High temperature piezoelectric drill

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ABSTRACT

The current NASA Decadal mission planning effort has identified Venus as a significant scientific target for a surface in-situ sampling/analyzing mission. The Venus environment represents several extremes including high temperature (460°C), high pressure (~9 MPa), and potentially corrosive (condensed sulfuric acid droplets that adhere to surfaces during entry) environments. This technology challenge requires new rock sampling tools for these extreme conditions. Piezoelectric materials can potentially operate over a wide temperature range. Single crystals, like LiNbO3, have a Curie temperature that is higher than 1000°C and the piezoelectric ceramics Bismuth Titanate higher than 600°C. A study of the feasibility of producing piezoelectric drills that can operate in the temperature range up to 500°C was conducted. The study includes the high temperature properties investigations of engineering materials and piezoelectric ceramics with different formulas and doping. The drilling performances of a prototype Ultrasonic/Sonic Drill/Corer (USDC) using high temperate piezoelectric ceramics and single crystal were tested at temperature up to 500°C. The detailed results of our study and a discussion of the future work on performance improvements are presented in this paper.

KEYWORD: High Temperature, Piezoelectric Drill, Rock sampling, Venus.

1. INTRODUCTION

The current NASA mission planning effort has identified Venus as a significant scientific target for a surface in-situ sampling/analyzing mission. The Venus environment represents several extremes including high temperature (460°C), high pressure (~9 MPa), and potentially corrosive (condensed sulfuric acid droplets that adhere to surfaces during entry) environments. This technology challenge requires new rock sampling tools for these extreme conditions. Piezoelectric materials can potentially operate over a wide temperature range. Single crystals, like $LiNbO_3$, have a Curie temperature that is higher than 1000°C and the piezoelectric ceramics Bismuth Titanate higher than 600°C. A study of the feasibility of producing piezoelectric drills that can operate in the temperature range up to 500°C was conducted. The study includes the high temperature properties investigations of engineering materials and piezoelectric ceramics with different formulas and doping. The drilling performances of the prototype Ultrasonic/Sonic Drill/Corer (USDC) using high temperate single $LiNbO_3$ crystal were tested at temperature up to 500°C.

2. High Temperature Piezoelectric Materials

The piezoelectric material that is used to produce the sampler is the key to its ability to function in Venus environments. In order to identify effective materials, we evaluated and characterized high temperature (HT) piezoelectric material samples [Sherrit et al, 2004]. For this purpose, we used an Agilent 4294A precision impedance analyzer and a d_{33} meter measured the electrical characteristics at both room and at temperatures up to 500°C. We investigated the electromechanical properties of 1-inch diameter discs that are made of single crystal 36° Y-cut $LiNbO_3$ to determine its aging characteristics. The results are listed in Table 1 together with the properties of the high temperature piezoelectric ceramics.

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In addition we tested 3 types of high temperature electrode materials including 1) sputtered platinum film, 2) gold-palladium thick film and 3) sputtered gold film. We found that the use of sputtered gold electrodes sustained the most severe degradation while the both sputtered platinum and gold-palladium films were stable up to 1000 hrs. Based on our results and the fabrication ease we are now using sputtered platinum film as the electrodes. The results for the aging test at 500°C for 1000 hours of $LiNbO_3$ with the Pd-Au and Pt electrodes were plotted for the capacitance and planar coupling as a function of time at 500°C and are shown in Figures 1.

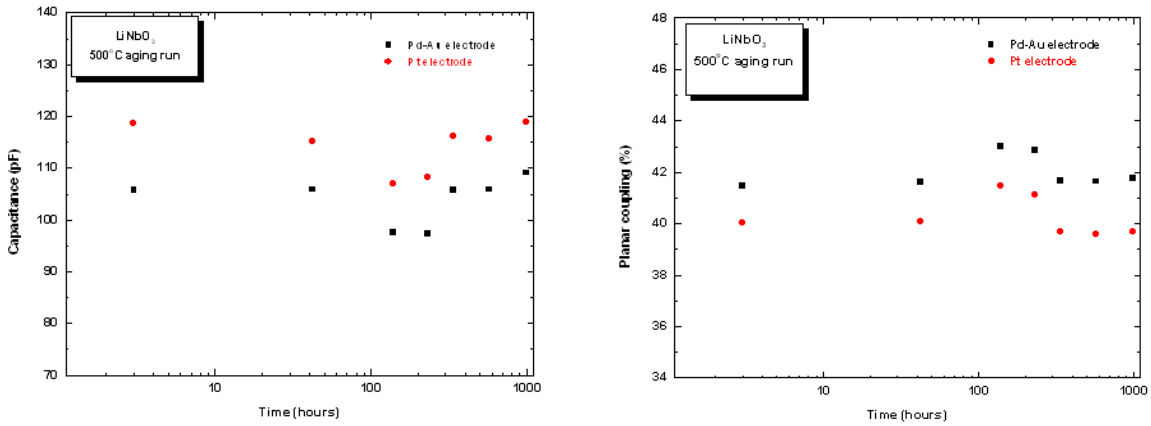

FIGURE 1: Capacitance and planar coupling as a function of time at 500°C for $LiNbO_3$.

In parallel to evaluating the $LiNbO_3$ crystal at high temperatures, new HT piezoelectric ceramics were developed. Our candidate piezoelectric ceramic material is Bismuth Titanate. Discs were made and tested for HT performance and the data were tabulated for the various samples and are documented in Tables 1 with the $LiNbO_3$ as a reference. The data imply that the thickness coupling coefficient at 500°C is about 15 to 20%. The test results are very encouraging and the material with a Tungsten (W) dopant appears promising because of its relatively high Q, low loss, high Tc and high d33. We are continuing to investigate tuning of the Tungsten dopant in the $Bi_4Ti_3O_{12}$ powder mixture. Effective mixtures will be identified and HT piezoelectric rings will be made using hot isostatic pressure to insure the production of robust ceramic compositions. Currently, a set of 1-inch diameter rings is being made for integration into the HT USDC for drilling tests at high temperatures

TABLE 1: The electromechanical measured properties of the LiNbO3 crystals and the Bismuth Titanate with various doping contain.

Material	T_C (°C)	K	loss	d_{33} (pC/N)	Q_p	k_p	500°C			
							K	loss	Q_p	resistivity
Modified $Bi_4Ti_3O_{12}$	666	118	0.5%	16 (16)*	3000	3.7%	300	41%	200	$7.4x10^6$
$Bi_{3.887}Ti_{2.866}W_{0.146}O_{12}$ - Fe_2O_3	~620	154.6	1%	14 (13)	2900	3.3%	590	62%	50	$1.5x10^6$
$Bi_{3.9}Ti_{2.85}W_{0.15}O_{12}$- Fe_2O_3	~620	156.8	1%	11.5 (11)	2000	3.1%	670	67%	46	$1x10^6$
$Sr_{0.8}Ca_{0.2}Bi_4Ti_4O_{15}$- Fe_2O_3	595	143.7	0.4%	12 (11.5)	5600	2.9%	461	42%	360	$1.9x10^6$
$Sr_{0.6}Ca_{0.4}Bi_4Ti_4O_{15}$- Fe_2O_3	644	146.8	0.25%	8 (8)	5800	2.6%	463	100%	120	$2.9x10^5$
$Bi_{3.93}Ti_{2.9}W_{0.1}O_{12}$- MnO_2	657	158	0.5%	17 (11)	3700	4.3%	421	44%	45	$3.6x10^6$
$Bi_{3.96}Ti_{2.9}W_{0.1}O_{12}$- MnO_2	~650	145	0.3%	18 (12)	3900	4.3%	370	40%	40	$5.6x10^6$
W doped $Bi_4Ti_3O_{12}$	637	165.7	1.5%	17 (15.5)	1800	3.4%	309	16%	1000	$\sim 5x10^6$
$LiNbO_3$ (36° Y-cut)	1150	62	0.5%	40 (40)	1500	46%	104	6%	500	$3.8x10^6$

* The value in parenthesis is the data obtained after 500°C.

3. Finite Element Analysis of Transducers with HT Piezoelectric Materials

In addition to the effort to improve the performances of piezoelectric materials, we are also investigating the proper transducer design that will allow for using relatively low performance piezoelectric materials and still drill effectively. As a first step we investigated the performances of the transducers using the HT piezoelectric materials to replace the piezoelectric ceramic PZT-8 in so called "baseline" USDC transducer that was developed for operation at room temperature. Finite element models were used to analyze these transducers [Bao et al, 2003]. . The modeled transducer consists of a piezoelectric stack, a horn, a backing block, a pre-stress bolt and a Belleville washer. The primary results for the baseline transducer using Lithium Niobate single crystal are shown in Figures 3 and 4. Figure 3 illustrates the mode shape of the first resonance. It is a longitudinal mode with maximum displacement at the tip of the horn. Figure 4 is the input admittance curve at the frequency range around the resonance.

These results suggest that using Lithium Niobate in the baseline transducer will have a resonance frequency and mode shape similar to that using PZT-8. However, the maximum conductance is much lower, which implies the power under the same voltage will be much lower. Increasing the driving voltage will partially compensate for the disadvantage of the high input resistance but it is ultimately limited by electric break down. Further, the high loss at high temperature as shown in the Table 1 may result in a rapid overheating when operating the drill in a high temperature environment and operating with duty cycling may be required. We are continuously investigating the possible designs to increase the power capability of the transducer using the model analysis.

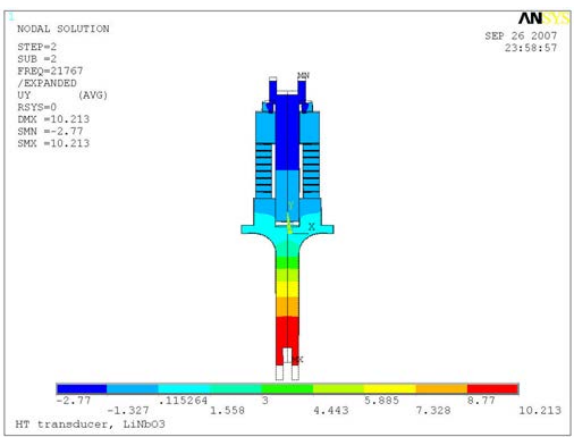

FIGURE 3: First longitudinal mode shape for the $LiNiO_3$ material. The color scale shows displacement in the vertical direction. The resonance frequency of the transducer is 21.767 kHz

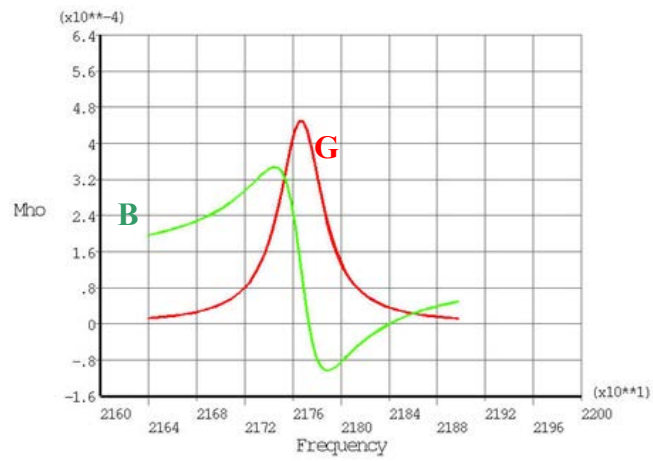

FIGURE 4: The input admittance response around the first resonance frequency for the $LiNiO_3$ material. G is the real part (conductance) and B is the imaginary part. The mechanical Q was set to 500.

4. Breadboard Transducers and Impedance Analysis at High Temperature

A $LiNbO_3$ transducer (see figure 5) was constructed and tested over the range from room temperature to 500°C

FIGURE 5: The HT transducer with LiNbO3 stack that we assembled and used as our initial prototype HT actuator.

The parameters that vary with temperature were extracted from the measured data and plotted in Figures 6 to 9. Figure 6 shows the effective coupling factor of the transducer at the first longitudinal resonance mode that the transducer is operated at. The effective coupling is proportional to the square root of mechanical energy over the total (mechanical and electrical) energy of the oscillating transducer at the resonance frequency. This factor directly affects the power capacity and efficiency of the transducer and a higher coupling factor is preferred. Figure 7 shows the mechanical Q. A high mechanical Q means low loss and a strong resonance can be achieved. The impedance of the transducer at the resonance frequency can be modeled as a capacitor and a resistor connected in parallel. The capacitance and the resistance at resonance are shown in figures 8 and 9 over the temperature range. The vibration amplitude of the transducer excited by a voltage is proportional to the inverse of the resistance. The performance degradation at high temperature is predicted due to the decrease of the effective coupling factor, mechanical Q and increase of the resistance as observed.

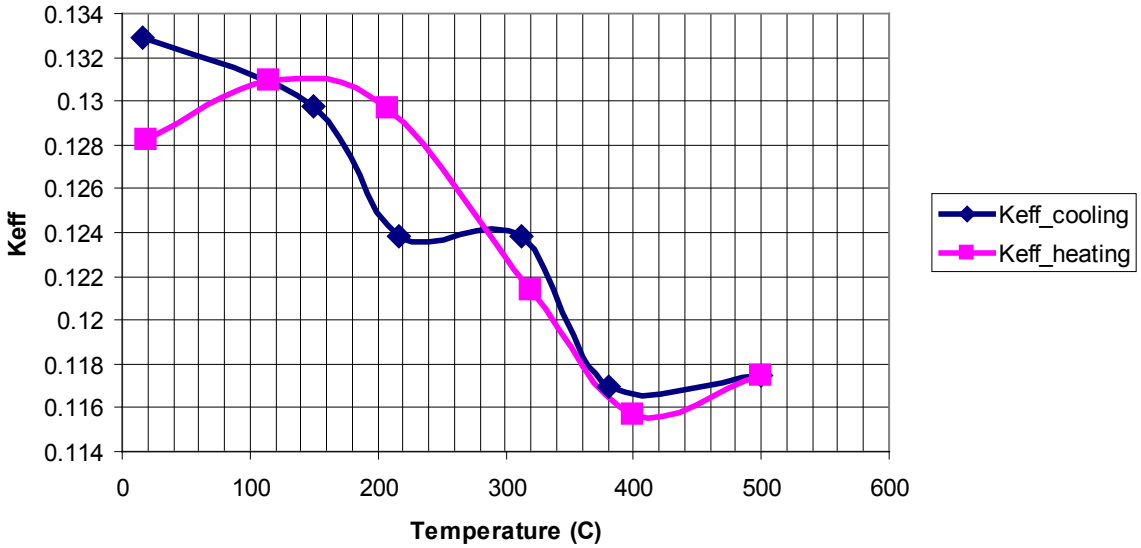

FIGURE 6: The effective electromechanical coupling factor as a function of temperature.

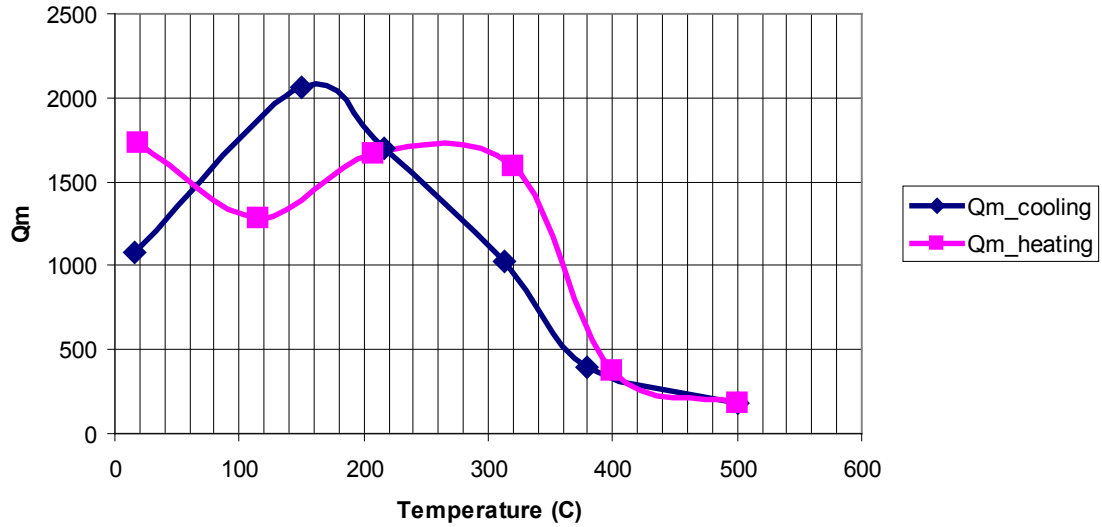

FIGURE 7: The mechanical Q_m of the transducer as a function of temperature. The Q_m is proportional the inverse of the mechanical loss.

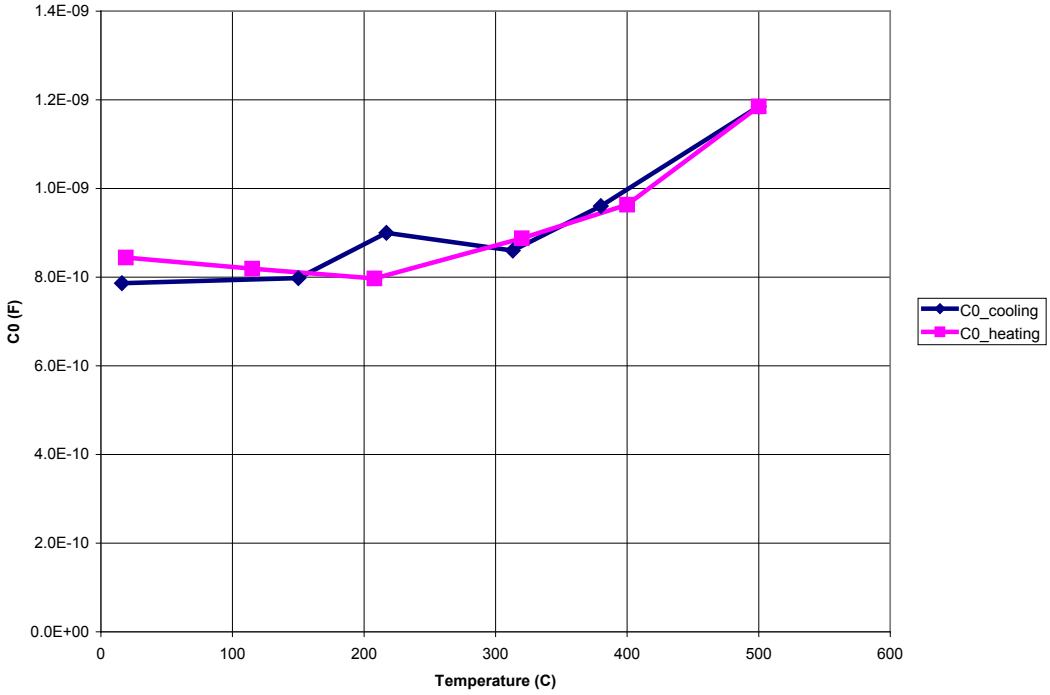

FIGURE 8: The capacitance C_0 of the transducer as a function of temperature. A 50% increase of the capacitance was observed.

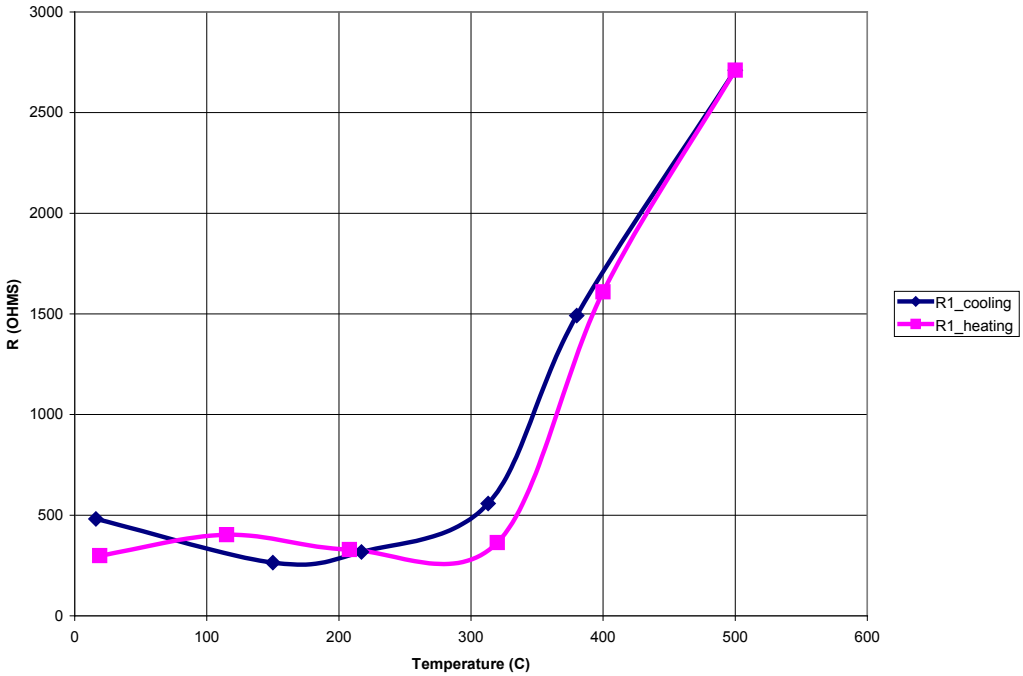

FIGURE 9: The resistance R_1 of the transducer as a function of temperature. The increase of the resistance at temperature above 300ºC implies higher input voltage will be required to excite the transducer.

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5. Drill Test at High Temperature

The fabrication and assembly of the testbed consisted of a furnace and an assembly that allowed the HT USDC to be evaluated both internal and external to the furnace and a retaining structure for the rocks used in the drilling tests at temperatures as high as 500ºC. The furnace itself is capable of operating temperature of up to 1200ºC allowing, if needed, to conduct higher temperature tests of the USDC and the piezoelectric stacks. To test the operation of this horizontal tube shape furnace we procured customized insulating side caps that have a center hole and we used one of these holes (see on the right in Figure 10) for insertion of a high temperature bit that we produced. Initially, the USDC was placed outside the chamber (Figure 10) and it was pushed pneumatically to drill with controlled preload to investigate the rock/bit interactions at high temperature..

FIGURE 10: Photographic view of the furnace that was developed as a HT testbed. For the initial testing, rock samples were placed inside the chamber and were drilled at various temperatures while the USDC was placed outside and pushed pneumatically to assess rock and bit interactions at high temperatures.

To test the USDC with the HT piezoelectric stacks inside the chamber we constructed a fixture that is shown schematically in Figure 11. This fixture allows sliding the USDC while drilling as well as securing the position of the drilled rocks along the bit path. The USDC is pushed from outside the chamber using the controlled preload system that was developed and tested for this apparatus.

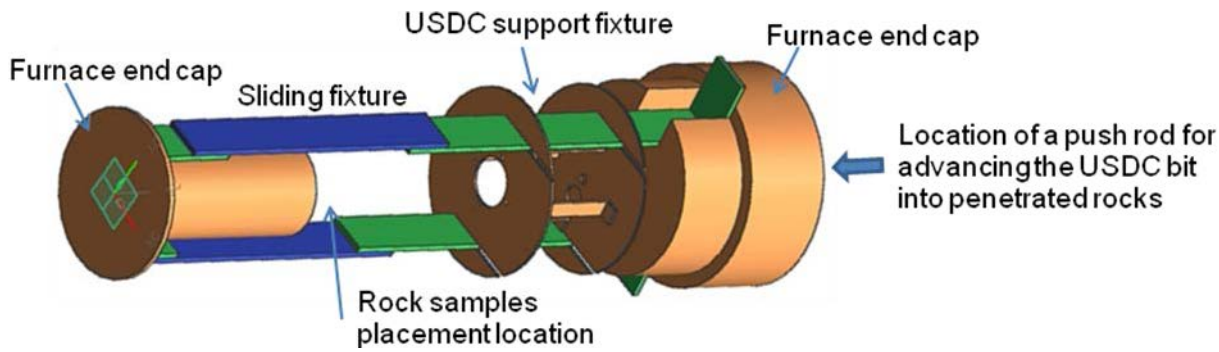

FIGURE 11: Schematic view of the support fixture for testing the USDC and its drilling performance inside the HT chamber.

A USDC that can operate at high temperatures was produced to support the testing of the developed piezoelectric actuator. The key components of the USDC are the actuator, free-mass and bit. A schematic cross-sectional diagram of the USDC and the actuator are shown in Figure 12 and 13, respectively. To insure that the actuator can operate at the required 500°C we made the horn of Titanium and the stress bolt and backing of stainless steel. We used Belleville Inconel washers to maintain the pre-stress at high temperatures. The use of titanium allowed for low mass device having high mechanical strength. Eight $LiNbO_3$ discs were mounted onto the actuator and held in compression by the stress bolt to prevent fracture of the discs during operation. To design the actuator and determine its resonance frequency we modeled it analytically both thermally and electromechanically. Using the HT chamber that was shown in Figure 11 we tested the impendence characteristics of the actuator at RT and 500°C.

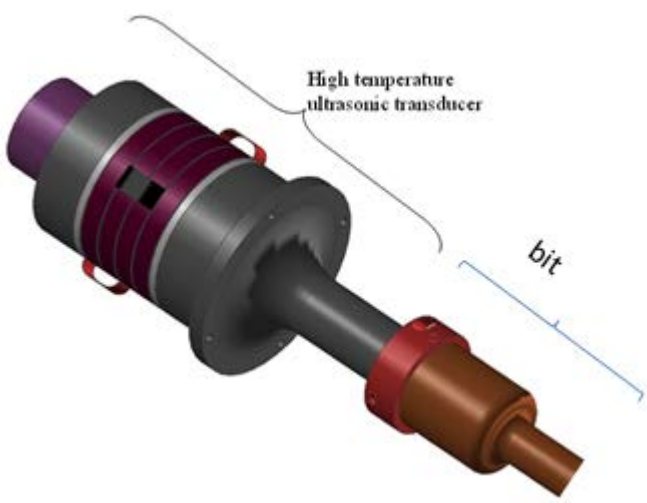

FIGURE 12: Schematic view of the HT USDC that is being developed.

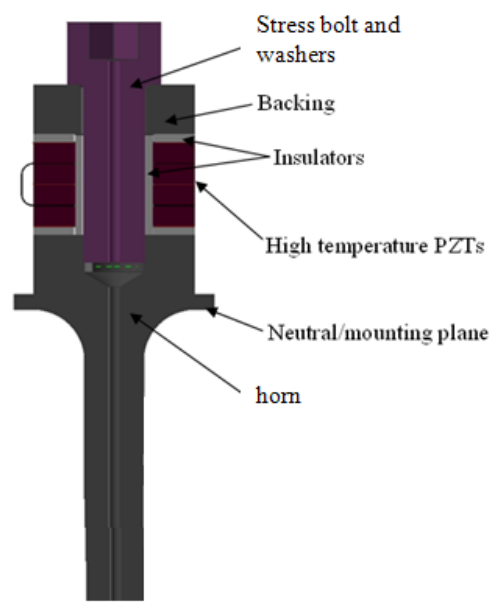

FIGURE 13: A cross section view of the HT USDC actuator.

In our initial testing our prototype HT bit, which was made of Crucible CPM-3V and hardened to HRC 63, degraded as a result of drilling at 500ºC (from outside the chamber). To improve the drill performance, Tungsten Carbide WA-2 (HRA 92) using tube shape rods were designed and manufactured. A schematic view of the bit is shown in Figure 14.

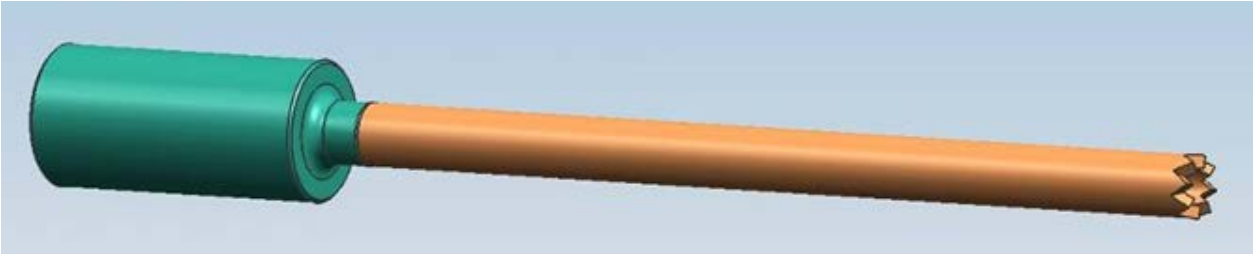

FIGURE 15: CAD illustration of the coring bit and its base (left section) for use with the HT USDC.

The breadboard USDC was tested from room temperature up to 500ºC. It drilled the limestone at room temperature with a drilling rate of around 3 mm/min and severely degraded the performance to almost no drilling at 500ºC. For a very light Pumice rock, the drilling rate was around 1.3 mm/min at 500ºC compared with 50 mm/min at room temperature.

5. SUMMARY

In an on-going study, we are developing a piezoelectric drill that can be used to sample rocks in high temperature environments corresponding to the surface of Venus (460°C). The high temperature properties of a variety of piezoelectric materials including $LiNiO_3$ single crystals were evaluated. A high temperature USDC was constructed using $LiNiO_3$ crystals to replace the originally used piezoelectric material PZT-8. The HT USDC worked and drilled Pumice rock in a test furnace at 500°C. However, as predicted by FE modeling and impedance analysis, the performance degraded severely at high temperatures. In parallel we are developing new HT piezoelectric ceramic materials and the properties of the Bismuth Titanate with Tungsten dopant appear promising. As we continue this investigation, we will test the performance of the USDC using the newly-developed high temperature ceramic materials and continue to investigate proper transducer designs that will allow for using relatively low performance piezoelectric materials and drill effectively at high temperatures.

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