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Laser Supported, Thermal Rock Weakening and Drilling for Hard Rock and Geothermal Applications

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ABSTRACT

There has been a substantial increase in interest in recent years for widespread exploitation of geothermal energy. However, the progress still hinges on finding cost-effective solutions to drill into hard crystalline rocks. Conventional drilling almost solely relies on mechanical abrasion and has effectively been used by the oil and gas industry for over 100 years, also by incremental modification and optimization of the drilling process. However, problems in conventionally drilling of geothermal reservoirs mainly include a very low rate of penetration with very high bit wear. Therefore, multiple attempts are underway worldwide to develop a novel drilling method to overcome the latter problems and facilitates deep drilling process a more economical and safer operation. Thermal drilling techniques such as Laser supported Drilling, could potentially be such fundamental change and thus, significantly improve drilling into deep geothermal reservoirs. International Geothermal Centre in Bochum is investigating such innovative thermal drilling technologies, especially mechanically assisted LaserJet drilling. It employs a laser-water-jet (LWJ) to deliver additional thermal energy to the rock surface. The beam induces thermal stresses by a sudden increase in temperature, which consequently does result in rock's mechanical strength reduction and thermal spallation. The now softened hard rock may easily be drilled out with the optimized mechanical drill bit. This paper will discuss the results obtained from the fundamental investigation of rock breaking via thermal spallation and thermal rock softening and the requirements for putting LaserJet drilling into a full-scale drilling setup.

1. INTRODUCTION

Interest in geothermal energy resources has increased substantially over the recent years while it represents a large enough renewable resource that can be used to supply the high energy demand while having a minimal environmental impact. Geothermal resources tend to be found in deeper and harder geologic formations than typically found in hydrocarbon reservoirs and on the other hand drilling and completion processes, and costs tend to be the critical factor in making geothermal resources a technical and economical feasible energy source. Various economic studies show that around 50 to 70 % of the total investment needed to develop a geothermal resource comes from drilling costs alone(Lukawski et al., 2014; Petty, Livesay, Mansure, & Bauer, 2006). These costs are considerably higher for geothermal resources while the costs follow an exponential increase with depth (Tester et al., 2006), and noticeably the geothermal resources tend to be found in deeper and harder geologic formations than conventional hydrocarbon reservoirs.

Today's drilling methods still heavily rely on technologies based on conventional rotary drill bits to mechanically break the rock and thus, having to mainly overcome its high strength and, furthermore, requiring large amounts of energy and time. Drilling technologies and processes from the oil & gas industry have been continuously improved to make more efficient and economical drilling processes. However, drilling speeds or rates of penetration (ROP) of conventional drilling technologies suffer significantly in deep and hard formations(Gupta & Roy, 2006). Problems mainly include a very low rate of penetration (1 m / hr. or less), very high bit/tool wear-rates and thus, the low service life of, e.g., under 50 hrs.(Lukawski et al., 2014). These problems lead to numerous, lengthy, and expensive round trips and consequently, very high overall drilling costs. Therefore, there is a great need for tools with higher ROP and low wear rates to reduce drilling trip time and cost. Consequently, a reduction of the forces acting on the mechanical drilling tools must be attained to enhance drill bit service life and reach higher rates of penetration(Glowka, 1985).

Attempts to develop alternative, novel drilling technologies such as microwave (Hassani, Radziszewski, & Ouellet, 2008; Jerby, Dikhtyar, Aktushev, & Grosglick, 2002; Jerby et al., 2014), electro-plasma (Bazargan, Jalalifar, Koohian, & Habibpour, 2013; Gajdos, Kristofic, Jankovic, Horvath, & Kocis, 2015; Gajdos et al., 2016), hydrothermal spallation(Augustine, 2009a), electro-impulse(Schiegg, Rødland, Zhu, & Yuen, 2015; Voigt & Anders, 2016), and LaserJet drilling(S Jamali, Wittig, & Bracke, 2017; Shahin Jamali, Wittig, & Bracke, 2018) has been taking place worldwide in the past 20 to 30 years to overcome the latter problems by delivering more and different energy to the bit and break the rock more efficiently (Tester et al., 2006)

International Geothermal Centre in Bochum is investigating innovative thermal drilling technologies, especially mechanically assisted LaserJet drilling while the concept of LaserJet drilling being based on laser-induced thermal spallation and rock softening. The presented study aims at demonstrating the application possibilities of LaserJet mechanically assisted drilling and its operational readiness through laboratory experiments. Thereby, the deeper understanding of rock properties, the physics of laser-rock interaction, spallation process and laser rock softening process and their transfer to practical applications have been presented and could be the vital building blocks of making laser-based thermal drilling, a technical and economical feasible drilling process.

2. THERMAL DRILLING METHODS

Thermal drilling methods mainly make use of heat to apply exert stress on the rock. Rock removal can be achieved either by melting, spallation, or vaporization. The use of thermal energy to apply stress on rock has the advantage that the need for direct contact between the tool and rock may be omitted which reduces the tool wear and thus, tripping times, and consequently overall costs significantly(Wideman, Sazdanoff, Unzelman-langsdorf, & Potter, 2011). Microwave, electro plasma, hydrothermal spallation, electro impulse and LaserJet drilling are currently the leading developing novel drilling technologies worldwide(Augustine, 2009b; Gajdos et al., 2015; Hassani, Nekoovaght, & Gharib, 2015; Jerby et al., 2014; Kocis, Kristofic, Gajdos, Horvath, & Jankovic, 2015; Potter, Potter, & Wideman, 2010; Schmidt, Janssen, & Brecher, 2017; Xu, Reed, Parker, & Graves, 2004).

2.1 Laser-Water-Jet (LWJ)

LASER is a physical principle which stands for "Light Amplification by Stimulated Emission of Radiation." The precise controllability of modern laser sources has enabled the possibility to deposit a predefined specific amount of energy onto the specimen surface by control of the laser irradiation time from milliseconds (pulsation) to continuous wave (CW) operation mode.

The high-power optical system used for the LaserJet Drilling research project consists of three main parts. A high-power diode-pumped ytterbium fiber laser (IPG YLS-30000), with an output power of up to 30 kW and beam wavelength of 1070 nm, has been used to generate the required laser beam. The operating power is dynamic and ranges from 10% to full power with no significant change in the beam divergence or beam profile throughout the entire range. Table. 1 summarizes the high-power laser generator specifications.

The central part of the optical system is the laser head. The laser head has been developed within the LaserJetDrilling project consortium with the purpose of high-power Laser-Water-Jet (LWJ) production. A high-power fiber optic cable is used to transport the laser beam from the generator to the laser head. Water and laser are fed through from the top part of the head, and the resulted water guided laser jet exists the other end of the head through a specially designed nozzle.

Table 1: High-power optical system specifications

CHARACTERISTICS	MIN.	TYP.	MAX.	UNIT
Operation Mode		CW / Modulated		
Polarization		Random		
Nominal Output Power	30000			W
Emission Wavelength (λ)	1068		1080	nm
Output power Modulation Rate			8	kHz
Red Guide Laser Power		0.4	0.5	mW

Laser-Water-Jet (LWJ) is used for the delivery of laser energy onto the rock surface. LWJ is defined as a laser beam coupled into a laminar water-jet using the physical principle of total internal reflection. The concept of coupling a laser beam into a laminar water-jet is illustrated in Figure 1. The focal point of a laser beam is focused through the coupling unit in which a laminar water jet is formed. After passing through the nozzle, the laser radiation is reflected at the phase-boundary and guided within the water-jet with a constant diameter. Water-jet diameter, and thus the laser spot diameter, remains constant until jet-breakup. By use of an LWJ, the working range of a laser beam compared to a conventionally focused laser beam can be increased significantly(Brecher, Janssen, Eckert, & Schmidt, 2016; Schmidt et al., 2017).

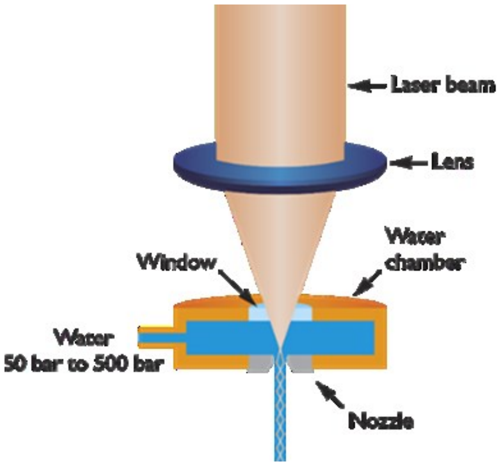


Figure 1: Water guided laser jet concept(Wagner et al., 2009)

2.2 Laser thermal rock softening and spallation process

The concept of LaserJet drilling is based on laser-induced thermal spallation and rock softening. As the laser beam hits the rock surface in a controlled manner, the induced temperature is intended to be in a range of 550 to 600 °C to stay in the spallation temperature zone and soften the rock at the same time.

Thermal spallation is defined generally as applying excessive rapid thermal energy, rather than mechanical stress and penetration, onto a rock surface resulting in thermal stresses that do initiate weakening of rock and results in fragmentation of the solid into spalls, which are disk-like flakes, by expanding the existing flaws in the rock structure. The spalls, which have an average size of 0.1 to 2 mm, will be dislodged from the rock surface and washed away utilizing cutting transport (Augustine, 2009a; Rothenfluh, 2013). Parallel to this process, the temperature is also one of the critical factors that have a significant impact on changing rock's geomechanically parameters. Thermally-induced high temperatures in the rock lead to the start of growing thermal stresses inside, which leads to propagation and expansion of micro-cracks and fissures. As temperature increases, the expansion continues and eventually reaches a point that the rock structure starts to weaken, and thermal softening occurs. It has been shown that granite softening process starts at 100°C and continues up to temperatures around 800 °C. The approximate reduction in uniaxial compressive strength is in range of 10, 15 and 80 % for temperatures of 100, 600 and 800 °C respectively (Chen, Ni, Shao, & Azzam, 2012; Ezzedine, Rubenchik, & Yamamoto, 2015; S. Jamali, Wittig, & Bracke, 2019; Keshavarz, Pellet, & Loret, 2010; Pinińska, 2007; Sygała, Bukowska, & Janoszek, 2013).

Error! Reference source not found.2. shows the primary function of the process, with the laser beam being the thermal energy delivery system. The spallation process may only occur if, (a) the sample material has existing flaws or weaknesses. (b) The process begins with the surface of the material starting to expand as heat is applied across its surface and causes the flaws and fissures in the material to grow, (c) the induced thermal stresses start to grow and results in buckling of the upper surface. (d) The material begins to be stressed compressively, but it is the tensile stress applied at the edges being responsible for forming spalls, which leads to the final failure and ejection of the spall(Preston & White, 1934).

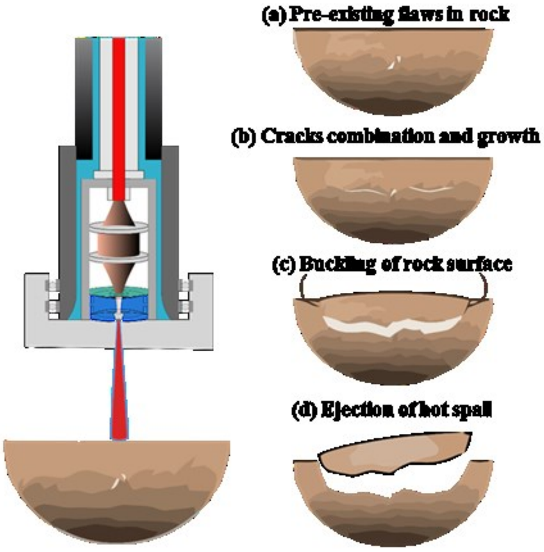


Figure 2: Thermal spallation process mechanism induced by laser(S. Jamali, Wittig, & Bracke, 2017)

3. LASER-ROCK INTERACTION EXPERIMENTAL METHODS

Laser-rock interaction tests have been conducted to study the interaction between the water-guided high-power laser beam and multiple rock types during the occurrence of thermal spallation and thermal rock softening processes. Results of the experiments have led to the understanding of the LaserJet rock destruction process and obtain the necessary data to enable LaserJet drilling in field-scale efficiently. The main investigated rock types included Grimsel granite, Quartzite, Obernkirchener Sandstone.

In order to minimize the effects due to boundary conditions, sample thickness, and global cracking during the experiments, the regions of the rock sample which undergo thermal spallation process must be confined. This issue has been overcome in this study by having a relatively large rock mass and applying additional artificial confinement pressure. Consequently, the samples had been prepared as blocks of 150x150x150 mm, and each sample have been clamped by two half-cylindrical aluminum blocks to bring the required confinement pressure to the rock.

The laser experiments for both thermal spallation and rock softening have been set up and carried out in a test-stand as is schematically shown in Figure 3. The synchronous control of the laser source and axis system allows predefined automated tests to be carried out. The experiments were observed visually via a camera with a filter matching the laser radiation wavelength. A pilot laser beam was connected permanently to enable detecting disturbances of the water jet during and after the experiments.

The laser-rock softening results presented in this study were obtained using the same laser test stand and in addition the scratch testing device which was developed during the course of this research project based on multiple conducted research studies(Adachi, Detournay, & Drescher, 1996; Detournay, Drescher, Defourny, & Fourmaintraux, 1995; Detournay, Drescher, & Hultman, 1997). The schematics of the scratch test setup is also illustrated in Figure 3. The setup consists of a sample housing, the cutting element, force measurement system, and a three-axis positioning system. The force measurement system consists of three independent force sensors that are required to measure the forces during the rock scratching process. Both force components are monitored and measured during the process by use of three independent force sensors pre-installed in the sample housing. One sensor is installed parallel to the cutter movement direction to record the tangential force, and two sensors are installed perpendicular to the movement, so they can measure the normal force along the length of cutting.

The force sensors are connected to a data acquisition system which is connected to a laptop computer. Monitoring, test control, and data acquisition are performed from the computer using software written in MATLAB environment. The scratch test setup is kinematically controlled via a three-axis table on which the sample housing is mounted.

The axis system is used consequently to adjust the cutter position, the cut length, and the depth of cut. The dimensions can be adjusted with a precision of 0.1 mm. The cutter speed can also be adjusted to multiple predefined steps. The movement control and measurement system use a stepper indexer and a power supply. The cutting element consists of the cutter and the cutter holder. The cutter holder accepts replaceable drill bit studs. Hard metal drill studs of 12 mm width have been used for the purpose of this study. From the measured cut length, the applied laser energy could be calculated based on the laser treatment parameters. The force measurements, as were described earlier, will be used for specific energy and drilling strength calculations.

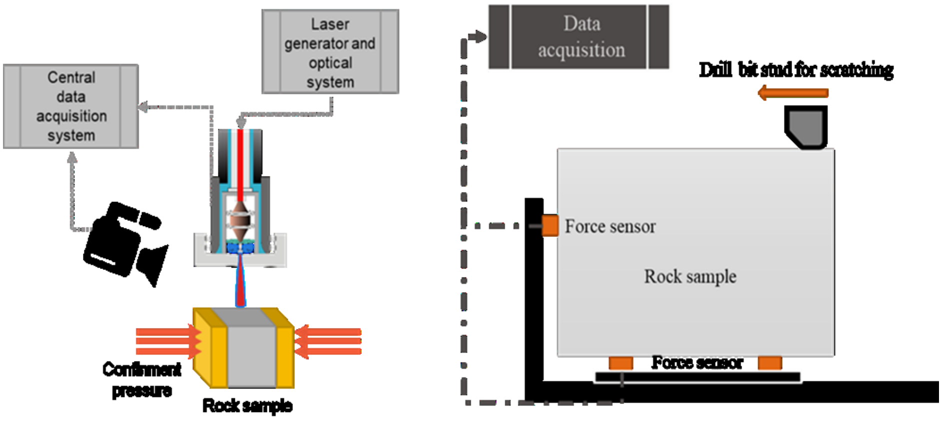


Figure 3: schematically illustration of (left) LaserJet lab drill test stand including Acoustic emission and visual data acquisition system and (right) the scratch test setup including sample housing, cutting element, force sensors and data acquisition system

4. RESULTS AND DISCUSSIONS

Multiple types of experiments have been designed and carried out stepwise to study laser-rock interaction. In each step, one of the possible parameters affecting the LaserJet-rock interaction has been studied from primary to complex parameters. The considered parameters have been studied regarding a single pulse, lines, and circles include

- Energy requirements (spallation, melting, and vaporization zones)
- Discharge type (continuous and pulsed)
- Radiation time
- Peak power
- Power intensity
- Repetition rate
- Rock sedimentation orientation

As the Laser cartridge generates the LaserJet, the thermal spallation, and rock softening processes begin and will eventually result in weakening, penetration, and ejection of hot spalls from the rock surface. The subsequently treated surfaces have been evaluated and analyzed accordingly.

Over 1,000 conducted experiments have led to multiple lased, treated surfaces and destructed holes, which all have been precisely evaluated, quantified and analyzed via acoustic emission signals, scratch testing system and 3D microscopic measurements through self-developed codes.

In each series of experiments, one of the possible parameters which could affect the laser-rock interaction has been studied from primary to more complex parameter combinations. In the first step, as the laser head generates the LaserJet based on the pre-defined parameters, the rock gets treated with the laser beam latter to laser-rock interaction which may eventually result in thermal spallation and rock softening. The subsequently treated rock surface has been used in the scratch test setup to evaluate and quantify the softening effect in each parameter combination and has also been analyzed through 3D microscopy to evaluate the thermal spallation effects. It should also be noted that the scratch tests have also been carried out on not lased rock samples to obtain the values needed for benchmarking the rock softening effect outcomes. The benchmark scratch test experiments have been conducted using various depths of cut values to also fully obtain the values needed for comparison between softened and so-called un-softened rock samples.

The benchmark tests on Quartzite rock samples have been unsuccessful due to the very hard nature of the rock. Consequently, there have been theoretical baseline values included in the results for this rock type based on the obtained results from rock characterization experiments and the other two rock types. The evaluated, resulting variables from the scratching process include the rock strength (drilling specific energy), the laser-treated rock fracture toughness, and the drilling strength.

The thermal spallation evaluated and studied variables include removed depth (gradient), laser affected area, removed volume, specific energy (SE), specific kerfing energy (SKE) and rate of penetration (ROP). SE for every parameter combination has been measured and calculated. SE is defined as the energy required to remove a specific unit volume of rock and is being used to compare different rock removal processes (Altindag, 2003). For the purposes of this study, the SE values have also been used to compare the intended novel LaserJet drilling process to other drilling methods.

Figure 4 shows examples of thermal spallation specific energy calculation results for all three studied rock types. Figure 4 is illustrated based on SE values versus various radiation times conducted with constant 7 kilowatts of laser power under fixed beam size of 2.0 millimeters, and the right diagram shows the SE values as a function of laser power applied at a constant exposure time of 175 ms.

The SE results for the stated fixed values were chosen based on the evaluation of the overall results from all conducted experiments, identification of the physical reaction through the occurrence of spallation or melting process in the generated holes. A thermally melted hole is defined as a hole that has shown signs of melted deposits inside and in surrounding edges of the hole, in contrast to a thermally spalled one that has a clear hole without any sign of melted deposits.

The constant power SE graphs show that all the rock types had low SE values for short irradiation times. The SE values get decreased by increasing the radiation time at a constant power until 150 ms (Figure 4). It could be an indication that the rock removal process is in the spallation zone, which was eventually confirmed by visual inspection of the generated holes. After 150 ms of irradiation time, the SE starts to increase, meaning that the mechanism has gradually started to shift to a combination of spalling and melting.

There are high SE values at very low powers (4 kW), as can be seen in Figure 4, since the energy absorption has been only high enough to heat the rock thermally and partially fracture it, resulting in the high SE values for rock removal. It should be noted that the SE values for Grimsel granite show an increase from 4 to 5 kW power. The reason behind it is mostly due to the high heterogeneity of this rock type resulting in variable laser beam absorption levels on the rock surface. As the power is increased at a constant irradiation time, a larger volume of rock could get influenced, fractured, and removed. Therefore, as it can be seen in Figure 4, the SE values start to decrease. This trend continues until the possible start of the rock melting process. The transition from pure spallation to melting process can be seen by the sudden change in the slope of the graphs.

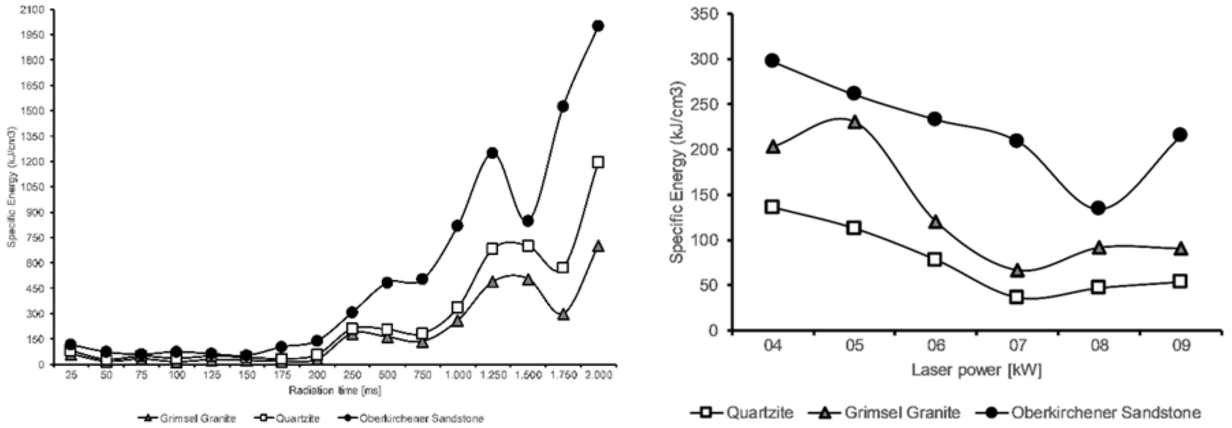


Figure 4: SE values versus irradiation time at a constant power of 7 kW (left) and SE values versus laser power at a constant irradiation time of 175 ms (right)

The rock softening experiments' results overview is presented in Figure 5, which represents the results for rock strength as the studied geo-mechanical parameter on all the studied rock types. The figure consists of three principal graphs representing each rock type. Each point on the graph represents an average of the obtained values from multiple conducted experiments in the corresponding experiment type. Examination of the CW rock softening experiments' results shows that the rock softening phenomenon is happening in all the studied rock types. Comparing the untreated samples' baseline values with the CW laser-treated results show that the rock strength value has been reduced by 58, 33, and 60 percent on average for Grimsel granite, Obernkirchener sandstone, and Quartzite samples respectively. The minimum and maximum softening effects on strength reduction have been 5 and 92 percent for granite samples, 5 and 62 percent for the sandstone samples, and 29 and 96 percent for Quartzite samples, respectively.

The pulsating laser treatment results show that the pulsating laser beam is also capable of inducing rock softening in all three rock types. Comparison of the baseline and the laser treatment experiments' values show that the rock strength values have been reduced by an average of 68, 56, and 76 percent for granite, sandstone, and Quartzite samples due to pulsating laser beam treatment softening effects, respectively. The minimum and maximum impact of rock softening on strength values reduction have been 15 and 98 percent in granite samples, 21 and 92 percent reductions in sandstone samples, and 25 and 99 percent in Quartzite samples, respectively.

It should be noted that the Quartzite rock is so hard that it had been almost impossible to mechanically scratch (penetrate) it. However, the laser treatment has resulted in a significant softening in Quartzite samples, which have led to transforming them into a "soft," scratchable (drillable) state. The significance of softening in Quartzite goes as far as reducing the rock strength to almost zero in pulsating experiments.

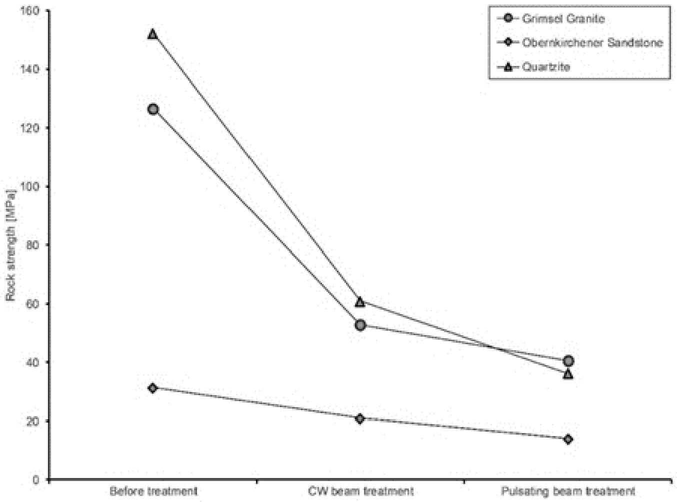
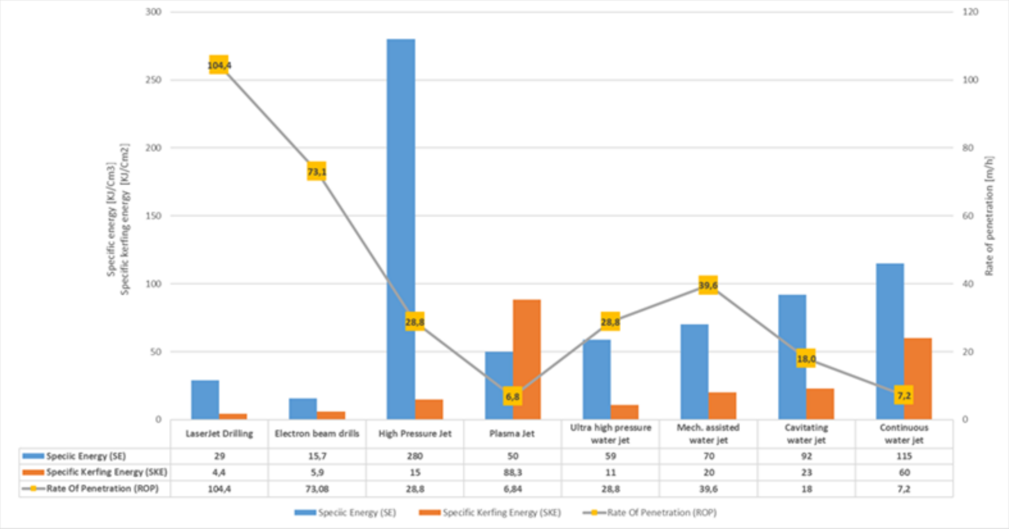


Figure 5: Laser-induced thermal rock softening results overview

Detailed examination of CW and pulsating treatment experiments results indicate that the average reduction in the mentioned geo-mechanical parameter value is more significant in pulsating beam treatment compared to the CW beam treatment experiments, which makes the pulsating laser treatment a more suitable candidate to be applied in combined laser-mechanical drilling applications.

A comparison has been made between LaserJet drilling (LJD) and other rock drilling processes (Figure 6). The x-axis represents the classification of novel drilling methods. The initial lab tests were conducted to understand the technical feasibility of LaserJet drilling on hard rocks by using a LaserJet rather than a conventional laser beam and being able to compare its efficiency to other novel drilling methods. In total, the SE and SKE values for LJD shows that wider and deeper holes may be created with the use of LJD compared to other drilling methods.

It can be deducted from Figure 6 that by applying higher power intensities and having relatively low specific energy values, high rates of penetration ranging from 2 to 15 times more than other methods can be achieved in an energy-efficient manner (Altindag, 2003; Graves, Anibal, Gahan, & Parker, 2002; Kollé, 1999; Nixon & Schumacher, 1971; Summers & Henry, n.d.). Low SE and SKE values for LJD do represent the fact that with lower applied energy values compared to other methods, a more prominent rock sample surface may be affected and consequently removed.



	LaserJet Drilling	Electron beam drills	High Pressure Jet	Plasma Jet	Ultra high pressure water jet	Mech. assisted water jet	Cavitating water jet	Continuous water jet
Speciic Energy (SE)	29	15,7	280	50	59	70	92	115
Specific Kerfing Energy (SKE)	4,4	5,9	15	88,3	11	20	23	60
Rate Of Penetration (ROP)	104,4	73,08	28,8	6,84	28,8	39,6	18	7,2

Figure 6: Novel drilling methods comparison based on SE, SKE and ROP values

5. CONCLUSION

The application of high-power laser for drilling processes has been investigated and demonstrated in this study through the analysis of laser-rock interaction.

The initial research results proved that (deep and hard) reservoir rocks can be drilled either by using a high-power laser through spallation, melting, or vaporization with thermal spallation proven to be the most efficient thermal rock removal in combination with transformation mechanisms through rock softening of various type of rocks including hard and very hard rocks into a drillable state using a high-power laser through thermally-induced rock softening.

The extensive experiments plan was developed to study the laser-rock interaction and material removal process under various laser and rock conditions. Over 1000 experiments were conducted where the laser and rock conditions were varied. The final tests were performed on the Obernkirchener sandstone, Grimsel granite, and Quartzite.

The thermal rock softening results proved to be very promising. As an example, the strength of the softened granite sample could be successfully reduced to nearly the strength of an untreated sandstone. It indicates the potential of such a softening process for drilling applications in hard, abrasive rock formations.

The overall analysis of the results suggests that application of thermal spallation and thermal rock softening allows to efficiently facilitate a combined laser mechanical-assisted drilling system with a possible increase in the rate of penetration of the cutting tool with reduced drilling torque and weight on bit requirement and therefore having a lower energy consumption. Additionally, the drilling costs could be noticeably lessened by improving the drill bit life and reducing the overall drilling time.

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