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Joint ICTP-IAEA Advanced Workshop on Multi-Scale Modelling for Characterization and Basic Understanding of Radiation Damage Mechanisms in Materials

12 - 23 April 2010

Theoretical modeling of plastic deformation in materials under heavy ion, light ion and fast neutron irradiations

A. Ryazanov

Russian Research Centre "Kurchatov Institute"
Moscow
Russian Federation

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Theoretical Modeling of Plastic Deformation in Materials under Heavy, Light Ion and Fast Neutron Irradiations

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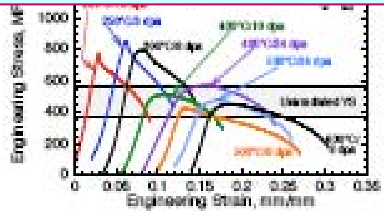
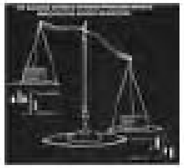
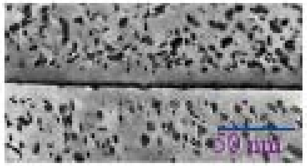
Main Physical Phenomena of Radiation Resistance in Fusion Structural Materials

- Radiation hardening and embrittlement ($<0.4\ T_M$, >0.1 dpa)

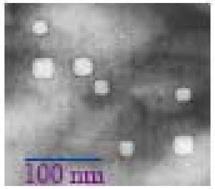


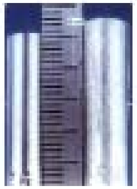
- Phase instabilities from radiation-induced precipitation (0.3-$0.6\ T_M$, >10 dpa)

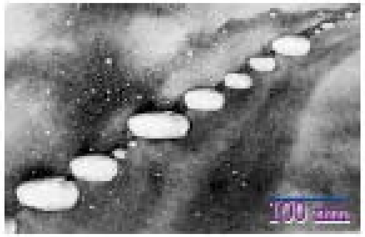
- Irradiation creep ($<0.45\ T_M$, >10 dpa)

- Volumetric swelling from void formation (0.3-$0.6\ T_M$, >10 dpa)





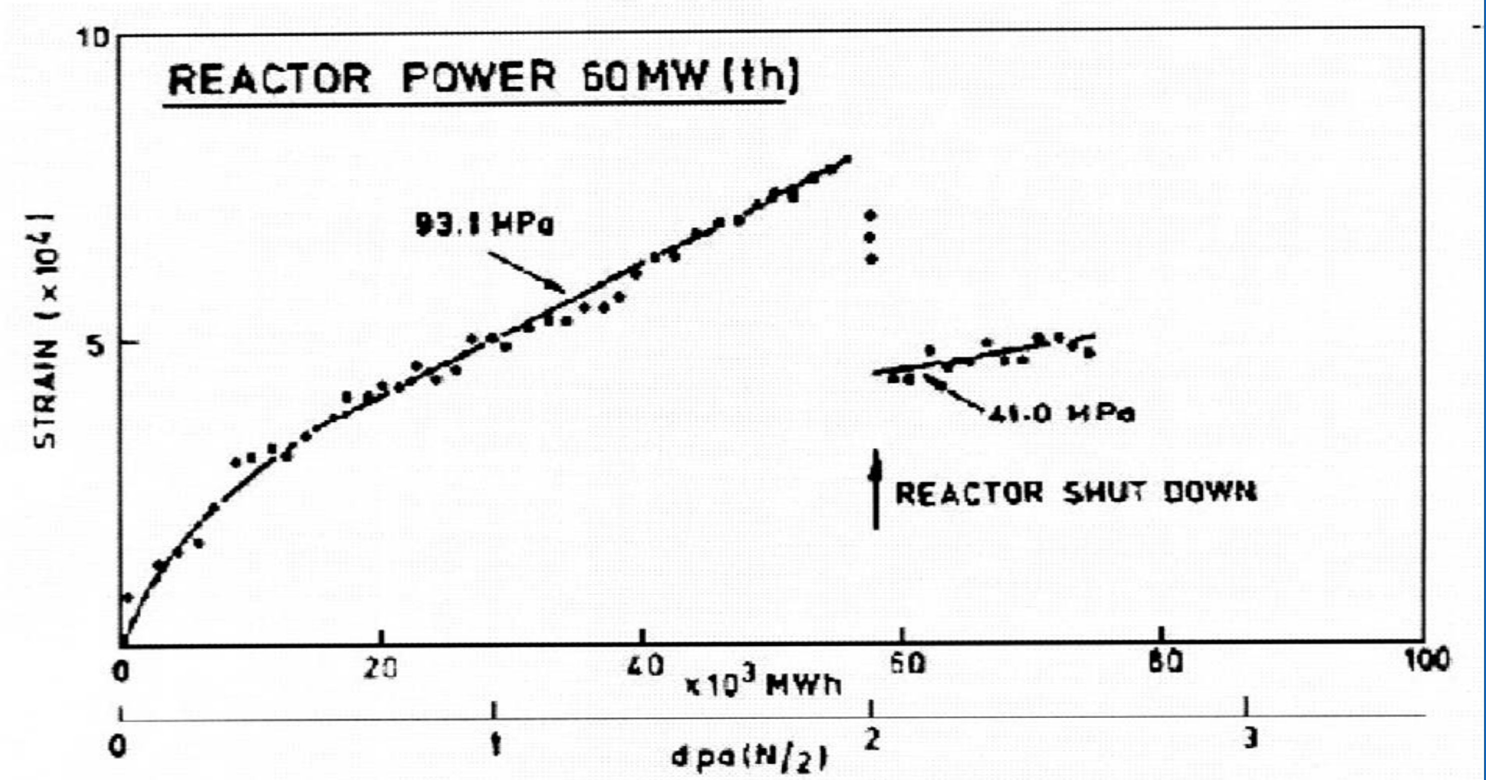
- High temperature He embrittlement ($>0.5\ T_M$, >10 dpa)



Transient Creep Stage under Fast Reactor Irradiation

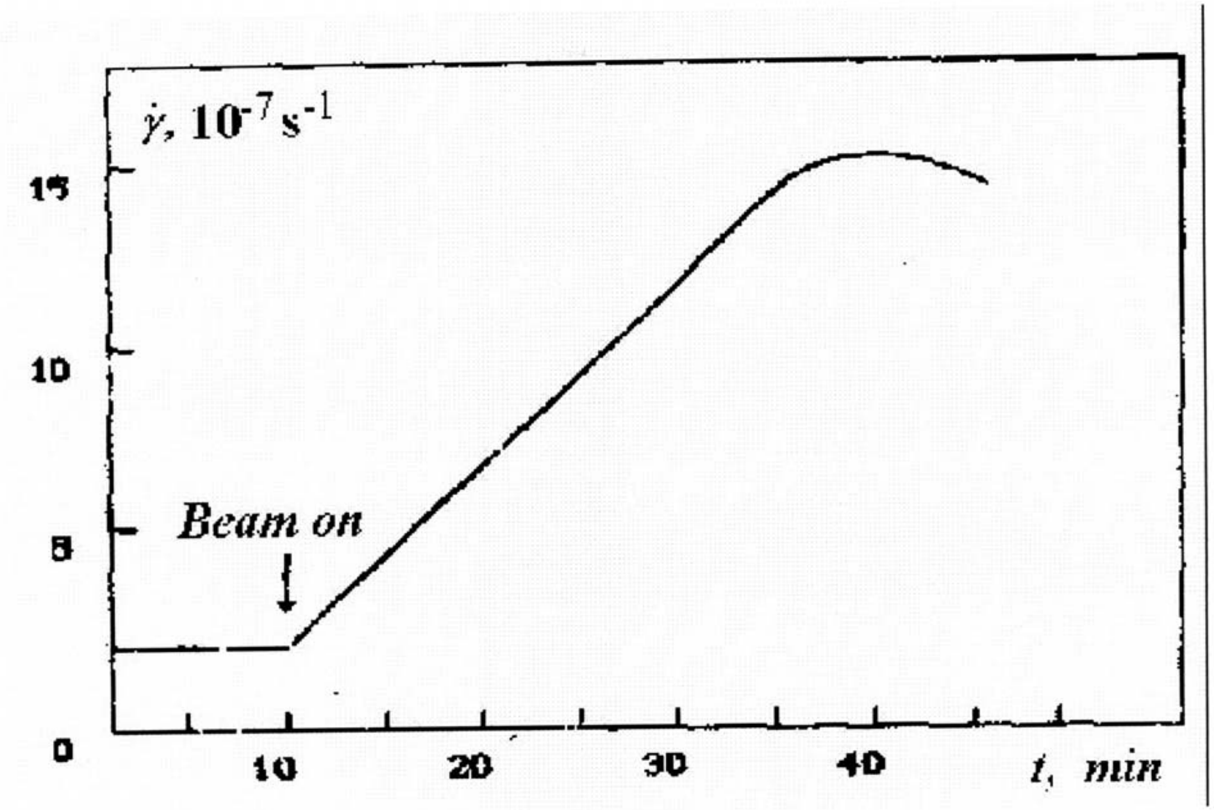
Neutron irradiation

(D. Mosedale, D.R.Harries,1997)



Initial Stage of Creep Rate Kinetics in Al under 2 MeV Electron Irradiation

Flux of electrons is $\varphi_e = 10^{13} e^- /(cm^2 s)$ (Yu. M. Platov, 1998)



Comparison of Fission and Fusion Structural Materials Requirements

	Fission (Cen.1)	Fission (Cen.IV)	Fussion (Demo)
Structural alloy maximum temperature	< 300°C	500-1000°C	550-1000°C
Max dose for core internal structure	~ 1 dpa	~ 30 - 150 dpa	~ 200 dpa
Max transmutation helium concentration	~ 0,1 appm	~ 3 -15 appm	~ 2000 appm (~ 10000 appm For SiC)
Coolants	H_20	He, H_20, Pb-Bi, Na	He, Pb-Li, Li
Structural Materials	Zircaloy, Stainless steel	Ferritic steel,SS, superalloys, C-composit	ODS,& Ferritic/martensitic steel, V –alloy, SiC-composite

Materials for Fusion Reactors

- **Graphite Materials :**
  Graphite, C-C composits

- **Metallic Materials:**
  Austenitic Steels, Ferritic – martensitic Steels, ODS materials, V-alloys

- **Ceramic Materials:**
  SiC – composits, Al2O3, MgO, ZrO2

Main Peculiarities of Radiation Effects In Fusion Structural Materials

1. Production of high concentration of Helium (~2000 appm)

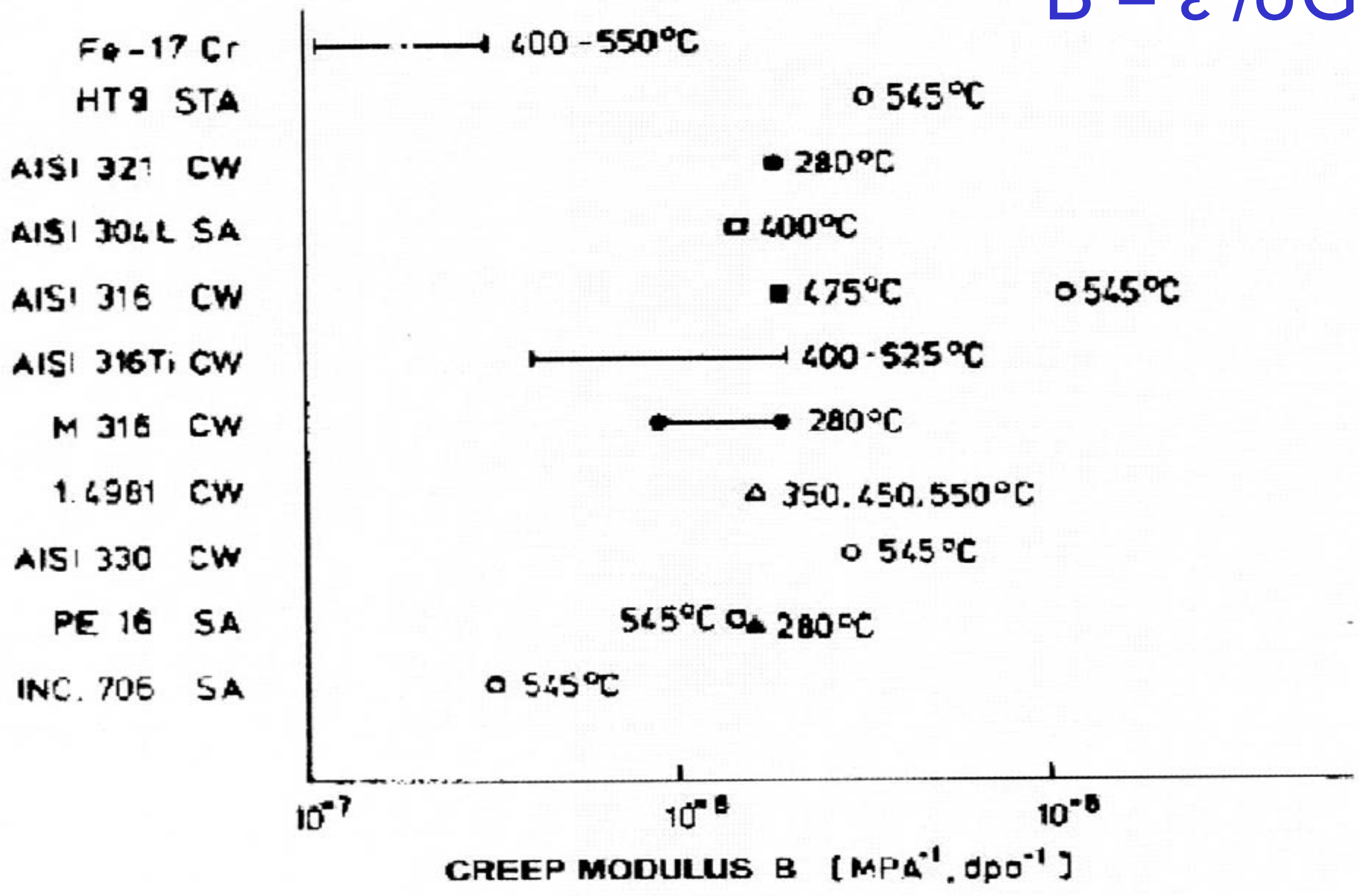
2. Effect of 14 MeV neutrons on Production of High Density of Cascades and Sub-cascades

3. Production of Point Defect Cluster Formation in Cascades and Sub-cascades

4. Production of High DPA doses of Point Defects (~200 DPA)

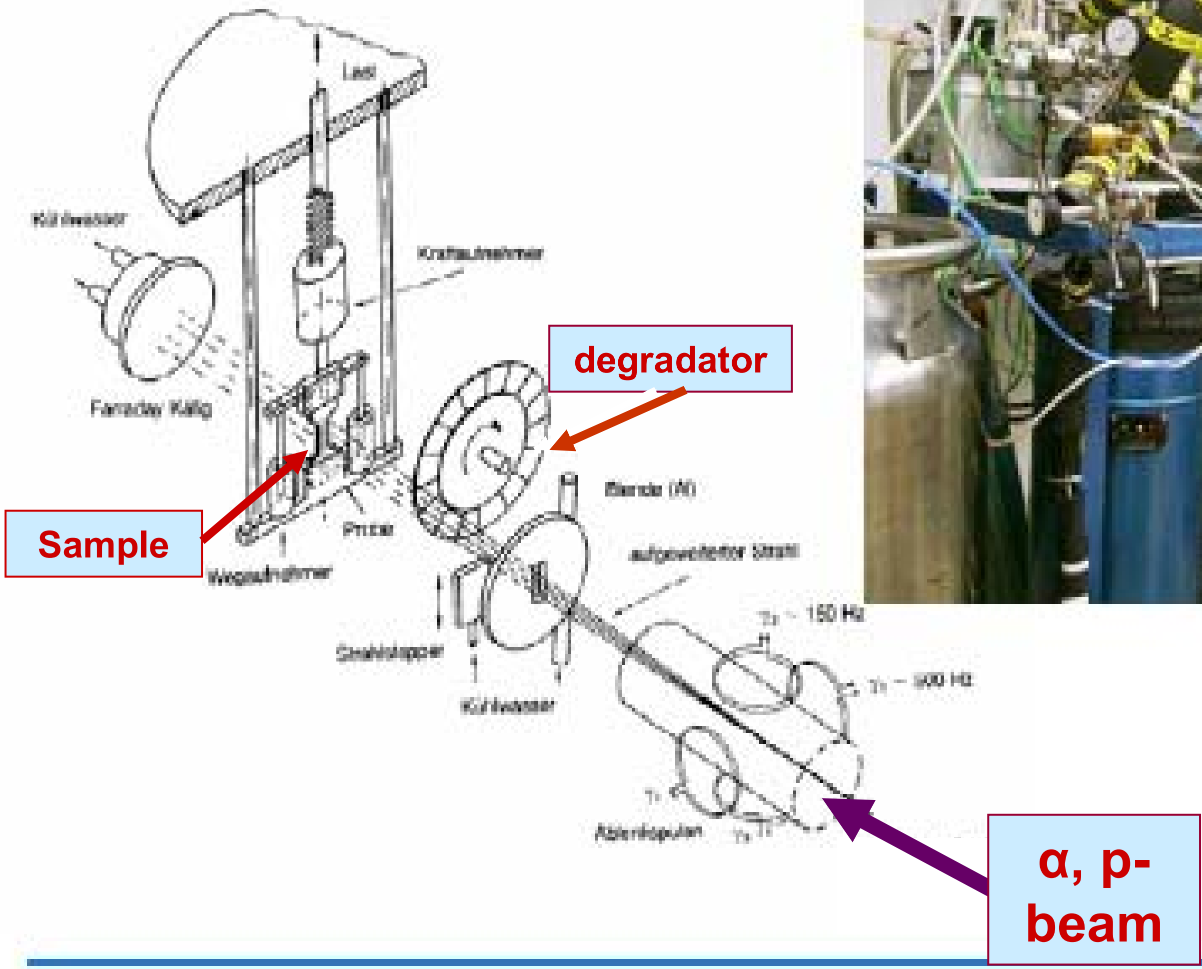
Creep Modules on a Steady Stage for a Number of Austenitic Steels

$B = \varepsilon / \sigma G t$

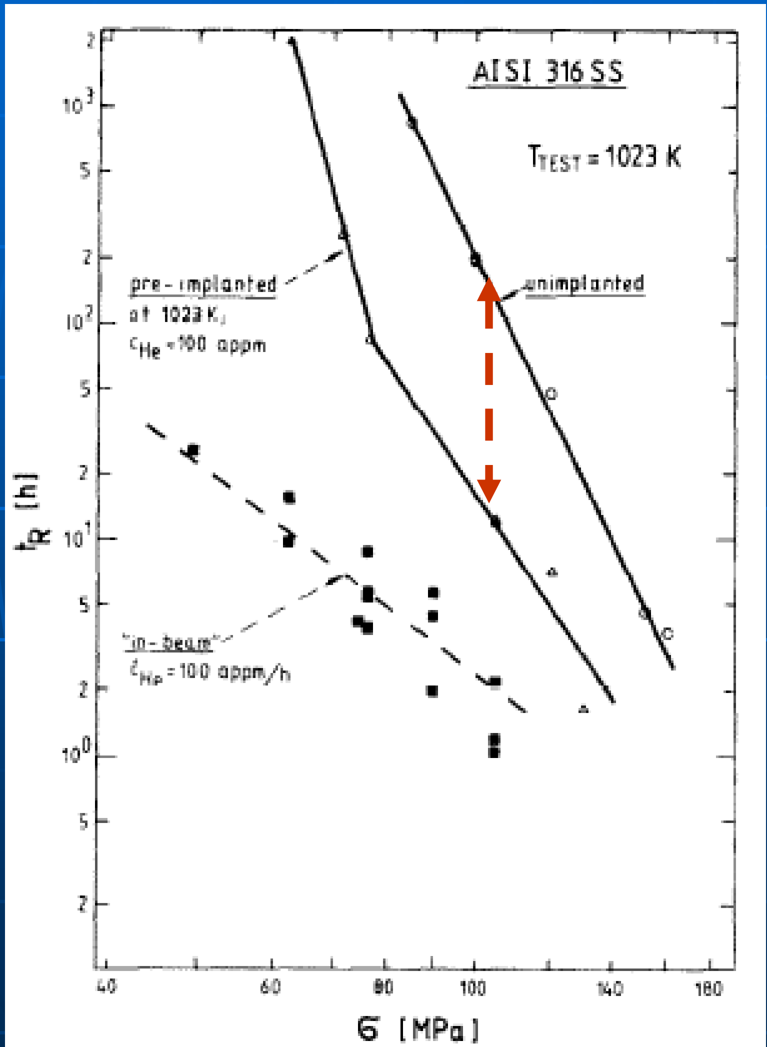


In beam mechanical tests in FZJ

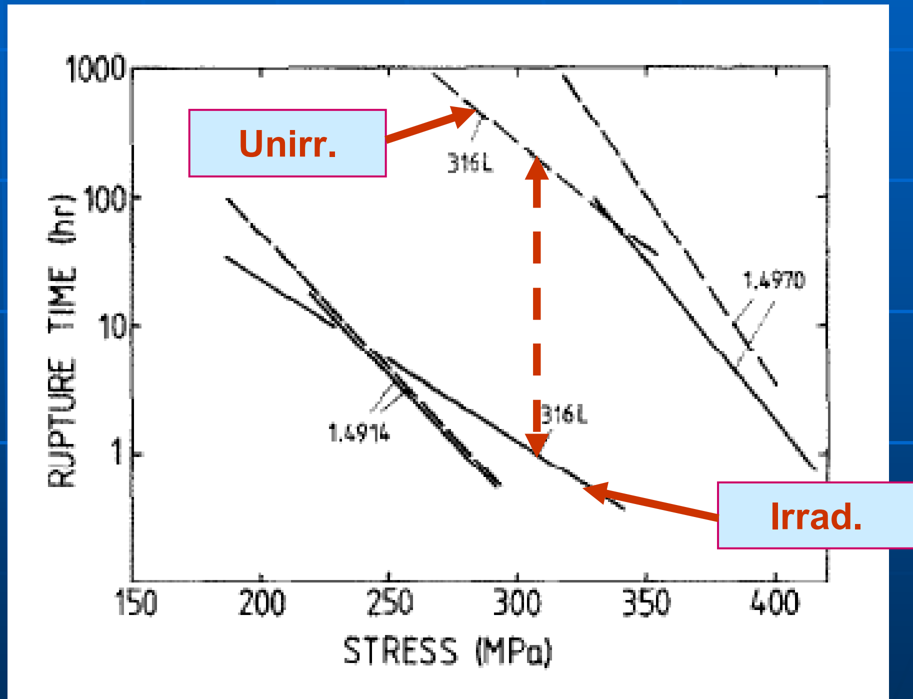
(P.Jung, H.Ullmaier, J.Chen)



Rupture time (t_R) as a function of applied stress

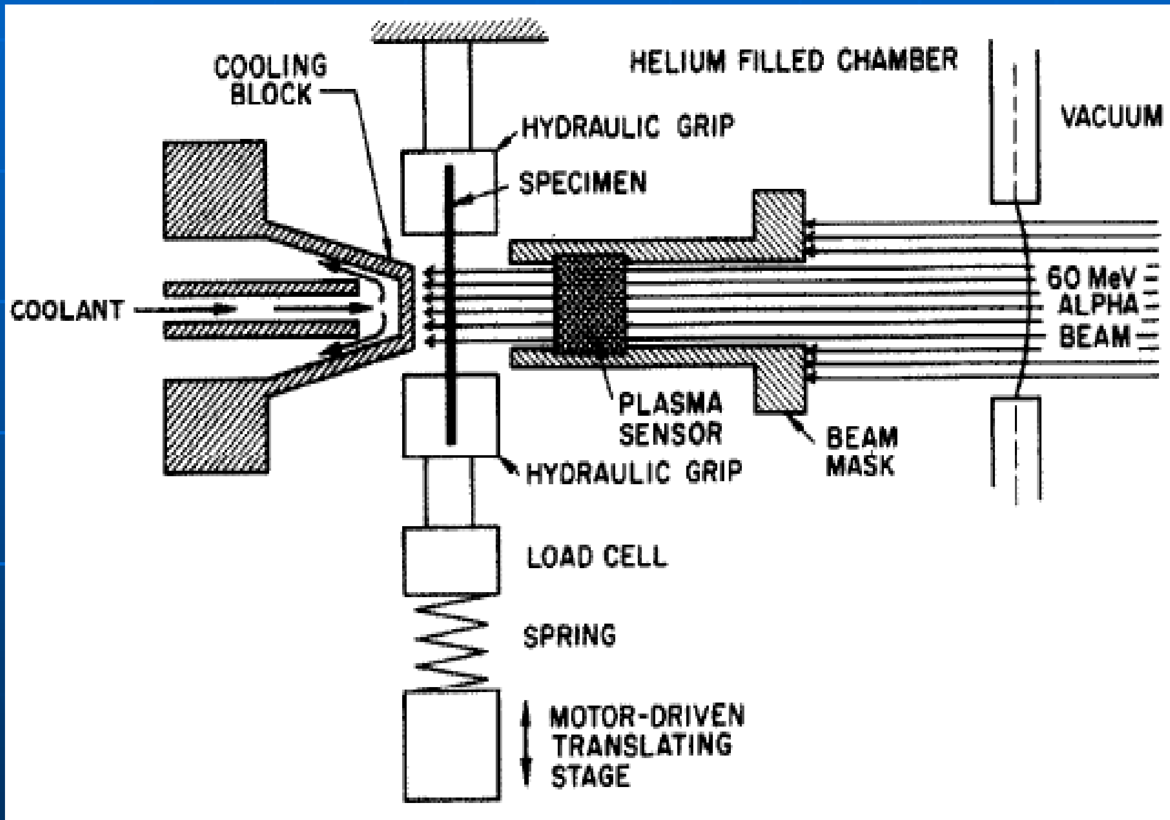


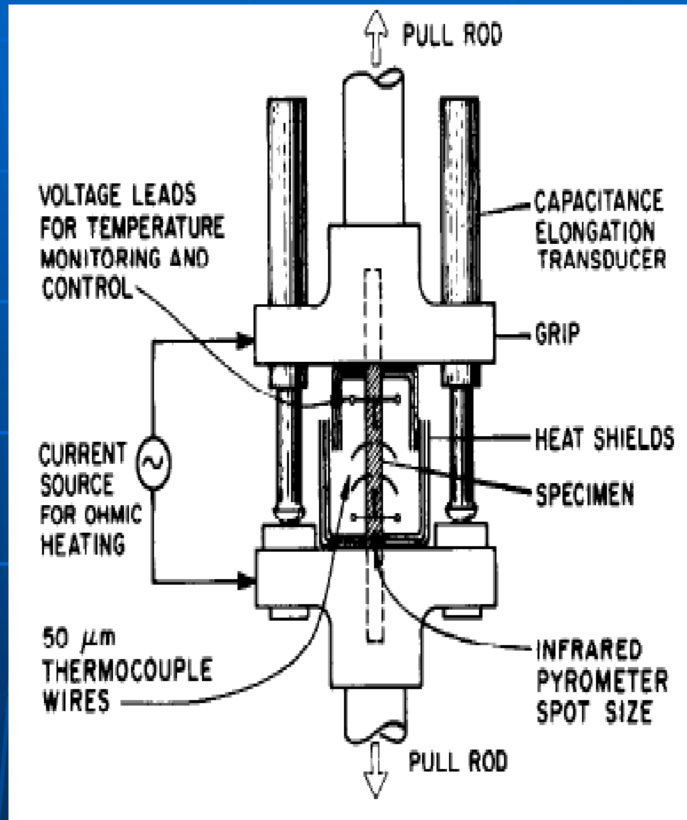
G_{he} ~ 100 appm/h, T =873 K



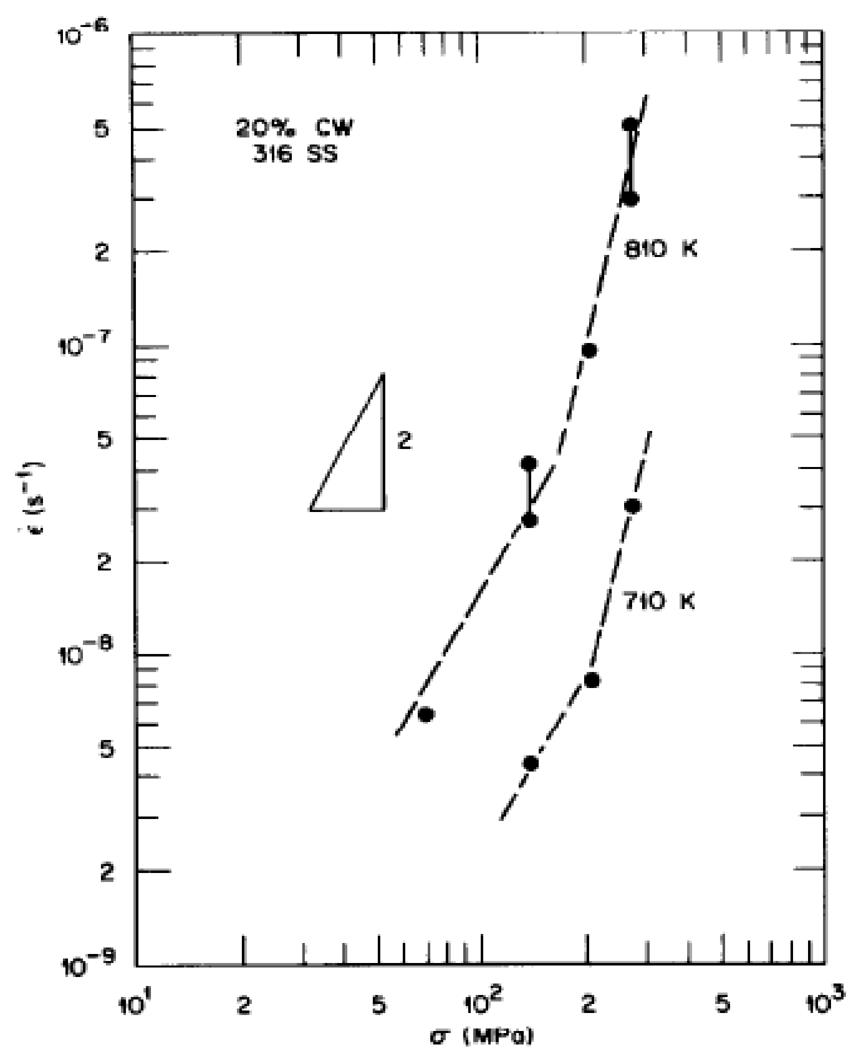
(P.Jung, H. Ullmaier)

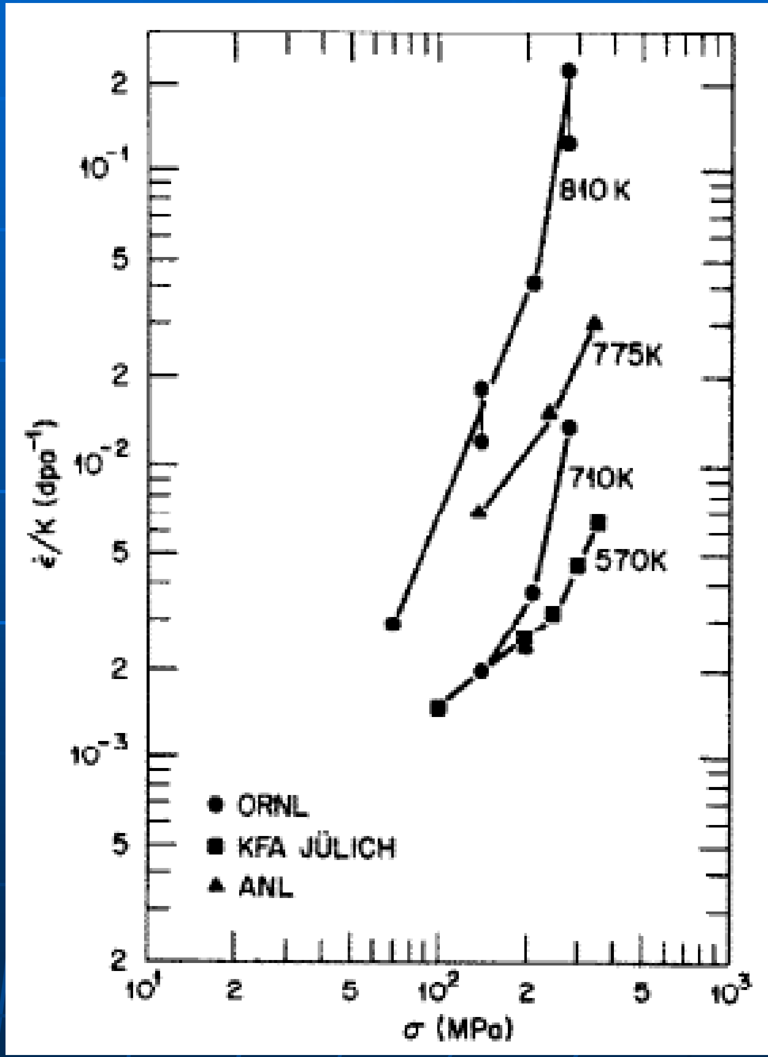
Experimental schematic for the ORNL Irradiation Creep Facility



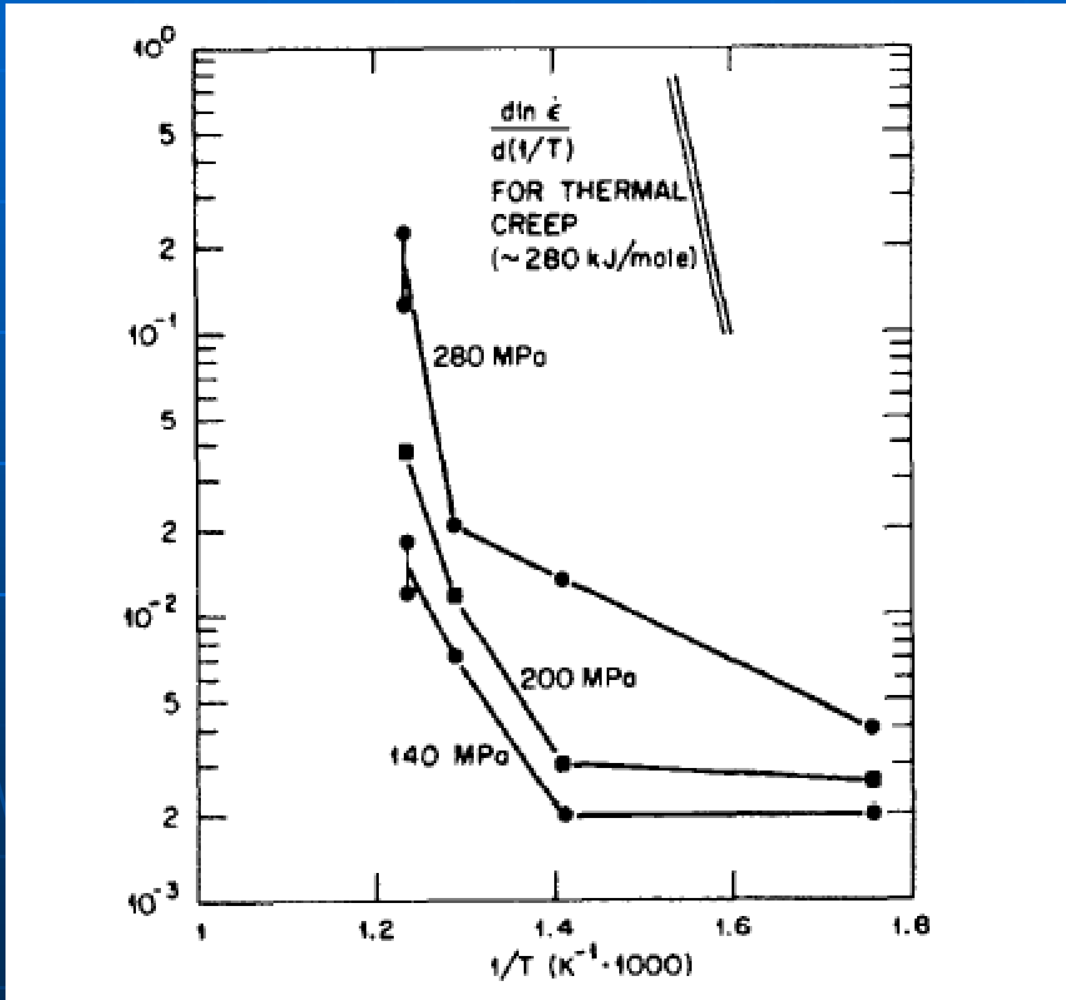


Irradiation Creep Strain Rates for 20% CW 316 SS

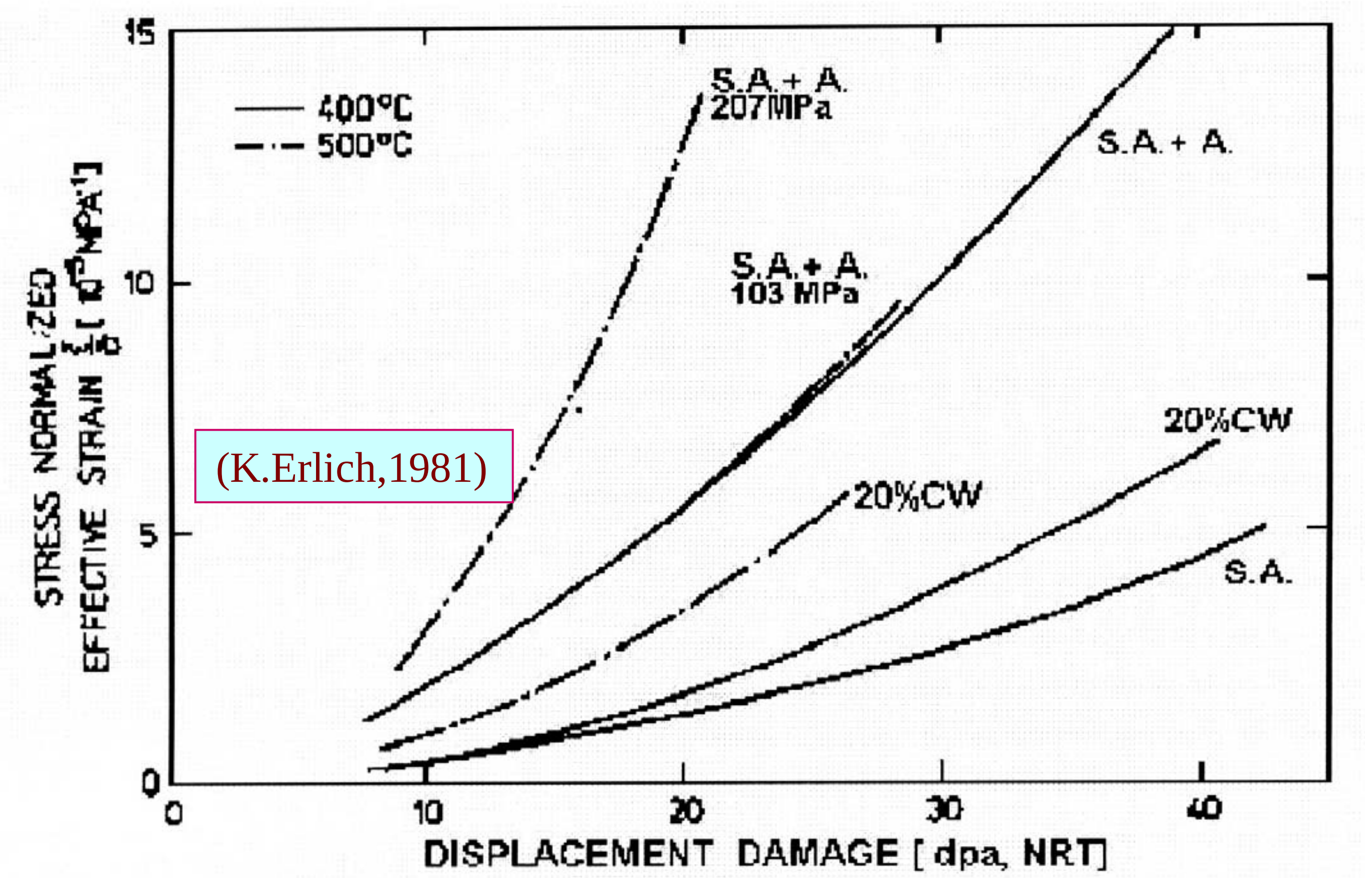




Temperature Dependence for Irradiation Creep Rates for 20% CW 316 SS

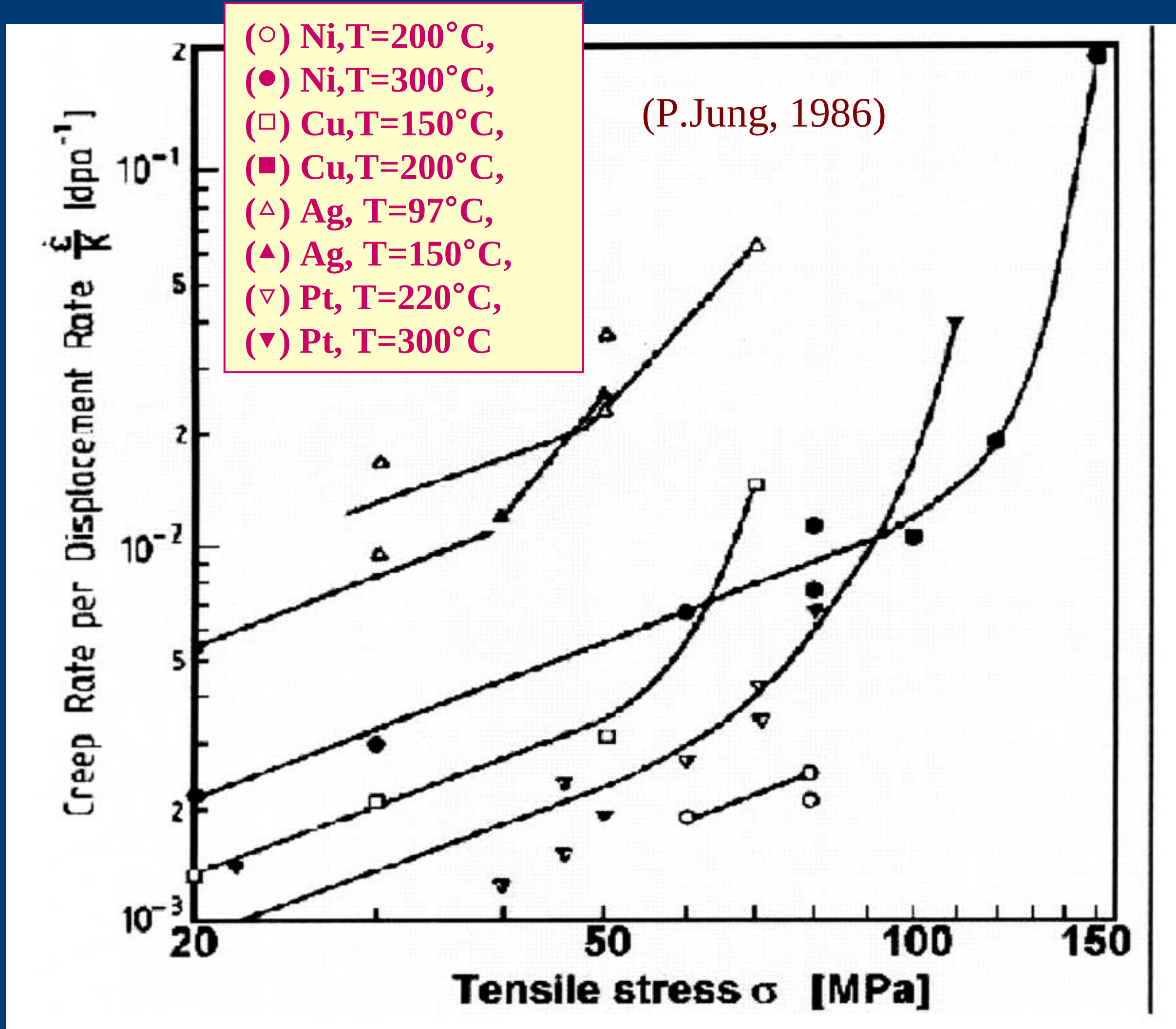


Influence of Thermo-mechanical pretreatment on Irradiation Creep Behavior in Type AISI 316 SS

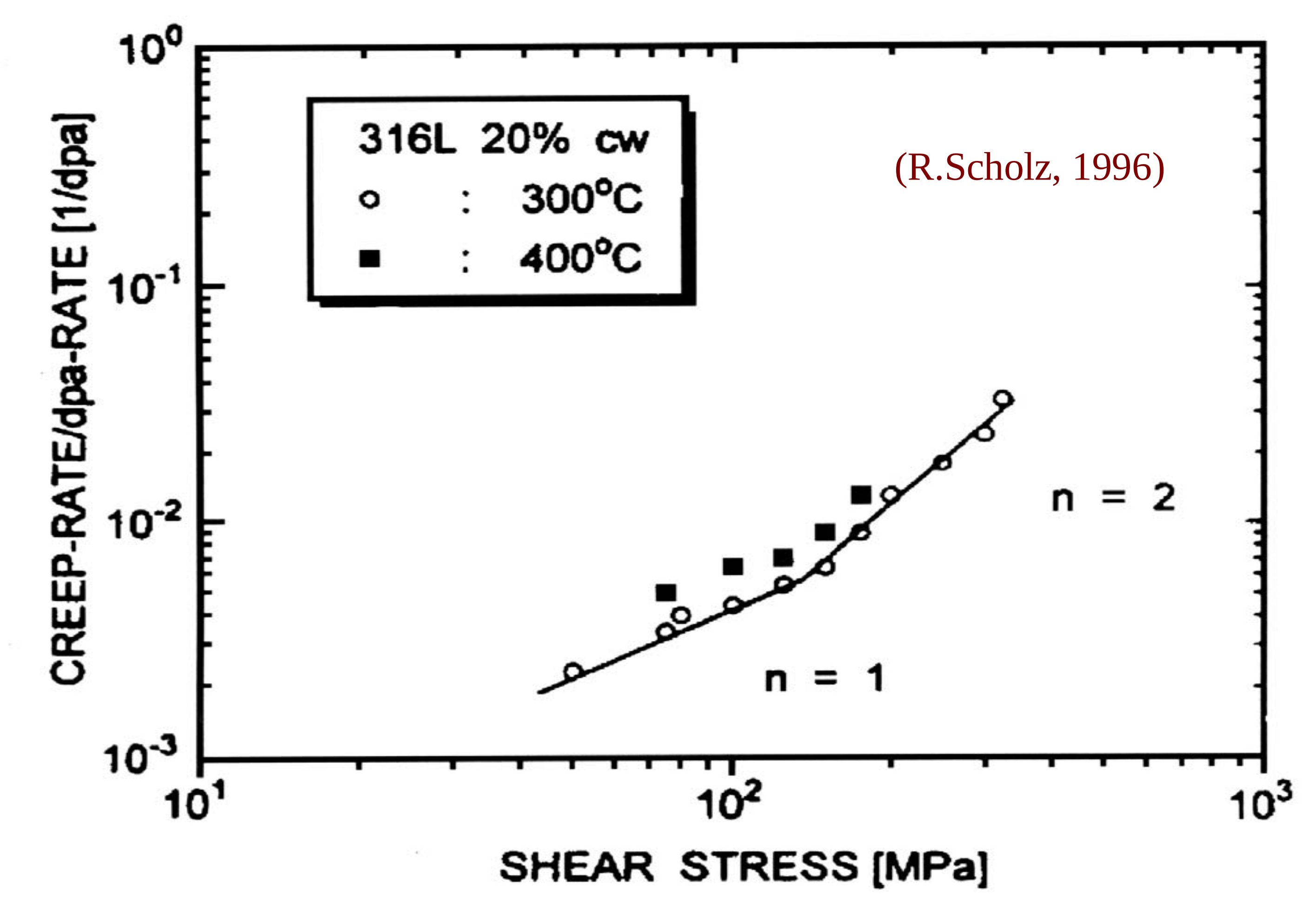


(K.Erlich,1981)

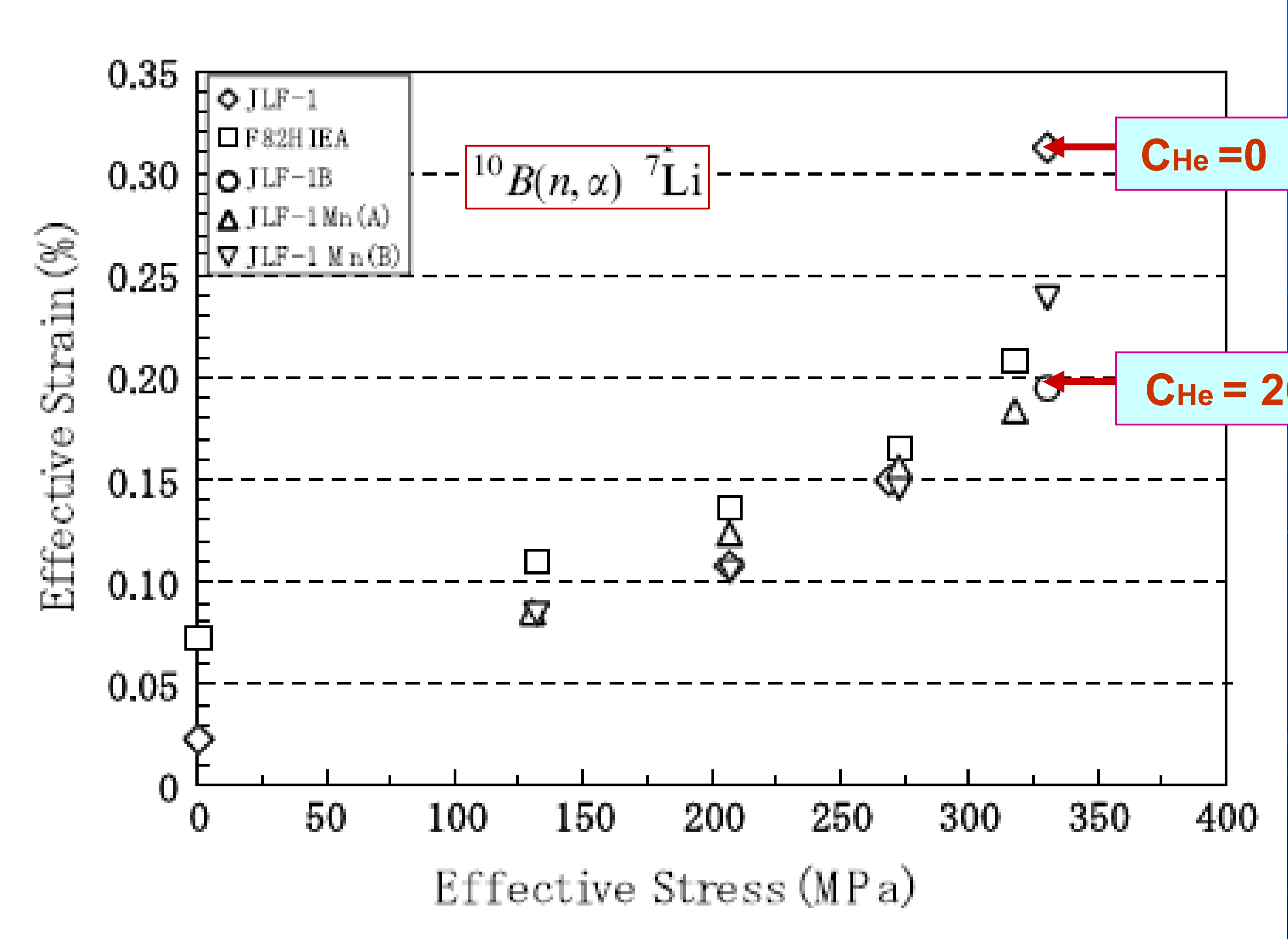
Creep rates as a function of tensile stress in proton irradiated high purity metals at various temperatures



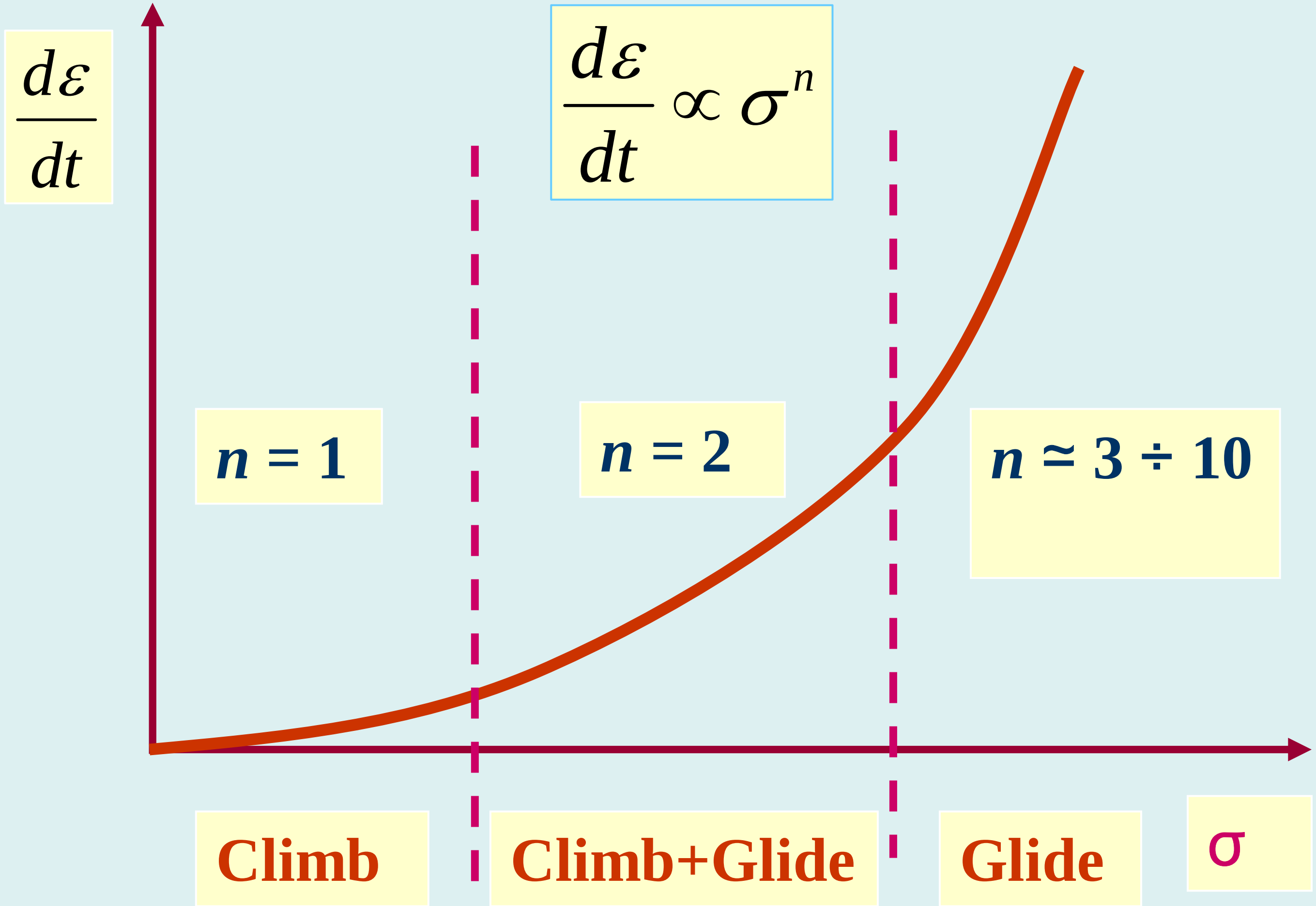
Stress dependence of the irradiation creep rate for 20% CW 316L SS



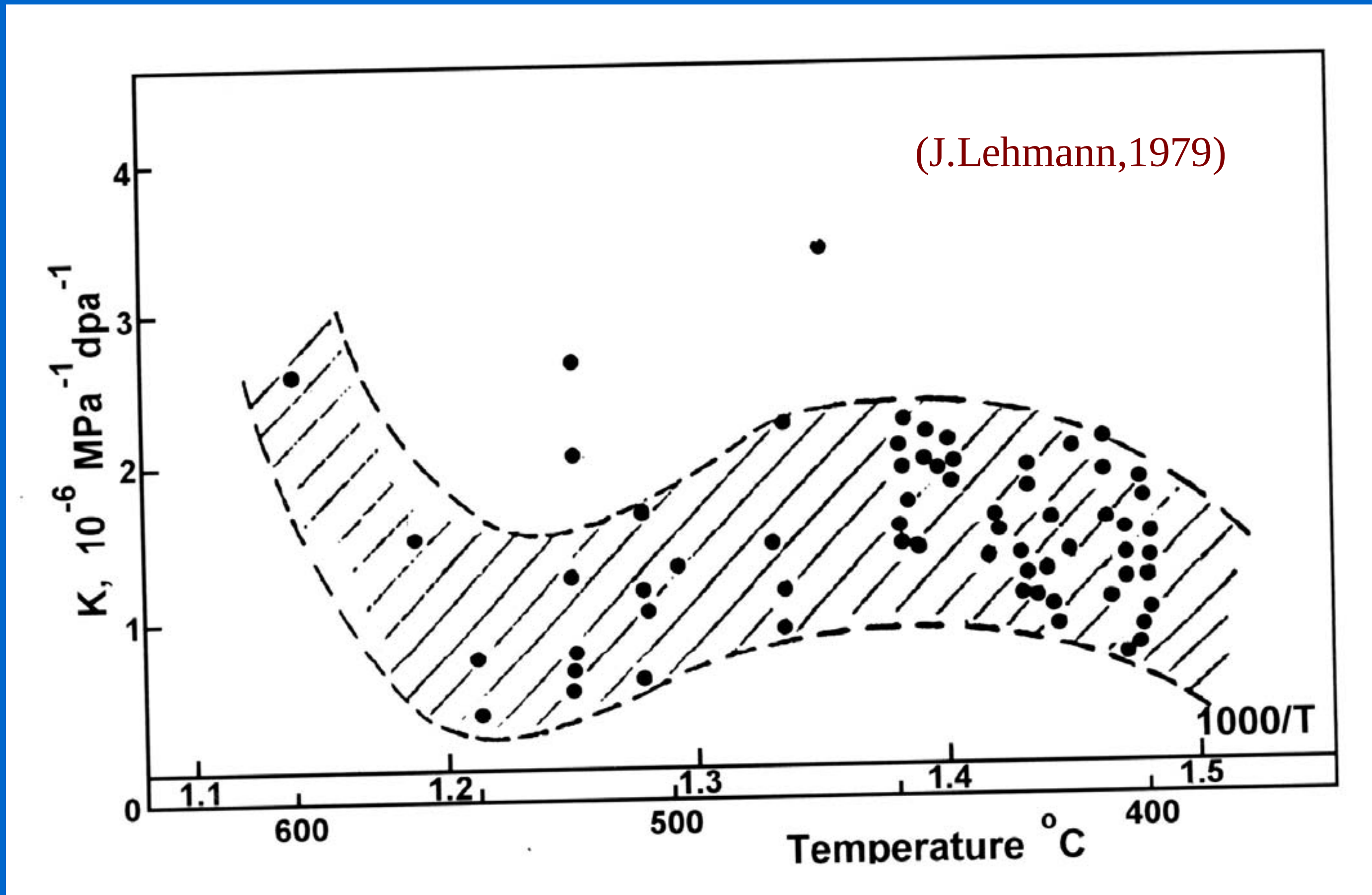
Stress Dependence of Radiation Creep of RAFs under Neutron Irradiation (HFIR) at 5 dpa and at T=573 K (A.Kohyama, 2007)



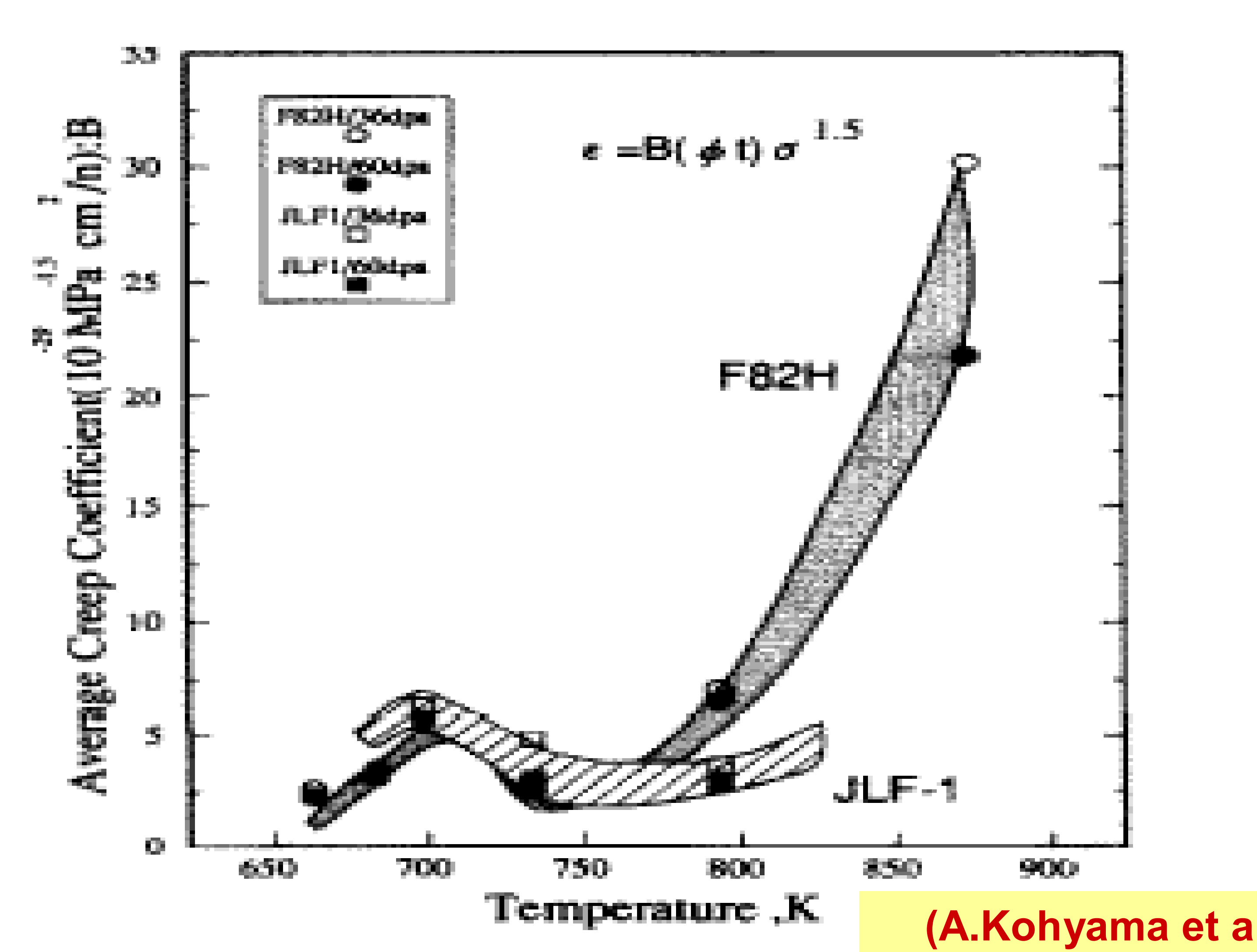
Stress dependence of the dislocation motion mechanisms for the irradiation creep rate



Irradiation temperature dependence of creep modulus for 20% CW 316L SS



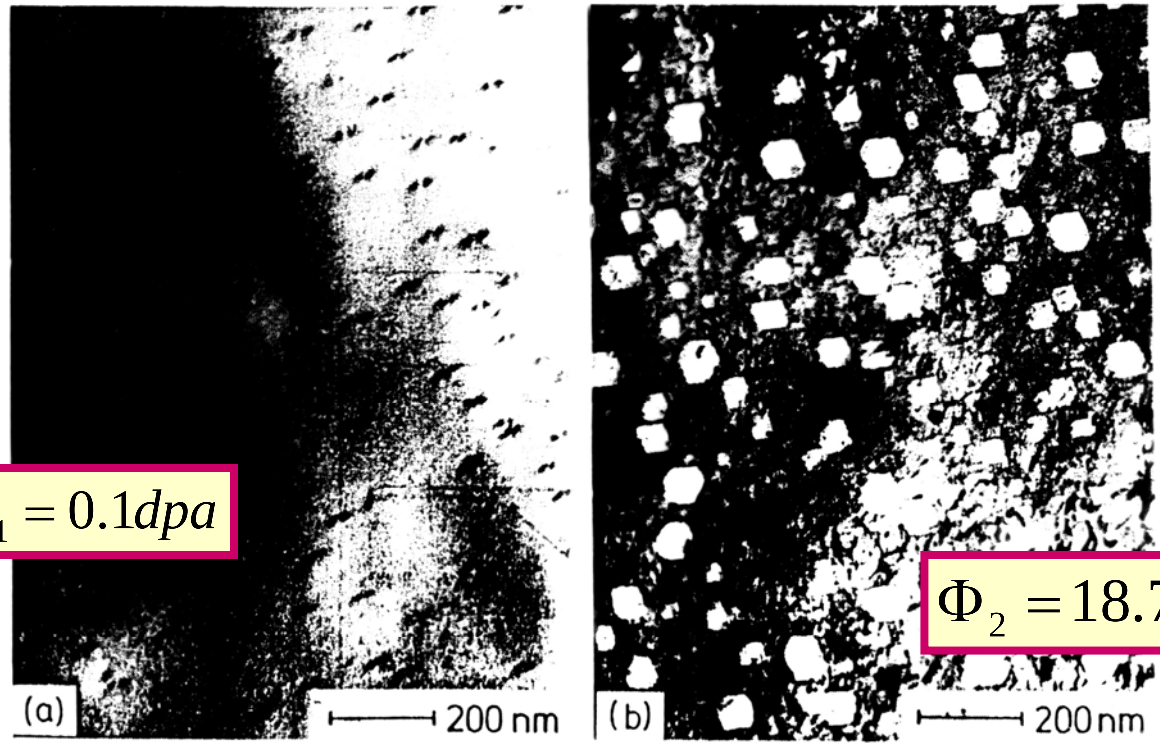
Temperature dependence of irradiation creep modulus for low-activation 12Cr-2W ferritic steels



(A.Kohyama et al.,1994)

TEM observations of dislocation loops (a) and voids (b) in 316 SS on the different stages of irradiation creep

(N. Igata et al.,1985)

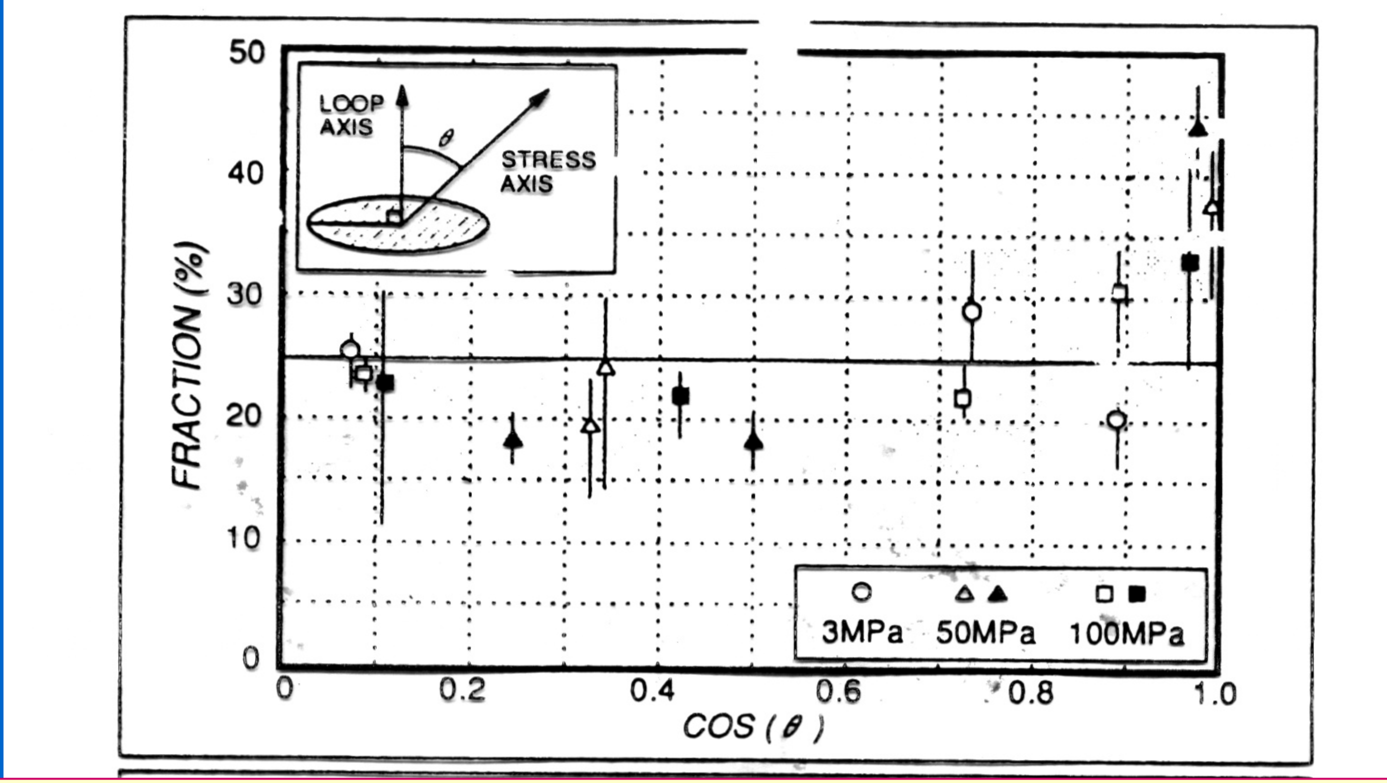


$\Phi_1 = 0.1 dpa$

$\Phi_2 = 18.7 dpa$

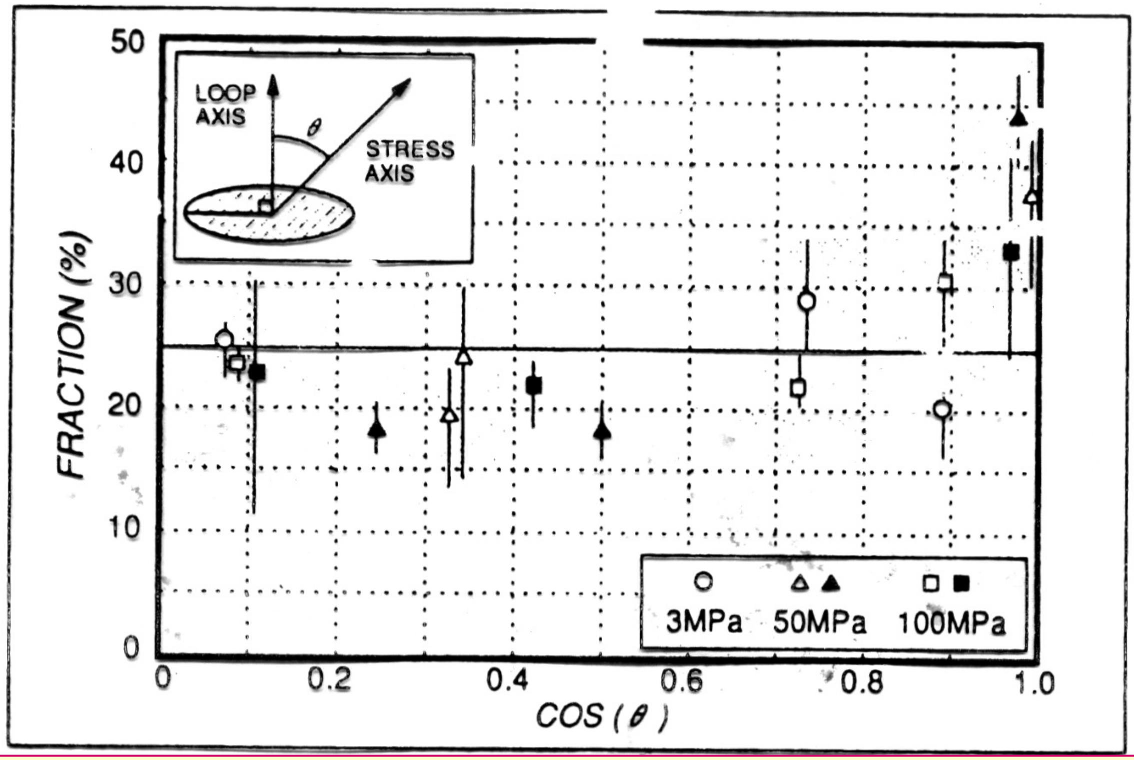
Microstructure changes under applied stress 80 MPa at T=500°C and at the different doses of irradiation

TEM observation of dislocation loop fracture in the dependence on the orientation relatively to tensile stress



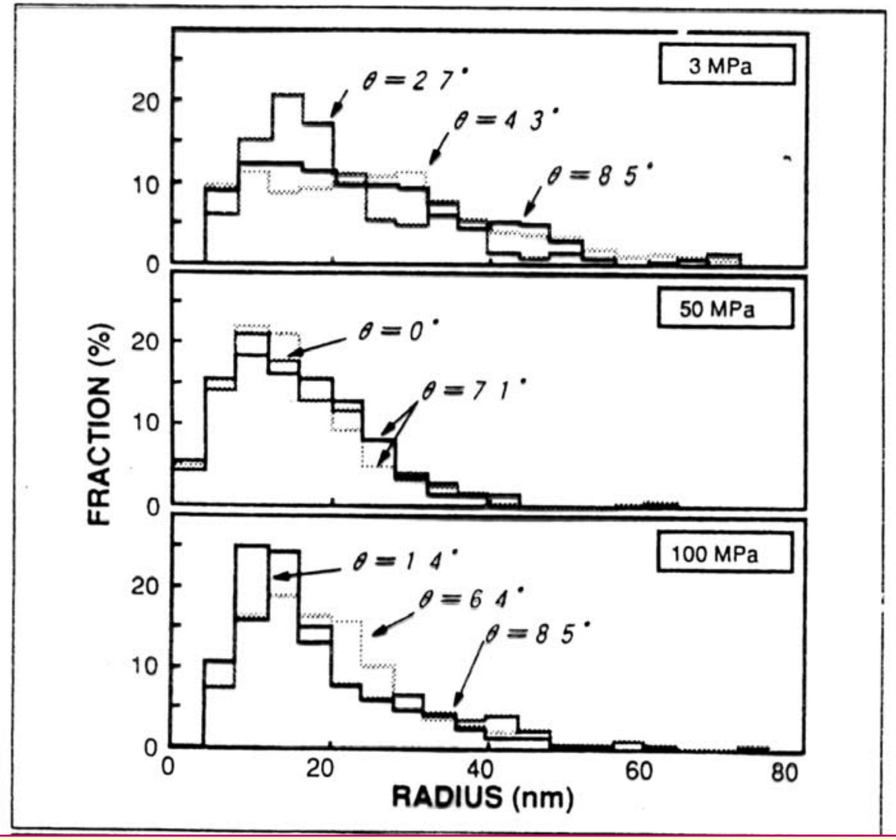
Irradiation of 316 SS by Ni ions with the energy E = 4 MeV up to dose 3 dpa at T=500°C under different stresses from 3 Mpa to 100 Mpa (A. Kohyama et al., 1994).

TEM observation of dislocation loop fracture in the dependence on the orientation relatively to tensile stress



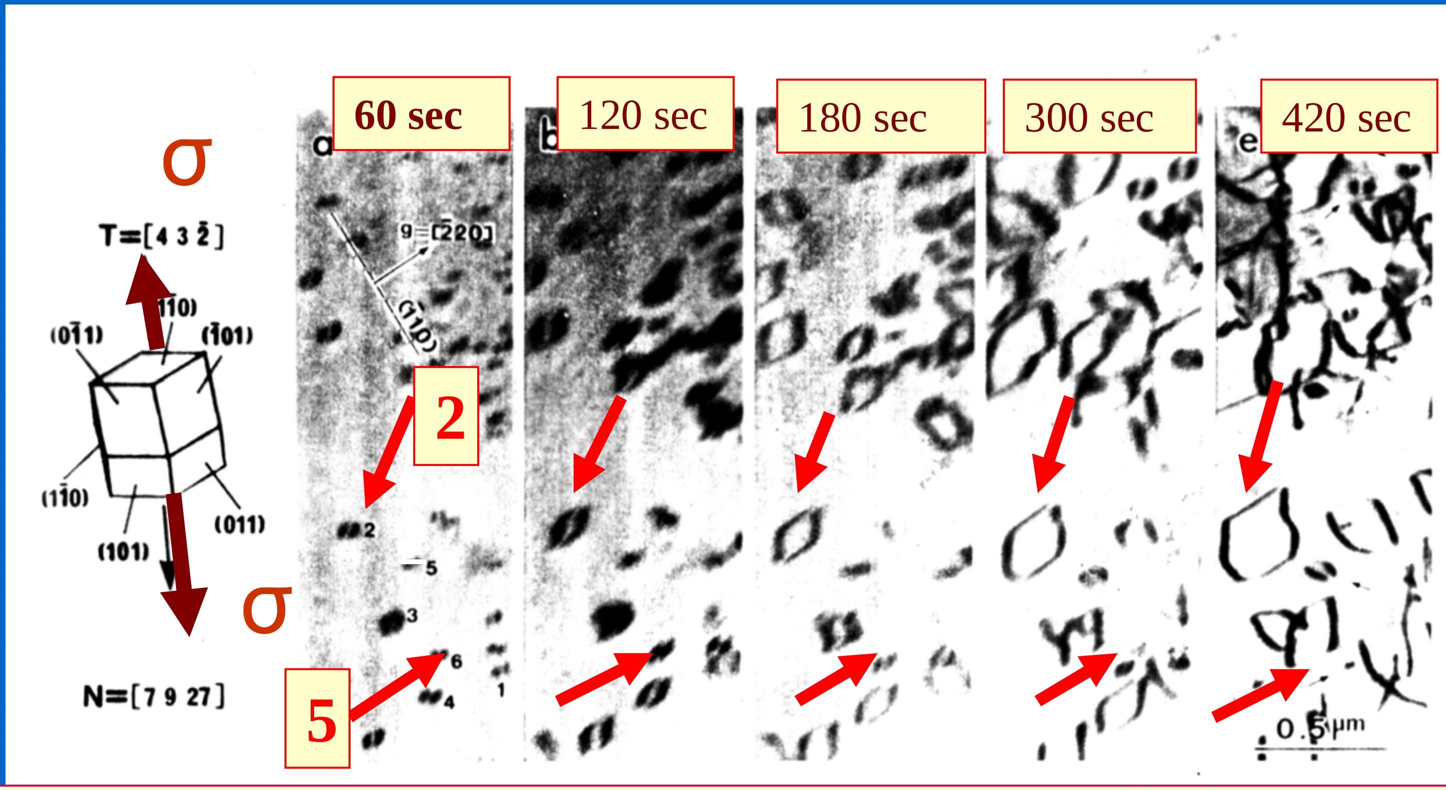
Irradiation of 316 SS by Ni ions with the energy E = 4 MeV up to dose 3 dpa at T=500°C under different stresses from 3 Mpa to 100 Mpa (A.Kohyama et al., 1994).

Size distribution of Frank loops on the planes in the dependence on the orientation relatively to tensile stress



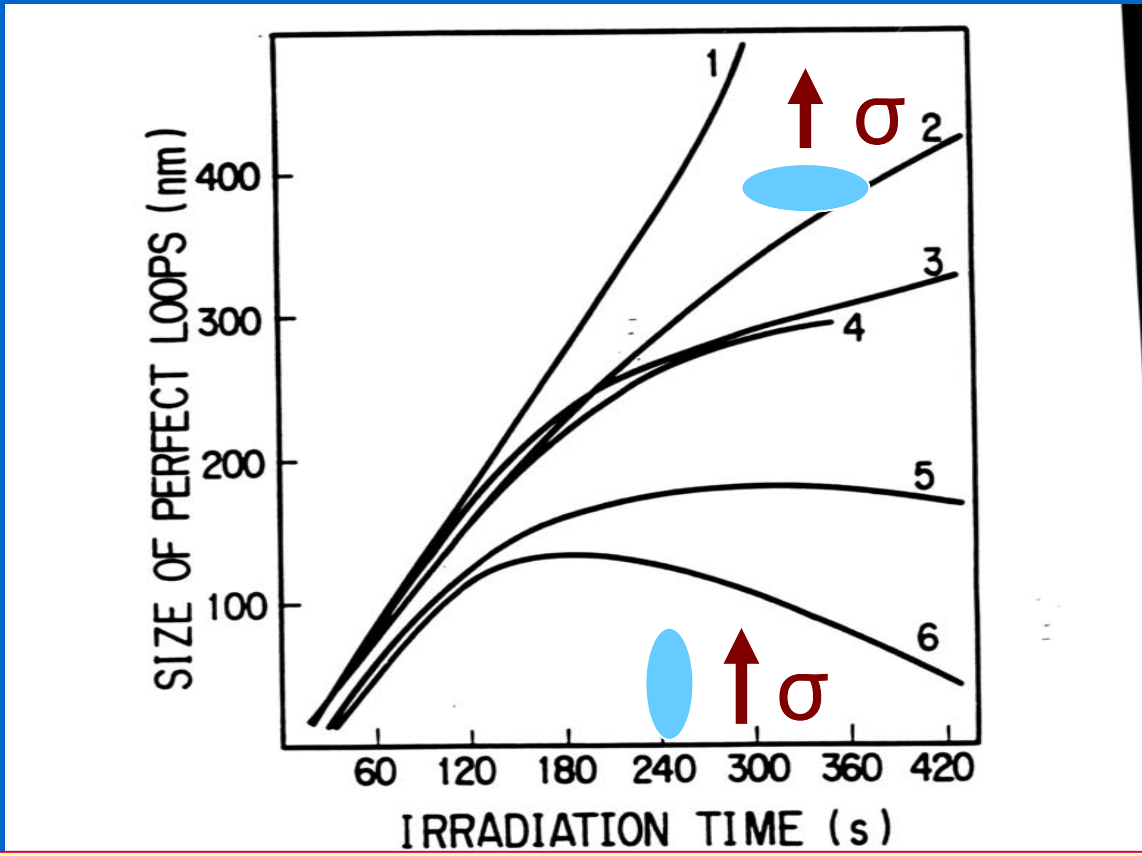
Irradiation of 316 SS by Ni ions with the energy E = 4 MeV up to dose 3 dpa at T=500°C under different stresses from 3 Mpa to 100 Mpa (A.Kohyama et al., 1994).

Effect of electron irradiation on the growth of dislocation loops in annealed stressed Ni sample in the dependence on the orientation relatively to tensile stress



Electron irradiation of annealed Ni sample with applied load 50 MPa and generation rate of point defects G=2.10-3 dpa/s at T=500°C.Nucleation of defect clusters was completed after first *60 s* (a) and then they continued to grow with dose to become perfect loops :(b), (c), (d) and (e). (S.Jitsukawa, F.Garner, 1992)

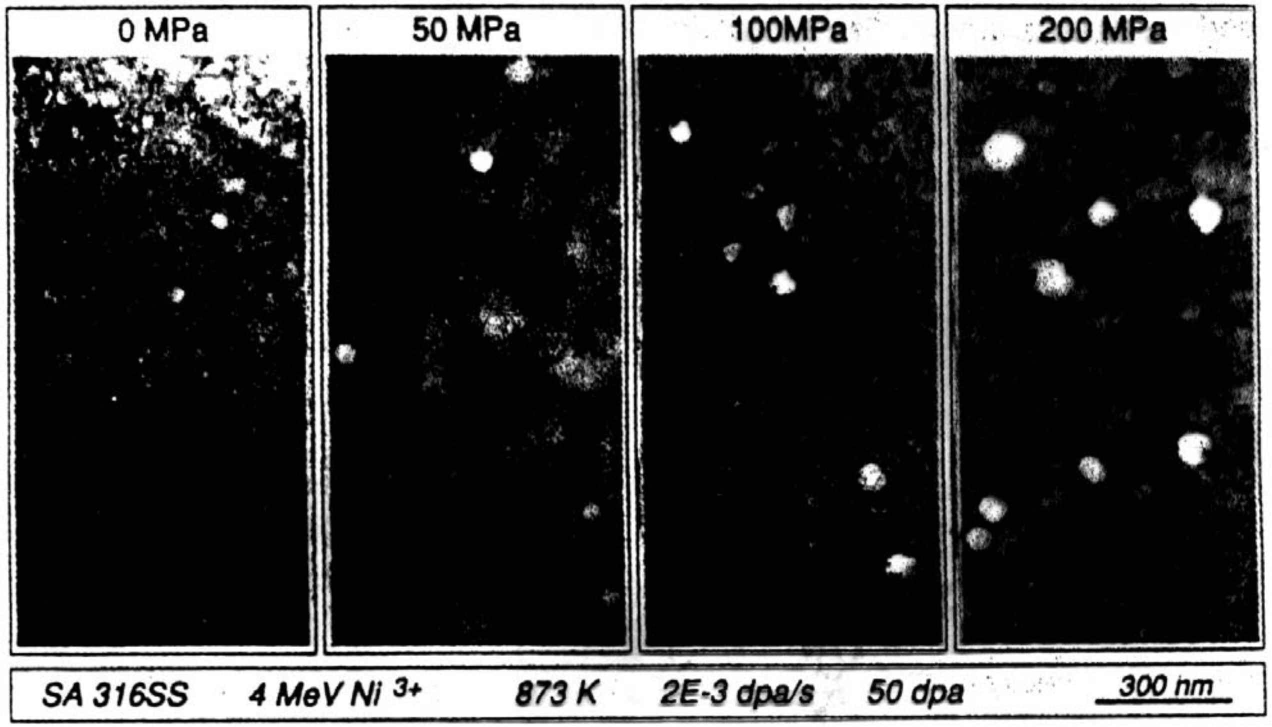
Growth kinetics of dislocation loops during electron irradiation in annealed stressed Ni samples in the dependence on the orientation relatively to tensile stress



Curves 1 to 6 show the growth of dislocation loops in the dependence on tensile stress orientation in annealed Ni sample

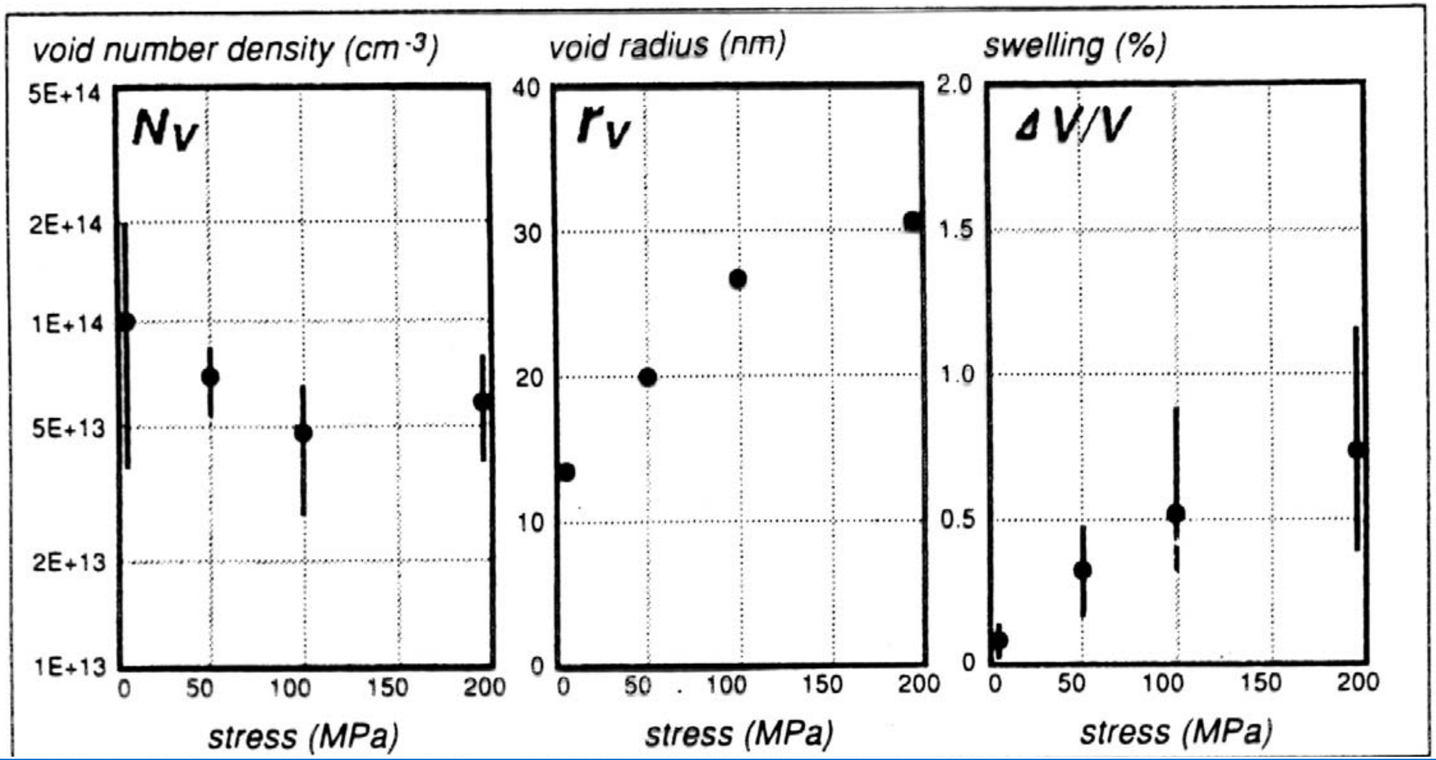
(S.Jitsukawa, F.Garner, 1992)

TEM observation of cavity microstructure in ion irradiated type 316 SS under different tensile stresses



Irradiation of 316 SS by Ni ions with the energy E = 4 MeV up to dose 50 dpa at T=600°C under different stresses from 50 Mpa to 200 Mpa (A.Kohyama et al., 1994).

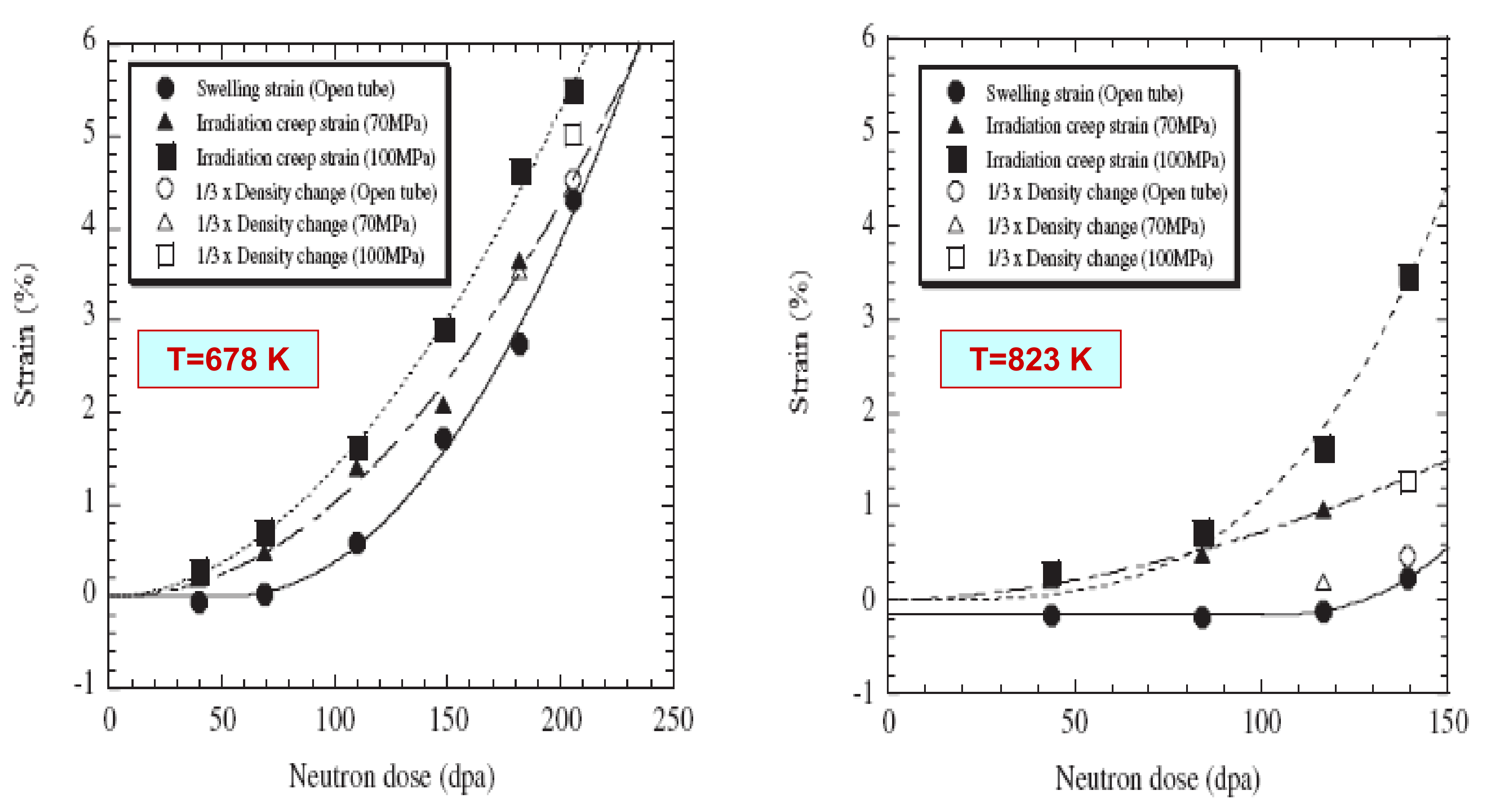
Stress dependence of void number density, void radius and radiation swelling in ion irradiated type 316 SS



Irradiation of 316 SS by Ni ions with the energy E = 4 MeV up to dose 50 dpa at T=600°C under different stresses

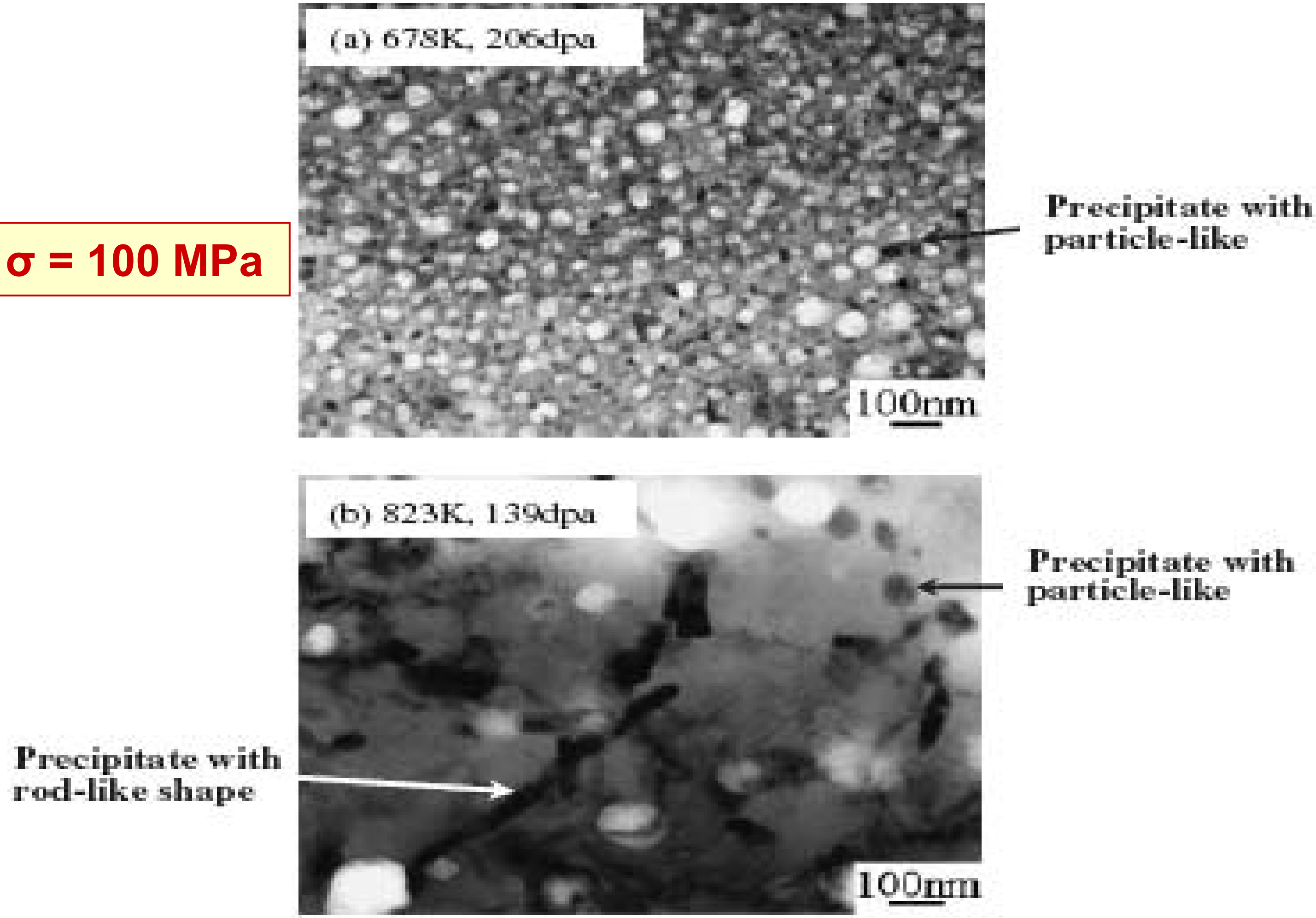
(A.Kohyama et al., 1994).

Neutron Dose Dependence of Strain Radiation Creep Deformation in PNS316 at High Doses (S.Ukai, 2007)



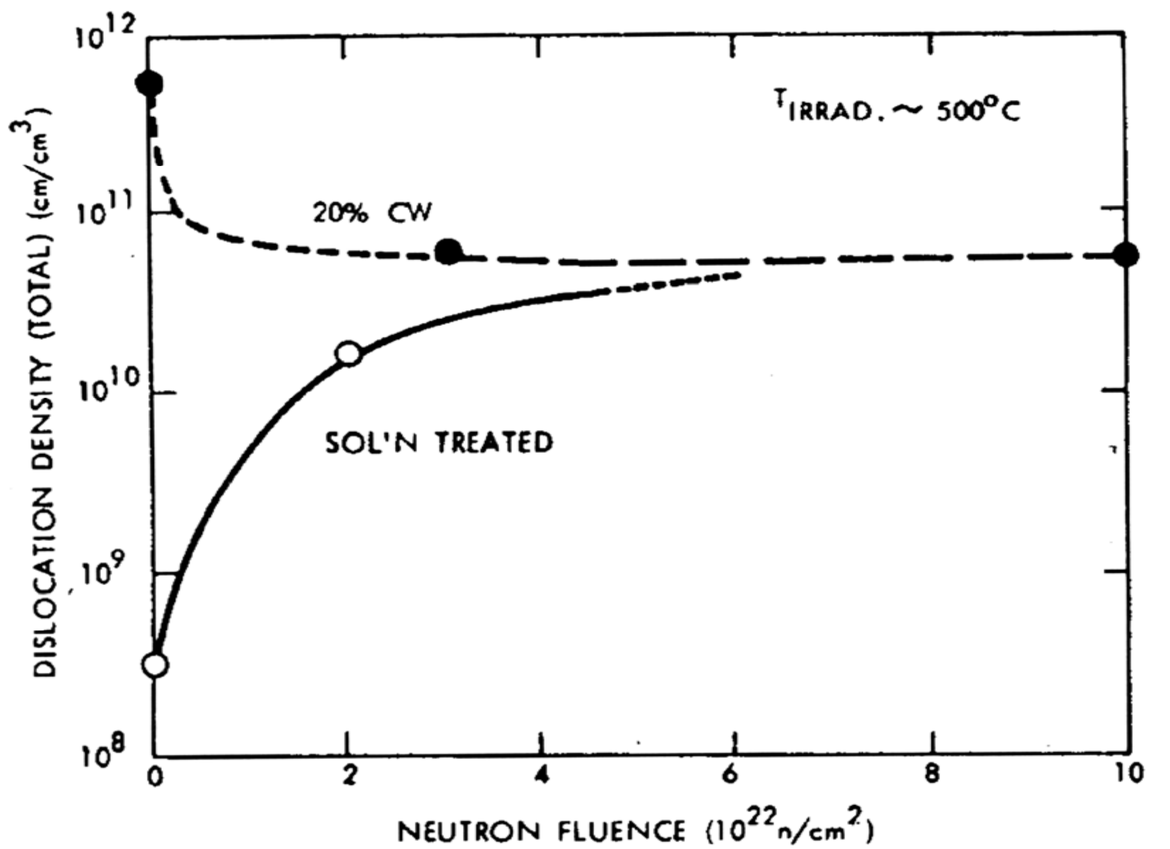
Microstructure of Strained PNS316 at High Neutron Doses (S.Ukai, 2007)

σ = 100 MPa

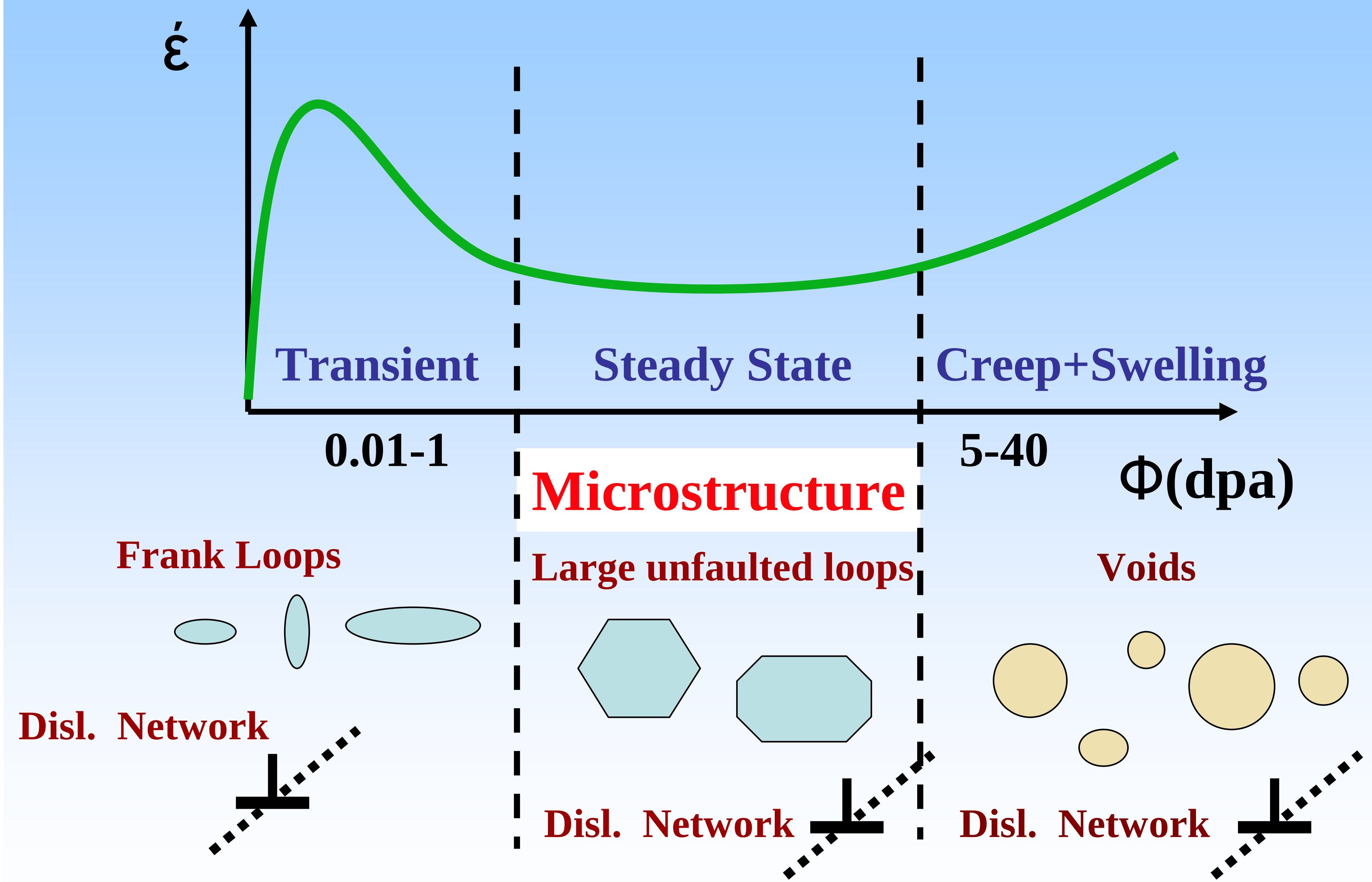


Development of Dislocation Density during Neutron Irradiation in type AISI 316 SS

(H.R Brager,1977)



Physical Stages of Irradiation Creep



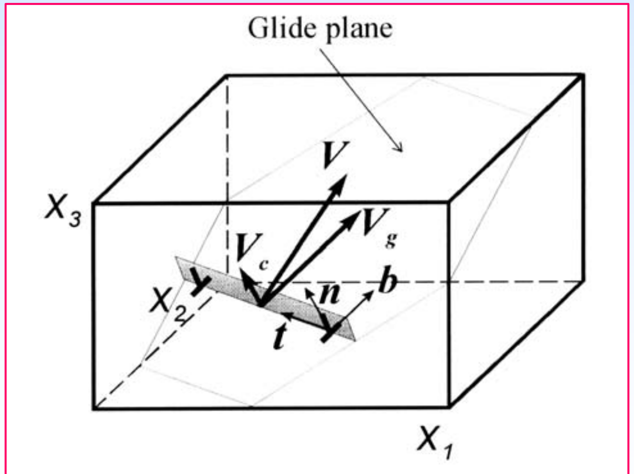
Theoretical Models of Irradiation Creep

1.General relations

The deformation rate is obtained as an integral over all dislocation segments.

$$\dot{\varepsilon}_{ij} = \Omega^{-1} e_{imn} \int V_m t_n b_j dl, \qquad (1)$$

Here *V* is the dislocation segment velocity, *t* is a unit vector along the dislocation line, *b* is the Burgers vector, where the considered segment belongs, Ω is the sample volume and *eimn* is the anti-symmetric Kronecker's tensor.



$$\boldsymbol{V}^k = -V_c^k \boldsymbol{n}^k + V_g^k \hat{\boldsymbol{b}}^k, \qquad (2)$$

$$\hat{\boldsymbol{b}}^k = \boldsymbol{b}^k / b \qquad \boldsymbol{n}^k = [\hat{\boldsymbol{b}}^k \times \boldsymbol{t}^k]$$

$V_g^k and V_c^k$ **are the glide and creep velocities of dislocation**

The total deformation creep rate is equal

$$\dot{\varepsilon}_{ij}^D = \rho b \left\langle \hat{b}_i \hat{b}_j V_c \right\rangle + \frac{1}{2} \rho b \left\langle (\hat{b}_i n_j + n_i \hat{b}_j) V_g \right\rangle, \qquad (3)$$

ρ is `the dislocation density

Creep mechanisms based on stress-induced dislocation climb

Climb velocity *Vck* is determined by point defect currents per unit dislocation length, *J*a (a = *v* for vacancies and a = *i* for interstitials) as

$$V_c^k = b^{-1}(J_i - J_v).$$

Point defect current to a dislocation is equal

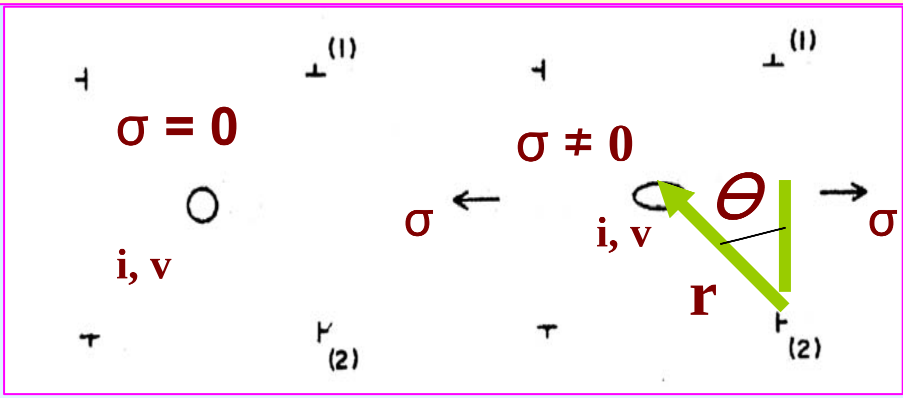
$$J_\alpha^k = Z_\alpha^k D_\alpha (C_\alpha - C_{\alpha 0}^k),$$

Here *Zak* are the "bias factors", which are determined by the sink geometry, orientation in space and the efficiency of sink elastic interaction with point defects; *C*α (*α* = *i*,*v*) are the concentrations of point defects, *Dα* are the diffusion coefficients for a-type point defects

Concentrations of point defects are determined in the material by point defect generation under irradiation and loss of them at sinks or mutual recombination

$$\frac{dC_\alpha}{dt} = G - \rho \langle J_\alpha \rangle - \sigma_R (D_i + D_v) C_i C_v,$$

Stress-modified modulus interaction of point defects with dislocations (SIPA)



Interaction energy of a *k*-type dislocation with α type of point defect

$$U_\alpha^k = k_B T \frac{R_\alpha^k}{r} \sin\theta,$$

is the radius of dislocation interaction with point defects, which equals to

$$R_\alpha^k = \frac{\mu\omega b}{\pi k_B T}\left(e_\alpha^0 + p_\alpha^K \frac{\sigma}{E} + p_\alpha^\mu q^k \frac{\sigma}{\mu} \right),$$

Here *E* and μ are the Young modulus and the shear modulus of material, e_α^0 is the effective dilatation of a point defect, p_α^K, p_α^μ are determined by the elastic polarizabilities of point defects, q^k characterizes of the dislocation orientation

Expression for bias-factor *Za*

$$Z_\alpha^k = \frac{2\pi}{\ln(2R_d / R_\alpha^k)} \approx Z_\alpha^0 \left(1 + \frac{Z_\alpha^0 p_\alpha^\mu}{2\pi e_\alpha^0} q^k \frac{\sigma}{\mu} \right),$$

Irradiation Creep Rate

$$\frac{d\varepsilon}{dt} = K\frac{\sigma}{\mu}G, \qquad K = B\frac{1}{dpa}$$

K **is the creep modulus,** ***B*** **is the irradiation creep compliance,** ***G*** **is the generation rate of "freely migrating" point radiation defects.**

$$G = \zeta G_{NRT}$$

G_{NRT} **is the "ballistic" generation rate, calculated by NRT-standart,**

ζ **Is the correction factor, which is determined by the PKA energy spectrum, corresponding to particular experimental set of irradiation and material parameters. During fast-reactor neutron irradiation** $\zeta \sim 0.1\text{-}0.2$**.**

$$B_{kl} = S_{kl}^{EMA}\left(\frac{Z_i^0 p_i^\mu}{2\pi e_i^0} - \frac{Z_v^0 p_v^\mu}{2\pi e_v^0}\right),$$

S_{kl}^{EMA} **is the structure factor, determined by dislocation orientation distribution with respect to the applied load**

$$S_{kl}^{EMA} = 3\nu\left\langle \hat{b}_k\hat{b}_l\left((\boldsymbol{ts})^2 - <(\boldsymbol{ts})^2>\right)\right\rangle + 3\left\langle \hat{b}_k\hat{b}_l\left((\hat{\boldsymbol{b}}\boldsymbol{s})^2 - <(\hat{\boldsymbol{b}}\boldsymbol{s})^2>\right)\right\rangle.$$

Using the estimates $p_i^\mu \approx 0.5, p_v^\mu = 0, Z_i^0 \approx 3, e_i^0 \approx 1.5$

$$B_{kl} \propto S_{kl}^{EMA} \approx 1$$

Primary (transient) irradiation creep stage

Dislocation loop kinetics in loaded materials under irradiation

Two effects of external stress on dislocation loop kinetics:

1) *The stress-induced preferred nucleation* (SIPN) of dislocation loops, where density of loops is determined by

$$N^k = N_0^k \exp\left(\frac{m\tilde{\sigma}_{nn}\omega}{k_B T}\right),$$

where N_0 is the volume density of k-type loops without loading; σ_{nn} is the component of stress deviator tensor normal to the loop extra-plane, and m = 2-3.

2) *The orientation anisotropy of point defect absorption by loops* due to SIPA-type mechanisms, where σ_{nn} growth rate of dislocation loops with the orientation m is equal .

$$V^m \equiv \frac{dR^m}{dt} = b^{-1}\left(\eta_i^m D_i C_i - \eta_v^m D_v (C_v - C_{v0})\right),$$

where η_α^m is the dislocation loop bias factor for point defects of type a at the loops with orientation m and balance equations for point defects are equal .

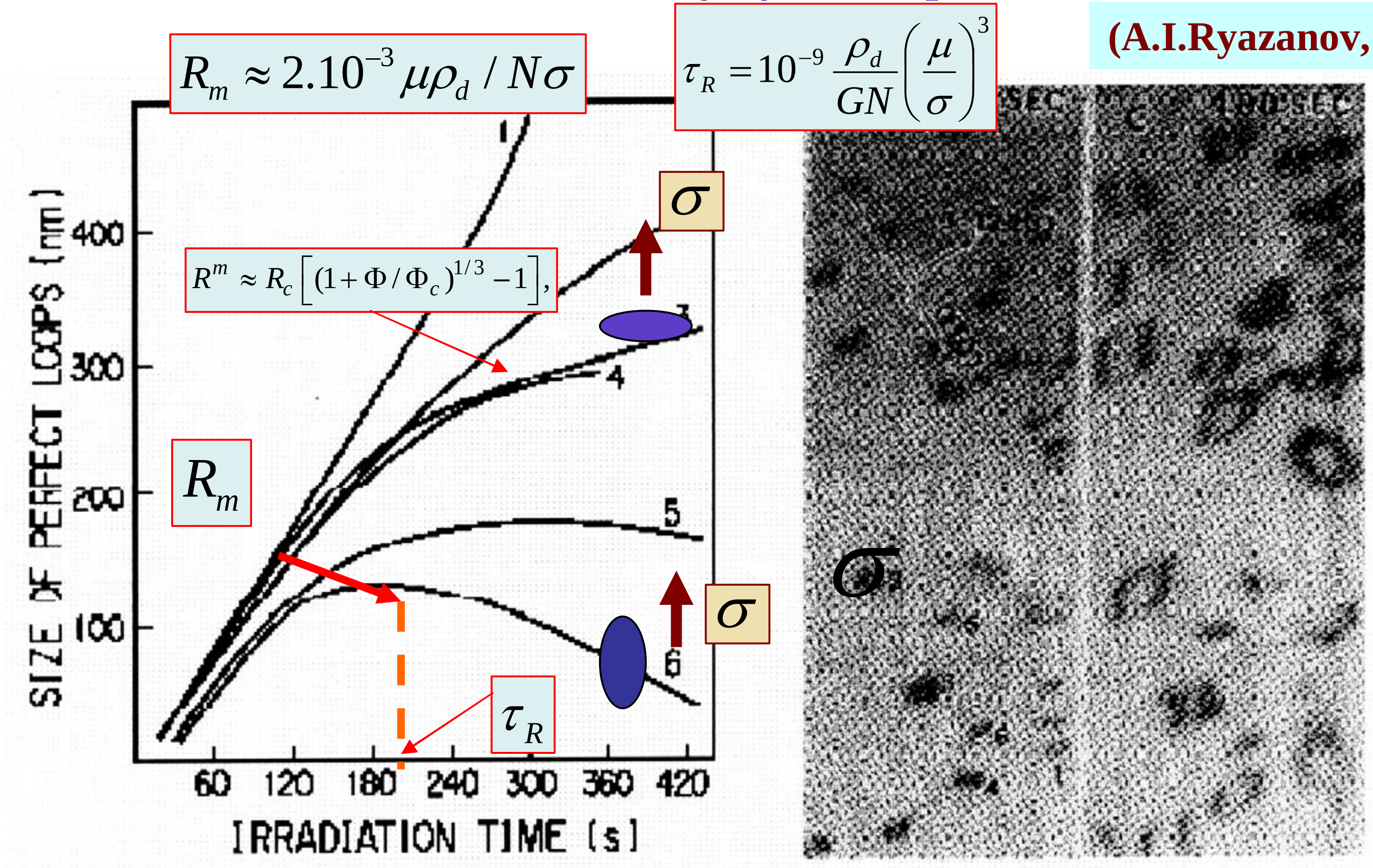
$$G - k_\alpha^2 D_\alpha (C_\alpha - C_{\alpha 0}) - \sigma_R (D_i + D_v) C_i C_v = 0,$$

Theoretical dislocation loop growth rate with the m orientation is equal

$$V^m(R) = \frac{G\Phi(G/G_R)}{bk_i^2 k_v^2}\left(A^m \rho + B^m \rho_L\right), \qquad \Phi(x) = \frac{2}{1+\sqrt{1+x}}.$$

Am **characterizes the efficiency of diffusional interaction between the dislocation loops and network dislocations, *Bm* is defined only by the loop bias factors..**

(A.I.Ryazanov, V.Borodin)

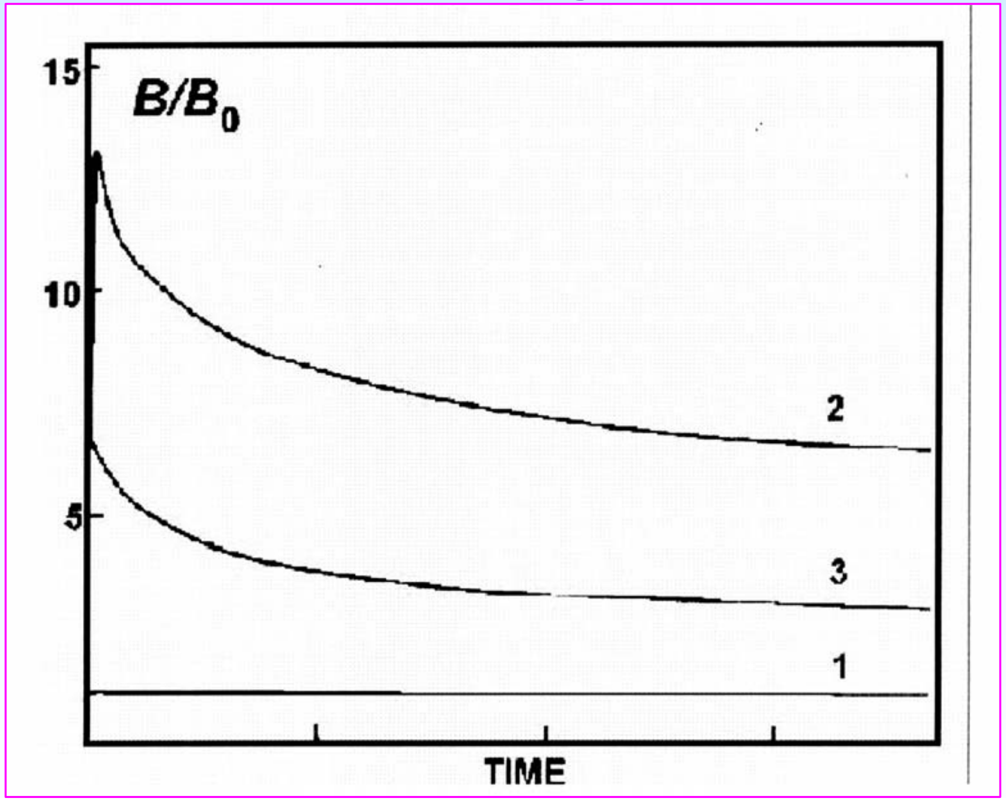


The dependence of loop sizes in electron irradiated Ni on irradiation time. Numbers at the curves indicate the loops shown TEM pictures (S.Jitsukawa, F.Garner, 1992).

Irradiation creep rate due to dislocations and dislocation loops

$$\dot{\varepsilon}_{ij}^{tot} = \dot{\varepsilon}_{ij}^{D} + \dot{\varepsilon}_{ij}^{L} \qquad \dot{\varepsilon}_{ij}^{L} = 2\pi b \sum_{m=1}^{M} \hat{b}_i \hat{b}_j \int_0^{R_{max}} V^m(R) f^m(R,t) R dR,$$

Vm = dR/dt **is the loop growth rate**



The qualitative behavior of irradiation creep modulus (normalized per steady-state value) as a function of time t at the transient stage, as predicted by different models:(1)-SIEMA without preferential nucleation of aligned dislocation loops; (2)-SIEMA with allowance for the preferential nucleation of aligned dislocation loops; (3)-when network dislocations are discrete sinks (A.I.Ryazanov,V.Borodin).

Stress-induced diffusion anisotropy (SIDA)

Diffusion tensor in a crystal lattice can be presented as

$$D_{\alpha,ij} = \nu_\alpha \sum_{\boldsymbol{h}} \lambda_{\boldsymbol{h}} h_i h_j \exp\left(-\frac{E_\alpha^h}{k_B T}\right),$$

ν is the vibration frequency of point defects in the lattice, *hi* is the *i*-th component of a vector h, connecting an equilibrium point defect position with one of the neighbour equilibrium positions, *Eah* is the energy barrier of diffusion jump in the direction *h*, λ the factor that takes into account of the dumbbell diffusion mechanism (for interstitial atoms)

Under the action of small elastic deformations *e ij*(*r*), weakly varying on the length scale of interatomic distance, the energy *Eah* can be written down as

$$E_\alpha^h = E_\alpha^m - P_{\alpha,kl}^s(\boldsymbol{h})e_{kl} - \frac{1}{2}Q_{\alpha,klmn}^s(\boldsymbol{h})e_{kl}e_{mn},$$

$P_{\alpha,kl}^S, Q_{\alpha,klmn}^S$ **are the force and elastic polarizability tensors in a saddle point.**

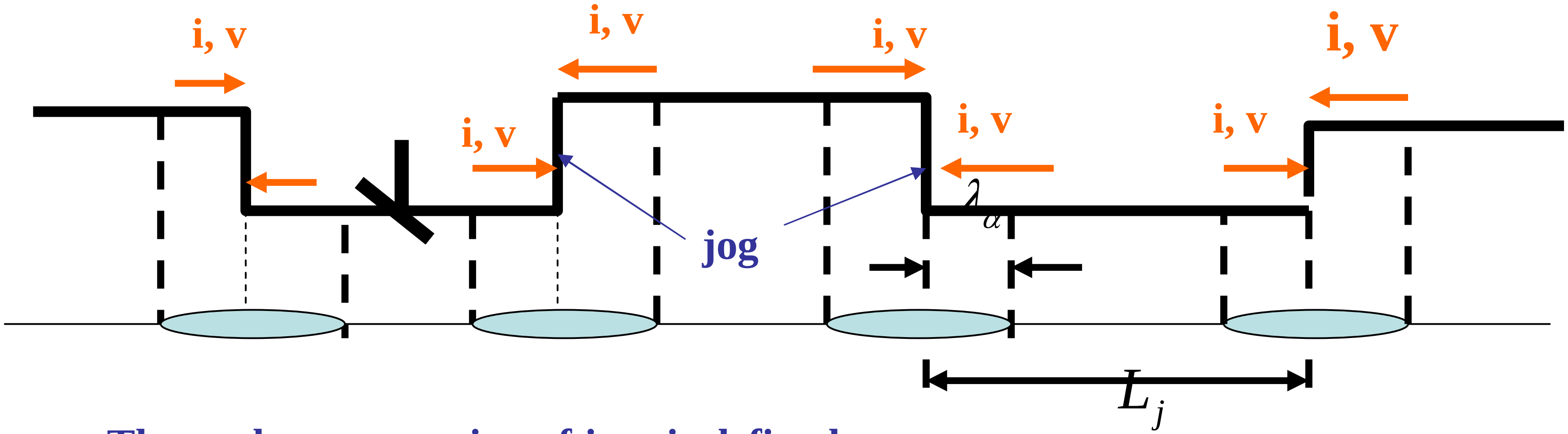
Bias factors for cubic lattice can be presented at $\sigma\omega/k_B T$ « 1 as

$$Z_\alpha^k = Z_\alpha^0\left(1 - \frac{(1+\nu)}{2(1-2\nu)} e_\alpha^s q^k \frac{\sigma\omega}{k_B T}\right),$$

$$q^k = d_\alpha^{(2)}(\boldsymbol{st}^k)^2 + d_\alpha^{(3)}\sum_{p=1}^{3}(\boldsymbol{se}_p)^2(\boldsymbol{t}^k\boldsymbol{e}_p)^2,$$

$d_\alpha^{(2)}, d_\alpha^{(3)}$ **are the factors determined by point defect force tensors in saddle points**

Irradiation Creep Induced by Kinetics of Point Defects in Dislocation Core



Thermal concentration of jogs is defined as

$$C_j^{th} = a \exp\left(-\frac{E_j}{k_B T}\right),$$

Ej **is the energy of jog formation on dislocation line**

Mean free path of point defects along dislocation line $\lambda_\alpha \approx (D_{\alpha d}\tau_\alpha)^{1/2}$

$$\lambda_\alpha^k = a \exp\left(\frac{\Delta Q_\alpha^k}{k_B T}\right),$$

$\Delta Q_\alpha = (E_{b\alpha} + E_{m\alpha} - E_{m\alpha}^d)/2, E_{m\alpha} and E_{m\alpha}^d$ **are migration energies of point defects in the bulk and in the dislocation core, and** $E_{b\alpha}$ **is their energy of binding with dislocations,** ***Ej*** **= 0.3-0.4 eV for undissociated dislocations in Cu and Al, and** ***Ej*** **~ 4 eV for dissociated dislocations in Cu.**

Estimations: $\lambda_v \approx 10^2 a, \lambda_i(FCC) \approx 10^2 a, \lambda_i(BCC) \approx 10^{5-6} a$

$L_J \approx C_J^{-1} \approx 10^{4-5} a$

1) Dislocation as an ideal sink for point defects: $L_J \le 2\lambda_\alpha,$

2) Dislocation as "discrete" sink for point defects: $L_J >> 2\lambda_\alpha$

The external load can change the values of jog energy formation, formation and migration energies of point defects in dislocation core, $E^d_{f\alpha}$ and $E^d_{m\alpha}$, thus changing the mean free path

Table 5
Vacancy migration energy E^d_{mV} and self-diffusion energy Q^d_V for the jump $1 \leftrightarrow 5$ under external shear loads

Energies (eV)	Load type		
	σ_{12}	σ_{23}	σ_{31}
E^d_{mV}	0.54	0.41	0.42
	0.07	0.01	0.01
Q^d_V	1.32	1.09	1.10

Note: The upper values of E^d_{mV} correspond to the jump $1 \leftrightarrow 5$, the lower ones to the jump $5 \rightarrow 1$.

$$\lambda_\alpha^k \propto \exp\left\{\frac{1+\nu}{6(1-2\nu)} \frac{p^k_{\alpha,ij}\sigma_{ij}\Delta V^d_\alpha}{k_B T}\right\},$$

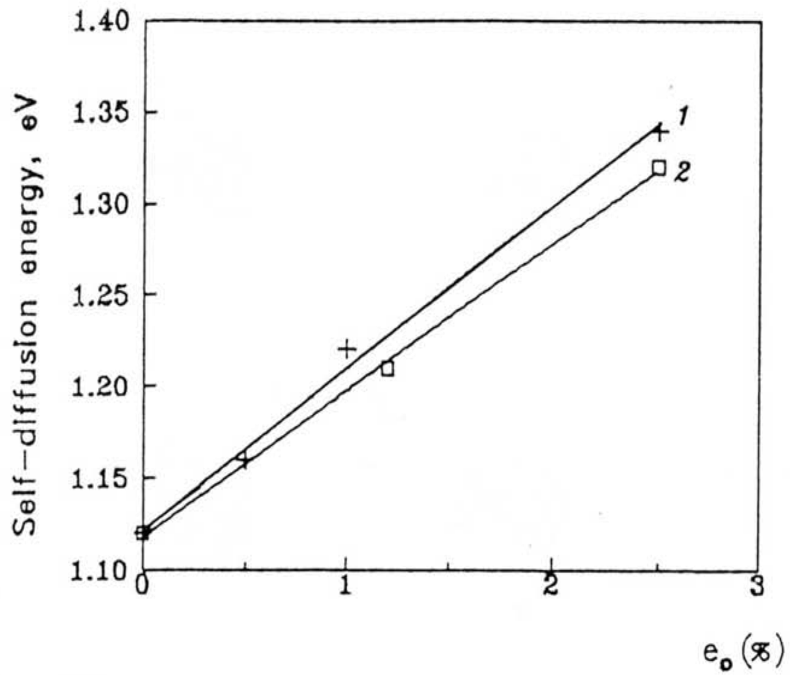


Fig. 3. The energy of self-diffusion along the dislocation core as a function of e_0. (1) $e_{11} = e_0$; (2) $e_{12} = e_0$.

Irradiation creep compliance for“ discrete“ dislocation sinks for point defects

In the case of “discrete” dislocation line or low jog concentration in the dislocation core ($L_J >> 2\lambda_\alpha$) the bias factors can be written as

$$Z_\alpha^k = \beta_\alpha^k \lambda_\alpha^k C_j^k,$$

1. For the stress enhanced jog nucleation (SEJN) the creep compliance is equal taking into account $\beta_i \approx \beta_v \approx 5, \Lambda = 2, e_i^0 \approx 1.5, \left|e_v^0\right| = 0.5$

$$B_{kl}^{JN} = 0.03 S_{kl}^{JN} \frac{\mu\omega}{k_B T}.$$

$$S_{kl}^{EJN} = < \hat{b}_k \hat{b}_l (\zeta_j (\boldsymbol{bs})^2 - < \zeta_j (\boldsymbol{bs})^2 >) >$$

2. The contribution to creep compliance from the orientatial anisotropy of pipe diffusion (PDA) of point defects along dislocation cores

$$B_{kl}^{PDA} = (e_i^d S_{i,kl}^{PDA} - e_v^d S_{v,kl}^{PDA}) \frac{K\omega}{12 k_B T},$$

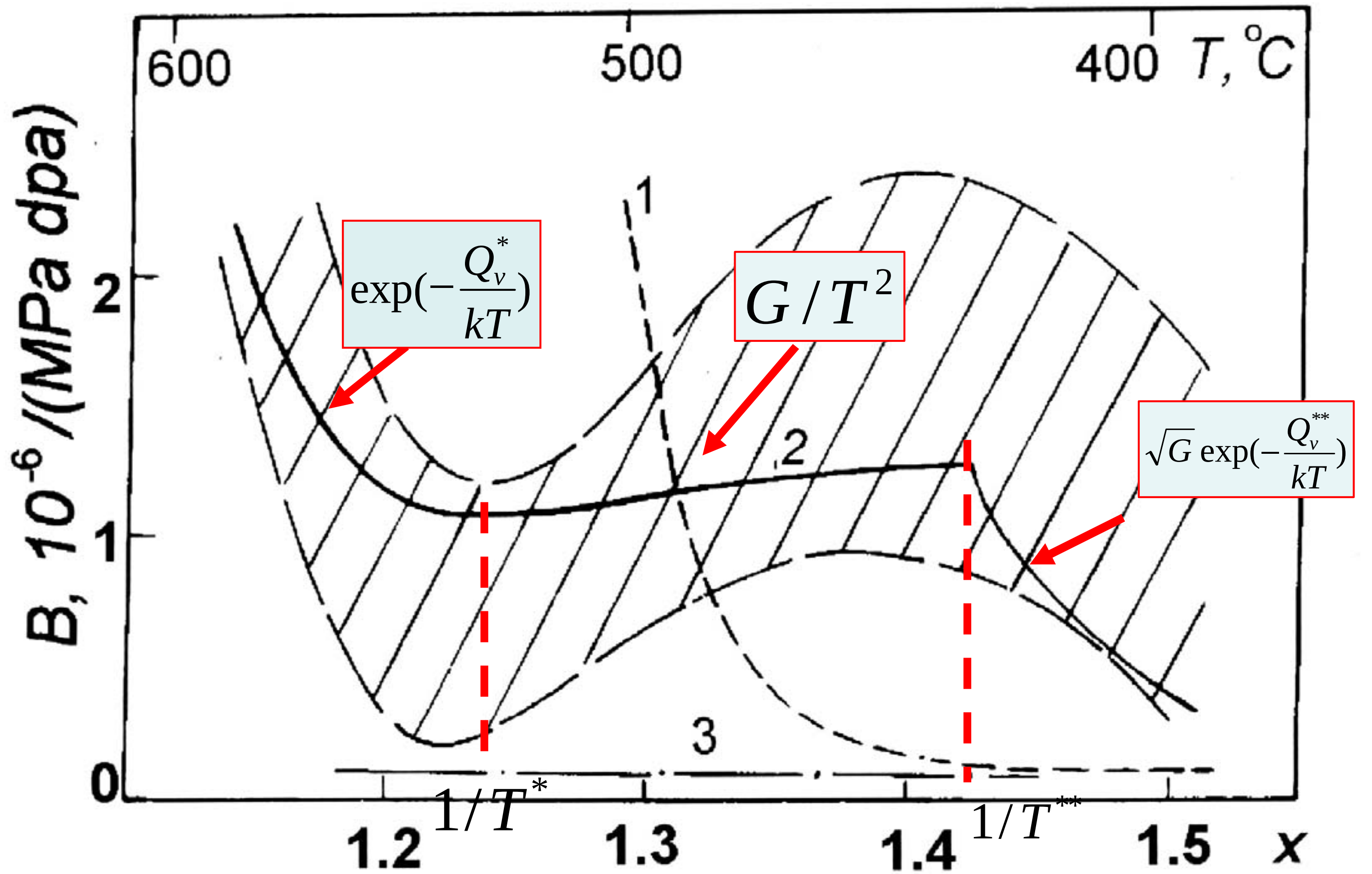
$$S_{\alpha,kl}^{PDA} = \left\langle \hat{b}_k \hat{b}_l (p_{\alpha,11}^d - < p_{\alpha,11}^d >) \right\rangle,$$

$$B_{kl}^{JN} \approx B_{kl}^{PDA} \approx B_{kl}^{VDA}$$

Structural factors S for various microscopic mechanisms of point defect absorption by dislocations under irradiation

Dislocation distribution	Irradiation creep			Thermal creep, S^{T}_{nn}
	Elastic modulus modification, S^{EMA}_{nn}	Bulk diffusion anisotropy, $S^{(2)}_{nn}$	Dislocation core diffusion anisotropy, * $S^{PDA}_{\alpha,nn}$	
Fully isotropic	$\frac{2(2-\nu)}{15}$	$-\frac{2}{45}$	$\frac{2}{15}(p^{d}_{\alpha,11}-1)$	$\frac{4}{45}$
Cubic	$3f_1(1-f_1-\nu f_3)$	$-f_1 f_3$	$f_1\{f_2(p^{d}_{\alpha,11}-p^{d}_{\alpha,22})+f_3(p^{d}_{\alpha,11}-p^{d}_{\alpha,33})\}$	$f_1(1-f_1)$

Irradiation Creep Temperature Dependence

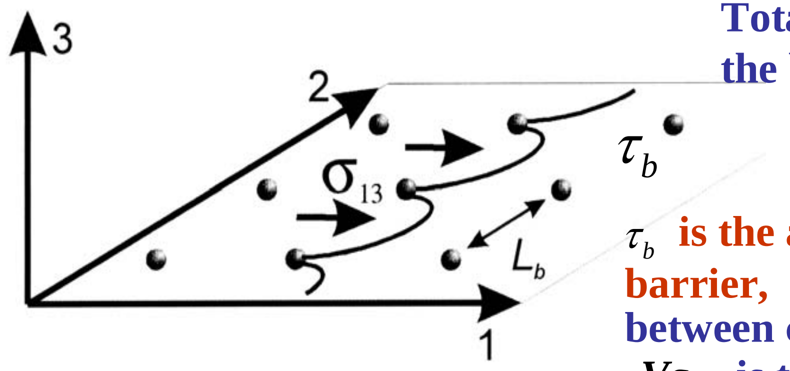


$T^*/T_m \approx 0.16 - 0.2$

$T^{**}/T_m \approx 0.5$

Temperature dependence of the irradiation creep rate modulus for the cases when dislocations are continuous (curve 1) and discrete (curve 2) sinks for point defects (A.Ryazanov, V.Borodin, JNM, 1987). Curve 3 represents the results of Bullough for SIPA mechanism. Experimental creep rate values for neutron irradiated 316 SS is shown (shaded).

Irradiation creep mechanisms based on climb-limited dislocation glide



Total time lost by a dislocation in order to shift from the barrier to the next one is equal

$$\tau = \tau_b + (L_g / V_{g0})$$

τ_b is the average time required for a dislocation to overcome a barrier, ***Lg*** is the average distance glided by a dislocation between consecutive pinning barriers in the glide plane, ***Vg0*** is the glide velocity.

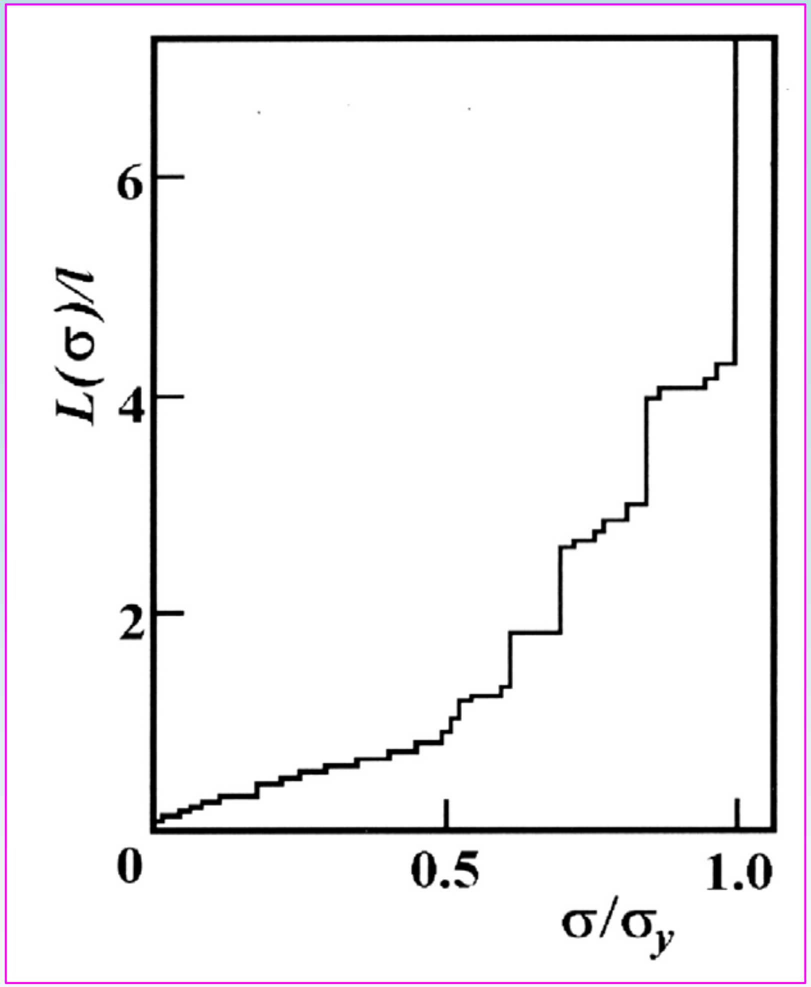
The average glide velocity is equal

$$V_g = \frac{L_g}{\tau} = \frac{1}{1 + \frac{V_{g0}\tau_b}{L_g}} V_{g0}. \qquad \frac{1}{\tau_b} = \nu_{d0} \exp\left(-\frac{U_b}{k_B T}\right) + \frac{|V_c|}{h},$$

ν_{d0} is the attempt frequency, ***Ub*** is the activation energy of barrier overcome and ***h*** is the barrier geometrical "height“, |***Vc***| is the dislocation climb velocity.

Because the climb velocities are usually sufficiently low, so ***h/Vc*** » ***Lg/Vg0*** and the irradiation creep rate determined by dislocation glide is equal

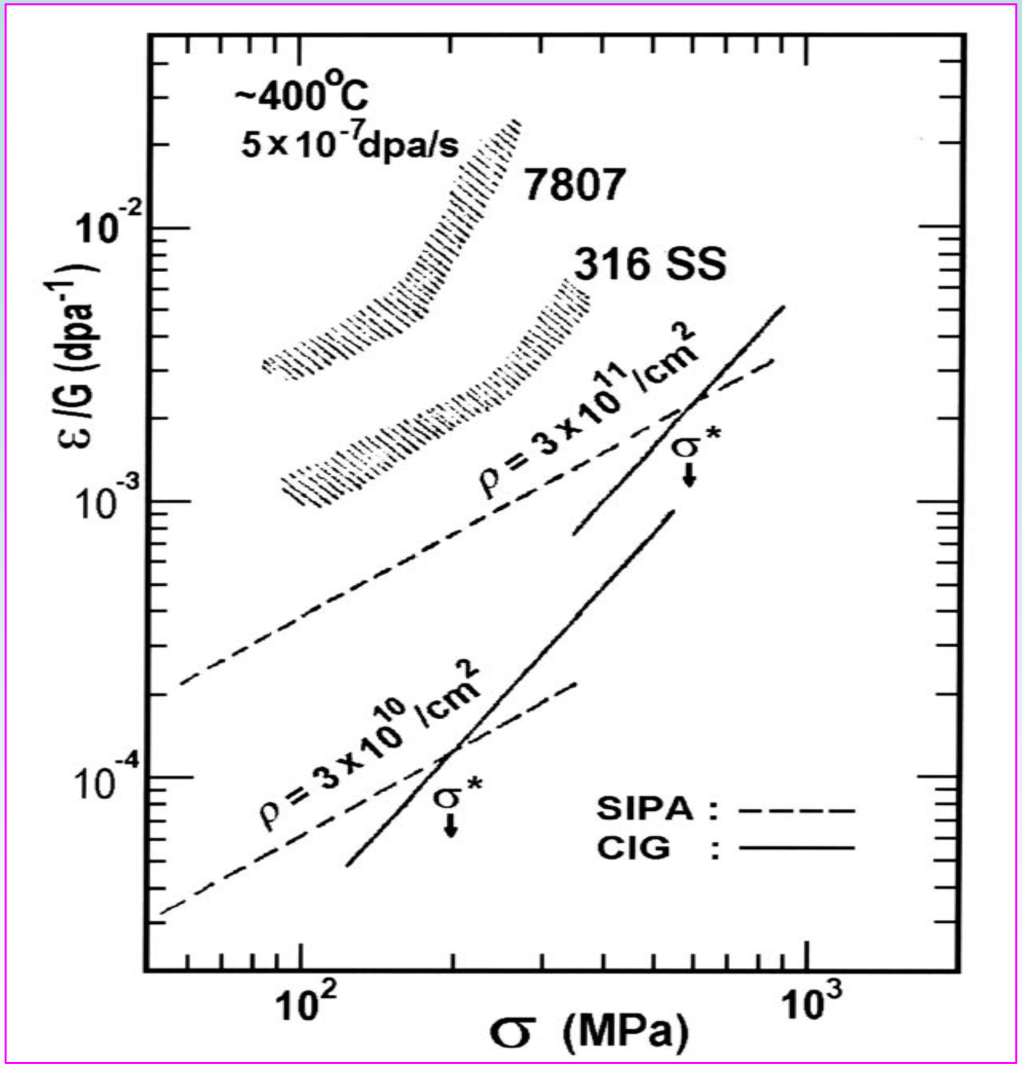
$$\dot{\varepsilon}_{kl}^{DG} = \frac{1}{2} \rho b \left\langle (\hat{b}_i n_j + n_i \hat{b}_j) |V_c| \frac{L_g}{h} \right\rangle,$$



The average dislocation glide distance as a function of shear stress in the dislocation glide plane (according modeling by V. Kirsanov)

h **is of the order of the average distance between dislocations, i.e.**

$$h \approx (\pi\rho_d)^{-1/2}$$



Comparison of creep rate between theoretical results (SIPA-Stress-Induced Preference Absorption, CIG-Climb-Induced Glide) and the experimental ones, as a function of stress. The hatched area indicate the experimental values of the 7807 alloy and type 316 SS. The σ* denotes the critical stress (N. Kishimoto).

Summary

- **The results presented here allow to clarify some physical mechanisms of irradiation creep phenomenon in irradiated fusion structural materials.**
- **The radiation induced plastic deformation in fusion structural materials under irradiation depends on many parameters: initial microstructure, irradiation temperature, cascade efficiency, generation rate of point defects, accumulation of defect clusters (dislocation loops, voids and precipitate density), helium accumulation.**
- **The analysis of transient stage of irradiation creep leads to the conclusion that the kinetics of loop growth is defined by diffusion interaction between loops of different orientations, leading to redistribution of point defects between "favorably" and "unfavorably" oriented loops with respect to loading direction. The strong dose dependence of irradiation creep at the transient stage is predicted when the loop nucleation dependence on stress orientation is taken into account.**
- **Investigations of an irradiation creep dependence on the irradiation temperature show that this dependence is described better by "discrete" dislocation model and three temperature intervals exist with different temperature dependencies.**
- **It was shown that dependence of in-reactor creep rate on point defects generation rate *G* is markedly different for three temperature intervals. In the low-temperature region, where point defect annealing behavior is dominated by recombination, $\dot{\varepsilon}_{ij}^{DC} \propto \sqrt{G}$ .At intermediate temperatures the creep rate is described by usual linear law $\dot{\varepsilon}_{ij}^{DC} \propto G$. Finally, in the high temperature region the basic contribution to the irradiation creep rate is given by thermal component of creep.**

- **The value of irradiation creep compliance *B* is determined by the specific mechanisms resulting in anisotropy of bias factors including stress-induced elastic module anisotropy (SIPA), stress-induced diffusion anisotropy (SIDA) and mechanisms related to the effect of stress on point defect absorption by dislocations** $B_{kl}^{JN} \approx B_{kl}^{PDA} \approx B_{kl}^{SIDA} >> B_{kl}^{SIPA}$ **.**

- **Investigations of irradiation creep dependence on load intensity in materials show, that at $\sigma < \sigma^*$ the dependence of creep rate on stress value has universal linear character, irrespective of the mechanism ensuring anisotropy of point defect absorption by dislocations. For mechanisms based on the modification of thermofluctuative parameters (such as diffusion barriers, energies of jog nucleation on dislocations, etc.), the critical stress σ^* has the order of $\sigma^* \sim k_B T / \omega$, which gives values of about several hundreds MPa at typical reactor temperatures of 300-600°C. It is interesting to note, that these values are order of magnitude as yield stress of irradiated metals, which naturally promotes a question, whether such mechanisms can be responsible for observed non-linearity of irradiation creep at $\sigma > \sigma^*$.**