Tribological investigation of high temperature coatings for Venusian conditions. V. Tsigkis[1] , K. Bashandeh[1], P. Lan[2], and A. A. Polycarpou[1], [1]Mechanical Engineering, Texas A&M University, College Station, TX, United States (tvasilis@tamu.edu), [2]ATSP Innovations, Houston, TX, United States.

Introduction: Venus, which is also called Earth's twin, has been the topic of new explorations to understand and investigate our planet and the feasibility of the existence of other habitable planets. Venus is similar to Earth in terms of size, distance from sun, mass, and composition [1]. However, significant technical challenges exist in Venus exploration. Compared to Earth, the surface pressure is nearly 92 times higher and the environment is primarily 96% CO_2 gas, and 3.5% N_2, with minute amounts of Ar, H_2S, SO_2, HF, and HCl (with SO_2 being the dominant minor gas) coupled with extremely hot (~462°C) and dry conditions [2,3]. The successful accomplishment of future NASA missions on the in-situ investigation of Venusian surface in a long duration operation requires bearing materials in the landers that can withstand such extreme environmental conditions (i.e., high-pressure (HP), high-temperature (HT)) [1]. Protection against HTHP is a key required technology for a Venus exploration mission [3]. The first step in selecting the appropriate material is to build and test a prototype that can closely simulate the environmental conditions on Venus.

Herein, we designed a high temperature, high pressure tribological test setup which provides capability in excess of the atmospheric pressure of the Venusian surface. We performed proof-of-concept tribological testing including materials developed by NASA, and high temperature alloys. This capability will be vital in evaluating tribo-components, for example drills, electric motors, actuators, and bearings for use on the Venusian surface.

Sample preparation: Inconel 718 (INC 718) purchased from Altemp Alloys, Inc was used as a substrate for the coatings under examination. The disk specimens were coated with Nedox PF-F (General Magnaplate), $TiMoS_2$ (IBC Coatings Technologies), and DLC (Oerlikon Balzers). The pin mating surfaces were coated with PS400, prepared at Adma Products, Inc. The approximate thickness values for the coatings, as given by the vendors were 12-23 μm, 1-2 μm, 2 μm, and 200 μm, for Nedox PF-F. $TiMoS_2$, DLC, and PS400, respectively.

Experimental procedure: For the tribological experiments, shown in **Figure 1** of the HPHT experiments, we selected 5 different tribo-pairs for evaluation under 350 psi (2.4 MPa) CO_2 atmosphere at 462°C, contact pressure of 3.5 MPa, sliding speed of 0.2 m/s, and with 6000 sliding cycles in 30 min. We used 3-pin sample contacts against a flat disk sample, with a total nominal contact area of 25.7 mm^2. The tribo-pair Inconel 718 vs. Inconel 718 (INC 718 vs. INC 718) served as the benchmark to gauge the effect of each coating (PS400, Nedox, $TiMoS_2$, and DLC) on the tribological performance.

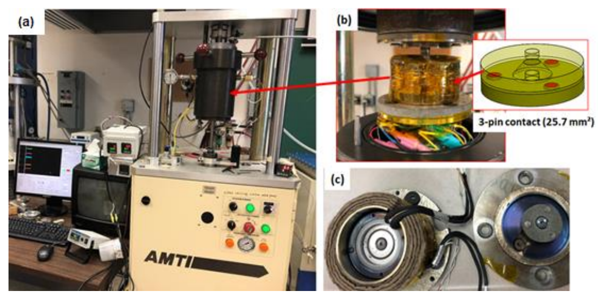

Figure 1. HPHT tribological testing, (a) assembled HT stage in HP chamber testing under 2.4 MPa/350 psi CO_2 pressure at 462 °C, (b) HT stage mounted on the HP pressure chamber, (c) samples after testing.

Experimental results: 5 different tribo-pairs were tested and characterized via different analytical techniques to investigate the wear mechanisms and to explain their tribological performance. **Figure 2(a)** summarizes the average Coefficient of Friction (COF) values, and **Figure 2(b)** the disk wear rates following the experiments at 462°C CO_2 atmosphere. PS400 vs. DLC produced the lowest COF (0.32), followed by PS400 vs.$TiMoS_2$ and PS400 vs. INC 718. PS400 vs. Nedox generated the highest COF (0.66). EDS analysis was implemented to explain the tribological response of the tribo-pairs, and the elemental analysis is listed in **Table 1**. When PS400 coated on INC 718, the tribological performance of the tribo-pair (INC 718 vs. INC 718) improved significantly, due to the considerable amount of PS400 solid lubricants (CaF_2, Ag) being activated and transferred to the counter surface, therefore lubricating the interface. The tribological incompatibility (i.e., similar composition, both get high percentage of Ni) between PS400 and Nedox and the absence of adequate lubrication at the interface induced a high COF. Despite that the $TiMoS_2$ coating was removed from the contact, a low COF maintained, probably due to the high amount of surface oxidation (high amount of O) and the presence of Ag solid lubricants transferred from the counter surface. Furthermore, the low COF of PS400 vs. DLC was attributed to the graphitization of the DLC coating, which acted as a solid lubricant. The high amount of C certifies the integrity of the coating. Also, as seen in **Figure 2(b)**, coating both the contacting surfaces reduced the wear on the disks significantly, with the lowest wear value observed for DLC, followed by Nedox.

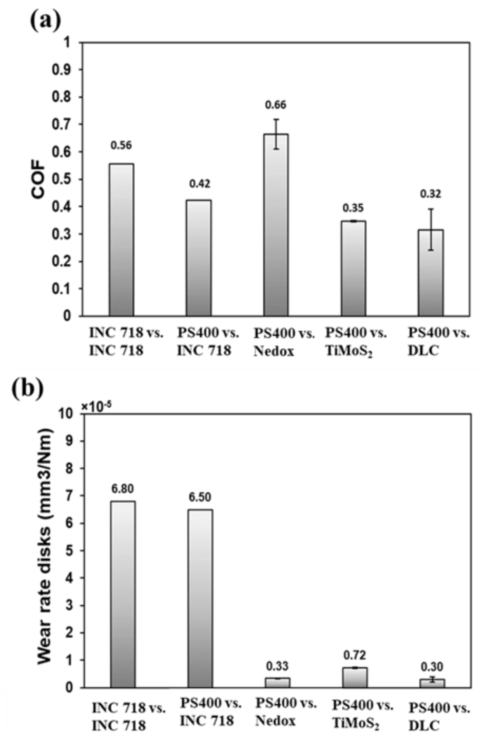

Figure 2. Experimental results showing (a) the average COF, and (b) the disk wear rates of the tribo-pairs.

Table 1. Elemental analysis via EDS of uncoated and coated disks following tribo-testing against PS400.

	Elements (at%)	C	O	Al	Ti	Cr	Fe	F	Ni	Mo	Ag	Ca	P
Disk specimens	INC 718	-	11.42	3.39	0.96	16.09	12.66	5.59	45.85	2.13	0.58	0.3	-
	Nedox	-	3.22	0.57	-	-	-	-	76.05	-	-		20.16
	Nedox-out	-	3.96	0.58	-	-	-	-	74.12	-	-		21.34
	$TiMoS_2$	-	27.38	1.72	4.19	4.25	1.77		48.58	8.07	2.97		-
	DLC	90.05	1.1	-	-	8.4	0.12	-	0.27	-	0.06		-

To qualitatively measure the amount of graphitization of the DLC coating after the tribological experiment against PS400, Raman Spectroscopy was employed. **Figure 3** shows the Raman spectra of the as-received DLC coating and after the experiment. The as-received DLC showed a wide spectrum, with the typical G band. Obvious peak splitting appeared only after exposing the coating at 462℃ due to the majority of sp^3 bonds in the structure of the as-received DLC. After the high temperature test, DLC graphitized and a "shoulder" peak centered at the I_D band can be observed. The peak intensities of each of the two spectra were fitted to two Gaussian line shapes for the D and G peaks. The as-received sample possessed a low I_D/I_G = 1.75, indicating a diamond-like structure. However, after the experiment the intensity ratio increased significantly to 3.4, therefore, a significant graphitization of the DLC coating occurred. After the experiment, the position of I_G was shifted towards higher frequencies, from 1520 to 1565 cm^{-1}, indicating an increase in the amount of graphite per unit volume [4].

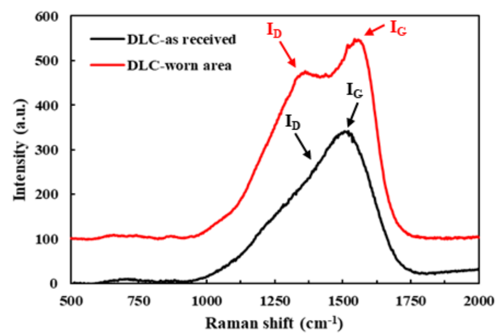

Figure 3. Raman spectra of as-received, and after tribo-experiment of DLC coating against PS400.

In conclusion, PS400 vs. DLC and PS400 vs. $TiMoS_2$ demonstrated the best tribological performance among the tribo-pairs under investigation, when tested under Venusian atmosphere, therefore opening new frontiers in testing the tribo-pairs under different parameters, such as ring-on-flat contact and higher pressures, which are closer to realistic applications.

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References: [1] Rehnmark F. et al. (2017) *Proc. of ESMATS*. [2] Taylor F. W. et al. (2018) *Space Sci Rev 214:35.* [3] Brandon R. S. (2019) *Electronic Thesis or Dissertation*. [4] Deng X. et al. (2013) *Tribology Online. 8(4):257-64.*