Comparison of W-alloys and CFCs Exposed to High Heat Flux and Ablation

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Abstract

A portion of the Sandia HHF database on CFCs and tungsten alloys considered for use in solid wall applications is presented. These materials were tested as part of the MFE program, but the results may be applicable to IFE chambers as well.

Carbon fiber composites were exposed to heat fluxes up to ~100MW/m² for shots typically of 1.5s in the Electron Beam Test System at Sandia National Laboratories. The heat flux was focused on a square 1 x 1 cm at the centers of samples 2.5 x 2.5 cm and 1.0 cm in height; the thermal expansion of the center region causes high thermal strains. The most basic results from all of these tests is that, as expected, none of the CFC samples fractured.

Some CFCs achieved higher heat fluxes than others while their surface temperatures remained below a threshold of 2800°C. One sample received the highest heat flux observed in such tests with the surface temperature remaining under 2800°C.

The fatigue performance and resistance to surface erosion of both US and RF grades of W-alloys were tested between 1997 and 2001. A summary of the test results for low-cycle thermal fatigue and combined plasma disruption/HHF testing is reported. During low-cycle thermal fatigue, bulk samples 17x17 mm² and 3 or 5 mm thick were cyclicly loaded by e-beam at 1 Hz to generate a localized temperature spike and plastic strains on the tile surface. Over 14,000 cycles were performed. For the disruption/HHF testing, actively cooled W-alloy armor was tested.

In the most recent CFC survey, a total of 28 samples were tested; 6 of these were duplicates where samples with thermocouples were placed adjacent to samples without thermocouples. The thermocouples were used to measure the absorbed heat and to calculate the fraction of the beam power absorbed. The samples were tested to 100MW/m² with 1.5s shots and then selected samples were tested at 60MW/m² for shots up to 3.5s.

Five samples of Allied Signal 2-D CFC Type 865-19-4 were tested. This carbon fiber composite, or CFC, is the "brake pad material" used for tiles in TFTR.

Two samples each were oriented with an edge of the 2-D CFC architecture facing the electron beam. The last sample had the 2-D plane perpendicular to the electron beam.

Sandia National Lab. : CFC High Heat Flux Test December 1998

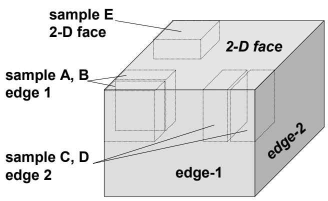
No.	Type I.D	weave	Thermal Conductivity z-dir.	Normal	Parallell	Density (g./cc)	wt. loss (g.)
13	4D-Thr	4-D	**121.7**	121.7	141.5	1.82	0.0017
15	4D-TG-C	4-D	**185.1**	185.1	242.6	1.87	0.0137
17	4D-TG-D-R	4-D	**97.8**	97.8	96.5	1.70	0.0009
25	Fi-BD-P	Quasi 3-D	**27.6**	20.3	27.6	1.57	0.0000
27	Fi-BD-N	Quasi 3-D	**20.3**	20.3	27.6	1.57	0.0010
29	Chop-TG-P	Chopped	**35.0**	35.0	17.5	1.82	0.0004
31	Chop-TG-N	Chopped	**17.5**	17.5	35.0	1.82	0.0001
33	Chop-Pitch-P	Chopped	**159.9**	159.9	41.0	1.73	0.0006
35	Chop-Pitch-N	Chopped	**41.0**	159.9	41.0	1.73	0.0001
38	2D-Pitch-BD-P	2-D	**157.4**	54.4	157.4	1.73	0.0013
39	2D-Pitch-BD-N	2-D	**54.4**	157.4	54.4	1.73	0.0007
42	2D-Phenol-1.78	2-D	**162.1**	24.5	162.1	1.78	0.0012
45	To-Yo 10x10						0.0007
47	4D-TG -HIP	4-D	**78.8**	78.8	120.7	1.72	0.0009
48	2D-Phenol-1.52	2-D	**101.6**	12.7	101.6	1.52	0.0017
51	3D-TG	3-D	**241.9**	241.9	167.5	1.67	0.0083

Sandia National Lab. : CFC High Heat Flux Test August 1999

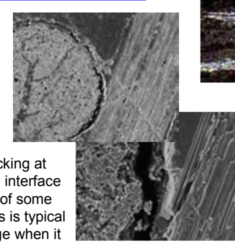
No.	Type I.D	weave	Thermal Conductivity z-dir.	Normal	Parallell	Density (g./cc)	wt. loss (g.)
1	4D-nae	4-D	**125.0**	125.0	117.0	1.95	0.0006
2	4D-nae	4-D	**125.0**	125.0	117.0	1.95	0.0006
3	4D-24	4-D	**61.0**	61.0	54.0	1.82	0.0002
4	4D-24	4-D	**61.0**	61.0	54.0	1.82	-0.0002
5	4D-24	4-D	**61.0**	61.0	54.0	1.82	0.0001
6	4D-24	4-D	**61.0**	61.0	54.0	1.82	0.0000
7	2D-L-24-P	2-D	**104.0**	30.0	104.0	1.98	-0.0049
8	2D-L-24-P	2-D	**104.0**	30.0	104.0	1.98	-0.0025
9	2D-L-24-P	2-D	**104.0**	30.0	104.0	1.98	0.0003
10	2D-L-24-P	2-D	**104.0**	30.0	104.0	1.98	0.0004
11	4D-KO	4-D	**100.5**	100.5	117.5	1.88	0.0000
13	4D-nae	4-D	**125.3**	125.3	117.0	1.96	0.0015
20	2D-L-2700-P	2-D	**144.6**	37.8	144.6	1.97	0.0002
26	4D-2(n)	4-D	**104.0**	104.0	103.6	1.79	0.0004
30	4D-3	4-D	**206.7**	206.7	191.0	1.71	0.0003
31	4D-3	4-D	**206.7**	206.7	191.0	1.71	0.0003
32	4D-4	4-D	**187.7**	143.6	187.7	1.94	0.0007
38	4D-7	4-D	**144.1**	144.1	162.6	1.86	0.0009
15	4D-TG-C	4-D	**185.1**	185.1	242.6	1.87	0.0005
51	3D-TG	3-D	**241.9**	241.9	167.5	1.67	0.0000
	Quasi 3-D	3-D					0.0000

Conclusions on CFC Testing

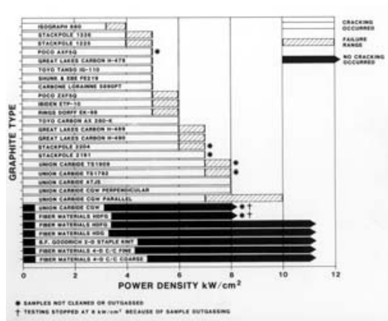
- The Allied Signal 2-D CFC Type 865-19-4 samples received 1.5s shots at heat fluxes to 120MW/m².
- The CFCs from Korea Aerospace Industries, KAI (formerly Daewoo) performed well. Sample K20 had the longest time to reach 2600°C* (at 92MW/m²) measured in this test or another test of various CFCs done for the US TPX Project.
- K20 has a 2-D architecture (K20). Samples, which had 3-D architecture and higher thermal conductivities in both the parallel and perpendicular directions but lower densities, did not perform as well. In these tests, heat flows downward and also radially outward from the central heated area. The radially outward flow may be more important in how quickly the surface temperature at the center rises.
- Among the samples with the longer times to reach 2600°C, the time for K20 was slightly longer. Although other samples had a similar architecture, K20 had a higher processing temperature a somewhat higher thermal conductivity.
- Weight loss measurements were also taken, and K20 had the least weight loss within the group of KAI samples tested.



2-D carbon fiber composite Allied Signal (Type 865-19-4)

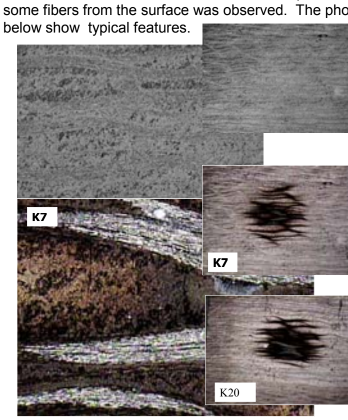


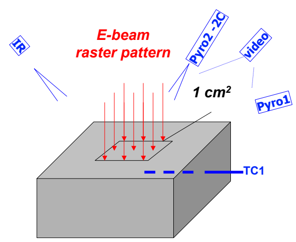
K1 - Cracking at fiber tow interface and loss of some fiber ends is typical of damage when it occurred



Surface Features

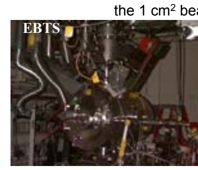
The samples were observed with a low magnification optical microscope and a scanning electron microscope (SEM) before and after testing. The the most prominent feature is the blackening of the surface where substantial vaporization of carbon has occurred. Other features observed include some cracking in the fiber tows and in the matrix. Also, in the first round of tests, separation of some fibers from the surface was observed. The photos below show typical features.

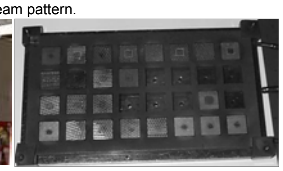




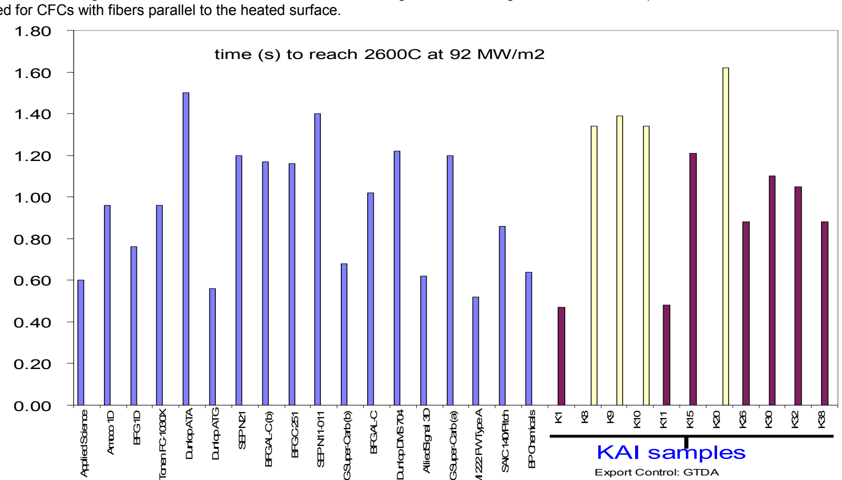
Basic diagnostics for EBTS tests on un-cooled samples

During these tests, the samples are held in a graphite holder (photo below) that is clamped to a water-cooled copper plate. The plate is held on a computer-controlled X-Y table that is moved to position one sample under the 1 cm² beam pattern.





High heat flux testing of uncooled, carbon fiber composite (CFC) samples, has been done as a simple screening test on candidate CFCs for various fusion applications. Few samples are expected to fail through gross or obvious damage since this class of materials is quite tough. However, some differences in response among the samples are evident in post-test microscopic evaluations. The test was originally used as a screening test of various graphites, some of which did show gross fractures during the tests. The test has continued in use as a general screening test, but newer test procedures are required for CFCs with fibers parallel to the heated surface.



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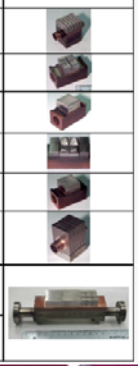
Comparison of W-alloys and CFCs Exposed to High Heat Flux and Ablation

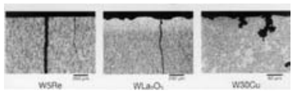
Actively cooled tungsten subjected to HHF and plasma disruptions

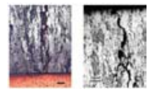
Geometry of tiles	W/Cu joining technique	Testing conditions: Heat flux, MW/m²	Testing conditions: Number of cycles	Picture
20x5x10 (#115)	Brazing	15	1000	
10x10x10 (#124)	Brazing	17.5	1000	
20x20x10 (#123)	Brazing	10	1000	
10x10x10 (#74)	Casting	20-27	2900	
20x20x10 (#117-1)	Casting	10	1000	
20x25x3 (monoblock)	Casting	17	260	
9x9x10 (HPV mock-up)	Casting	7 10 12,5 20	1000 1000 1000 2000	
27x27x10 (HPV mock-up)	Casting	7 10 12,5	1000 1000 1000	

W-2%Re <111> orientation

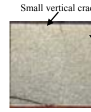
Disruption facilities in the Russian Federation

Facility	Energy density MJ/m²	Power density GW/m²	Pulse duration ms	Particles Energy keV	Plasma density m^{-3}	B field T	Beta value	Plasma stream Size, cm
MK-200UG Pulsed plasma gun with long drift tube	15	300-400	0.04-0.05	1.5(ion) 0.15(elect)	2×10^{21}	2	0.3	6.5 diam.
GOL 3-II Long mirror trap	8-10	1000-1300	0.01-0.02	1-3 (ion) 800(elect)	10^{21}	2-12	0.01-0.3	6 diam.

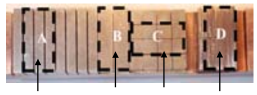




W-1% La_2O_3

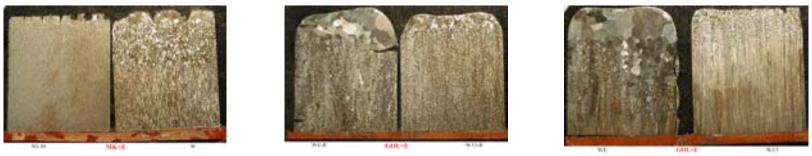


W-Re recrystallized

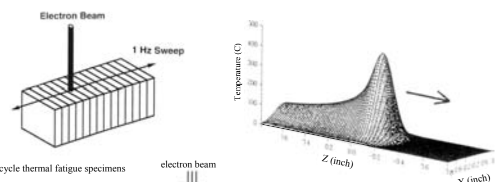


geometry selection mock-up

Comparisons:
A variety of parameters can be compared to rate the various tungsten grades and joining techniques. For the CFCs, time at a particular heat flux before reaching a maximum temperature was the criterion. Weight loss due to vaporization or ablation is another equally important measure. For actively cooled specimens, the maximum heat flux achieved before melting or excessive cracking is important. In low cycle thermal fatigue, either the maximum observed crack depths or the number of cycles until crack initiation, were used to rate the tungsten grades. All are a measure of damage resistance to high heat flux.

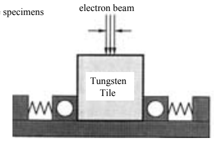


Electron Beam Low Cycle Thermal Fatigue

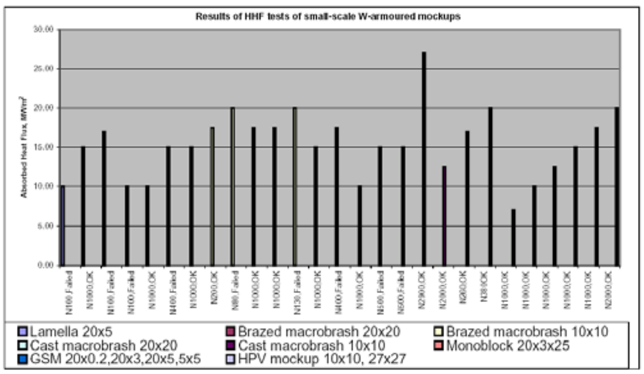


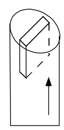
Low-cycle thermal fatigue specimens

1000 W gaussian e-beam spot
Moving at 200 m/s from left to right
Approx. 0.8 kJ/m²

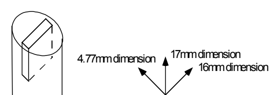


Setup with tungsten tiles clamped to water-cooled copper blocks with Papyex interlayer.

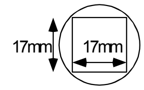




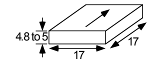
Cutting scheme of single crystal specimens. The arrow shows the axis of the rod



Cutting Scheme for Vacuum Melted Material

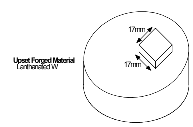


Cutting Scheme for Swaged Material



Sample geometry of thermal fatigue specimens.

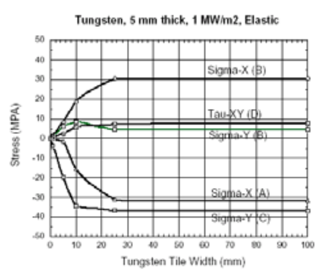
The case for tungsten rod armor: at tile dimensions less than 4 mm, the thermal stresses across the width are substantially reduced. This results in a more robust tile to heat sink joint.

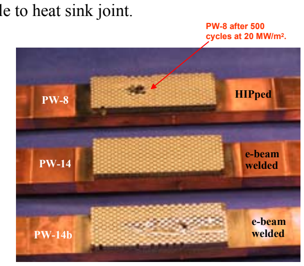


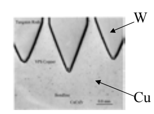
Cutting Scheme for Upset Forged Material

GRADE	PRODUCT FORM	SOURCE	DIMENSIONS (mm) Length	Width	Thickness
Pure	Swaged Bar	Plansee	17	17	4.77
W - 1%La_2O_3	Swaged Bar	Plansee	17	17	4.77
W - 1%La_2O_3	Upset Forged	Plansee	17	17	4.77
Pure	Vacuum Cast	Efremov	17	16	4.77
Pure	SC - <111>	Efremov	17	17	5
Pure	SC - <110>	Efremov	17	17	4.8
Pure	SC - <100>	Efremov	17	17	4.8

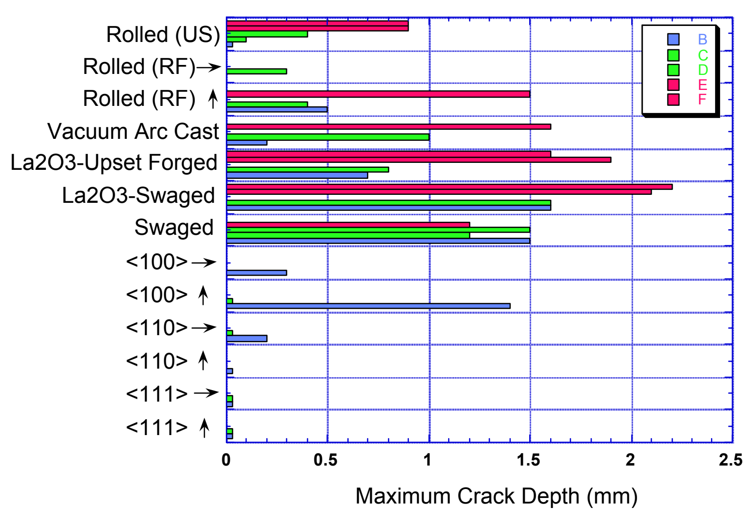
Product Forms:
Swaged Bar - Slight grain orientation parallel to thickness, fully recrystallized
Upset Forged - Upset forged material - Grain orientation roughly equiaxed.
SC - Single Crystal - Crystal orientation of rod provided
Vacuum Cast - Vacuum melted and cast material







Tungsten Low Cycle Thermal Fatigue



Recommendations
Single crystal W and inexpensive rolled W sheet are prime candidates for testing on Sandia's Z-machine or RHEPP. Oxidation of W during chamber sweeping may be an issue. If tritium retention is not an issue, then some of the newer 2-d CFCs are also good choices for further testing. 3-d and 1-d CFCs have lower performance. Isotropic graphites and pyrolytics should be avoided.

Conclusions
A large international database exists on fatigue performance and fracture toughness for CFC and tungsten alloys developed under various MFE programs in the last twenty years. Many of these vacuum compatible materials are robust and should be considered for use in IFE chamber applications. More exotic chamber options, including refractory-coated velvets, porous coatings and liquid metals, may be photon ablation resistant, but ion-induced damage, shock, effects of MHD forces and outgassing remain as serious issues requiring further study.

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