in defocusing of the laser beam due to the workpiece angle, leading to an increase in roundness deviation. The programming of a pure circular path of the cross table therefore becomes a spline interpolation for the inclined workpieces in the CNC control. The interpolation points of the spline interpolation were distributed evenly over the circular movement. However, due to the high computational effort of the spline interpolation and the readjustment for the exact approach of the support points on the motion path, it was not possible to achieve the feed rate of $v_{fL} = 200\ mm/min$ at a high resolution. Fig. 4 (a) shows the resulting feed rates for the movement of the cross table with the largest diameter for 360 support points (1° advancing angle), 180 support points (2° advancing angle) and 90 support points (4° advancing angle). The lower feed rate results in a significant increase in process time, see Fig. 4 (b). An angle of 2° was therefore selected as a compromise between the roundness of the bore hole and the required process time.

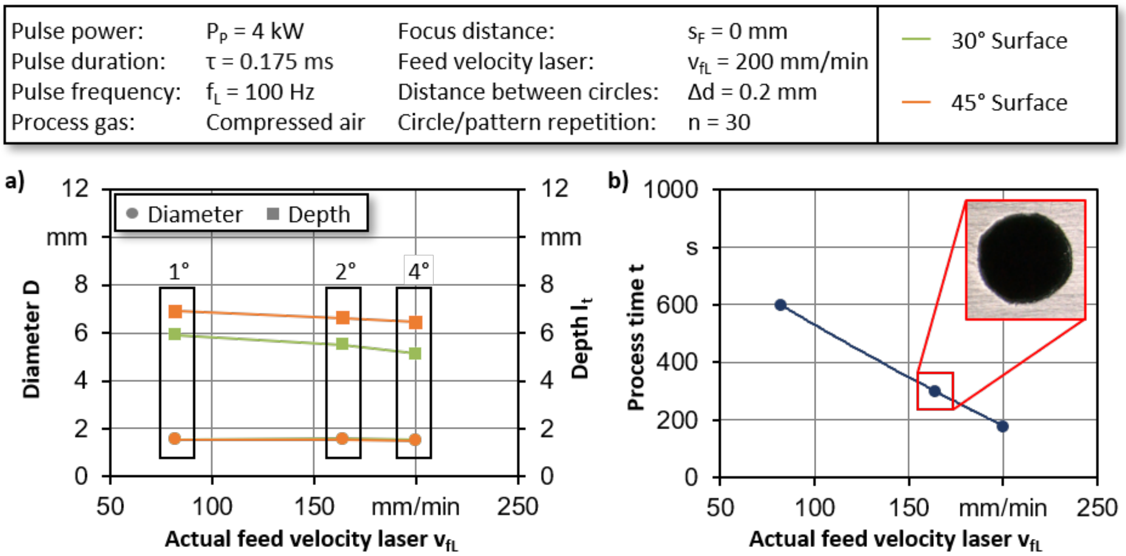

Fig. 4. (a) Influence of the advancing angle on the actual feed velocity of the laser v_{fl}, the laser pilot hole diameter D and depth l_t;
(b) Influence of the actual feed velocity of the laser v_{fl} on the required process time t

Fig. 5 shows the resulting laser pilot holes both for the flat workpiece geometry and for the angles of $\gamma = 30°$ and $\gamma = 45°$. Regarding the bore hole diameter, the laser pilot holes almost fulfilled the requirements of mechanical pilot holes. Slight deviations in roundness are due to the existing backlash of the cross table axes. Overall, however, all holes have a sufficient drilling depth and have a cylindrical area that is suitable for guiding the single-lip drilling tool in the beginning of the mechanical drilling process.

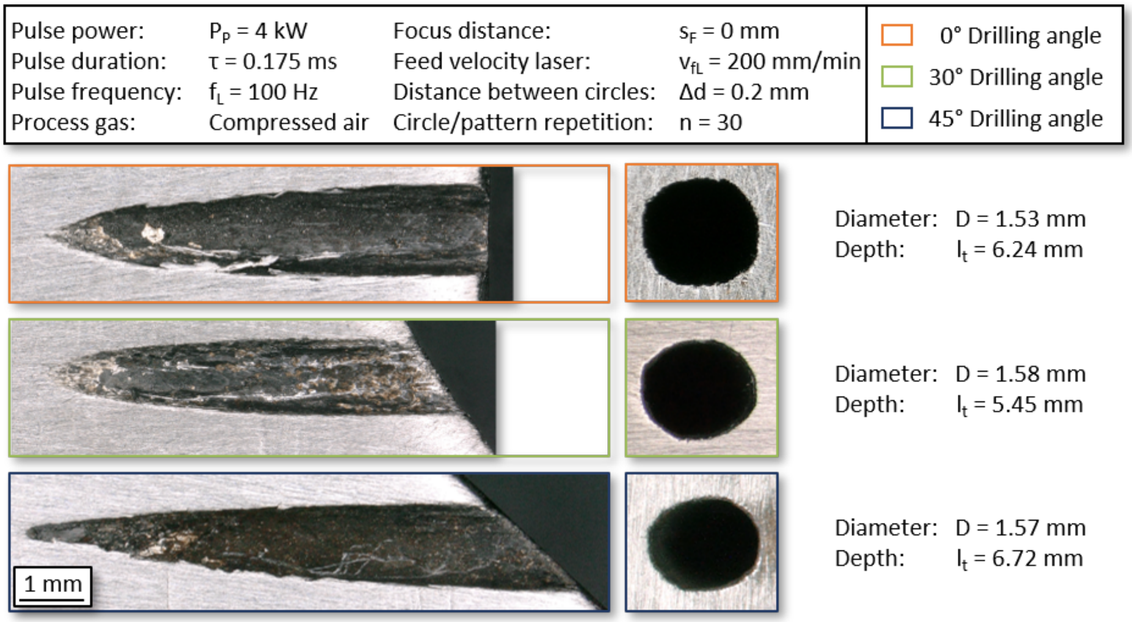

Fig. 5. Cross sectional images of the laser pilot holes in dependence on the drilling angle γ

4. Process Combination of helical laser drilling and subsequent single-lip deep hole drilling

After identifying suitable process parameters for the laser pilot holes, which serve as a drilling guide for the subsequent single-lip deep hole drilling process, the process combination was conducted. The laser optics are positioned axially parallel to the deep hole drilling spindle. The cross table enables the movement of the workpiece from laser pilot hole drilling directly into the working area for mechanical drilling, see Fig. 1. As there is no need for a second clamping operation, the risk of tool breakage due to misalignment during the positioning of the single-lip drill in the laser pilot hole at the beginning of the drilling process is significantly reduced. Fig. 6 shows the two-step process that was used to position the drilling tool in the laser pilot hole and the process parameters of the single-lip deep hole drilling process. The process starts with a reduced spindle speed of $n = 300$ *rev/min* up to a positioning depth of $l_{tp} = 1.5$ *mm*. Then the spindle speed was increased to $n = 3000$ *rev/min* to enable the tool to cut excess material solidified on the laser pilot hole wall while the tool moves to a depth of $l_{tp} = 3$ *mm*. Once the tool was completely positioned inside the pilot hole, the deep hole drilling process started by drilling blind holes with a length-to-diameter ratio of $l/D \approx 40$. The cutting parameters used for the solid carbide single-lip deep hole drilling tool are manufacturer specifications and represent standard values for machining austenitic steels. Referring to the results of the previous chapter, the process combination of helical laser pilot hole drilling and single-lip deep hole drilling was carried out for the three different drilling angles. In the following, it is investigated whether the different drilling angles have an influence on the subsequent mechanical single-lip deep hole drilling process. For this purpose, both the roughness and the straightness deviation of the bore holes were evaluated. Furthermore, tool life and the occurring process forces were analyzed. For statistical significance, a repetition of the test was carried out for all drilling angles. The determined values thus represent average values from two tools.

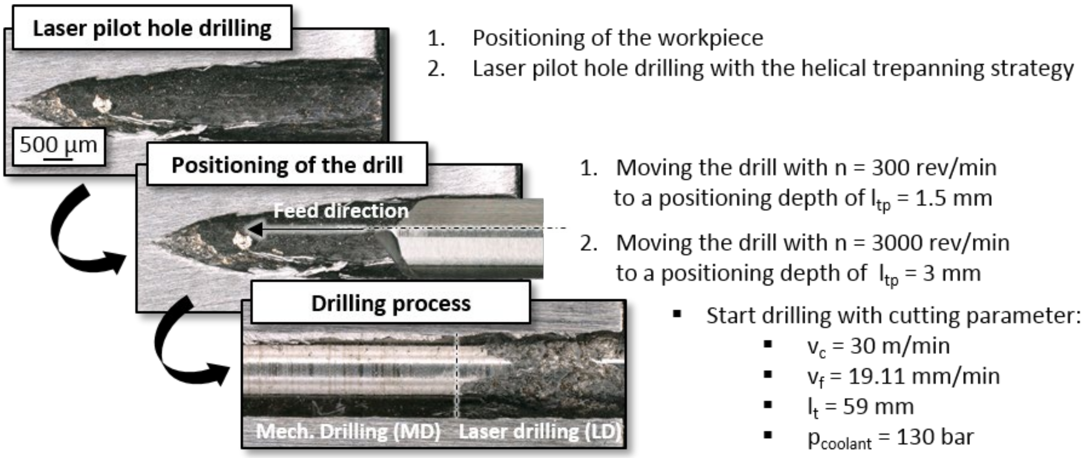

Fig. 6. Procedure of the process combination of laser pilot hole drilling and subsequent single-lip deep hole drilling

Regarding the surface roughness, a significant difference between the bore hole inlet and the bore hole outlet can be seen, see Fig. 7 (a). The determined values represent average values from 4 bore holes. The bore hole inlet represents the laser pilot hole area with an average surface roughness of all drilling angles of *Rz = 2.43 µm*. The bore hole outlet, representing the mechanically generated bore hole, obtained an average surface roughness of *Rz = 0.84 µm*, which is comparable to conventional deep hole drilling strategies that include mechanical pilot hole drilling or the use of a drill bush. The lower surface quality of the laser pilot hole can primarily be explained by the occurrence of recast layers, which significantly reduce the surface integrity of the bore hole. The standard deviation, which is significantly higher for the laser pilot holes, indicates a larger degree of inconsistencies of the bore hole surface, which corresponds to a surface resulting from solidified material.

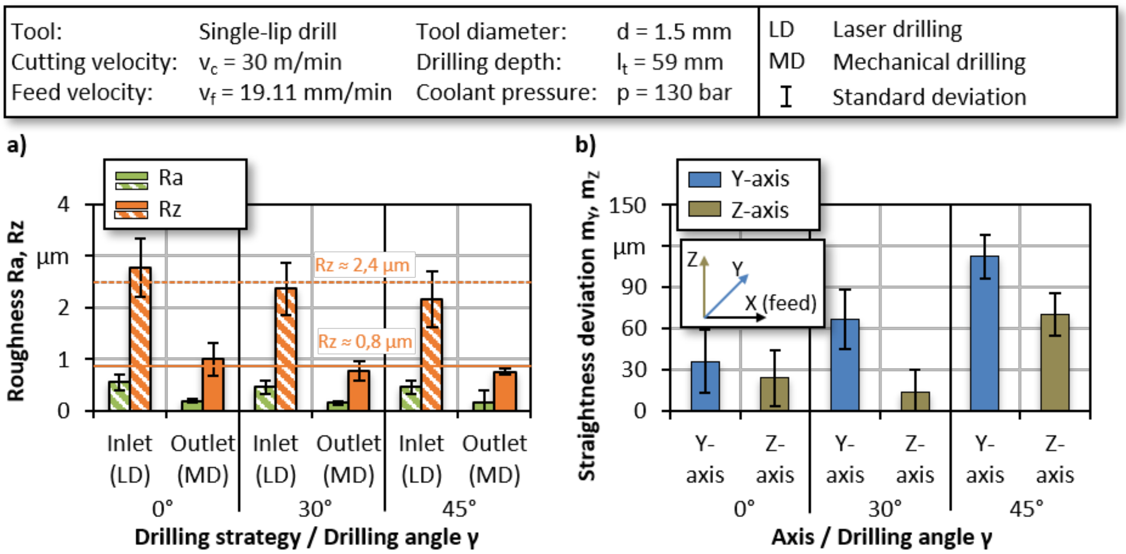

Fig. 7. (a) Influence of the drilling strategy / drilling angle γ on the surface quality; (b) Influence of the drilling angle γ on the straightness deviation m_y, m_z

In contrast to the surface roughness, the drilling angle has a significant effect on the realized straightness deviation of the bore holes (see. Fig. 7 (b)). Both the tool deflection in Y and in Z direction were analyzed. The X-axis represents the feed direction of the tool. It is evident that especially in the Y-direction, with increasing drilling angle, a larger straightness deviation occurs. This is related to slight differences in the laser pilot hole geometry on an inclined surface due to the movement of the cross table in the direction of the laser axis. Fig. 5 shows a slightly different curvature at the bore hole bottom for the upper and lower part of the laser pilot hole leading to an asymmetrical shape that can deflect the drilling axis especially for $\gamma = 45°$.

The wear measurements of the tools were carried out after every 10th bore hole, which corresponds to a drilling path of $l_f = 590\ mm$. The maximum wear mark width VB_{Max} on the flank face of the tool, was measured, to analyze the wear behavior. The results show a comparable wear behavior for all three workpiece geometries with slowly increasing wear mark widths, see Fig. 8 (a). All tools reached a total drilling path of $l_f = 7.08\ m$ without any tool breakages or chipping at the cutting edge. In contrast to the tool wear the feed force and the drilling torque show an influence of the drilling angle. Both the feed force F_f and the drilling torque M_B show a marginal increment due to the increase of the drilling angle, see Fig. 8 (b). This can be explained by the higher straightness deviations of the bore holes leading to a bending of the tool and therefore higher mechanical loads. Especially in single-lip deep hole drilling, the contact of the guide pads into the bore hole wall, is responsible for the surface quality and is directly correlated to the process forces. Therefore, the tendency of improved surface roughness at a drilling angle of $\gamma = 45°$ can be explained by the increase of the drilling torque, see Fig. 7 (a). In summary the results corroborate the investigations of the process combination involving single pulse laser pilot hole drilling with a tool diameter of $d = 0.5\ mm$ (Michel, 2018) and show that laser pilot holes with higher diameters produced by helical laser drilling can be used as a drilling guide for single-lip deep hole drilling processes.

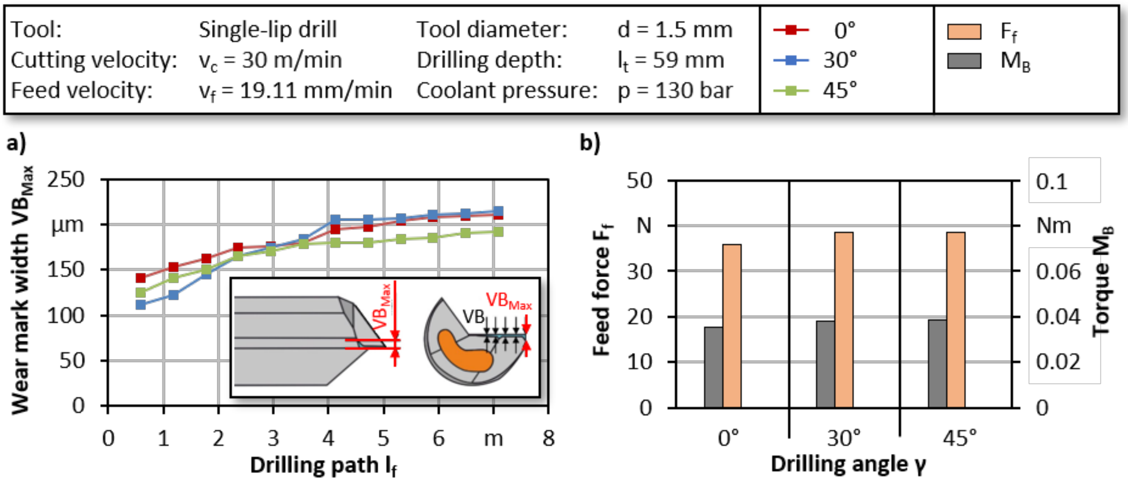

Fig. 8. (a) Influence of the drilling path l_f on the tool wear; (b) Influence of drilling angle γ on the process forces F_f and M_B

5. Conclusion and outlook

Within the scope of the presented investigations, the generation of laser drilled pilot holes for the single-lip deep hole drilling process with a diameter of $d = 1.5\ mm$ was analyzed. By varying the laser drilling strategy, the process gas and the laser parameters, it was possible to generate laser pilot holes on flat workpieces that are suitable as a drilling guide for the mechanical deep hole drilling process. By programming the workpiece movement via spline interpolation, the helical laser drilling process could be successfully transferred to inclined workpiece geometries. The quality of the laser holes is limited not only by the high melt content when using millisecond lasers, but also by the limited dynamics of the cross table of the special machine based on a conventional deep hole drilling machine. However, it was possible to implement the process combination of laser pilot hole drilling and single-lip deep hole drilling for all workpiece geometries. The continuous wear progression of the tools proves a stable drilling process.

The aim of further investigations will be to optimise the quality of the laser pilot holes and to positively influence the straightness and thus the hole quality with an improved guidance of the single-lip drilling tool in the laser pilot hole. To produce a consistently high surface quality, machining with step drilling tools is planned. When transferring the laser process to other materials, the creation of laser pilot holes in surface-hardened components is particularly suitable due to the wear-free machining with the laser in the hardened surface layer.

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