Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geo-Drill: Development of novel and cost-effective drilling technology for geothermal systems

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Keywords: Geo-Drill, geothermal, drilling, DTH, materials and coatings

ABSTRACT

Geothermal is one of the most under-utilized renewable energy sources due to relatively higher investment costs, less certainty of output and longer development cycle. One of the major elements contributing to the overall cost in any deep geothermal project, is related to the drilling of production and re-injection wells. Cost increases result from increased drilling depths, longer tripping times (higher Non-Productive Times), potentially harsh environments, uncertainties of lithologies and potentially poor "resource" qualities (Temperature, Permeability). It is estimated that drilling costs contribute between 30 and 70% of the overall expenditure of a deep geothermal project. The project Geo-Drill (Funded under the EU's H2020 programme, Grant agreement no 815319) is focused on the development of a "holistic" drilling technology that has the potential to drastically reduce the cost of drilling to large depths (5km or more) and at high temperatures (250°C or more). The scope of Geo-Drill is: a) to develop and test advanced materials and coatings in simulated geothermal environments for drilling components, including graphene oxide based materials, cermet coatings, Nickel alloy coatings, nanocrystalline/amorphous coatings, high entropy alloy coatings etc., b) to test and validate new designs and joining technologies for components such as drill bit, tool joint, etc., c) to design and manufacture a prototype 4 inch DTH mud hammer integrated with drill monitoring system based on 3D printed sensors combined with simulators, d) test and validate prototypes in laboratory environments, followed by field testing and validation at IEG-Fraunhofer's test site in Bochum, Germany. In this paper, developments in the early stage of Geo-Drill related with novel materials and coatings, new DTH mud hammer design are being reported.

1. INTRODUCTION

To meet the challenge of future energy demands, the European Commission has created several energy policies, aiming to increase the share of renewable energy sources (RES) to at least 27% of the total energy consumption by 2030 and 55% by 2050. The share of electric energy consumption from RES is predicted to increase significantly, reaching as much as 97% by 2050 [1]. Geothermal energy intends to significantly increase its importance within the energy mix, offering advantages of base-load supply of electrical generation, direct heat and Combined Heat and Power (CHP), independent of variable climatic conditions compared to some other renewables (notably wind and solar). Worldwide electricity production from geothermal increased from 6833 MWe (megawatts electric) in 1995 to 9966 MWe in 2008, and direct use in 2005 displaced more than thirty million barrels of oil [2].

Deep Geothermal, however, remains one of the most underutilised renewable resources, despite some of the clear advantages it has. This stems, in part, from its relatively high upfront costs, making it currently more cost-effective in geologically active regions, where hydrothermal systems are present such as Northern Italy, Turkey, Iceland, etc.. A major factor of the cost in any geothermal project is related to the drilling procedure, where the cost increases in proportion to the drilling distances, tripping times, harsher environments associated with high temperatures, pressures and the corrosive geothermal fluid, including reduced information of lithology. It is estimated that the drilling costs contribute between 30 and 70% of the overall expenditure of a deep geothermal project [3]. According to a Gas Research Institute (GRI) study conducted in 1990, 48% of the drilling time of a typical well is spent on drilling the well, 27% of the time spend changing bits or putting tubular casing in place, and 25% of the time spent measuring well and formation characteristics [4]. Therefore, major cost reductions would result from increasing the overall rate of penetration (ROP), by reducing the need for tripping through improved component life (e.g. bits and hammers) as well as by enabling superior sensor data measurements while drilling to make better real-time decisions, optimizing drilling efficiencies.

The objective for Geo-Drill is to develop an 'holistic' drilling technology that has the potential to reduce the cost of drilling to large depths (5km or more) and at high temperatures (250°C or more). Four main scopes are covered: a) to develop and test advanced materials and coatings in simulated geothermal environments for drilling components, such as graphene oxide based materials, cermet coatings, Ni alloy coatings, nanocrystalline/amorphous coatings, high enthalpy alloy coatings etc., b) to test and validate new designs and joining technologies for components such as drill bit, tool joint, etc., c) to design and manufacture a prototype 4 inch DTH mud hammer integrated with drill monitoring system based on 3D printed sensors combined with simulators, d) test and validate prototypes in laboratory environments, followed by field testing and validation at IEG-Fraunhofer's test site in Bochum, Germany. This paper reports technologies involved and preliminary findings from early stage of the project, including failure mode and effects analysis (FMEA), development of advanced materials and coatings and concept of Geo-Drill DTH mud hammer.

2. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Components working in the geothermal drilling environment have to face repeated impact, abrasion, erosion and wear from rock breaking, cuttings, corrosive environments etc., resulting in lower lifetime. Worn out/damaged tool needs to be replaced by tripping; physically pulling the drill system out of the wellbore and then running it back in. These problems can result in risk and economic loss due to reduced overall ROP and increased non-productive time (NPT), and even loss of well/hole. For example, tripping can take up to 1.5 days costing €25,000 per day in delay cost. It is one of the main reasons of the increases of the levelized cost of energy (LCOE). To achieve the Geo-Drill goal of LCOE reduction it is imperative that the lifetime of different drilling tools should be increased. Therefore, Failure Mode and Effects Analysis (FMEA) was carried out, rating failure modes to identify the most vulnerable tools with shorter lifetimes, understanding causes of failures and the effects failures have on operational efficiencies.

The FMEA focused on effects caused by fatigue, vibration, abrasion, corrosion, wear and erosion in geothermal well drilling systems. Geothermal drilling in hard rock aggravates the operating conditions for materials used to fabricate downhole drilling tools. The unfavourable geological conditions and the repeated impact for breaking the rock also cause damages. Material types, grades and possible treatments (heat, nitriding, carburisation etc.) are identified, as most current failures, are due to poor quality materials, QA/QC and finishing processes. The FMEA has been summarised based on Severity (S), Occurrence (O), Detection (D) and Risk Priority Number (RPN) for drill bit and hammer assembly (Table 1, Table 2). The most serious forms of damage for drill bit can occur for a number of reasons, including wear, fracture, failure of the striking/anvil face, shank failure and drill body/matrix failures. The failure mode with the highest RPN value is drill bit insert wear that occurs when a compressive stress on the joint surfaces between the insert and the abrasive particle exceeds the breaking strength of the abrasive particles. The most serious forms of hammer assembly include but are not limited to anvil failure, chuck body nut failure, chuck nut thread failures, cylinder (internal sleeve), hammer back head/body, piston and valve failures. The most critical failure mode is hammer body fatigue, stress cracks and thread breakage. This analysis suggests that protections from fatigue, vibration, abrasion, erosion and corrosion are needed for geothermal well drilling tools, and also provides a strong basis to estimate the effect such solutions would have on the system. The results of the FMEA are intended to be used to support and further determine the applicability of using the novel technologies developed in this project to reduce geothermal well drilling cost by increasing the rate of penetration (ROP) and by improving component life, thereby reducing the need of tripping (process of pulling the entire drill string).

Table 1: The FMEA for drill bit based on the highest rated answers

Process Step/Input	Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			
Bit Body/Matrix Failure	Breakage of body.	Possibility of bit jamming if bit breaks into large piece(s). Loss of well, if body failure cannot be fished or milled out.	9	Poor quality materials. Erosion of body, by formation/flushing. Incorrect handling/operation	5	QC/QA of body materials. Care not to overrun bits (do not exceed anticipated design life). Handle correctly.	4	180	45
Bit Shank Failures	Shank of bit fails, leaving majority of bit in the well.	Fishing operation, sidetrack or loss of well.	9	Overheating of shank. Material defects. Poor manufacturing process.	5	Material inspections.	9	405	45
Failure of Striking/Anvil Face	Stress cracking, breakage of striking face.	Hammer becomes inoperable, possible major damage to hammer. Bit shank failure. Fishing operation or loss of hole.	9	Overheating of shank. Material defects. Poor manufacturing process.	5	None.	10	450	45
Insert Failure	Breakage	Premature failure, damage to bit matrix/body. Lower/loss of penetration. Increased tripping or inefficient drilling and number of usable teeth reduces	8	Poor quality inserts (sintering issues). Incorrect insertion of inserts into bit body/matrix. Fractured formations, improper usage/operation. Change in rock formation / local drilling conditions etc	7	Use of high quality inserts (high quality sintered carbides or PCD inserts) Operator training, attention to drill monitors.	5	280	56
Insert Wear	Premature wear	Loss of hole gauge, reduced ROP. Increased tripping time	9	Abrasive formations, improper operation. Poor quality Inserts	8	Correct selection of inserts. High strength sintered carbides required with good cohesive strength. Proper operation. Attention to drill monitors, to avoid excessive insert wear and possible wellbore problems	9	648	72

Table 2: The FMEA for the hammer assembly based on the highest rated answers

Process Step/Input	Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			
Anvil	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	5	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	225	25
Chuck nut body failure	Excessive wear due to erosion of body material.	Loss of bit. Break-up of chuck, leading to drill string becoming stuck.	9	Poor materials. Improper flushing of cuttings. High velocity of cuttings in tight annulus. Turbulent flow around bit/chuck.	5	QA/QC of materials. Visual inspection between runs.	9	405	45
Chuck nut threads	Failure of threads at root of male section	Loss of bit. Fishing operation. Possible loss of well.	9	Incorrect torque setting of chuck into hammer body. Erosion of chuck body. Poor materials.	6	Torque monitors. Visual inspections, between runs. QA/QC	7	378	54
Cylinder (internal sleeve)	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	4	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	180	20
Hammer Back Head	Failure of male thread connection into hammer body and failure of male thread into drill string.	Loss of hammer. Loss of well.	10	Poor quality materials/manufacturing process(es). Incorrect handling, during make-up/break-out. Erosion from cuttings.	6	QA/QC of materials. Visual inspection between runs. Operator training.	8	480	60
Hammer Body (External Casing)	Fracture and stress cracks. Breakage of (female) threads.	Failure of hammer. Loss of well.	10	Poor quality materials/manufacturing process(es). Incorrect handling, during make-up/break-out. Erosion from cuttings.	7	QA/QC of materials. Visual inspection between runs. Operator training.	5	350	70
Piston	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	5	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	225	25
Valve	Stress Fracture	Loss of drilling time, through tripping out/in.	4	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	4	QA/QC of materials. Visual inspection between runs. Operator training.	4	64	16

3. DEVELOPMENT OF ADVANCED MATERIALS AND COATINGS

Improving performance of materials or applying a surface protection to drilling components are the two most efficient methods that can be used to improve component lifetime. To seek suitable protection/strengthening approaches for drilling components for the geothermal drilling environment, a wide range of materials and coatings are being explored and optimised in Geo-Drill. The aim is either, to improve the properties of drilling components against erosion and corrosion, or to reduce their friction performance in sliding hammer parts.

3.1 Graphene oxide (GO) modified material and coatings

Graphene Oxide (GO) is a 2D material synthesized by the strong oxidation of graphite. During the oxidation process, oxygenated functionalities such us hydroxyls, epoxides and carboxylates are introduced in the graphite structure making the material hydrophilic, compatible with a wide range of matrices and very versatile. On the other hand, the increase of the interlayer distance makes the interaction between flakes weaker, facilitating exfoliation in water to monolayer flakes; known as graphene oxide. The main advantage of the use of graphene oxide is the low loading needed for enhancement of properties. This is a consequence of the main characteristics of the nanomaterial: its flake shape, high Brunauer–Emmett–Teller (BET) surface area and high aspect ratio that enable a strong interaction between the graphene material and the matrices.

Geo-Drill aims to improve the tribological properties of materials such as tungsten carbide (WC) and PTFE (Polytetrafluoroethylene) coatings by the addition of this novel nanomaterial. In the case of WC bulk material, a ball milling process was being optimized to successfully mix WC powder with GO. As it can be observed from Figure 1, GO sheets were well adhered on the WC particles. After parametrization, bulk pieces were fabricated through sintering. In the WC-Co matrix, the cobalt binder phase that appeared as a darker region in the SEM backscatter mode micrographs became more apparent after sintering (Figure 2). This change in microstructure resulted in an unmeasurable wear rate after a dry sliding wear test with a counter chromium steel ball. Large abrasive wear scars were observed on the counter chromium steel surfaces under an optical microscope. The scar diameter of the WC-Co bulk material doped with GO was found to be approximately twice the diameter of the scars on the ball in contact with the pure WC-Co material.

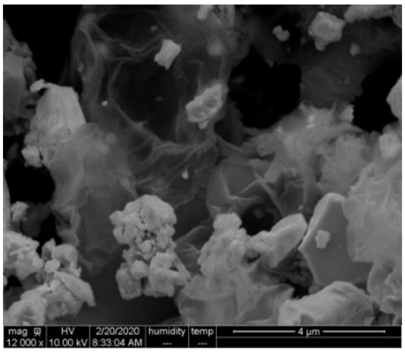

Figure 1: SEM image of WC powder mixed with GO through ball milling process

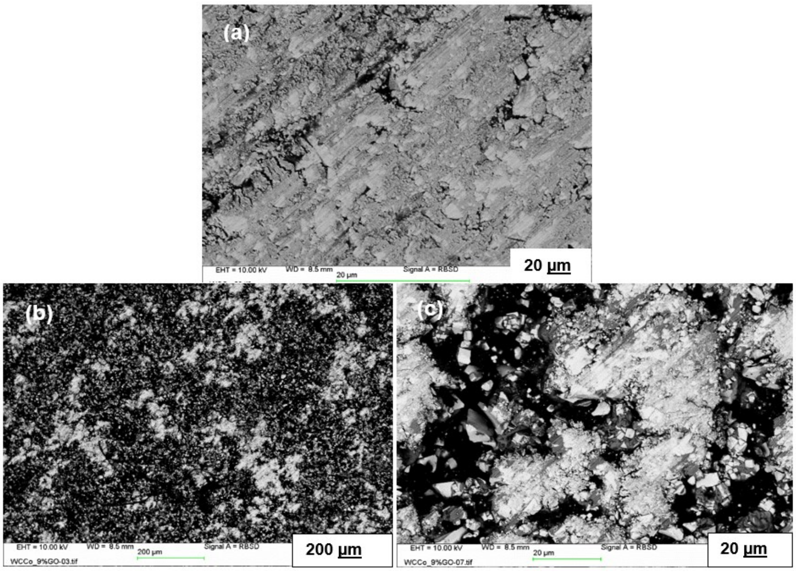

Figure 2: SEM analysis under back-scattered mode of WC-Co bulk material: (a)WC-Co, and (b), (c) WC-Co+9wt%GO.

GO modified PTFE coatings were also developed from a commercial coating that is already used in oil and gas industry, called Xylan G5844. Both GO and reduced GO (a more thermally stable variant) were tested, the former was selected as the best candidate due to its better compatibility. Then mixtures were prepared by using a high shear mixer (Dispermat) by varying GO additions (0.5, 1.0, 2.5 and 5.0 wt%), velocities and times. Generally, a higher GO amount increases the viscosity of the mixture and makes it difficult to process. Preliminary testing results show that the developed GO-PTFE coating with small fractions of the GO reinforcement is the most promising. Increasing amount of GO nanoparticles, lead to the formation of defects during the polymeric coating process, i.e., for 2.5wt and 5wt% GO samples cracks formed as can be seen in Figure 3. A drastic reduction in friction coefficient was observed for Xylan+0.5wt%GO on a coated carbon steel from 0.55 to 0.13 during a sliding wear test. Accordingly, the corresponding wear rate of the coating was 10-fold lower compared to the carbon steel substrate.

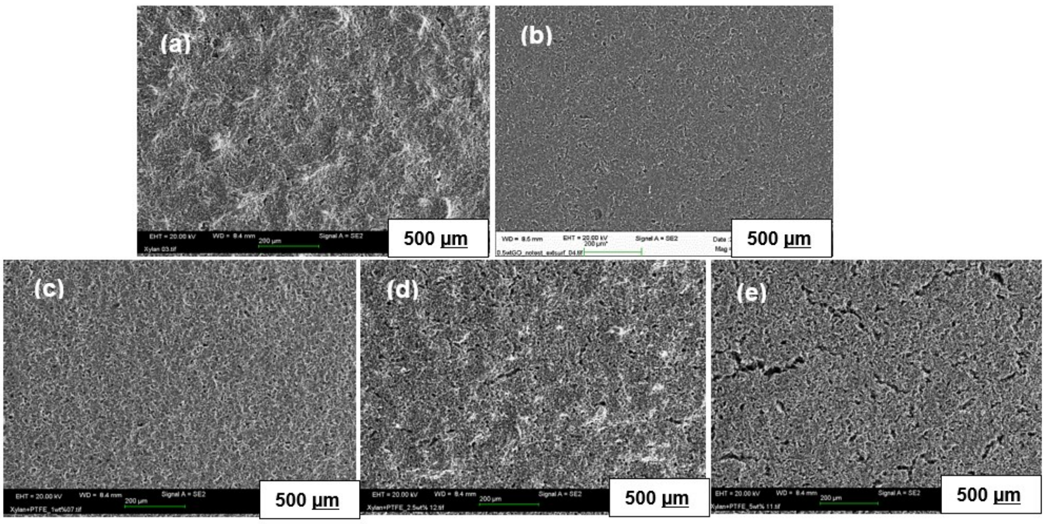

Figure 3: SEM analysis developed GO coatings in Geodrill: (a)Xylan coating, (b) Xylan+0.5wt%GO coating, (c) Xylan+1wt%GO coating, (d) Xylan+2.5wt%GO coating, and (e) Xylan+5wt%GO coating

3.2 Thermal sprayed cermet and alloy coatings

The thermal spray process is the most versatile modern method for surface coatings in terms of economics, range of materials applied and protected, and the scope of application. It is therefore one of the most popular and successful techniques to deposit thick coatings as protective layers for hardfacing of drilling tools [5,6]. High Velocity Oxygen Fuel (HVOF) spraying is one of the most popular technique to deposit thick coatings for drilling tools among various thermal spray technologies. It works by mixing fuel and oxygen, feeding into a combustion chamber and being ignited. The combustion of gases produces a high temperature (2500-3200°C) and pressure in the chamber, which is ejected through a nozzle at supersonic speeds (Figure 4). The velocity may reach values near 2000m/s for HVOF, in contrast to approximately 100 m/s for flame spraying and 1000m/s for plasma spraying. This can result in dense and good adherent coatings [5]. HVOF is primarily used to deposit cements, metals and alloy coatings, such as WC-CoCr, WC-Ni, CrC-NiCr, Ni alloys and steels. HVOF also demonstrated capability in depositing dense ceramic coatings, such as hydroxyapatite, Al_2O_3, ZrO_2, Cr_2O_3. These coatings enhance surface properties of components to enable cost-effective and high-performance approaches. It is especially beneficial for materials with lower melting point and those that are subjected to thermal degradation at high temperatures.

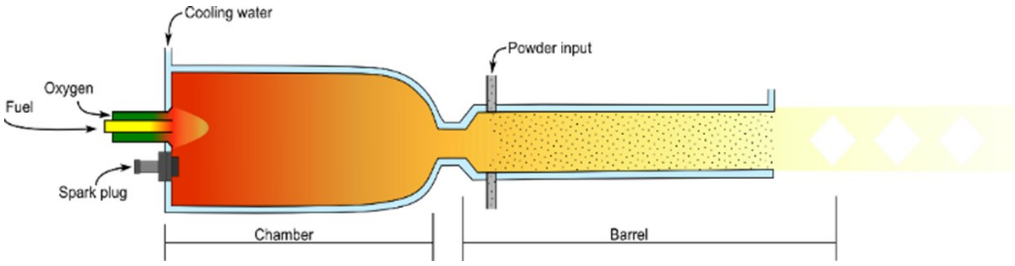

Figure 4: Schematic diagram of HVOF process

In Geo-Drill, a particular focus has been on developing cermet coatings and high strength alloy coatings through HVOF (JP5000), including tungsten carbide, chromium carbide, self-fluxing alloy, nanocrystalline/amorphous and high entropy alloy coatings. Those materials can cover a wide range of maximum servicing temperature from 500 to 820°C. Among those, many researchers have observed that WC coatings exhibited higher hardness, fracture toughness and therefore superior wear-resistant performance compared with other carbides. WC coatings deposited through HVOF benefit by having lower porosity and decarburization rate, high hardness and excellent wear resistance [7]. While WC based coatings are usually used below 500°C, Cr_3C_2 based coatings can service at temperatures up to 800°C and are commonly used in high temperature wear applications, offering superior oxidation and corrosion resistance [8]. Self-fluxing alloys contains substantial amounts of boron and silicon which possess the interesting property of 'self-fluxing'. Both additives react with oxides at high temperatures to form low melting point borosilicate which prevents further oxidation of active elements in the alloys [9]. It can also be blended with cermet particles for improved wear resistance while being able to perform at service temperatures up to 820°C. In addition to above materials, nanocrystalline/amorphous alloys and high entropy alloys (HEAs) are recently developed materials. Nanocrystalline/amorphous were investigated as a more economical alternative candidate for replacing cermet coatings. The mechanical properties of such material can be largely enhanced when size of crystallites becomes nanometric[10]. HEAs are defined to have at leave five elements that bring together unique properties. The high mixing entropy allows them to have a lower free-energy and higher phase stability.

Images of the microstructure of these developed coatings, taken during parameter optimisation trials, are presented in Figure 5. It can be observed that all the coatings adhere well along substrate surface profile, indicating good adhesion. Their porosity measured using at least 20 images according to ASTM E2109-01:2007 is 0.9±0.3%, 1.1±0.1%, 2.4±0.3%, 3.6±0.7%, 1.6±0.3% for WCCoCr, CrC-NiCr, self-fluxing (NiCrFeSiB), nanocrystalline/amorphous, high entropy alloy (CoCrFeNiMo0.85) coating, respectively. Hardly any pores could be observed for WCCoCr coating. The measured microhardness values on the polished cross section surface of these coatings ranged from 558 to 1218$HV_{0.3}$. Samples will be further tested in simulated geothermal drilling environment for evaluation in the next stage.

3.3 Electroless Nickel (EN) plating of PTFE composite coatings

Electroless Nickel (EN) plating can be used to deposit a uniform layer (or layers) of nickel-phosphorus with thickness ranging from a few µm to tens of µm on a base material (also referred to as substrate). It is particularly suitable for applying coatings uniformly on parts that have a complex and intricate geometry. It is a chemical process wherein a nickel-phosphorus alloy is deposited on a substrate using an aqueous solution, without the application of electric current. Properties of electroless nickel- phosphorus (ENP) coatings such as resistance to wear and corrosion, fouling, scaling (or their combination such as anti-corrosion and anti-scaling) can be tuned by optimising its microstructure. Specifically, by choosing the alloy chemistry, performing post-plating heat treatments, incorporating nanoparticles (that provide a specific functionality such as hydrophobicity, high hardness, and low coefficient of friction) into the matrix of the plated layer, or by applying a combination of them, ENP coatings can be tailored to provide optimum performance for a particular application.

A lot of hammer parts used in drilling operations for geothermal use low alloy steels, which are subjected to both wear and corrosion during their lifetime. ENP coatings with a homogeneous distribution of PTFE particles (<1µm) can potentially offer increased corrosion and wear resistance compared with low alloys steels, and can increase the tool life. PTFE particles have a very low coefficient of friction and high lubricity, and therefore offer increased wear resistance. The development of EN coatings in Geo-Drill includes depositing duplex ENP coatings onto steel substrates. Specifically, in order for ENP coating to adhere well to the substrate, an adhesion layer/bond coat/undercoat will be first deposited for improved adhesion strength, following functional EN layer containing a homogeneous distribution of PTFE particles (referred to as topcoat) on the top (Figure 6).

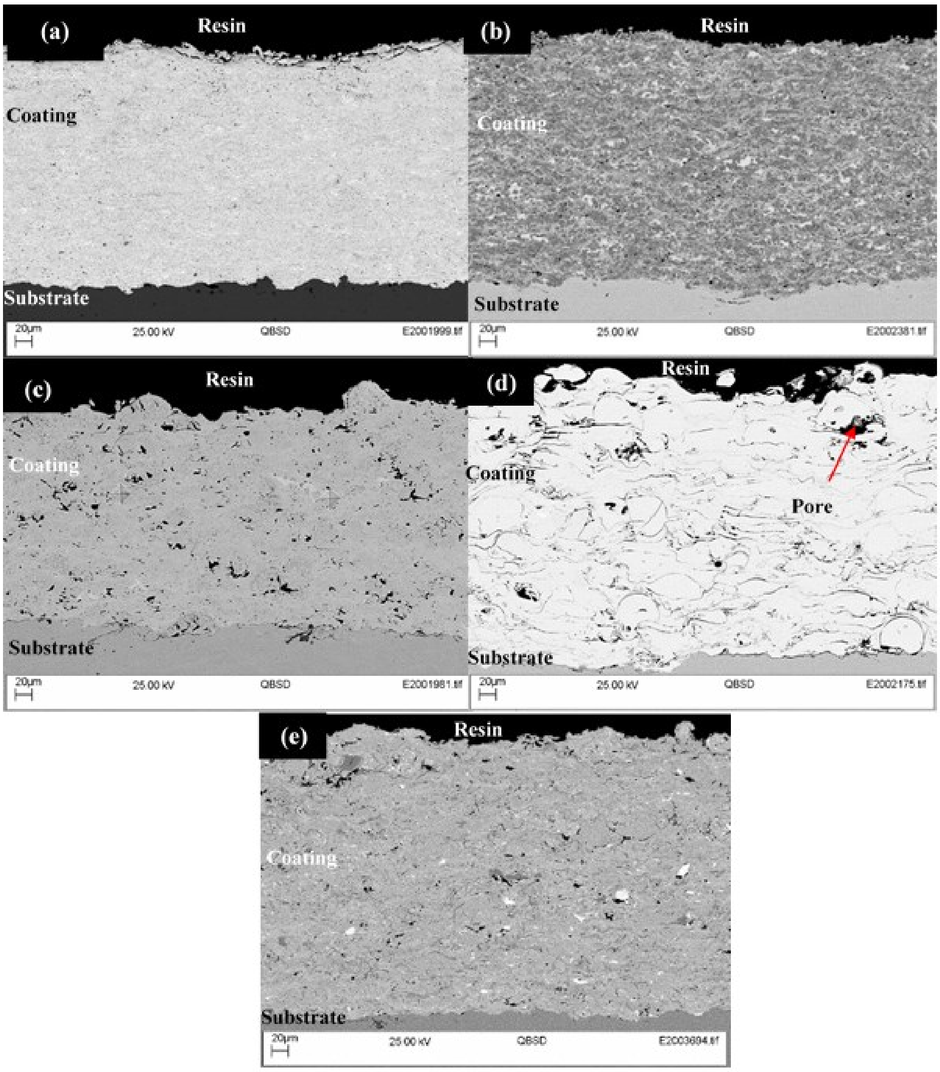

Figure 5: SEM analysis under back-scattered mode of developed HVOF coatings onto carbon substrate: (a)WCCoCr coating, (b)CrC-NiCr coating, (c) self-fluxing (NiCrFeSiB) coating, (d) nanocrystalline/amorphous coating, (e) high entropy alloy (CoCrFeNiMo0.85) coating

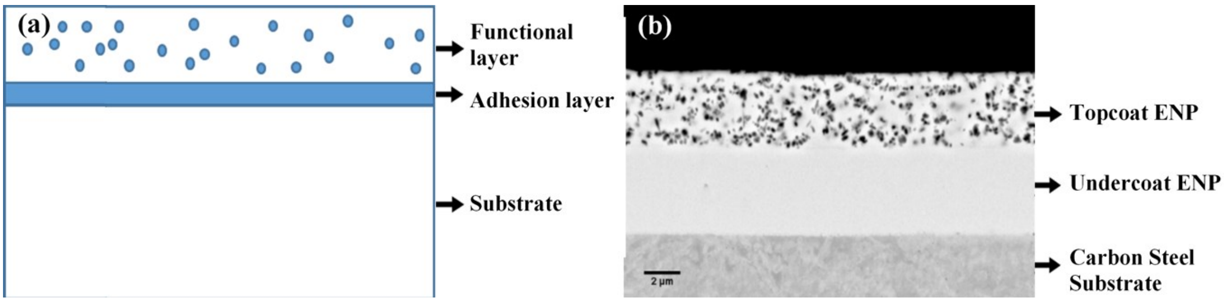

Figure 6: Duplex electroless nickel coating, with features within the functional layer represents PTFE particles: (a) Schematic image of the coating, (b) SEM image of coating deposited onto carbon steel substrate

4. NOVEL DTH MUD HAMMER ASSEMBLY

Traditional water/mud hammers, both commercial and research prototypes, have a) many components; b) direct mechanical contact between these components; c) very tight tolerances and gap dimensions. This contrasts with an innovative DTH hammers having:

- Very high reliability due to few moving mechanical parts. The probability of failure due to wear of such moving, mechanical parts is thereby reduced.
- Almost independent from environmental influences. A new piston control may be used independently of shocks, vibrations, accelerations and temperature. It is also functional under high pressures.

Design of Geo-Drill DTH mud hammer uses less parts and fluidic switches instead of a hard valve system inside the tool. It regulates fluid flow to the piston by reducing an oscillating outflow, which governs the reciprocating motion of the piston (Figure 7). The fluidic switch is fed by drill mud (green line) and distributes the flow to the outlet ports (red and blue line). These ports are connected to the percussion mechanism, which includes a cylinder with a pressure chamber at the top and bottom and a piston. By initiating pressure in the upper or lower pressure chamber, the piston alternates between the top dead (TD) and bottom dead (BD) position with a given frequency $fpiston$. Ideally, this piston movement describes a sine wave. When the piston reaches the bottom dead position, the lower pressure chamber is emptied, and the fluidic switch is triggered to change the outlet direction at the outlet ports. The mudflow is guided through the right outlet port (red line), pressure increases in the lower chamber and the piston is moved upward. Once the piston reaches the top dead position, the lower pressure chamber is filled completely with fluid and the upper chamber empty. Again, the switch is triggered to change the outlet direction at the outlet ports and the mudflow is guided now through the left outlet port (green line). The piston is moved downward and the cycle ends once it reaches the bottom dead position again. The fluidic switch and oscillating piston motion have been simulated as a two-way coupled fluid-structure interaction system using an Arbitrary Lagrangian-Eulerian (ALE) method [11] and parametric shape optimizations of typical switch geometries have been carried out using Large Eddy Simulation (LES) and surrogate-based optimization (SBO) combined with Genetic Algorithms (GA), see example results in Figure 8. Here, the LES and ALE simulations were carried out with the Flowphys software suite, while DAKOTA [12] was used for the SBO and GA.

In addition to the above, current DTH water hammers are not handling particulate flows well, for example insufficiently filtered re-cycled water or drilling mud, and are rather intended to be used with fresh water. Therefore, they are designed with relatively "small" flowrates (e.g. 600 L per drilled meter with a 4-inch hammer). Geo-Drill DTH mud hammer is designed to allow for particulates, i.e. re-circulated water or drilling mud, the needs for filtration are greatly reduced. Therefore, the design flow rates of Geo-Drill will be higher than in current commercial water-based DTH hammers. This, together with superior well cleaning capabilities enabled by using drilling mud rather than just water, especially additives such as for example polypropylene beads15, will greatly improve the cuttings transport.

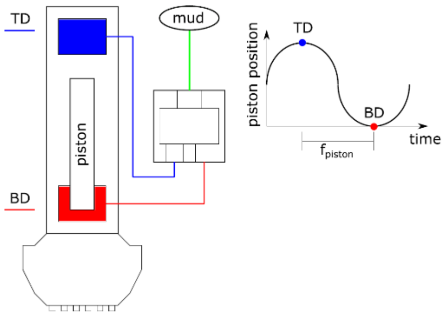

Figure 7: Implementation of fluidic switch in the percussion system of a DTH hammer

Figure 8: a) Simulation of fluidic switch and percussion system; b) Parametric optimization of a fluidic switch

Once design of a new percussion system is being optimised, selected advanced materials and coatings, together with selected joining technologies (e.g. HIP process and friction welding) that are currently under development will be applied on key parts of drilling system. This includes but not limited to drill bit, hammer parts, tool joint, stabiliser etc. A sensor and data acquisition system is also under development and will be integrated with drill string and hammer in a later stage of the project. The final Geo-Drill system will be validated through field testing in Bochum, Germany. It is hoped that success in the project could significantly improve lifetime of DTH drilling system with better performance for operating in the aggressive environments of geothermal drilling, hence the CAPEX and environmental load in terms of carbon and water footprint will be reduced from the reduced component replacement.

5. CONCLUSIONS AND FUTURE WORK

To reduce drilling cost while improving rate of penetration (ROP), a wide range of technologies are being explored in Geo-Drill. The failure mode and effects analysis (FMEA) were summarized based on both the highest severity and the highest value for the RPN for drill bit and hammer assembly, rating failure modes to identify the most vulnerable tools with short lifetime. Advanced materials and coatings were explored to seek suitable protection/strengthening approaches of drilling components, including GO modified bulk WC and PTFE coatings, HVOF coatings (WCCoCr, CrC-NiCr, self-fluxing (NiCrFeSiB), nanocrystalline/amorphous, high entropy alloy (CoCrFeNiMo0.85) coating), and electroless Ni-PTFE coatings. These materials can serve from room temperature up to 820°C, and to either improve erosion and corrosion resistance or reduce friction in sliding parts of drilling components. Geo-Drill DTH mud hammer was designed using fluidic switches instead of a hard valve system, to reduce moving mechanical parts and to enable using drilling mud.

At following stage of Geo-Drill, work will continue on testing and ranking the developed materials and coatings, optimizing joining technologies including HIP process and friction welding. Tool joint with new design will be investigated and manufactured, with capability of integrating Geo-Drill advanced monitoring system based on robust 3D printed sensors combined with simulators. In the final stage, a Geo-Drill system composing 4" fluidic hammer, enhanced 5" drill bit, 3.5" drill pipe, 4" stabilizer, and sensor string & data acquisition system will be validated.

ACKNOWLEDGEMENTS

The work is part of Geo-Drill "Development of novel and cost-effective drilling technology for Geothermal Systems", which is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 815319. The authors would also like to acknowledge the resources and collaborative efforts provided by the consortium of the Geo-Drill project.

REFERENCES

[1] European commission: Energy Roadmap 2050, (2011).

[2] Finger, J. and Blankenship, D.: Handbook of best practices for geothermal drilling, Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550, (2010).

[3] Dumas, P., and Antics M.:Report on Geothermal Drilling,. Ungemach, (2013).

[4] Gahan, Brian C, and Batarseh, S.: Laser Drilling - Drilling with the Power of Light. United States: N. p., (2004).

[5] MagnaniI M., SuegamaI P. H., ReccoII, A.; GuilemanyIII, J. M.; FugivaraI, C. S., and BenedettiI, A. V.: WC-CoCr coatings sprayed by high velocity oxygen-fuel (HVOF) flame on AA7050 aluminum alloy: electrochemical behavior in 3.5% NaCl solution. Mat. Res. 10, (2007), 377-385.

[6] Cheniti, B., Miroud, D., Hvizdoš, P., Balko, J., Sedlák, R., Csanádi, T., Belkessa, B., and Fides M.: Investigation of WC decarburization effect on the microstructure and wear behavior of WC-Ni hardfacing under dry and alkaline wet conditions, *Materials Chemistry and Physics*, **208**, (2018), 237-247.

[7] Cui, X., Wang, C., Kang, J., Yue, W., Fu, Z., and Zhu, L.: Influence of the corrosion of saturated saltwater drilling fluid on the tribological behavior of HVOF WC-10Co4Cr coatings, *Engineering Failure Analysis*, **71**, (2017), 195-203.

[8] Akhtari-Zavareh, M., Sarhan, A. A. D., Razak, B., and Basirun, W.: The tribological and electrochemical behavior of HVOF-sprayed Cr3C2–NiCr ceramic coating on carbon steel, *Ceramics International*, **41**(4), (2015), 5387-5396.

[9] Shieh, Y., Wang, J., Shih, H. C., and Wu, S.: Alloying and post-heat-treatment of thermal-sprayed coatings of self-fluxing alloys, *Surface and Coatings Technology*, **58** (1), (1993), 73-77.

[10] Cherigui, M., Feraoun, H. I., Feninehe, N. E., Aourag, H., Coddet, C.:Structure of amorphous iron-based coatings processed by HVOF and APS thermally spraying, *Materials Chemistry and Physics*, **85**(1), (2004), 113-119.

[11] Kjellgren, P. and Hyvarinen, J.: An arbitrary Lagrangian-Eulerian finite element method, *Computational Mechanics*, **21**, (1998), 81-90.

[12] Adams, B.M., Bohnhoff, W.J., Dalbey, K.R., Ebeida, M.S., Eddy, J.P., Eldred, M.S., Hooper, R.W., Hough, P.D., Hu, K.T., Jakeman, J.D., Khalil, M., Maupin, K.A., Monschke, J.A., Ridgway, E.M., Rushdi, A.A., Seidl, D.T., Stephens, J.A., Swiler, L.P., and Winokur, J.G.: Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.12 User's Manual, Sandia Technical Report SAND2020-12495, November 2020.