

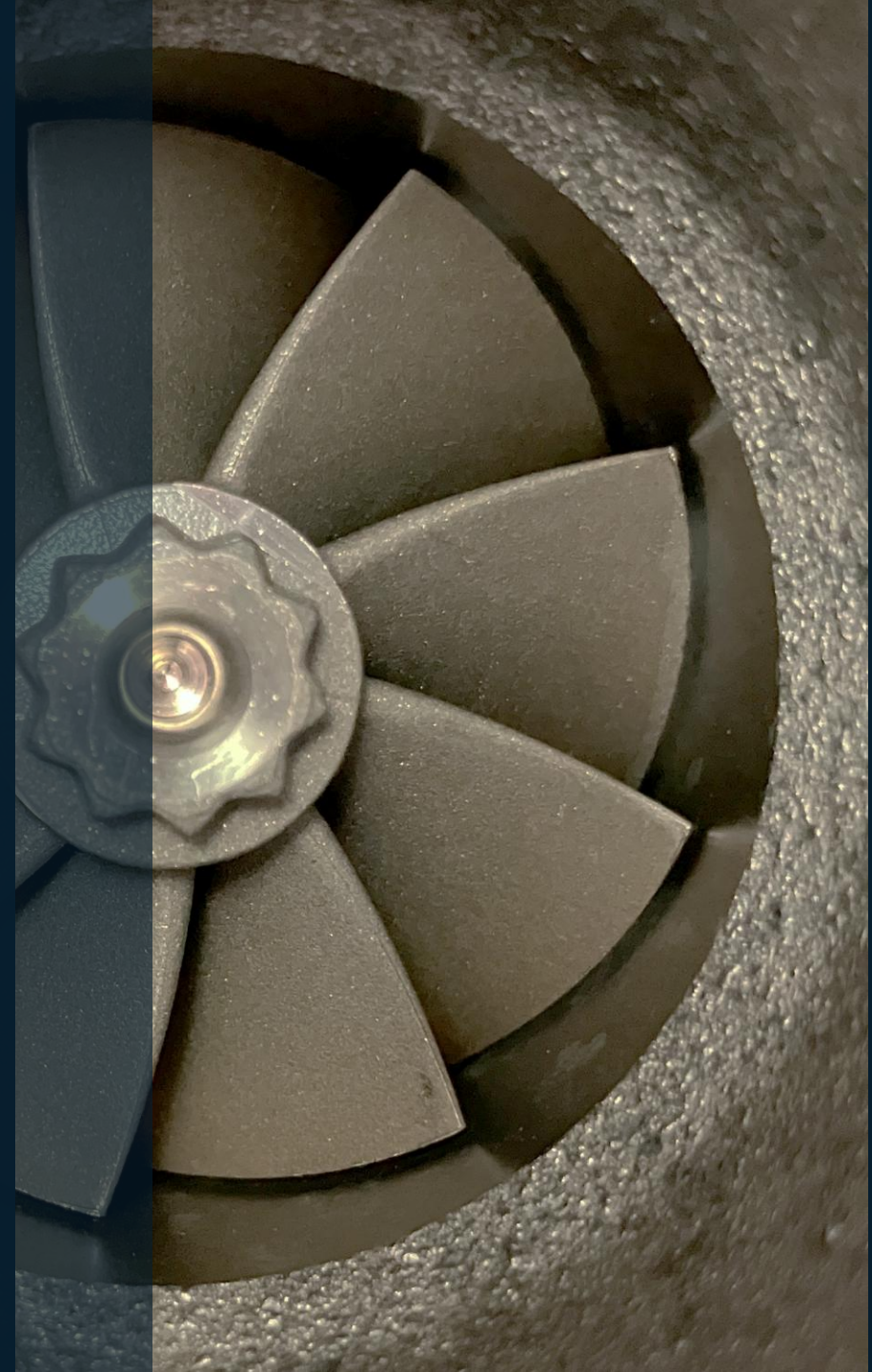
Improved Creep Life Prediction of Turbocharger Turbine Wheels

Using Measured Operating Temperature and Grain Size Effects

Akihiro Asano
Toyota Motor Corporation

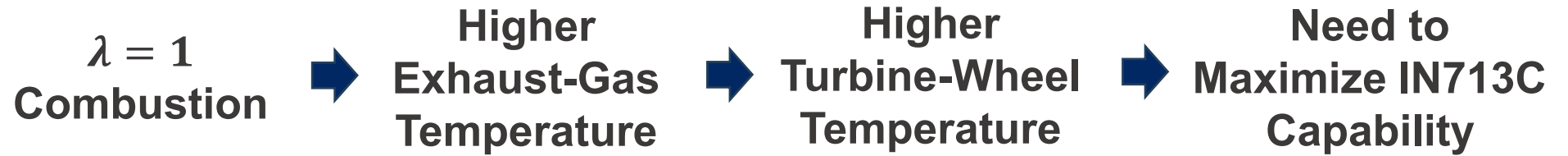
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TOYOTA



1	Introduction
2	Turbocharger Configuration and Target Component
3	Life Design Procedure
4	Temperature Distribution Prediction
5	Development of a Grain-Size-Dependent Creep Model
6	Life Prediction, Failure Validation and Design Guidelines
7	Conclusion

Background



Challenge

**Mismatch Between
CAE Prediction and
Actual Creep Failure**

- Failure life mismatch
- Failure location mismatch

Possible Cause

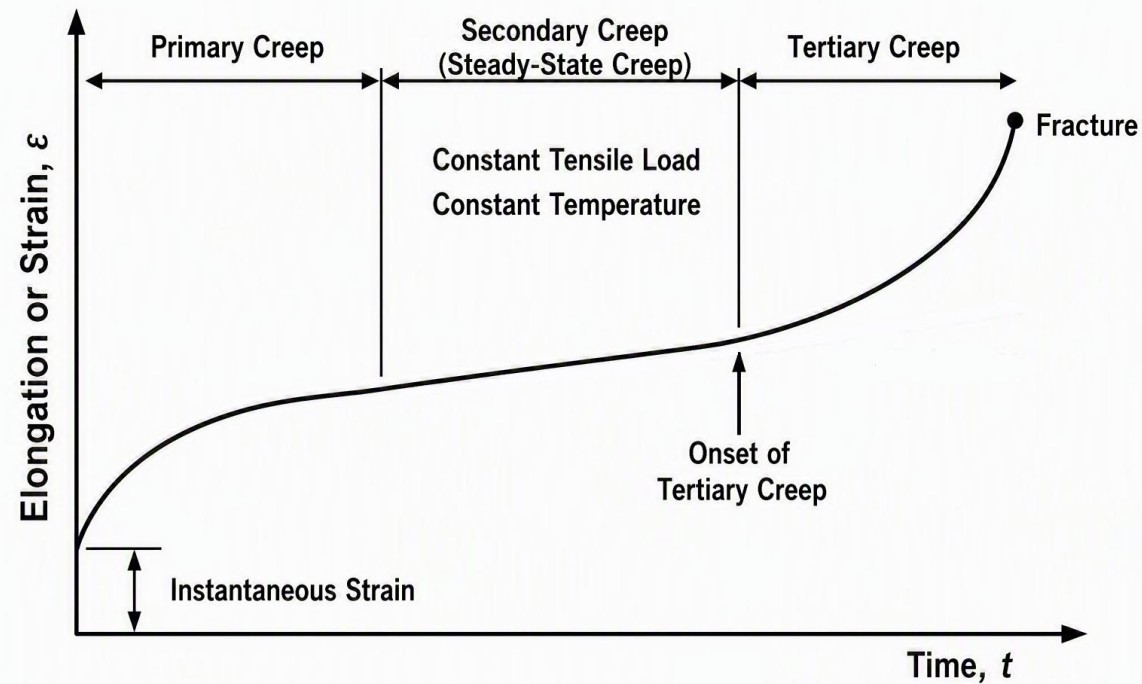
- Temperature prediction errors
- Grain-size effects not considered

Objective

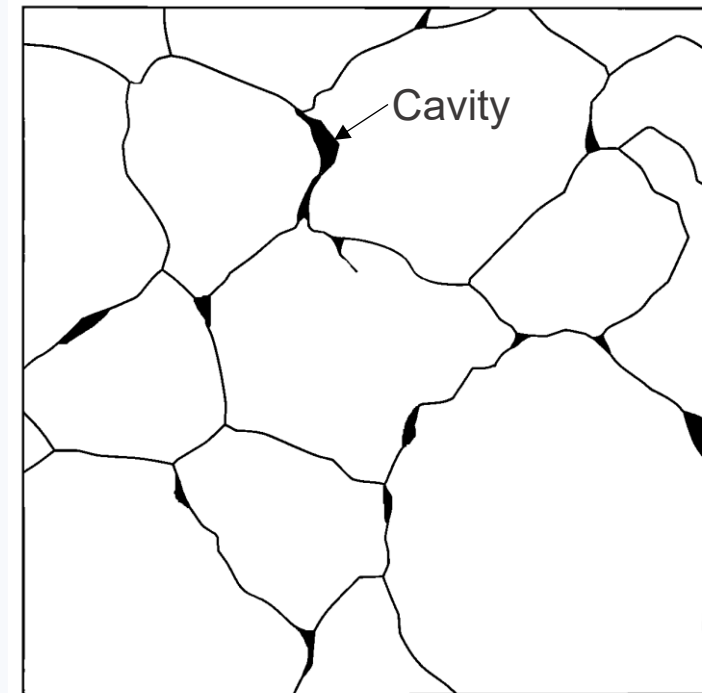
**Develop a creep-life prediction model
for future high-temperature turbine-wheel design**

What is Creep?

- Time-dependent increase in strain under high temperature and stress
- Grain-boundary cavity growth leads to fracture
- Fine grains show higher creep rates and shorter creep life



Creep Curve
Creep deformation behavior



Grain-boundary cavity formation and growth

2. Turbocharger Configuration and Target Component

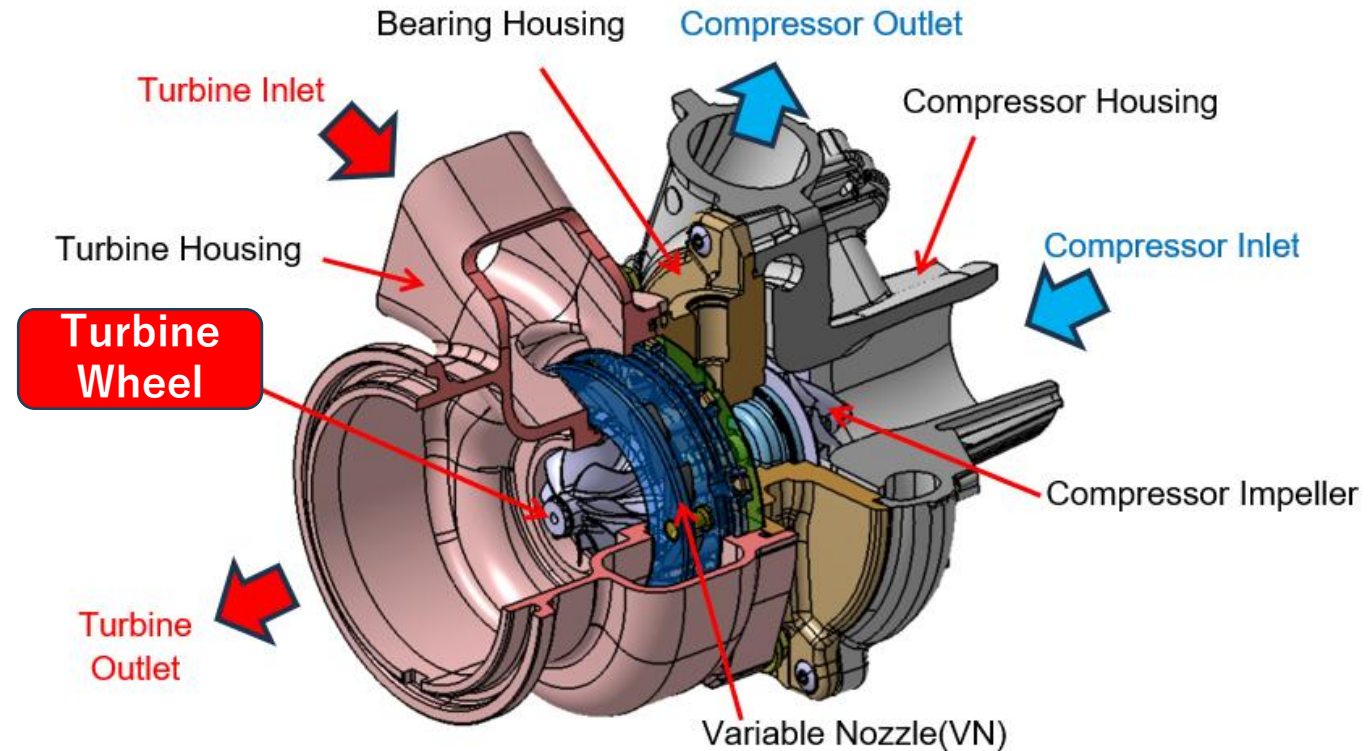
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Turbocharger:

Recovers exhaust-gas energy through the turbine and boosts intake air with the compressor to increase engine power.

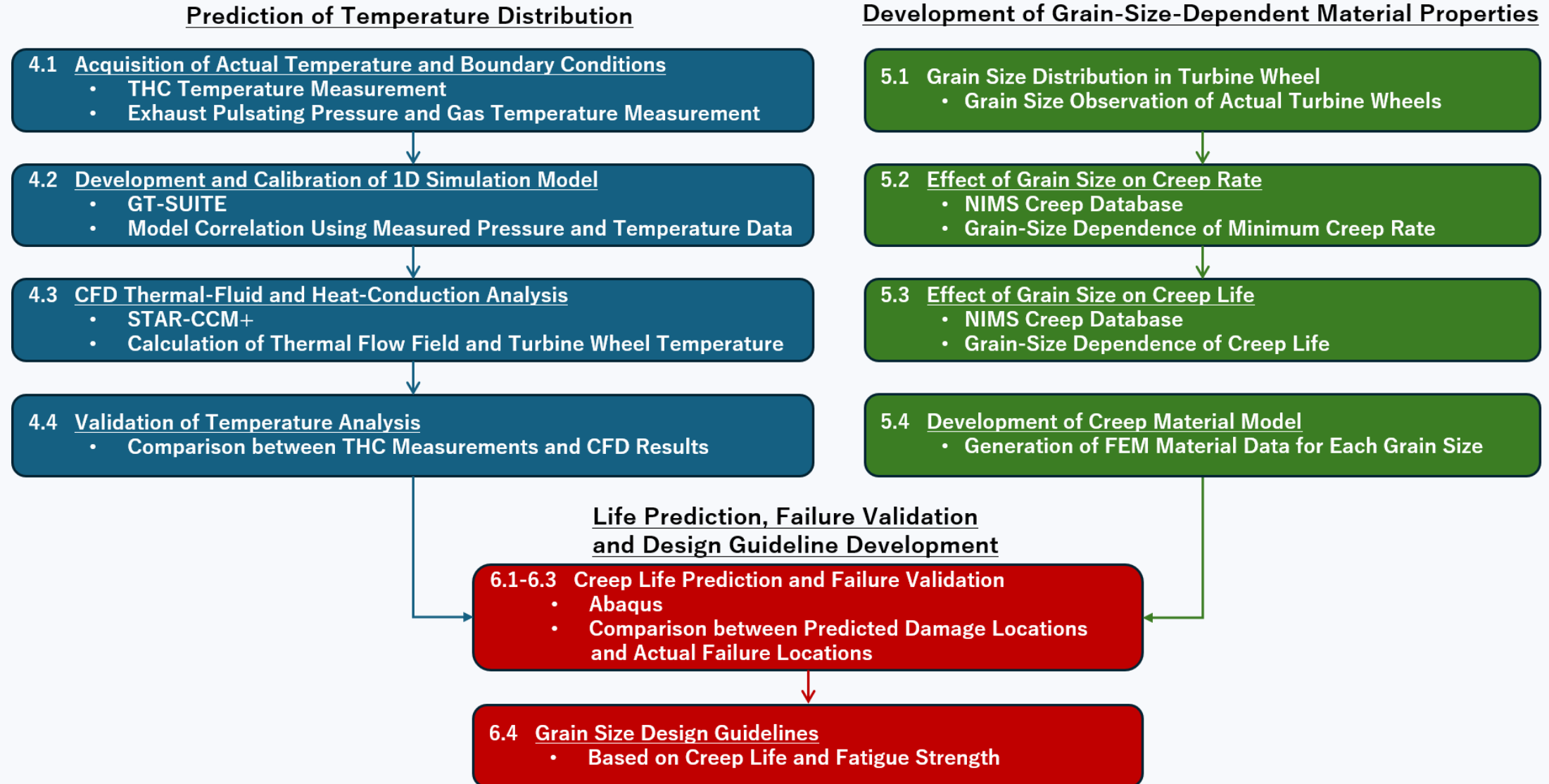
Turbine Wheel:

A high-speed rotating component subjected to high centrifugal stress and elevated temperatures. Therefore, creep durability is critical.



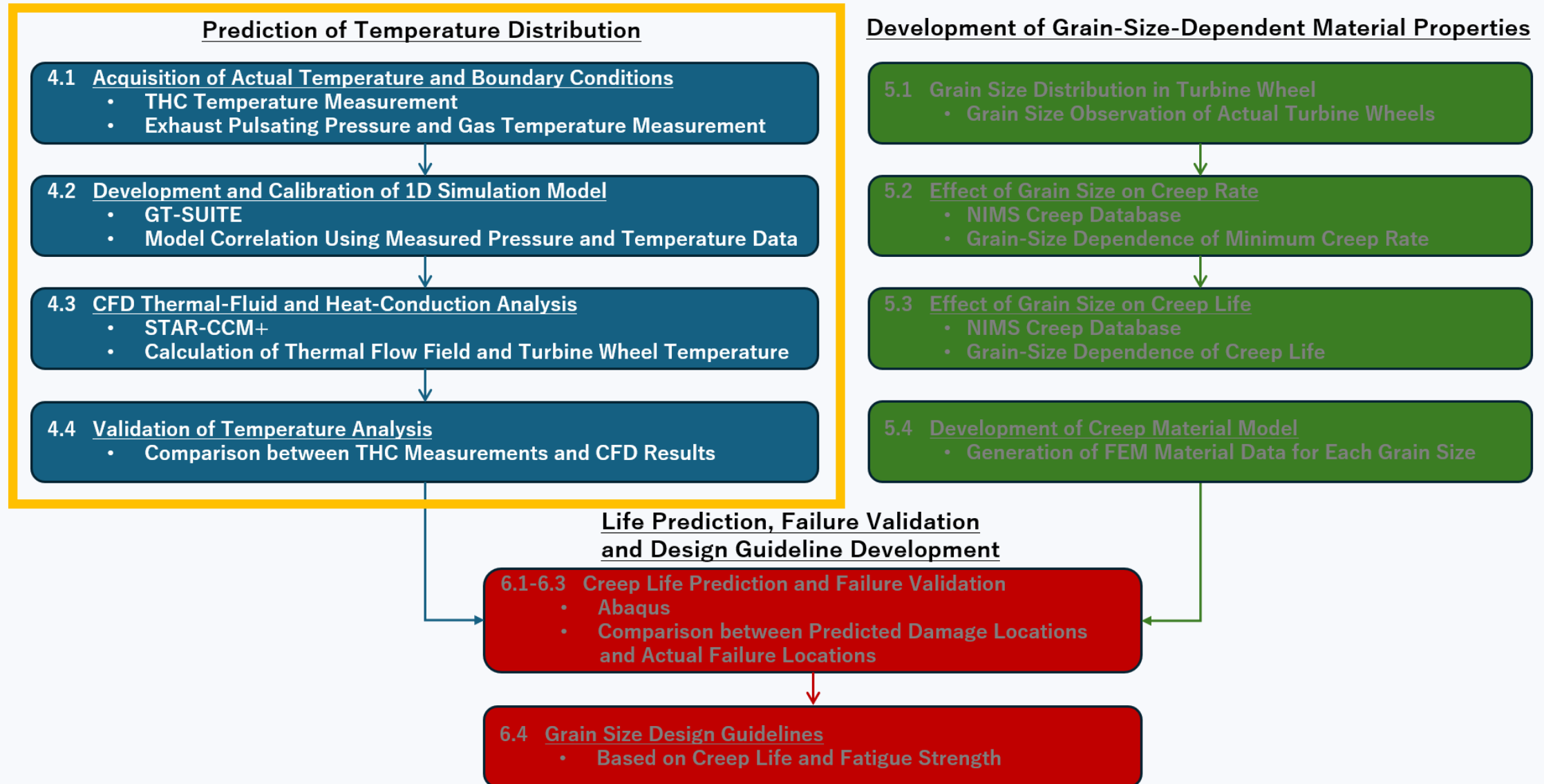
3. Life Design Procedure

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4. Temperature Distribution Prediction

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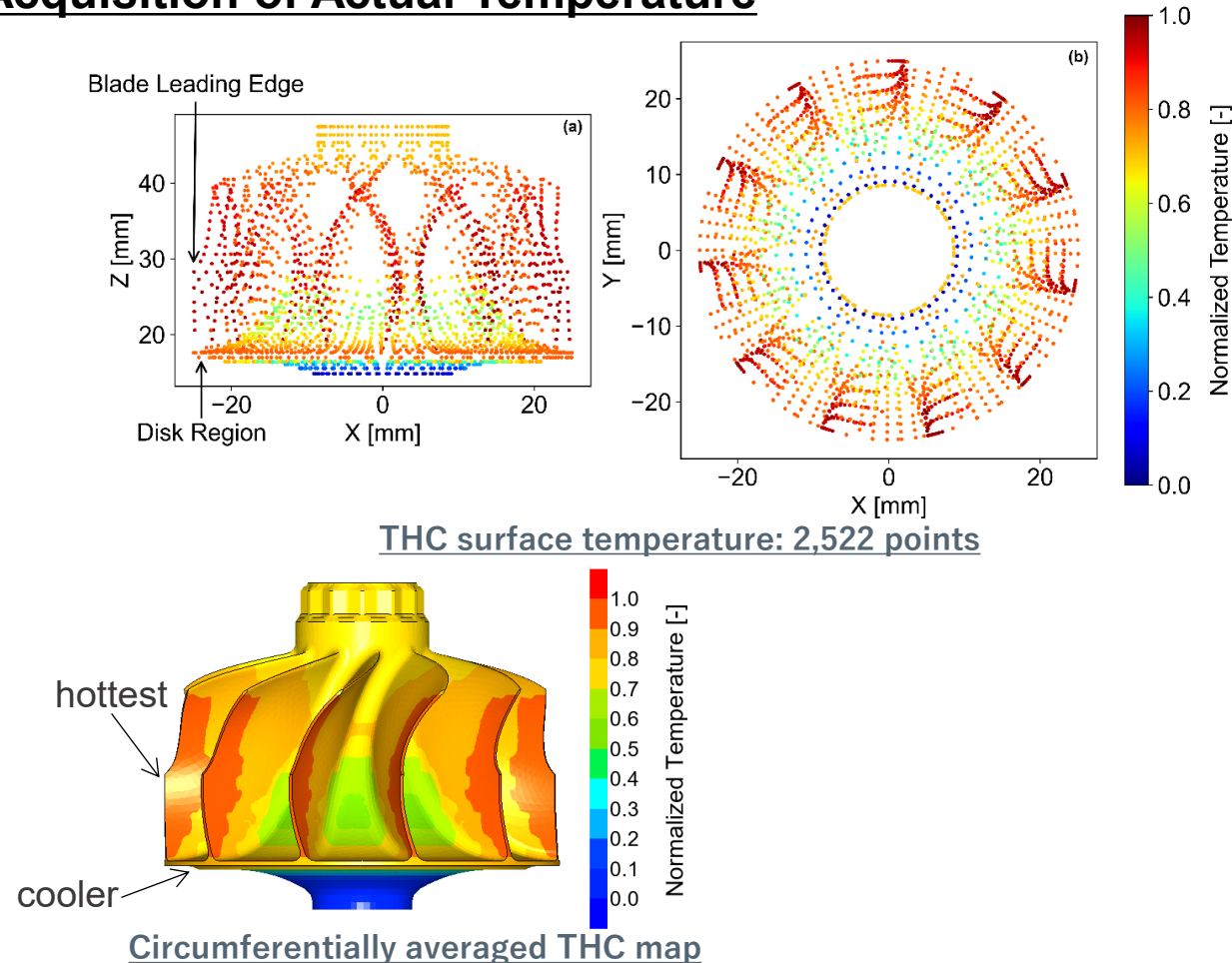


4.1. Acquisition of Actual Temperature and Boundary Conditions

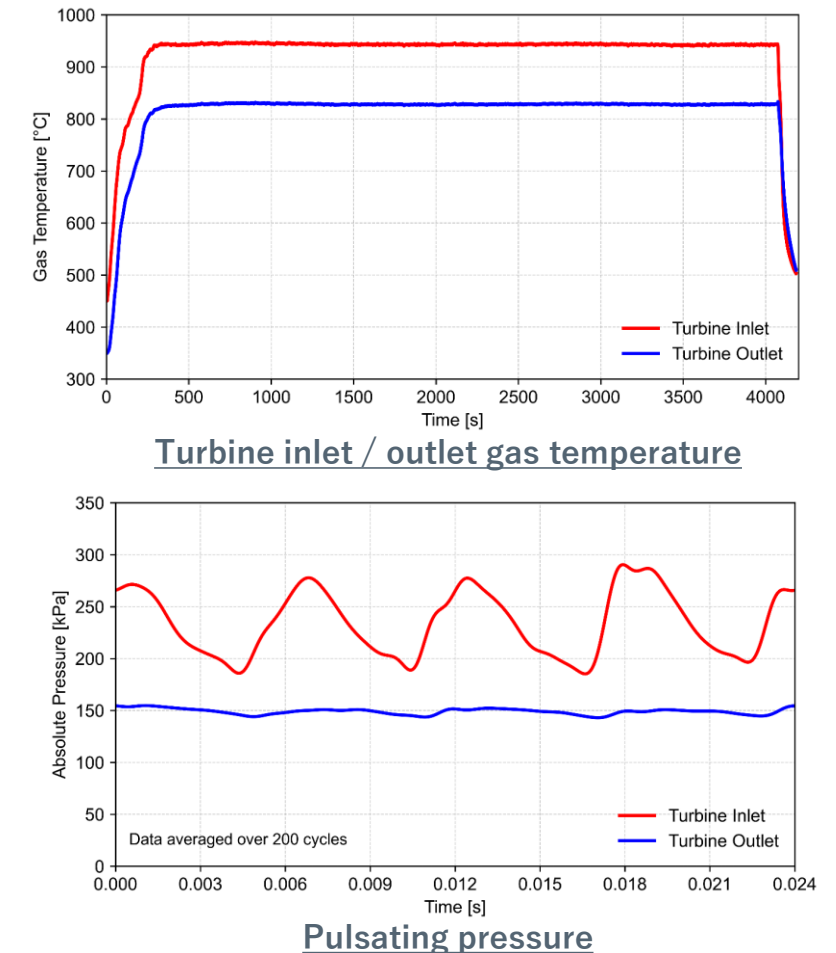
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- Target engine: 2.4-L turbocharged inline-4 engine
- Measured turbine-wheel temperature distribution using Thermal History Coating (THC)
- Measured gas temperature and pulsating pressure used as 1D/CFD boundary conditions

Acquisition of Actual Temperature



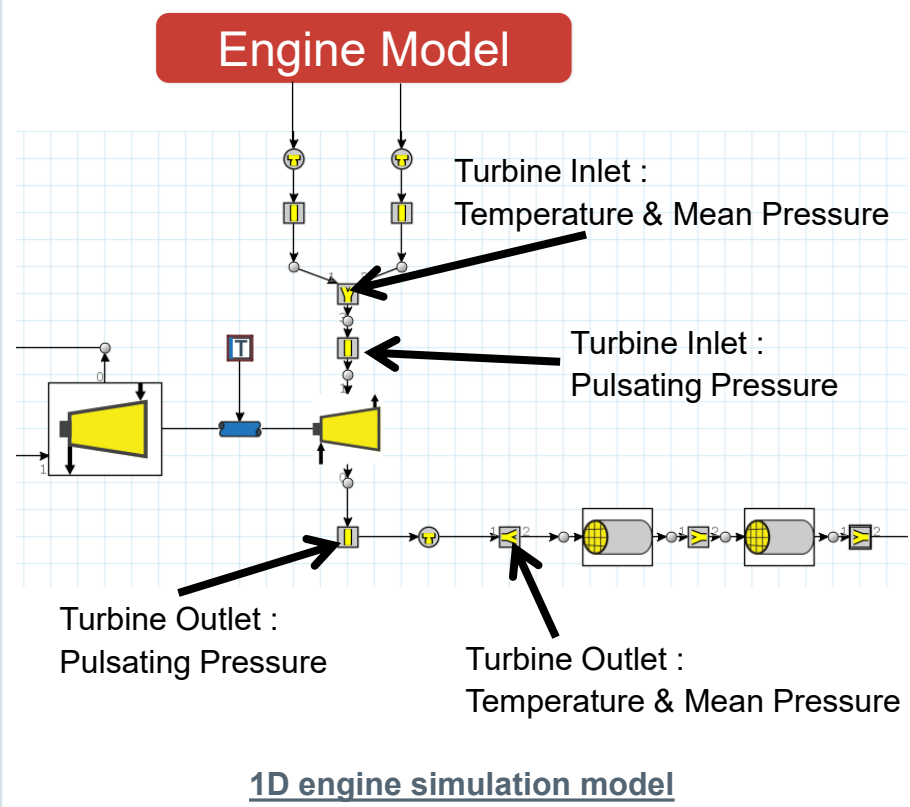
Acquisition of Boundary Conditions



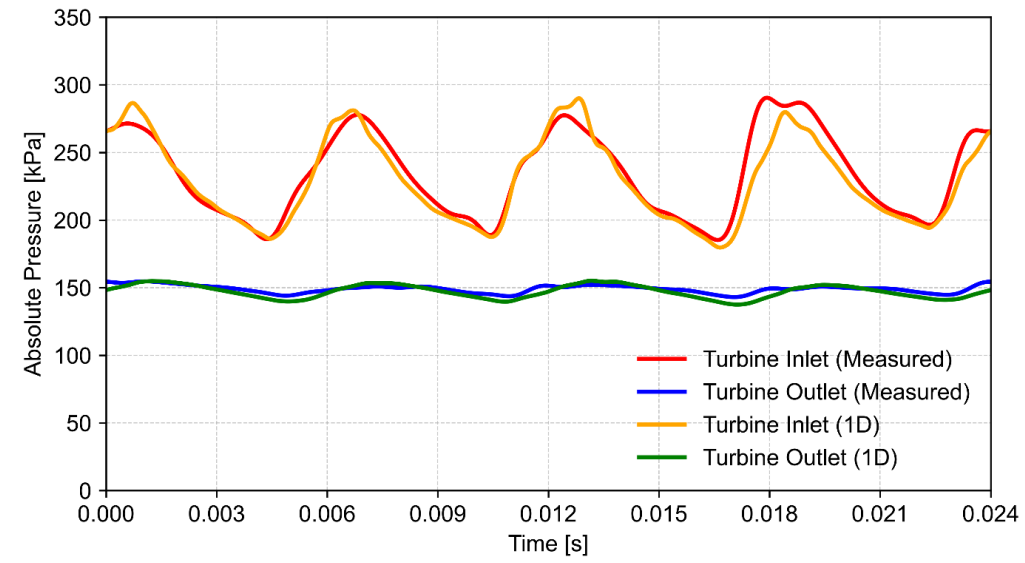
4.2. Development and Calibration of 1D Simulation Model

- 1D model calibrated using measured pressure and gas temperature
- Good agreement between simulation and measurements
- 1D-derived unsteady flow rate and gas temperature applied as CFD boundary conditions

1D Simulation Model



Calibration Results



Measured vs. predicted pulsating pressure

measured vs predicted mean temperatures and pressures

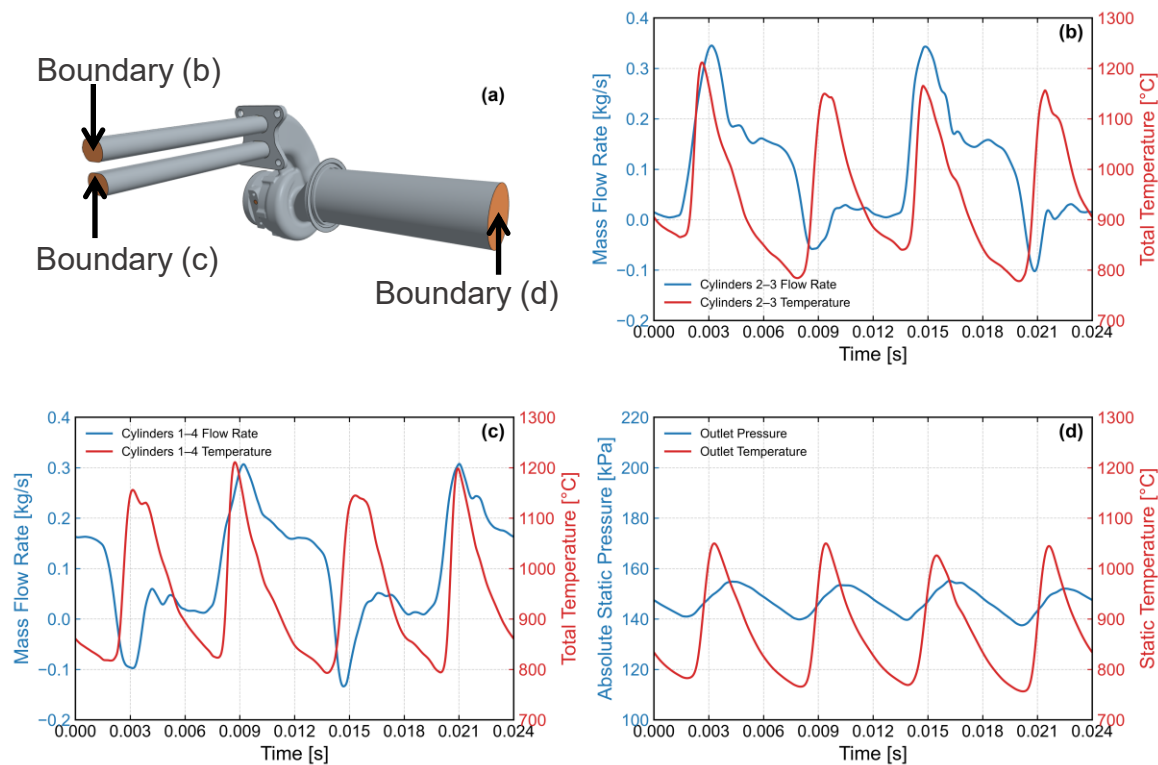
	Turbine Inlet		Turbine Outlet	
	Temperature [°C]	Mean Pressure [kPa abs]	Temperature [°C]	Mean Pressure [kPa abs]
Measured	943.4	236.2	827	147.8
1D	943.8	240.0	836	147.4

4.3. CFD Thermal-Fluid and Heat-Conduction Analysis

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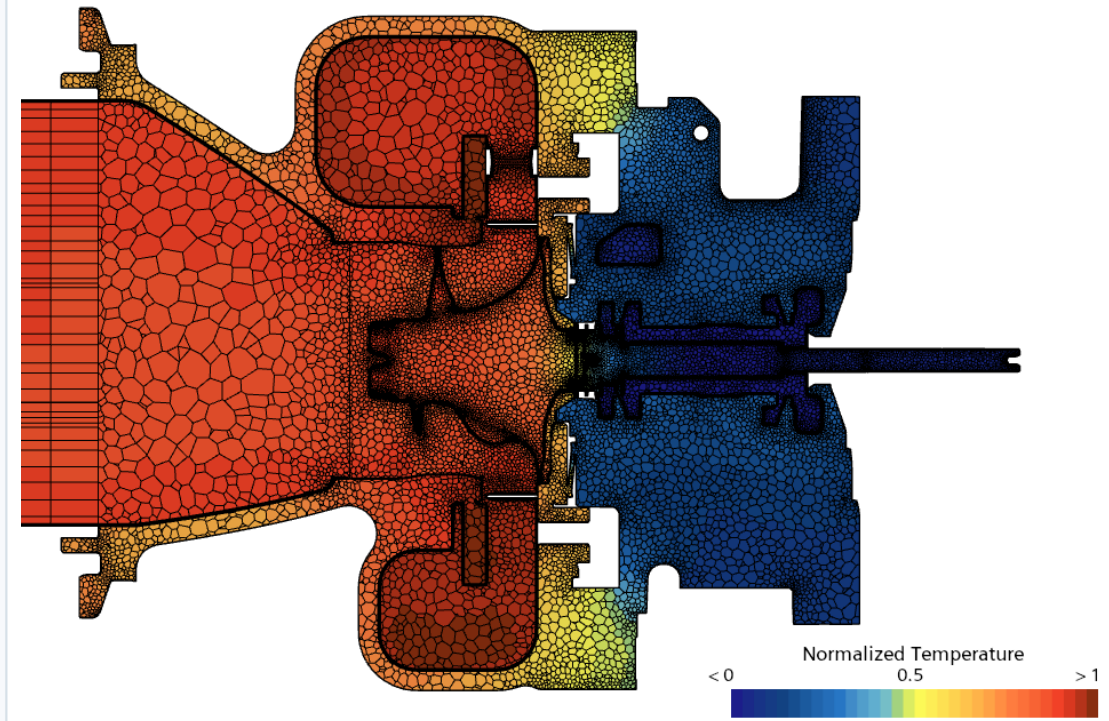
- Whole-turbo thermal-flow CFD including gas, water, oil, and air cooling
- Heat transfer from the turbine wheel to the bearing housing was identified
- Whole-turbo modeling is essential for accurate turbine-wheel temperature prediction

CFD Model and Boundary Conditions



CFD model and transient boundary conditions

Predicted Temperature Distribution



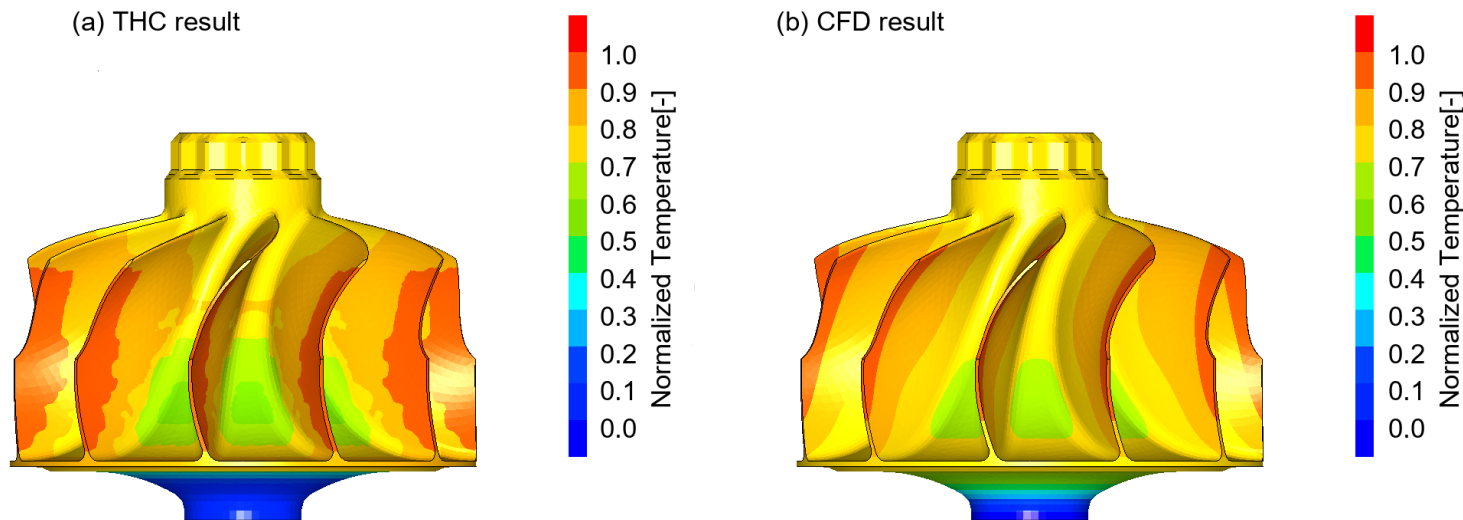
Predicted temperature distribution

4.4. Validation of Temperature Analysis

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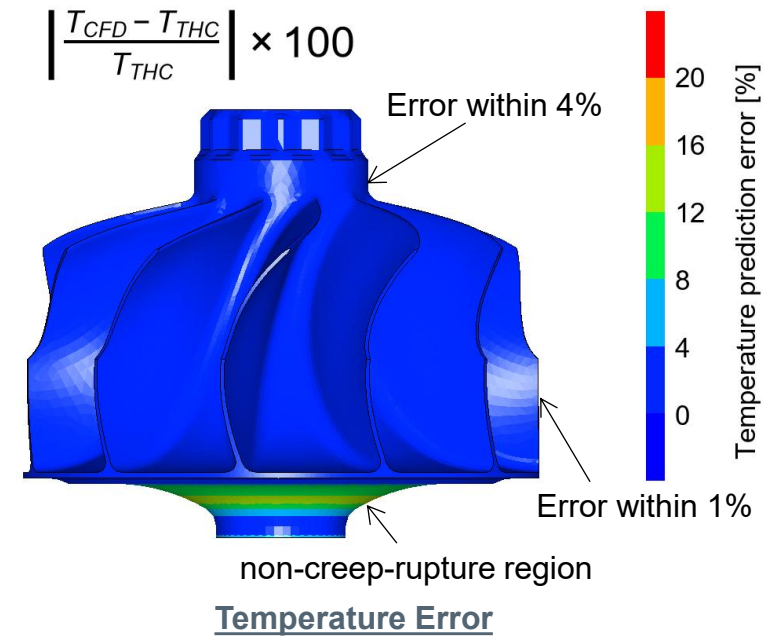
- Validated the turbine-wheel temperature distribution by comparing THC measurements with CFD results
- Highest temperature at the blade leading edge, decreasing toward the shaft center
- Within 4% difference from THC measurements in the blade region used for creep evaluation

THC Measurement vs. CFD Prediction



THC measurement vs. CFD prediction

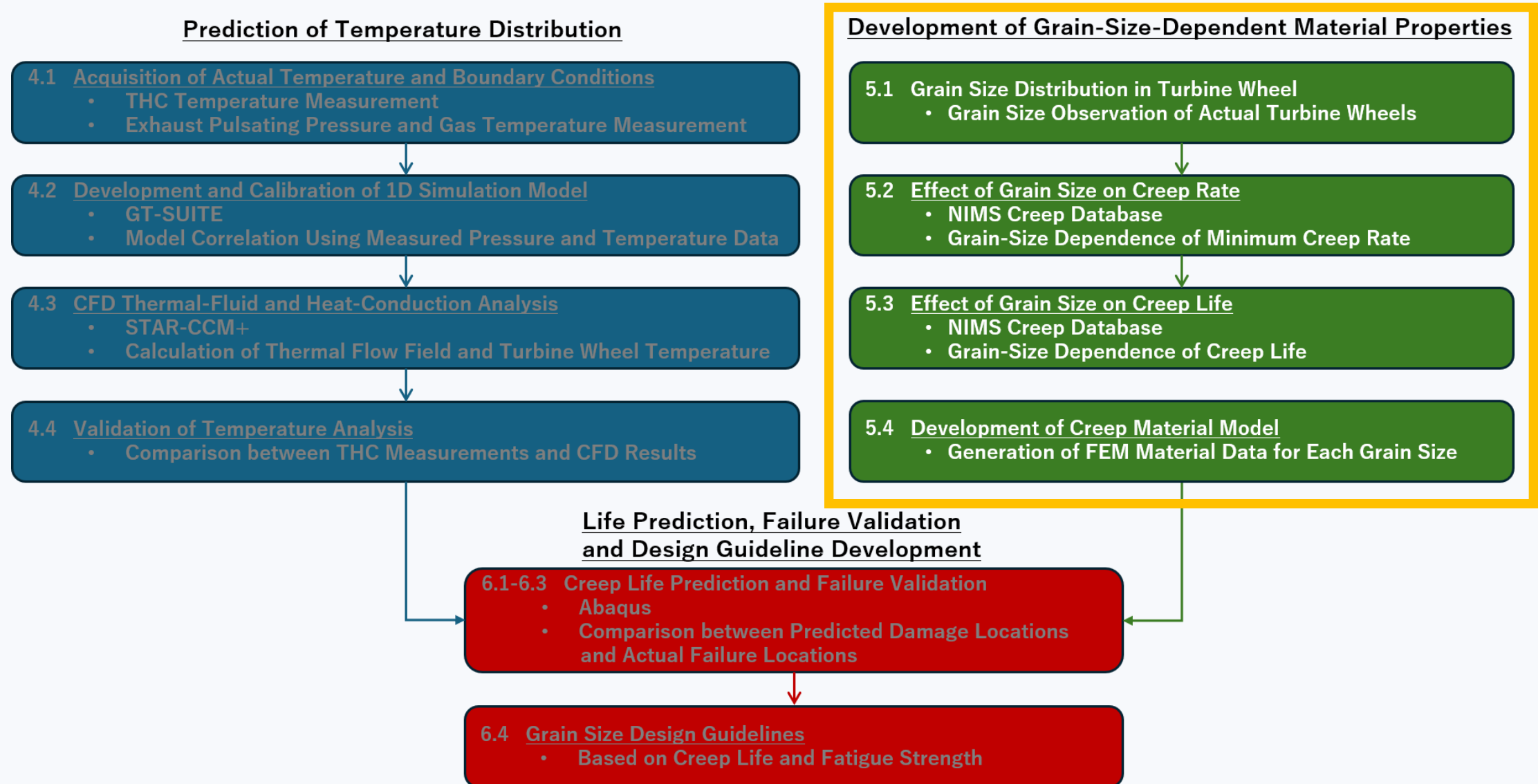
Temperature Error



Temperature Error

5. Development of Grain-Size-Dependent Material Properties

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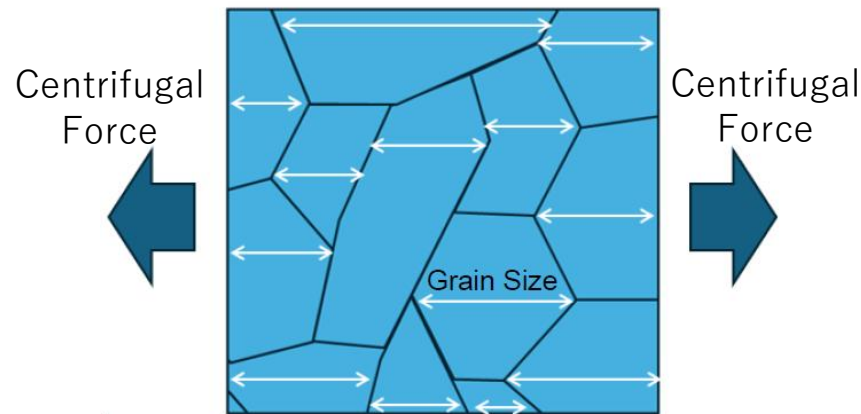


5.1. Grain Size Distribution in the Turbine Wheel

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- Examined the microstructures of three turbine wheels and measured the maximum grain length along the centrifugal-force direction
- Grain size decreased from 4.3 mm at the center to 0.5 mm at the blade tip.

Grain Size Distribution within the Turbine Wheel



Center

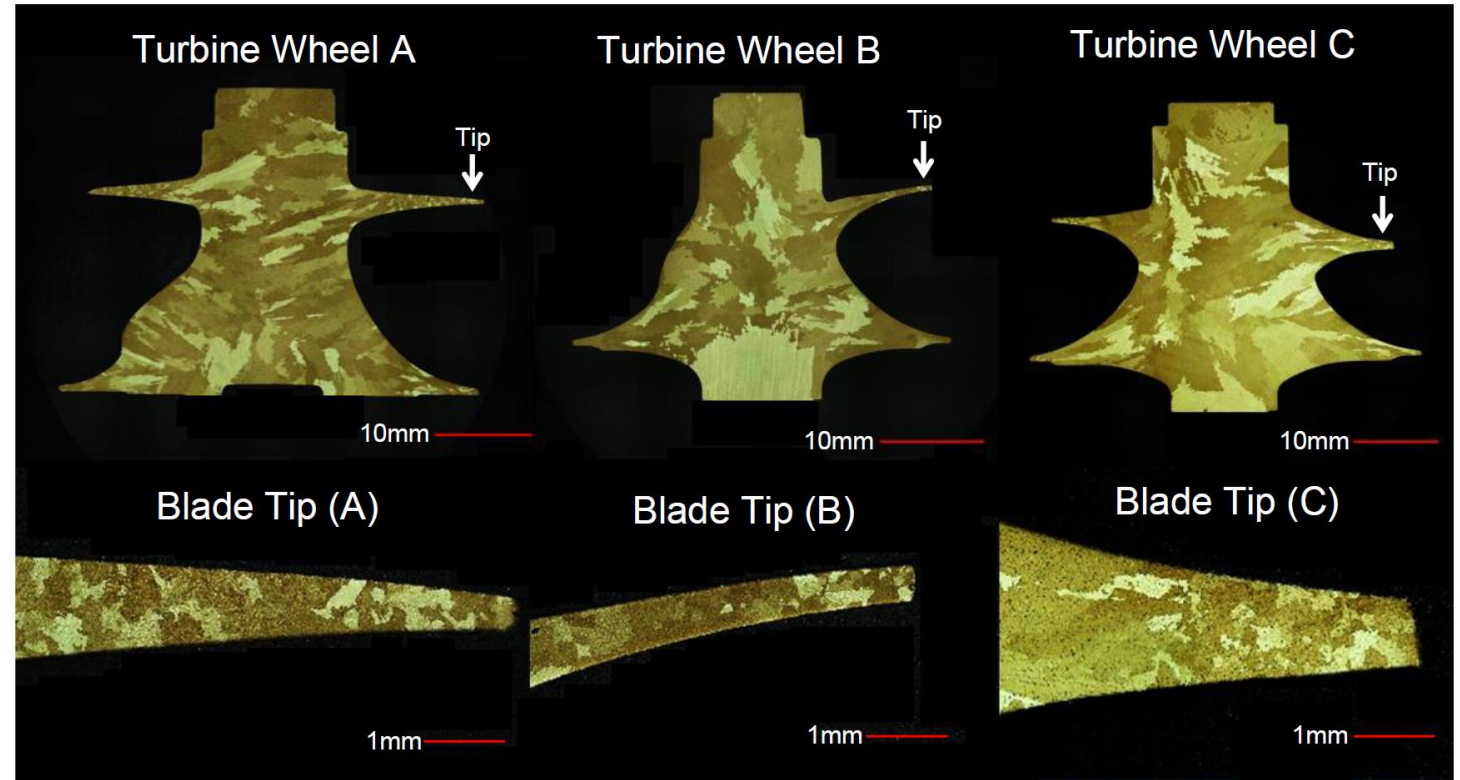
4.3 mm

average grain size

Blade tip

0.5 mm

average grain size



5.2. Effect of Grain Size on Creep Rate

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- Grain-size effects quantified using NIMS creep data
- Fine grains increased the minimum creep rate below 875°C ($m = -1$), whereas grain-size dependence disappeared above 925°C ($m = 0$)
- Grain-boundary sliding dominates at lower temperatures, while active dislocation motion at higher temperatures reduces grain-size effects

Grain-Size Exponent as a Function of Temperature

$$\dot{\epsilon}_{min} = A \cdot d^m \cdot \sigma^n \cdot \exp\left(-\frac{Q_c}{R \cdot T}\right)$$

$\dot{\epsilon}_{min}$: Minimum Creep Rate

A : Material Constant

d : Grain Size

m : Grain Size Exponent

σ : Stress

n : Stress Exponent

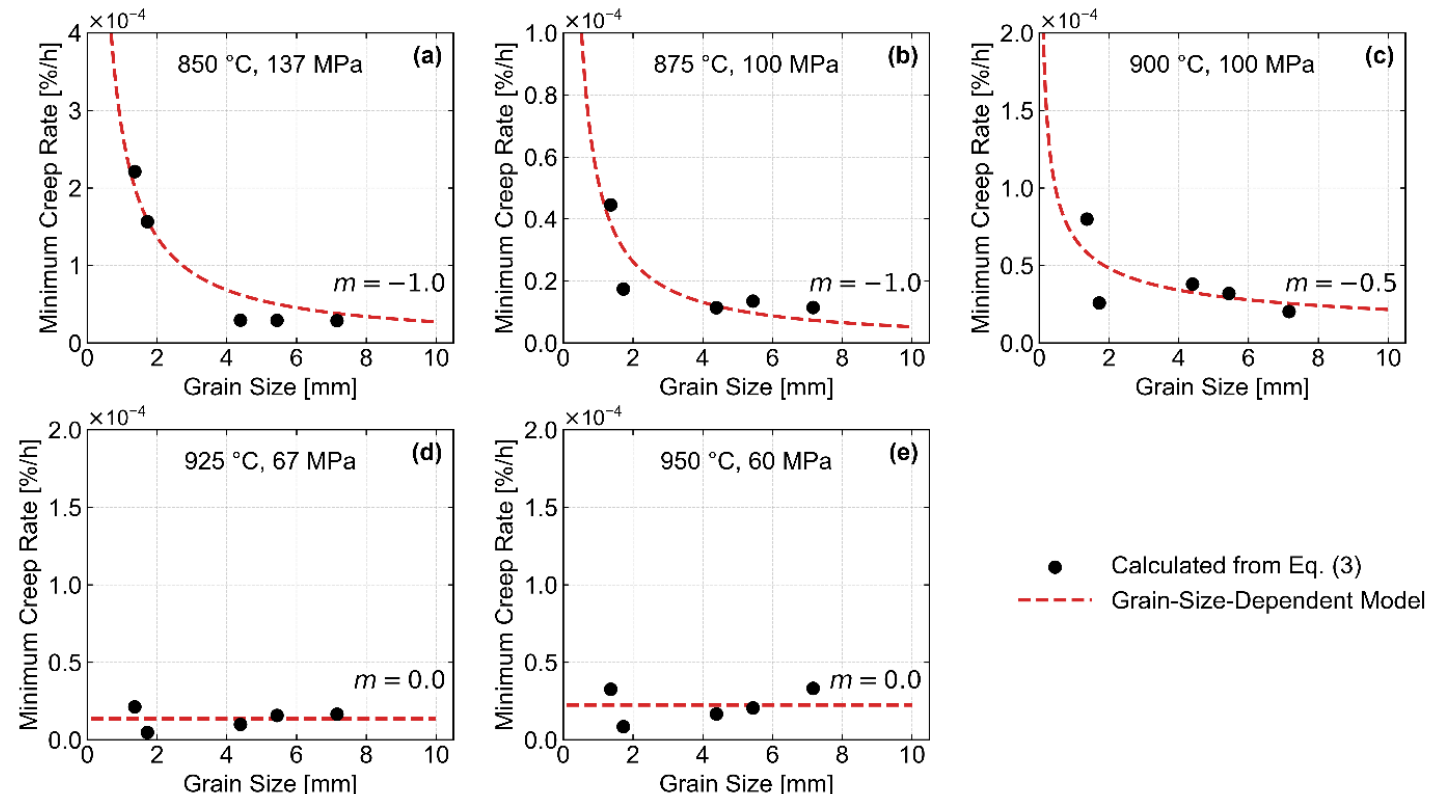
Q_c : Apparent Creep Activation Energy

R : Gas Constant

T : Absolute Temperature

Grain-size dependence of minimum creep rate

	850°C	875°C	900°C	925°C	950°C
m	-1	-1	-0.5	0	0
n	6.01	5.43	4.92	4.47	4.07
Q_c [MJ/kg]	11.19				
Q_c [kJ/mol]	324.17				



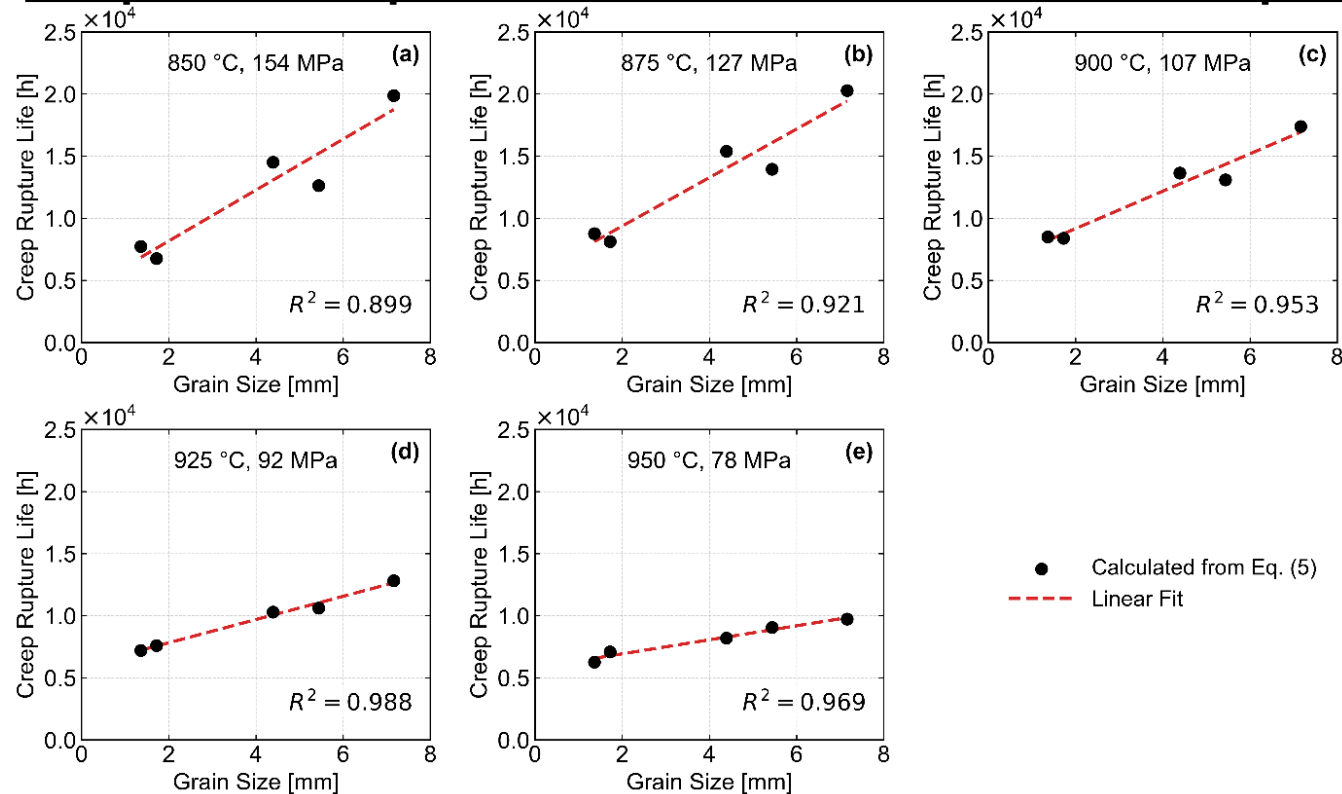
Grain-size dependence of minimum creep rate

5.3. Effect of Grain Size on Creep Life

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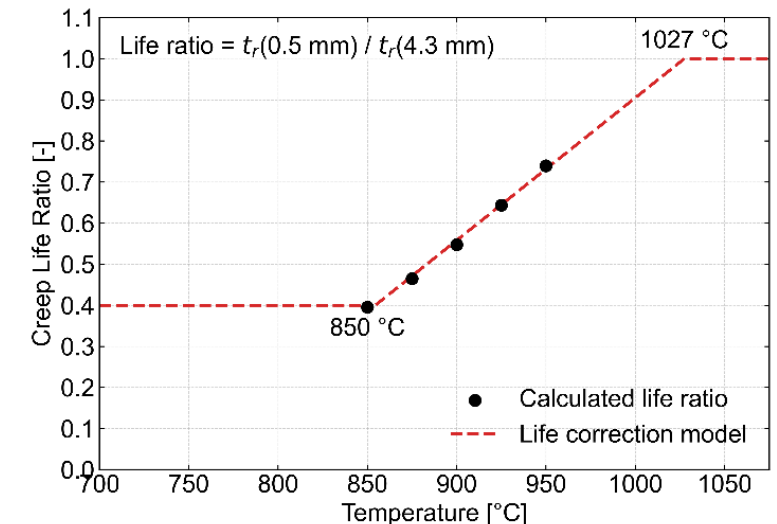
- Creep life decreased with decreasing grain size, while grain-size dependence weakened at higher temperatures
- Creep life of 0.5 mm grains was 0.40x at 850°C and 0.74x at 950°C relative to 4.3 mm grains
- Developed a Creep Life Ratio (CLR) model enabling grain-size-dependent creep-life prediction

Temperature Dependence of Grain-Size Effect on Creep Rupture Life



Grain-size dependence of creep rupture life

$$CLR = \begin{cases} 0.40, & T_c \leq 850 \\ C_1 \cdot T_c + C_2, & 850 < T_c < 1027 \\ 1.00, & T_c \geq 1027 \end{cases}$$



Temperature dependence of creep life ratio

5.4. Development of Grain-Size-Dependent Creep Material Model

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- Developed a creep material model using creep data for 4.3 mm grains
- Introduced the grain-size exponent m to describe grain-size-dependent creep rates
- Reproduced creep curves considering temperature-dependent grain-size effects

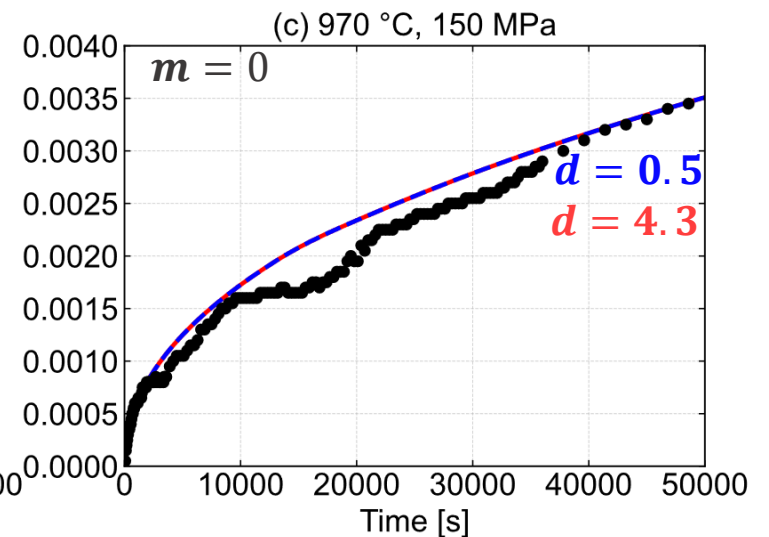
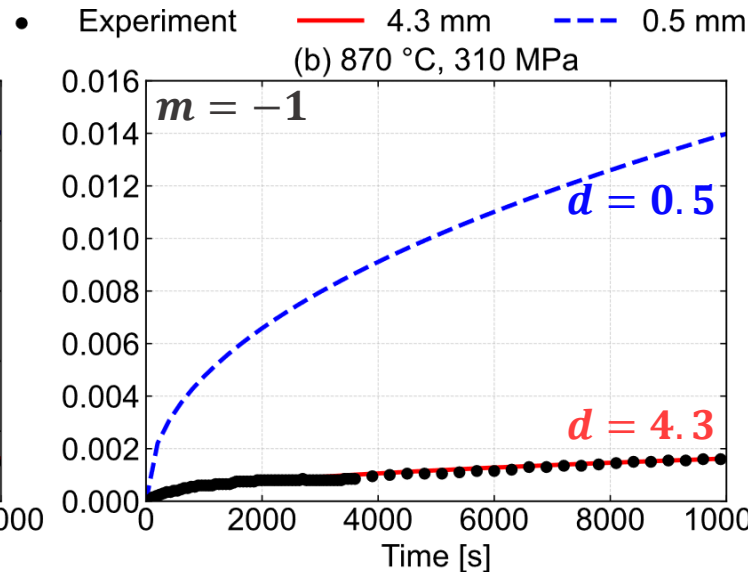
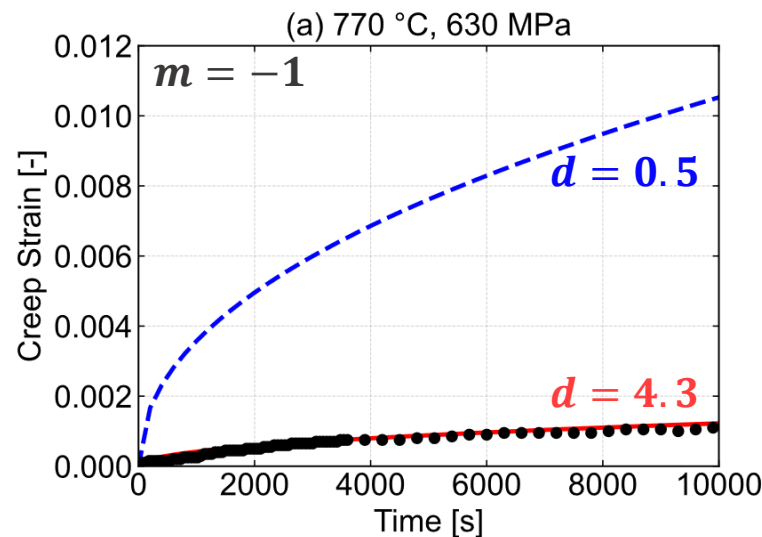
Creep Material Model for CAE

$$\dot{\epsilon}_c = A \cdot \left(\frac{d}{d_{base}} \right)^m \cdot \sigma^n \cdot t^q$$

(Created for each temperature)

$\dot{\epsilon}_{min}$: Creep Rate
 A : Material Constant
 d : Grain Size
 d_{base} : Base Grain Size
 m : Grain Size Exponent

σ : Stress
 n : Stress Exponent
 t : Time
 q : Time Exponent



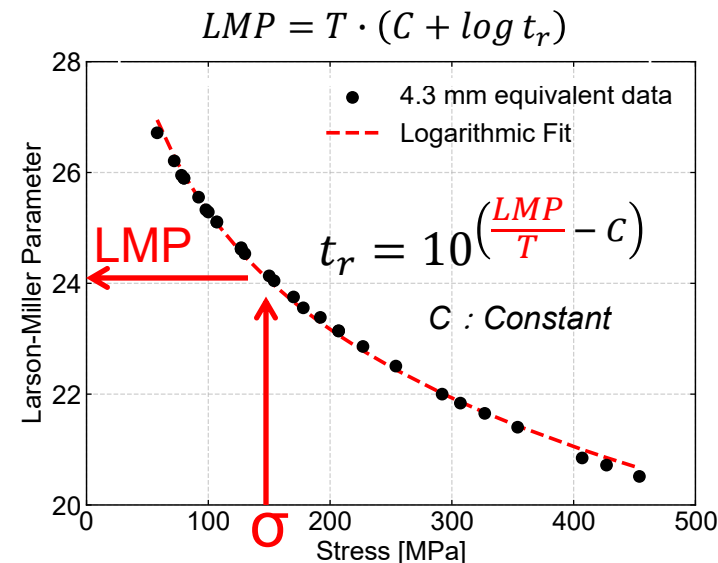
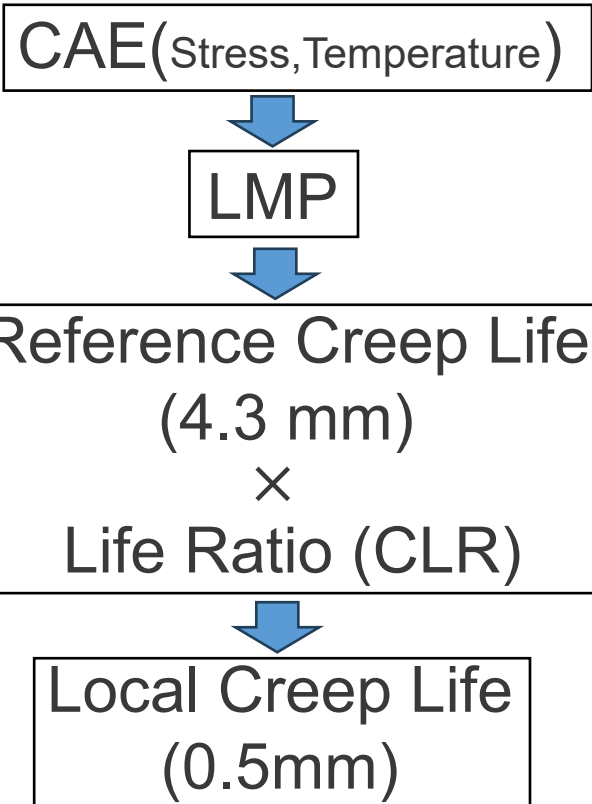
Comparison of Experiments and Model Predictions

5.4. Development of Grain-Size-Dependent Creep Material Model (Cont.)

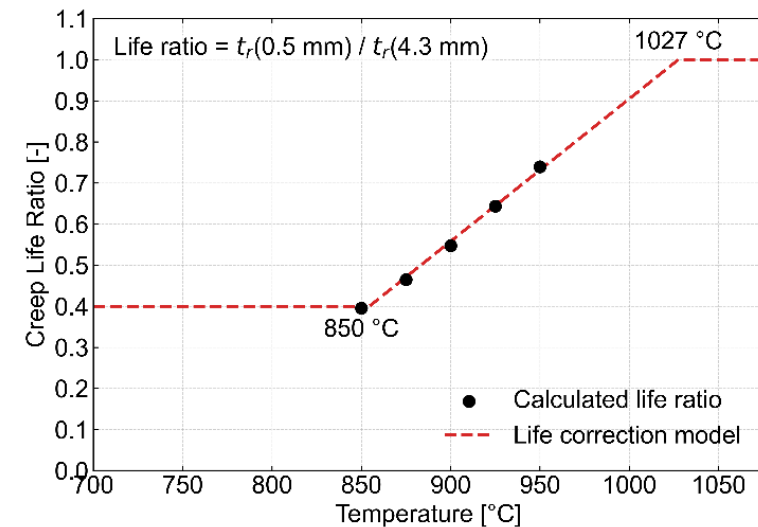
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- Calculated creep life for the reference grain size (4.3 mm) using the LMP method based on CAE-predicted stress and temperature
- Applied the Creep Life Ratio (CLR) to account for grain-size-dependent life variation
- Enabled creep-life prediction considering the actual grain-size distribution within the turbine wheel

Grain-Size-Dependent Creep-Life Prediction



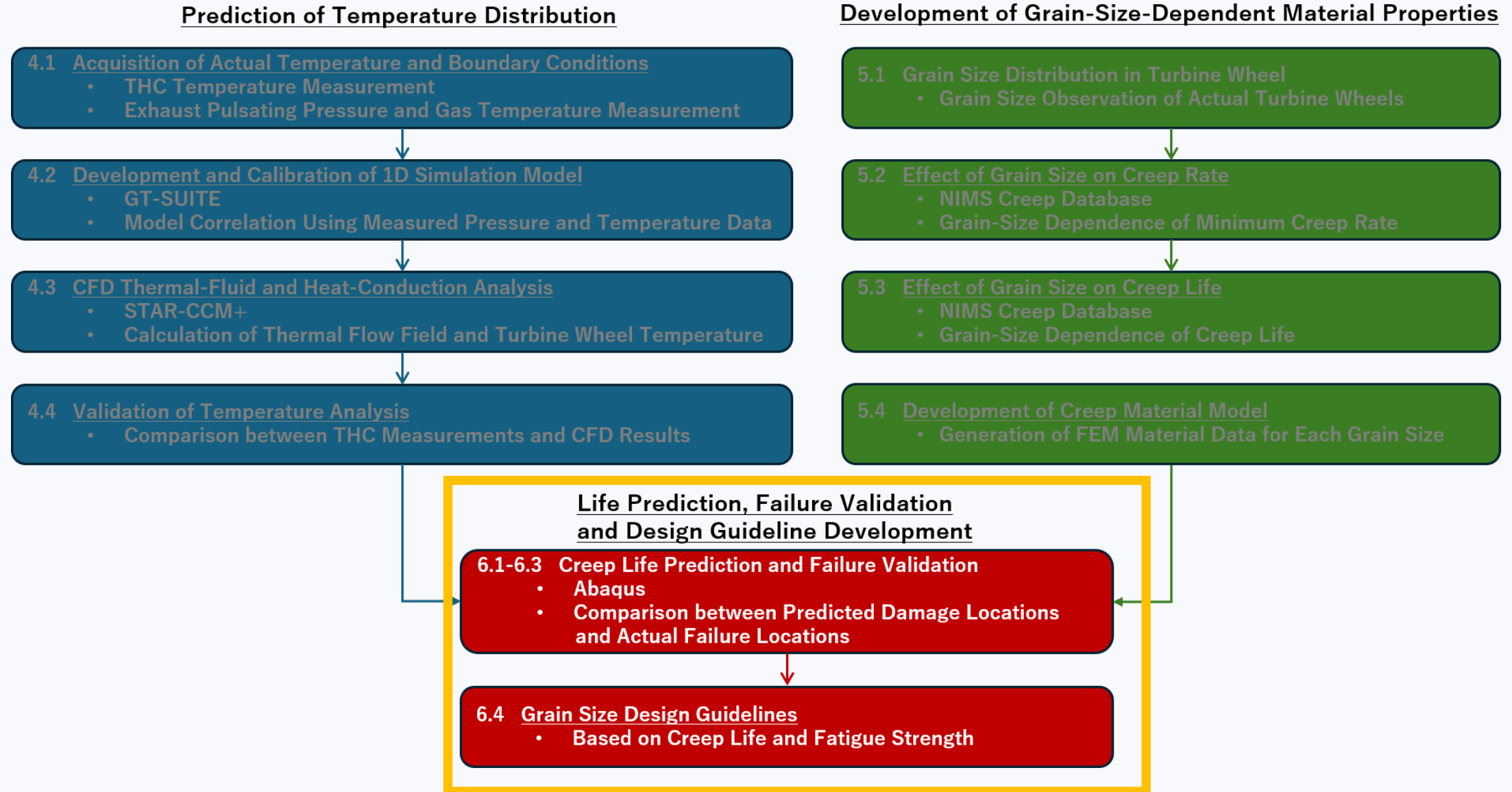
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Local
= Creep
Life

6. Life Prediction, Failure Validation and Design Guidelines

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6.1. Analysis Model and Boundary Conditions

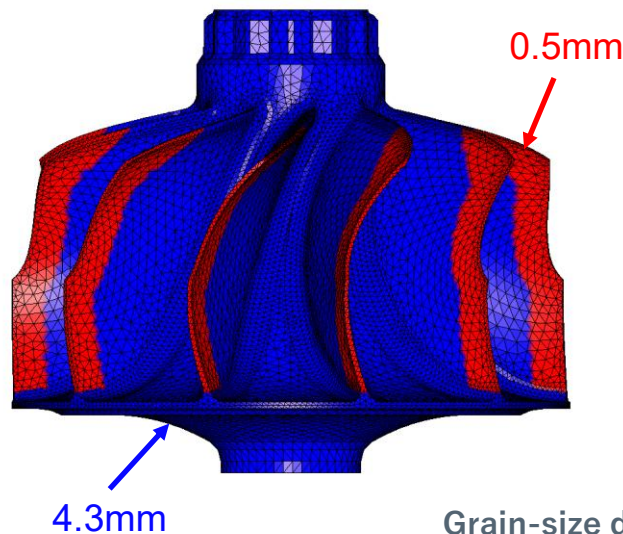
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- Reflected the grain-size distribution observed in an actual failed turbine wheel in the FEM model
- Applied CFD-predicted temperature distribution and centrifugal load as boundary conditions
- Performed creep analysis using the grain-size-dependent creep material model

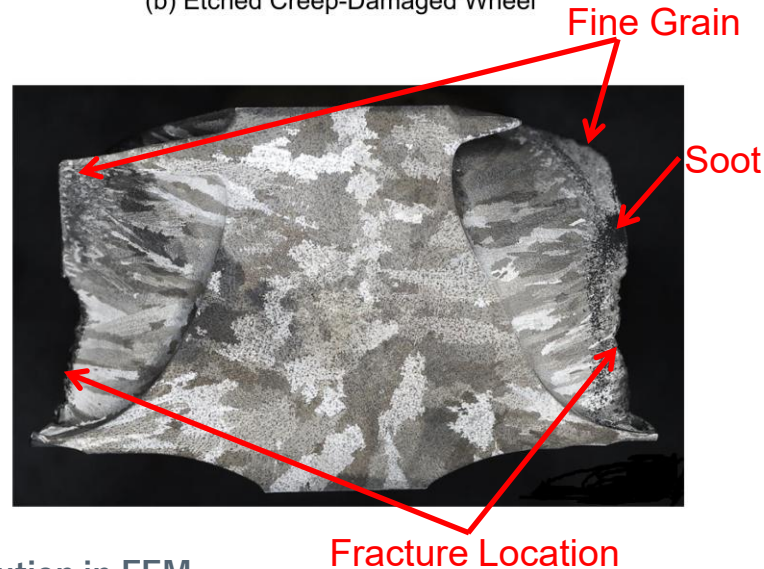
Actual Grain-Size Distribution in FEM

0.5 mm 4.3 mm

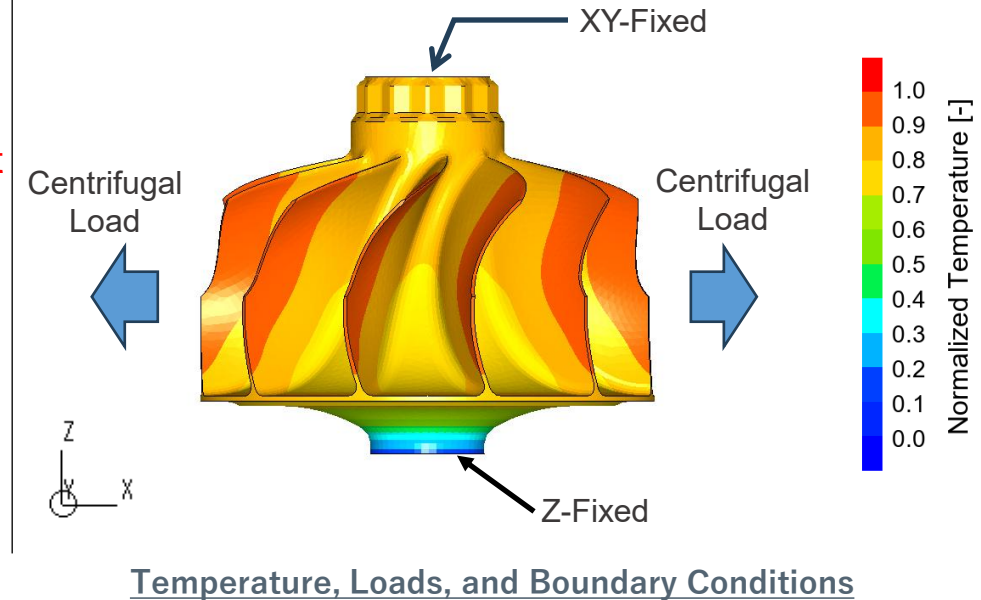
(a) FEM Grain Size Distribution



(b) Etched Creep-Damaged Wheel



Grain-size distribution in FEM



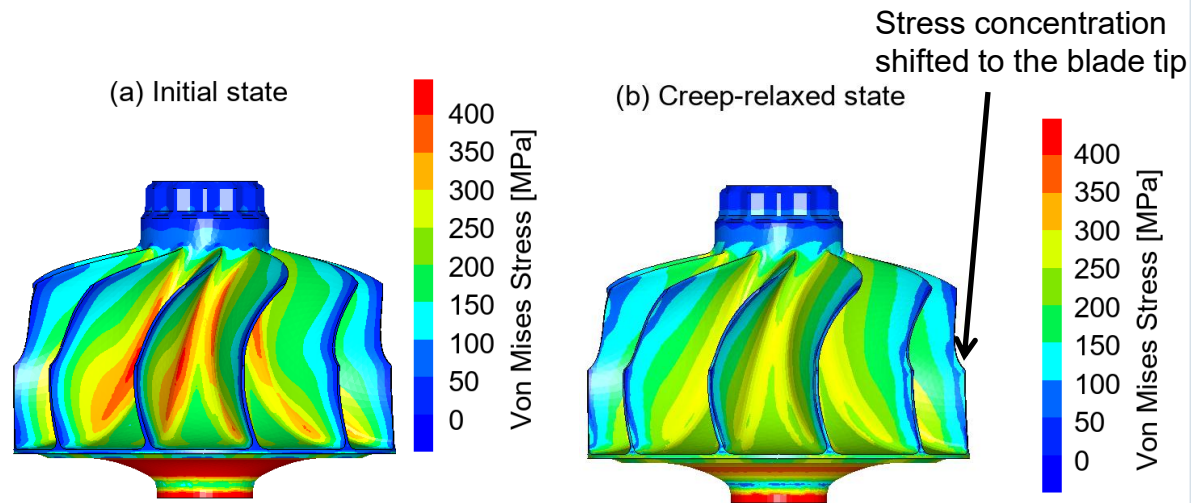
Temperature, Loads, and Boundary Conditions

6.2. Stress Redistribution and Residual Stress

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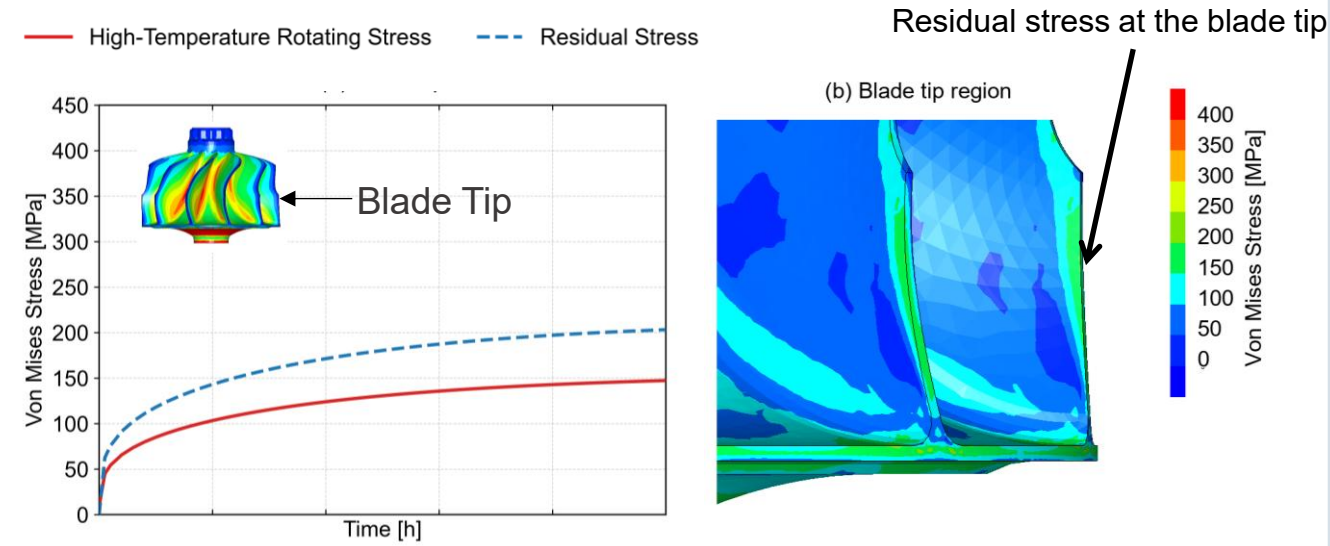
- Creep deformation during high-temperature operation relaxed stress at the blade root and redistributed it toward the blade tip
- Stress redistribution significantly changed the stress state from the initial condition
- The redistributed stress remained after unloading as residual stress at the blade tip

Stress relaxation by creep deformation



Creep-Induced Stress Redistribution

Residual Stress Generated by Stress Redistribution



Residual Stress Formation

6.3. Comparison between Predicted Creep Life and Actual Failure

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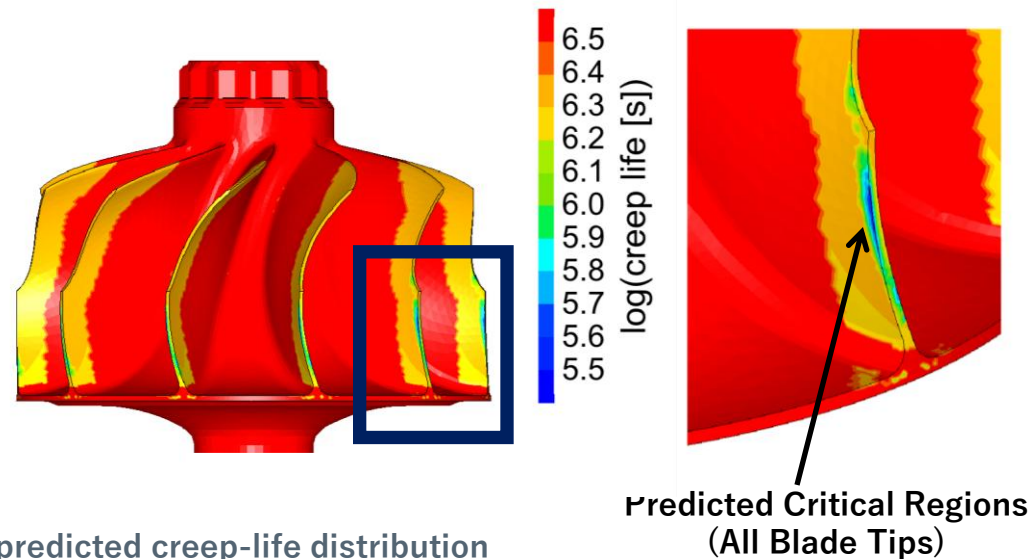
- Developed a life-prediction method using operating temperature and residual stress
- The predicted short-life region showed good agreement with the actual fracture location at the blade tip
- The predicted life was within the same order of magnitude as the actual service life, demonstrating reasonable reproduction of creep-damage behavior

Comparison of Actual Fracture and Predicted Creep-Life Distribution

Actual Fracture



Predicted Creep Life



Actual fracture and predicted creep-life distribution

Fracture Location

**Aligned with the
Blade Inlet Tip**

Rupture Life

Within 42 h

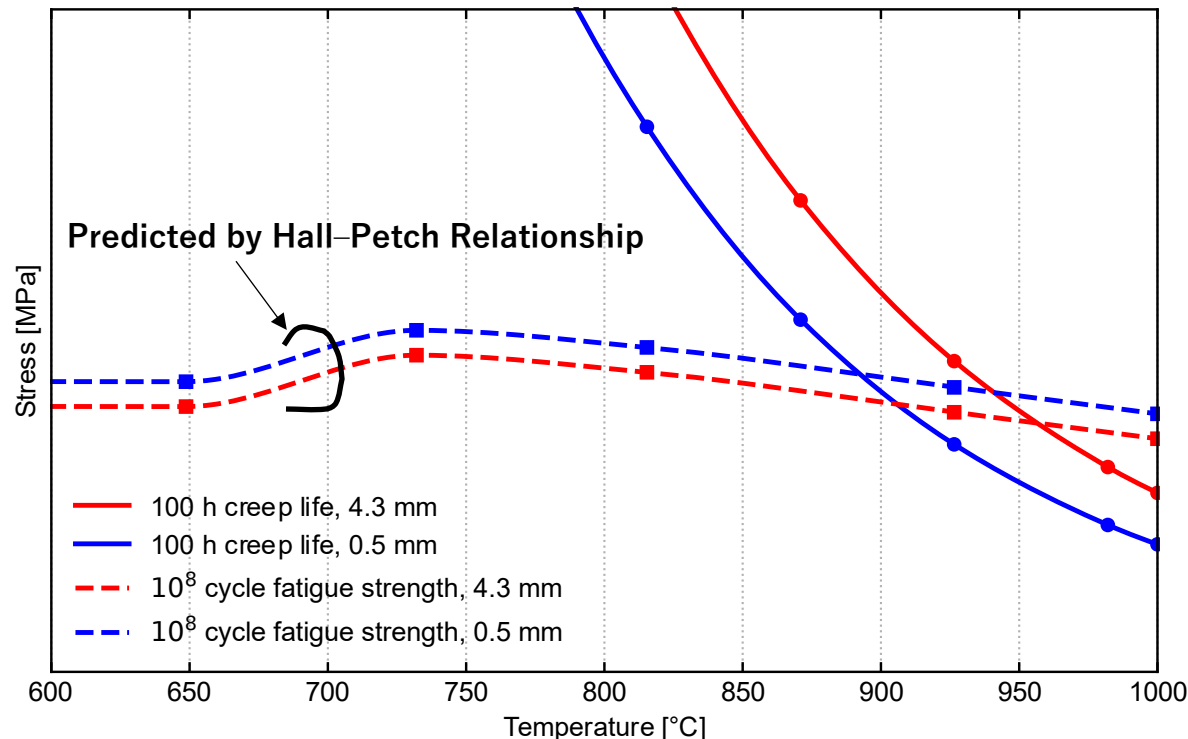
**Life Reproduced within the
Same Order of Magnitude**

6.4. Effect of Grain Size on Creep Life and Fatigue Strength

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- Compared the 100h creep-rupture strength and 10^8 -cycle fatigue strength for grain sizes of 4.3 mm and 0.5 mm
- Grain-size dependence of the 100h creep-rupture strength was greater than that of the fatigue strength
- The relationship between fatigue strength and 100 h creep-rupture strength reversed at around 900°C
- Grain-size design focused on creep performance is important for high-temperature applications

Comparison of 100 h Creep-rupture Strength and 10^8 -Cycle Fatigue Strength



100 h creep-rupture strength vs. 10^8 -cycle fatigue strength

Below ~900° C
Fatigue Strength Dominates

Above ~900° C
Creep Strength Dominates



(a) Coarse grains



(b) Fine grains

Actual turbine wheels: coarse vs. fine grains

Design message

**Prioritize Coarser Grains
for High-Temperature
Applications**

**The improvement in creep life
outweighs the reduction in
fatigue strength**

Established a Creep-Life Prediction Method Considering Temperature and Grain Size

- 1 Predicted turbine-wheel temperatures within 4% of measurements in the creep-critical blade region.**
- 2 Clarified that fine-grained regions exhibit higher creep rates and shorter creep life.**
- 3 Developed a grain-size-dependent material model for creep deformation and life prediction.**
- 4 Reproduced the actual fracture location and predicted the rupture life within the same order of magnitude.**
- 5 Above approximately 900°C, creep becomes more critical than fatigue, favoring coarser grains for high-temperature applications.**



Thank you for your attention !