

Additively Manufactured Fracture Disk for Testing Shape Memory Polymer Based Lost Circulation Material for Geothermal Applications

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ABSTRACT

Lost circulation is the most extensive and expensive operational problem documented in geothermal well-construction. Mud losses have a high impact during drilling geothermal wells, mainly due to their high frequency and the associated high cost. The highly fractured rock environment found in geothermal drilling is one of the most common causes of massive mud loss events. Fractures that measure thousands of microns are complicated to cure. Operational consequences of lost circulation are diverse, but the most critical one is stuck pipe and well-control issues. These events represent a significant impact on NPT in geothermal wells. Despite being widely studied, lost circulation is still the most problematic and expensive issue in geothermal drilling. The most utilized corrective approach to prevent lost circulation is using lost circulation materials (LCM). The intention is to bridge and seal the wellbore fractures. Researchers have studied the bridging and sealing efficiency of different LCMs using slotted disks to recreate geothermal fractures. However, natural fractures are irregular, with randomness in their size and shape. In this case, materials successfully tested in the laboratory cannot replicate the same performance in field operations.

This paper presents a novel approach for building a fracture using additive manufacturing to test shape memory polymer based lost circulation material. Additive manufacturing allows for the production of objects with accurate geometric shapes. In this case, a fracture was designed, which was inspired by a natural fracture shape from a wellbore image log, and printed by a 3D printer. The novel fracture disk was used to test the shape memory polymer based lost circulation material. Shape memory polymers can be programmed to expand at downhole high temperatures. The results show that shape memory polymers can seal and bridge the complex fracture by adding sealing pressure and supporting a wellbore strengthening strategy.

1. INTRODUCTION

Additive manufacturing is a production concept through which the material is deposited layer by layer in a controlled manner where it is needed. This technique, commonly known as 3D printing, produces custom geometric shapes that are difficult to replicate using other more conventional methods. Compared to traditional manufacturing techniques, this technology reduces intermediate processes making it possible to obtain components faster. Moreover, no waste is generated using only the material for manufacturing the part. The components have a lower cost and are produced more sustainably.

Additive manufacturing has been used in the geothermal industry for different applications. Bit bodies, downhole tools components, rotors, and stators for positive displacement drilling motors can be built for geothermal applications (Polsky et al., 2020, Armstrong et al., 2021). Additive manufacturing can mimic rock properties (Zhou and Zhu, 2018). Mechanical properties can be analyzed using 3D printing technology to support failure analysis of rock-type materials (Jiang et al., 2018, Gell et al., 2019). Flow in porous media has been recently researched using additive manufacturing. Yang et al. (2020) used additive manufacturing to resemble a fractured-vug porous media to simulate multiphase flow. Ishutov et al. 2015 used a 3D printer to reproduce a sample of a known sandstone, reproducing its properties for reservoir characterization. Ardila et al. (2019) analyzed rock wettability preference using 3D printed samples that imitated porous rock matrix.

Mud losses are the most impacting problems reported during geothermal well construction, owing to their high frequency and high cost. One of the most typical causes of significant mud loss events is the geothermal fields' severely fragmented rock environment. Fractures of 1 to 3 thousand microns or more are complicated to bridge and seal (Vivas et al. 2020). The usage of LCM is the most common troubleshooting action to cure mud losses. The LCMs can be used in a preventative strategy, better known as wellbore strengthening, or as a corrective action to cure or mitigate the impact of the losses once they occur (Magzoub et al., 2021).

In this study, additive manufacturing is used to replicate a natural fracture to evaluate the performance of an LCM, in this case, a shape memory polymer. In this research, we analyzed experimentally the challenges faced to test a non-metal additive manufactured component at temperatures of 150°C (302°F). Besides, the difference in LCM performance to bridge and seal a slotted disk (which is the usual way to resemble a fracture in conventional filtration tests), compared to sealing a natural-shape fracture printed using additive manufacturing, is presented.

2. MATERIALS AND METHODOLOGY

2.1 Fracture Design

One of the most important features of 3D printing is the possibility to recreate forms that would be difficult and expensive using conventional manufacturing processes. The natural fractures have a known randomness that is not reflected in the conventional fracture disks used in filtration experimental research. In Fig. 1, a formation micro-imager well-log (FMI) from the Utah FORGE well 58-32 was utilized for extracting a natural fracture. For this study, the natural fracture was converted into an image as a scalable vector graphic (SVG). This fracture image was subsequently turned into a 3D model using Computer-Aided Design (CAD) software. Then the image of the fracture was included in a 3D printed disk. This way to design a fracture for laboratory research provides the opportunity to build a fracture disk that mimics particular fracture shapes for a fit-for-purpose analysis. Another advantage is the test reproducibility, since a design can be exported and printed in any 3D printing. This provides the opportunity to replicate the experiment in other laboratories, and made the results comparable.

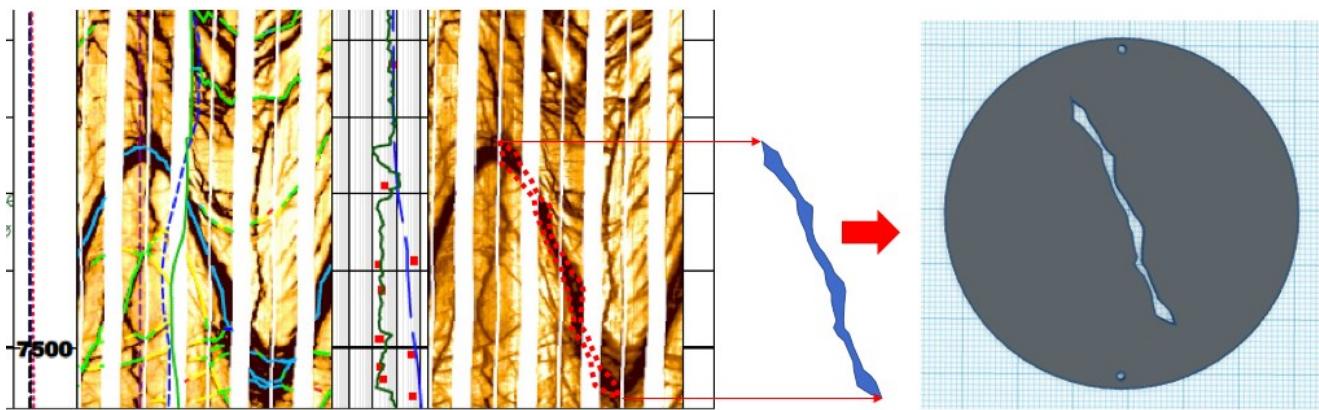


Figure 1: Fracture design based on a FMI log from Utah FORGE well 58-32. FMI image from Moore and Nash, 2018

There are noticeable differences between the fracture disks conventionally used in filtration tests. The disks used in a high pressure-high temperature plugging tester (HPHT PPT) are made of metal and have a thickness of 6 mm (Fig. 2). The reason of using metal (aluminum or steel) is due to the high temperature of the tests. For geothermal energy applications it is expected to perform experiments at temperatures of at least 150°C (302°F).

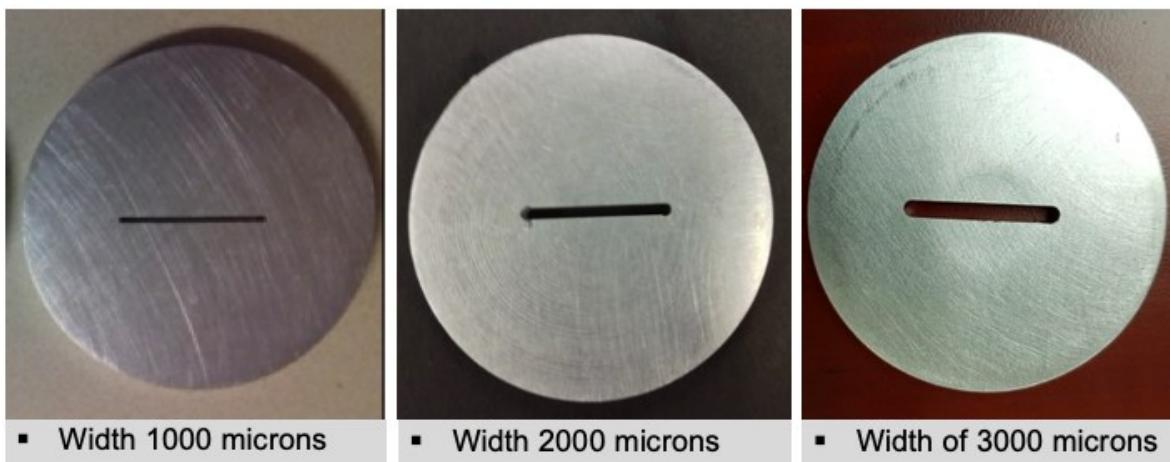


Figure 2: Conventional fracture design for filtration tests using a HPHT PPT.

One of the limitations of the disks is the small thickness. When testing the effectiveness of LCM, the limited disk thickness can affect their performance. The main reason is due to the way a LCM works. An effective LCM requires to have particles large enough to generate a bridge that will serve as a foundation where smaller particles will be placed to generate the seal to prevent or cure the mud losses (Vivas and Salehi, 2022). In this case, as the fracture is wider, the bridge is going to be generated deeper inside the fracture. This limits the width of the fracture for the laboratory tests. The main challenges of LCM experimental research for geothermal are the wide fracture width expected in geothermal environments, and, the high temperatures required to mimic the geothermal drilling environment.

The fracture thickness is limited by the shape of the PPT cell, which contains a tapered section with an O-ring where the fracture disk is placed. Taking advantage of the 3D printing flexibility, a new design that allows to increase the disk thickness from 6 mm to 25.4 mm (1 inch) is presented in the Fig 3.

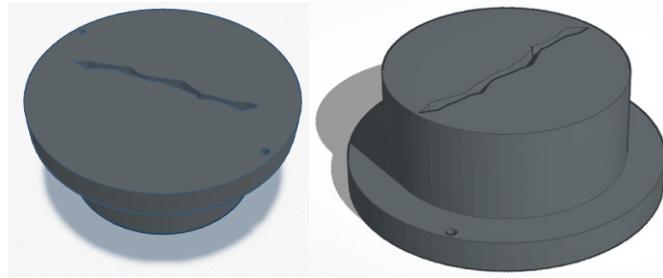


Figure 3: New fracture design with an extended fracture thickness.

2.1 3D Printing Process

The Fused Deposition Modeling (FDM) technology, which uses a thermoplastic polymer in a filament to make three-dimensional objects, is used in this study's 3D printer. In a similar printing process described by Anyaezu et al. (2021), the printing nylon filament is extruded through the printer hot extruder at a temperature of 250°C (482 °F). The filament is heated before being placed layer by layer on a build plate through the heated nozzle. To achieve dimensional precision, the 3D printer employs a specially heated and sealed chamber. In contrast, the Stereolithography Apparatus (SLA) prints 3D objects using a laser source and liquid resin (Anyaezu et al., 2021). Depending on the complexity of the slicing properties of the design, the printing process can take hours. The fracture was first sketched using real-time pictures of wellbore fractures.

In Fig. 4 (a) the printed fracture design is presented. In the Fig. 4 (b) the difference in thickness between the conventional fracture disk and the new design is depicted. The new fracture disk design offers a better representation of an actual fracture compared with the traditional slotted disks.



Figure 4: New fracture design with an extended fracture thickness.

3. HPHT EXPERIMENTS

3.1 Filtration Experiment

The filtration tests were performed with an HPHT PPT apparatus in static conditions. The 3D-printed fracture was placed at the top of the cell without issues (Fig. 5b). The new design allows using the modified disk without the need to alter any component of the PPT cell.

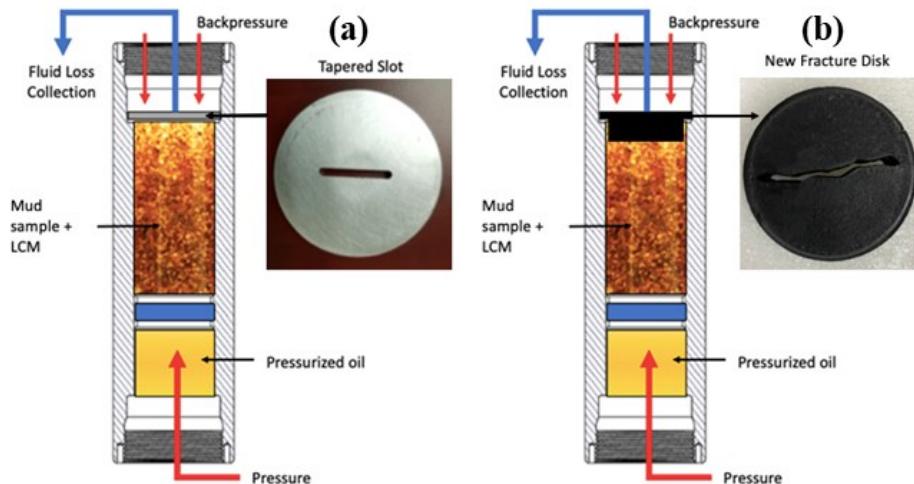


Figure 5: Schematic of the PPT cell with the conventional slotted disk (a) and the PPT cell with the new 3D printed fracture disk (b), showing that any modification in the PPT chamber was required for the new application.

The fluid utilized in the test is a water-based mud formulation. Distilled water was mixed with bentonite at 20% (rheology additive), lime at 5% (alkalinity control), and lignite at 5% (Deflocculant). The MW of the sample was adjusted to 1.2 g/cc (10 ppg) by adding barite. All components have been proven thermally stable up to 204.4°C (400°F) (Vivas and Salehi, 2021).

The LCM material tested is a shape memory polymer (SMP). The SMP are programmable smart LCM that can be activated by temperature (Mohamed et al. 2022). The SMP can be programmed by a combination of heat and load to have a momentary deformation (Fig. 6) in a process called programming cycle. Once the programming cycle ends, the material has a smaller volume, offering the advantage to circulate them through drilling assembly restrictions (such as the measuring while drilling tools or the drill bit nozzles) without plugging them. The SMP are programmed to activate at a desired temperature, in this case when the temperature is equal or above the programming temperature, the SMP returns to its original shape (activation cycle) (Mohamed et al. 2022). The activation temperature is adjusted to the formation temperature to assure that the SMP recovers the size and shape inside the fractures for curing mud losses. SMP are ideal materials to geothermal drilling, due to their low cost, high flexibility and easy programming process (Liu et al. 2009)

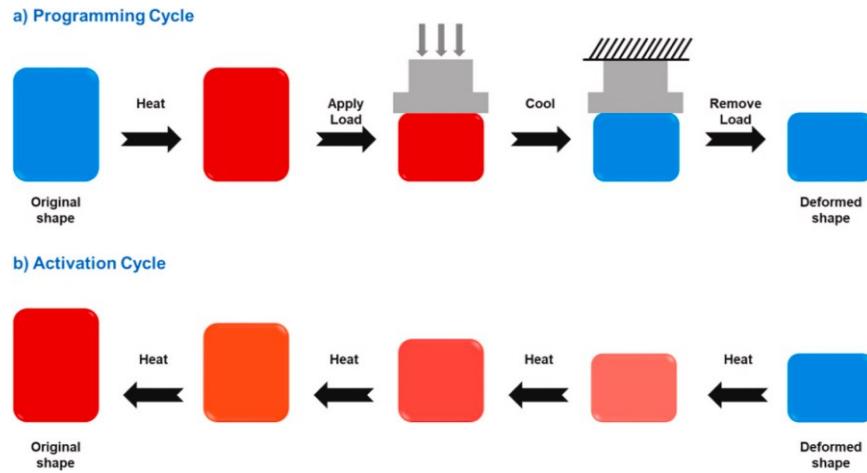


Figure 6: SMP programming and activation cycle (Mohamed et al. 2022).

3.2 High Temperature Tests

The initial experiments were focused on finding the best 3D printing parameters to create a fracture that could withstand a temperature up to 150°C (302°F). Carbon fiber reinforced Nylon was selected as the material for the manufacturing since it has a higher heat deflection temperature than other materials such as polyethylene terephthalate glycol (PETG), polylactic acid (PLA), and acrylonitrile butadiene styrene (ABS). Nylon carbon fiber has a tensile strength of 66 MPa, and a tensile modulus of 6,000 MPa. The melting temperature of this material is 250°C (482°F), so the printer extruders have to reach that temperature for printing the novel disk.

First a fracture disk with an infill density lower than 30% was tested using a temperature of 121°C (250°F). In Fig. 7 it is depicted how the printed sample was heavily deformed.

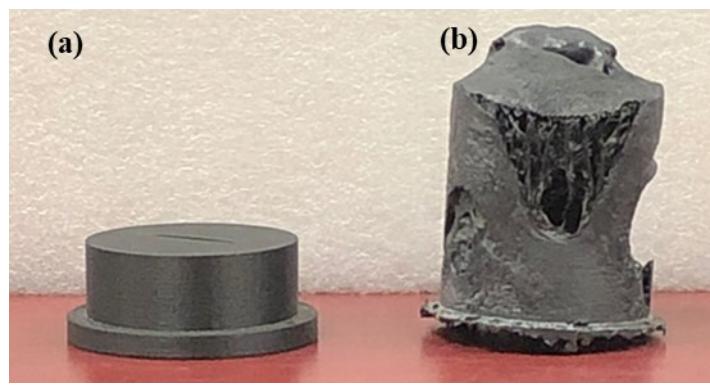


Figure 7: (a) fracture disk before test, (b) fracture disk after test at 121°C (250°F).

As testing for geothermal requires to perform tests at high temperatures, different printing configurations were attempted to meet the geothermal testing configurations. Three tests were performed with 30%, 60% and 94% of infill density, and their results are presented in Table 1 and Fig. 8, respectively. One important downside of increasing the density is that the printing process can take several hours, reaching up to 12 hours in the 94% density sample.

After the tests it was observed that the deformation of the 3D printed samples started at the reduced diameter section of the fracture. This behavior was attributed to the direct contact of the reduced diameter section with the walls of the steel-made PPT cell. In that case the

reduced diameter section of the disk with 94% infill density was decreased from 54 mm to 50 mm so it was not longer in direct contact with the wall of the cell (Fig. 9).

Table 1: Summary results of 30%, 60% and 94% of infill density

Infill density (%)	Temperature reached (°C/°F)	Relevant observations
30	93.3/200	The width of the fracture was reduced, and the polymer fracture disk shape was buckled.
60	121.1/250	The fracture kept its width, but the disk shape was deformed.
94	150/302	The fracture kept its width and there were no appreciable deformations on the disk structure.

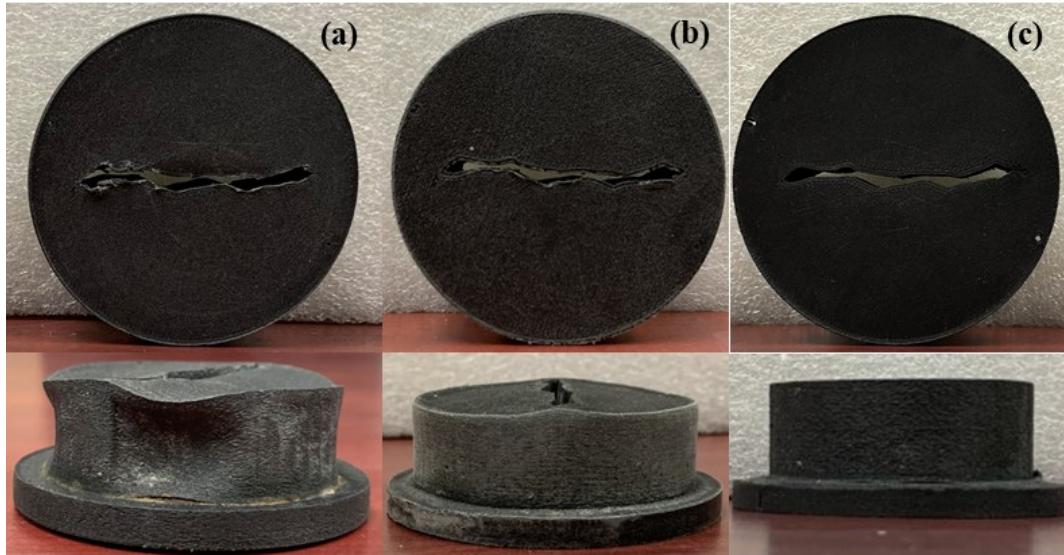


Figure 8: Test results using an infill density value of (a) 30% at 93.3°C, (b) 60% at 121.1°C, and (c) 94% at 150°C.

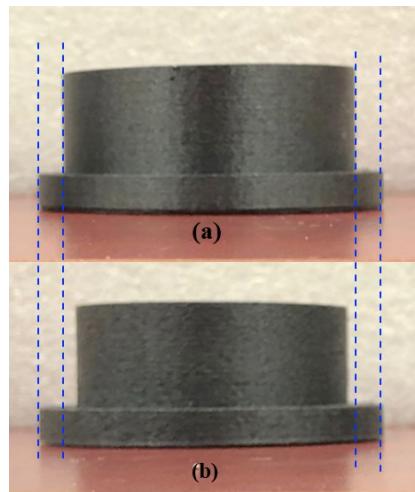


Figure 9: 94% fracture disk (a) before and (b) after reduced diameter section decrease.

3.3. Fracture sealing using SMP

After determining optimal printing parameters for the fracture, the next step consisted of testing whether it was possible to seal and bridge the fracture by using shape memory polymer (SMP). Anyaezu et al. (2021) found out that by increasing the concentration of SMP the

filtration volume was reduced. They also mentioned that the optimum concentration value of SMP for this application was around 4% since the volume filtration reduction achieved with it after 30 minutes was not changing significantly any longer.

The cumulative filtration volume for all the permeability plugging tests did not exceed 15 cc, indicating that the addition of a 4% by weight of SMP was sufficient to satisfactorily seal and bridge the fracture. Additionally, the fracture withstood the 150°C temperature for all three tests without noticeable deformation (Fig. 10).

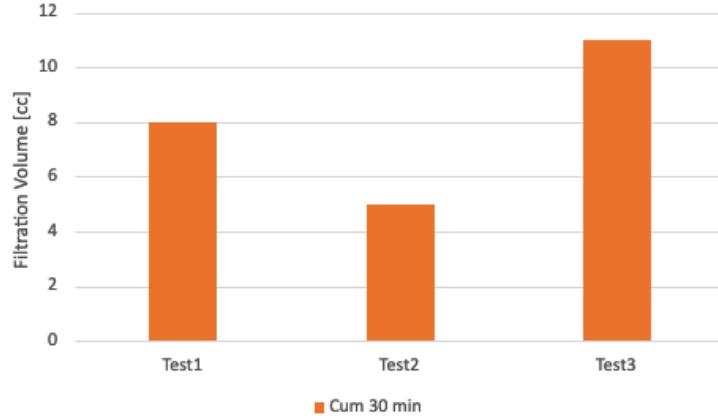


Figure 10: Cumulative filtration volume collected after 30 minutes.

All three experiments were maintained at a confined pressure of 5516 kPa and a backpressure of 2068 kPa, for 3447 kPa of differential pressure on the fracture. Once the filtrate was collected, the maximum differential pressure on the fracture recorded was 8275 kPa in all three experiments (Fig. 11). The differential pressure would be higher, but for safety reasons, the pressure in the cell was limited at that point.

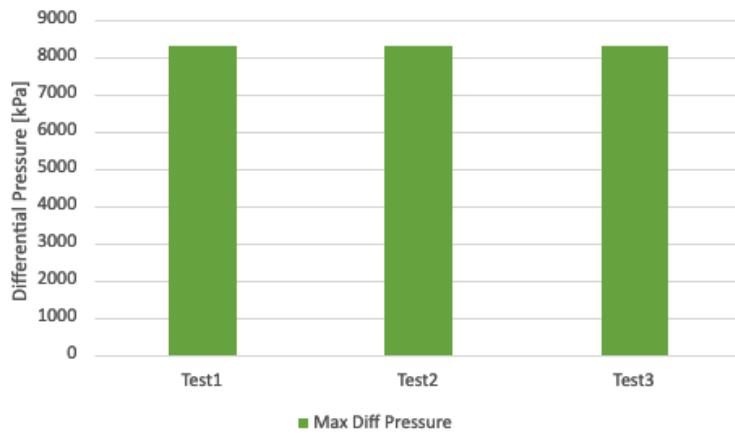


Figure 11: Sealing pressure after filtration test.

3.3. Comparison with conventional disk

Fig. 12 depicts the two fracture disks after the permeability plugging test was conducted. The operational conditions during testing the conventional and the novel disk were the same: 5516 kPa at 150°C for 30 minutes with a water-based mud with 4% of SMP. Despite the area of the 3D printed fracture is greater than the area of the slotted disk, the amount of filtration for the conventional disk was higher (Table 2). Besides, the maximum sealing pressure in the conventional disk was lower compared with the novel fracture. This may be attributed to the fact that the novel disk has a larger thickness which allows the SMP to generate the bridge deeper inside the fracture. Notwithstanding these results, we should also consider the effect of the difference in material type, fracture height, thermal conductivity impacting filtration and pressure.

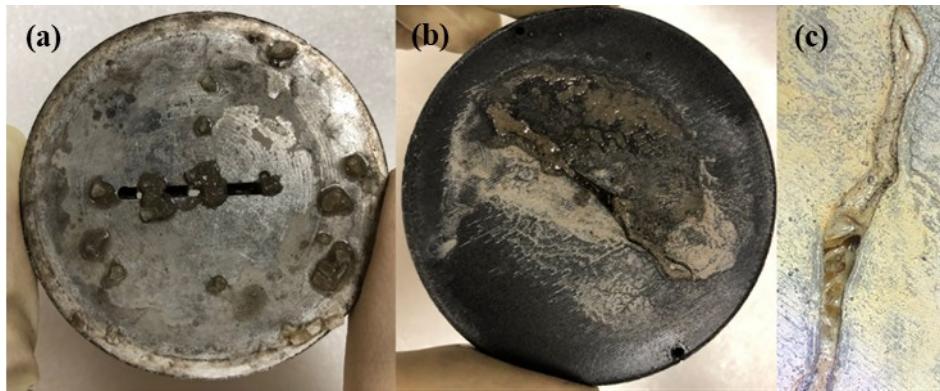


Figure 12: (a) conventional metal disk, (b) novel fracture disk after PPT, (c) image where it can be seen that the SMP bridges and small mud solids seal the fracture.

Table 2: Comparison of filtration results using a conventional slotted disk and the 3D printed fracture disk with the new design.

	Conventional metal fracture disk	Novel fracture disk	Difference
Cumulative filtration volume after 30 min (cc)	28	8	250% more cumulative filtration
Maximum differential pressure after 30 min (kPa)	5170	8275	37% less sealing pressure

4. CONCLUSIONS

This work shows the use of 3D-printed PPT disks with a realistic fracture shape that reflects the randomness of natural fractures. The capability of reproducibility represents a benefit of using 3D-printed disks, opening the possibility to replicate the experiment in other laboratories, despite the complexity of the fracture. Furthermore, fast and easy prototyping of samples offers flexibility to adjust the printed component.

The carbon fiber reinforced nylon printed fracture disks with some modifications can stand a temperature of 150°C during 30 minutes of testing time. Besides, it was found that experiments can be repeated with the same specimen, showing that the printing conditions (94% of infill density) and the modifications in the shape, allowed a successful high temperature filtration tests.

The SMP demonstrates their capability to bridge and seal a fracture at 150°C, making this material suitable for geothermal applications. The maximum sealing pressure of 8275 kPa opens the possibility to use this material not only for curing mud losses, but also for wellbore strengthening strategies. The experiments confirm that 4% by weight of SMP is appropriate for bridging and sealing at 150°C.

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