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1            Highly Stable Tribological Performance and  
2            Hydrophobicity of Porous Polyimide Material filled  
3            with lubricants in simulated Space Environment

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## 19 Abstract

20 Space exploitation and development need high-performance materials for spacecraft so as to  
21 maintain the long service life and reliability of mechanical equipment. The purpose of the  
22 present study was to exploit a new material with durable life, stable friction coefficient and low  
23 wear rate in harsh space environments. Two kind of solid-liquid synergetic lubricating  
24 composites have been prepared by perfluoropolyethers (PFPE) or chlorinated-phenyl and methyl  
25 terminated silicone oil (CPSO) filled in porous polyimide (PPI). Tribological performance and  
26 hydrophobicity of oil-filled PPI were evaluated by contact angle analyses and a ball-on-disk  
27 tribometer before and after proton irradiation in simulated space environment. After proton  
28 irradiation, two composites can maintain stable hydrophobic performance. More importantly, the  
29 friction coefficients of CPSO/PPI and PFPE/PPI increased slightly from 0.07 and 0.05 to 0.1 and  
30 0.14, respectively. The wear rates of CPSO/PPI and PFPE/PPI also increased slightly from  $5.13$   
31  $\times 10^{-5}$   $\text{mm}^3/\text{Nm}$  and  $4.23 \times 10^{-5}$   $\text{mm}^3/\text{Nm}$  to  $5.75 \times 10^{-5}$   $\text{mm}^3/\text{Nm}$  and  $6.19 \times 10^{-5}$   $\text{mm}^3/\text{Nm}$ ,  
32 respectively. The CPSO/PPI composite showed the smallest change in hydrophobicity, friction  
33 coefficient and wear rate before and after proton irradiation. The mechanism of highly stable  
34 hydrophobicity and tribological performance was mainly based on continuous self-healing surface,  
35 stored oil in the pores of PPI can creep to the surface of material to repair the damage induced by  
36 Pr irradiation, which ensured that the material has the stable and durable hydrophobicity and  
37 tribological properties in proton irradiation environment.

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39 KEYWORDS: Porous polyimide filled with lubricants; Solid-liquid synergetic lubricating;  
40 Simulated space irradiation; Hydrophobicity and tribological performance.

41

## 42 Introduction

43 The durability of material in rigorous environments is important for the service life and  
44 reliability of mechanical equipment, especially for the assemblies applied to space exploitation  
45 and development.<sup>1-5</sup> Spacecraft carries its missions affected by many complicated and  
46 changeable environmental factors, including thermal cycles ranging hundreds centigrade, ultra-  
47 high vacuum, high-energy cosmic radiation particles, etc. Among them, protons, electrons,  
48 atomic oxygen and ultraviolet rays could severely erode the materials used in the spacecraft and  
49 then induce the equipment failure, especially for proton radiation, which caused the worst  
50 damage to polymer materials.<sup>6-11</sup> Therefore, developing durable materials that can apply to  
51 extremely rigorous space environment is still a highly challenging task.

52 In recently years, considerable efforts have been dedicated to develop new materials for  
53 space applications, and mostly is studies on the single stable performance by mixing material,  
54 composite film, etc. The incorporation of carbon nanotubes into the polyimide matrix resulted in  
55 the enhanced thermo-optical properties in space environment.<sup>5</sup> Polyhedral oligomeric  
56 silsesquioxane incorporated into a Kapton-like polyimide, showing the favorable radiation  
57 resistance.<sup>12, 13</sup> The Pb/PbS composite film could keep stable low friction coefficient in vacuum  
58 condition for a long time.<sup>14</sup> Perfluoropolyether-filled anodic aluminum oxide showed highly  
59 durable hydrophobicity in simulated space environment.<sup>15</sup> However, these materials could not  
60 completely suffice the properties requirement of spacecraft special materials.

61 A desired goal is that the materials own the durable life, stable friction coefficient, low wear  
62 rate and durable hydrophobicity in harsh space environments.<sup>16-20</sup> In this context, the  
63 development of simple and efficient strategy by solid-liquid synergetic lubricating, which would  
64 achieve this goal, would be a highly desirable and attractive alternative. Liquid lubricants coated

65 on the surface of materials would be degraded in space irradiation environment,<sup>21-23</sup> which was  
66 not necessarily the best choice. Herein, we designed a kind of material with porous structures  
67 that can be used as a reservoir to store liquid lubricants. When the outermost oil molecules of  
68 porous material are degraded by space irradiations, stored lubricants in the porous gaps of  
69 material can creep and spread all over the surface of material to maintain the self-healing  
70 lubrication, which provides a new strategy to construct new type of materials for the applications  
71 of space science.

72 Polyimide (PI), a kind of important self-lubricating material, widely applied in space science  
73 because PI exhibits superior friction and wear characteristics in vacuum.<sup>24-27</sup> In our previous  
74 work, PI material has initial high friction coefficient and surface carbonization under proton  
75 irradiation environment, which could affect the stability of moving parts.<sup>28</sup> A kind of porous PI  
76 film with an ordered surface was also prepared, but PI film could not apply to lubricating  
77 material because of poor mechanical strength.<sup>29</sup> On the basis of these work, a new PI composite  
78 material was designed by filling liquid lubricants into the porous PI material to address the  
79 durable lubricating problems in irradiation environment. To the best of our knowledge, there has  
80 been no attempt via porous PI filled with lubricants to studied on the tribological behavior and  
81 hydrophobicity in extremely rigorous space environment, thereby making an important research  
82 work.

83 In this paper, the porous polyimide (PPI) block material was prepared by cold press and  
84 sintering technology using polyimide powder, and then the PPI block was immersed in the liquid  
85 lubricants to obtain the oil-containing PPI material. The perfluoropolyethers (PFPE) and  
86 chlorinated-phenyl and methyl terminated silicone oil (CPSO) were selected as liquid lubricants  
87 owing to excellent characteristics including very low volatility, high thermal resistance, non-

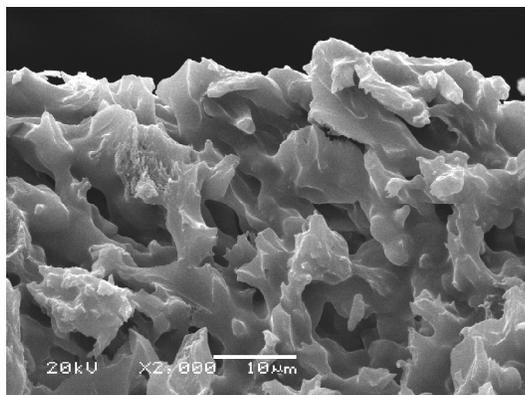
88 flammability and low surface energy.<sup>30, 31</sup> Then the PFPE and CPSO-filled PPI materials were  
89 subjected to proton irradiation test in simulated space environment because proton irradiation  
90 seriously affected tribological behavior of the PI materials.<sup>21, 32</sup> The hydrophobicity and  
91 tribological properties of oils-filled PPI materials were evaluated by contact angle (CA) analyses  
92 and a ball-on-disk tribometer. Multiple characterization techniques were employed to  
93 investigate changes in surface structures using attenuated total reflectance infrared spectroscopy  
94 (ATR-FTIR), micro-Raman spectroscopy and scanning electron microscope (SEM).

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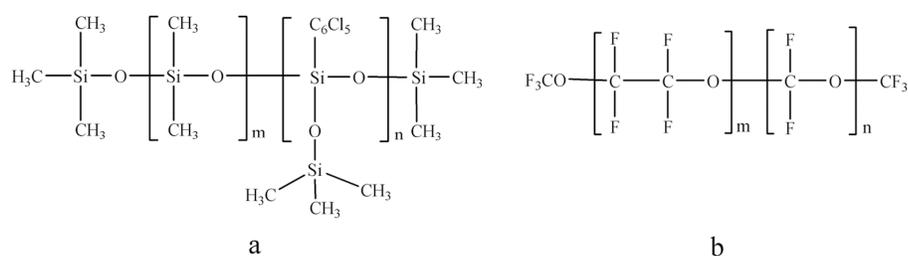
## 96 **Experimental**

### 97 **Materials**

98 The used PI powders with the particle size of 400 mesh were purchased from Shanghai  
99 Research Institute of Synthetic Resins, which has the density of 1.35 g/cm<sup>3</sup> and the glass  
100 transition temperature 250 °C. The PPI material was prepared by cold press and sintering  
101 technology, during which the PI powders were cold pressed in mold under a pressure of 30 MPa  
102 for 30 min and then sintered in an oven at 300 °C for 240 min to form a 20 × 12 × 15 mm<sup>3</sup> block  
103 which was finally cut into 20 × 12 × 2 mm<sup>3</sup> blocks for irradiation and wear test. The SEM picture  
104 of cross section of PPI sample was shown in Fig. 1. The prepared PPI samples were firstly dried  
105 in the vacuum under 120 °C for 2 h and then quickly immersed in the selected lubricating oil for  
106 24 h in the vacuum under 120 °C to fully infiltrate into the inner pore, followed by wiping the oil  
107 in the surface with cotton cloth. The liquid lubricants used were chlorinated-phenyl and methyl  
108 terminated silicone oil (CPSO) and perfluoropolyethers (PFPE, Fomblin M30), and the  
109 corresponding chemical formulation were shown in Fig. 2. CPSO was supplied by Lanzhou  
110 Institute of Chemical Physics. PFPE was obtained from Solvay solexis. Inc. and used as received.

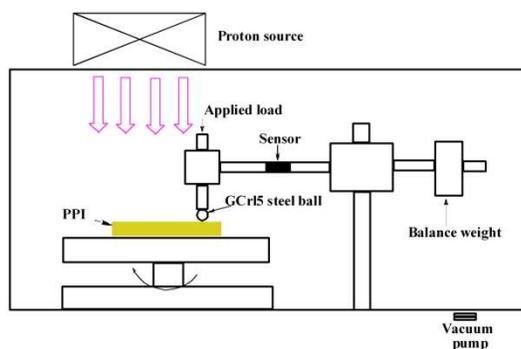


**Fig. 1** SEM picture of cross section of PPI sample.



**Fig. 2** The chemical formulation of the CPSO (a) and PFPE (b).

## Test methods

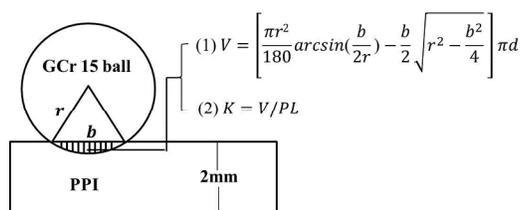


**Fig. 3** The schematic diagram of proton irradiation equipment.

The oil-filled PPI was then put into a chamber of a space environment simulation facility at Lanzhou Institute of Chemical Physics to conduct proton (Pr) irradiation at  $10^{-3}$  Pa (as shown in Fig. 3). The Pr irradiation was carried out at an accelerative voltage of 25 kV and the flux of

125 protons was determined to be about  $6.25 \times 10^{15}$  ions/cm<sup>2</sup>·s. The exposure time of Pr irradiation  
 126 was controlled as 5 min which was selected due to Pr irradiation possessing higher energy for  
 127 corroding organic compounds molecules.<sup>15, 21</sup>

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**Fig. 4** Calculation formula of the wear rate.

132 The friction and wear behavior of the bare PPI and oil-filled PPIs before and after Pr  
 133 irradiation against GCr15 steel ball were tested on a ball-on-disk tribometer in a vacuum level of  
 134  $3 \times 10^{-4}$  Pa. The GCr15 steel ball with a standard 3 mm diameter have the chemical composition  
 135 (in wt%): Mn (0.20-0.40), Si (0.15-0.35), Cr (1.30-1.65), C (0.75-0.85), P ( $\leq 0.026$ ), S ( $\leq 0.020$ )  
 136 and Fe balance. The hardness and elastic modulus are 6.9 GPa and 208 GPa, respectively. The  
 137 steel ball slid on sample disk that rotate at a speed of 0.126 m/s under the load of 5 N for 1800 s  
 138 with a rotational diameter of 10 mm. Fig. 4 shows the calculation for wear rate. Where b and d  
 139 respectively denote the width and the diameter of the wear track (10 mm), r refers to the radius  
 140 of the steel ball, V is the wear volume loss of PPI block (mm<sup>3</sup>), K (mm<sup>3</sup>·Nm<sup>-1</sup>) correspond to  
 141 wear rate value, P is the applied (N) load and L is the sliding distance (m). In order to minimize  
 142 the error, three specimens were tested under each condition to attain the average wear rate of  
 143 samples.

#### 144 **Characterization**

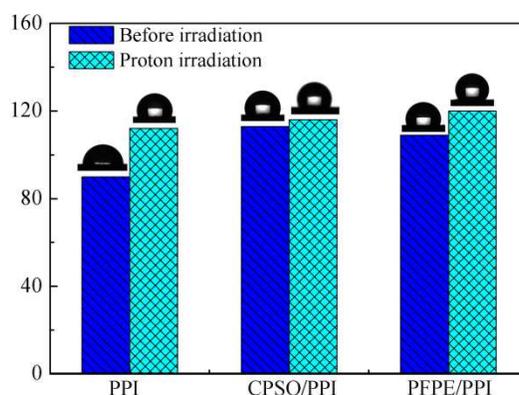
145 Contact angles (CA) were measured using a DSA-100 optical contact-angle meter (Kruss,

146 Germany) at room temperature (20 °C) by injecting 5  $\mu$ L double distilled water on the samples  
147 surface. Images were captured with a Digital Camera (Sony, Japan) and the average CA values  
148 were obtained by testing the same sample at five different positions. The infrared spectroscopic  
149 measurements were carried out on a Nexus 870 FTIR spectrometer (Nicolet, USA) using the  
150 attenuated total reflection (ATR) technique with a germanium crystal. A JEM-5600LV scanning  
151 electron microscope (SEM, JEOL, Japan) and an optical microscope were used to observe  
152 surface micrographs of samples. The ingredients of worn surfaces on steel ball were analyzed by  
153 a laser micro-Raman spectroscopy (LabRam HR800, Japan) at an excitation wavelength of 633  
154 nm and energy dispersive X-ray spectroscopy (EDS).

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## 156 Results and discussion

### 157 Hydrophobicity



158

159 **Fig. 5** Contact angles of bare PPI and oil-filled PPI before and after Pr irradiation.

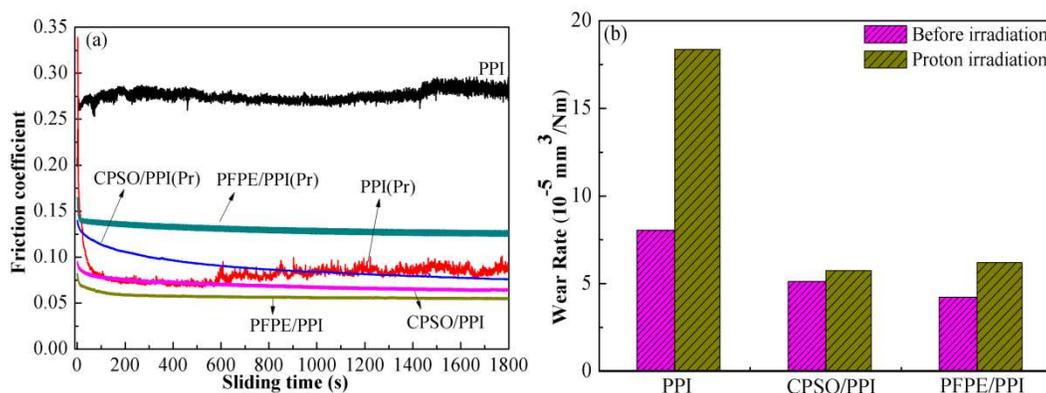
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161 The CA of water was measured to investigate the hydrophobicity performance of bare PPI  
162 and oil-filled PPI before and after Pr irradiation, and the results were presented in Fig. 5. Bare  
163 PPI, without any liquid lubricant, had a water CA of 90 °. After impregnated with CPSO and  
164 PFPE liquid lubricatin oil, the CA increased from 90 ° to 113 ° and 109 °, respectively. After Pr  
165 irradiation for 5 min, it can be easily seen that the CA of bare PPI, CPSO/PPI and PFPE/PPI

166 increased to 112 °, 116 ° and 120 °, respectively. The above results indicated that filling the oils  
 167 in PPI can enhance its hydrophobic property. In addition, these new composite can maintain  
 168 stable hydrophobic performance after Pr irradiation compared with the bare PPI, especial for the  
 169 CPSO/PPI sample.

## 170 Tribological performance

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172

173 **Fig. 6** The friction coefficient variation (a) and the wear rate (b) of bare PPI and oil-filled PPI before and after  
 174 Pr irradiation.  
 175

176 Friction coefficient and wear rate are the main indexes to evaluate tribological property. The  
 177 changes in friction and wear behaviors of PPI and oil-filled PPI against GCr15 steel balls before  
 178 and after Pr irradiation were comparatively investigated using a ball-on-disk tribometer. Fig. 6a  
 179 display the friction coefficient variations of bare PPI, CPSO/PPI and PFPE/PPI before and after  
 180 Pr irradiation. Before Pr irradiation, it can be seen that the friction coefficient of the bare PPI  
 181 sample is the highest with an obvious fluctuation in a range of 0.26-0.29. While, the friction  
 182 coefficients of CPSO/PPI and PFPE/PPI remained respectively very stable at about 0.07 and 0.05,  
 183 which is almost 1/4 and 1/6 of the friction coefficient of the bare PPI. After Pr irradiation, the  
 184 friction coefficient curve of bare PPI sample exhibited a drastic fluctuation, in which the initial  
 185 friction coefficient increased to 0.34 and the steady friction coefficient decreased to 0.10.

186 Whereas, the friction coefficients of CPSO/PPI and PFPE/PPI increased slightly from to 0.07 and  
187 0.05 to 0.10 and 0.14, respectively, and the curve is still stable. The bar charts in Fig. 6b present  
188 the wear rates of PPI, CPSO/PPI and PFPE/PPI before and after Pr irradiation. The wear rates of  
189 all samples have different degrees of increment after Pr irradiation. As for bare PPI, the wear rate  
190 after Pr irradiation is  $18.36 \times 10^{-5} \text{ mm}^3/\text{Nm}$ , which is about 2.3 times of that before Pr irradiation  
191 ( $8.06 \times 10^{-5} \text{ mm}^3/\text{Nm}$ ). In the case of CPSO/PPI, the wear rate after Pr irradiation is  $5.75 \times 10^{-5}$   
192  $\text{mm}^3/\text{Nm}$ , which is about 1.1 times of that before Pr irradiation ( $5.13 \times 10^{-5} \text{ mm}^3/\text{Nm}$ ). As for  
193 PFPE/PPI, the wear rate after Pr irradiation is  $6.19 \times 10^{-5} \text{ mm}^3/\text{Nm}$ , which is about 1.5 times of  
194 that before Pr irradiation ( $4.23 \times 10^{-5} \text{ mm}^3/\text{Nm}$ ). Therefore, filling oil in PPI is effective in  
195 decreasing the friction coefficient and wear rate to achieve super low-friction and wear resistance  
196 materials. Meanwhile, the friction and wear behavior of bare PPI is very sensitive to Pr  
197 irradiation, but the oil-filled PPI showed wonderful stability under Pr irradiation environment.  
198 Especially for CPSO/PPI that exhibited the smallest change in friction and wear behavior before  
199 and after Pr irradiation.

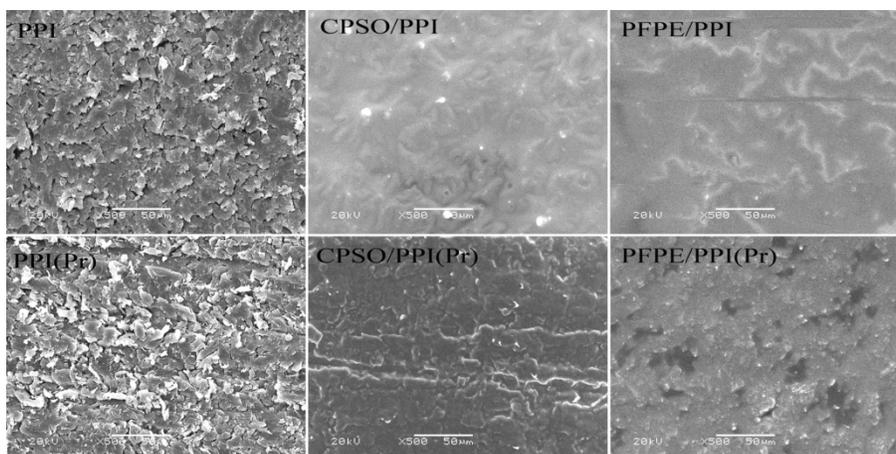
## 200 **Microstructural analysis**

201 To investigate the reason of the durable and stable hydrophobicity and tribological properties  
202 of the oil-filled PPI under Pr irradiation environment, the chemical structures, surface  
203 morphologies, and worn surface of the oil-filled PPI and steel ball were characterized by SEM,  
204 ATR-FTIR, Raman and EDS.

205 The surface morphologies of PPI and oil-filled PPI were observed by SEM before and after  
206 Pr irradiation, and the results were shown in Fig. 7. Compared to the bare PPI, the surfaces of  
207 CPSO/PPI and PFPE/PPI are relatively smooth, indicating that both CPSO and PFPE completely  
208 covered the rough PPI surface. After Pr irradiation, the surface of bare PPI was seriously eroded

209 to become much rougher, but the CPSO/PPI and PFPE/PPI still keep relatively smooth surfaces.

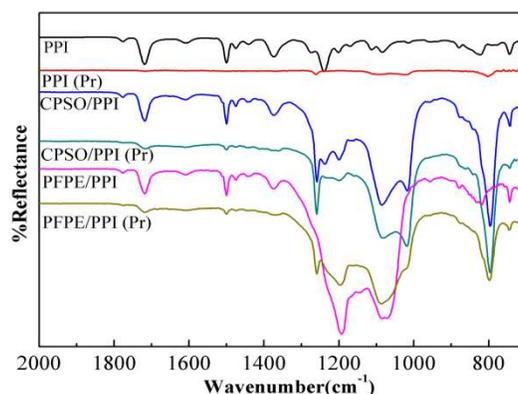
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212 **Fig. 7** SEM surface morphologies of PPI and oil-filled PPI before and after Pr irradiations.

213



214

215 **Fig. 8** FTIR-ATR spectra of PPI and oil-filled PPI before and after Pr irradiation.

216

217 The changes in chemical structures of bare PPI and oil-filled PPI surface before and after Pr

218 irradiation were investigated by FTIR-ATR, and the result was given in Fig. 8. It is clear that

219 bare PPI have the characteristic peaks at  $1717\text{ cm}^{-1}$  (C=O),  $1498\text{ cm}^{-1}$  (C=C),  $1372\text{ cm}^{-1}$  (C-N-

220 C),  $1240\text{ cm}^{-1}$  (C-O-C). When filled with CPSO or PFPE oil, except for the characteristic peaks

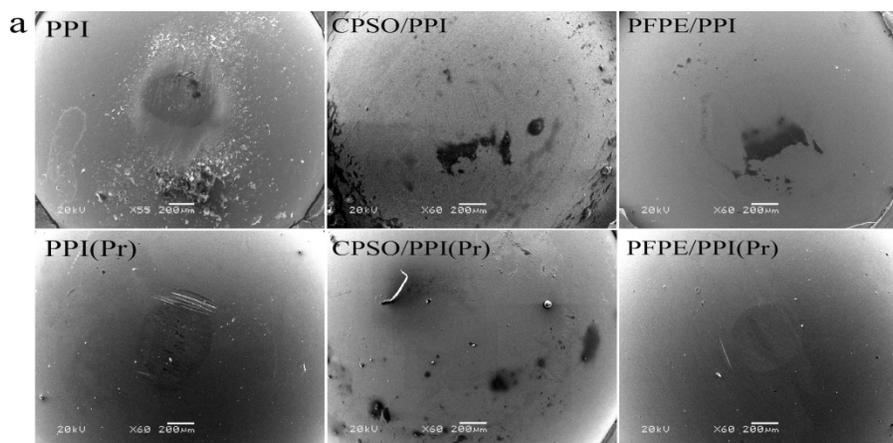
221 of PPI, it can be seen the characteristic peaks of the CPSO at  $1255\text{ cm}^{-1}$  (-CH<sub>3</sub>),  $1065\text{ cm}^{-1}$

222 (Si-O-Si),  $795\text{ cm}^{-1}$  (-Si-C-) and the characteristic peaks of PFEP at  $1090\text{ cm}^{-1}$ (C-O-C),  $1194$

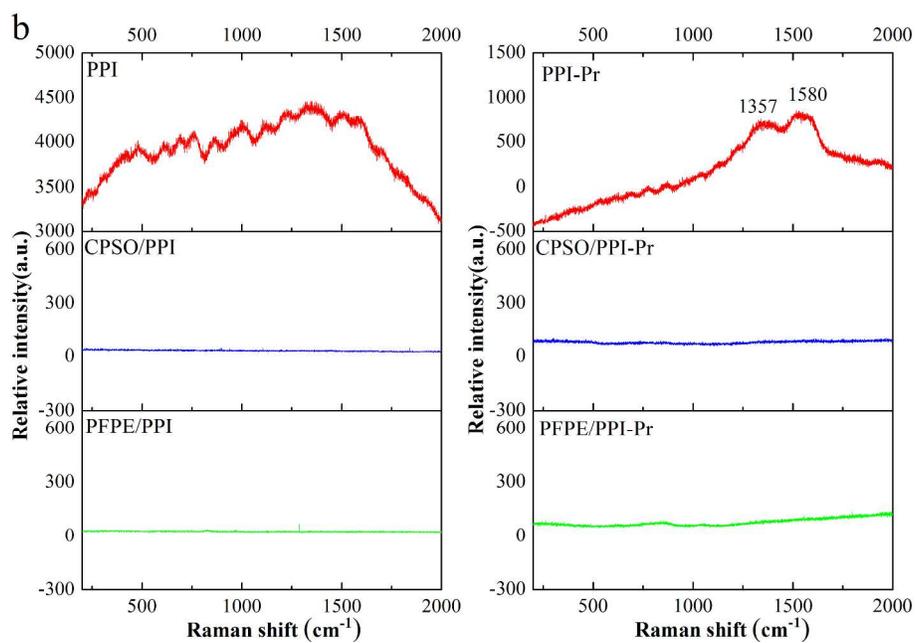
223  $\text{cm}^{-1}$  (CF),  $1230 \text{ cm}^{-1}$  ( $\text{CF}_2$ ).<sup>15, 33</sup> The chemical degradation of material induced by irradiation  
224 can be conveniently investigated by following the intensity changes of various FTIR peaks.<sup>34</sup> In  
225 addition, many research results showed that Pr irradiation could induce chain scission reaction  
226 occurring in organic polymer materials and then the the intensity of the characteristic peaks may  
227 reduce obviously.<sup>33, 35-37</sup> In this test, after Pr irradiation the intensity of the characteristic peaks  
228 for PPI in both bare PPI and oil-filled PPI decreased greatly. In contrast, the intensity of the  
229 characteristic peaks for both CPSO and PFPE oil reduced very slightly, which is not consistent  
230 with evidence in the reference that the Pr irradiation can seriously erod the oil molecules. The  
231 reason for this inconsistent is that the stored oil molecules in the prorous structure of PPI tends to  
232 spread out from the pore structure to the top surface of PPI due to the low surface energy.<sup>38</sup>

233 The worn surfaces of steel ball were analyzed in detail by SEM, Raman and EDS, and the  
234 results were presented in Fig. 9. As for the bare PPI, there was accumulated continuous transfer  
235 layer presented on the steel ball surface before and after Pr irradiation (Fig. 9a). As shown in Fig.  
236 9b, the Raman spectra of transfer layer of bare PPI before irradiation did not have specific peaks,  
237 which indicated that the composition of transfer layer was considered as polymer-like carbon. On  
238 the other hand, the spectrum of transfer layer of bare PPI after irradiation displayed two broad  
239 peaks at  $1357 \text{ cm}^{-1}$  and  $1580 \text{ cm}^{-1}$  that correspond to the D and G bands of disordered and  
240 ordered graphite, which indicated that a graphite-like structure was formed in the transfer layer.  
241 In contrast, there was no continuous transfer layer on the steel ball surfaces of the oil-filled PPI  
242 before and after Pr irradiation (Fig. 9a). In addition, no characteric peaks in Raman spectra were  
243 observed most likely because the changes occurred on the steel ball was out of the detection limit  
244 of the applied Raman system. Moreover, the EDS was used to analyze the elements on the steel  
245 ball. As shown in Fig. 9c, elements Si and F were detected in the steel ball surfaces of the oil-

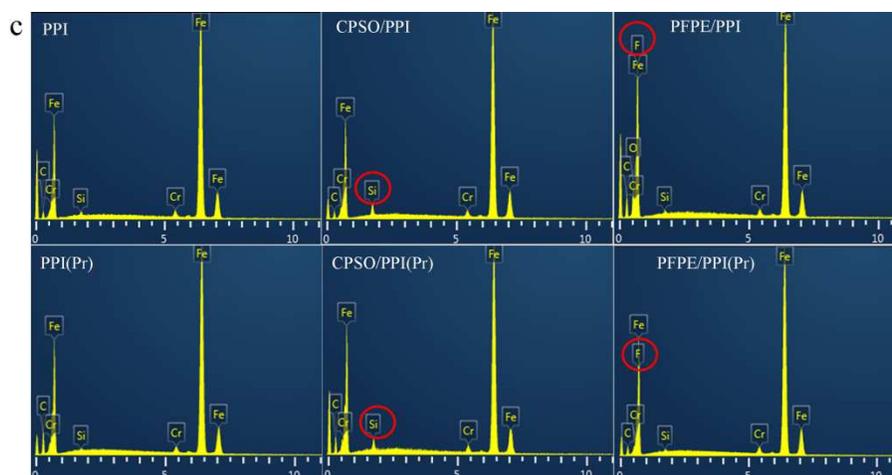
246 filled PPI before and after Pr irradiation, indicating that the steel balls surface of the oil-filled PPI  
247 contained lubricating oil which can prevent the solid-to-solid contact and then reduce the friction  
248 coefficient and wear rate.  
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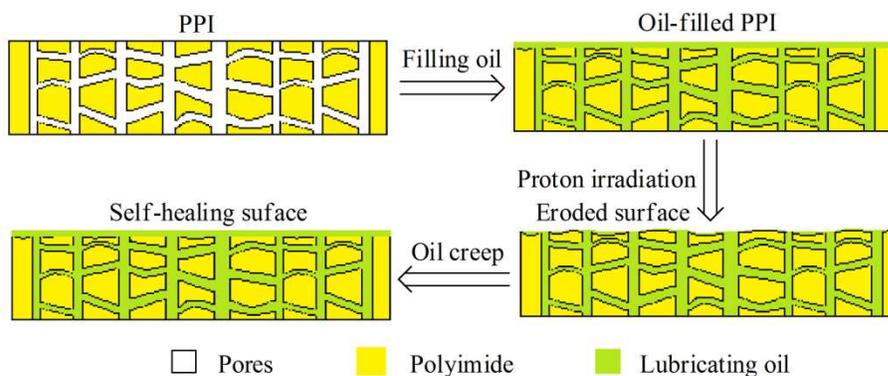


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253  
254 **Fig. 9** SEM images (a) of steel ball worn surfaces for PPI and oil-filled PPI before and after Pr irradiation, (b)  
255 are the corresponding Raman spectra and (c) the corresponding EDS spectra, respectively.  
256

257 According to the above analysis results, it can be easy to deduce the mechanism of the  
258 stability and durability of the hydrophobicity and tribological performance of oil-filled PPI under  
259 Pr irradiation, and the schematic was illustrated in Fig. 10. After the Pr irradiation in simulated  
260 space environment, the bare PPI has a significant change in hydrophobic properties and  
261 tribological performance because Pr irradiation could erode the surface structure. Though the  
262 surface of oil-filled PPI was also suffered some damage, the stored oil molecules in the porous  
263 structure of PPI tends to creep on the surface of PPI especially for the CPSO oil due to the lower  
264 surface energy. Therefore, the ability to withstand Pr irradiation damage was mainly based on  
265 continuous self-healing surface as a result of stored oil in the porous structure of PPI, and the  
266 lubricants oils could spread out from its micropores onto the contact surface to form a  
267 homogeneous and plain oil film which enhanced hydrophobicity and reduced its friction  
268 coefficient and wear rate. Meanwhile, a balance may be maintained between the irradiation  
269 damage and self-healing of oil-filled PPI, which ensured that the material has the stable and  
270 durable hydrophobicity and tribological properties in Pr irradiation environment.  
271



**Fig. 10** Schematic illustration of explaining possible self-healing mechanism of oil-filled PPI under Pr irradiation.

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## 276 Conclusions

277 In sum, two kind of PPI composite materials were designed and fabricated by filling PFPE or  
278 CPSO oils into the PPI pore. Oil-filled PPI showed the highly stable and durable hydrophobicity  
279 and tribological performance compared with the bare PPI, especially for the CPSO/PPI  
280 composite which had the smallest changes in hydrophobicity, friction coefficient and wear rate  
281 before and after Pr irradiation. Combining with the characterizations of SEM, ATR-FTIR, Raman  
282 and EDS, Pr irradiation could induce the surface damage of all test samples. The graphite-like  
283 substance was formed on bare PPI surface, but the CPSO/PPI and PFPE/PPI still keep relatively  
284 smooth surfaces. These excellent performances of oil-filled PPI in simulated space environment  
285 was mainly attributed to the stored oil in the pores of PPI tends to spread all over the PPI surface  
286 to maintain the self-healing hydrophobicity and lubrication.

287

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## 293 References

- 294 1 L. Rapoport, N. Fleischer and R. Tenne, *Adv. Mater.*, 2003, 15, 651-655.
- 295 2 Y. Zhang, X. Yin, J. Wang and F. Yan, *RSC Adv.*, 2014, 4, 55752-55759.
- 296 3 J. G. Smith Jr, J. W. Connell, D. M. Delozier, P. T. Lillehei, K. A. Watson, Y. Lin, B. Zhou and Y. P. Sun,  
297 *Polymer*, 2004, 45, 825-836.
- 298 4 J. G. Smith, J. W. Connell, K. A. Watson and P. M. Danehy, *Polymer*, 2005, 46, 2276-2284.
- 299 5 N. Atar, E. Grossman, I. Gouzman, A. Bolker and Y. Hanein, *ACS Appl. Mater. Inter.*, 2014, 6, 20400-  
300 20407.
- 301 6 H. Koshiishi and H. Matsumoto, *J. Atmos. Sol.-Terr. Phy.*, 2013, 99, 129-133.
- 302 7 X.-H. Zhao, Z.-G. Shen, Y.-S. Xing and S.-L. Ma, *Polym. Degrad. Stab.*, 2005, 88, 275-285.
- 303 8 M. Tagawa, M. Muromoto, S. Hachiue, K. Yokota, N. Ohmae, K. Matsumoto and M. Suzuki, *Tribol. Lett.*,  
304 2005, 18, 437-443.
- 305 9 V. A. Shuvalov, N. I. Pis'mennyi, G. S. Kochubei and N. A. Tokmak, *Cosmic Res.*, 2014, 52, 99-105.
- 306 10 M. Tagawa, K. Yokota, K. Kishida, A. Okamoto and T. K. Minton, *ACS Appl. Mater. Inter.*, 2010, 2, 1866-  
307 1871.
- 308 11 P. A. Bertrand, *Tribol. Lett.*, 2010, 40, 187-198.
- 309 12 T. K. Minton, M. E. Wright, S. J. Tomczak, S. A. Marquez, L. Shen, A. L. Brunsvold, R. Cooper, J. Zhang,  
310 V. Vij, A. J. Guenther and B. J. Petteys, *ACS Appl. Mater. Inter.*, 2011, 4, 492-502.
- 311 13 G. Song, X. Li, Q. Jiang, J. Mu and Z. Jiang, *RSC Adv.*, 2015, DOI: 10.1039/C4RA14727H.
- 312 14 G. Ma, B. Xu, H. Wang, S. Chen and Z. Xing, *ACS Appl. Mater. Inter.*, 2014, 6, 532-538.
- 313 15 R. Guo, H. Hu, Z. Liu, X. Wang and F. Zhou, *RSC Adv.*, 2014, 4, 28780-28785.
- 314 16 T. K. Minton, J.-F. Roussel and J.-F. Roussel, *ACS Appl. Mater. Inter.*, 2010, 2, 2687-2688.
- 315 17 G. Li, X. Liu and T. Li, *Composites Part B-Eng.*, 2013, 44, 60-66.
- 316 18 K. A. Watson, F. L. Palmieri and J. W. Connell, *Macromolecules*, 2002, 35, 4968-4974.
- 317 19 R. L. Fusaro, *Tribol. Int.*, 1990, 23, 105-122.
- 318 20 M. T. Tagawa, Masahito and K. Yokota, *Acta Astronaut.*, 2008, 62, 203-211.

- 319 21 X. Liu, L. Wang, J. Pu and Q. Xue, *Appl. Surf. Sci.*, 2012, 258, 8289-8297.
- 320 22 X. F. Liu, J. B. Pu, L. P. Wang and Q. J. Xue, *J. Mater. Chem. A*, 2013, 1, 3797-3809.
- 321 23 X. Liu, L. Wang and Q. Xue, *Tribol. Int.*, 2013, 60, 36-44.
- 322 24 I. Gofman, B. D. Zhang, W. C. Zang, Y. Zhang, G. L. Song, C. H. Chen and Y. Li, *J. Polym. Res.*, 2013, 20,  
323 258-267.
- 324 25 B. Liu, M. Ji, J. G. Liu, L. Fan and S. Y. Yang, *High Perform. Polym.*, 2013, 25, 907-918.
- 325 26 F. Xiao, K. Wang and M. Zhan, *J. Mater. Sci.*, 2012, 47, 4904-4913.
- 326 27 M. Iwata, A. Ohnishi, H. Hirose and F. Tohyama, *J. Spacecr. Rockets*, 2001, 38, 504-509.
- 327 28 M. Lv, F. Zheng, Q. Wang, T. Wang and Y. Liang, *Wear*, 2014, 316, 30-36.
- 328 29 C. Wang, Q. H. Wang and T. M. Wang, *Langmuir*, 2010, 26, 18357-18361.
- 329 30 L. J. Weng, H. Z. Wang, D. P. Feng, W. M. Liu and Q. J. Xue, *Ind. Lubr. Tribol.*, 2008, 60, 216-221.
- 330 31 M. Marchetti, M. H. Meurisse, P. Vergne, J. Sicre, M. Durand and J. Durand, in *Proceedings of the 8th*  
331 *European Space Mechanisms and Tribology Symposium*, ed. D. Danesy, 1998, vol. 438, pp. 233-238.
- 332 32 M. Lv, Y. Wang, Q. Wang, T. Wang and Y. Liang, *Radiat. Phys. Chem.*, 2015, 107, 171-177.
- 333 33 R. Huszank, S. Z. Szilasi and D. Szikra, *J. Phys. Chem. C*, 2013, 117, 25884-25889.
- 334 34 E. J. Petersen, T. Lam, J. M. Gorham, K. C. Scott, C. J. Long, D. Stanley, R. Sharma, J. Alexander Liddle,  
335 B. Pellegrin and T. Nguyen, *Carbon*, 2014, 69, 194-205.
- 336 35 R. Huszank, D. Szikra, A. Simon, S. Z. Szilasi and I. P. Nagy, *Langmuir*, 2011, 27, 3842-3848.
- 337 36 M. Porubská, O. Szöllös, A. Kóňová, I. Janigová, M. Jašková, K. Jomová and I. Chodák, *Polym. Degrad.*  
338 *Stab.*, 2012, 97, 523-531.
- 339 37 B. X. Liu, X. Q. Pei, Q. H. Wang, X. J. Sun and T. M. Wang, *Appl. Surf. Sci.*, 2011, 258, 1097-1102.
- 340 38 P. Saravanan, N. Satyanarayana, D. H. Minh and S. K. Sinha, *Wear*, 2013, 307, 182-189.