Fatigue Life Prediction for GlidCop

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Background

We have been wrestling with the thermal limitation issue for high-heat-load components made of GlidCop.

What is the limitation?

Melting

Easily handled

Fracture

Very complicating, because it is dominated by stress range and/or strain range.

↓ depend on

Temperature distribution, Configuration, Restraint condition, Stress-strain behavior in the plastic region, Heat load condition· ·

Target : Low-Cycle-Fatigue Life Prediction

Considering Top-UP operation at SPring-8

Basic Procedure

- Strain range calculated by elastic-plastic analysis
- <Compare> ↕ *Fatigue Life Estimation*
- Fatigue property of GlidCop

Fatigue Property of GlidCop (1)

Low-cycle Fatigue Test (strain-controlled)

a) In air @ RT, 100°C, 200°C, 400°C, 600°C

b) In vacuum @ 200°C, 300°C

@ pp-wave , pc-wave

Fatigue life in vacuum is considered to be longer than that in air, because there is no fatigue acceleration by oxidation in vacuum.

Definition of the fatigue life

The number of cycles at which the peak tensile stress during each cycle dropped by 25% from its initial value

(Japanese Industrial Standards Z2279-1992).

⇩

~2mm-long cracks were typically observed.

Fatigue Property of GlidCop (2)

TOTAL PLASTIC ELASTIC

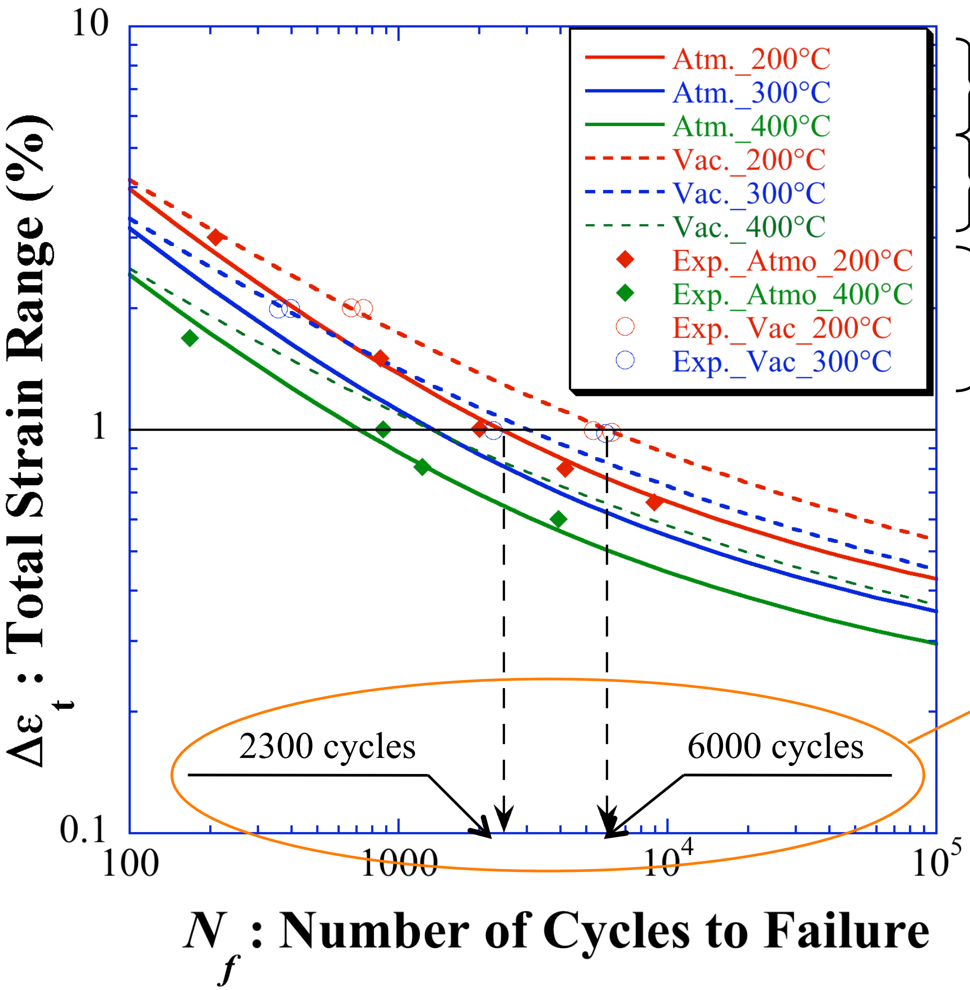
$$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = A \cdot N_f^{-\alpha} + B \cdot N_f^{-\beta}$$

(Manson-Coffin's rule) *(Basquin's rule)*

We attempted to formulate a $\Delta\varepsilon_t$-N_f diagram at any temperature,
assuming that α and β do not depend on the temperature but on the environment.
= Temperature- and air- dependent property is only represented by A and B.

Environment	Temperature T (°C)	Manson-Coffin A	Manson-Coffin -α	Basquin B	Basquin -β
Atmosphere	100	60.8	-0.6	1.15	-0.086
	200	51.9	-0.6	1.01	-0.086
	400	30.9	-0.6	0.71	-0.086
	any	*-0.1*T+71.31*	*-0.6*	*-0.0015*T+1.295*	*-0.086*
Vacuum	200	31.2	-0.48	1.1	-0.086
	300	24.6	-0.48	0.95	-0.086
	any	***-0.066*T+44.4***	***-0.48***	***-0.0015*T+1.4***	***-0.086***

Fatigue Property of GlidCop (3)



for Air

for Vacuum

Formulated predictions (curves)

$$\Delta\varepsilon_t = A \cdot N_f^{-\alpha} + B \cdot N_f^{-\beta}$$

Low-cycle-fatigue test data (symbols)

When comparing the difference of the environment, the dashed line is always above the solid line with the same color.

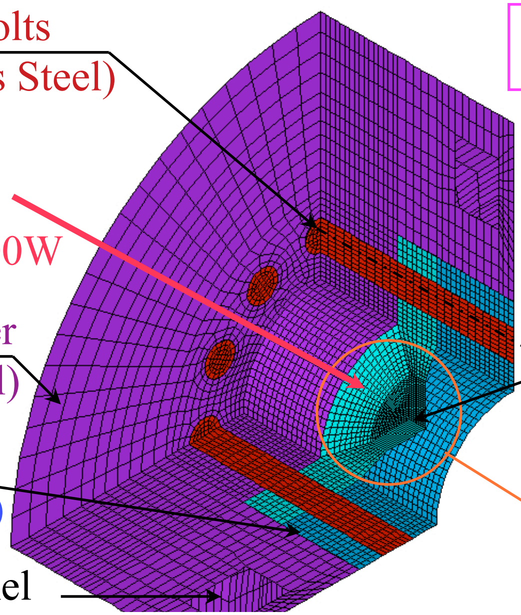
The ratio at 200°C =6000/2300=2.6 @$\Delta\varepsilon_t$=1%.

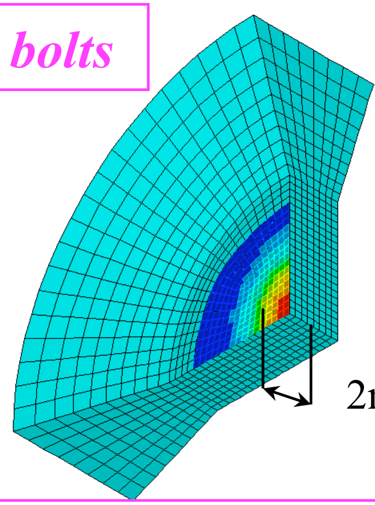
- The observed cycles (symbols) are quite well reproduced by the formulated ones (curves).

- The fatigue life in vacuum is longer than that in air. (ratio at 200°C is 2.6 @Δεt=1%)
- The difference has a tendency to increase on the lower-strain-range region.

Fatigue Fracture Experiment

Axial tension by tightening bolts

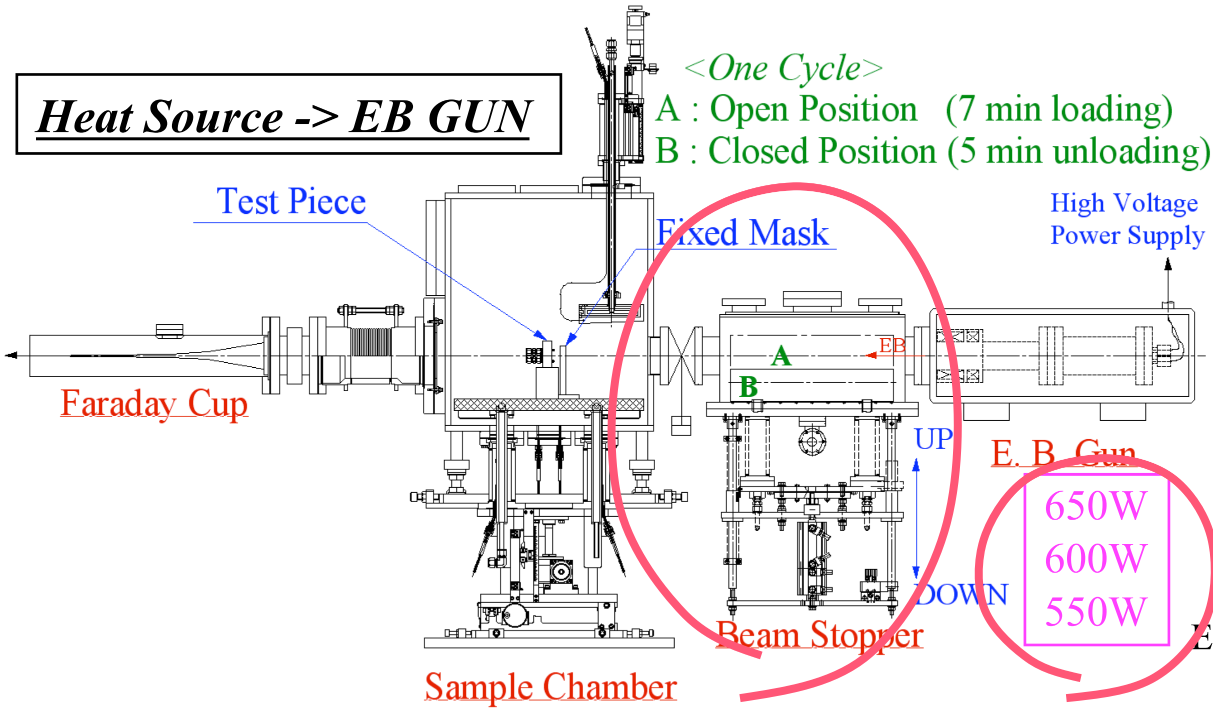




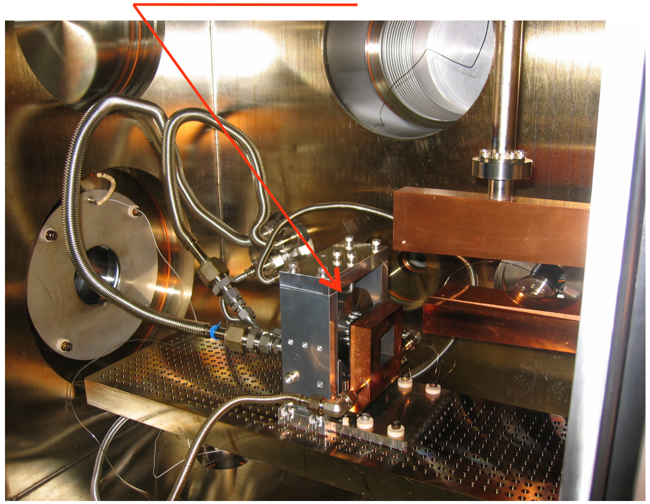
Tapered Configuration

e the strain in the central area locally.

Heat Source -> EB GUN



Test Piece

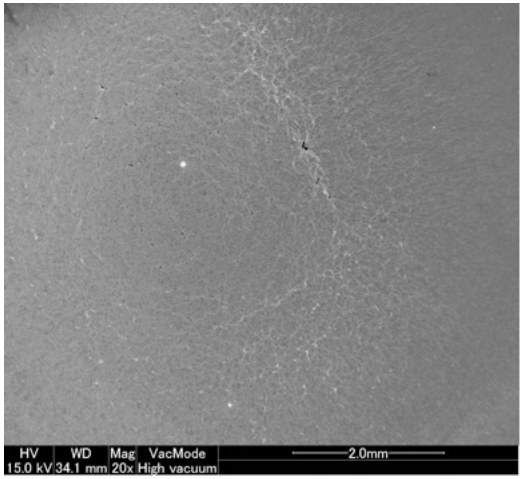


Experimental setup inside the sample chamber

Experimental Results (1)

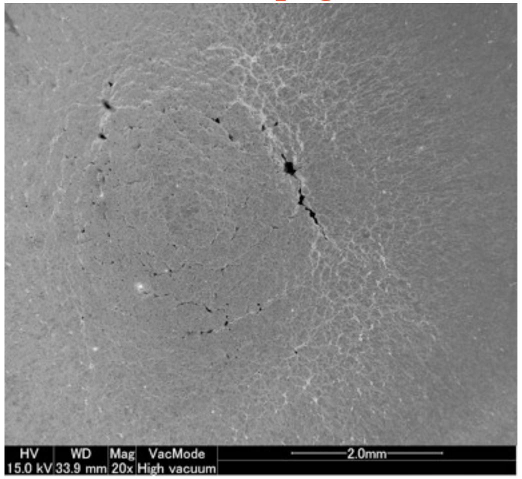
650W

Crack Initiation



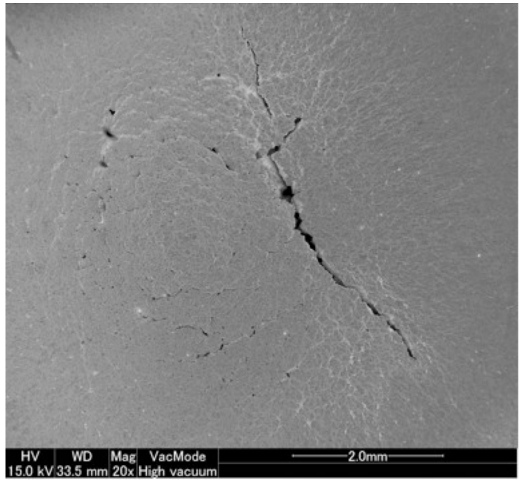
150 cycles (x 20)

Crack Propagation



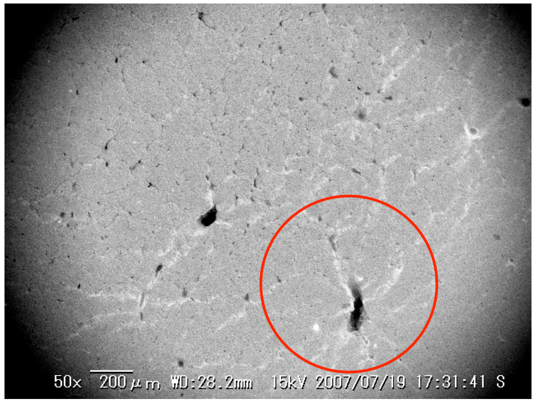
230 cycles (x 20)

Fracture

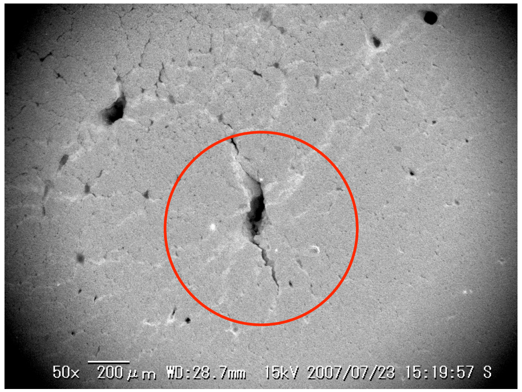


260 cycles (x 20)

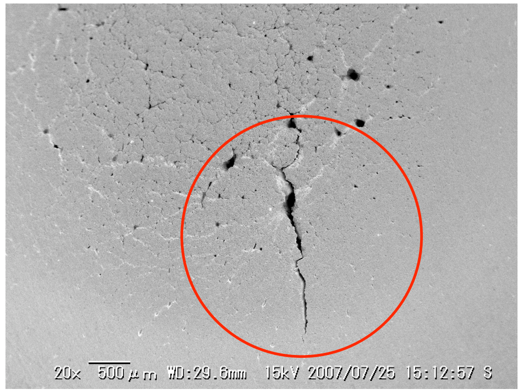
600W



300 cycles (x 50)



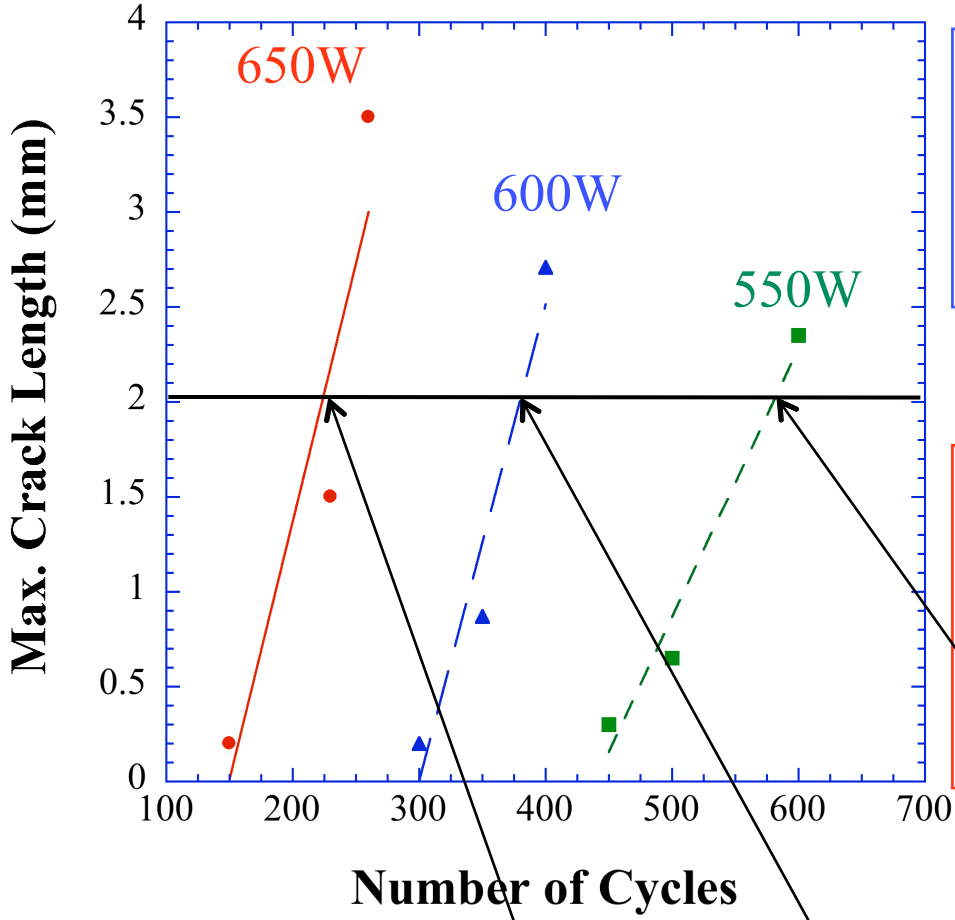
350 cycles (x 50)



400 cycles (x 20)

Magnified SEM photographs of the area around the center of the TP

Experimental Results (2)



The appearance of a crack should be treated as a phenomenon that signals *the beginning of fracture after crack propagation.*

← ***2mm***

In accordance with the results of the low-cycle-fatigue test, the observed life was considered as the number of cycles after which *the maximum crack length reaches 2 mm.*

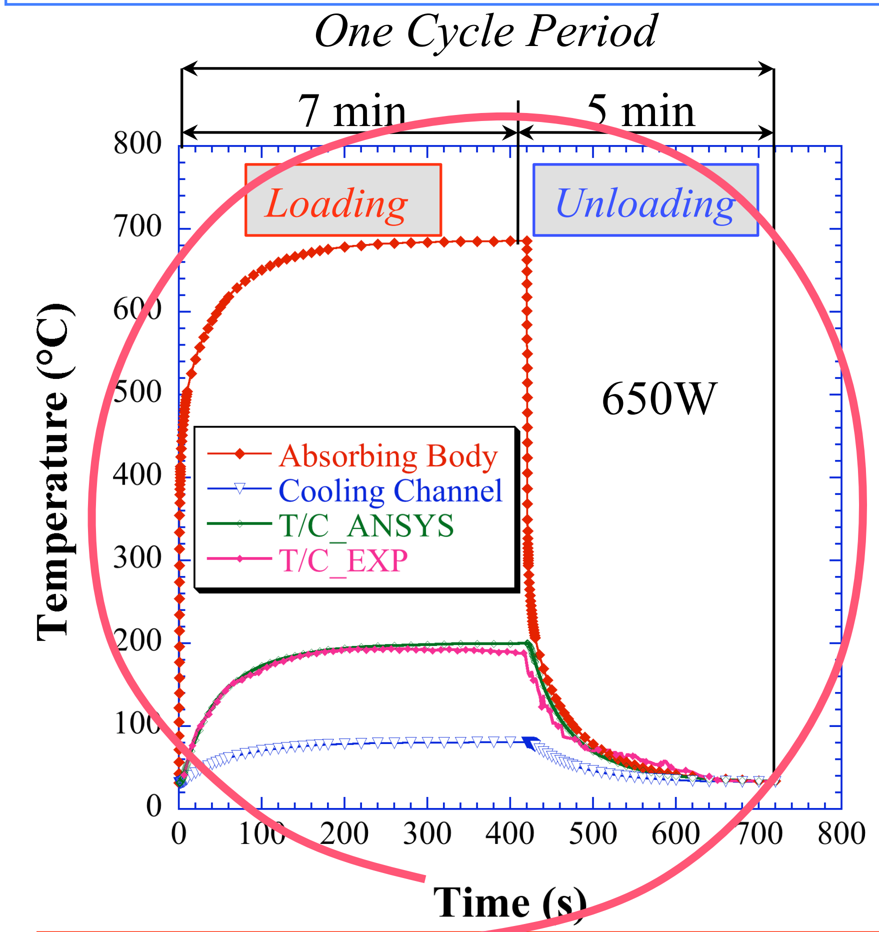
	Cyclic Heat Load		
	650W	600W	550W
Observed Life	*220 cycles*	*380 cycles*	*580 cycles*

Elastic-Plastic Analysis (Preparation)

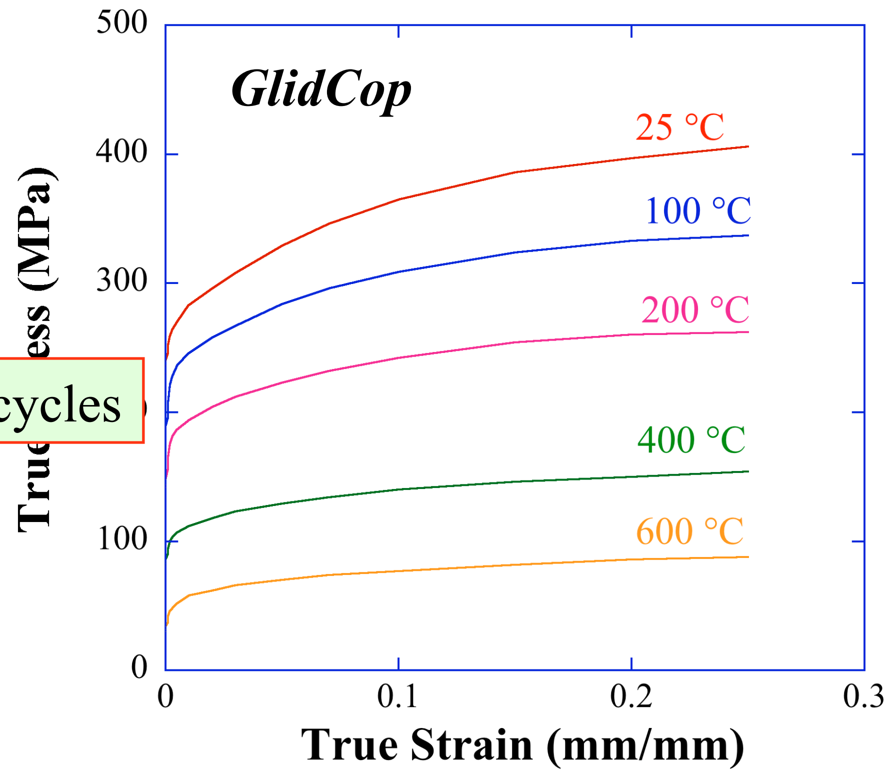
<Purpose> : To calculate the total strain range ($\Delta\varepsilon_t$)

Time history of spatial temperature distribution covering 1 cyclic heat load

Temperature-dependent stress-strain diagrams in the plastic region



x 8 cycles



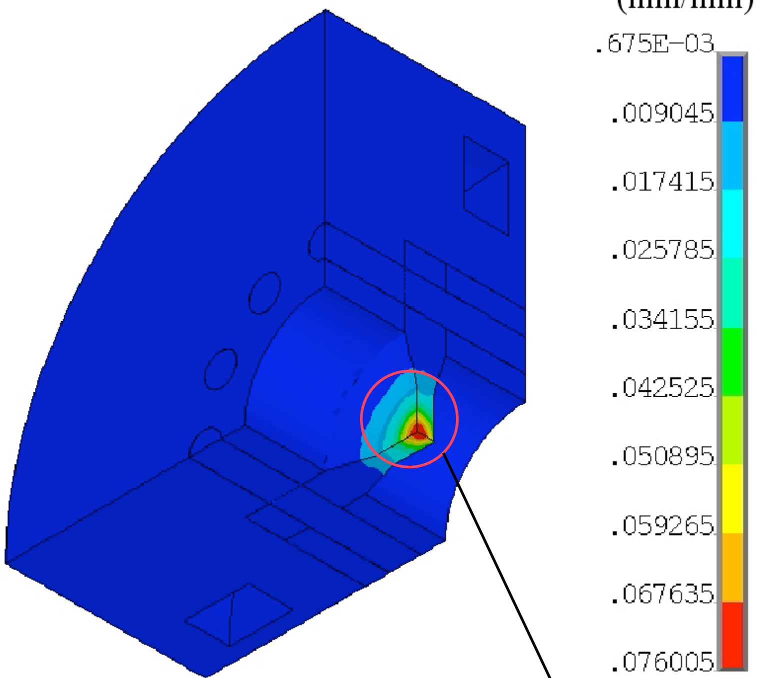
Furthermore, after defining restraint conditions and the hardening rule, the elastic-plastic analysis was conducted *by applying the cyclic heat load eight times*.

Elastic-Plastic Analysis (Results)

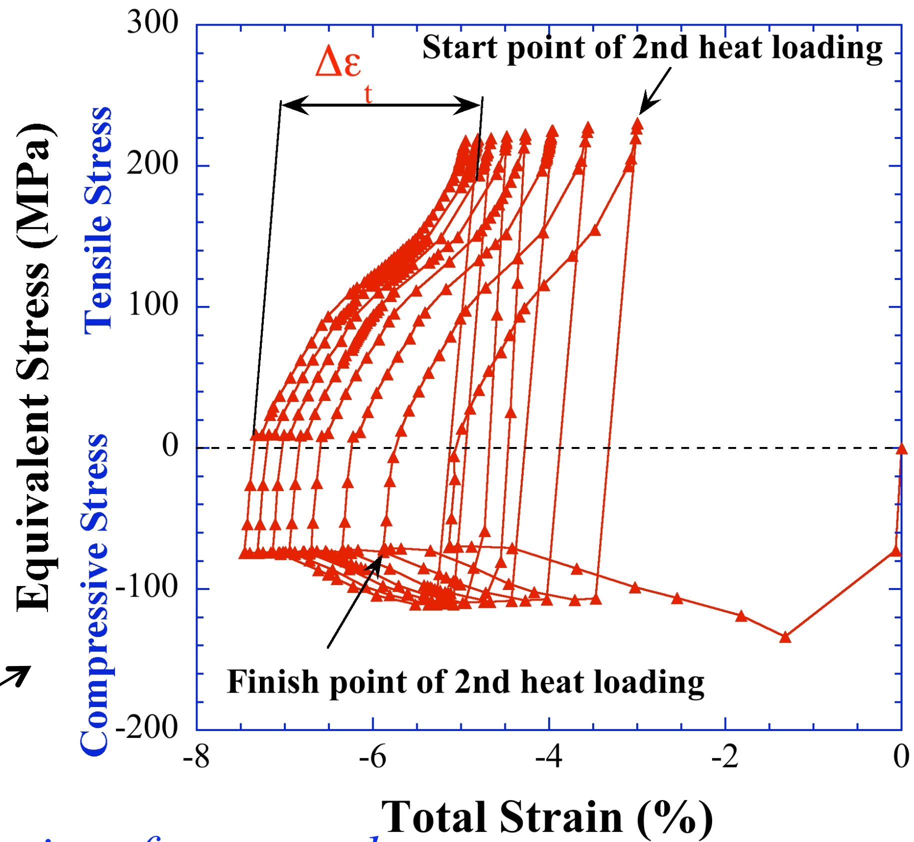
Contour Plot of eqv. plastic strain

Hysteresis Loop of total strain and eqv. stress

Just before the 8^{th} irradiation was stopped



Max. value appears at the center of GlidCop body.



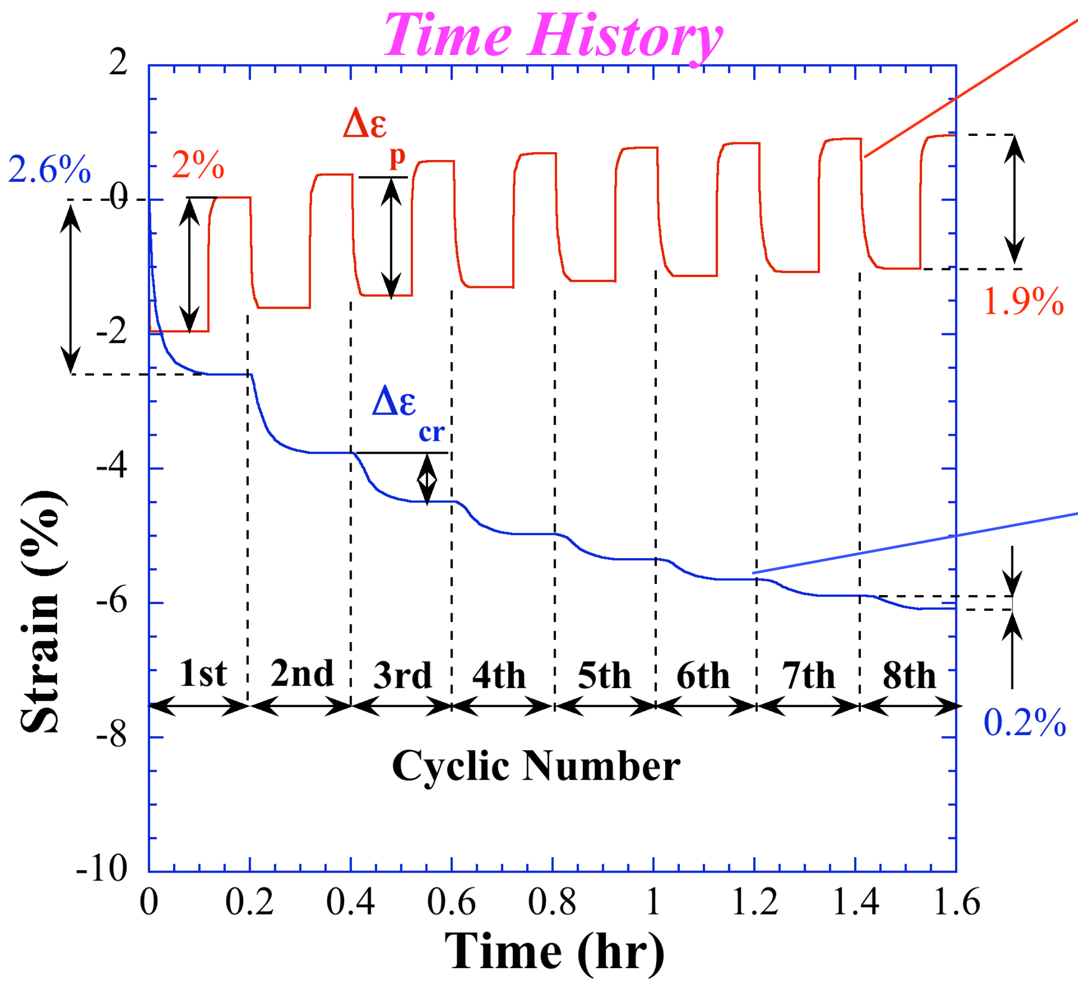
Time histories of stress and strains for the central element.

$\Delta\varepsilon_t$ converges to about ***2.64%*** (2.34% $\Delta\varepsilon_p$ + 0.30% $\Delta\varepsilon_e$).

Influence of Creep

Creep Test @ 100°C, 200°C, 400°C, 600°C to develop a creep constitutive equation.

ANSYS Creep option : Norton Model (secondary creep only)



Equivalent Plastic Strain

$\Delta\varepsilon_p$ at the 1st cycle : 2.0 %

↓

almost constant

↓

$\Delta\varepsilon_p$ at the 8th cycle : 1.9 %

Equivalent Creep Strain

$\Delta\varepsilon_{cr}$ at the 1st cycle : 2.6 %

↓

gradually decreases

↓

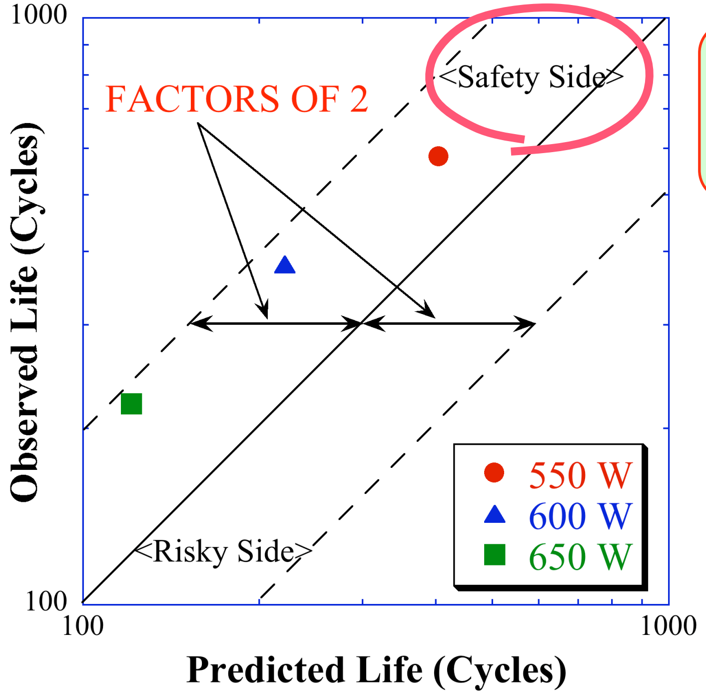
$\Delta\varepsilon_{cr}$ at the 8th cycle : 0.2 %

$\Delta\varepsilon_p$ dominates the entire fatigue behavior.

Comparison between Exp. and Analysis

Cyclic Heat Load (W)	Max. Power Density (W/mm2)	Body Temperature (°C)		Strain Range (%)			Predicted Life (Number)	Observed Life (Number)
		Maximum	Mean	Plastic	Elastic	Total		
650	56.0	685.9	359	2.34	0.30	2.64	**121**	***220***
600	51.6	634.2	333	1.96	0.28	2.24	**221**	***380***
550	47.3	582.7	307	1.61	0.30	1.91	**405**	***580***

Mean temperature : with a high of the maximum temperature and a low of 32°C.



<$\Delta\varepsilon_t$ – N_f relation in vacuum at temperature of T °C>

$$\Delta\varepsilon_t = (-0.066 \times T + 44.4) \cdot N_f^{-0.48} + (-0.0015 \times T + 1.4) \cdot N_f^{-0.086}$$

Max. Temp.	Mean Temp.	$\Delta\varepsilon_t$	Allowable $\Delta\varepsilon_t$
600°C	315°C	***0.70 %***	***0.23 %***
500°C	265°C	***0.78 %***	***0.26 %***
400°C	215°C	***0.85 %***	***0.28 %***
300°C	165°C	***0.93 %***	***0.31 %***

Safety Factor : 3

<Condition>

Target cyclic number : 10,000 cycles

Cooling water temperature : 30 °C

Random Heat Load

Period	1st →	2nd →	3rd
CASE 1	650W	600W	550W
CASE 2	550W	600W	650W

arbitrary decided heat cycles were applied (1st, 2nd)

detected N corresponding to the 2 mm-long crack. (3rd)

Assumption : "Cumulative Linear Damage Low" --> *Miner's Rule*

$$\sum \frac{n_i}{N_i} = 1$$

n_i : number of applied cycles at strain range ($\Delta\varepsilon_i$)
N_i : number of cycles to failure at strain range ($\Delta\varepsilon_i$)
n_i/N_i : fatigue damage at strain range ($\Delta\varepsilon_i$)

$1/N_i$ of the life should be consumed by each cycle.

	1st	2nd	3rd	$\sum \frac{n_i}{N_i}$
CASE 1	**75** cycles	**160** cycles	**240** cycles	***1.94***
CASE 2	**265** cycles	**160** cycles	**40** cycles	***1.71***

← (Sum of the consumptions)

$$\sum \frac{n_i}{N_i} = \frac{75}{121} + \frac{160}{221} + \frac{240}{405} = 1.94$$

$$\sum \frac{n_i}{N_i} = \frac{265}{405} + \frac{160}{221} + \frac{40}{121} = 1.71$$

Summary and Future Plans

1. From the results of low-cycle-fatigue tests on GlidCop, the environment-dependent relation between $\Delta\varepsilon_t$ and N_f at any temperature has been successfully presented based on the Manson-Coffin equation.

2. We applied a cyclic heat load to a specially designed test piece, and continuously observed the fracture behavior to determine the observed life.

3. In parallel, the fatigue life was predicted by the hysteresis loop of the elastic-plastic analysis.

4. As a result, we could predict the fatigue life within a factor of 2. Furthermore, from this fruitful result, the allowable total strain range for each maximum temperature was proposed.

5. Based on this study, the thermal limitation of currently existing high-heat-load components of SPring-8 front ends made of GlidCop can be detected, and this is the subject of our future study.