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DELIVERABLE D2.6

Process optimisation for maximum drilling speed and diameter

Lead Beneficiary: FhG-IAPT

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Disclaimer

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ABBREVIATIONS AND GLOSSARY OF ACRONYMS

Acronym	Extended definition
IAPT	Research Institution for Additive Manufacturing Technologies
WP	Work package

Symbol	Unit	Definition
d, d_1, d_2	mm	Diameter of the laser beam on the rock surface
$P_{\mathrm{L}\,1}$, $P_{\mathrm{L}\,2}$	kW	Laser power
w, w_1, w_2	mm	Working distance

EXECUTIVE (or PUBLISHABLE) SUMMARY

As part of the DeepU project, Fraunhofer IAPT was responsible for developing the laser gas drill head and the laser drilling process to create a scaled-down U-tube heat exchanger. In order to achieve optimized drilling performance as function of the type of rock, optimal parameters for laser power, spot diameter, gas flow rate, and temperature conditions were determined. Using the process limits researched, Fraunhofer IAPT produced a U-tube in rock material as a scaled-down model of an ultradeep geothermal heat exchanger, on which the new process for very deep ground tubes was validated for the first time.

1. INTRODUCTION

The efficient use of the newly developed cutting-edge technology for non-contact laser drilling is based on the developed innovative laser gas drilling head for various drilling orientations and on the developed laser drilling process for various rock types. Both elements were implemented by the Fraunhofer IAPT in WP2 of the project DeepU. These findings are essential for the laser drilling for deep geothermal energy exploitation, which is proposed in the DeepU project.

In order to solve the question of maximum rock material excavation and therefore maximum drilling speed, this report is concentrated on the process optimization for a maximum drilling speed and an optimal borehole diameter. This includes the exploration of process limits, dealing in particular with the optimal parameters for laser power, spot diameter, gas flow rate, and temperature to determine the achievable drilling speed as a function of rock type.

2. OPTIMIZATION OF THE LASER POWER

2.1 INTRODUCTION

The well-defined laser power is essential to achieve the suitable melting temperature on the rock surface, as the acting intensity is a function of laser power on the irradiated area. Furthermore, the melting threshold of each rock type is directly related to the spotted intensity. Consequently, the laser power is primarily responsible for the energy supply in the laser drilling process.

2.2 LASER-ROCK INTERACTION

Each rock type exhibits a characteristic laser-rock interaction. The petro-thermo-mechanical phenomena that occur during laser irradiation are spallation, melting, and evaporation. This classification provides information about the most effective rock removal process. Spallation occurs at lower temperatures (<700 °C) on specified rocks such as sandstone. Laser drilling by melting occurs at higher temperatures such as basalt and by evaporation at high temperatures (>2000 °C) such as limestone.

However, achieving higher temperatures during rock interaction by increasing the effective intensity means increasing the laser power, which results in an increase in the energy required to generate the laser power. This inevitably leads to higher costs for laser light generation and thus per meter of rock drilled. In addition, larger drill diameters also require higher laser power keeping the effective intensity constant. The key aspect here is that any change in the drill diameter causes a fourfold change in laser power, as shown in Figure 1. The support points are shown: a) diameter d_1 = 100 mm, laser power $P_{\mathrm{L}\,1}$ = 30 kW and b) diameter d_2 = 200 mm, laser power $P_{\mathrm{L}\,2}$ = 120 kW, respectively.

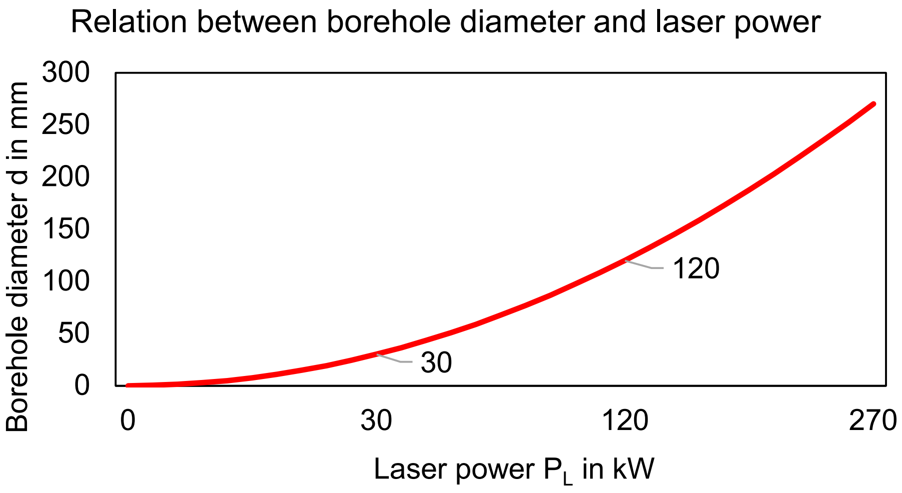

Figure 1: Relation between borehole diameter and laser power at constant intensity

Besides the fact that a higher temperature in the rock generally requires higher laser power, the rock's melting point counteracts the continuous increase in laser power. Thus, in spalling rocks, such as sandstone and granite, a similar borehole diameter can be achieved as with rocks with a higher melting point, even though less laser power is used. In summary, the laser power was individually tailored to the investigated rock types and their laser-rock interaction, as well as their thermal spallation, melting, and evaporation behavior, for optimal material removal and extraction, taking into account the borehole diameter to be achieved.

3. OPTIMIZATION OF THE GAS STREAM

3.1 INTRODUCTION

For a continuous drilling process, constant blowing out of the cuttings is essential. Key parameters are the gas flow rate and the applied gas pressure. The gas flow rate is necessary to blow out the cuttings from the bottom and to transport them along the void space around the drill string to the earth's surface. The bigger the cuttings are, the higher the gas flow rate must be. Moreover, the gas pressure creates the impulse acting on the melt and the cuttings at the borehole bottom. The higher the gas pressure , the higher the impulse and the better the melt can be blown out from the borehole bottom. Since they are inversely related, finding the optimal ratio between flow rate and gas pressure as well as suitable sequencing for the activation of the nozzles are crucial. Therefore, different nozzle patterns and parameter sets were tested and analysed to enable the most effective blowing out action.

3.2 THE NOZZLE SYSTEM OF THE DRILL HEAD

Figure 2 shows the arrangement at the bottom of the drill head, highlighting the five nozzle segments. Segment one is a large centre nozzle that provides a high nitrogen flow to shield the optics inside the laser gas drill head from cuttings. All other segments contain of four nozzles. The nozzles are controlled by solenoid valves.

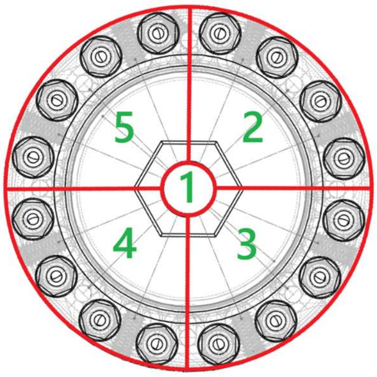

Figure 2: Nozzle arrangement at the bottom of the drill head

Due to the arrangement of the nozzles and the possibility of a specific control, various flow conditions can be generated in the borehole, and the gas flow rate as well as the gas pressure can be controlled to optimize the gas stream condition. In summary, the cuttings are set into defined movements and transported out of the borehole.

3.3 GAS STREAM CONFIGURATION

To optimize the gas stream configuration for a maximum excavation result, a transparent plastic tube was used as a borehole model, into which a printed, round-shaped element was inserted resembling the bottom of the borehole. The borehole model was filled with clay balls, which served as substitutes for the cuttings. Figure 3 illustrates the setup.

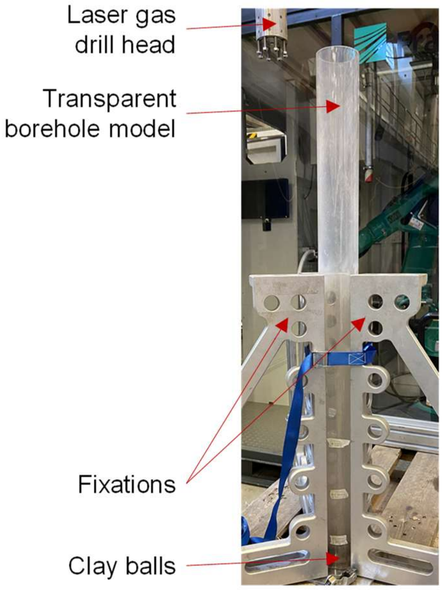

Figure 3: Setup to optimize the gas stream configuration

For the parameter optimization, the drill string was inserted into the borehole model at varying working distances from the bottom. Subsequently, different parameter sets were studied. This included the nozzle diameter, the distance between the laser gas drill head and the borehole bottom, as well as parameters such as the time span during the nozzle segment activation, the overlap between segments, and pre- and post-gas flow of the centre nozzle before and after drilling.

In summary, it was recognized that an overlap, or several segments switched on at the same time, as well as large nozzle diameters, lead to a stamping effect in which the clay balls are pressed onto the bottom of the borehole instead of being blown out. A suitable time for specific sequences was determined, which must be neither too short nor too long.

Finally, optimal parameter sets for the gas stream were found, based on the compromise between the required gas flow rate and the applicable gas pressure, to enable the most effective blowing out and transport of the cuttings out of the borehole.

4. INTERACTION

4.1 WORKING DISTANCE

In addition, to the adjustable parameters of laser power and gas pressure or gas flow rate, the drilling process is determined by the working distance w between the lower end of the laser gas drill head and the bottom of the borehole, see Figure 4.

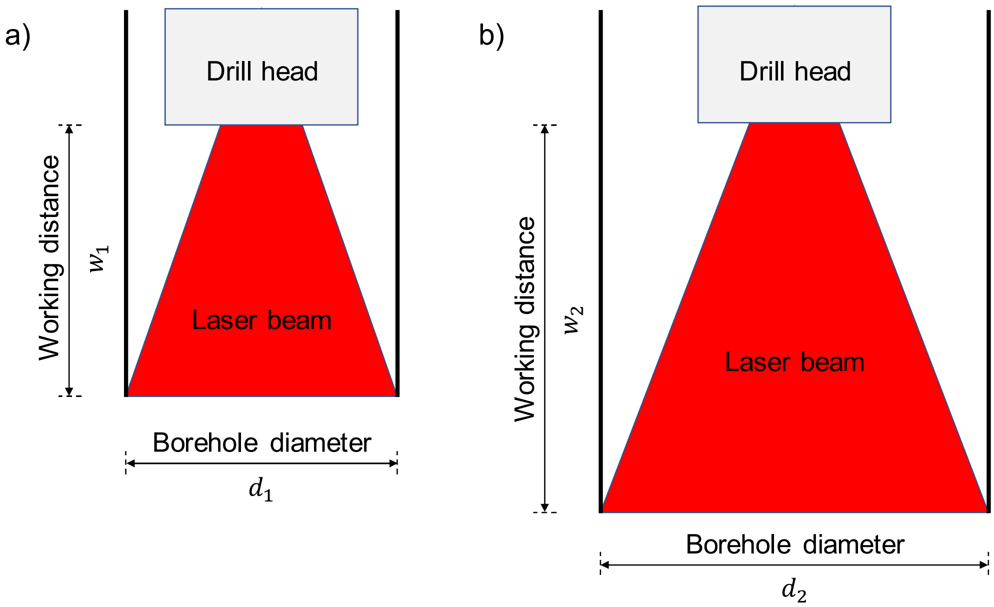

Figure 4: Relation between working distance and borehole diameter

With a fixed focal length of the laser optics, the laser spot diameter d is related to the working distance w. The greater the drilling distance, the larger the laser spot on the rock surface inside the borehole, so that the intensity of the laser beam decreases and the melting effect is reduced, see Figure 4b). Rock types with a greater tendency to spallation and therefore lower energy requirements during drilling can also be reliably processed at a greater working distance, which means lower intensity. The greater the intensity required to detach rock particles from the rock mass, the smaller the working distance must be, see Figure 4a). However, there is a lower limit in this regard, as the drill diameter resulting from the working distance must provide sufficient space or width for the drill string and, in addition, the annular space around the drill string must be created, through which the cuttings are transported out of the borehole. If the working distance is too short and the laser spot size is therefore too small, there will be no annular space around the drill head and the drilling progress will inevitably be stopped.

Furthermore, the working distance interacts with the gas flow used to blow out the melt of the borehole. A shorter distance means that a more powerful gas stream acts on the molten rock, facilitating the removal and transport of the cuttings. Conversely, the reliable removal of the molten rock also ensures that the working distance does not decrease and that the drilling progress continues uninterrupted. The shorter the distance, the greater the blowing effect of the gas stream. However, there is also a limit here because a minimum safety distance between the drill head and the laser process zone must be maintained so that the laser gas drill head and, in particular, the optics for laser beam guidance are not damaged.

4.2 DRILLING SPEED

The drilling speed is the most important target variable in laser drilling. Under given boundary conditions and specifications, such as the rock type, the drilling diameter to be achieved, and the drilling depth, the drilling speed becomes the key evaluation criterion for the laser process. The effort required to use the laser can only be justified if the process offers a cost or efficiency advantage over conventional drilling. The achievable drilling speed is primarily a result of the laser power used. The greater the available power and the more the power can be concentrated, the higher the possible drilling speed. The maximum could be realized if the rock were not only melted but also largely evaporated. However, this physical effect requires extremely high power levels, which would be very costly to provide.

The applied gas stream also influences the drilling speed. A high speed requires sufficient gas pressure and gas flow rate for particle removal. If this pressure or gas flow rate is not available, the drilling speed must be adapted, that means reduced. The need for adjustment can be recognized by an unwanted reduction in the working distance during the drilling process caused by molten rock accumulating at the bottom of the borehole.

However, it is not only the process speed that determines drilling progress; the operation of adding new drill pipes to the existing string also impacts on the depth that can be achieved when drilling downwards within a day or an hour. During repositioning, the individual sections of the drill string are connected to each other and then lowered into the borehole using a drill rig. While another drill string segment is being swung into position, the laser must of course be switched off, as the drill pipe crosses the beam path. At this point, the drilling process is temporarily halted. Once the drill segments have been positioned and connected, the laser can be switched on again, and drilling can continue. Studies have shown that this process takes between 30 and 120 seconds.

A major advantage of laser drilling is that, unlike conventional drilling tools, the laser beam cannot wear out because there is no mechanical contact with the rock. As a result, it is not necessary to bring the tool to the earth’s surface, replace it, and lower a new tool back into the borehole, which would require dismantling the drill string into all its individual segments and then reassembling it. The duration of this process correlates with the drilling depth at which the worn tool needs to be replaced. It is quite possible that this tool change will take 1 to 2 days, during which no drilling progress will be made. The service life of mechanical tools depends on the type and hardness of the rock, so that, for example, in granite or basalt, more frequent wear-related drilling interruptions are necessary, which are not existing with laser drilling. The actual achievable drilling speed is therefore subject to various influences and can only be determined as an average over several days of drilling or even an entire borehole.