High precision deep drilling with ultrashort pulses

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Ultrashort laser pulses appear very promising for material removal with highest precision. However, our investigations show several unexpected quality problems such as formation of recast, ripples, and irregular hole shapes even in the femtosecond-pulse regime. In this contribution influences on drilling efficiency and hole quality by several process parameters such as repetition rate and pulse duration will be presented and discussed. Furthermore different processing techniques to increase the drilling velocity will be shown. A suitable device for that purpose is a trepanning optic which was specially designed for the drilling of injection nozzles. By a variable angle of beam incidence it allows to produce holes with a well-defined conicity in combination with the high precision achieved by helical drilling.

Keywords: Drilling, laser ablation, ultrashort pulses, process technology

1. Introduction

In the case of high precision holes, e. g. for fuel injection nozzles, conventional processes cannot meet the increasing requirements with regard to reduced dimensions and tolerances. Up to now the achievable accuracy of laser drilled holes in metals is limited by the relatively large amount of molten material when drilling lasers with pulse durations in the range of nanoseconds or longer are used. Shortening the pulse duration down to the femtosecond regime is generally considered a suitable recipe to avoid melt formation. Our investigations have shown that this is valid for the drilling of thin materials or when very low pulse energies are used [1, 2]. However, for an efficient drilling of deep capillaries, higher pulse energies are required and therefore recast can only be avoided by a reduction of the pulse duration in combination with well-elaborated drilling procedures.

2. Drilling with ultrashort pulses

2.1 Pulse duration

In general, when drilling with ultrashort pulses a recast free material processing without thermal stress to the material is expected and in consequence highest precision of the laser drilled holes. Our experimental and theoretical investigations revealed, that with decreasing pulse duration - melt production can be reduced but cannot be avoided entirely [3,4,5] and that the ablation process of steel is essentially of thermal nature even in the femtosecond pulse range. The thin melt layers produced by each pulse can accumulate to thick recast layers. This is illustrated by the left frame in Figure 1 showing a hole that was percussion drilled in a 1 mm thick steel plate by 500 fs pulses and without any special processing technique. On the other hand, nonlinear interaction mechanisms are playing an important role in femtosecond ablation. Figure 1 (right) shows an example for the effect of a nonlinear interaction with the atmosphere near the laser focus causing strong deformation of the laser beam and finally irregular hole shapes [6,7]. Theoretical considerations show that below approximately 10 ps a further reduction of pulse duration is expected to be without significant effect on thermal behavior, at least as far as metals are considered [4,5]. On the other hand the scattering

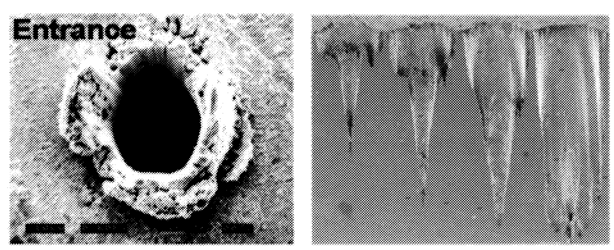

Fig. 1 Problems in drilling of steel with femtosecond pulses. Left: Hole entrance of a percussion drilled hole in steel with thick recast layer (s = 1 mm, τ = 500 fs, λ = 775 nm, H = 390 J/cm²). Right: Longitudinal section of a steel plate showing blind holes with increasing number of pulses (s = 1 mm, τ = 125 fs, λ = 800 nm, H = 330 J/cm²).

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effect which can cause irregular hole shapes (Figure 1 right) strongly decreases when the pulse duration is increased to several picoseconds, or appears only at higher energy densities, respectively. Using pulse durations in this range higher energy densities can be applied to increase process efficiency during drilling without a loss in quality. From these considerations a pulse duration around 5–10 ps appears to be optimal for micro-machining of metals.

2.2 Increasing hole quality and drilling efficiency

The problem of recast and beam deformation described above can be solved if the energy density is reduced to a value only slightly above the ablation threshold of the material. In this case holes with sharp edges, smooth sidewalls can be produced that are obviously free of recast. However, this can only be achieved at a processing speed that is several times longer than in nanosecond drilling and far from being economically useful. For this reason suitable processing techniques have to be found to overcome the quality problems occurring at high energy densities.

As shown in previous publications, the quality of a hole can be significantly enhanced using the helical drilling technique [3,8, 9] where the ablation front penetrates the workpiece on a helical path. The improvement in accuracy can be attributed partially to the imposition of a well-defined beam movement which determines the resulting hole profile rather than the sometimes distorted beam shape or the statistically influenced ablation process. Additionally, material expulsion becomes easier due to an ablation spot size that is small compared to the channel diameter. Therewith it is possible to produce holes with very good cylindricity and small burr.

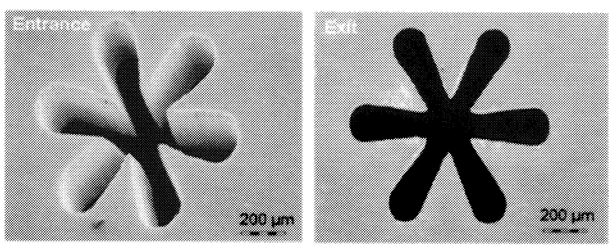

Fig. 2 Entrance and exit of a nozzle design (used for spinnerets) produced with an ps-laser (τ_H = 10 ps, λ = 1064 nm, f_p = 20 kHz, Q = 200 µJ/pulse. Technique: Lasermicromachining).

An further development of the helical drilling technique is the so-called laser micromachiningfor non-circularly shaped holes [9]. An application demonstrating the possibilities of this technique is shown in Figure 2 where a special geometry necessary for spinnerets in steel with a thickness 0.4 mm was produced. The surface is nearly free of recast material and the flanks are very smooth with sharp edges.

Despite the helical drilling technique the process efficiency is quite small up to now. The main reason for that is that the repetition rate of commercially available ultrashort pulsed laser systems with high pulse energies that are suitable for deep drilling is limited to only a few kHz. Hence, an important aim was to investigate the influence of higher repetition rates on process efficiency and hole quality. A prototype of an 8 kHz system was available with an external modulator allowing to change the repetition rate while the pulse energy remains constant. Figure 3 displays the influence of the repetition rate on the drilling time for percussion drilling of 1 mm thick steel with 5 ps pulses. The dashed curve represents the drilling time to be theoretically expected if a constant number of pulses necessary for full penetration is assumed. The experiment shows that this assumption is approximately valid. This could also be confirmed for helical drilling.

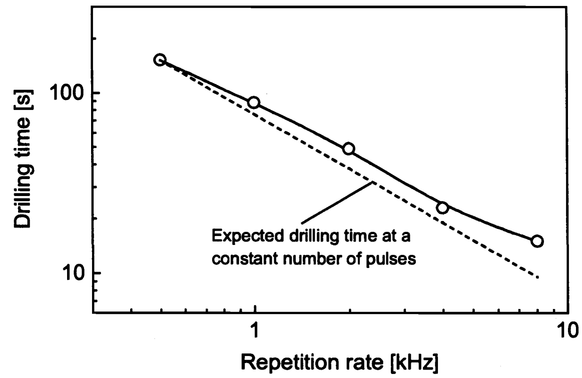

Fig. 3 Influence of the repetition rate on drilling time (steel, 1 mm, τ_H = 5 ps, λ = 1030 nm, Q = 330 µJ/pulse, percussion drilling).

A negative effect of the higher repetition rate on the hole quality could not be observed at all (Figure 4). Experiments with another laser system operating at 20 kHz and 10 ps pulses demonstrated that even at this repetition rate an effect on hole quality was not discernible and that the drilling time can be further reduced.

In view of the high potential for increasing the process velocity in drilling with longer pulses when using vacuum [10], investigations on this matter were also carried out with ultrashort pulses. The diagram in Figure 5 depicts the effect of pressure on drilling rate and hole diameter in dependence

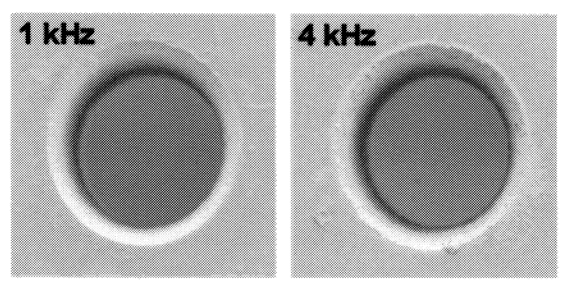

Fig. 4 Holes produced with different repetition rates revealing no effect on hole quality (steel, 1 mm, τ_H = 5 ps, λ = 1030 nm, Q = 330 µJ/pulse, helical drilling).

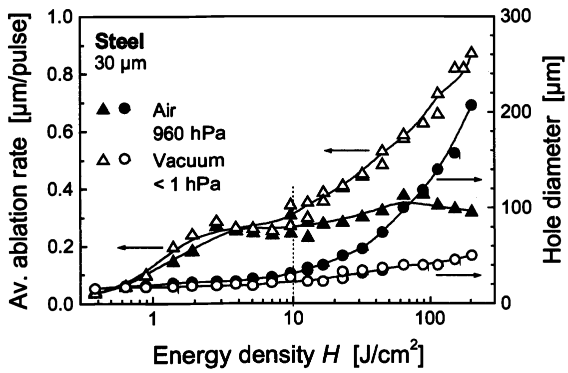

Fig. 5 Effect of pressure on drilling rate and diameter depending on energy density (Steel, $\tau_H = 110$ fs, $\lambda = 800$ nm, $f_p = 1$ kHz, $d_f = 18$ µm, in air).

on the energy density. For energy densities above 10 J/cm² the reduction of the ambient pressure leads to an increase of the average ablation rate and a reduction of the hole diameter. While at atmospheric pressure a strong widening beyond the beam diameter is observed, the hole diameter increases only slightly when vacuum is applied. When hole widening is avoided in vacuum, the linear drilling rate steadily increases with the energy density. On the contrary, a saturation of the drilling rate is observed when widening occurs at atmospheric pressure. Thus the total volume ablation rate is not affected when the ambient pressure is reduced [5]. An explanation for the smaller hole diameters obtained in vacuum conditions can be given by the reduced nonlinear interaction with the atmosphere (scattering) [3,6, 7], which can have a strong influence on the hole shape at atmospheric pressure (see Figure 1 right). Thus, by means of a reduced ambient pressure the depth ablation rate for percussion drilling can be increased by an order of magnitude in spite of the constant volume ablation rate. So on the one hand holes can be drilled with smaller diameters, on the other hand holes with larger diameters, which are usually generated by helical drilling, can be produced with a higher velocity.

The implementation of a vacuum chamber into a processing station would allow to benefit from the advantages of reduced pressure during drilling. However, this would require time-consuming and therefore expensive loading and unloading processes and is furthermore relatively inflexible for practical purposes. To overcome these drawbacks, a special vacuum nozzle was designed based on the principle of an aerodynamic window, Figure 6. The nozzle offers high flexibility for the geometry and handling of the workpiece. Enabling furthermore a fast variation of the pressure even during the drilling process, the nozzle allows to develop novel laser processes which combine the advantages of fast drilling at reduced pressure with the smoothing effect of the laser-induced plasma during the hole widening and cleaning phase after the material is pierced through [9]. The realization of such a nozzle is in progress at the moment.

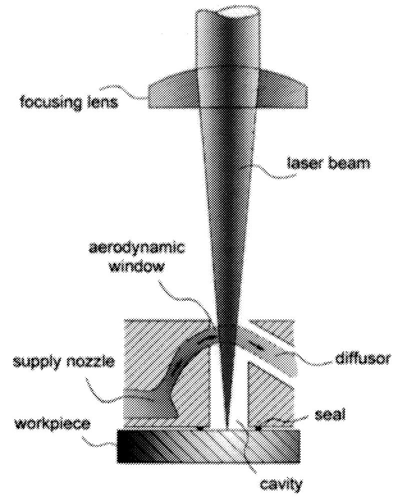

Fig. 6 Concept of a vacuum nozzle based on the principle of an aerodynamic window.

3. Polarization Effects

3.1 Influence on hole quality

Our investigation in drilling with ultrashort pulses revealed a strong influence of polarization on hole quality. An effect that can often be observed especially for thick materials is the deformation of the shape of the hole exit such that it looks rather oval than round, Fig. 7 a). These deviations from circularity are reproducibly oriented in the same direc-

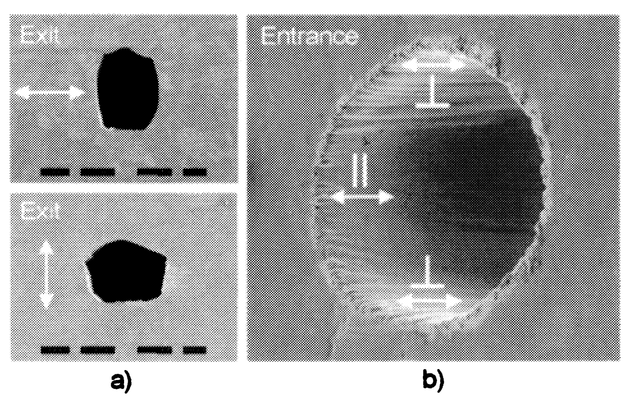

Fig. 7 a) Influence of the direction of the polarization on the shape of the hole exit ($\tau_H = 120$ fs, $\lambda = 780$ nm, $f_p = 1$ kHz, steel, 1 mm). b) Ripple formation on the wall surface of a hole for helical drilling with a linearly polarized fs laser ($\tau_H = 120$ fs, $\lambda = 800$ nm, $f_p = 1$ kHz, $d_f = 18$ µm, H = 310 J/cm², in air, steel, 0.5 mm).

tion. The orientation is dependent on the direction of polarization, which was proven by turning the polarization by 90° by means of a half-wave plate. An influence on the shape of the hole entrance was not observed. The effect can be attributed to the different reflectivity of parallel and perpendicular polarization at the hole walls [11].

A second effect of polarization is the formation of ripples on the surface of the hole wall, Fig. 7 b). The ripples are nonuniformly distributed around the hole wall. In regions of perpendicular polarization (with respect to the plane of incidence which corresponds to a direction of the electric field vector orthogonal to the hole wall) they are much more pronounced than in regions of parallel polarization, where they can be completely suppressed. The reason for the ripple formation is not clear up to now but we believe them to develop from characteristic structures on the planar surface, which are caused by scattering effects at the beginning of the drilling process [11].

3.2 Polarization control

To overcome the negative influence of polarization on hole quality it is necessary to use polarization control during the helical drilling process. Using a circularly polarized laser beam the influence on the shape of the hole exit can be avoided, but the problem of ripple formation cannot be solved. A possibility to avoid the deformations from circularity as well as the formation of the ripples is to control the plane of the linear polarization by a rotation of the workpiece. With this technique, the direction of polarization with respect to the hole wall can be adjusted to meet the demands of the process. Figure 8 shows a hole produced in 500 µm thick steel by a rotation of the workpiece with 5 ps pulse duration and parallel polarization. The exit appears to be perfectly circular, it has sharp edges and the hole wall is smooth.

The main disadvantage of this technique for industrial applications is that the hole axis must coincide to the axis of rotation. Thereby the flexibility of this method is very low at best. Frequently, the use of this method is impossible due to complex and heavy workpiece geometries. A better method would instead rotate the linear polarization synchronously to the beam movement during the helical drilling process.

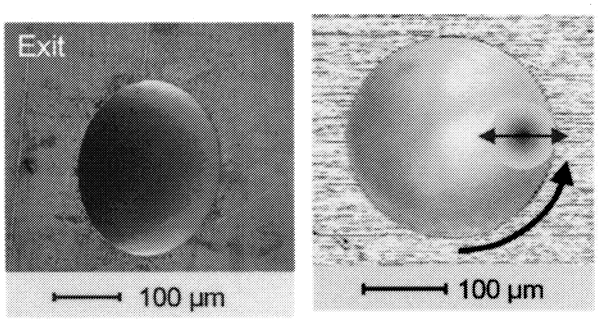

Fig. 8 Exit of a hole produced in a 0.5 mm steel plate by rotation of the workpiece with an experimental picosecond laser with regenerative thin-disk amplifier (τ_H = 5 ps, λ = 1030 nm, f_p = 10 kHz, Q = 600 µJ/pulse).

4. Trepanning optic

In laser drilling of high precision holes very often large efforts are necessary to widen the hole exit for achieving cylindrical holes. For various industrial applications even holes with special geometries such as a negative conicity, e. g. for injection nozzles or spinnerets, and extraordinarily restrictive tolerances are required. With respect to these requirements a special trepanning optic was developed, Fig. 9. The optic is based on the principle of beam deflection by rotating optical wedges and combines the advantages of helical drilling with a variable inclination of the beam. Thereby high quality cylindrical holes with increased drilling velocity can be produced by short and ultrashort pulses as well as holes with negative conicity [8,11].

Figure 10 depicts the influences of inclination angle, drilling time, and pulse duration on hole cylindricity. When an inclination angle of 0° (normal incidence) is used, more than 10 s drilling time is needed to achieve an exit-to-entrance diameter ratio of one, which is equivalent to a cylindrical hole. For the shortest pulse duration of 120 fs, cylindricity can not be reached at all for the indicated set of parameters. Increasing the inclination angle up to 4°, cylindricity can be achieved for all pulse durations in about half the drilling time. Furthermore holes with negative conicity are possible at longer drilling times.

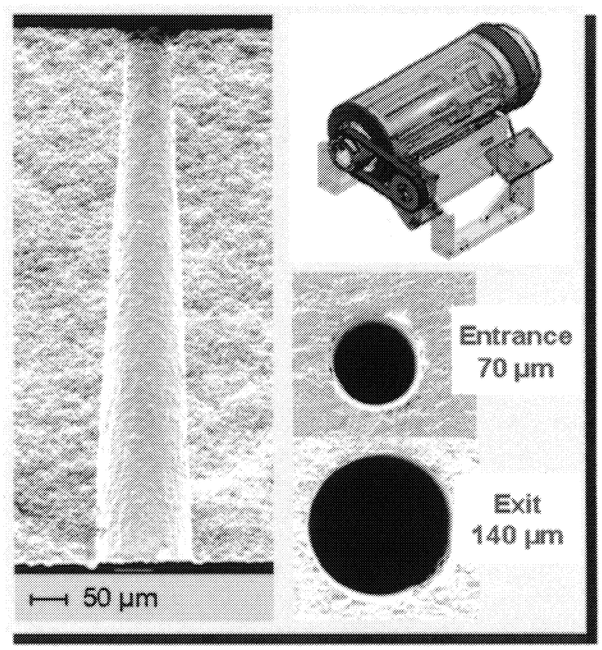

Fig. 9 Model of the trepanning optic and examples of conical holes in ceramics and steel produced by such an optic.

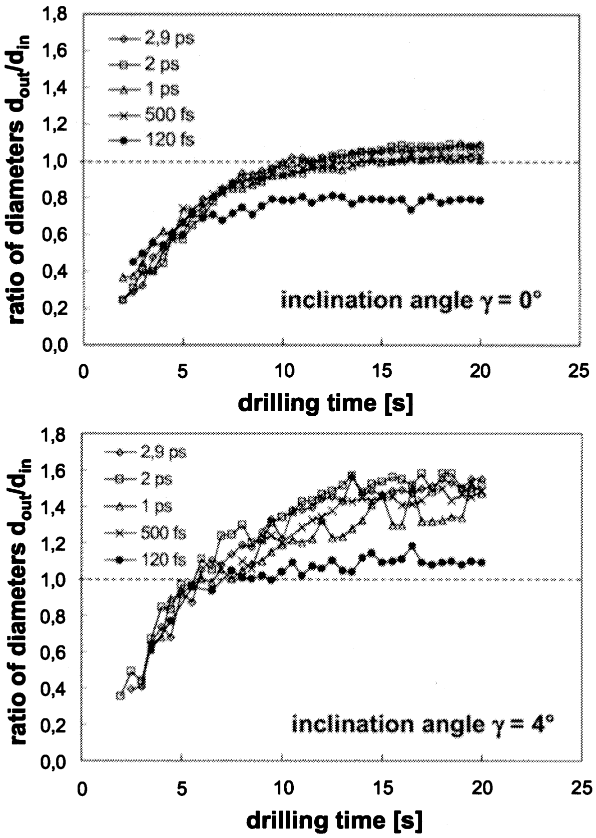

Fig. 10 Influence of drilling time and pulse duration on hole cylindricity. Upper graph: with perpendicular incidence; lower graph: with an inclination of 4° (Steel, s = 500 μm, λ = 780 nm, f_p = 1 kHz, Q = 900 μJ/pulse).

Besides the advantages described above, the optic offers a relatively simple possibility to control the polarization synchronized to the beam movement as described in section 3.2, see Fig. 11. By a fixed quarter-wave plate the linear polarization of the beam is transformed into circular. A second quarter-wave plate is combined with the wedges of the trepanning optic such that it is rotating with the same frequency. The circular polarization is again transformed into linear polarization, but it is now rotating with the frequency of the wedges and therewith synchronously with the laser beam movement. The polarization is hence always oriented in the same way with respect to the hole wall and can furthermore be adjusted by a rotation of the second quarter-wave plate relative to the wedges of the optic.

Investigations applying this technique have shown a remarkable improvement in quality (Figure 12), even though a perfect roundness as it is feasible by a rotation of the workpiece (compare Figure 8) could not be achieved. The reason for the remaining deformation from circularity is not polarization but rather an asymmetry of the beam profile. The hole to the right of Figure 12 shows beam intensity profiles

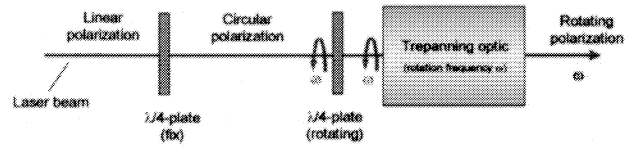

Fig. 11 Principle of polarization control by a trepanning optic in combination with quarter-wave plates.

extracted from a beam quality measurement. The asymmetry of the rotating beam profile has a direct impact on the hole exit shape. In comparison, the beam profile does not play a role when rotating the workpiece, because the same side of the beam is always interacting with the hole wall (Figure 8, right). In consequence, this means that for a polarization control by a trepanning optic and quarter-wave plates, a rotational symmetry of the laser beam is indispensable.

5. Conclusions

Our investigations have shown that the mere reduction of pulse duration down to the picosecond and femtosecond regime is not sufficient for avoiding melt layers and recast in high precision drilling. Furthermore several unexpected quality problems, which are much less pronounced when longer pulses are used, such as ripples and deformation of the hole shape caused by nonlinear effects or polarization do occur. To overcome these deficiencies and to produce holes with high precision as well as high efficiency, suitable processing techniques are required (Figure 13).

Precision as well as efficiency can be increased when a trepanning optic is used, which combines the quality advantage of helical drilling and drilling with an inclination angle, in order to produce holes with a well-defined conicity and to increase the drilling efficiency. The strong influence of polarization on hole quality can be avoided if the polarization is controlled in such a way that the linear polarization of the laser beam is always oriented parallel to the hole wall during the helical drilling process. This can be done using the trepanning optic in combination with quarter-wave plates. A

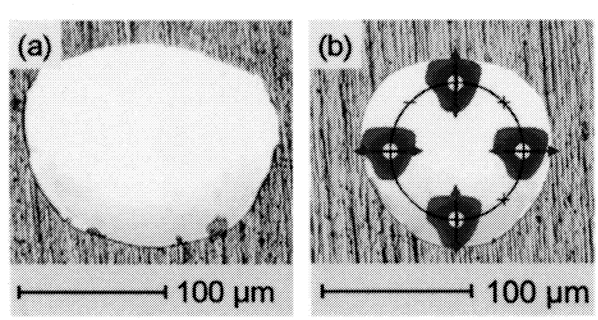

Fig. 12 Improvement of hole geometry using polarization control by a combination of quarter-wave plates and a trepanning optic during helical drilling process.

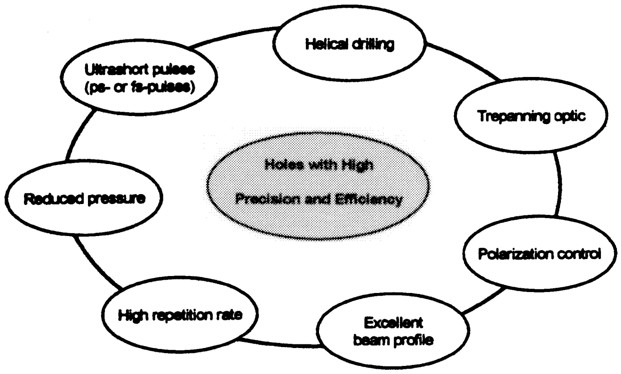

Fig. 13 Means to produce holes with high precision and efficiency.

radially symmetric beam profile then becomes one of the key requirements for the laser system. Drilling efficiency can be increased without loss in quality when laser systems with higher repetition rates are used. In addition a reduced pressure atmosphere leads to a further increase of drilling speed and furthermore can help to limit scattering effects.

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