Creep of beryllium pebbles after neutron irradiation to 6000 appm helium production

Vladimir Chakin[1], Rolf Rolli[1], Milan Zmitko[2]

[1]*Institute for Applied Materials - Applied Materials Physics, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*
[2]*Fusion for Energy, c/ Josep Pla, nº 2, Torres Diagonal Litoral Edificio B3, 08019 Barcelona, Spain*

Beryllium pebbles with 1 mm diameter are the reference neutron multiplier material in the Helium Cooled Pebble Bed (HCPB) blanket of ITER. High energy fusion neutrons cause swelling of the beryllium pebbles at the HCPB operation temperatures to 923 K. The radiation-induced swelling of beryllium as well as different thermal expansions of the beryllium pebbles and the structural material can cause the high thermal stresses in the pebble bed. Thermal creep of the pebbles should reduce the stresses because the relaxation. Neutron irradiation leads to degradation of mechanical properties, what expresses in the hardening and the embrittlement. This radiation effect hinders the effect of the relaxation.

In this study, creep properties of beryllium pebbles with 1 mm diameter produced by Rotating Electrode Method (REM) at NGK, Japan were studied. These beryllium pebbles were irradiated in the HFR, Petten, the Netherlands, at temperatures of 643, 723, 833, 923 K to 6000 appm helium production. The creep tests of individual pebbles were performed at temperatures which were equal to the irradiation temperatures by using of three different loadings per each temperature. For two lowest irradiation temperatures of 643 and 723 K, no creep effect was observed. The radiation hardening only occurs that manifests itself in significant reduction of the pebble deformation under loading. At higher irradiation temperatures of 833 and 923 K, the creep rates have significant values. The creep rates strongly depend on the testing temperatures and the loadings. At high irradiation temperatures the ability of beryllium pebbles to the significant deformation under applied loadings should provide the complete relaxation of the internal stresses in the beryllium pebbles.

Corresponding Author:

Dr. Vladimir Chakin
vladimir.chakin@kit.edu

Institute for Applied Materials - Applied Materials Physics,
Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

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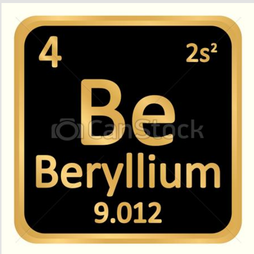
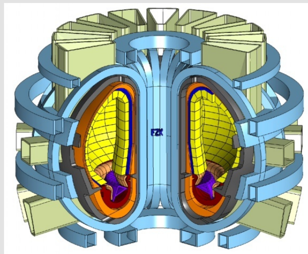
[2]*Fusion for Energy (F4E), Josep Pla 2, Barcelona, Spain*





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Outline

- Materials, pebbles, creep testing at FML
- HIDOBE-02: irradiation of unconstrained (free filled) Be pebbles and constrained Be pebble beds
- Optical microstructure of irradiated Be pebbles
- Creep behaviour of irradiated unconstrained and constrained Be pebbles
- Conclusions

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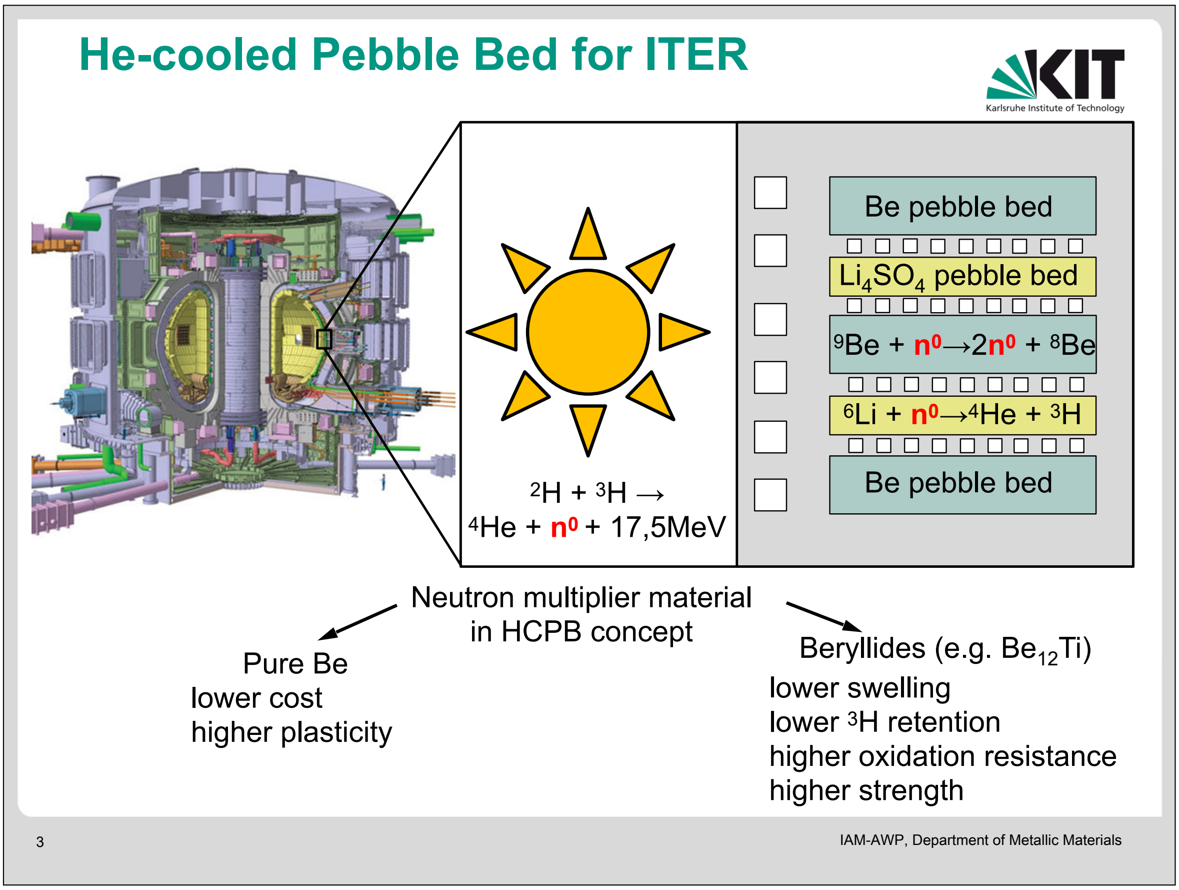
He-cooled Pebble Bed for ITER
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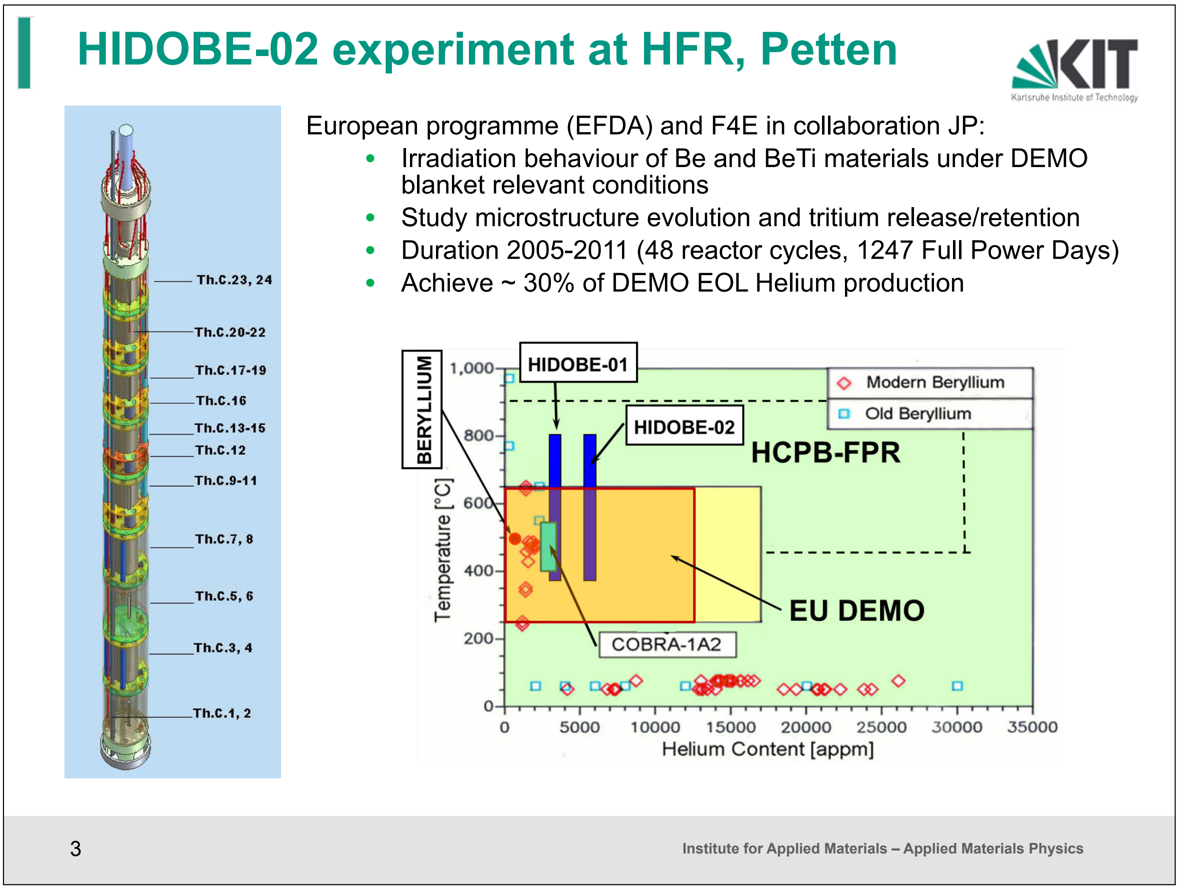
Be pebble bed
Li4SO4 pebble bed
9Be + n0→2n0 + 8Be
6Li + n0→4He + 3H
Be pebble bed
2H + 3H →
4He + n0 + 17,5MeV
Neutron multiplier material
in HCPB concept
Pure Be
lower cost
higher plasticity
Beryllides (e.g. Be12Ti)
lower swelling
lower 3H retention
higher oxidation resistance
higher strength
3
IAM-AWP, Department of Metallic Materials


HIDOBE-02 experiment at HFR, Petten
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Th.C.20-22
Th.C.17-19
Th.C.16
Th.C.13-15
Th.C.12
Th.C.9-11
Th.C.7, 8
Th.C.5, 6
Th.C.3, 4
Th.C.1, 2
European programme (EFDA) and F4E in collaboration JP:
Irradiation behaviour of Be and BeTi materials under DEMO blanket relevant conditions
Study microstructure evolution and tritium release/retention
Duration 2005-2011 (48 reactor cycles, 1247 Full Power Days)
Achieve ~ 30% of DEMO EOL Helium production
BERYLLIUM
HIDOBE-01
HIDOBE-02
Modern Beryllium
Old Beryllium
HCPB-FPR
EU DEMO
COBRA-1A2
Temperature [°C]
1,000
800
600
400
200
0
0
5000
10000
15000
20000
25000
30000
35000
Helium Content [appm]
3
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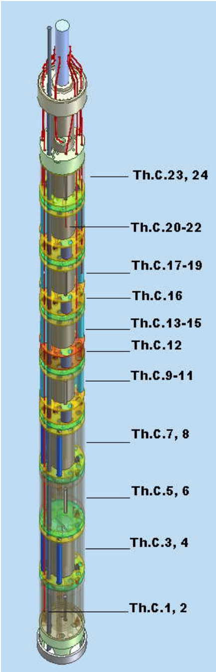
HIDOBE-02 experiment at HFR, Petten



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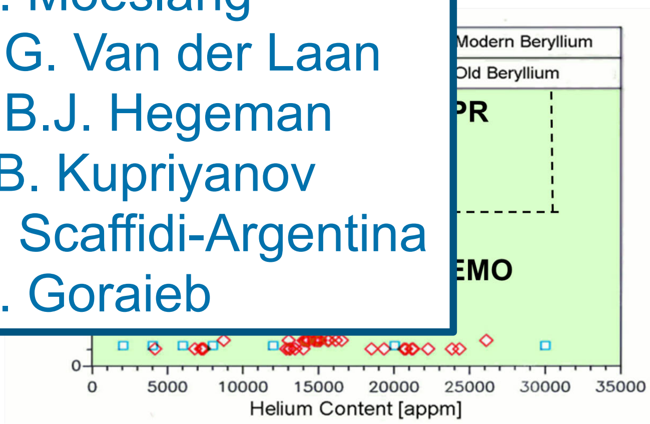
M. Dalle Donne
G.R. Longhurst
H. Kawamura
A. Moeslang
J.G. Van der Laan
J.B.J. Hegeman
I.B. Kupriyanov
F. Scaffidi-Argentina
A. Goraieb



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Irradiation parameters of Be pebbles in HIDOBE-02 compaign

Be pebble with Ø1 mm	T_{irr}, K	F, ×10^{26}, m^{-2}, E>1MeV	D, dpa	^4He, appm	^3H, appm
Unconstrained (free filled)	644	1.06	21	3632	367
	716	1.43	29	4751	502
	832	1.68	34	5524	596
	919	1.81	37	5925	644
Constrained	660	1.06	21	3632	367
	754	1.43	29	4751	502
	874	1.68	34	5524	596
	958	1.81	37	5925	644

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Chemical composition of Be pebbles with Ø 1 mm

Element	Content, wt.%
Be	99.5
BeO	0.36
Fe	0.094
Al	0.048
Mg	0.024
Si	0.029
U	<0.01

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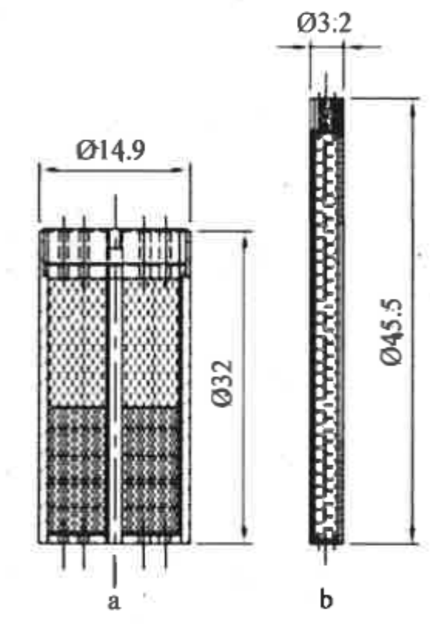
Placement of Ø 1 mm Be pebbles in HIDOBE-02



Unconstrained Be pebbles are placed in capsule with Ø 3.2 mm. The pebbles were filled free in the capsule.

Constrained Be pebble beds are placed in capsule with Ø 14.9 mm. It was filled by pebbles and then, screwed on with screw cap with torque wrench. In particular, after contact of the cap with the pebbles, another forced turn of the cap along the thread was done. In this position, the cap was spot welded to the capsule. In this way, additional internal stresses were created in the pebbles.

This allows to simulate internal state of the pebbles swelled after irradiation to higher neutron dose than that in HIDOBE-02 experiment.

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Pebble loading scheme in creep machine

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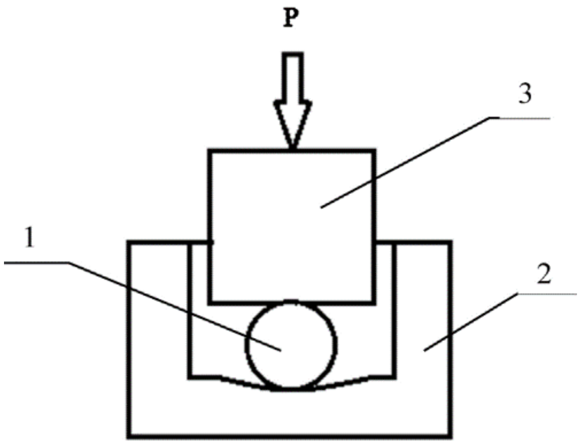

1 – pebble
2 – bottom
3 – loading piston

P – constant during creep test

$T_{test} = T_{irr}$ for each testing pebble

t = 80 h

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Creep testing parameters and shortly about results

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State	T_{irr}, K	T_{test}, K	P, N	Result
Unconstrained	644	643	100	no deformation
			110	cracks
			120	cracks
			150	cracks
	716	723	100	no deformation
			110	cracks
			120	cracks
	832	833	55	no deformation
			60	deformation
			70	deformation
	919	923	15	no deformation
			20	no deformation
			25	no deformation
Constrained	660	643	35	deformation
			50	deformation
			70	deformation
			100	cracks
	754	723	70	deformation
			100	deformation
			120	deformation
	874	833	35	deformation
			50	deformation
			70	cracks
	958	923	-	not dismantled

"No deformation" means that the load is not enough to produce deformation or destruction of the pebble.

"Cracks" means that cracks appeared as a result of loading.

"Deformation" means that as a result of loading, the pebble deformed through creep.

Therefore, only 10 diagrams (by red) from 23 diagrams of performed tests include really creep behavior therefore, they can be processed.

8 diagrams from 10 "red" diagrams ("deformation") are constrained pebbles. This means that constrained pebbles have comparatively better creep behavior.

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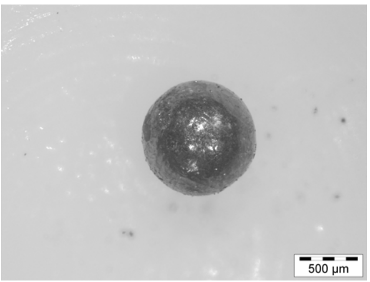
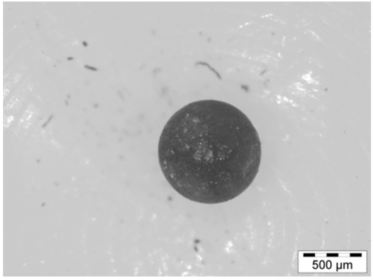
Examples of “no deformation” case after creep tests

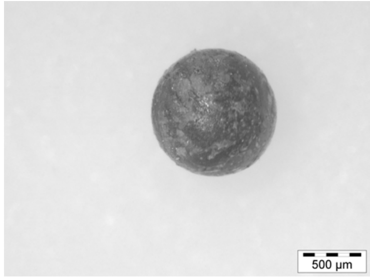
Unconstr., T_{test} = 643 K, P = 100 N



Unconstr., T_{test} = 833 K, P = 80 N



Unconstr., T_{test} = 923 K, P = 25 N



“No deformation” case was only for unconstrained Be pebbles (6 creep tests).

Reason for “no deformation” case is that was not enough load to deform or to break the tested pebble.

9

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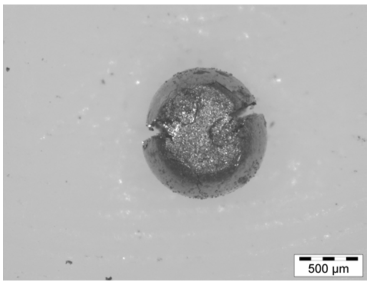
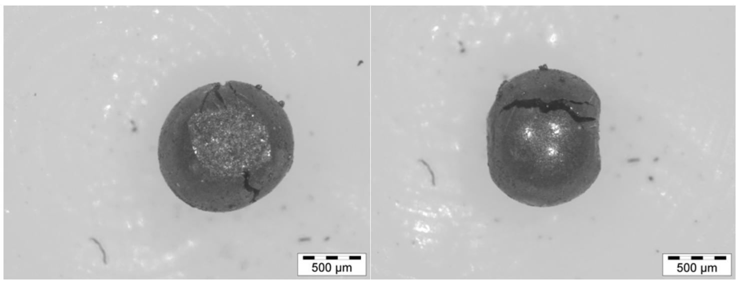
Examples of “cracks” case after creep tests

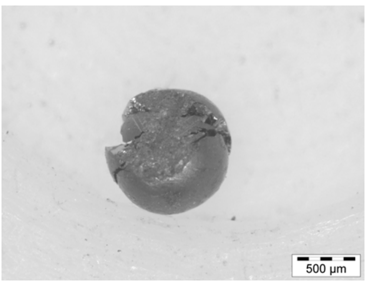
Unconstr., T_{test} = 643 K, P = 120 N



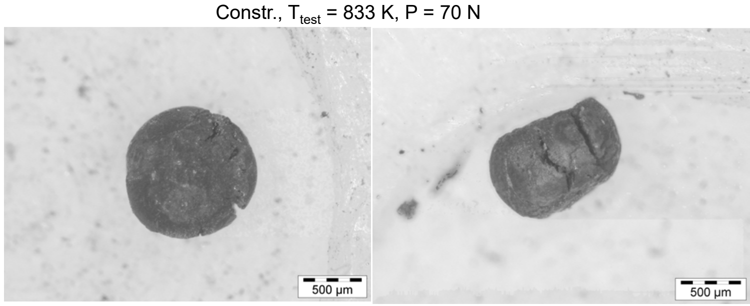
Unconstr., T_{test} = 723 K, P = 120 N



Constr., T_{test} = 643 K, P = 100 N



Constr., T_{test} = 833 K, P = 70 N



5 “cracks” cases are for unconstrained pebbles, 2 cases are for constrained pebbles.

10

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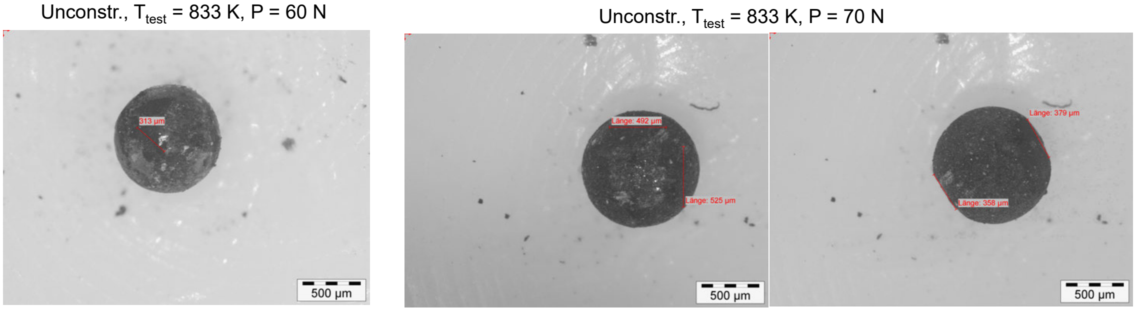
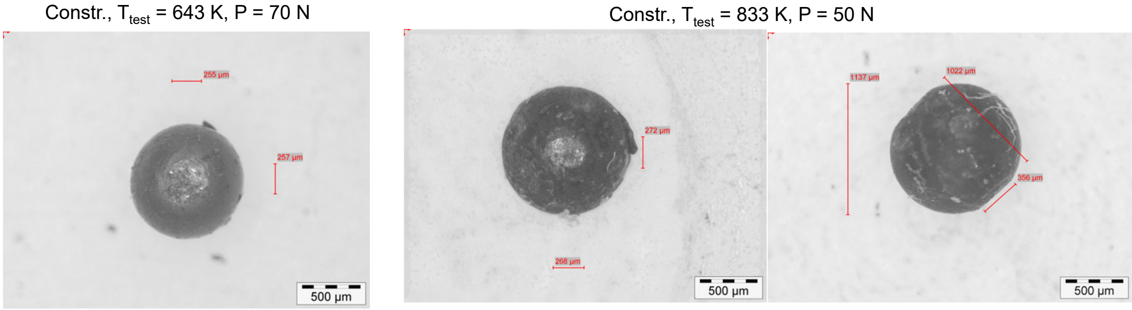
Examples of "deformation" case

Unconstr., T_{test} = 833 K, P = 60 N — Unconstr., T_{test} = 833 K, P = 70 N



Constr., T_{test} = 643 K, P = 70 N — Constr., T_{test} = 833 K, P = 50 N



2 "deformation" cases are for unconstrained pebbles, 8 cases are for constrained pebbles.

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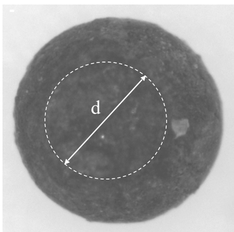
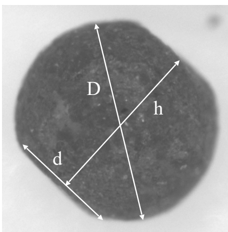
Parameters of indentations on irradiated Be pebbles after creep testing





D is diameter of pebble

d is indentation diameter as a result of the creep process

h is distance between opposite indentations

$\sigma = P/S = 4P/\pi d^2$, where σ is internal stress in the pebble under loading P, S is area of indentation with diameter of d

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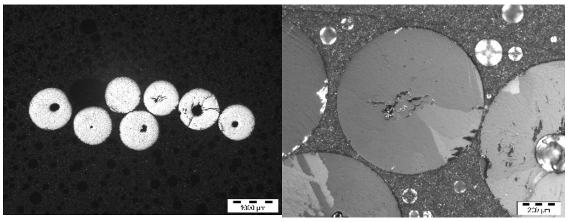
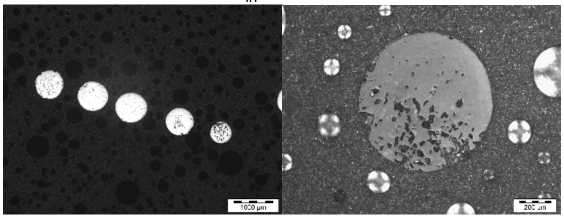
Microstructure of unconstrained Be pebbles after irradiation

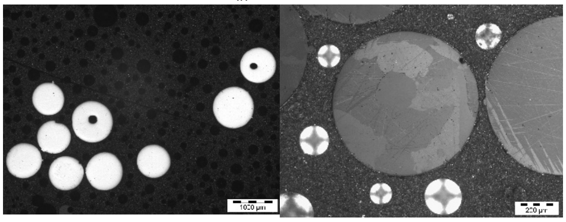
T_{irr} = 644 K



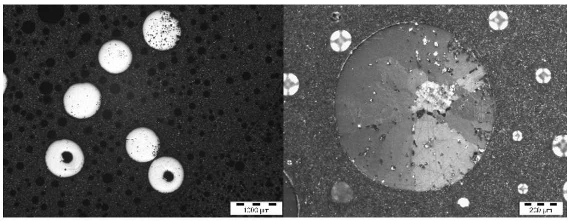
T_{irr} = 832 K



T_{irr} = 716 K



T_{irr} = 919 K



no pores ← → many big pores

There is a fundamental difference of microstructure evolution on irradiation temperature. No visible pores are after irradiation at two lowest T_{irr} (644 and 716 K). Many big pores are after irradiation at two highest T_{irr} (832 and 919 K).

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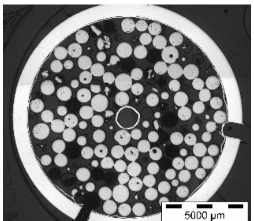
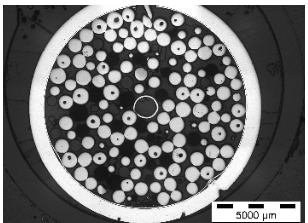
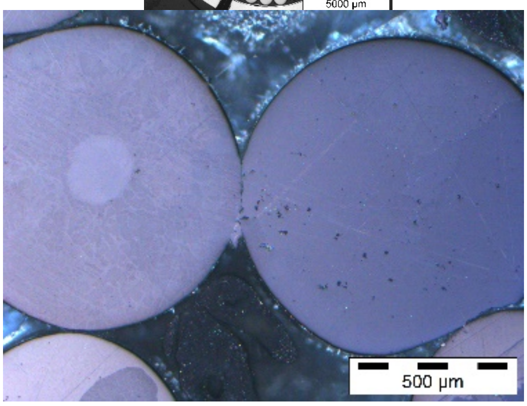
Microstructure of constrained Be pebble beds after irradiation

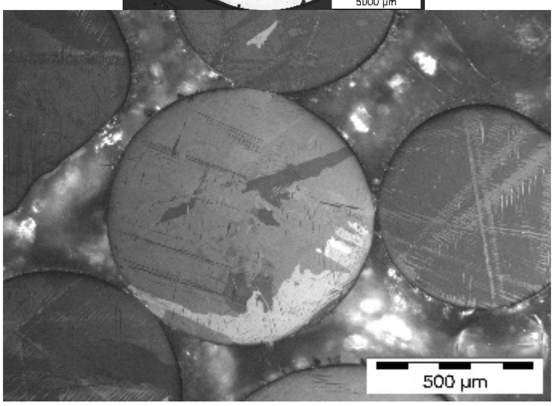
T_{irr} = 660 K





T_{irr} = 754 K





Also, no pores but constrained pebbles have much more sub-grains and twins compared to unconstrained pebbles.

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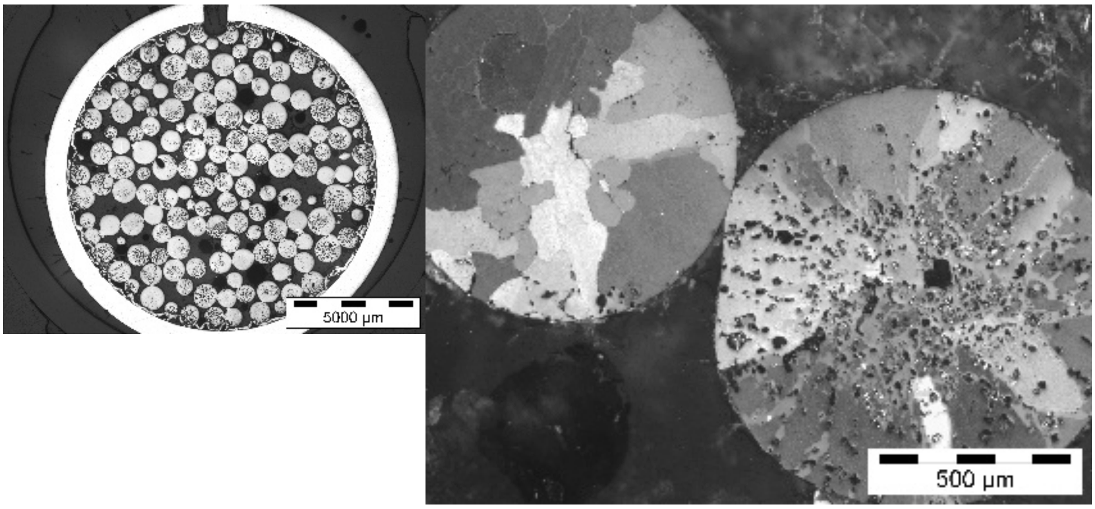
Microstructure of constrained Be pebbles after irradiation at 874 K



There are many big pores and developed sub-grain microstructure.

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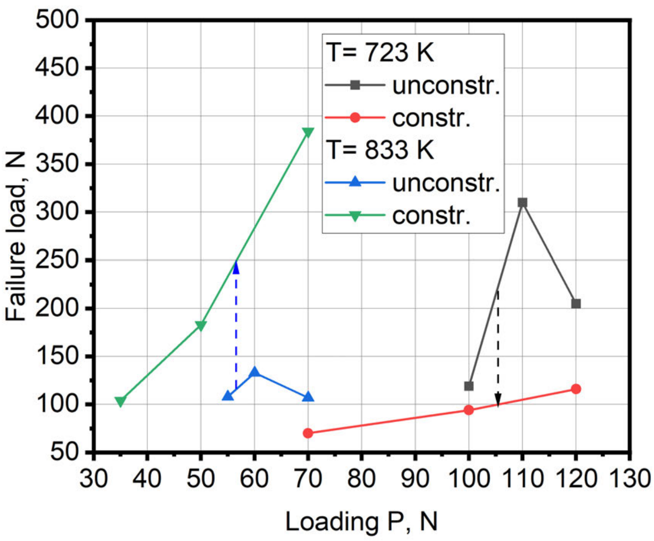
Failure load on loading of irradiated Be pebbles at T_{test} = 723 and 833 K



T_{test} = 643 K (0.412 T_m)
723 K (0.463 T_m)
Creep starts at T_{test}>0.5T_m
833 K (0.534 T_m)
923 K (0.592 T_m)

At 723 K is no creep: failure load of unconstrained pebbles is higher than that of constrained pebbles, and failure occurs at higher loading.

At 833 K is creep: failure load of unconstrained pebbles is lower than that for constrained pebbles, and failure occurs at lower loading.

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Examples of creep curves for unconstrained and constrained irradiated Be pebbles

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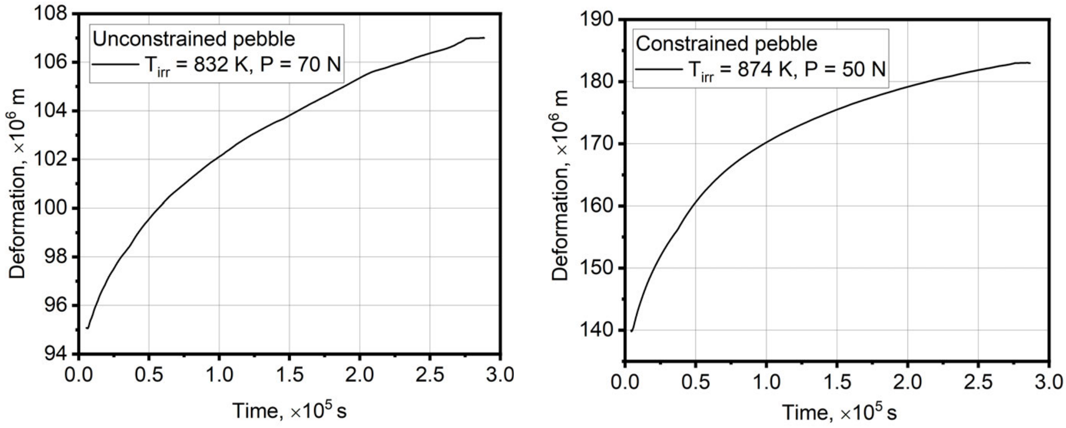

Both samples were tested at the same temperature of 833 K.

Shape of both curves is typical for creep tests.

Deformation for constrained pebble is significantly higher to unconstrained pebbles even though the loading was relatively less for constrained pebble (50 to 70 N).

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Creep rate determination in second stage

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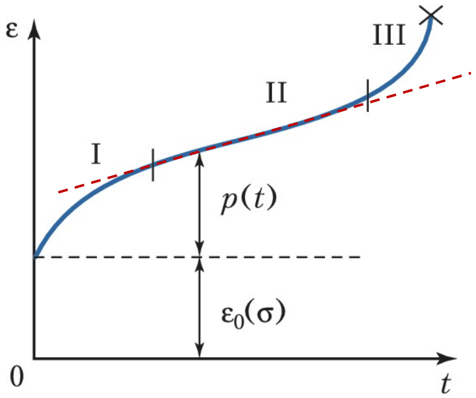

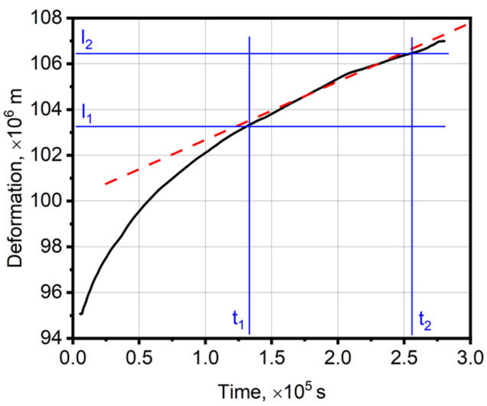

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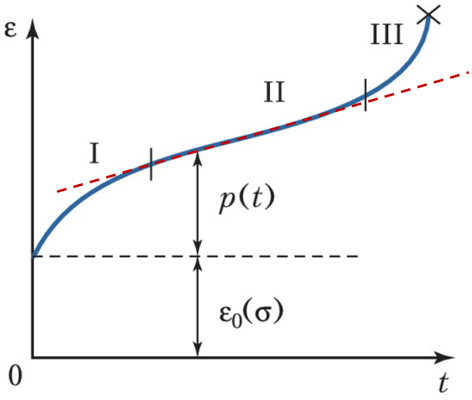
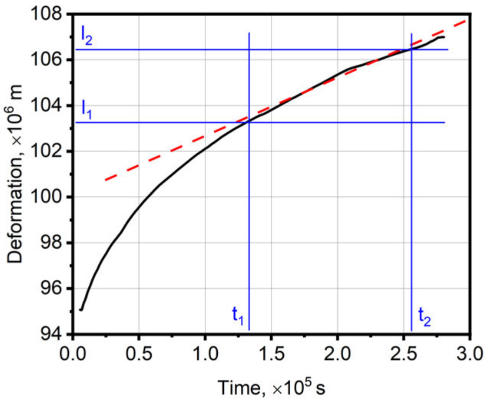
Creep rate determination in second stage





We carry out a linear approximation at second stage using experimental creep curve.

Steady-state strain-rate $\dot{\varepsilon} = (l_2 - l_1)/[(t_2 - t_1)\times h]$,
where l_1 and l_2 are deformation at beginning and end of selected segment of creep curve, t_1 and t_2 are time to reach beginning and end of selected deformation segment, h is distance between opposite indentations on tested pebble.

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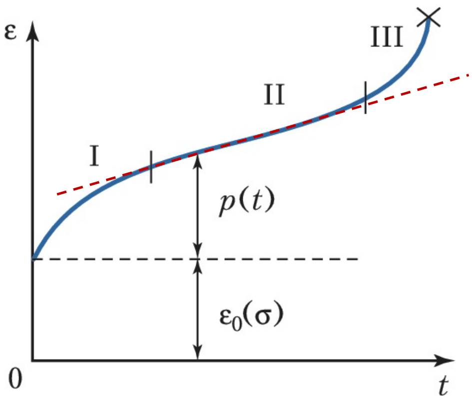
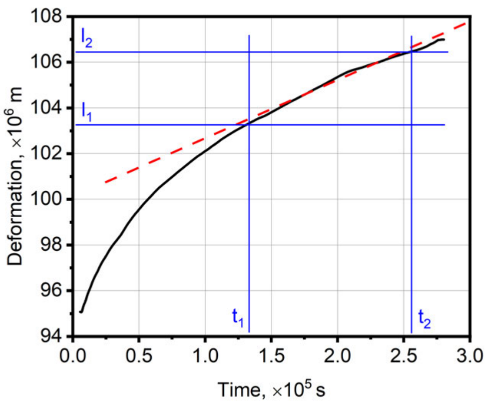
Creep rate determination in second stage

Classical creep curve has three stages





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Creep rate determination in second stage

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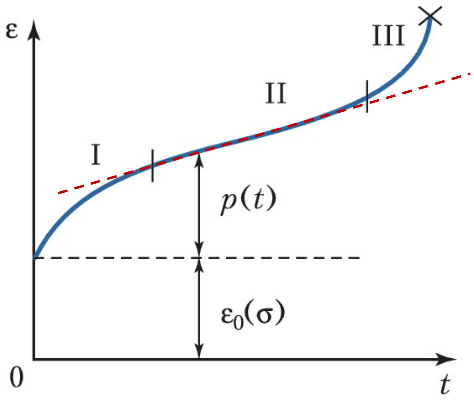
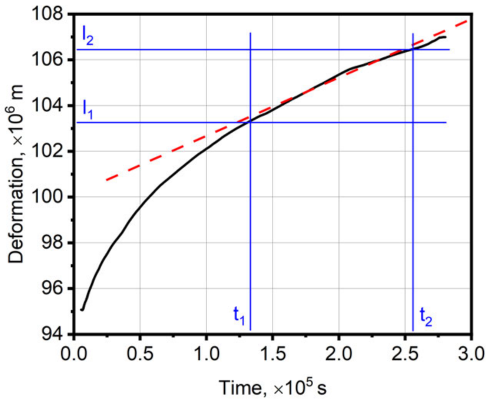


Experimental creep curve has only two incomplete stages



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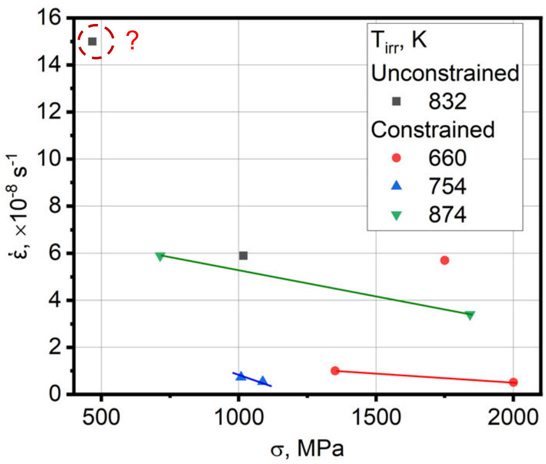
Dependence of steady-state strain-rate $\dot{\varepsilon}$ to stress σ



Dependence of steady-state strain-rate $\dot{\varepsilon}$ to stress σ

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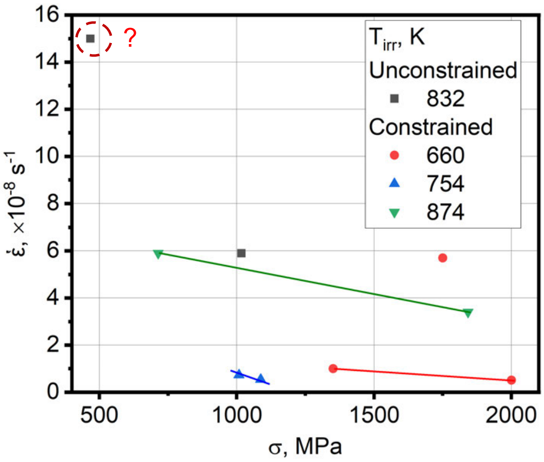

Creep behavior of constrained pebbles is logical. Creep rate at lowest temperature 660 K is similar to that at 754 K but it has higher applied stress. Creep rate at highest temperature 874 K is higher than that at lower temperatures.
Creep behavior of unconstrained pebbles is unclear because it was obtained a limited number of successful creep tests.

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Comparison of behavior of constrained pebble beds after irradiation at low- and high-temperatures

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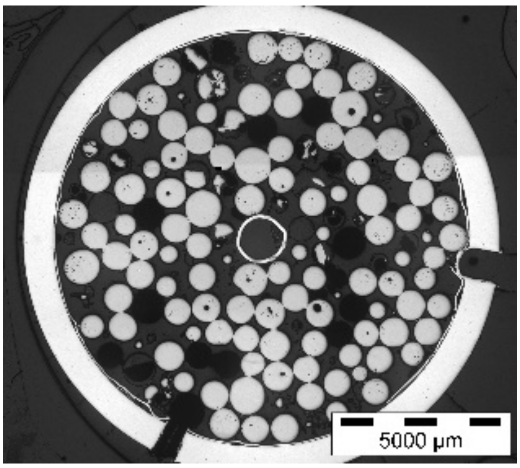
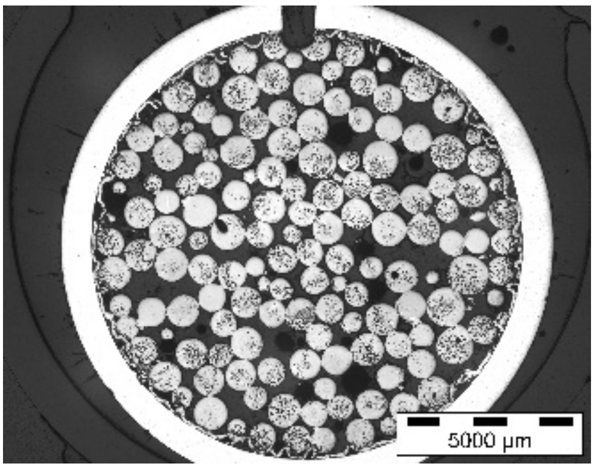
T_{irr} = 660 K (0.423 $_m$) – no creep



T_{irr} = 874 K (0.56T_m) – by creep



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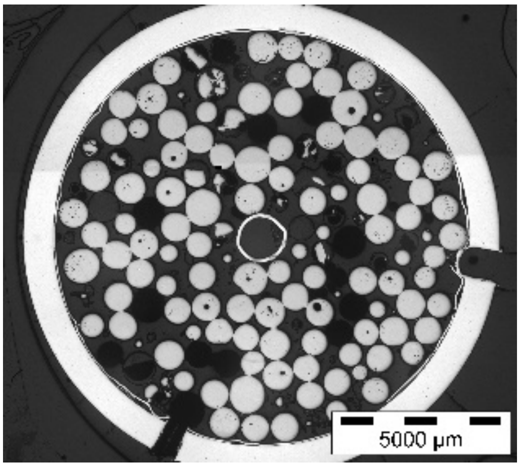
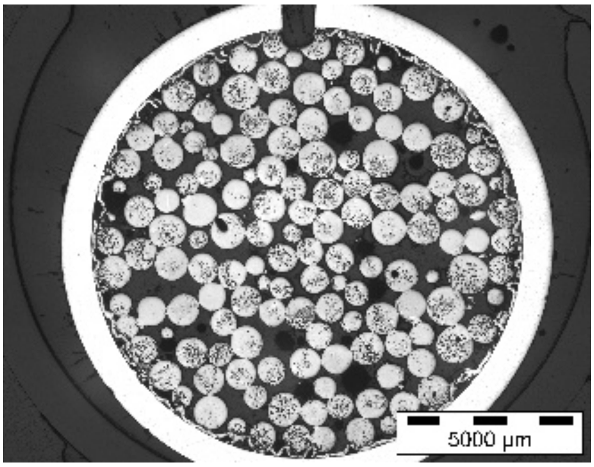
Comparison of behavior of constrained pebble beds after irradiation at low- and high-temperatures

T_{irr} = 660 K (0.423 $_m$) – no creep



T_{irr} = 874 K (0.56T_m) – by creep



Constrained pebble bed, if it concerns level of internal stresses in the pebbles, means state of the pebble bed after high-dose irradiation because high internal stresses were created in the pebbles already before irradiation.

Low-temperature irradiation (<0.5T_m) – no pores, not high swelling, formation of dislocation sub-grain microstructure but no creep deformation therefore, defragmentation of pebbles occurs.

High-temperature irradiation (>0.5T_m) – many big pores and high swelling, but sub-grains and creep deformation are available therefore, stress relaxation exists resulting comparatively less pebble defragmentation comparing to low-temperature irradiation.

Conclusions

Creep tests of Ø 1 mm Be pebbles irradiated to 6000 appm He production show difference of creep behavior of unconstrained (free filled) and constrained pebbles.

There are points:

- 10 from 23 performed tests include really creep behavior as "deformation" case. And 8 from 10 diagrams were obtained on constrained pebbles.
- There is transition to creep behavior between 723 K (0.463 T_m) and 833 K (0.534 T_m). Constrained pebbles at 833 K have comparatively higher failure load than that for unconstrained pebbles.
- Optical metallography shows very developed sub-gran microstructure in constrained pebbles. Unconstrained pebbles have practically no sub-grains.
- Concerning calculation of dependence of steady-state strain-rate to stress for constrained pebbles, it is logical behavior. For unconstrained pebbles, it was performed not enough successful creep tests (there were mainly "no deformation" or "cracks" cases).

This means that constrained pebbles have comparatively better creep behavior than unconstrained pebbles especially for irradiation at higher temperatures than 0.5T_m.

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22

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22

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Thank you for your attention!

See you again on BeWS-16?

23 Institute for Applied Materials – Applied Materials Physics