DYNAMIC RESPONSE OF FUSION REACTOR MATERIALS UNDER ELECTROMAGNETIC FORCE

Ryuta KASADA[1], Daiki ISHII[1], Masami ANDO[2], Hiroyasu TANIGAWA[2], Mitsuru OHATA[3], Satoshi KONISHI[1]

[1]*Institute of Advanced Energy, Kyoto University*

[2]*Japan Atomic Energy Agency*

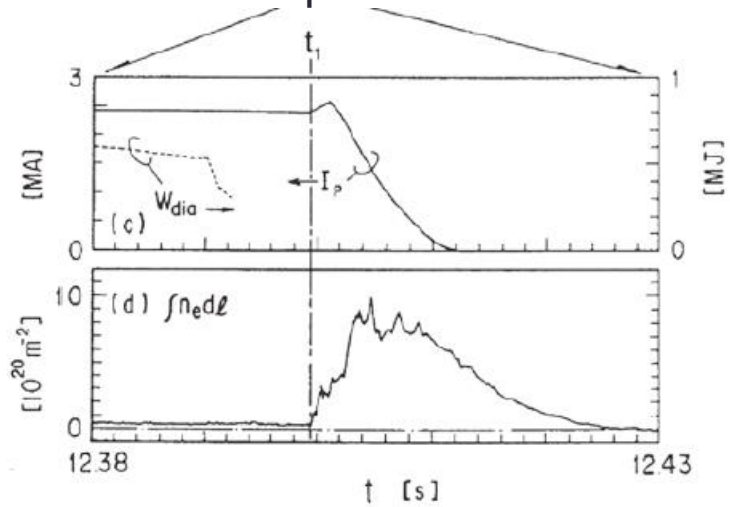
[3]*Osaka University*

Acknowledgements: Mr. T. Daigen, SHIMADZU Co.

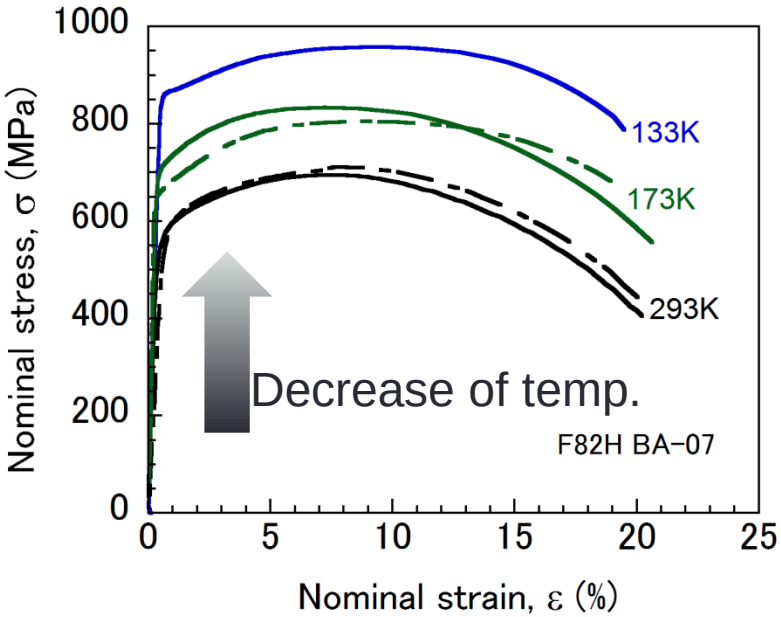
Background

- In fusion reactor, huge electromagnetic forces are loaded on the structural materials by eddy currents induced by the plasma disruption within 10ms.
- However there is no available data of dynamic tensile properties and dynamic fracture toughness of F82H under such high strain rate condition.
- Generally, the tensile strength and toughness of bcc alloys such as ferritic steels and tungsten have significant temperature dependence.
  - Deformation theory predicts that high strain-rate may have an impact on these properties.
  - In addition, irradiation damage may have an impact on the strain-rate sensitivity.

Current quench



Y. Kawano, A. Nagashima, K. Tsuchiya *et al.*, J. Plasma Fusion Res. 73, 870 (1997).

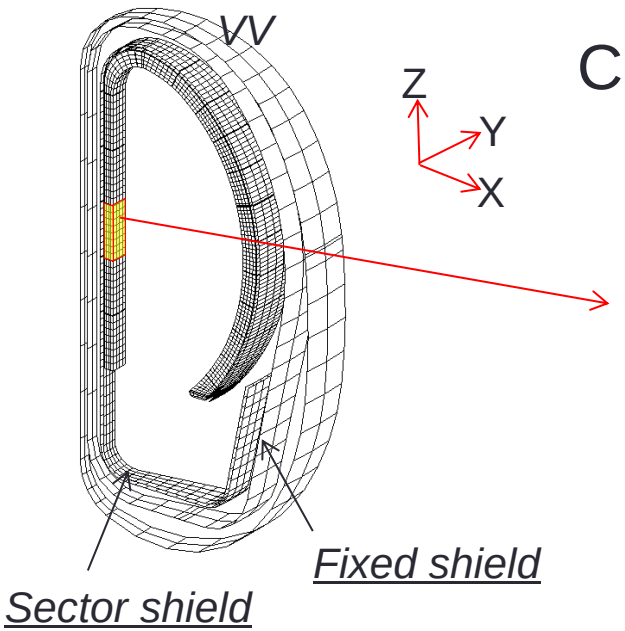


Courtesy of Dr.Ohata et al

Objective

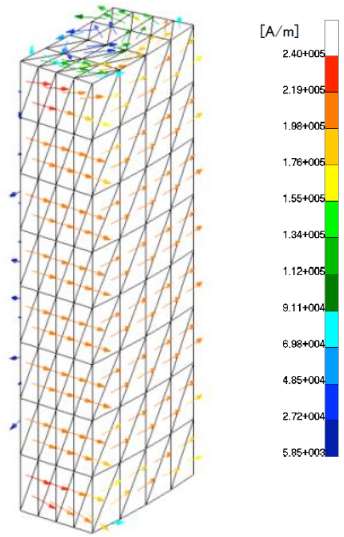
- Understanding deformation and fracture mechanism is important to avoid “unexpected” accidents.
- Previously, the tensile properties of RAF steels were only investigated for normal condition.
- This study investigates the high-speed tensile deformation behavior of RAF steel F82H.

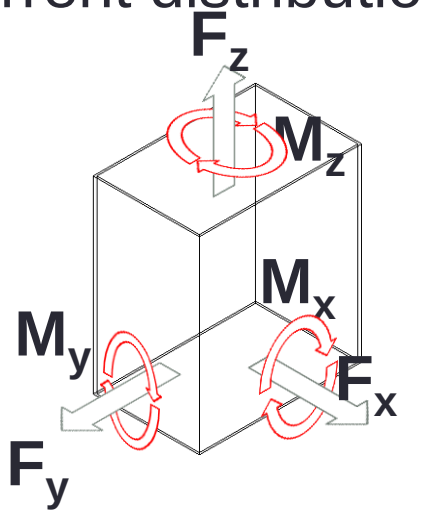
Analysis of electromagnetic force during disruption



FEM model

Calculated eddy current distribution



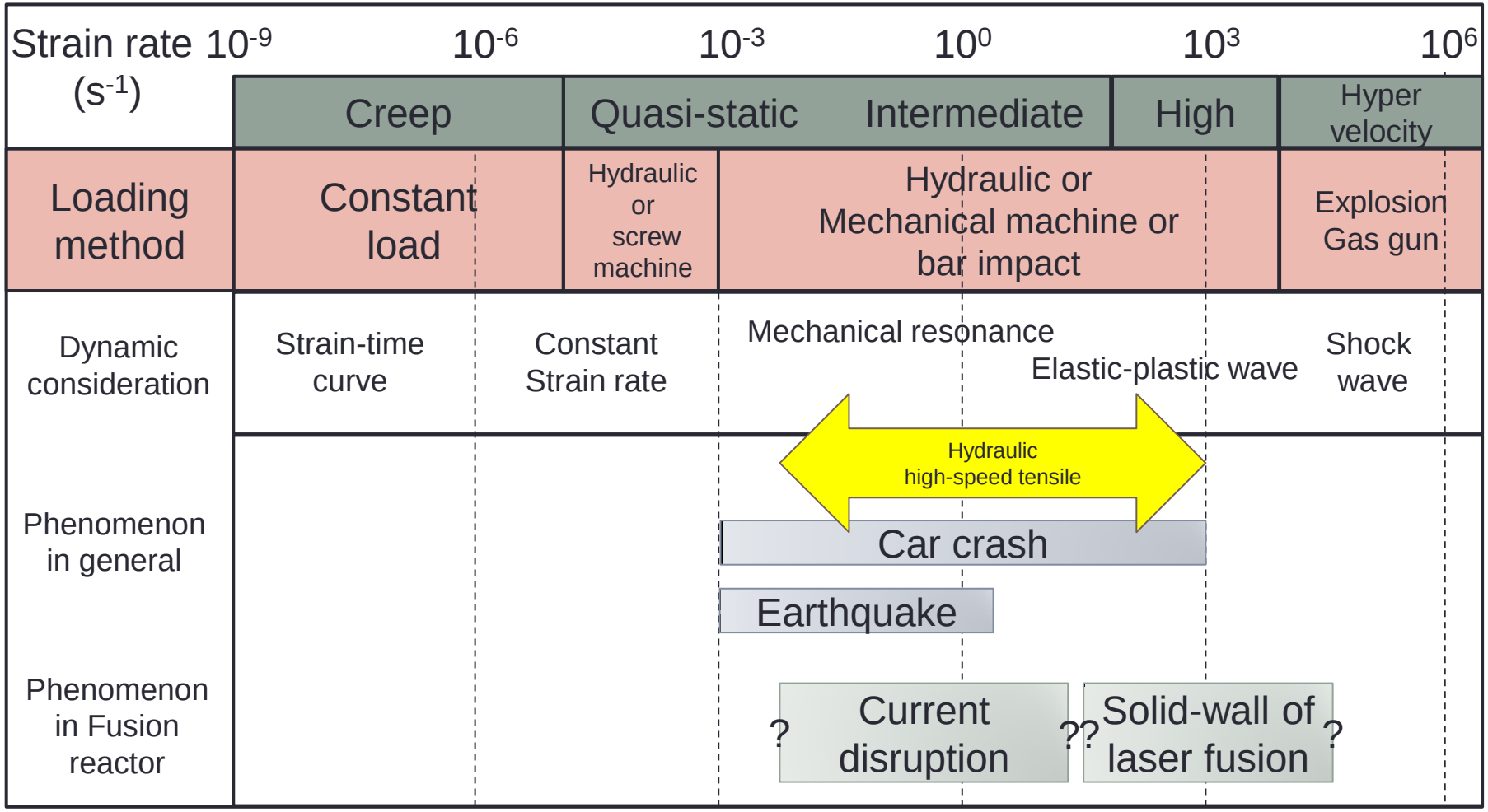


Plasma current (16.7MA) was assumed to linearly decrease in **30ms** .

- Substantial electromagnetic forces are loaded on the blanket structures across the large toroidal magnetic field.
- Estimated strain rate during current plasma disruption event is **0.1/s**.

H. Tanigawa et al., 24th IAEA Fusion Energy Conference – IAEA CN-197, Oct. 2012 ,USA

A strain-rate window of mechanical testing and possible mechanical situation in fusion blanket

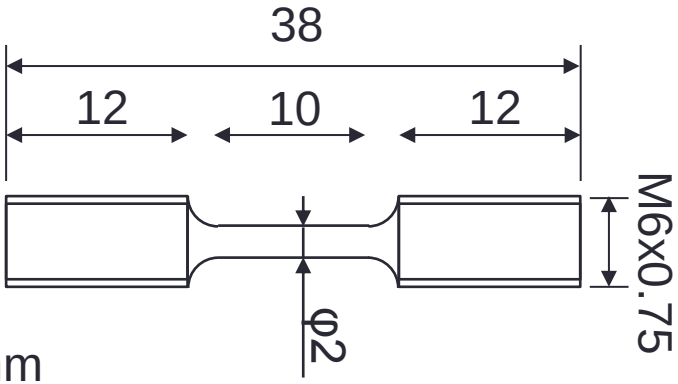


Based on Lindholm, “High strain testing”, Measurement of mechanical properties, Vol. 5, Techniques of Metals Research, Wiley Interscience (1971)

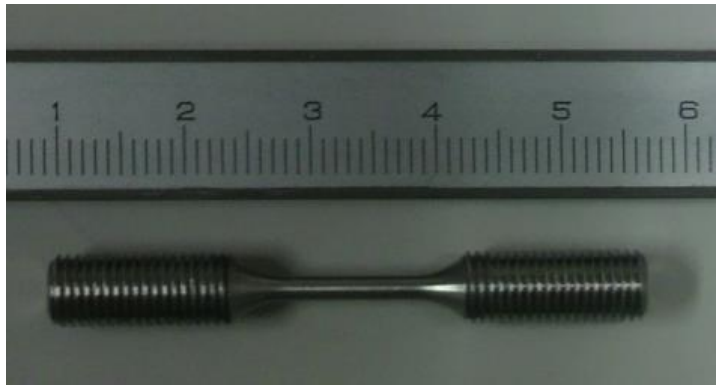
Material and specimen

- Material: F82H (BA07 heat)
  - Chem. Comp.: Fe-8Cr-2W-0.2V-0.04Ta-0.1C
  - Heat Treatment
    - N: 1040C x 40min and 960C x 30min
    - T: 750 C x1 hour
- Specimen:
  - Small round bar (Gauge: 2mmϕ x 10mm)

Courtesy of Dr. Tanigawa,JAEA

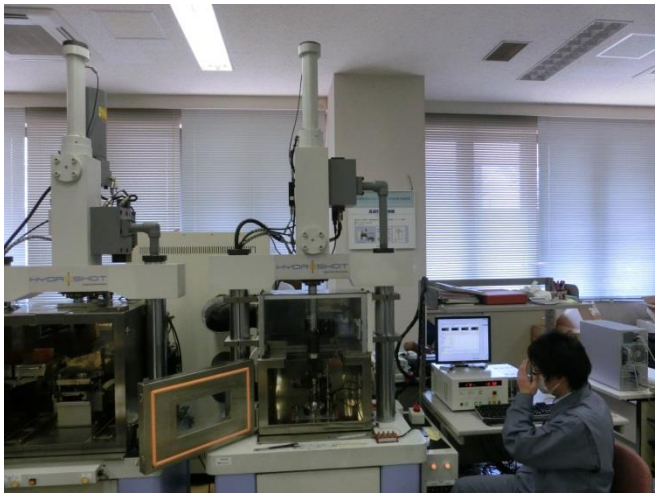


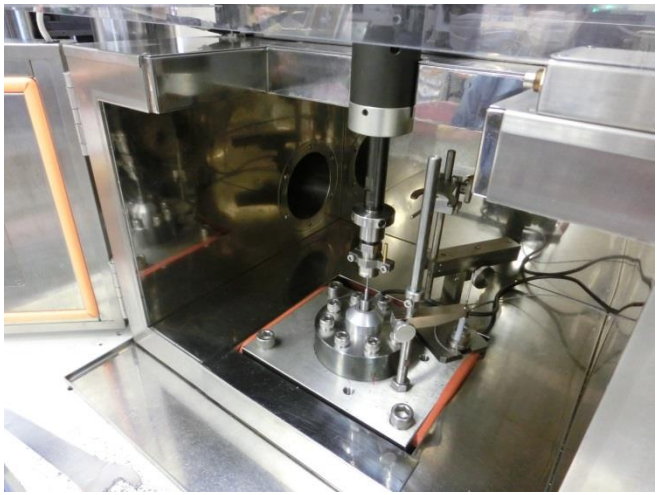
Unit: mm



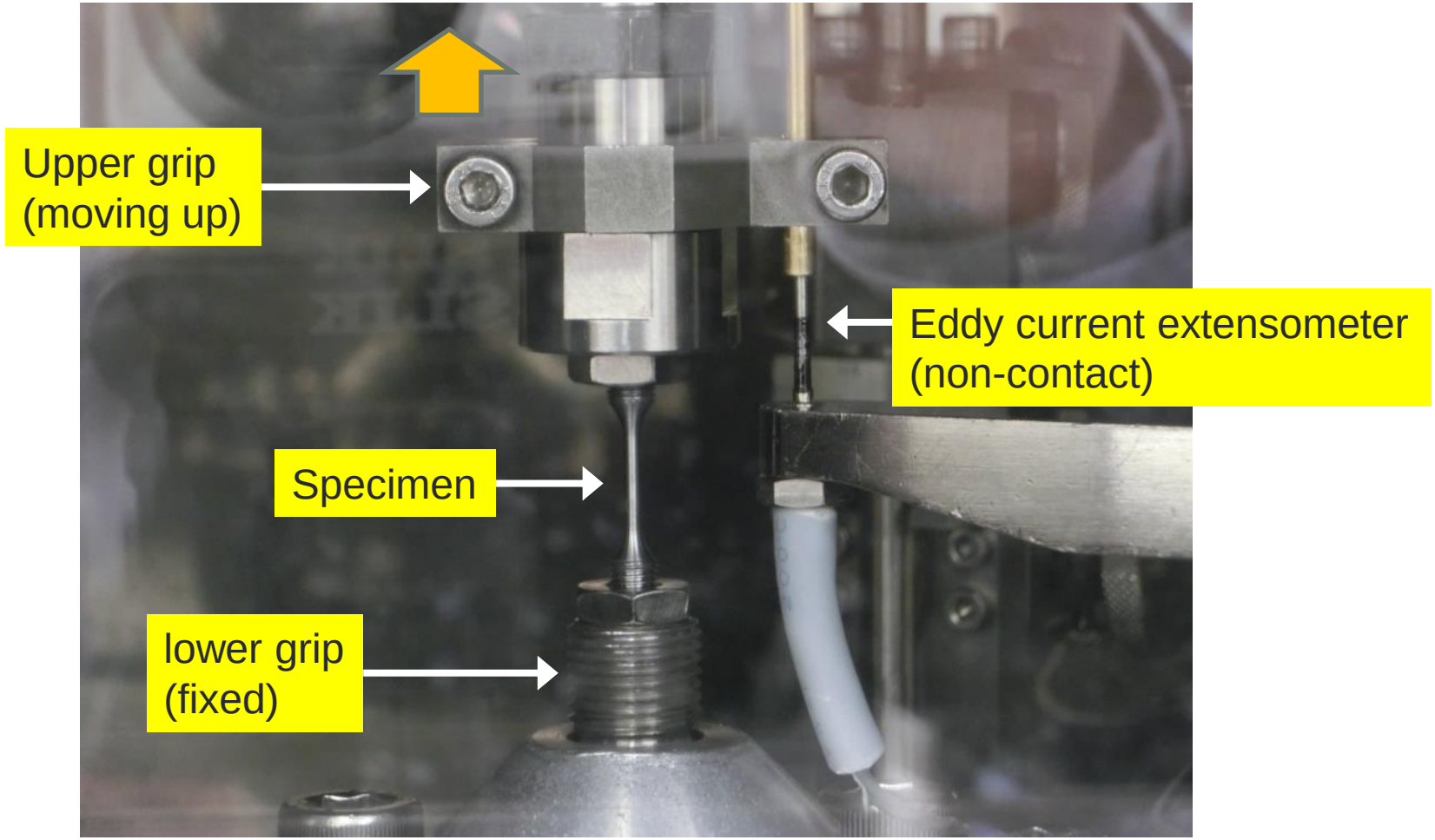
Method: High-speed tensile test

- Hydroshot HITS-T10（SHIMADZU Co.）
  - Hydraulic power supply
  - Force: 10kN
- Head speed (m/s):
  - 14, 1, (0.1), (0.01), 0.0001
  - ※bracket conditions were tested only at 296K.
- Nominal strain rate (/s):
  - 1400, 100, (10), (1), 0.01
- Temperature：296K, 423K



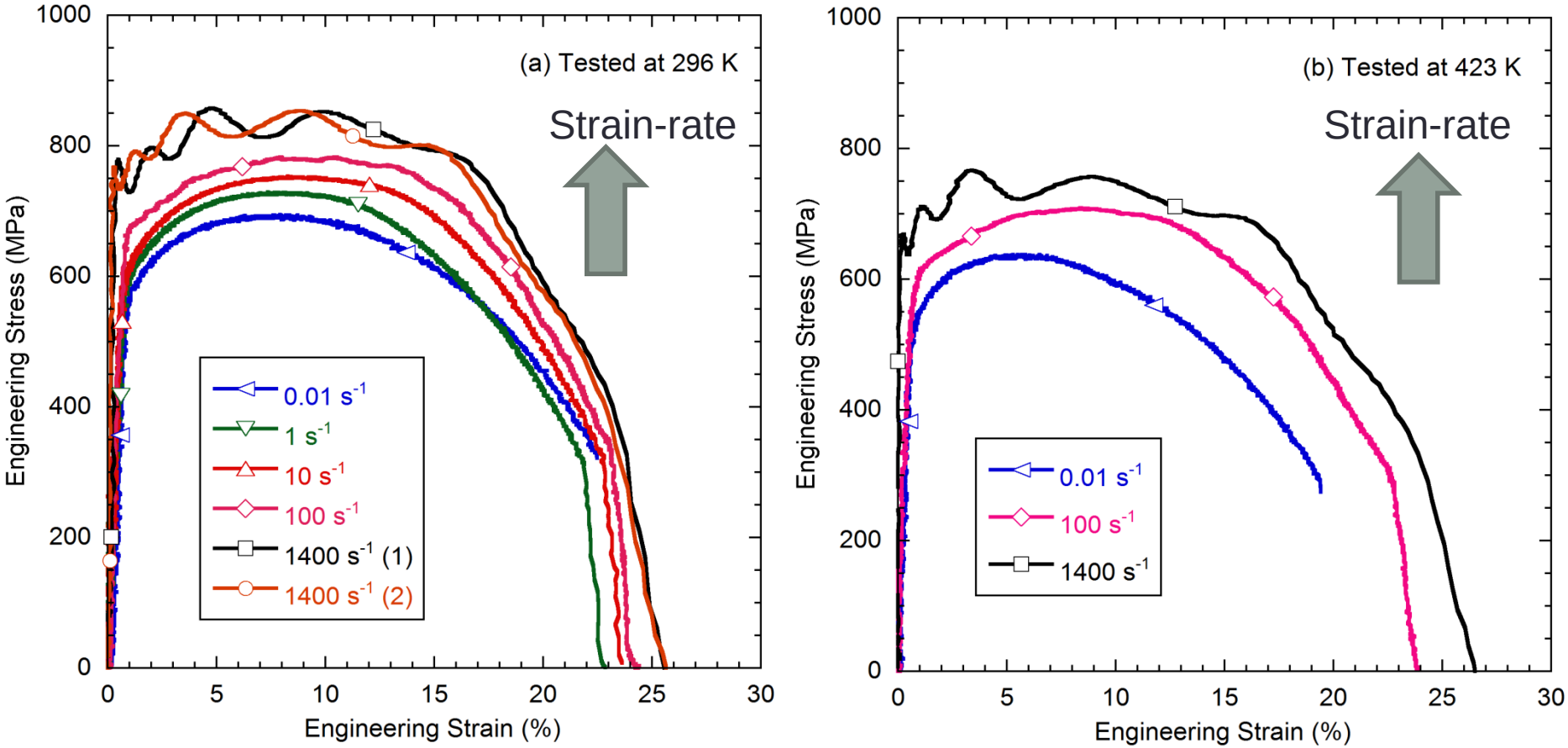


Testing configuration



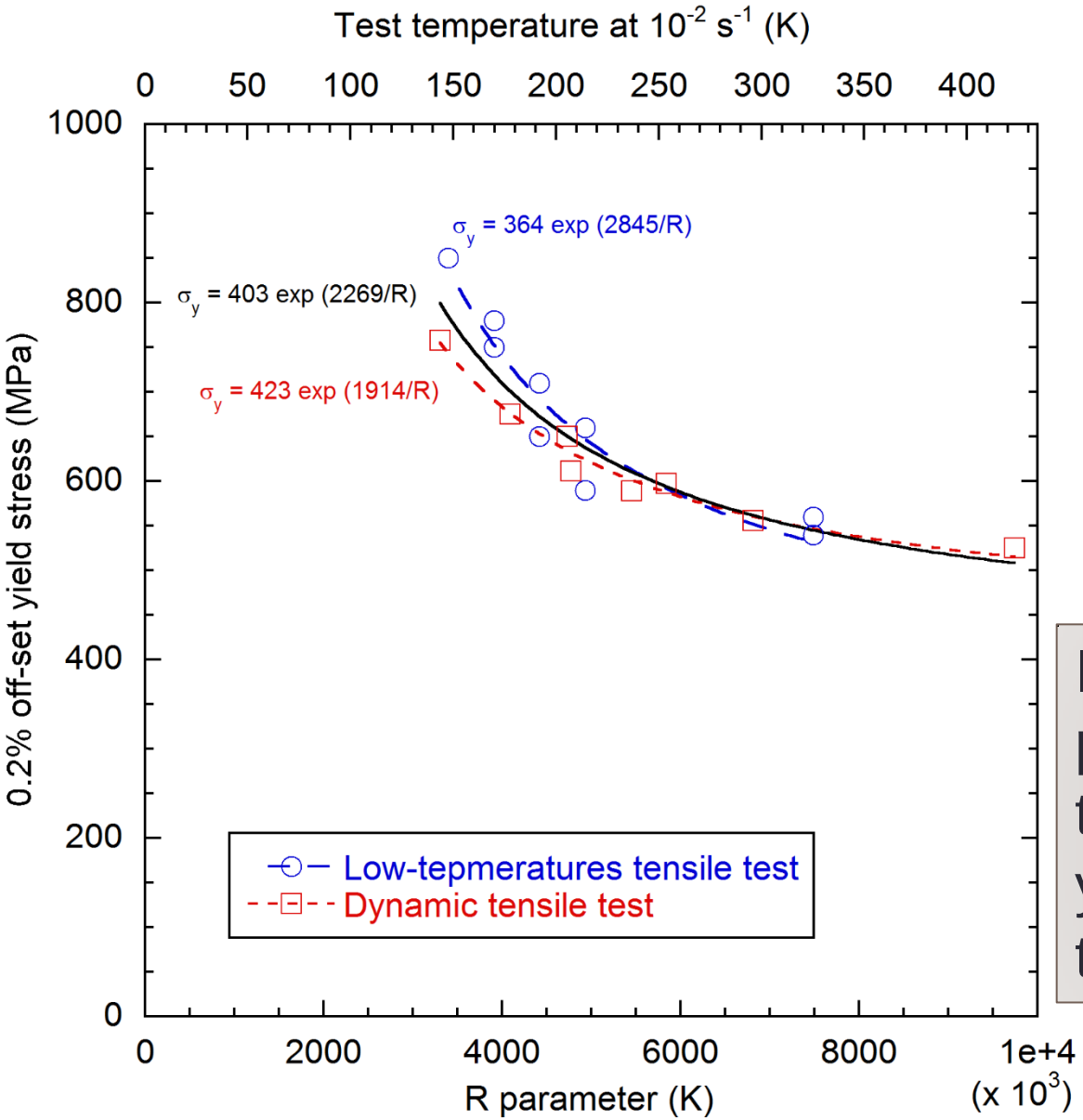
By a conventional (cheap) digital camera(Casio High-speed EXLIM) with 240fps

Strain-rate effect on nominal S-S curves



- Ringing phenomenon was observed in the S-S curves of high-speed tensile test with 1400s^{-1}(14m/s), but reproducible experiments were successfully performed.
- Results shows strain-effect on the both of strength and elongation at 296 and 423K

Strain rate-temperature parameter (R)



$$\sigma_y = \sigma_0 \exp(\alpha / R)$$

$$R = T \ln(\beta / \dot{\varepsilon})$$

β: Material Constant (10^8 s^{-1})

In the low R parameters, dynamic tests resulted in lower yield stress than low temperature tests.

Estimation of specimen temperature raising during high-speed deformation

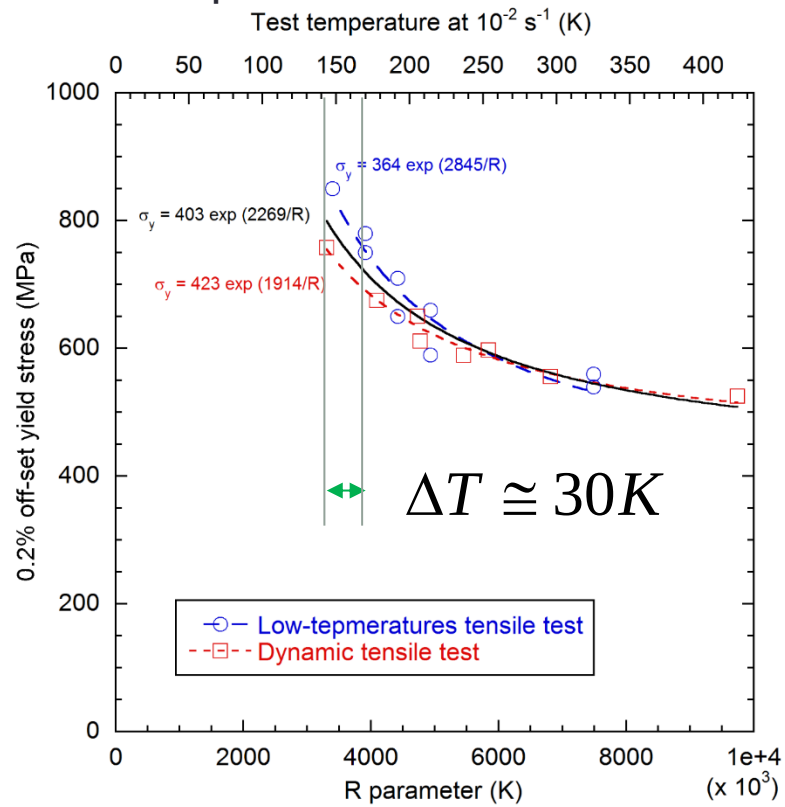
High-speed deformation can be stated as an adiabatic process.

$$\Delta T = \frac{1}{\rho V C_p} \int_0^{\varepsilon_f} \sigma d\varepsilon$$

F82H IEA-heat (by Shiba)
Density, ρ: 7.78 g/cm^3 at 293 K
Specific heat, C_p: 448 J/kg·K at 293 K
494 J/kg·K at 423 K

Deformation energy: 5.7 J for 1400s^{-1} at RT
Gauge section volume, V: 0.0314cm^3

$$\Delta T = 52K$$



Modified R parameter with a consideration of temperature-rising during dynamic tensile tests:

$$R = (T + \Delta T)\ln(\beta / \dot{\varepsilon})$$

Stronger often means more brittle.

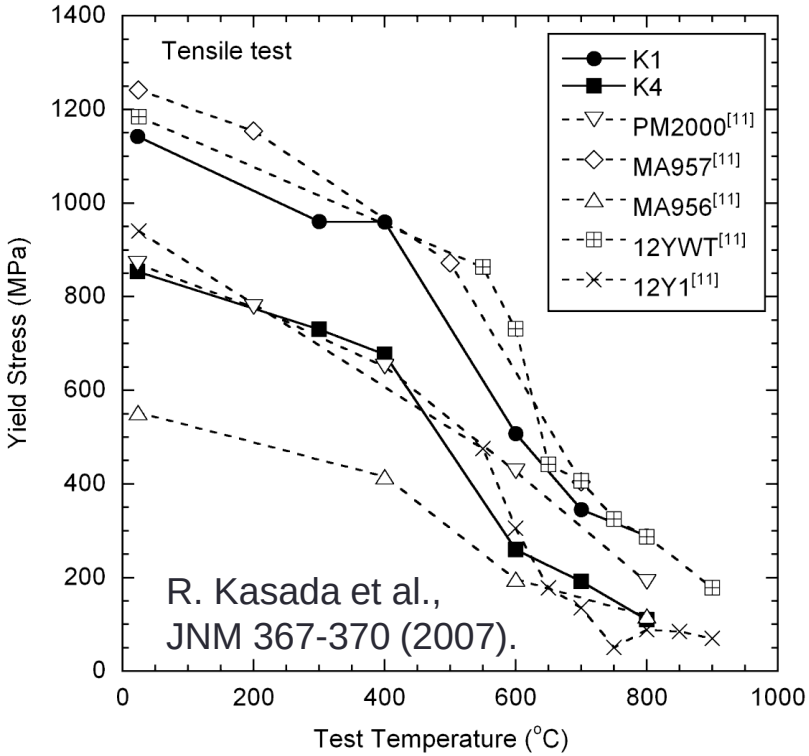


Fig. Tensile yield strength of F82H and ODS-FS

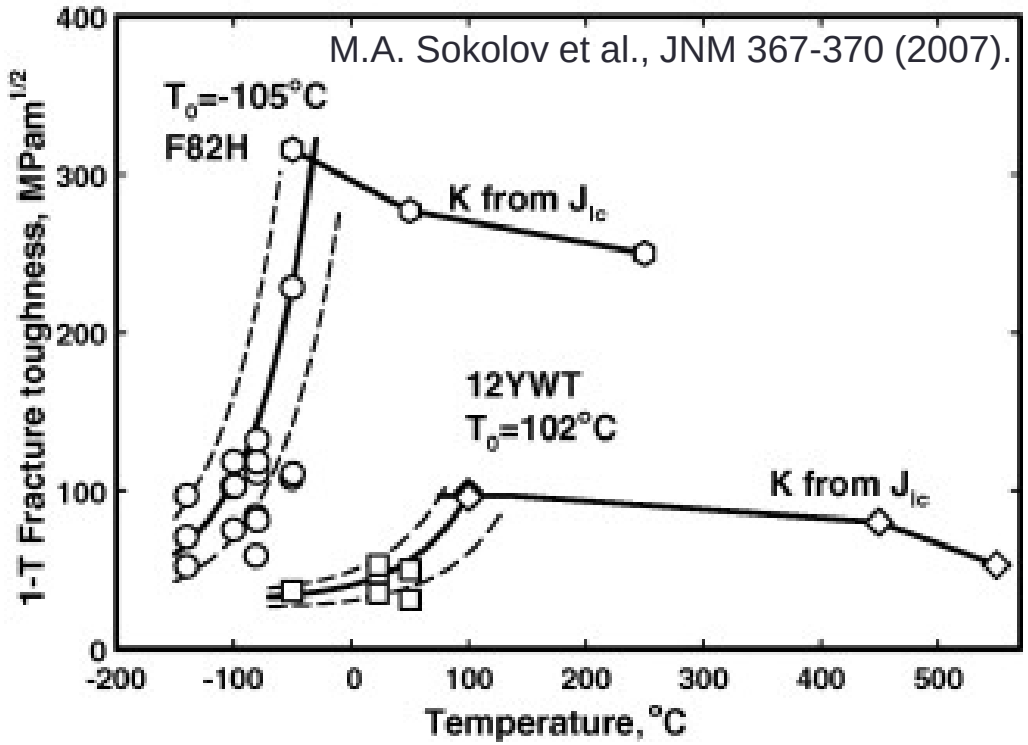


Fig. Fracture toughness of F82H and ODS-FS

<u>Unfortunately, higher strength material has lower fracture toughness.</u>

How can we determine a suitable design criteria for these materials with considering strength and toughness?

Towards structural design for irradiated RAF steels: Failure assessment diagram

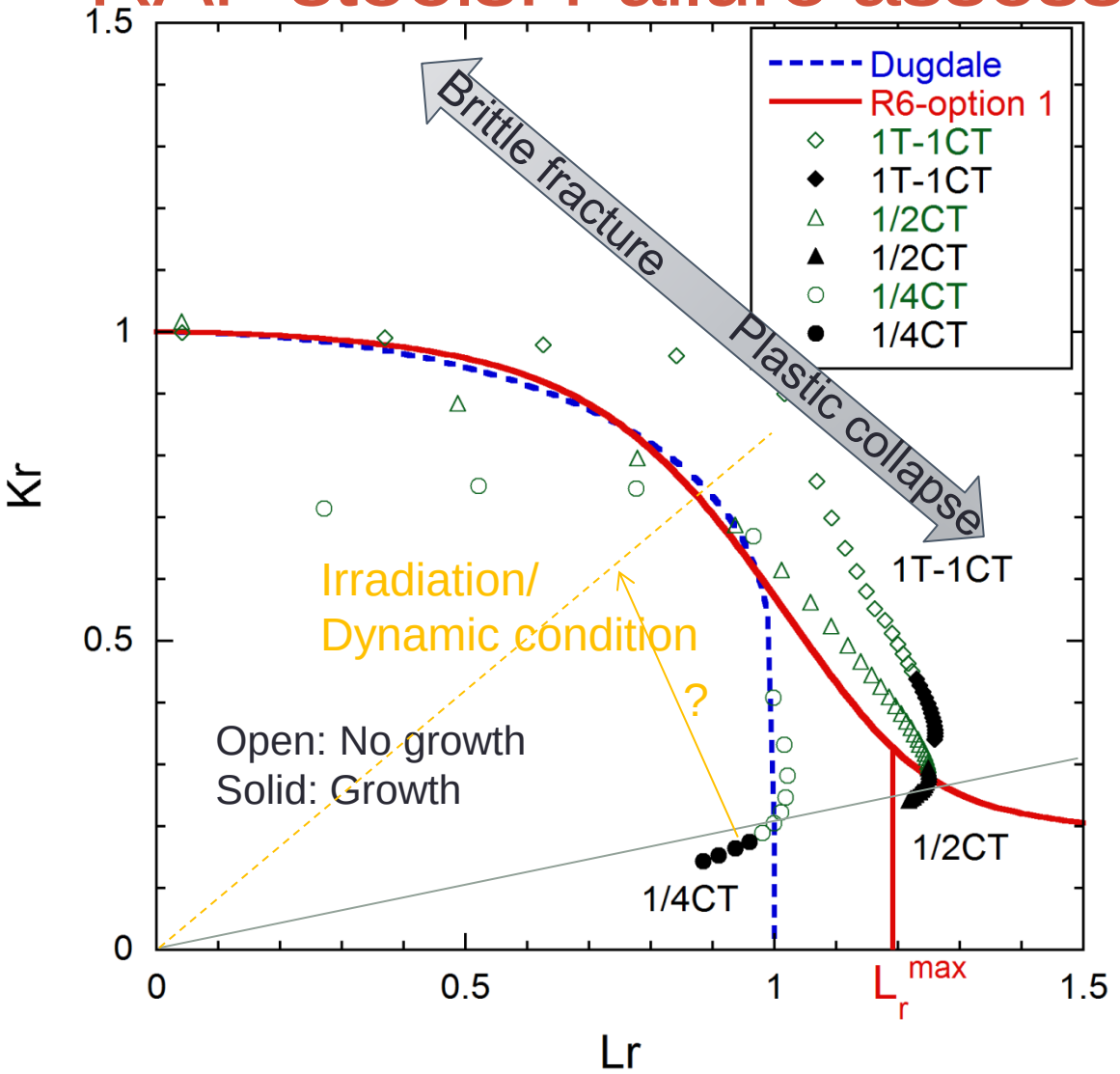


Fig. Failure assessment diagram

- FAD using 2-parameter approach on the elastic-plastic fracture has been used for the recent structural assessment because of its advantages: both of stress intensity factor *K* under small scale yielding (SSY) and stress s under full-yielding (FY) can be simultaneously treated and visualized.
- We've just begin to estimate the FAD on unirradiated F82H at normal condition (and dynamic condition).
- Next targets are n-irradiated one at normal and dynamic conditions.

Conclusion for 2nd content

- We found strain rate dependence of tensile properties of F82H.
  - Higher strength with High SR:
    - Activation volume analysis suggests a change of deformation mechanism.
    - Modified R parameter with considering temperature rising during the high-SR deformation can explain the temperature dependence of the tensile strength with different strain-rates.
  - Higher uniform elongation with high SR
  - Similar true fracture strain among strain rates.
- Future studies:
  - Investigate deformation mechanism under high strain rate
  - Dynamic fracture toughness of F82H
  - Strain-rate effect on neutron-irradiated materials
  - Establish failure assessment for highly-irradiated (embrittlement) RAF steels

Thank you for your attention.

Faster is Stronger, but probably more brittle!

ITER/LEGO, Oct. 2013, made by myself

Severe accident occurred during train-transportation by my students!