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NU_Html Nuclear & High Temperature Materials Laboratory

Effect of Recrystallization on Fatigue Crack Growth Characteristics of a Pure Tungsten

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Contents

[1] B.S. Kong et al., Materials 13(1) (2020) 244
[2] M. Li et al., Fusion Eng Des. 113 (2016) 162-170
[3] M. Li et al., Fusion Eng Des. 124 (2017) 468-472

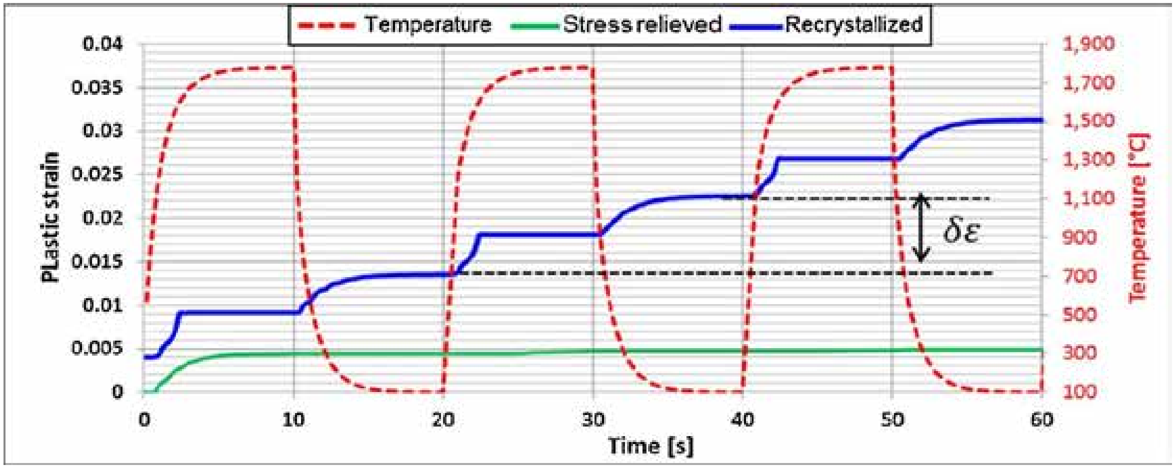
Plasma facing material (PFM) in fusion reactors

Characteristics of tungsten considered as PFM

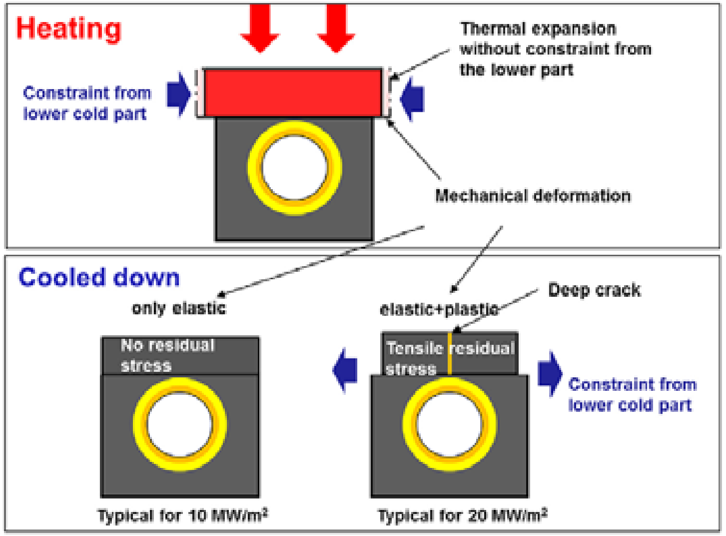
- High melting point, high thermal conductivity, and low tritium retention [1]
- Inherent low fracture toughness, high DBTT and low Recrystallization temperature

Thermal fatigue of PFM armor under high-heat flux (HHF)

- Tungsten(W) exposed to HHF in-service reactor [2]
- PFM exhibits high temperature gradient due to HHF cycles and coolant pipe ⇒ **Thermal fatigue**
- Fatigue crack generated by thermal fatigue [3]



▲ A schematic representing the temperature history of tungsten armor under HHF cycles [2]



▲ A schematic of the deep crack mechanism of tungsten armor under HHF cycles [3]

Introduction – Recrystallization

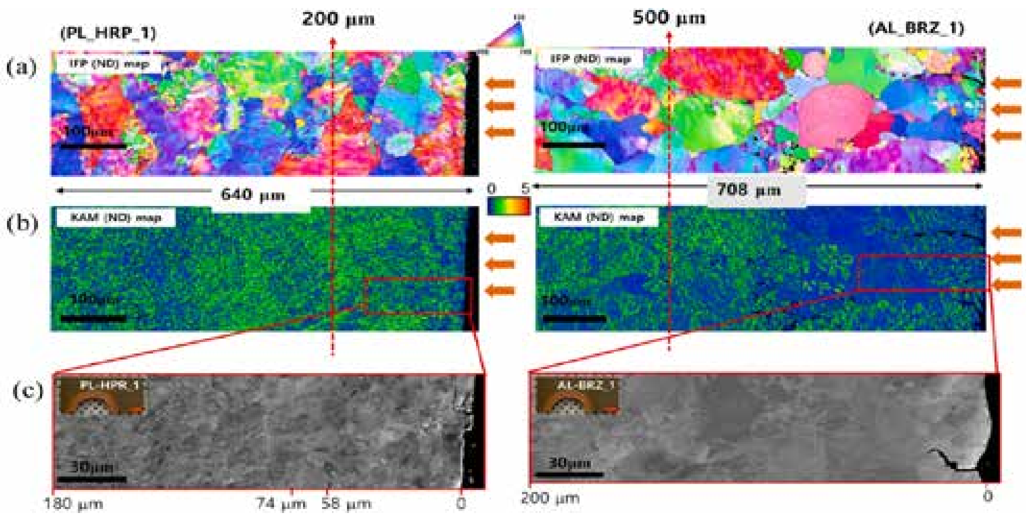
[4] H.C. Kim et al., Fusion Eng. Des. 170 (2021) 112530
[5] S. panayotis et al., Fusion Eng. Des. 125 (2017) 256-262
[6] G. Pintsuk et al., Fusion Eng. Des. 98-99 (2015) 1384-1388

Plasma facing material (PFM) in fusion reactors

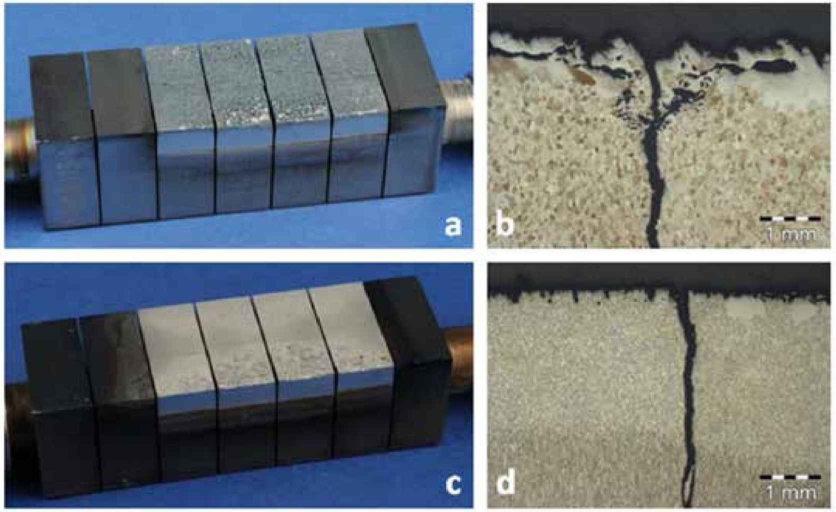
Recrystallization effect of heat flux facing surface of PFM

- **H.C. Kim et al., Fusion Eng. Des. 170 (2021) 112530**
  - Apply HHF test at 10 MW/m^2 up to 5,000 cycles, **recrystallization phenomena is observed [4]**
  - Decreasing yield strength due to recrystallization may promote fatigue crack [5]
- **G. Pintsuk et al., Fusion Eng. Des. 98-99 (2015) 1384-1388**
  - Apply HHF test at 20 MW/m^2 up to 1,000 cycles, **macro-crack is observed [4]**
  - Deep cracks propage in brittle mode to the W/Cu interface

⇒ Evaluation of fatigue crack growth on tungsten is crucial



▲ Microstructure profile of the HHF tested plansee and ALMT W in the surface region [4]



▲ Macro-crack image created on tungsten mock-up and surface exposured to HHF [6]

Research Objective

Evaluation of Recrystallization Effect on Fatigue Crack Growth Characteristics of a Pure Tungsten

Evaluation of J-integral Property considering strain-rate and Rx

➕

EBSD analyses for investigating evolution of microstructure

Ø **Evaluation of High Temperature Mechanical Properties of Pure Tungsten for Integrity of ITER Divertor**

Experimental

[1] B.S. Kong et al., Materials 13(1) (2020) 244

v Test Material : A.L.M.T Tungsten (W)

Ø IQ + IPF map

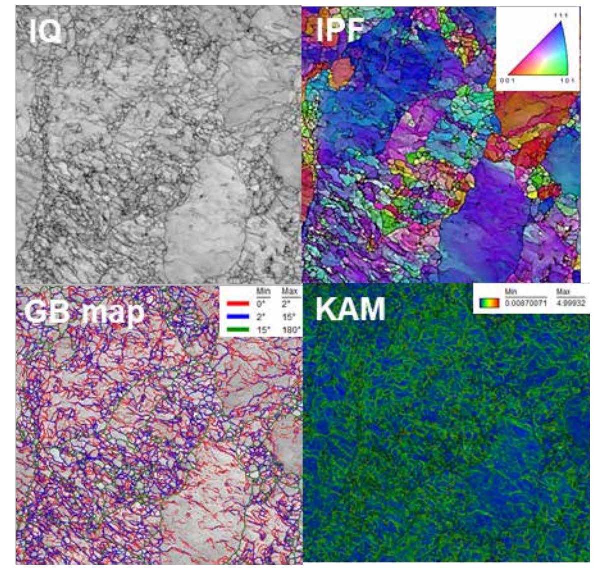
- Sub-grain structure within large grains (∵ TMP)

Ø Grain Misorientation map

- LAGB Fraction (~ 80%)
- HAGB Fraction (~ 20%)

Ø KAM map

- Deformation energy is homogeneously distributed



▲ **The EBSD results of A.L.M.T tungsten; (a) IQ, (b) IPF, (c) GB maps, and (d) KAM**

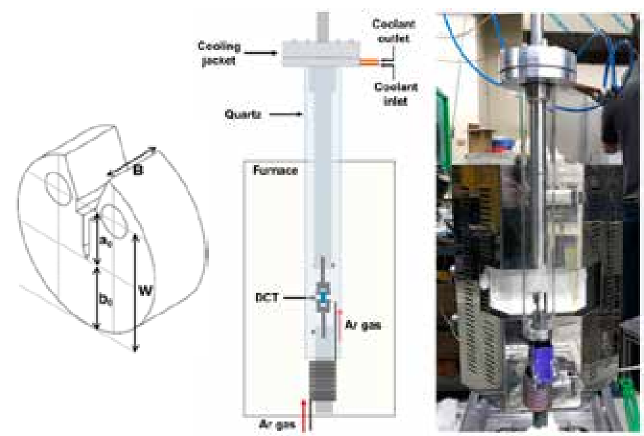
v Test Specimen & Facility

Ø Smaller disc compact (DCT) specimen

- Specimen geometry : a_0 = 2.7 mm, b_0 = 3.3 mm, B = 1.5 mm
  - ü **Complied with general proportions of ASTM-E399 & E1820**
- Notch direction perpendicular to the longitudinal direction
- **Notch root radius of the machined notch : ~ 70 μm**

Ø Test facility set-up in Ar environment

- To prevent excessive oxidation in high temperature
  - **Ar gas was injected into the quartz (Flow rate: 2K cc / min.)**



▲ **The Schematics of specimen and facility [1]**

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[2] M. Li et al., Fusion Eng Des. 113 (2016) 162-170
[3] M. Li et al., Fusion Eng Des. 124 (2017) 468-472

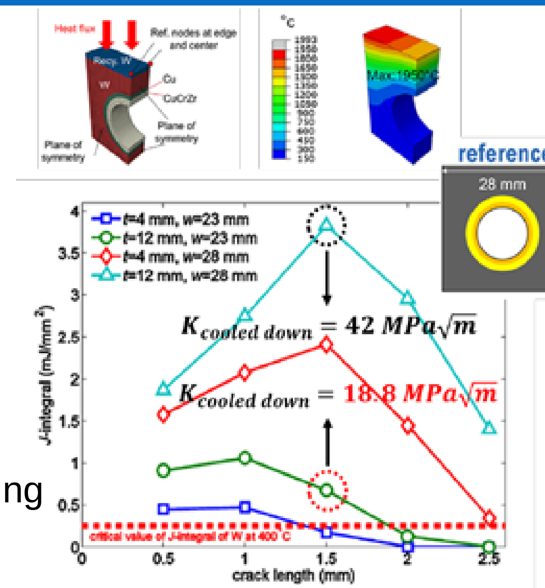
Fatigue Crack Growth Rate Test Procedure

Refer to simulation data assuming crack [2,3]

- $\Delta K = K_{max} - K_{min}$ = ~ 20MPam$^{1/2}$, R = 0.1, **($\dot{\varepsilon}$ = 3.0 x 10^{-2} s^{-1})**
- Perform K-increasing FCGR test **(P_{max}=250 N)**

Fatigue pre-crack process at elevated temperature

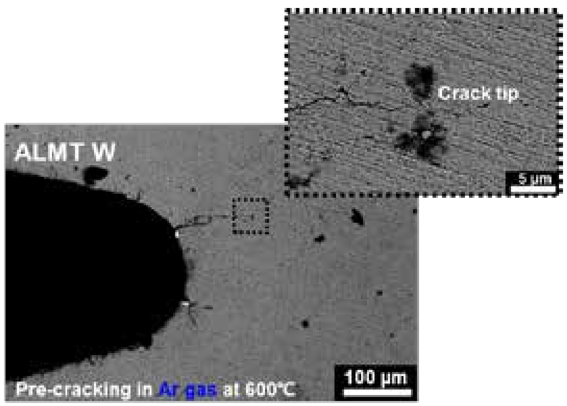
- Considering inherent brittleness (At higher than DBTT)
- Introducing pre-crack in Ar environment through tensile cyclic loading
  - Sharp pre-crack without oxides **(Notch root radius~0.2 μm)**



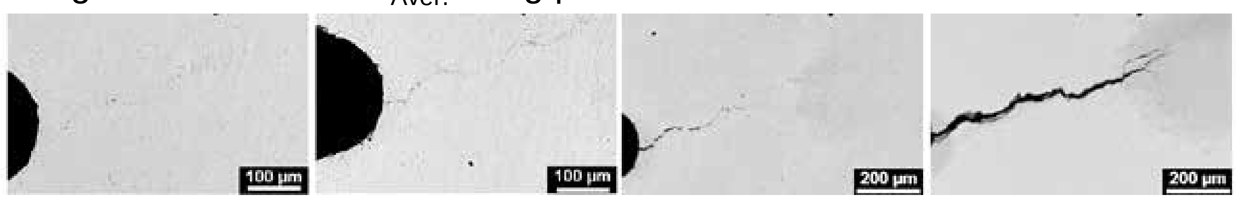
▲ J-integral values at the tip of a crack initiated at the armor surface [2,3]

Calculating the da/dN and ΔK values

- Measuring crack length using SEM (∵ Difficulty using DCPD and COD)
- Plot the graph after calculating the da/dN and $\Delta k_{Aver.}$ using parameters



▲ The morphology of fatigue pre-cracks



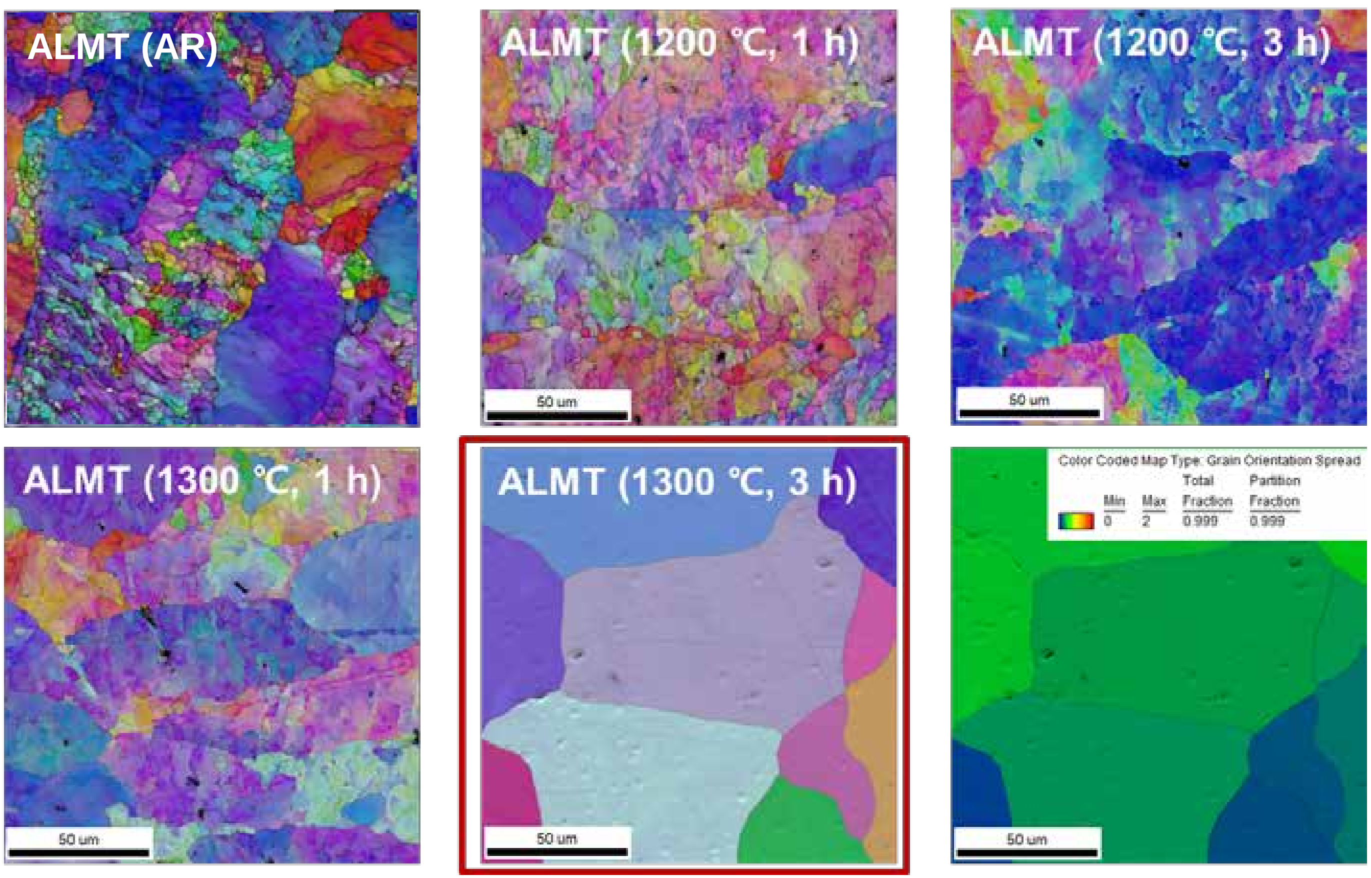
crack length (mm)	Crack length + notch	α = a/W (>0.2 valid)	Geometry constant	da/dN [m]	da/dN [mm]	del K (Average)
0.21	2.91	0.49	9.71	6E-06	6E-09	18.81
0.24	2.94	0.49	9.86	3.1E-05	3.1E-08	19.09
0.33	3.03	0.51	10.36	9.3E-05	9.3E-08	20.07
0.45	3.15	0.53	11.07	1.2E-04	1.2E-07	21.44
0.62	3.32	0.55	12.18	1.7E-04	1.7E-07	23.58
0.89	3.59	0.60	14.42	2.7E-04	2.72E-07	27.92

▲ Procedure of calculating the da/dN and $\Delta K_{Aver.}$

Results – Recrystallization condition

Recrystallization condition of ALMT W

- **Heat treatment trials for finding recrystallization condition**
- **EBSD results of ALMT W (1300℃, 3 h)**
  - Grain Orientation Spread (0°~2°) : Fully recrystallized W



▲ **Procedure of calculating the da/dN and ΔK**

Results – Tensile results

Tensile test results of pure tungsten

Tensile results of As-Received W

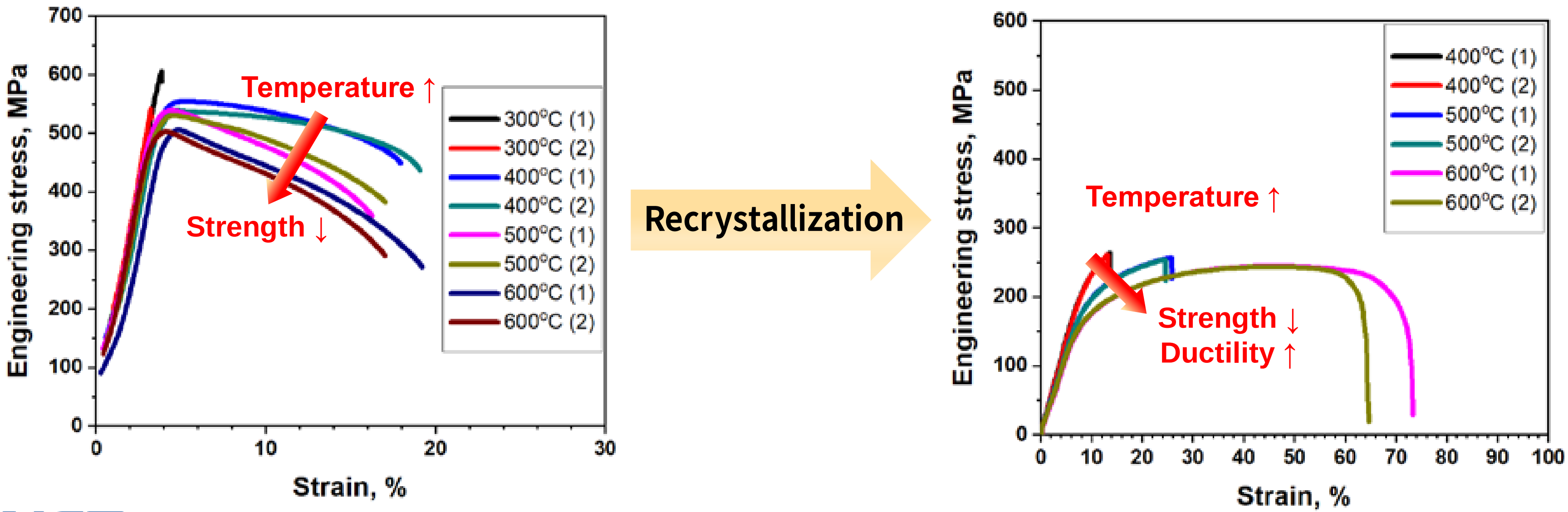
- Strength is decreased with increasing temperature
- Brittle behavior is observed below 300 ℃

Tensile results of Recrystallized W

- As temperature is increased, strength is decreased and elongation is significantly increased
- Brittle behavior is observed below 500 ℃

⇒ Using tensile results for evaluation of J-integral property and FCGR characteristics

<ALMT W> **<RXed ALMT W>**



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Results – FCGR characteristics

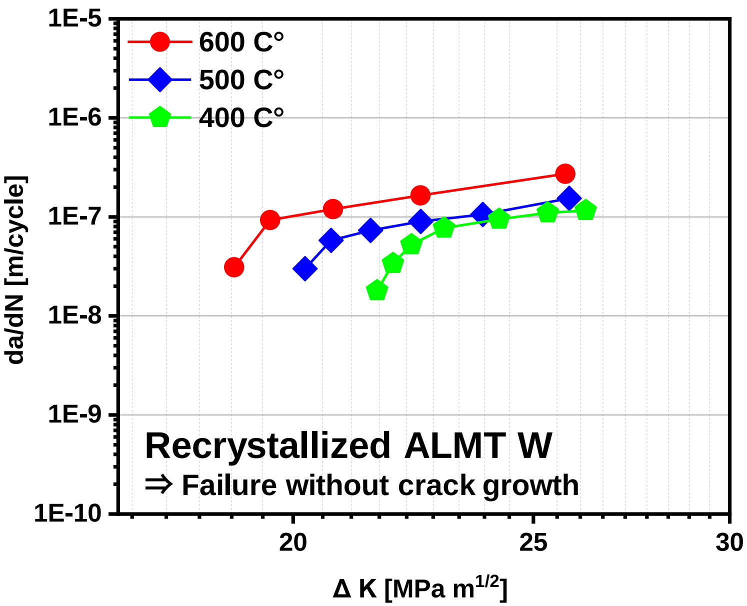
FCGR Test results

Plot the da/dN-ΔK curve using measuring crack length

- FCGR tests are conducted at elevated temperatures
  - **At 400 – 600 ℃**
  - **As temperature is increased, FCGR characteristic is decreased**
  - **All Recrystallized ALMT W is brittly fractured**

Calculating the parameters of Paris's law

- These constants were determined by curve fitting



▲ da/dN-ΔK graph of ALMT W

$$\text{Paris's Law}: \frac{da}{dN} = C \cdot \Delta K^{m}$$

Condition	Temperature	C	m
As-Received ALMT	600 ℃	1.25×10^{-12}	3.78
	500 ℃	7.71×10^{-12}	3.01
	400 ℃	3.98×10^{-11}	2.42
RXed ALMT	600 ℃	-	-
	500 ℃	-	-

▲ Procedure of calculating the da/dN and ΔK

Fractography of FCGRed Test specimen

As-Received ALMT W

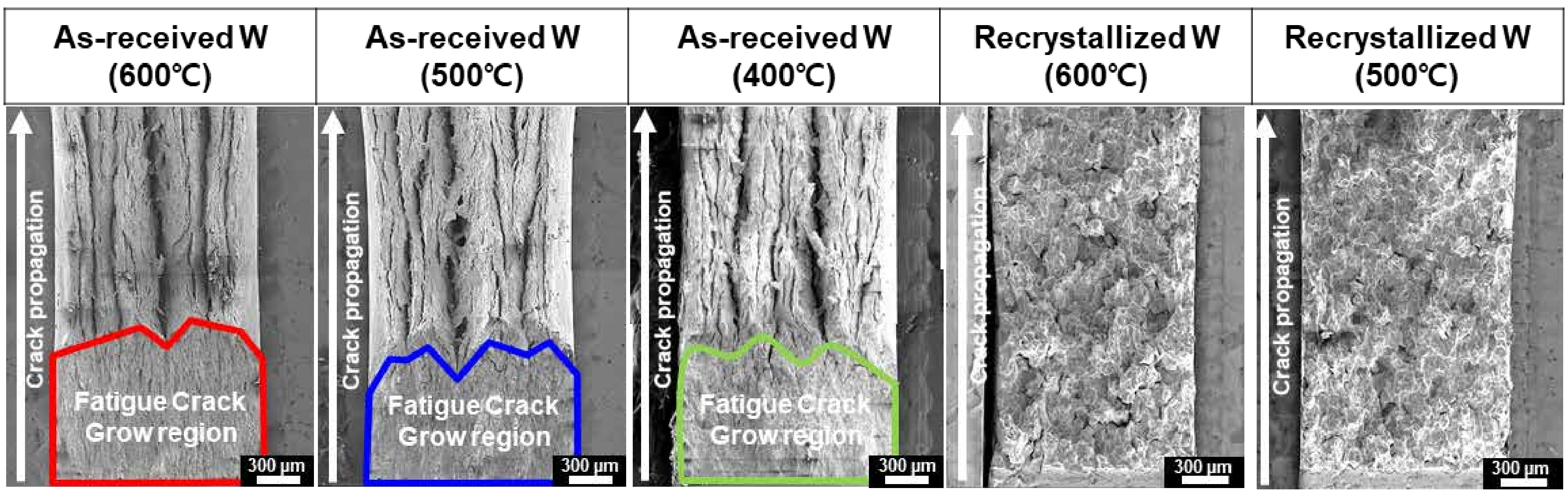
- Fatigue crack growth regions were observed
- Calculate K_{max} value using Fatigue crack growth region of As-Received ALMT W

Recrystallized ALMT W

- Intergranular failure without fatigue crack growth

<Estimated value>

$* K_{max., 600℃}$ = 29.5 MPa·$m^{1/2}$ $* K_{max., 500℃}$ = 28.6 MPa·$m^{1/2}$ $* K_{max., 400℃}$ = 27.3 MPa·$m^{1/2}$



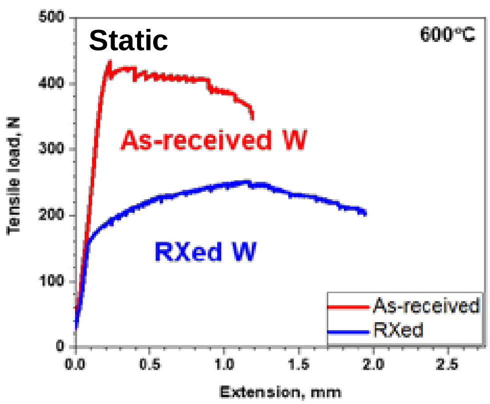
▲ SEM fractography of as-received and recrystallized ALMT W

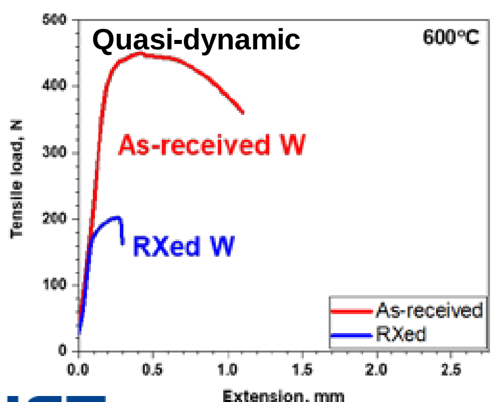
Results – Effect of Strain-rate in J-integral property

Effect of Strain-rate in J-integral property

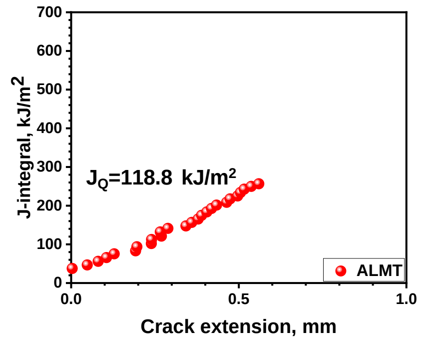
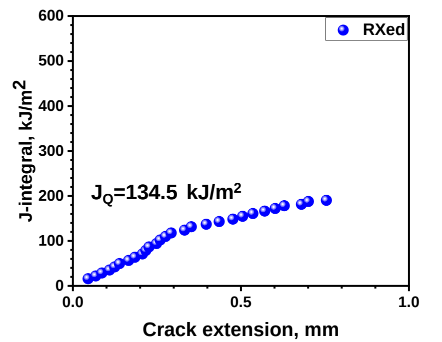
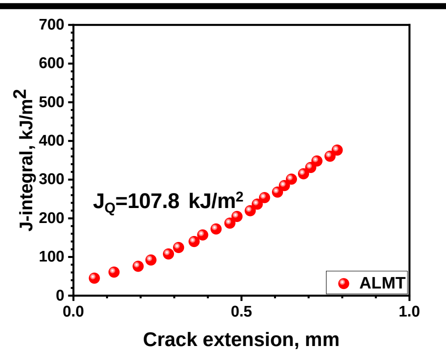
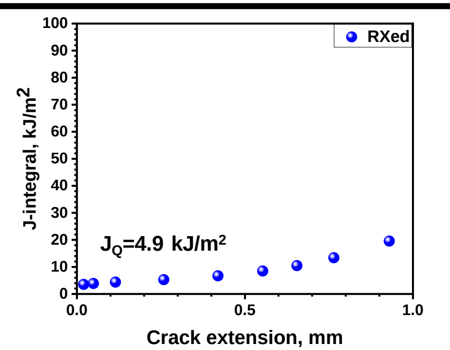
- **Static condition (1.33 x 10^{-4} s^{-1})**
  - Similar J-integral properties
- **Quasi-dynamic condition (5.30 x 10^{-2} s^{-1})**
  - J-integral property of Recrystallized W is significantly decreased

▼ **Load-Extension curve at 600 ℃**





▼ **J-integral curve at 600 ℃**

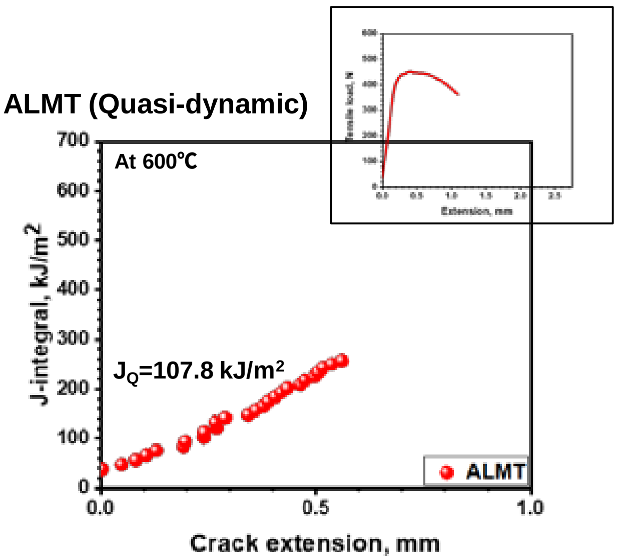
600℃	As-Received ALMT	RXed ALMT
Static		
Quasi dynamic		

Effect of Temperature in J-integral property (High strain rate)

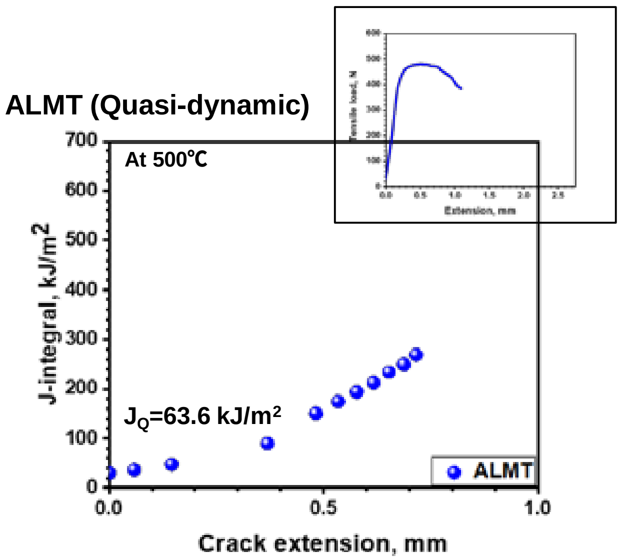
High strain rate condition (5.30 x 10^{-2} s^{-1})

- 600℃
  - **J_Q=107.8 kJ/m^2**
- 500℃
  - **J_Q=63.6 kJ/m^2**
- 400℃
  - **J_Q=48.9 kJ/m^2**

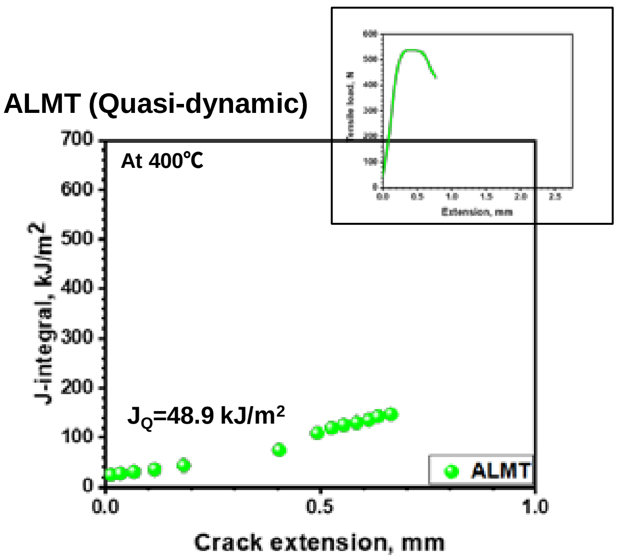
⇒ As temperature is decreased, J-integral property is decreased



▲ J-integral curve at 600℃



▲ J-integral curve at 500℃

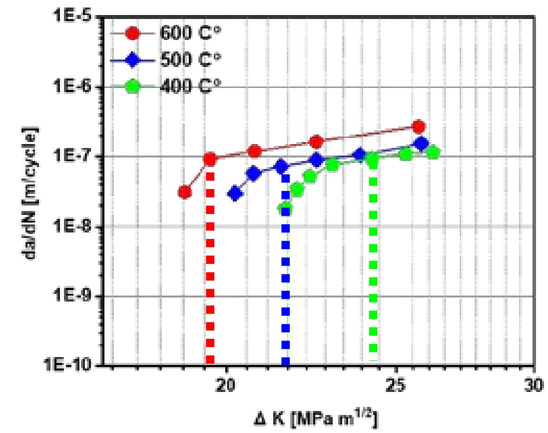


▲ J-integral curve at 400℃

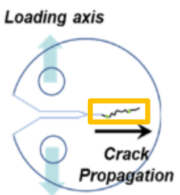
Results – Effect of Temperature FCGR chracteristics

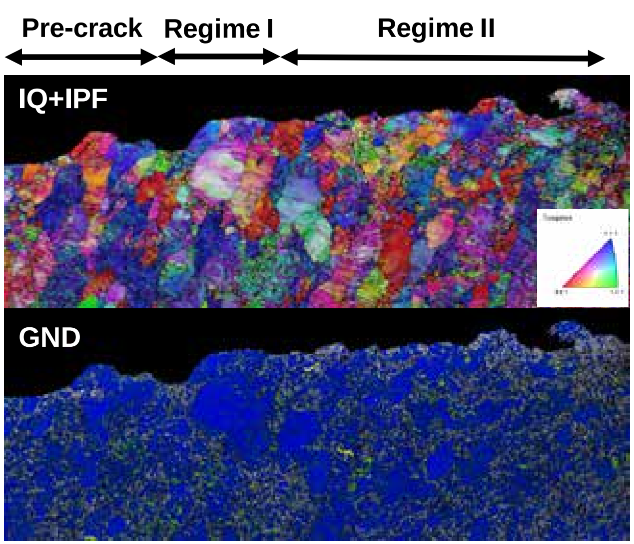
Effect of Temperature in FCGR chracteristics

- **Considering the starting point of regime B**
  - Referring the da/dN – ΔK graph
    - 600℃ (~ 334 μm), 500℃ (~ 494 μm), and 400℃ (~ 710 μm)
- **EBSD results of FCGRed specimens**
  - Compared to graph, starting points of regime B are similar
  - **Dynamic recrystallization is observed through EBSD result**
    - As temperature is increased, DRX is increased
    - As temperature is decreased, starting point of regime B moves away

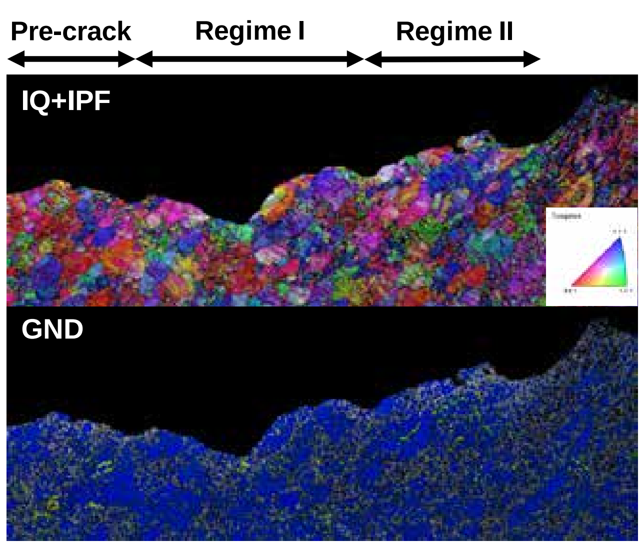


▲ da/dN-ΔK graph of ALMT W

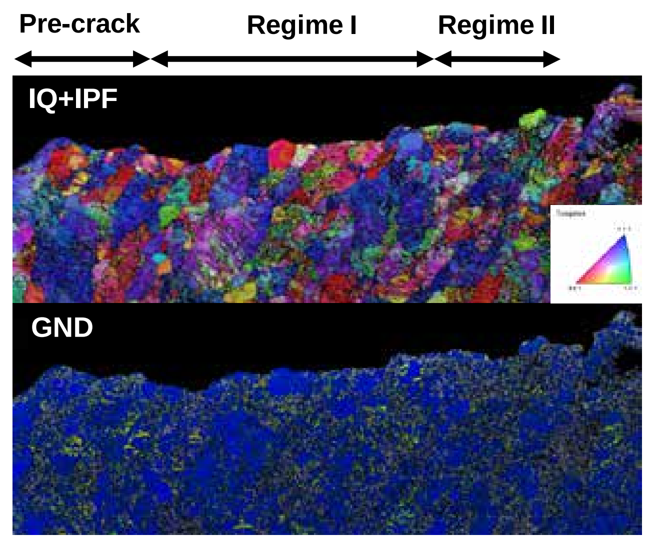




▲ EBSD results of FCGR test at 600 ℃



▲ EBSD results of FCGR test at 500 ℃



▲ EBSD results of FCGR test at 400 ℃

Energy for Earth !!

Thank you!

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