Lunar Surface Innovation CONSORTIUM Fall Meeting 2020

Stored Mechanical Energy and Carbon Onion Resilience Under Space Radiation

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INTRODUCTION

The lunar environment is extreme due to: vacuum, thermal stress and radiation. Nano-carbons are a promising approach to lubrication challenges in extreme environments including vacuum, radiation and non-terrestrial temperature regimes.

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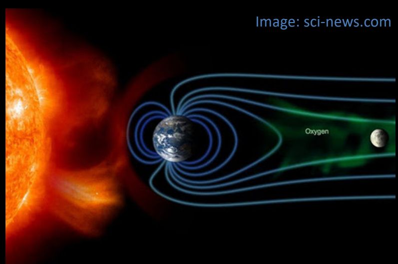


METHODS

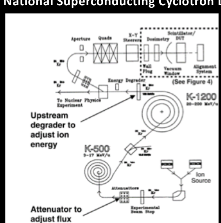
Researchers at Tokyo Institute of Technology have investigated the vacuum tribological performance of major types of nano-carbons [1a, b]. **The best vacuum tribological performance was achieved with carbon onions (COs).**

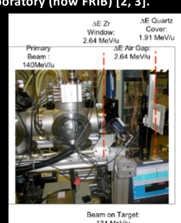
Carbon Lubricant Performances in Air and Vacuum [1 a, b]

Friction Coefficient	Carbon Onions	CNTs	C_{60}	Graphite	VGCFs
Air	**0.1-0.2**	0.5	0.5	0.2	0.5
Vacuum	**0.04-0.06**	0.2	0.6	0.6	0.2

This research further indicated that **nano carbons have a high tolerance for thermal stress [1 a].**

The present work focuses on the study of **radiation effects on COs using well-calibrated heavy ion beams at realistic solar wind energies at the National Superconducting Cyclotron Laboratory (now FRIB) [2, 3].**



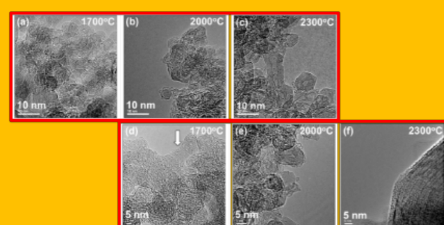


RESULTS

EXPERIMENTS:

- Relativistic heavy ion interactions with COs synthesized at 1700 °C, 2000 °C and 2300 °C, were investigated using primary beams of ~90% fully stripped argon-40 at 140 MeV/u, and calcium-48 at 140 and 70 MeV/u.
- Irradiation times that resulted in 10,000 Gray (Joule/kg) cumulative total dose (TD) for each sample proved sufficient to introduce non-destructive structural changes.
- Pre and post radiation characterization of temperature-series COs by HRTEM was performed in a JEOL 2200FS operated at 200 kV.

PRE-RAD: Tokyo Institute of Technology COs synthesized at 1700 °C, 2000 °C and 2300 °C displayed well-known Increasing polygonal character as a function of increasing growth temperature.



POST-RAD: The 1700 °C COs showed an increase in the polygonal character and fusion of adjacent onion pairs (arrow).

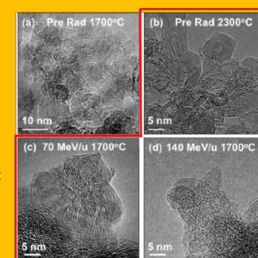
The 2000 °C COs showed fewer layer breaks in individual graphene shells and an overall increase in polygonal character that caused them to resemble pre-rad 2300 °C COs.

The 2300 °C COs showed the greatest variety of rearrangements, with the development of large crystallites of planar graphite (shown), long, 5-7 layer planar graphene ribbons, and occasional amorphous regions.

ENERGY VERSUS TIME:

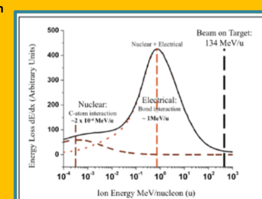
Calcium-48 experiments were also performed with 140 versus 70 MeV/u to investigate energy versus time equivalence for the same TD

POST-RAD: Post irradiation 1700 °C COs at (c) 70 MeV/u and (d) 140 MeV/u calcium-48 both resemble 2300 °C pre-irradiation carbon onions: **energy-time TD equivalence in the CO system.**



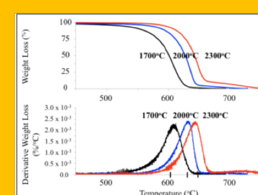
TOTAL ENERGY LOSS: Monte Carlo SRIM calculations for total energy loss dE/dx with individual nuclear and electronic interaction contributions [2]:

- Peak of the **nuclear contribution** at 2 x 10^{-4} MeV/u far from the beam-on-target 134MeV/u energy.
- Peak total energy loss ⇔ **peak electronic contribution** at 1 MeV/u but still far from the beam-on-target 134MeV/u energy.

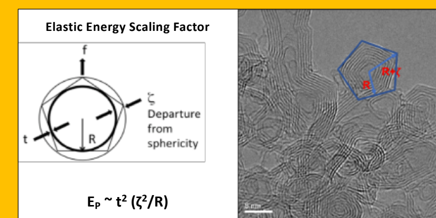


THERMOGRAVIMETRIC ANALYSIS (TGA):

- Nonlinear **increase in ease of dissociation** with increasing polygonal character.
- Most evident in **derivative weight loss**



ANALYSIS



$E_P \sim t^2 (\zeta^2/R)$

Summary of Measurements for Elasticity E Components

Variable /Specimen	1700 Pre-Rad	2000 Pre-Rad	2300 Pre-Rad	Ar 1700 Post-Rad	Ar 2000 Post-Rad	Ar 2300 Post Rad	Ca 1700 70MeV	Ca 1700 140MeV
Avg.ζ (nm) /STDEOM	0.706 /0.155	0.942 /0.125	1.40 /0.116	1.156 /0.221	1.591 /0.214	1.708 /0.214	1.141 /0.145	1.403 /0.138
Avg.# of Layers /STDEOM	6.4 /0.371	5.7 /0.3	6.3 /0.3	6.3 /0.213	7.8 /0.952	7.2 /0.412	6.7 /0.559	7.2 /0.52
Avg. Layer Thickness (nm) /STDEOM	0.346 /0.329	0.453 /0.027	0.463 /0.033	0.433 /0.031	0.379 /0.018	0.349 /0.017	0.435 /0.024	0.441 /0.027
Avg. Radius (nm) /STDEOM	2.502 /0.197	2.923 /0.166	3.093 /0.176	2.643 /0.196	3.432 /0.335	3.141 /0.263	2.787 /0.559	3.057 /0.281
$t^2 (\zeta^2/R)$	0.024	0.062	0.136	0.095	0.106	0.113	0.088	0.125

ANALYSIS applies Ref [4] approach to heavy ion irradiation of COs

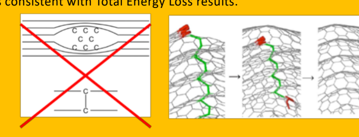
RESULT: Polygonal increase ⇔ stored elastic energy increase as shown by experimental scaling factors

PRE-RAD: Temperature-induced polygonal increase

POST-RAD: Radiation-induced polygonal increase

CONCLUSIONS

Graphene layer rearrangement driven by low-energy dislocation migration mechanisms only available in multi-layer **radial** situations [5] is consistent with Total Energy Loss results.



Highly polygonal COs are typically considered less defective/more perfect. However, our results indicate that release of the **increased elastic energy stored in highly polygonal COs can drive increased dislocation-driven rearrangement(s).**

Lower temperature synthesis COs may be more resilient to heavy ion induced rearrangement(s) and therefore preferable for lunar environments. A practical conclusion is that the polygonal character of a CO sample should be quantified prior to space lubricant applications.

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