Results from Studies of Thermomechanically-Induced Fatigue in GlidCop®

Jeff Collins, Jeremy Nudell, Gary Navrotski, Zunping Liu and Pat Den Hartog

Mechanical Engineering & Design Group
Advanced Photon Source, AES Division

Accelerator Systems Division Technical Seminar
Nov. 5, 2014

Outline for the Presentation

- General discussion about fatigue
- Review existing design criteria limits for GlidCop® AL-15
- Progression of testing & analysis to establish new design criteria limits
- Mechanical testing of GlidCop® AL-15
- Thermomechanically-induced fatigue in GlidCop® AL-15 studies
- FE photon shutter transient non-linear FEA
- Proposed new design criteria limits for GlidCop® AL-15
- Using the thermal fatigue model as a tool to geometrically optimize component designs
- Built-in safety in the new design criteria limits
- Conclusions

General Discussion about Fatigue

Low-Cycle Fatigue (LCF):

- Is dominated by high amplitude low frequency plastic strains
- The elastic limit of the material is exceeded and permanent plastic deformation occurs
- Number of cycles to failure < 10^4

High-Cycle Fatigue (HCF):

- Is dominated by low amplitude high frequency elastic strains
- The elastic limit of the material is typically not exceeded
- Number of cycles to failure 10^4 – 10^6 or more

Our Situation:

- For APS photon shutter operation we are in a region that involves both LCF and HCF
- The beam strike surface is in compression when the beam is present
- Most of the fatigue damage occurs from residual tension when the beam is turned off
- Fatigue damage on a beam strike surface is complicated because it involves tri-axial stress/strain

General Discussion about Fatigue

- Thermal fatigue ≠ Mechanical fatigue
- It is very hard to produce equivalent testing conditions
- Typically the slopes of the thermal and mechanical fatigue test results are similar

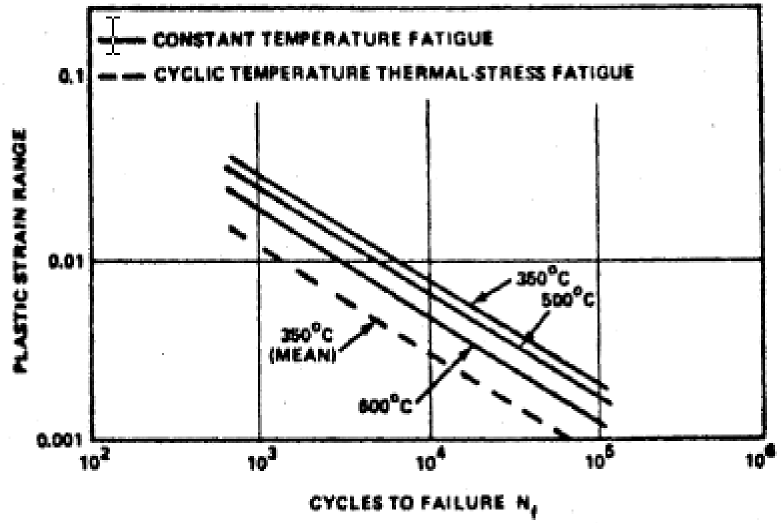


FIGURE E1-33. CYCLES TO FAILURE IN THERMAL-STRESS FATIGUE COMPARED WITH CYCLES AT CONSTANT TEMPERATURE IN SIMILAR PLASTIC STRAIN RANGE

NASA Technical Memorandum, TM-X-73307, Aeronautical Structures Manual, V.III (1975) Sect. E1, p68.

→ The general approach: 1) Obtain temperature dependent mechanical fatigue data
2) Perform thermal fatigue tests under actual operating conditions
3) Use mechanical fatigue model as a base to develop a thermal fatigue model based on observed damage from the thermal fatigue tests

Existing APS GlidCop® Design Limits

The APS has used conservative criteria for establishing the maximum thermal load acceptable for X-ray beam-intercepting components:

1. The maximum temperature on GlidCop® surfaces shall not exceed 300°C in order to avoid material creep.
2. The maximum temperature on the cooling wall shall not locally exceed the water boiling temperature, and thus only single-phase water is allowed.
3. The maximum von Mises stress for photon shutters shall not exceed 400 MPa, the room temperature yield stress of plate stock GlidCop® Al-15.

SPring-8 also uses T_{max} < 300°C on GlidCop® surfaces for their design criteria

Numerous studies have been performed in the synchrotron community to assess the thermal fatigue life of GlidCop®:

1. Study at the ESRF in collaboration with APS: 2005
2. Study at the APS, Phase I Testing: 2005-2006
3. Study at the APS, Phase II Testing: 2006-2007
4. Study at SPring-8: 2006-2008
5. Study at the APS, Phase III Testing (this study): 2011-2014

Progression of Testing & Analysis to Establish New Design Criteria Limits

Obtain temperature-dependent uniaxial mechanical fatigue data for GlidCop® AL-15

Derive temperature-dependent mechanical fatigue model from data

Transform mechanical fatigue model into thermal fatigue model by matching observed damage with life cycle predictions based on mean temperature

Define “failure” based on thermal fatigue model predictions and observed damage to samples

Obtain temperature-dependent true stress vs. true strain data for GlidCop® AL-15 in both compression and tension

Perform transient non-linear analysis on all test samples to determine total strain range and peak temperature

Perform transient non-linear analysis on all FE absorbers under present and MBA Upgrade conditions

Apply results to thermal fatigue model to assess life cycle predictions for each FE absorber case

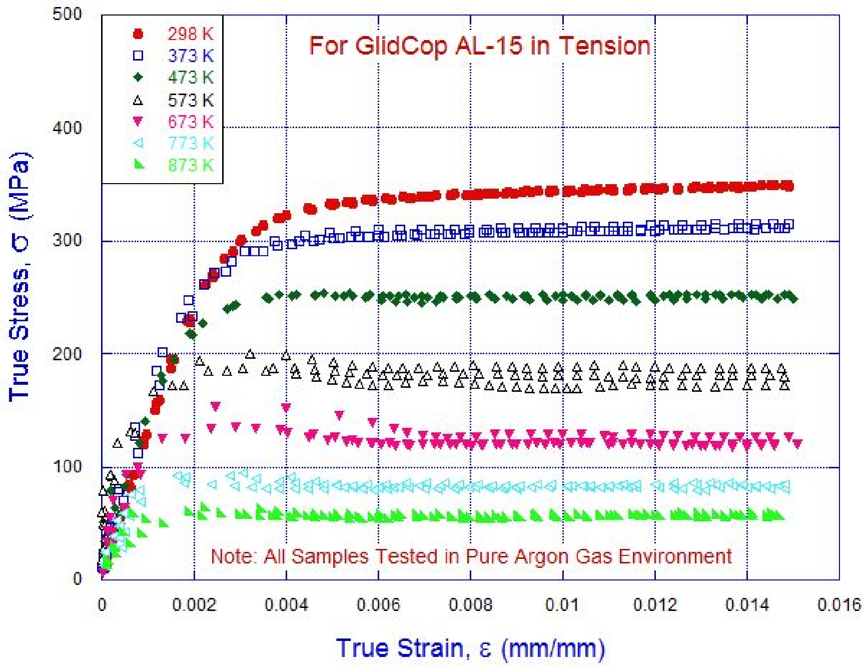
Perform thermomechanically-induced fatigue tests on numerous GlidCop® AL-15 samples at S29 beamline at various power loading conditions

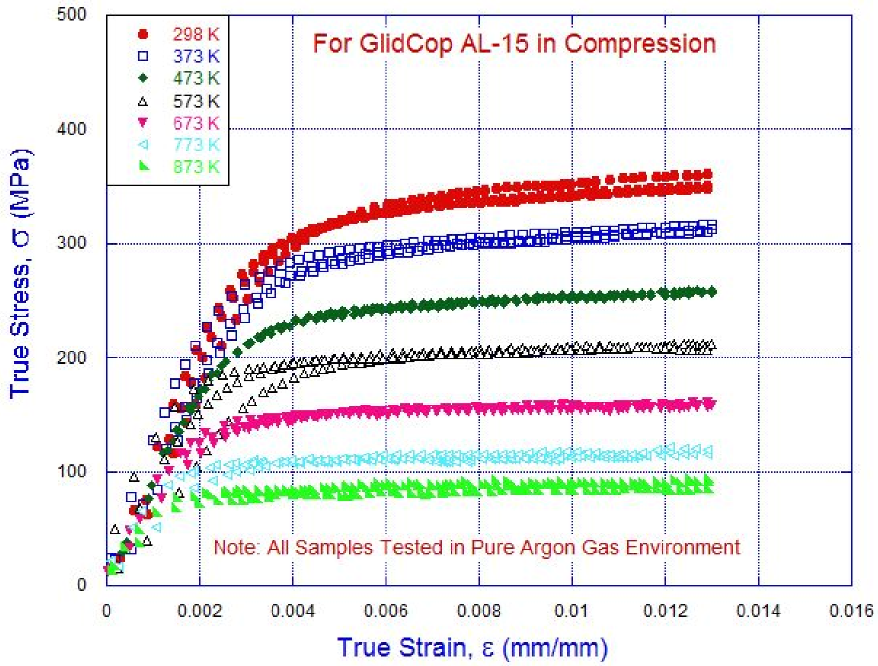
Perform metallurgical analysis on all test samples to assess surface conditions and crack presence / geometry

Propose new design criteria for GlidCop® AL-15 based on thermal fatigue as it applies to FE absorber analysis results. Explore how the criteria can be used to geometrically optimize component designs

Mechanical Testing of GlidCop® AL-15: True Stress vs. True Strain

- All tests were performed by Westmoreland Mechanical Testing & Research, Inc.
- Tension tests were performed in accordance with ASTM E21-09
- Compression tests were performed in accordance with ASTM E209-89a (2000)
- Seven different test temperatures were used
- Three samples were tested at each condition
- All samples were tested in pure argon gas (tests in vacuum were not available)

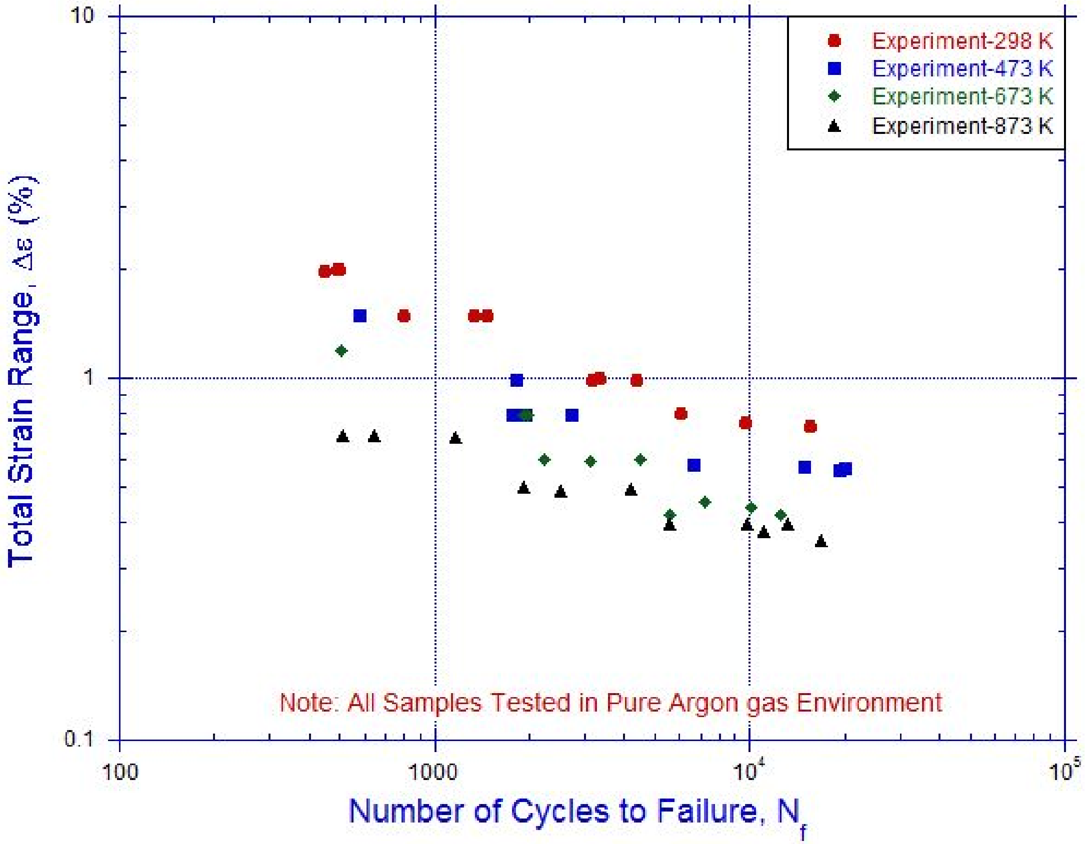


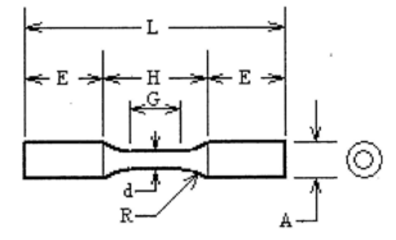


- True stress vs. true strain data are similar in tension and compression up to ~300°C
- All ANSYS transient non-linear simulations for this project use this data

Mechanical Testing of GlidCop® AL-15: Uniaxial Mechanical Fatigue Testing

- All tests were performed by Westmoreland Mechanical Testing & Research, Inc.
- Uniaxial mechanical fatigue tests were performed in accordance with ASTM E606-12
- Samples were machined from 1/2” x 6 3/8” GlidCop® AL-15 LOX extruded flats
- Four different test temperatures were used
- A total of 45 samples were tested
- All samples were tested in pure argon gas (tests in vacuum were not available)





	A	d	E	G	H	L	R
Dimension	0.400	0.200	0.90	0.600	1.200	3.00	0.50
Tolerance	+/-.004	+/-.002	+/-.05	+/-.01	+/-.02	+/-.05	+/-.02

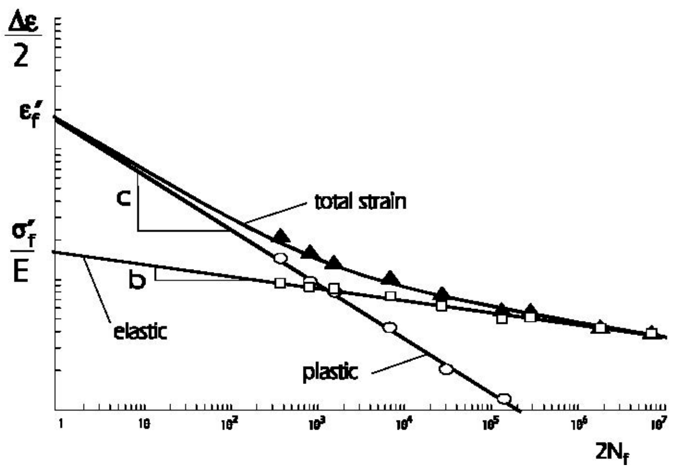
Surface Finish = 8Ra
M10X1 threads for elevated temperature specimens

Data Reduction for Uniaxial Mechanical Fatigue Tests

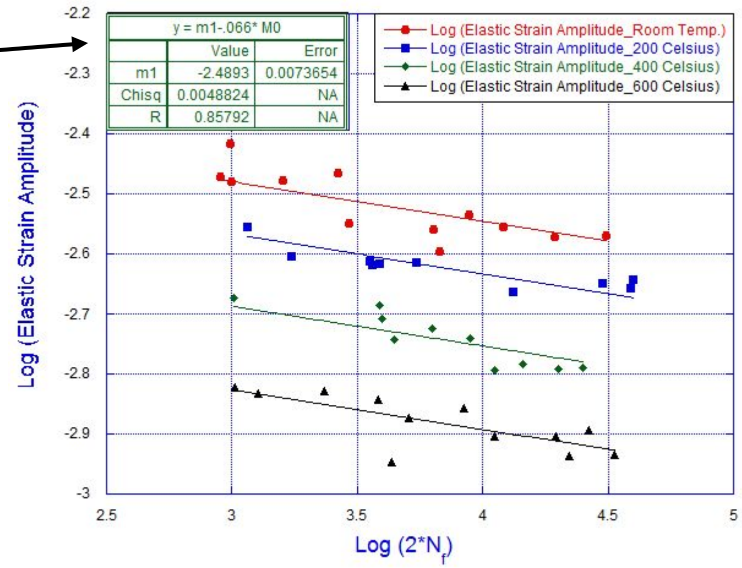
→ The Manson-Coffin equation and Basquin's law are used to reduce the data set

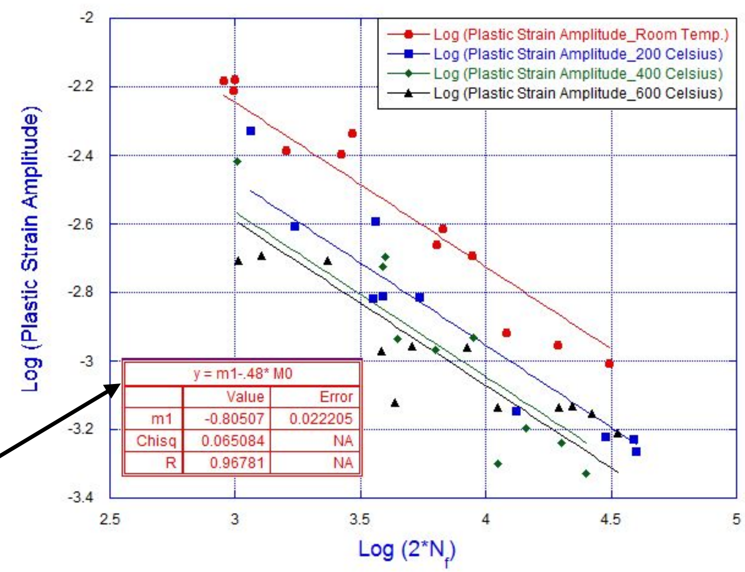
$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

Elastic Plastic



b = -.066





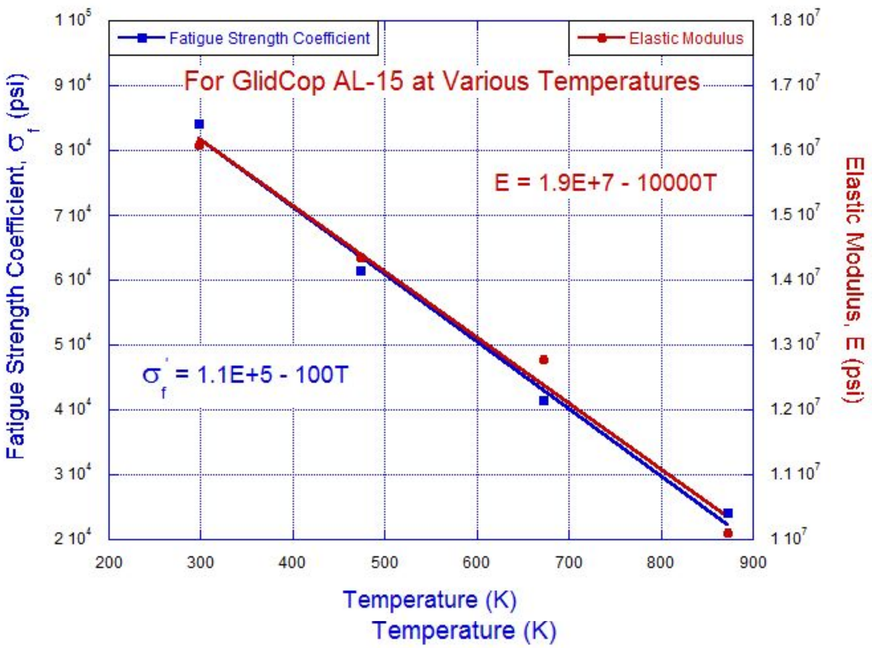
c = -.48

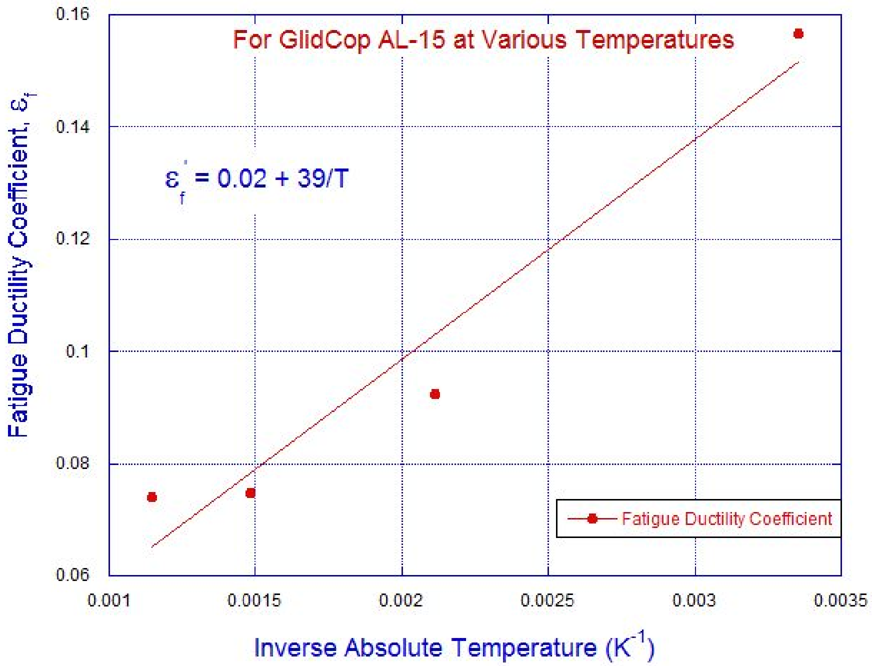
The following parameters are defined

E	the elastic modulus (Young's Modulus)
K'	the strain hardening coefficient
n'	the strain hardening exponent
b	the fatigue strength exponent (Basquin's exponent)
σ'_f	the fatigue strength coefficient
c	the fatigue ductility exponent (the Coffin-Manson exponent)
ε'_f	the fatigue ductility coefficient

Data Reduction for Uniaxial Mechanical Fatigue Tests

→ We can now solve for the Fatigue Strength Coefficient/Elastic Modulus and the Fatigue Ductility Coefficient





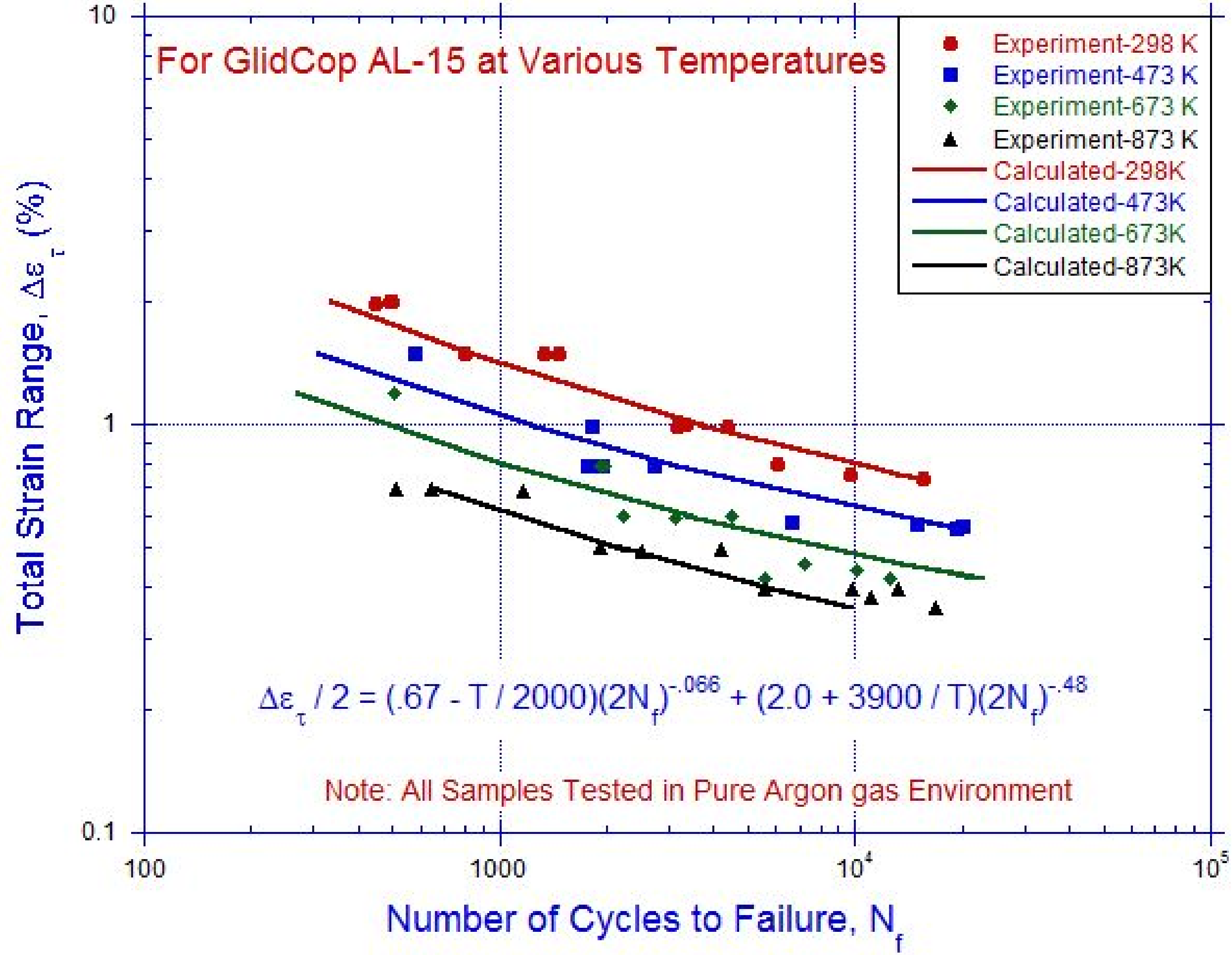
→ The Mechanical Fatigue Model for GlidCop® AL-15:

$$\frac{\Delta\varepsilon_t}{2} = \left(.67 - \frac{T}{2000}\right)(2N_f)^{-.066} + \left(2.0 + \frac{3900}{T}\right)(2N_f)^{-.48}$$

where:

$\Delta\varepsilon_t$ = Total Strain Range (%)
T = Sample Temperature (K)
N_f = Number of Cycles to Failure

Data Reduction for Uniaxial Mechanical Fatigue Tests



Thermomechanically-Induced Fatigue in GlidCop® Studies: Thermal Fatigue Model

- The mechanical fatigue model is transformed into a thermal fatigue model by redefining the temperature variable in the mechanical fatigue model as suggested by Taira (1973)
- The mean temperature between the maximum surface temperature and the cooling water temperature is used in the thermal fatigue model
- The thermal fatigue model is then used to predict the number of cycles to failure for each test sample
- Matching the observed surface damage on the samples with the thermal fatigue model prediction at 10,000 cycles defines "failure"

Thermal Fatigue Model:

$$\frac{\Delta\varepsilon_t}{2} = \left(.67 - \frac{T_m}{2000}\right)(2N_f)^{-.066} + (2.0 + \frac{3900}{T_m})(2N_f)^{-.48}$$

where:

$\Delta\varepsilon_t$ = Total Strain Range (%)
T_m = Mean Temperature (K) = average of T_{max} & T_{water}
N_f = Number of Cycles to Failure

S. Taira (1973), "Relationship between thermal and low-cycle fatigue at elevated temperatures," *Fatigue at Elevated Temperatures, ASTM STP 520*, American Society for Testing and Materials, 80-101.

A Note About Conducting Tests in a Pure Argon Gas Environment

- Takahashi from SPring-8 conducted a similar study in 2006-2008
- He noted the influence of the environment (air vs. vacuum) on the fatigue life

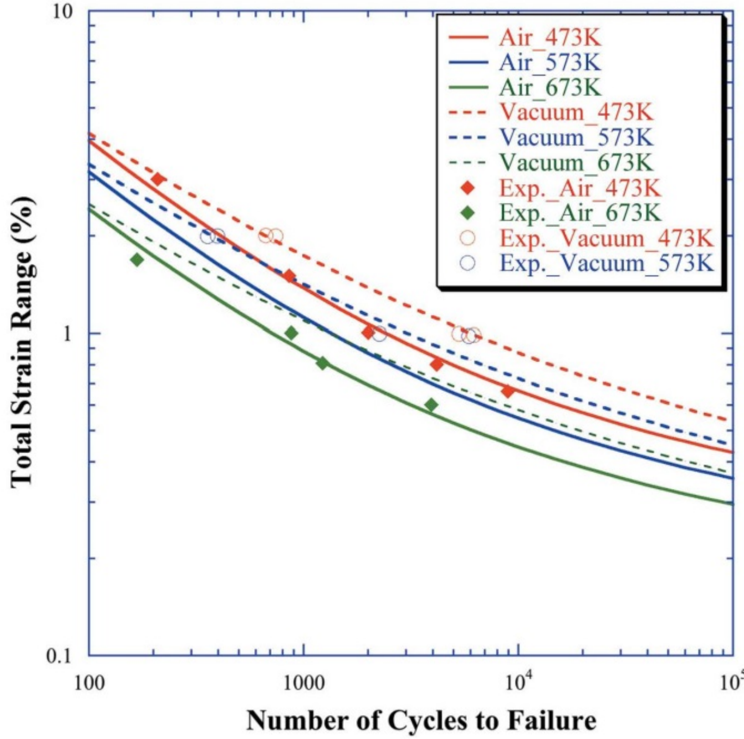
Takahashi's model:

$$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = AN_f^{-\alpha} + BN_f^{-\beta}, \qquad (1)$$

Table 1
Environment-dependent material properties of A, B, α and β in equation (1).

A and B are independently expressed as a function of temperature (T).

		Manson–Coffin		Basquin	
Environment	T (K)	A	$-\alpha$	B	$-\beta$
Atmosphere	373	60.8	−0.6	1.15	−0.086
	473	51.9	−0.6	1.01	−0.086
	673	30.9	−0.6	0.71	−0.086
	Any	$-0.1T + 71.31$	−0.6	$-0.0015T + 1.295$	−0.086
Vacuum	473	31.2	−0.48	1.1	−0.086
	573	24.6	−0.48	0.95	−0.086
	Any	$-0.066T + 44.4$	−0.48	$-0.0015T + 1.4$	−0.086



Our model:

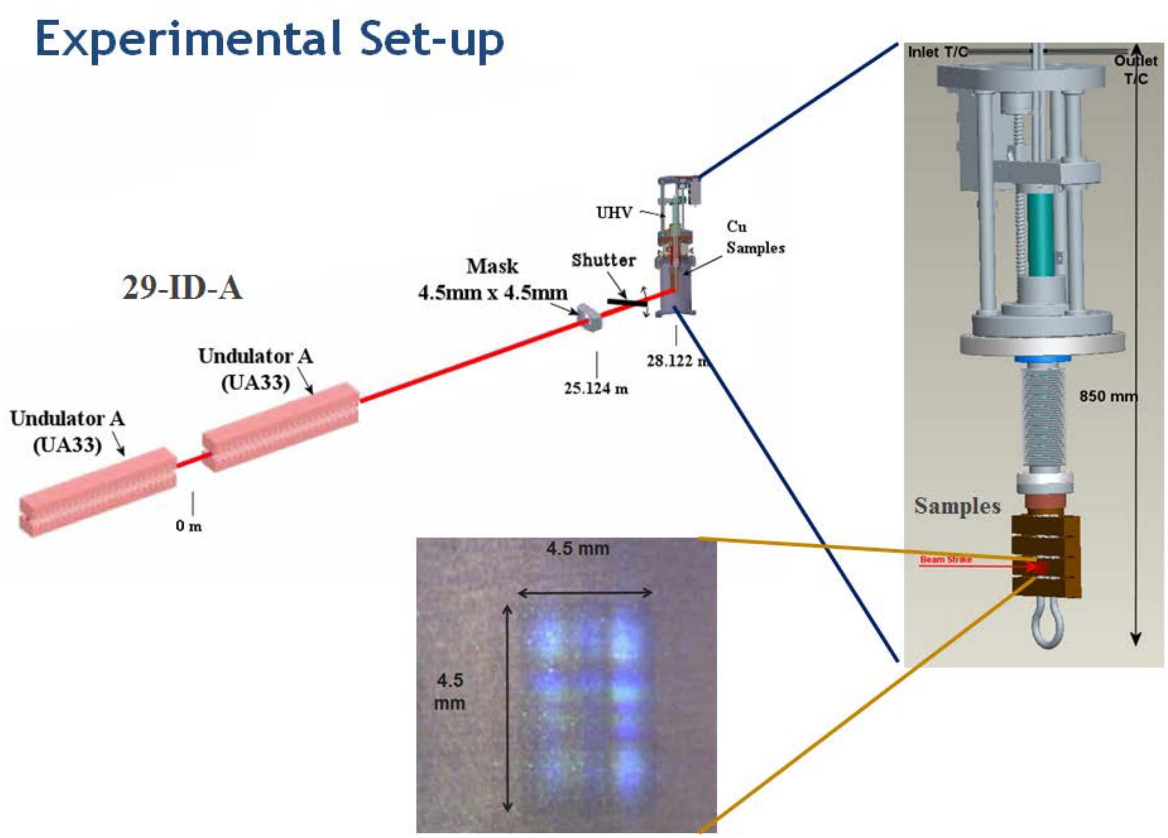
$$\frac{\Delta\varepsilon_t}{2} = \left(.67 - \frac{T}{2000}\right)(2N_f)^{-.066} + \left(2.0 + \frac{3900}{T}\right)(2N_f)^{-.48}$$

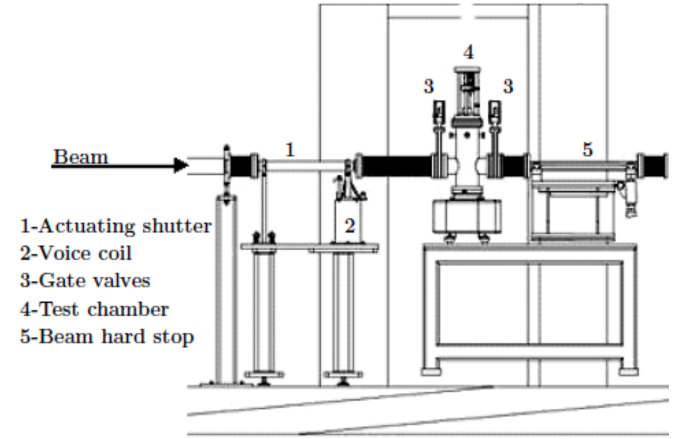
→ Testing in a pure argon gas environment yields similar results as testing in vacuum

[1] Takahashi, S., Sano, M., Mochizuki, T., Watanabe, A. and Kitamura, H., **"Fatigue life prediction for high-heat-load components made of GlidCop by elastic-plastic analysis"**, *J. Synchrotron Rad. (2008).* vol. 15, pp. 144-150.

Thermomechanically-Induced Fatigue in GlidCop® Studies: Experimental Set-up

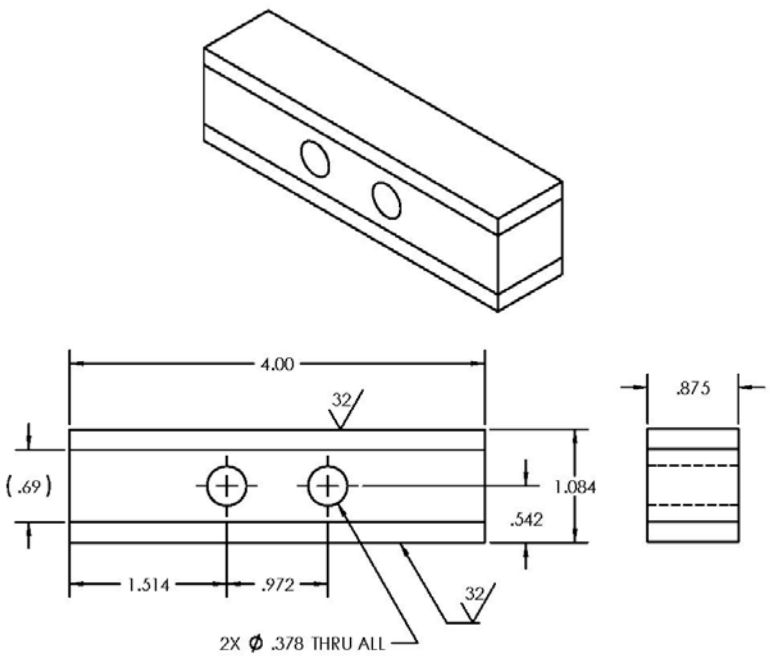
- Experiments were conducted at S29 FOE using two in-line U33.0 undulators
- A total of 30 GlidCop® AL-15 samples were tested
- Samples were subjected to 10,000 thermal cycles at normal incidence
- Various beam power loading conditions were applied to the samples



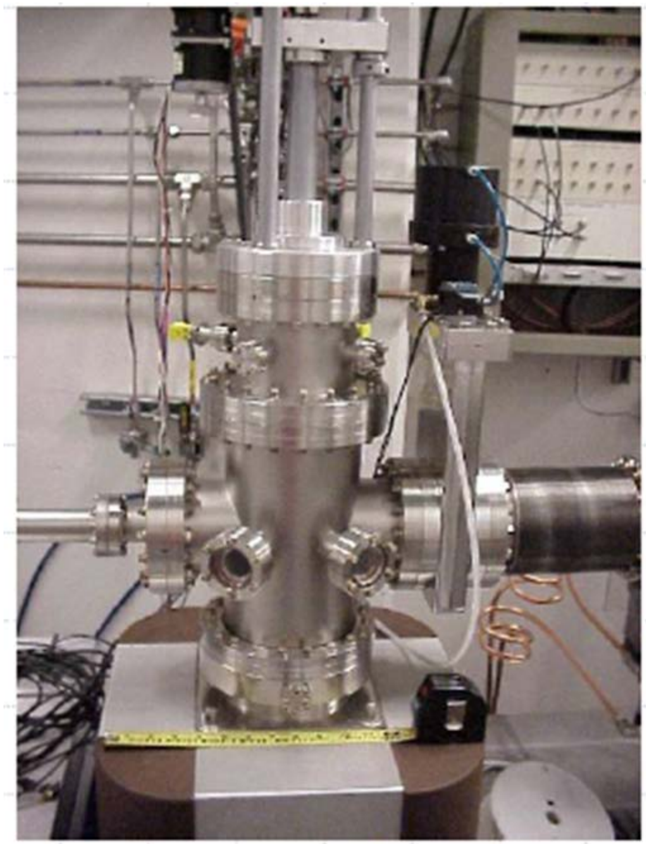


Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Fabrication

- The first set of samples were made of solid GlidCop® AL-15 LOX machined from 50-mm x 56-mm extruded bar stock
- The remaining samples used 1/2” x 6 3/8” GlidCop® AL-15 LOX extruded flats machined to a 5-mm plate thickness and explosion bonded to an OFHC copper base
- Each sample assembly contained 4 sample blocks brazed to a common copper cooling tube loop.
- The sample beam strike surfaces were machined to a surface finish of Ra ~ 16-μin

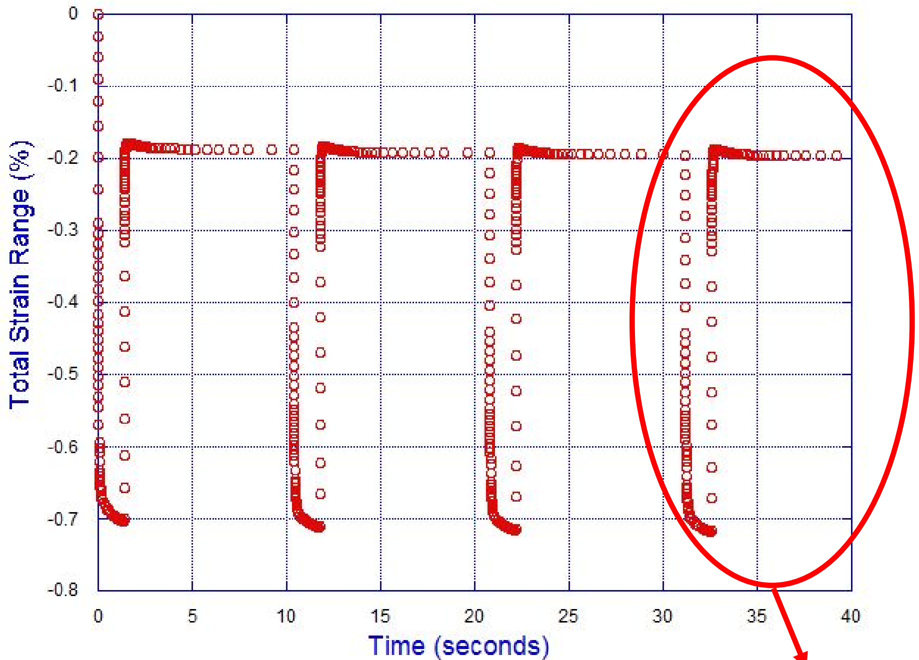


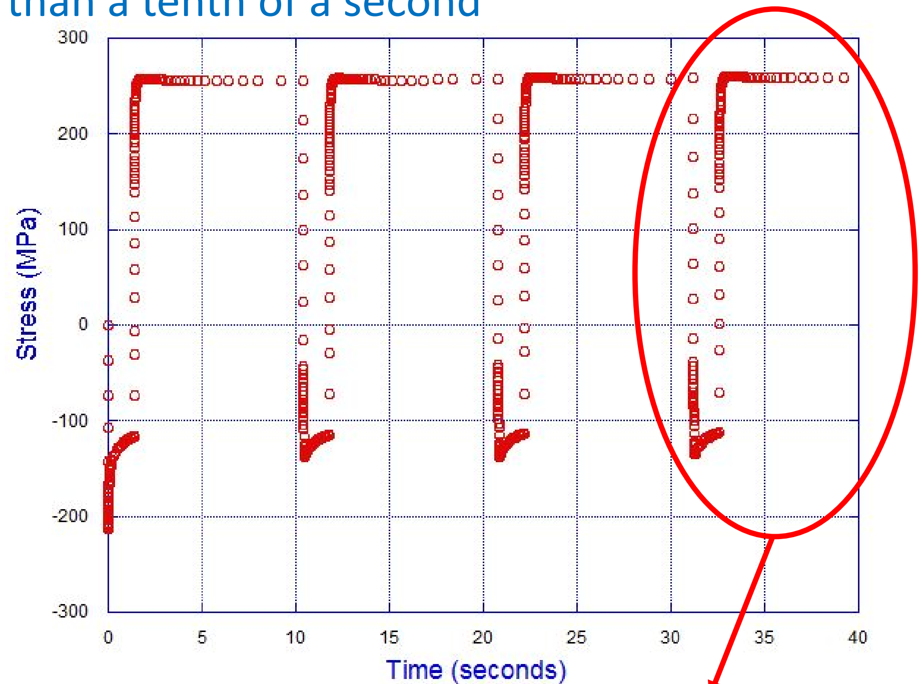
Dimensions are in inches

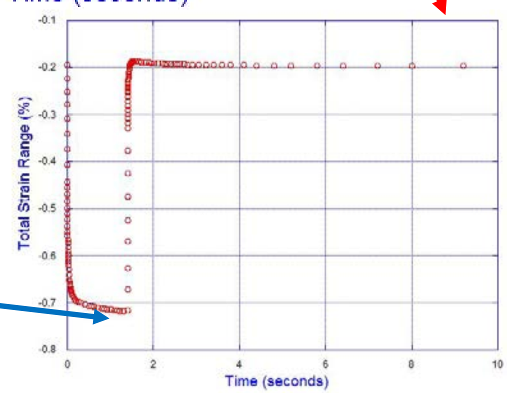


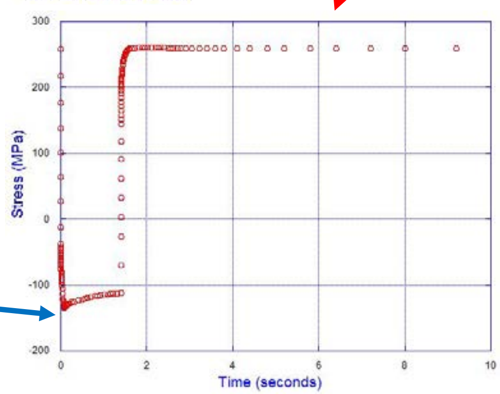
Thermomechanically-Induced Fatigue in GlidCop® Studies: Thermal Cycle Times

- Cyclic thermal loading was applied with 1.4-second heating and 9-second cooling
- The sample heating time is sufficient to achieve near steady-state total strain range
- Peak compressive stress is achieved in less than a tenth of a second









Near steady-state total strain range

Peak compressive stress in < 0.1 sec.

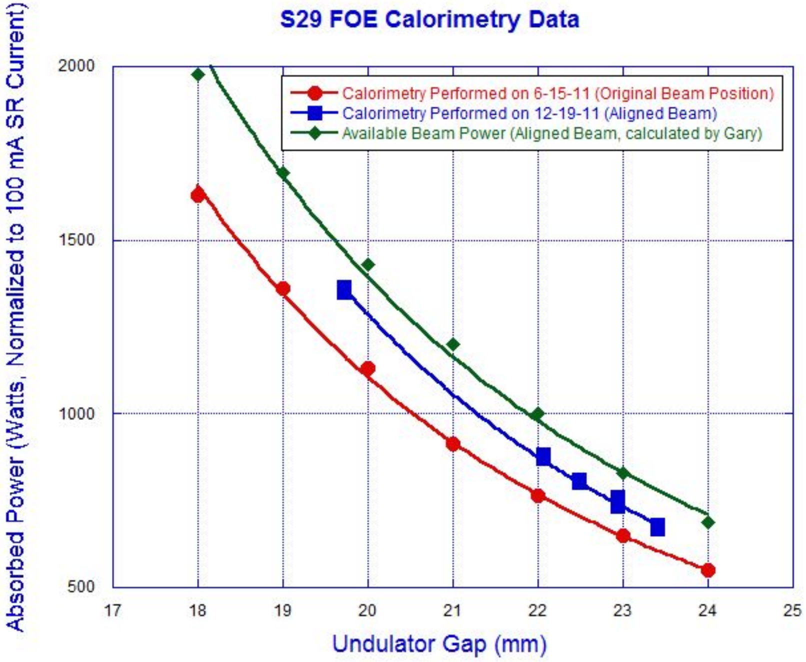
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Test Conditions

- We discovered after testing a number of samples that the beam was offset by .53-mm H x 1.18-mm V. The beam was centered for all subsequent sample tests
- Calorimetry measurements were performed for offset beam cases and centered beam cases
- The beam location for each sample was accounted for during ANSYS modeling

Sample Number	2- Undulator Gap (mm)	Total Absorbed Power, .89 Absorption Coefficient (W)	Peak Heat Flux (W/mm^2)	Number of Applied Cycles	Maximum Temperature , 1.4s heating (°C)	Surface roughness, R_a (μin)
37	23.411	689.75	101.46	10000	412	10.7
38	23.411	689.75	101.46	10000	412	17.85
34	22.933	753.83	108.58	10000	446	16.45
35	22.933	753.83	108.58	10000	446	17.35
20	22.07	758.28	122.82	10000	476	16.98
21	22.07	758.28	122.82	10000	476	13.73
22	22.07	758.28	122.82	10000	476	14.95
23	22.07	758.28	122.82	10000	476	12.8
24	22.07	758.28	122.82	10000	476	14.55
32	22.484	816.13	115.7	10000	479	13.78
33	22.484	816.13	115.7	10000	479	13.5
1	21.641	817.91	129.94	10000	509	7.33
9	21.64	817.91	129.94	10000	509	11.3
10	21.64	817.91	129.94	10000	509	12.98
11	21.64	817.91	129.94	10000	509	11.93
14	21.243	877.54	137.06	10000	542	13.35
29	22.07	881.1	122.82	10000	512	17.75
30	22.07	881.1	122.82	10000	512	15.73
31	22.07	881.1	122.82	10000	512	10.55
6	20.958	923.82	142.4	10000	567	6.83
7	20.317	1032.4	153.97	10000	624	7.03
4	19.715	1141.87	166.43	10000	683	7.2
16	19.715	1141.87	166.43	10000	683	11.35
44	20	1271.81	160.2	10000	707	9.43
45	19.5	1385.73	170.88	10000	761	11.23
46	19.5	1385.73	170.88	30000	761	9.75
43	19	1508.55	180.67	10000		10.4
41	18	1783.56	203.81	10000		10.9
42	17	2092.39	227.84	10000		12.78
47	11	4679.62	428.09	10000		9.95

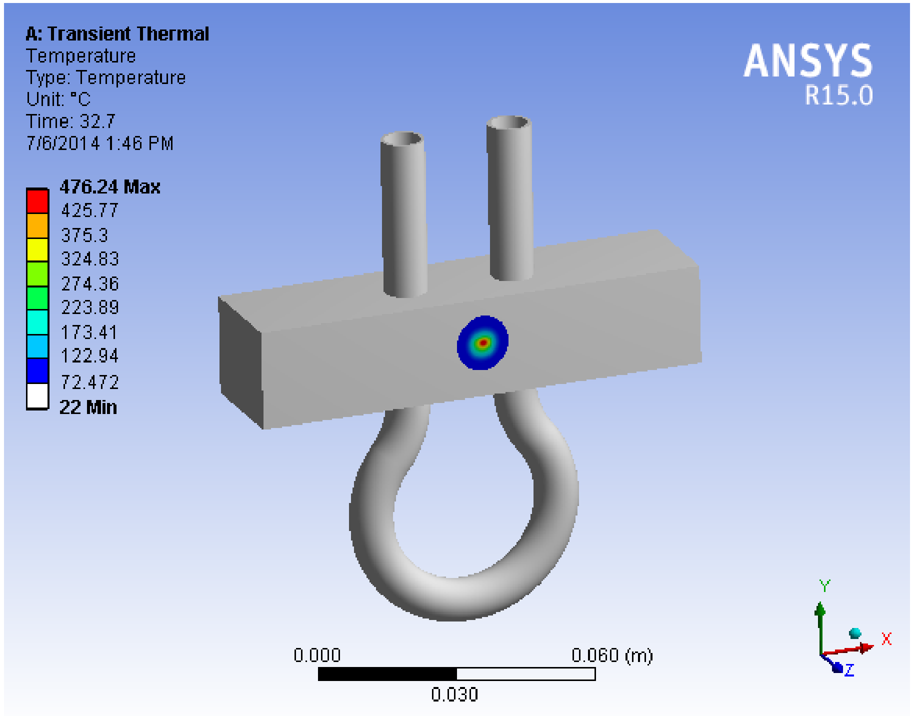
Beam offset .53mm H x 1.18mm V

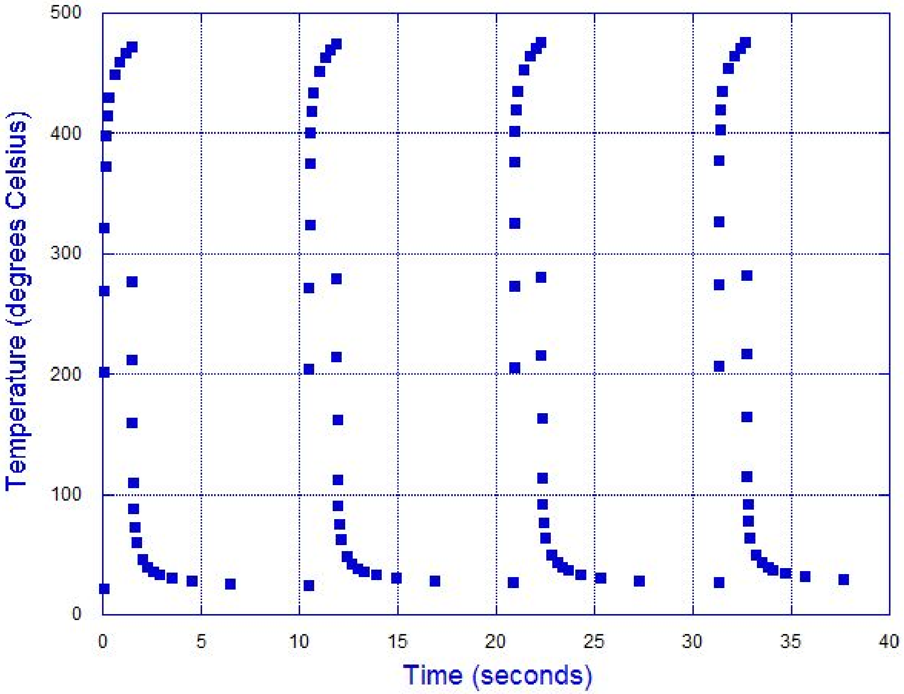
Beam centered



Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Modeling

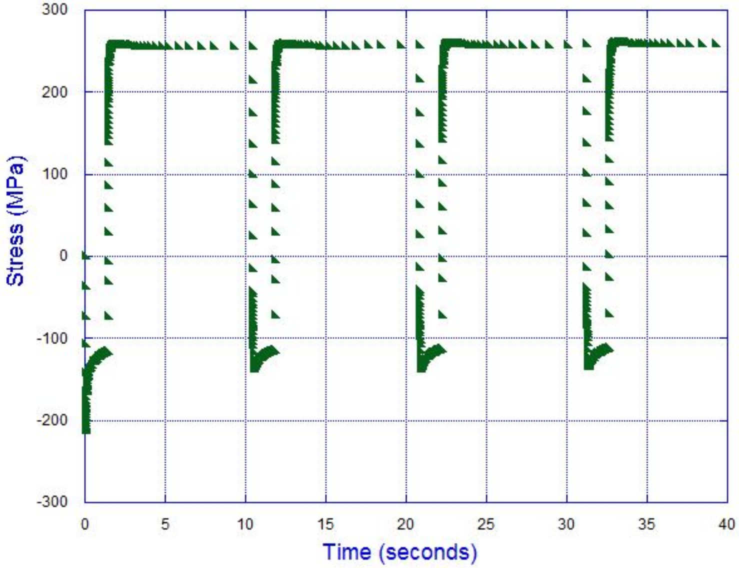
- Transient non-linear model simulations were performed using ANSYS for each sample test condition employing the multilinear kinematic hardening model
- SRUFF was used for all undulator power calculations
- True stress vs. true strain data were used in the simulations
- Temperature-dependent material properties were used in the simulations (thermal conductivity, specific heat, thermal expansion coefficient and Young's modulus)
- The simulations yield the maximum temperature and total strain range data required to predict the fatigue life for each sample

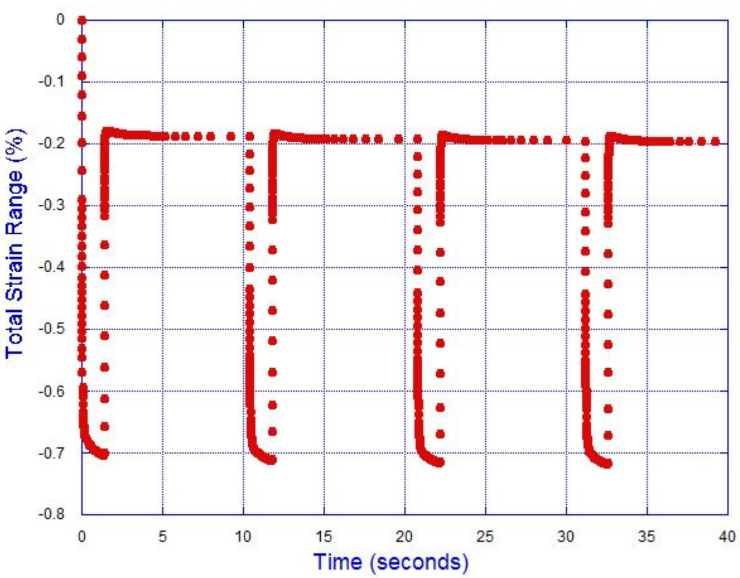


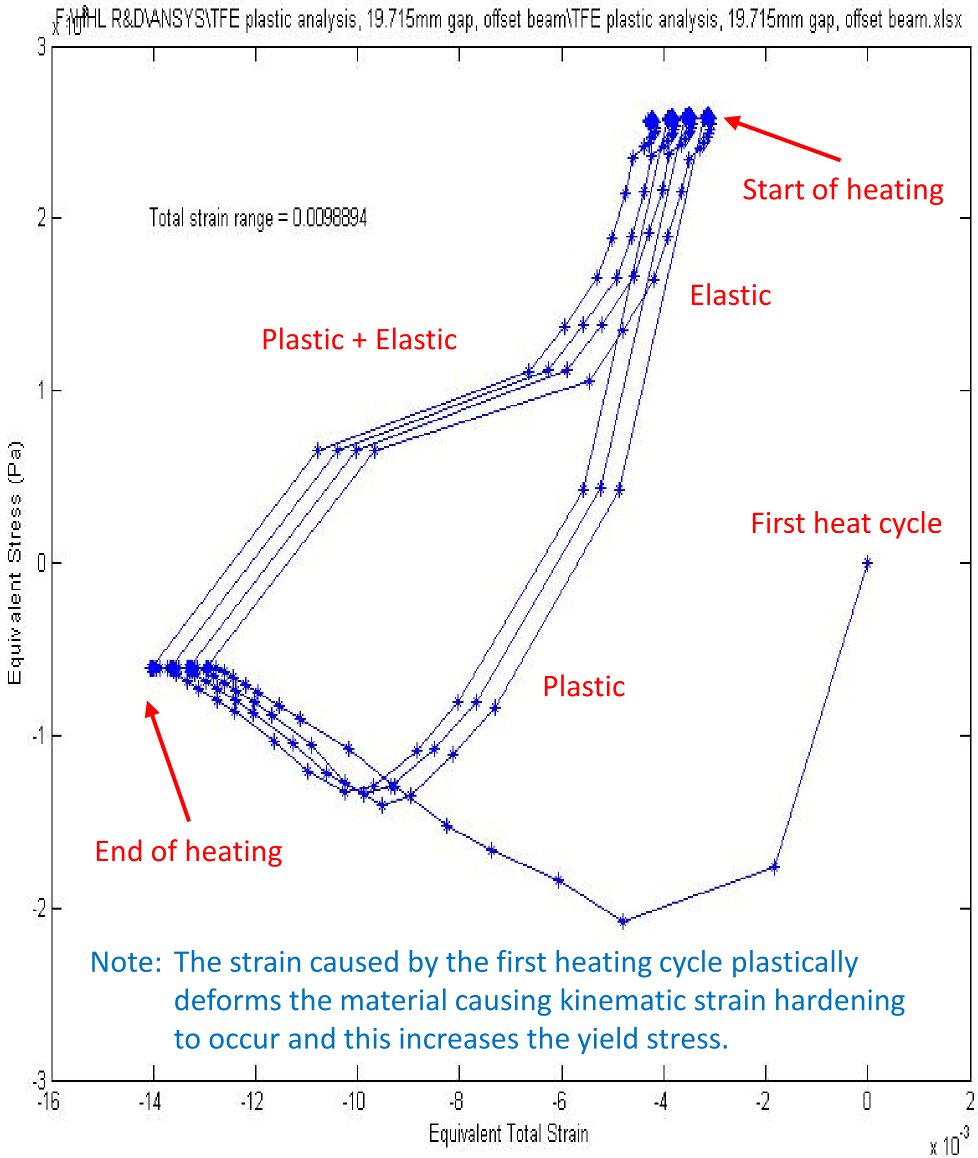


Analysis for samples 20-24

Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Modeling







Note: The strain caused by the first heating cycle plastically deforms the material causing kinematic strain hardening to occur and this increases the yield stress.

Analysis for samples 20-24

Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

- Test samples were metallurgically examined in-house for surface damage and crack presence/geometry

Evolution of GlidCop® Surface Damage with Increasing Power Loads

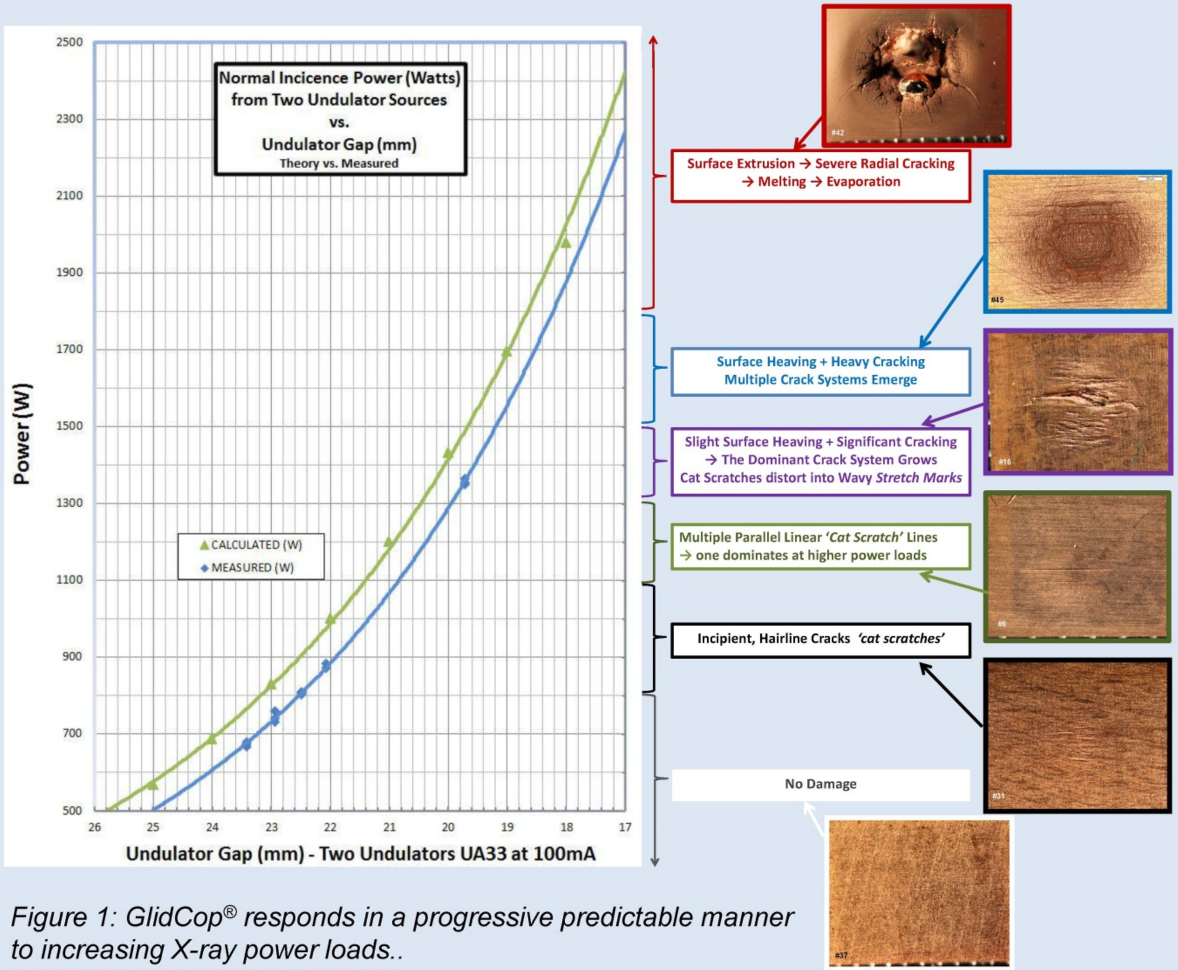
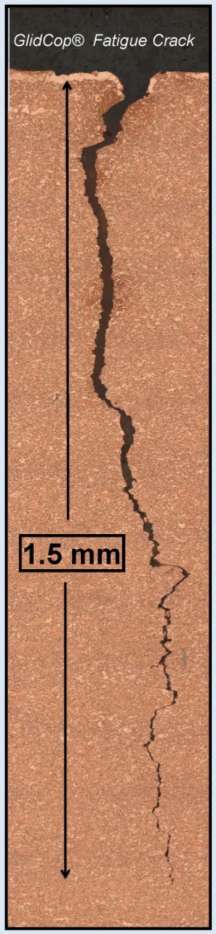


Figure 1: GlidCop® responds in a progressive predictable manner to increasing X-ray power loads..

Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

- After surface images were acquired, samples were cut, polished, etched and examined in sections to obtain information on crack morphology

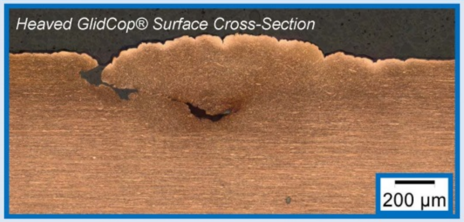
What is a ‘Crack’, a ‘Cat Scratch’ and a ‘Surface Heave’?



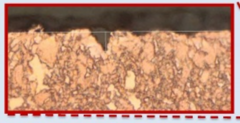
Cracks in GlidCop® are fascinating sinuous paths, always following grain boundaries, growing by fatigue processes from the surface down into the bulk metal.

It took 10,000 cycles of double undulator radiation at a 19.7mm gap, almost 1400 W of total power per cycle, to grow this crack in 30 hours.

Surface Heaving in GlidCop® is the result of high power being deposited on a surface constrained on all sides. The metal plastically deforms upward and folds, much like mountain building tectonics on earth. Note the folding and bending of the underlying planar grain structure in the heave. [Matches blue box of Figure 1]



‘Cat Scratch’ surface defect



‘Cat Scratches’ are shallow regions of surface grain drop-out. They always have rounded ‘V-like’ shapes and are the result of surface thermal compression ejecting weakly bound grains.

This surface has a 283 µm deep crack (right) and a 7.44 µm ‘cat scratch’ (left & magnified). [Matches green box of Figure 1]

Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

Evolution of GlidCop® Crack Morphology

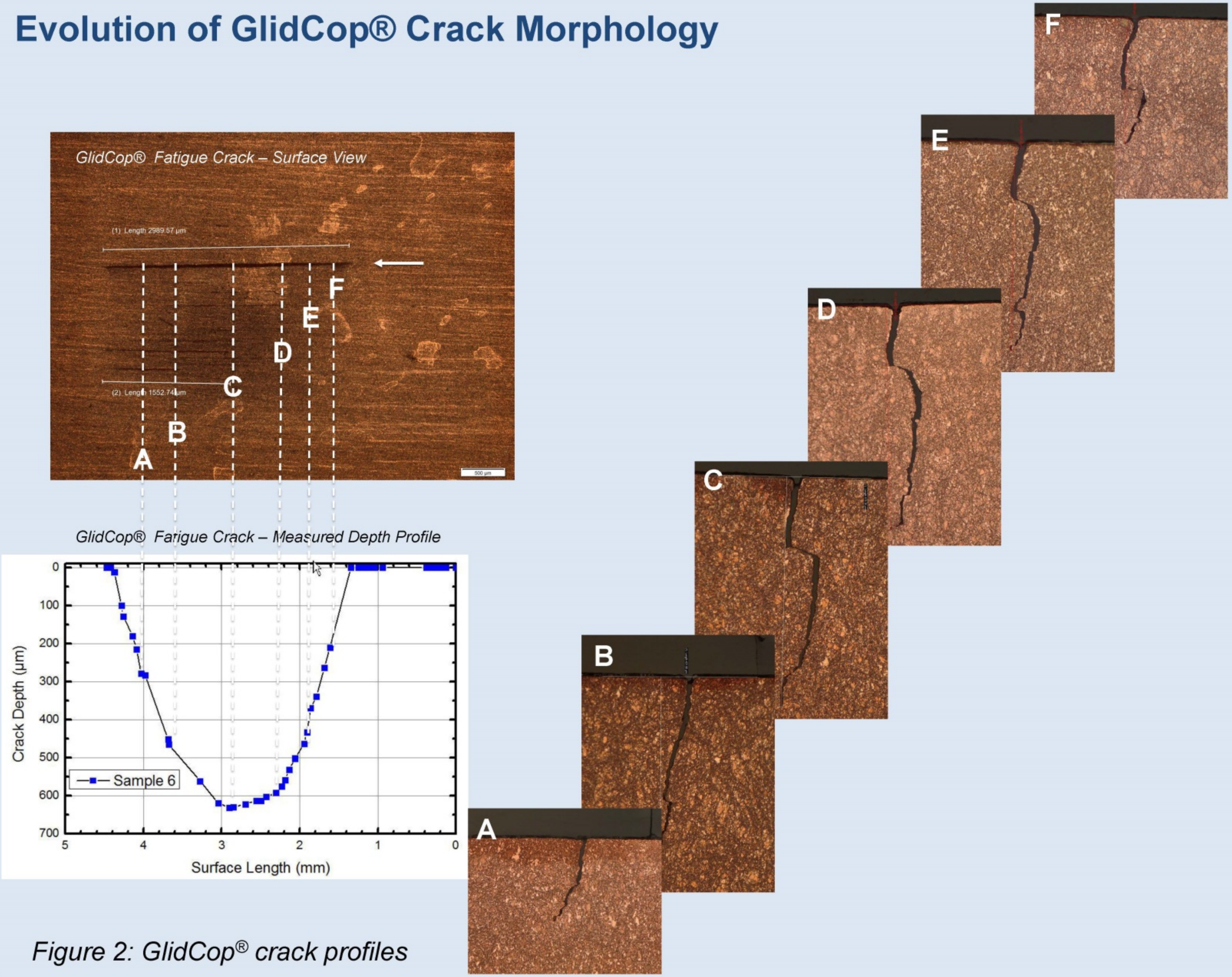


Figure 2: GlidCop® crack profiles

Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Data Base

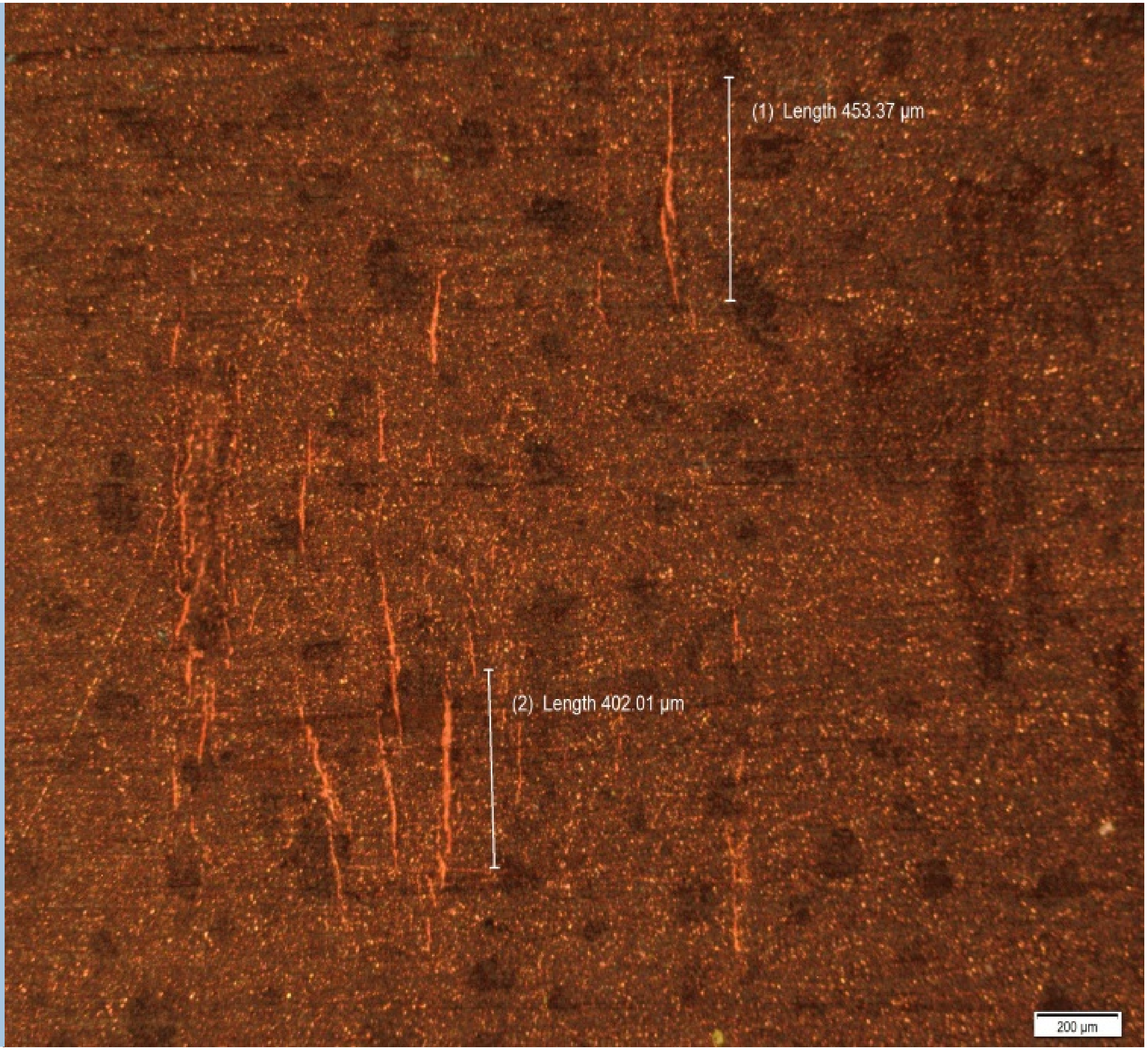
Group	Sample Number	Total Absorbed Power, .89 Absorption Coefficient (W)	Peak Heat Flux (W/mm^2)	Total Strain Range (%)	Maximum Temperature, 1.4s heating (K)	Mean Temperature (K)	Largest Crack Length (µm)	Largest Crack Width (µm)	Largest Crack Depth (µm)	Comments	Estimated Number of Cycles to Failure
	37	689.75	101.46	0.40738	685	492				No surface degredation	179,000
	38	689.75	101.46	0.40738	685	492				No surface degredation	179,000
	34	753.83	108.58	0.46806	719	509				No surface degradation	48,100
	35	753.83	108.58	0.46806	719	509				5 "cat scratches"	48,100
1	20	758.28	122.82	0.53048	749	524				No surface degradation	18,100
1	21	758.28	122.82	0.53048	749	524				No surface degradation	18,100
1	22	758.28	122.82	0.53048	749	524				No surface degradation	18,100
1	23	758.28	122.82	0.53048	749	524				No surface degradation	18,100
1	24	758.28	122.82	0.53048	749	524				No surface degradation, 10 stretch marks	18,100
2	32	816.13	115.7	0.53367	752	525				8 small "cat scratches"	17,300
2	33	816.13	115.7	0.53367	752	525	892	47.4	95	Several "cat scratches", 1 small shallow crack	17,300
3	1	817.91	129.94	0.60438	782	540	1815	11	105.8	7 "cat scratches", 5 small shallow cracks	7,650
3	9	817.91	129.94	0.60438	782	540	1238	32.3	235.8	Surface tears, 3 small shallow cracks	7,650
3	10	817.91	129.94	0.60438	782	540	453	11.3		"Cat scratches" and possible cracks	7,650
3	11	817.91	129.94	0.60438	782	540				Many "cat scratches", no cracks	7,650
3	14	877.54	137.06	0.67808	815	557	916	41		Several "cat scratches" and possible cracks	3,880
4	29	881.1	122.82	0.6094	785	542				13 "cat scratches", no cracks	7,220
4	30	881.1	122.82	0.6094	785	542	747	43.4	37	5 "cat scratches", 1 small shallow crack	7,220
4	31	881.1	122.82	0.6094	785	542				>20 "cat scratches" and stretch marks, no cracks	7,220
	6	923.82	142.4	0.73543	840	569	2989	56	630.6	13 "cat scratches", 1 long deep crack, 2 small shallow cracks	2,510
	7	1032.4	153.97	0.86914	897	598	2531	55.9		Many "cat scratches", several long deep cracks	1,110
	4	1141.87	166.43	0.98894	956	627	4329	53	1622	>15 "cat scratches",1 long deep crack	609
	16	1141.87	166.43	0.98894	956	627	3227	224	1218	Many "cat scratches", 1 long deep crack, 4 small shallow cracks	609
	44	1271.81	160.2	1.0487	980	639	2554	117	447.1	Surface "bulging", 2 long deep cracks, 1 small shallow crack	475
	45	1385.73	170.88	1.1464	1034	666				Surface "rumpling", several long deep cracks	320
	46	1385.73	170.88	1.1464	1034	666	4792	34.4		Numerous long deep cracks and melting	320
	43	1508.55	180.67				3623			Numerous long deep cracks and melting	
	41	1783.56	203.81				4624			Numerous long deep cracks and melting	
	42	2092.39	227.84				5269			Numerous long deep cracks and melting	
	47	4679.62	428.09				9668			Numerous long deep cracks and melting	

Beam offset .53mm H x 1.18mm V

Beam centered

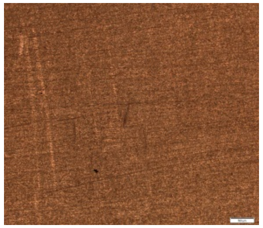
→ "Failure" yields "cat scratches" with the possibility of small shallow cracks < 2 mm in length

"Cat Scratches" are shallow regions of surface grain drop-out. They always have rounded "V-like" shapes and are the result of surface thermal compression ejecting weakly bound grains. Since the material is extruded, the copper grains are long and thin with dimensions on the order of several microns in depth/width and tens to hundreds of microns in length.



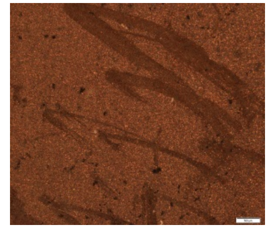
→ "Failure" yields "cat scratches" with the possibility of small shallow cracks < 2 mm in length

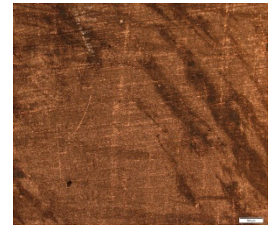
Thermomechanically-Induced Fatigue in GlidCop® Studies: “Failure” Zone


Sample 20

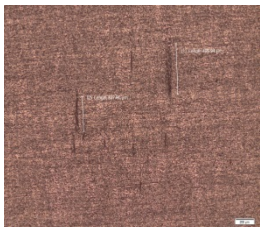

Sample 21


Sample 22


Sample 23


Sample 24

No surface degradation
N_f = 18,100 (1)


Sample 32

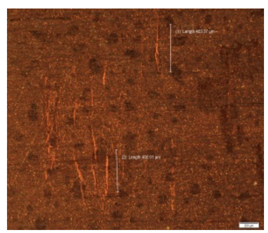

Sample 33

“Cat scratches”, 1 small shallow crack
N_f = 17,300 (2)

“Failure” Zone


Sample 1


Sample 9


Sample 10


Sample 11

“Cat scratches”, some small shallow cracks
N_f = 7,650 (3)


Sample 29


Sample 30

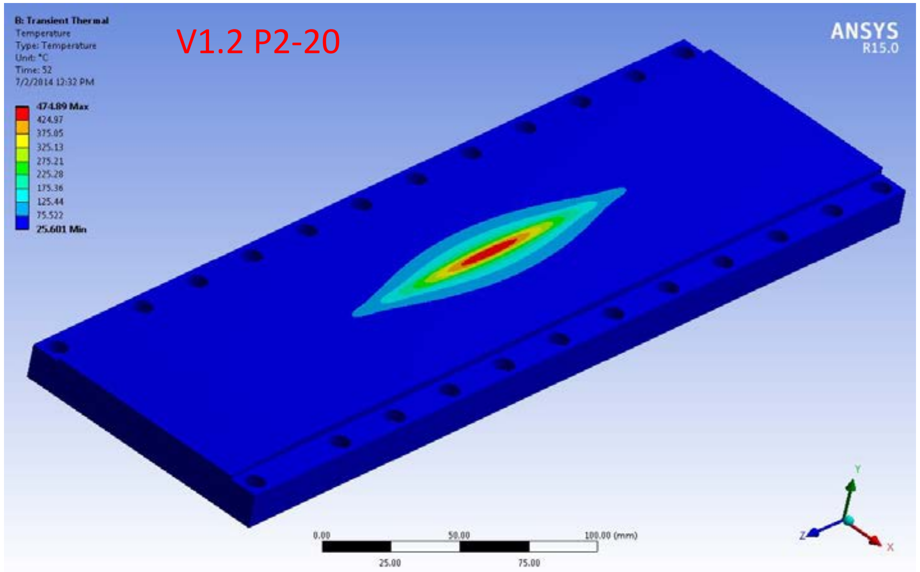

Sample 31

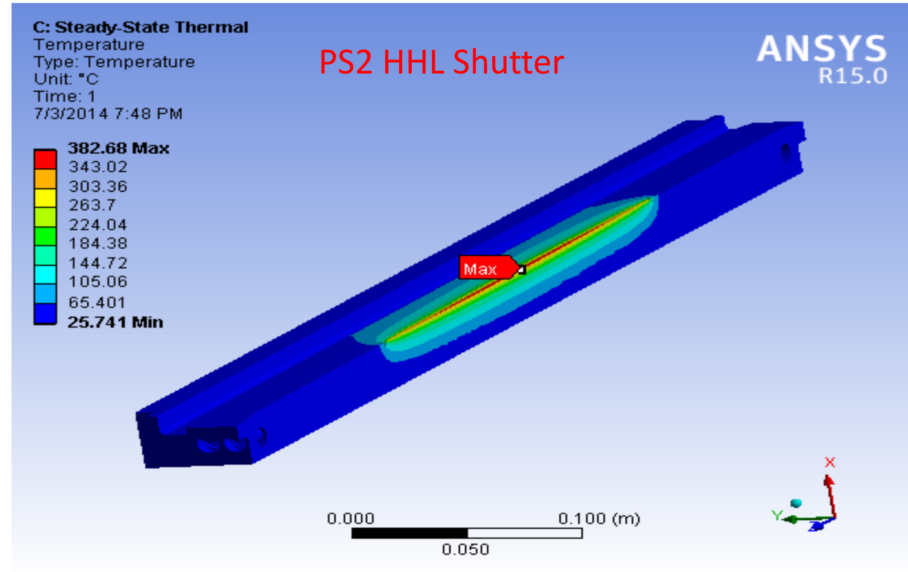
“Cat scratches”, 1 small shallow crack
N_f = 7,220 (4)

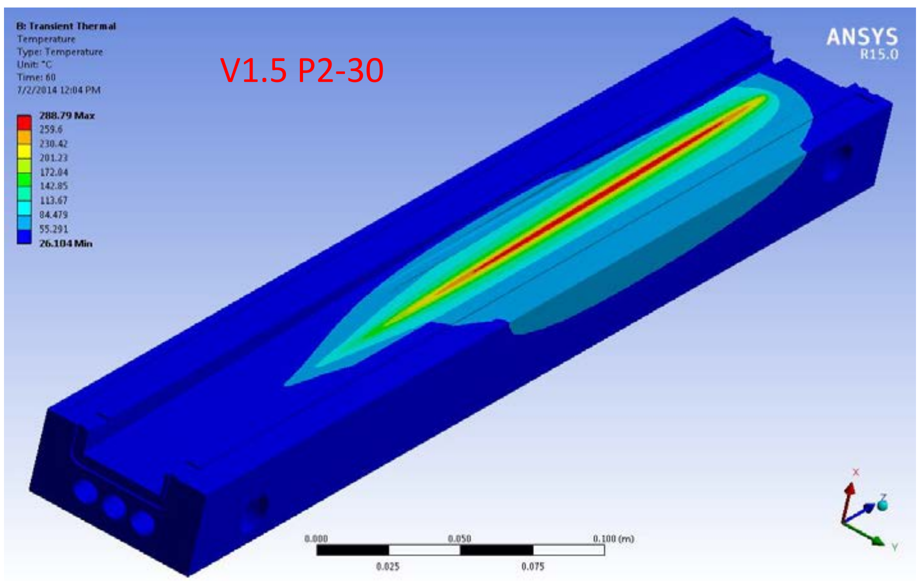
FE Photon Shutter Transient Non-Linear Analysis

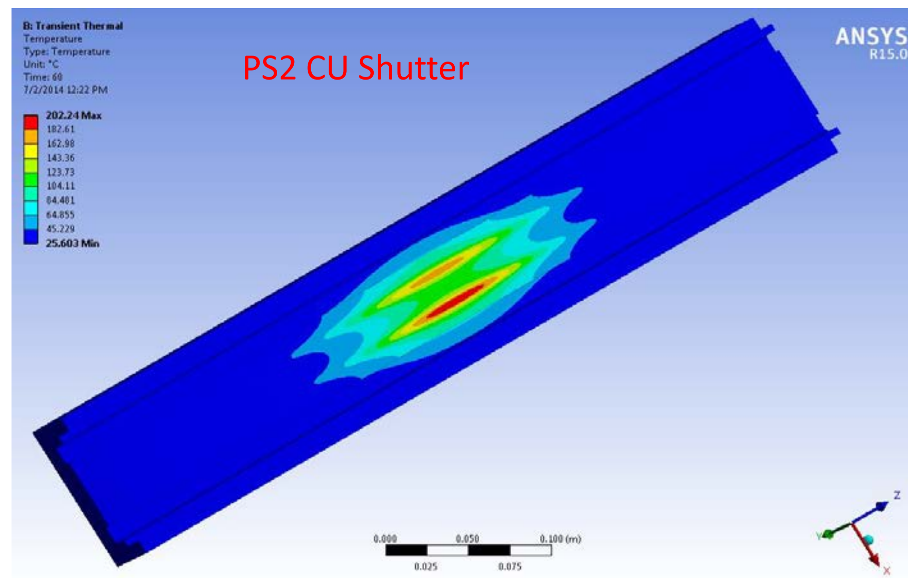
- Transient non-linear analyses were performed on the APS FE photon shutter designs in operation including V1.2 P2-20, V1.5 P2-30, PS2 HHL shutter and PS2 CU shutter
- Both the existing maximum design conditions and the maximum MBA lattice baseline conditions were considered
- True stress vs. strain data and temperature-dependent material properties were used in the simulations
- A 10-sec. heating and 40-sec. cooling cycle time was used, sufficient to achieve near steady-state total strain range
- For each transient simulation, a steady-state thermal simulation was performed first because the maximum steady-state temperature is used in the thermal fatigue model
- The simulations yield the maximum temperature and total strain range data required to predict the fatigue life for each shutter case

FE Photon Shutter Transient Non-Linear Analysis

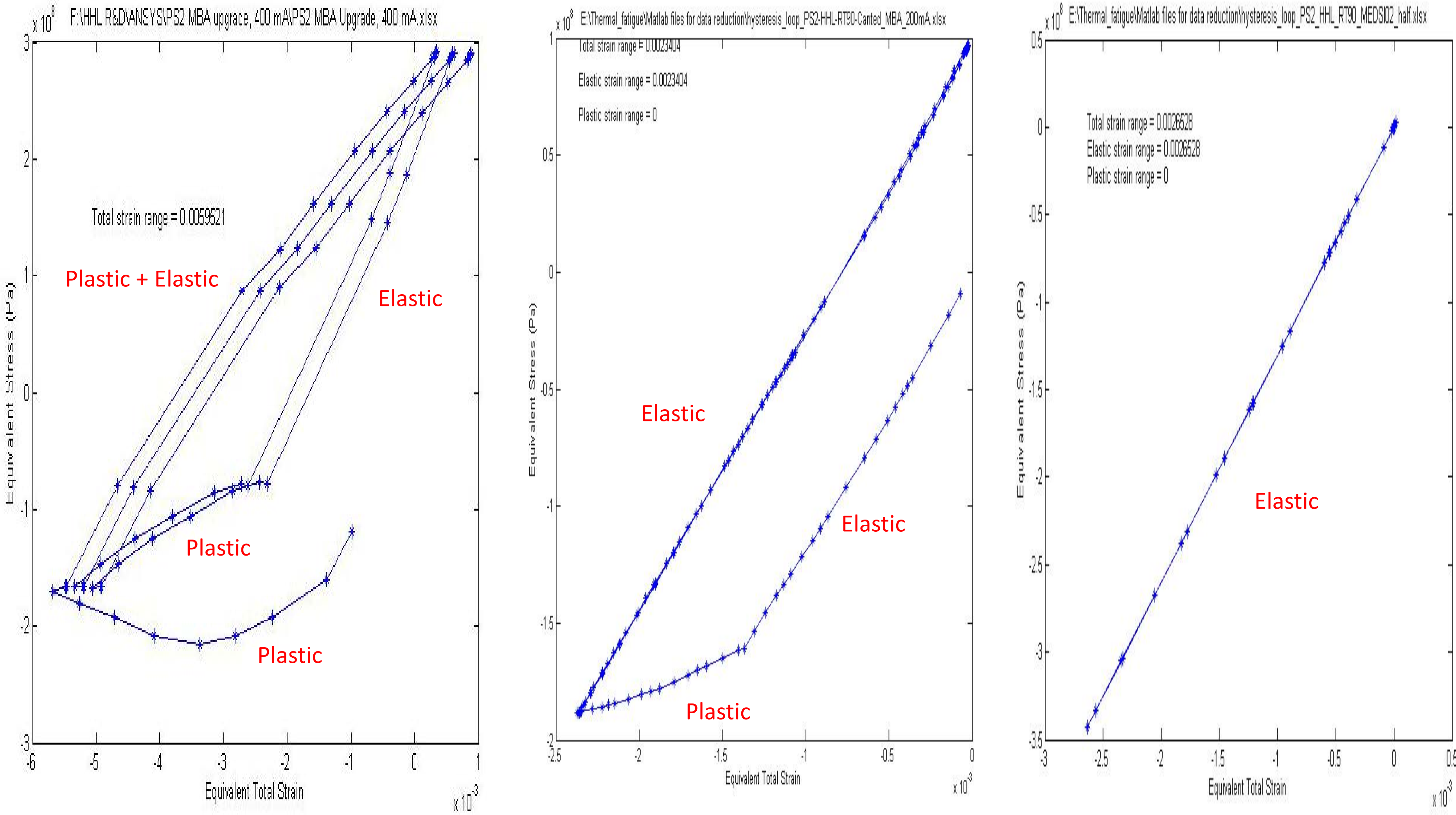








FE Photon Shutter Transient Non-Linear Analysis



FE Photon Shutter Transient Non-Linear Analysis

Photon Shutter Type	Operating Conditions	Source Parameters	Aperture Size at Shutter Location (mm x mm)	Total Power (W)	Peak Heat Flux (W/mm^2)	Maximum Temperature (°C)	Maximum Cooling Wall Temperature (°C)	Mean Temperature (K)	Peak Compressive / Tensile Stress (Mpa)	Elastic Strain Range (%)	Plastic Strain Range (%)	Total Strain Range (%)	Estimated Number of Cycles to Failure
V1.2 P2-20	Maximum Design Condition from TB-50	Single U33.0 130 mA	9 x 6	6,776	18.0	314.6	147.1	443.0 (169.8°C)	-204.8 / 236.0	0.35786	0.06882	0.42668	152,000
V1.2 P2-20	Water Boiling @ 153°C Condition	Single U33.0 137 mA	9 x 6	7,134	18.9	330.8	153.7	451.1 (177.9°C)	-211 / 250.3	0.36587	0.09170	0.45757	101,000
V1.5 P2-30	Maximum Design Condition from TB-50	Single U33.0 225 mA	9 x 6	11,911	33.4	290.4	94.8	430.9 (157.7°C)	-210.5 / 246.9	0.36629	0.09583	0.46212	114,000
V1.5 P2-30	> 20,000 Cycles to Failure Condition	Dual In-Line U27.5 275 mA	13.48 x 5.52	25,062	36.4	393.4	121.2	482.4 (209.2°C)	-203.6 / 252.1	0.37296	0.10417	0.47713	53,500
PS2 HHL Shutter	Maximum Design Condition from HHL FE Design Report	Dual In-Line U33.0 180 mA	5 x 6	14,600	24.5	248.2	91.9	409.8 (136.6°C)	-205.1 / 173.0	0.30881	0.00615	0.31496	9.57E+06
PS2 HHL Shutter	>20,000 Cycles to Failure Condition	Dual In-Line U27.5 392 mA	5.6 x 6.72	25,527	32.4	375.3	133.3	473.2 (200°C)	-215.4 / 286.6	0.38103	0.17255	0.55358	20,800
PS2 Canted Undulator Shutter	Maximum Design Condition from MEDSI02 Report	Dual Canted U33.0 with 1 mrad Beam Separation 200 mA	10 x 6	19,900	10.4	247.9	129.8	409.6 (136.5°)	-202.4 / 0.0	0.26528	0	0.26528	1.03E+08
PS2 Canted Undulator Shutter	Water Boiling @ 153°C Condition	Dual Canted U27.5 with 1 mrad Beam Separation 330 mA	5.6 x 6.72	20,445	15.9	331.5	153.8	451.4 (178.3°C)	-185.1 / 97.1	0.23395	0	0.23395	3.28E+08

Proposed New Design Criteria Limits for GlidCop® AL-15:

1. Components can be designed with a maximum surface temperature of 375°C or to where the cooling water will begin to boil; whichever occurs first will be the limiting criteria.

2. Components can be designed with a maximum surface temperature up to 405°C, the creep temperature for GlidCop® AL-15, if transient non-linear analysis is performed to ensure that the number of cycles to failure exceeds 20,000 cycles using the thermal fatigue model below:

$$\frac{\Delta\varepsilon_t}{2} = \left(.67 - \frac{T_m}{2000}\right)(2N_f)^{-.066} + (2.0 + \frac{3900}{T_m})(2N_f)^{-.48}$$

where: $\Delta\varepsilon_t$ = Total Strain Range (%)
T_m = Mean Temperature (K) = average of T_{max} & T_{water}
N_f = Number of Cycles to Failure

3. Components can be designed beyond the boiling point of the water if critical heat flux (CHF) analysis is performed to ensure that a dry-out condition can never be reached.

Note: A surface roughness of Ra ≤ 16 μin should be specified for the beam strike surface.

→ *For most component designs, only steady-state thermal analysis will be required to verify that the design meets the design criteria limits. Stress analysis is not required when the maximum surface temperature ≤ 375°C.*

→ *The thermal fatigue model provides a tool that can be used to geometrically optimize component designs.*

Using the Thermal Fatigue Model as an Optimizing Tool for Component Designs

- The thermal fatigue model can be used to geometrically optimize component designs
- Parameters such as cooling wall thickness, grazing incidence angle, cooling channel layout, etc. can be optimized through parametric study using the thermal fatigue model

Varying Grazing Incidence Angle for PS2 HHL Shutter with Fixed Cooling Wall Thickness = 9-mm:

Photon Shutter Type	Operating Conditions	Source Parameters	Grazing Incidence Angle (degrees)	Shutter Length (mm)	Total Power (W)	Peak Heat Flux (W/mm^2)	Maximum Temperature (°C)	Maximum Cooling Wall Temperature (°C)	Mean Temperature (K)	Peak Stress (Mpa)	Elastic Strain Range (%)	Plastic Strain Range (%)	Total Strain Range (%)	Estimated Number of Cycles to Failure
PS2 HHL Shutter	MBA Lattice Baseline Condition	Dual In-Line U27.5 200 mA	1.05	647.7	13,062	16.5	199.3	80.4	385.3 (112.2°C)	-196.9 / 117.5	0.25698	0	0.25698	2.38E+08
PS2 HHL Shutter	MBA Lattice Baseline Condition	Dual In-Line U27.5 200 mA	1.5	556.0	13,063	23.63	276.5	103.1	424.0 (150.8°C)	-199.3 / 193.9	0.33135	0.01847	0.34982	390,000
PS2 HHL Shutter	MBA Lattice Baseline Condition	Dual In-Line U27.5 200 mA	1.75	525.5	13,065	27.57	319.7	115.6	445.6 (172.4°C)	-198.6 / 236.3	0.3604	0.0735	0.4339	37,900
PS2 HHL Shutter	MBA Lattice Baseline Condition	Dual In-Line U27.5 200 mA	2.08	496.4	13,069	32.77	376.5	131.7	473.9 (200.8°C)	-197.0 / 277.5	0.39184	0.14963	0.54147	23,900

→ *The reduction in life cycle compared to the reduction in shutter length changes significantly between 1.5° and 1.75° and therefore the optimum grazing incidence angle lies between them*

Built-In Safety in the Proposed New Design Criteria Limits

- Surface damage is cumulative (*Miner's Rule*). Our thermal fatigue model assumes every thermal cycle will occur at the worst-case loading condition. In operation, a shutter will experience many load cycles much less than the worst-case loading condition

→ We can expect many more cycles to "failure" than the thermal fatigue model predicts

- Sample #47 was tested under the worst-case possible conditions we could achieve with two in-line U33.0 undulators operating at 100 mA with closed gaps at 11.0 mm. Even after 10,000 thermal cycles, the final crack length was < 10 mm and the maximum crack depth was < 2 mm

→ It is hard to imagine a scenario where a crack could ever reach the cooling channel considering the surface temperature here was above the melting point

Conclusions

- The new design criteria limits allows much higher operating limits compared to the old design criteria.
- For all of the APS photon shutter cases we have looked at, following the proposed new design criteria limits will yield 20,000 or more cycles to failure
- For most component designs, only steady-state thermal analysis will be required to verify that the design meets the new design criteria limits. Stress analysis is not required when the maximum surface temperature ≤ 375°C.
- The thermal fatigue model provides a tool that can be used to geometrically optimize component designs.
- Based on the new design criteria limits, all of the existing photon shutter designs except for the V1.2 P2-20 could be used for the APS upgrade.

To evaluate the new design criteria limits, thermomechanically-induced fatigue tests, performed at grazing-incidence angle on a photon shutter installed in an ID front end, are being considered.

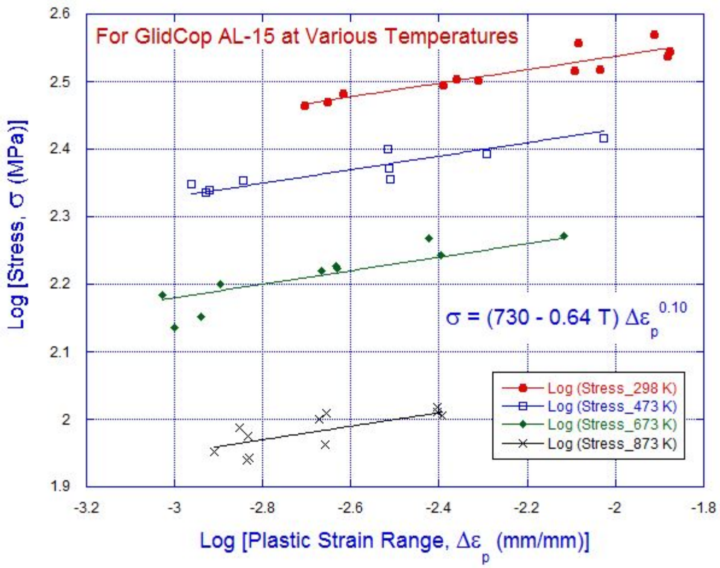
The following are slides not presented but may be of interest

Data Reduction for Uniaxial Mechanical Fatigue Tests

- The cyclic strain hardening relation can be found from the uniaxial mechanical fatigue data
- The cyclic strain hardening exponent (n) is a measure of how a material hardens from applied strain
- A value of n=0 → the material is a perfect plastic solid
- A value of n=1 → the material is a 100% elastic solid

$$\sigma = K \, \Delta\varepsilon_p^{\,n}$$

σ = Applied Stress (MPa)
$\Delta\varepsilon_p$ = Resulting Plastic Strain (%)
K = Cyclic Strain Hardening Coefficient (MPa)
n = Cyclic Strain Hardening Exponent



In our case:

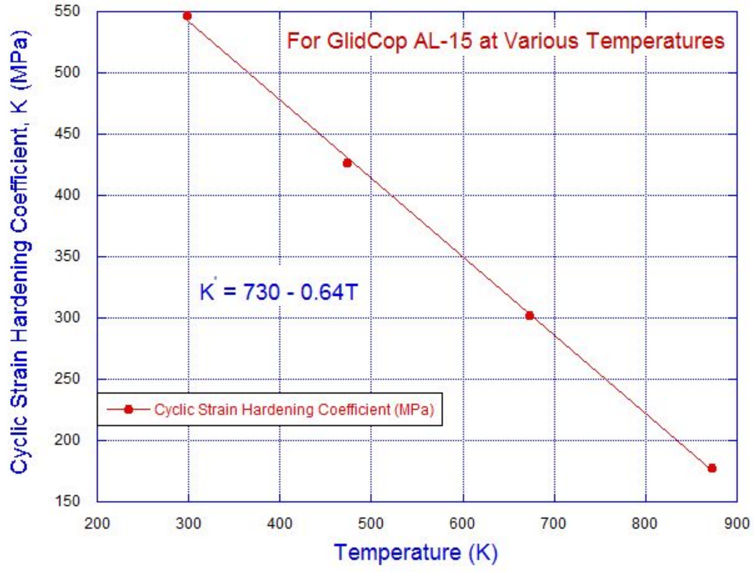
$$\sigma = (730 - 0.64\,T)\,\Delta\varepsilon_p^{\,0.10}$$

→ GlidCop® AL-15 behaves very differently than copper

Tabulation of n and K Values for Several Alloys [1]

Material	n	K (MPa)
Low-carbon steel (annealed)	0.21	600
4340 steel alloy (tempered @ 315°C)	0.12	2650
304 stainless steel (annealed)	0.44	1400
Copper (annealed)	0.44	530
Naval brass (annealed)	0.21	585
2024 aluminum alloy (heat treated—T3)	0.17	780
AZ-31B magnesium alloy (annealed)	0.16	450

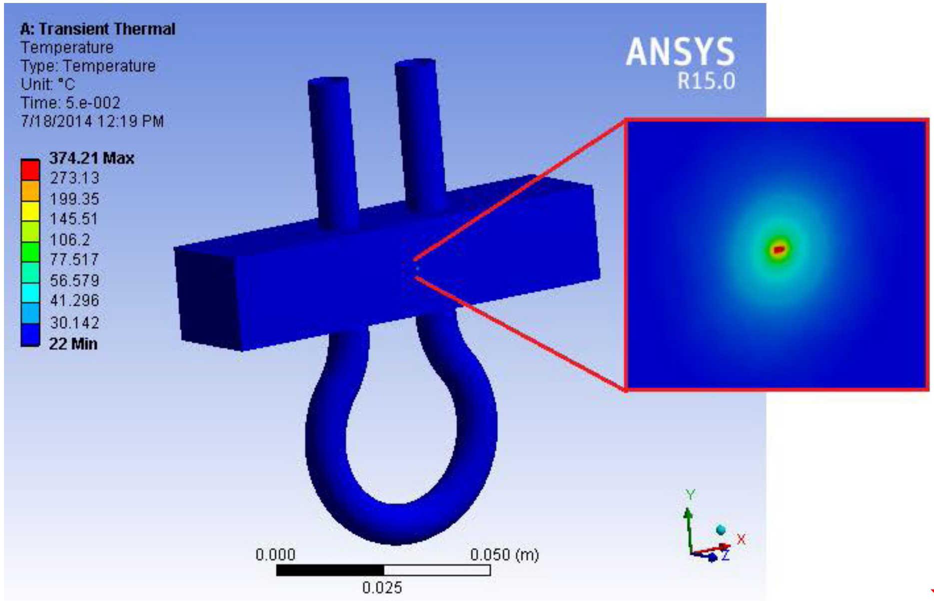
From Wikipedia

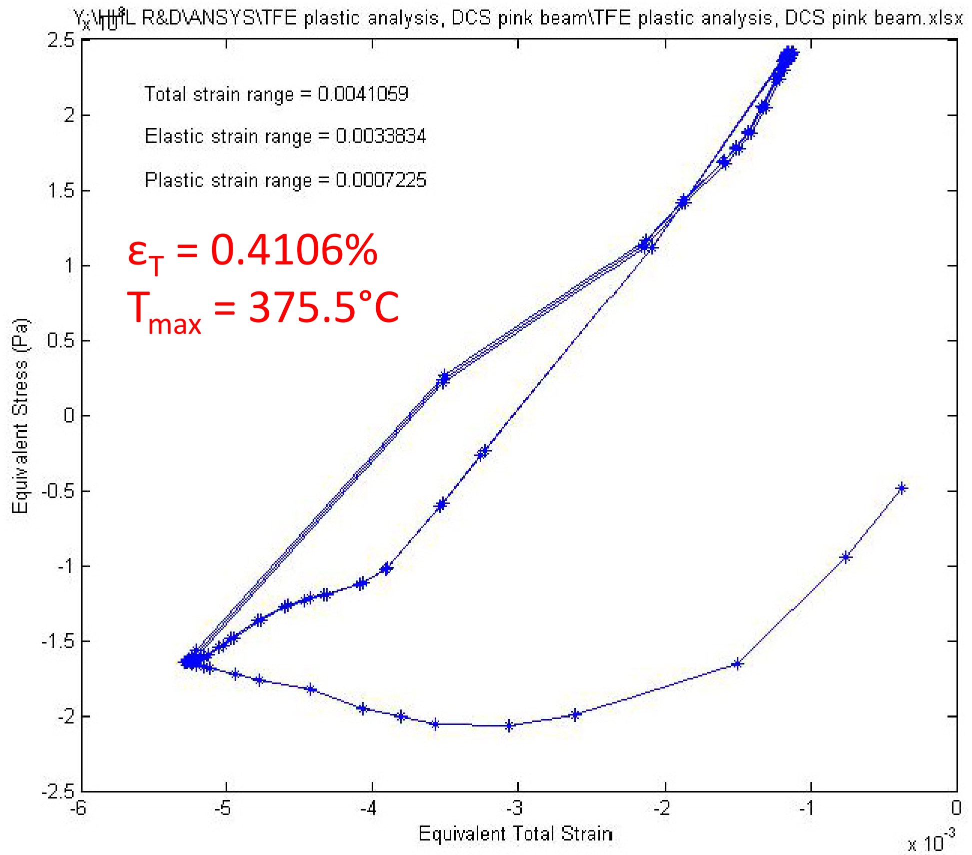


Can the Proposed New Design Criteria Limits be Applied to A Case with Very Small Beam Footprint Size?

Conditions:

- DCS pink beam conditions
- TFE sample, normal incidence
- 61.1 µm x 26.3 µm beam size
- 8.95 W total power
- Heat Flux = 5,570 W/mm^2
- 0.05 sec. heating, 0.05 sec. cooling
- 375.5°C steady-state (374.2°C transient)



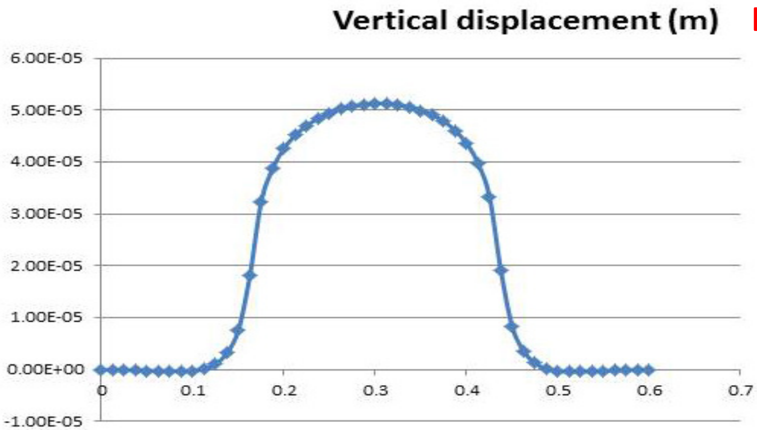


N_f = 205,500 cycles to failure

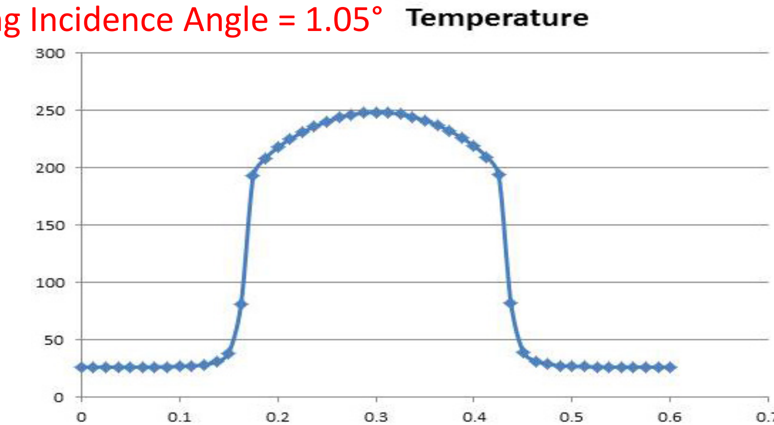
→ The proposed new design criteria limits work for a case with very small beam footprint size

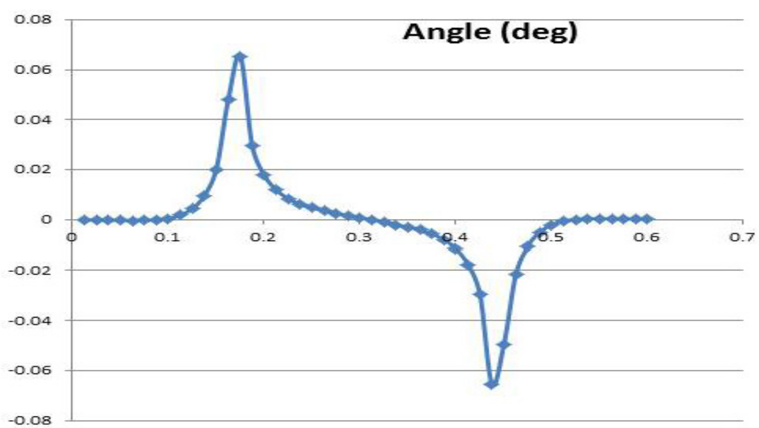
How Does a Thermal Bump Change the Grazing Incidence Angle?

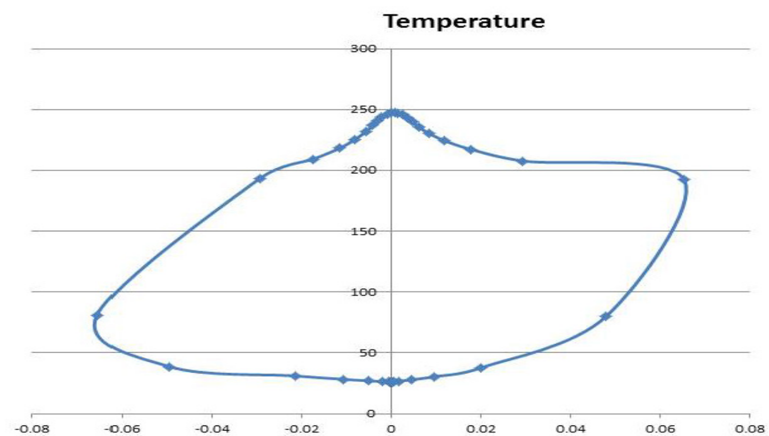
Photon Shutter Type	Operating Conditions	Source Parameters	Aperture Size at Shutter Location (mm x mm)	Total Power (W)	Peak Heat Flux (W/mm^2)	Maximum Temperature (°C)	Maximum Cooling Wall Temperature (°C)	Mean Temperature (K)	Peak Compressive / Tensile Stress (Mpa)	Elastic Strain Range (%)	Plastic Strain Range (%)	Total Strain Range (%)	Estimated Number of Cycles to Failure
PS1 HHL Shutter	Maximum Design Condition from HHL FE Design Report	Dual In-Line U33.0 180 mA	5 x 6	14,600	24.5	248.2	91.9	409.8 (136.6°C)	-205.1 / 173.0	0.30881	0.00615	0.31496	9.57E+06



Design Grazing Incidence Angle = 1.05°







→ The maximum thermal bump height is ~ 50 µm and the maximum angular change is ~ 0.07°.

→ The maximum angular change occurs well outside of the beam center, and the grazing incidence angle is unchanged at the beam center.