École de Technologie Supérieur

# Constitutive Modeling of Ingot Breakdown Process of Low Alloy Steels

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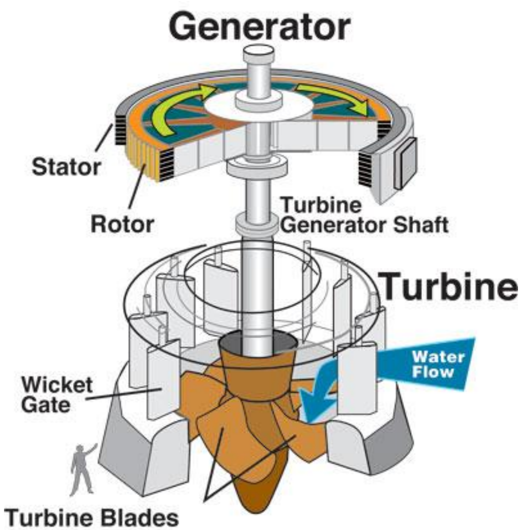
## ❑ Introduction

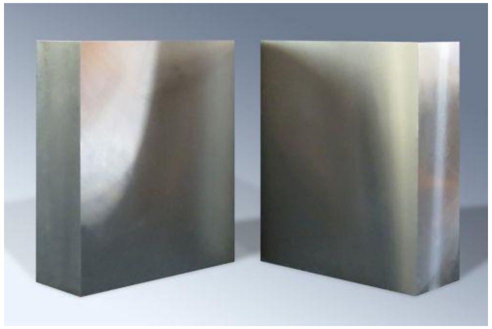
Plastic Product[1]




Hydro Power Turbine[2]

Plastic Injection Mold[3]

Turbine Shafts[5]

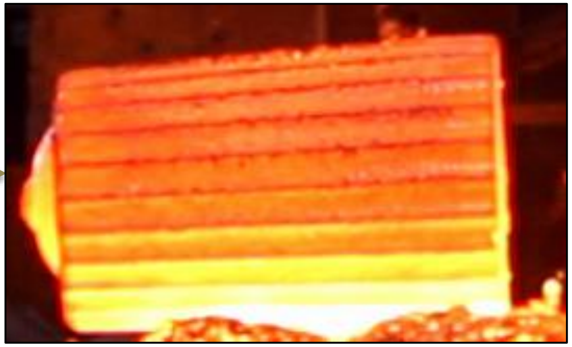


Mold Steels[4]

1. www.injectionplastic-mold.com
2. water.usgs.gov
3. www.ackormold.com
4. www.jepsculpture.com/bronze.html
5. www.Sorelforge.com

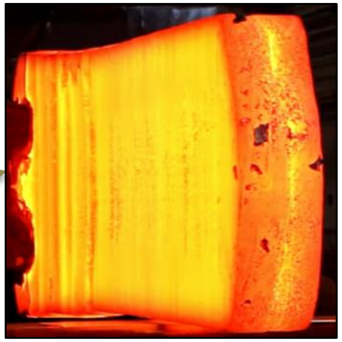
# ❑ Manufacturing Process for Mold Steels and Turbine Shafts

Casting

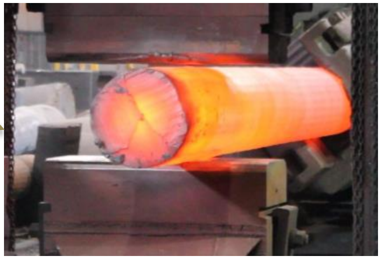


Ingot

Open Die Forging



Finish Forging for Mold Steels



Finish Forging for Turbine Shafts

Le génie pour l'industrie

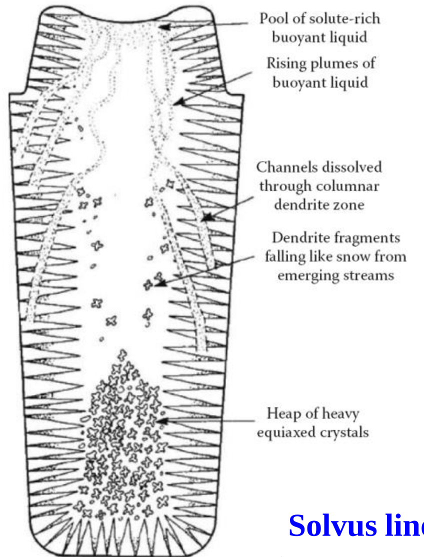
Industrial Research Chair in Forming Technologies of High Strength Alloys

STEELSIM 2015 MODELLING and SIMULATION of METALLURGICAL PROCESSES in STEELMAKING

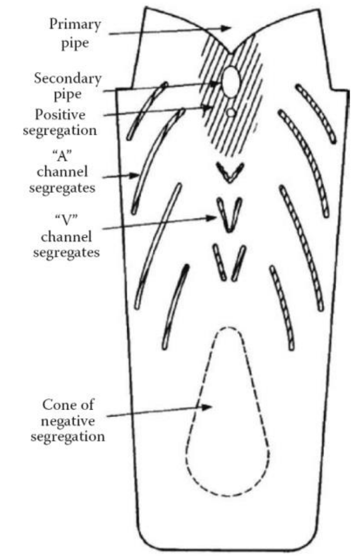
## ❑ Ingot Breakdown Process

### Casting Heterogeneities

#### Cast Microstructure

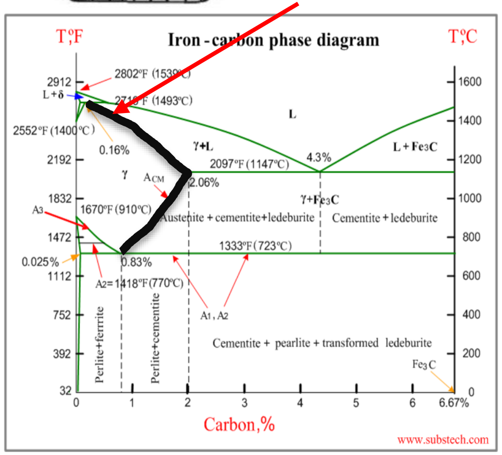


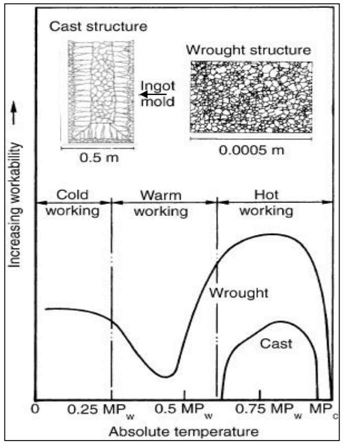

#### Macrosegregation




- An initial process for reducing an ingot to desired size.
- Conducted above γ solvus line to allow chemical homogenization and microstructural refinement.

**Solvus line**



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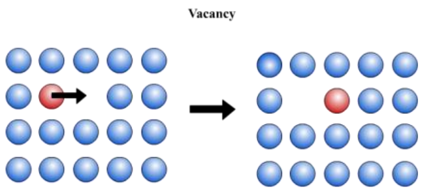
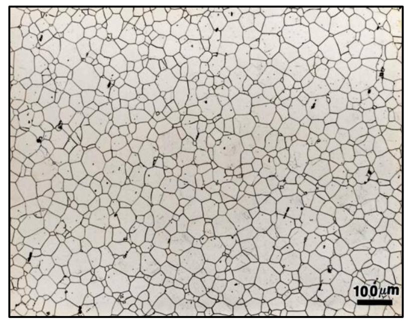
1. Handbook of Workability and Process Design G.E Dieter ASM International 2003
2.www.industrialheating.com

## ❑ Parameters affecting Microstructure during Hot Deformation

**Diffusion**




**Grain Refinement**




**Recovery**

**Dynamic Recrystallization**

**Meta Dynamic Recrystallization**

**Strain Rate** $\dot{\varepsilon}$ **Strain** $\varepsilon$ **Temperature** $T$ **Interpass time,** $t$

| $T + \dot{\varepsilon}$ | $T + \dot{\varepsilon} + t$ | $T + \dot{\varepsilon} + \varepsilon$ |
|---|---|---|
| **Recovery** **Dynamic Recrystallization** | **Meta Dynamic Recrystallization** | **Dynamic Transformation** |

**For As Cast Steel**

**Constitutive Equations is the output of every process**



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1- www.doitpoms.ac.uk
2- www.esci.umn.edu

To determine material flow behaviour of an as cast material

To derive constitutive equations using the experimental data


Develop a new material model

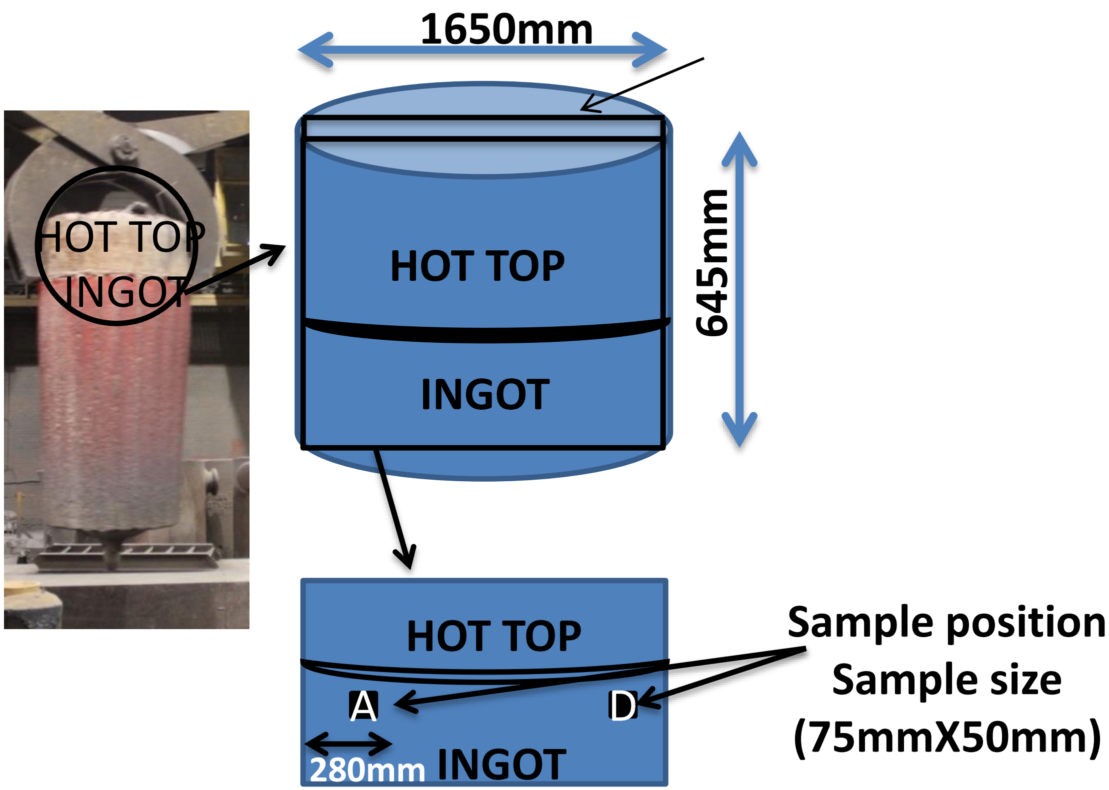
To run FEM simulations from the derived equations

# Experimental

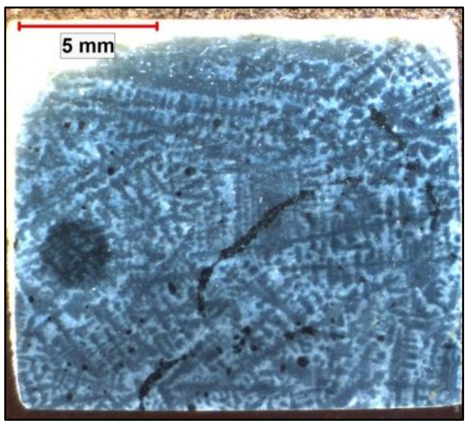
## ❑ Material Composition , Position and Microstructure

### Chemical Composition (wt%)

| C | Mn | Ni | Cr | Mo | Cu | Si |
|---|---|---|---|---|---|---|
| 0.37 | 0.84 | 0.25 | 1.87 | 0.46 | 0.16 | 0.39 |




Initial Microstructure




DAS ~200µm

# ❑ Determination of Cooling Rate, Interpass Time and Deformation Temperature

➢ **Videos Recordings of:**

1. **Furnace to press**
2. **Ingot breakdown process**
3. **Upsetting**
4. **Forging**
5. **Finish forging**

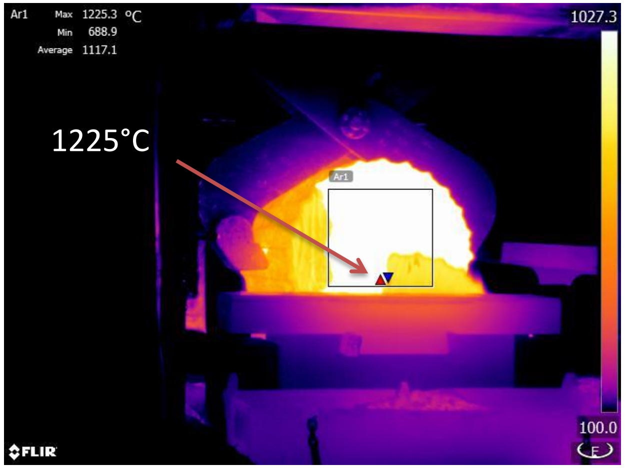
➢ **Videos than analyzed using FLIR software to get temperature readings and take snapshots.**

**Flir Thermal Camera**

## Cooling Rate Calculation

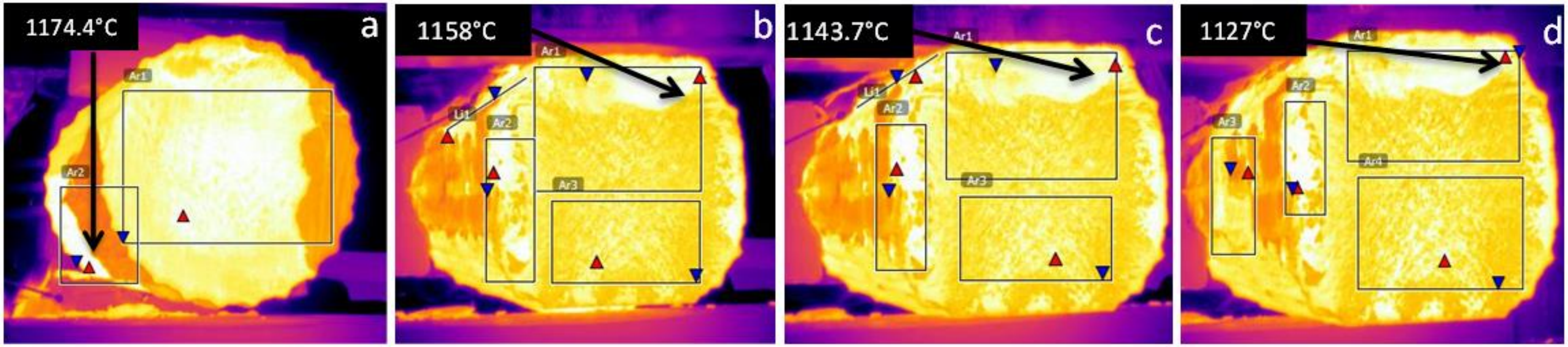
| Time (sec) | Temperature (°C) | Cooling Rate (°C/s) |
|---|---|---|
| 0 | 1260 | - |
| 159 | 1225 | 0.2 |
| 190 | 1174 | 1.6 |


**Ingot at the exit of furnace**




**Ingot before deformation**

## ❑ Deformation Temperature Measurement







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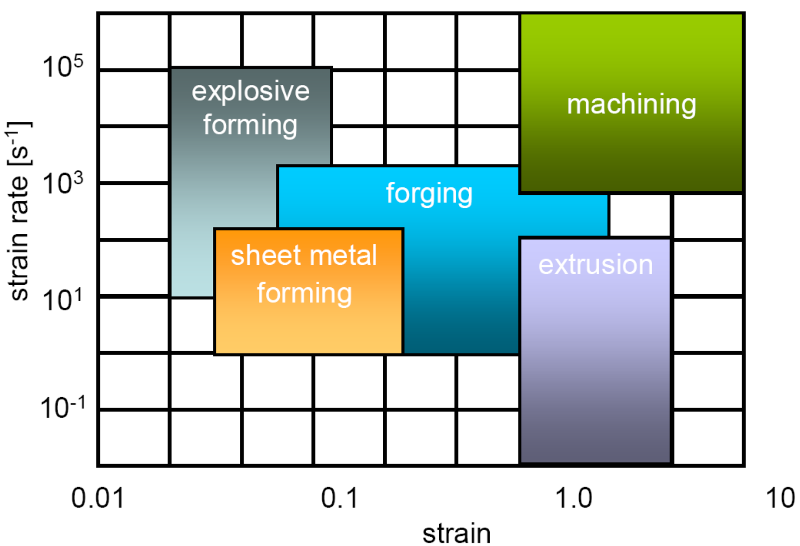
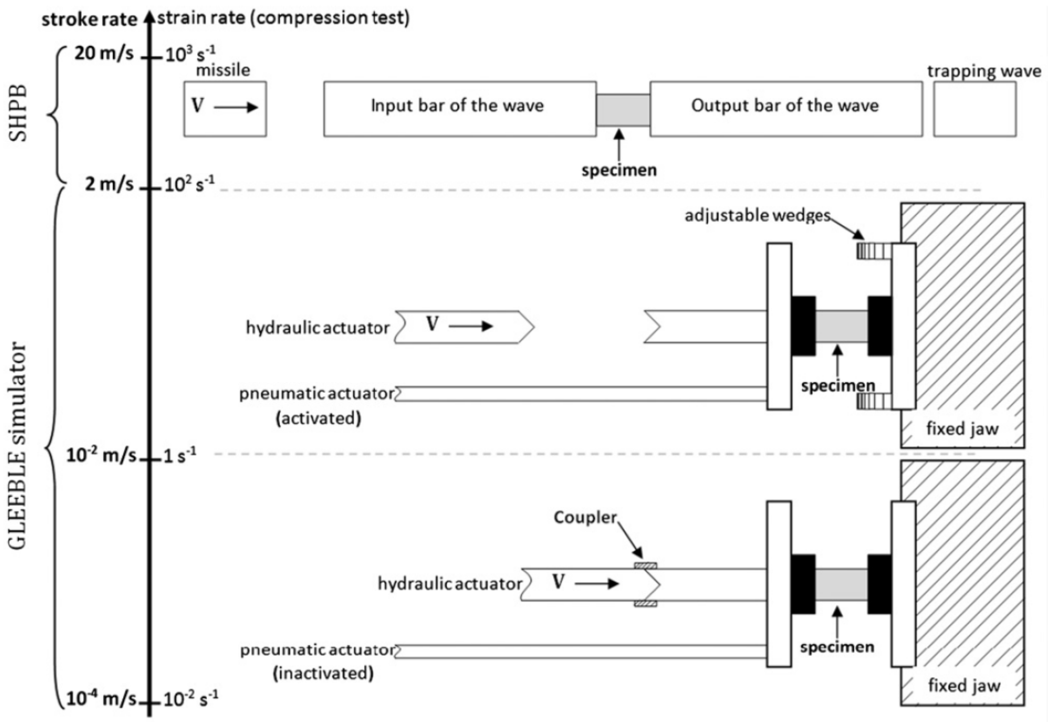
# ❑ Present Research on Modeling and Testing



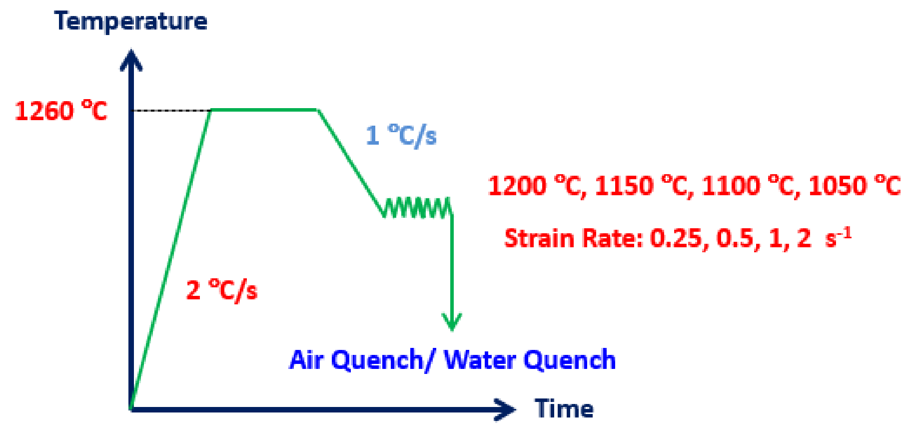

Characteristics of Principle Manufacturing Processes



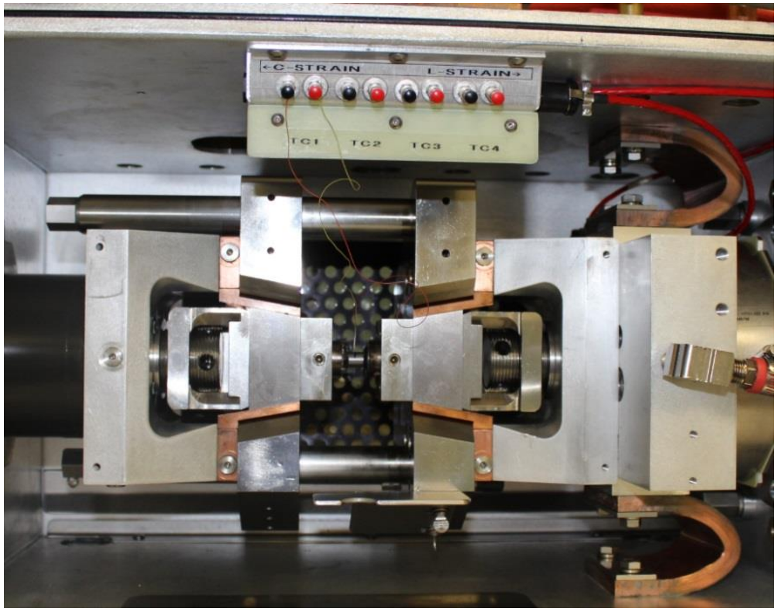

Configuration for Hot Compression Test

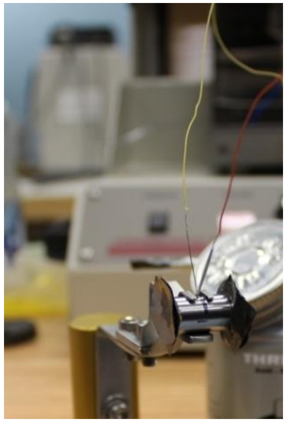
# ❑ Present Research on Modeling and Testing

Heating Rate in industrial furnace:
0.02hr/mm to 0.04hr/mm




Gleeble 3800® Thermomechanical



K-Type Thermocouples

Sample
Diameter:10mm
Length: 15mm



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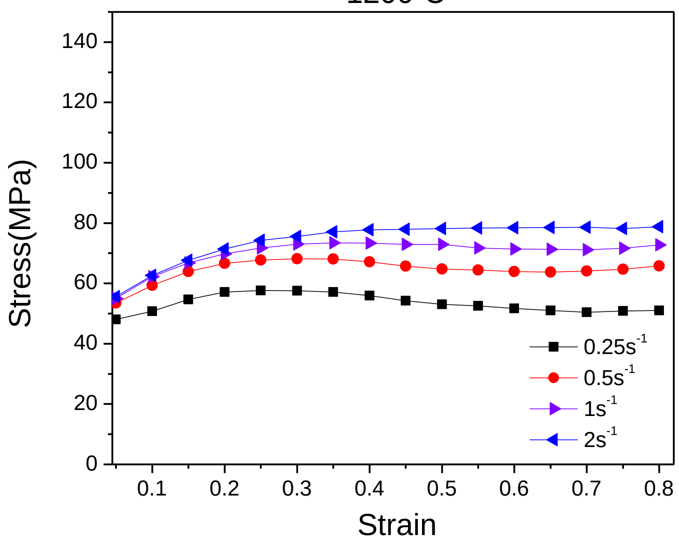
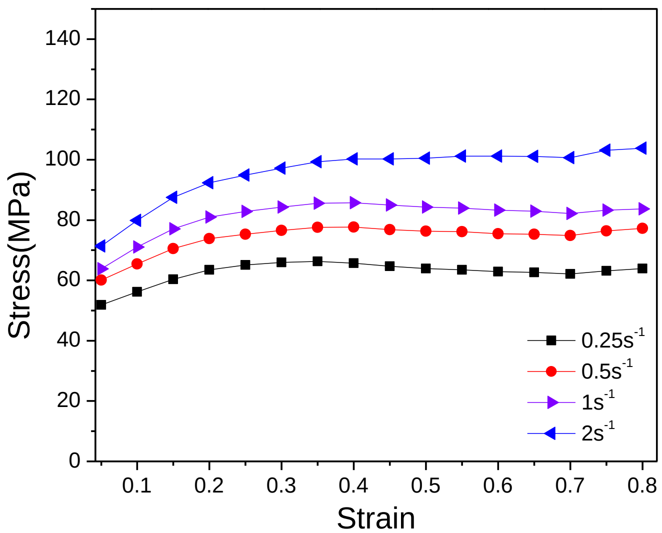
# Results

# ❑ Experimental Values

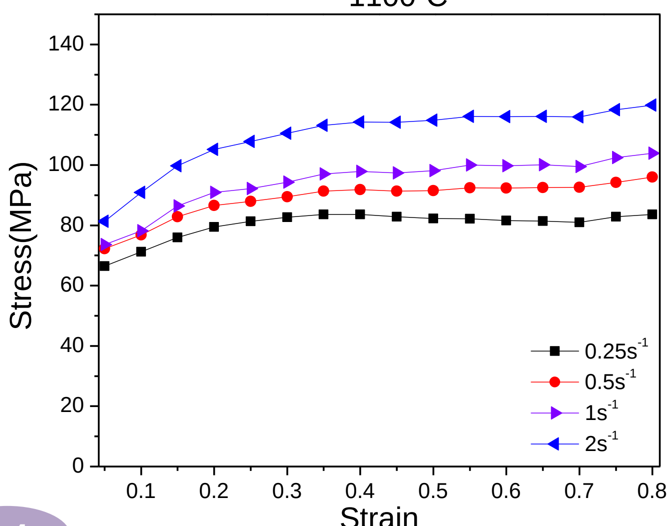
1200°C



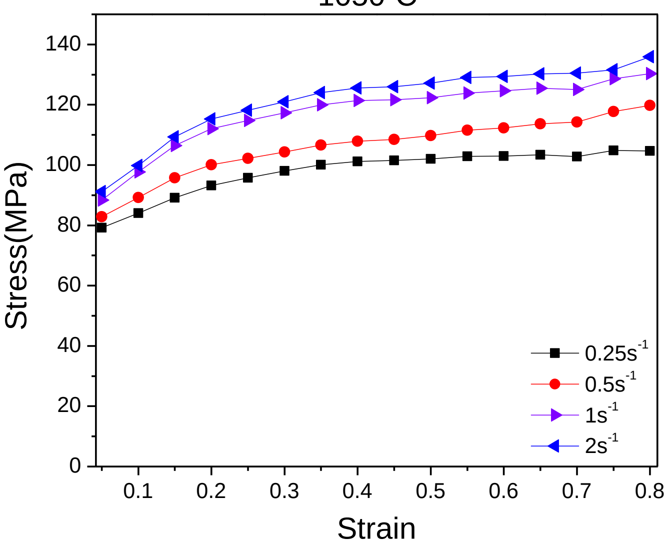

1150°C




1100°C




1050°C



# ❑ Material Model

$$\sigma = A - (A - B)\exp\left(-\frac{\varepsilon}{\varepsilon_0}\right)$$

→ **Strain hardening and dynamic recovery at large strains**

$$\sigma = k\varepsilon^n$$

→ **Strain hardening**

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) = A[\sinh(\alpha\sigma)]^{n'}$$

→ **Neglects the effects of strain**

$$\sigma = k\varepsilon^n \dot{\varepsilon}^m \exp\left(\frac{\beta}{T}\right)$$

→ **Simultaneous dependence on equivalent strain, strain rate and temperature**

$$\sigma = \frac{1}{\alpha}\sinh^{-1}\left[\frac{\dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)}{A}\right]^{\frac{1}{n'}}$$

→ **Accurate representation of the flow curve in hot deformation conditions**

$$\sigma = A\exp(m_1 T)T^{m_9}\varepsilon^{m_2}\exp\left(\frac{m_4}{\varepsilon}\right)(1+\varepsilon)^{m_5 T}\exp(m_7\varepsilon)\dot{\varepsilon}^{m_3}\dot{\varepsilon}^{m_8 T}$$

→ **Accurate representation of the flow curve in hot deformation conditions**

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)$$

→ **Accurate representation of the flow curve at high strain rate**

$$\sigma = \sigma_{ecr}(1 - W) + \sigma_{sat}W$$
$$\sigma_{ecr} = A(\dot{\varepsilon}, T)(\varepsilon + \varepsilon_0)^{B(\dot{\varepsilon}, T)}$$
$$\sigma_{sat} = C_0\exp(-C_1 T)\dot{\varepsilon}^{(C_2 + C_3 T)}$$
$$W = 1 - \exp(-R\varepsilon^{-s})$$

→ **Accurate representation of the flow curve in hot deformation conditions**

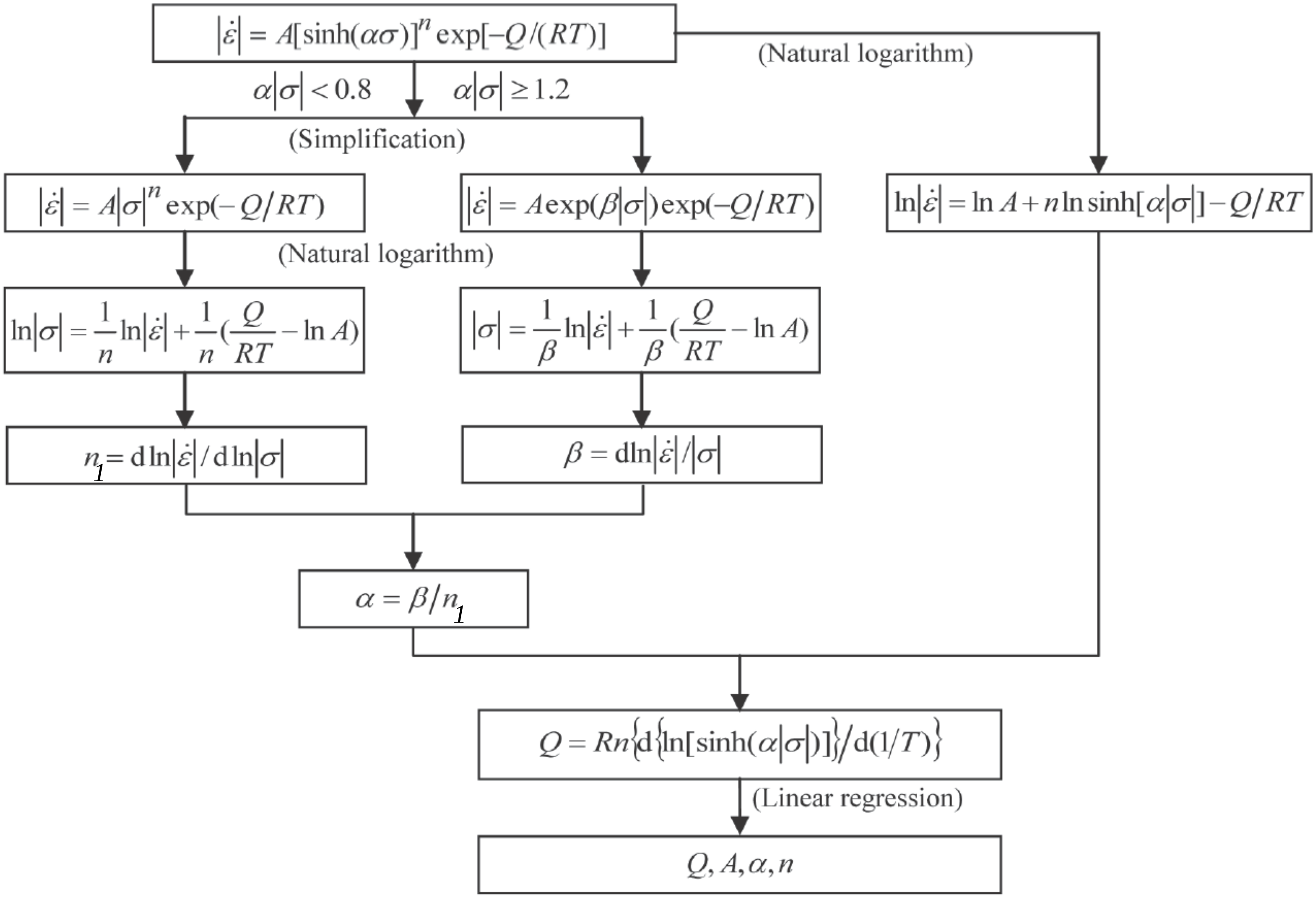
$$\sigma = \left[\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{st}}\right)^m \sigma_{st} + B\right]\exp\left[-p\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{st}}\right)^q (T - T_{st})\right]$$

→ **Deformation history taken into account when no recrystallization occurs**

## Advantages of Arrhenius Equation

- **Hyperbolic Sin Law, which can successfully predict high temperature deformation.**
- **Less number of material constants.**
- **Has been successful for predicting wide range of parameters.**

## ❑ Flow Diagram for Determining all Parameters in Zener Hollomon Constitutive Mode



# ❑ Calculation of Constants

$$\dot{\varepsilon} = A\,F(\sigma)\,\exp\left(-\frac{Q}{RT}\right)$$

$$F(\sigma) = \sigma^{n_1} \qquad (\alpha\sigma < 0.8)$$

$$F(\sigma) = \exp(\beta\sigma) \qquad (\alpha\sigma > 0.8)$$

$$F(\sigma) = [\sinh(\alpha\sigma)]^{n} \qquad (for\ all\ \sigma)$$

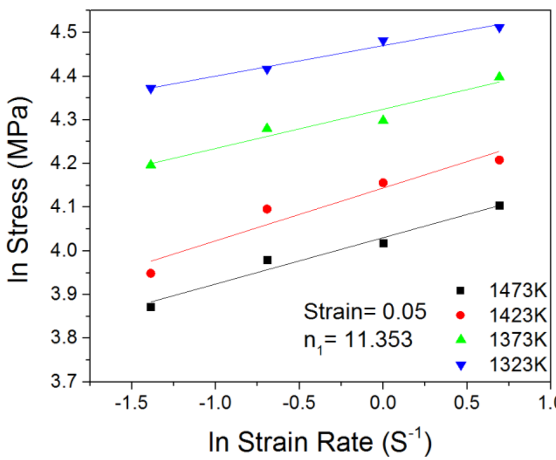
$$ln\sigma = \frac{ln\dot{\varepsilon}}{n_1} - \frac{lnB}{n_1}$$

$$\sigma = \frac{ln\dot{\varepsilon}}{\beta} - \frac{lnB'}{\beta}$$

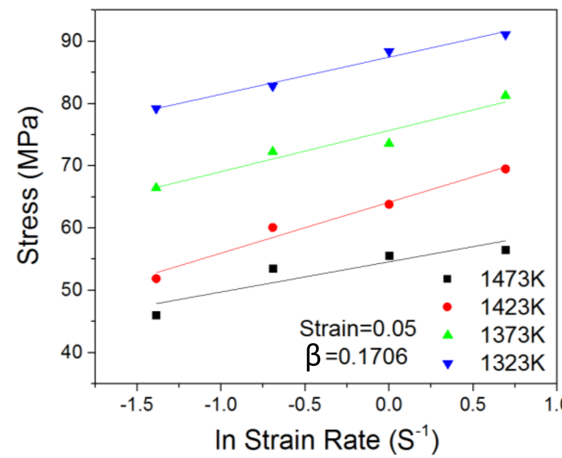
$$n = \frac{\partial ln\dot{\varepsilon}}{\partial ln[sinh(\alpha\sigma)]}\Big|T$$

$$Q = nR\,\frac{\partial ln[sinh(\alpha\sigma)]}{\partial(\frac{1}{T})}\Big|\dot{\varepsilon}$$

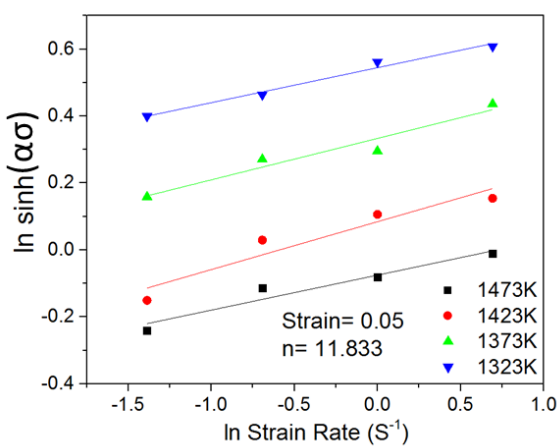
## $n_1$



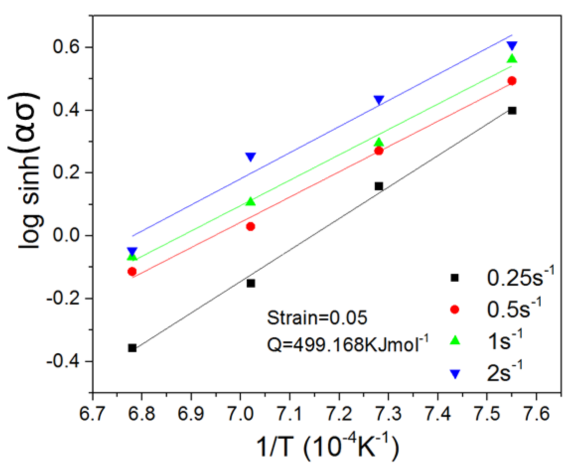

## β




## n




## Q



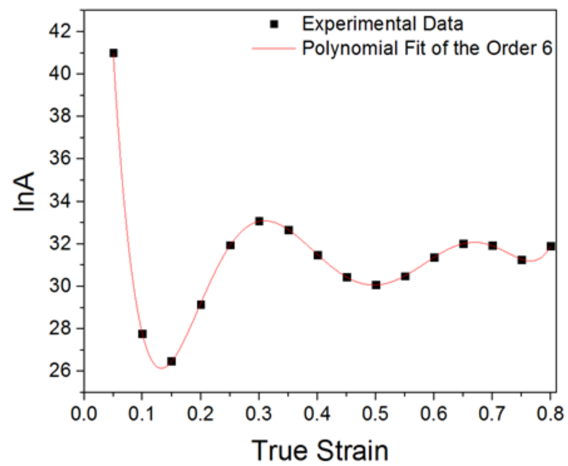
# ❑ Polynomial Function

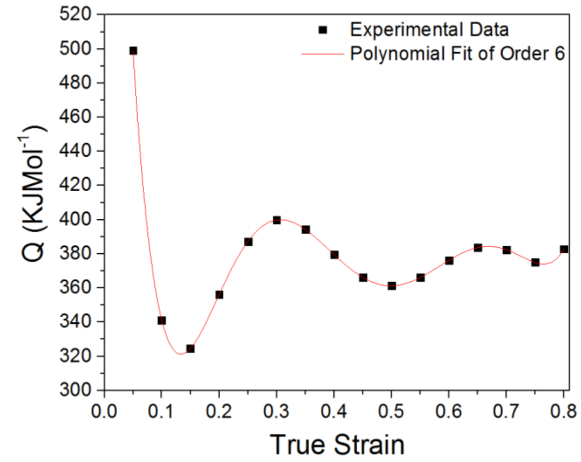
$$lnA = B_0 + B_1\varepsilon + B_2\varepsilon^2 + \cdots + B_m\varepsilon^m$$

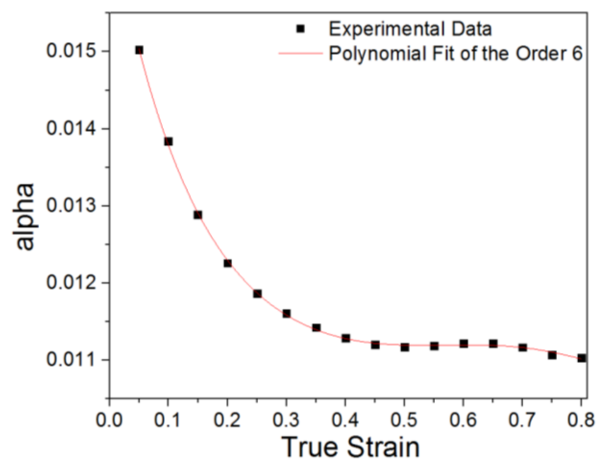
$$\alpha = C_0 + C_1\varepsilon + C_2\varepsilon^2 + \cdots + C_m\varepsilon^m$$

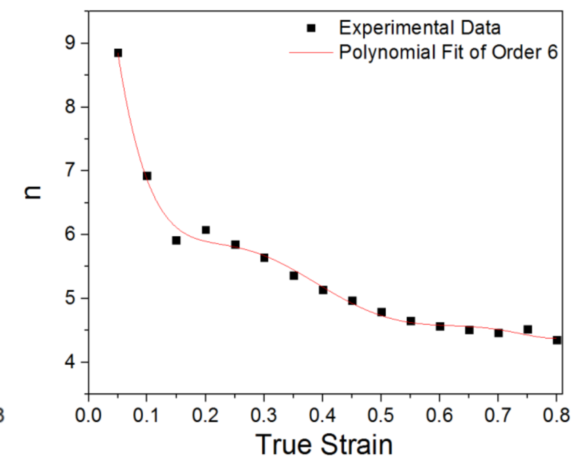
$$n = D_0 + D_1\varepsilon + D_2\varepsilon^2 + \cdots + D_m\varepsilon^m$$

$$Q = E_0 + E_1\varepsilon + E_2\varepsilon^2 + \cdots + E_m\varepsilon^m$$



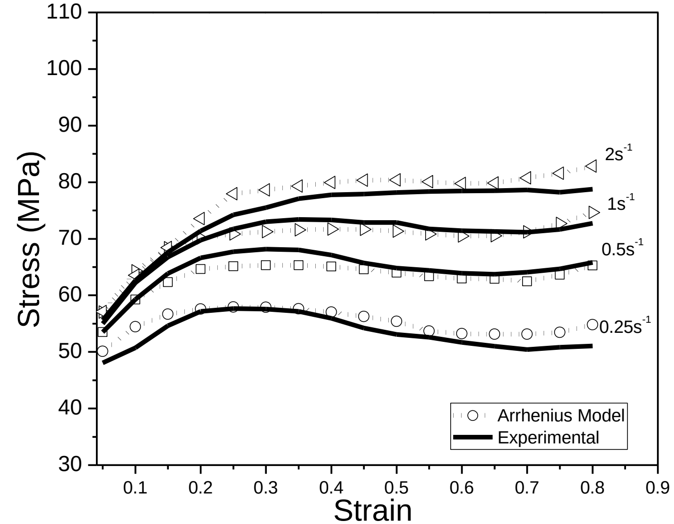



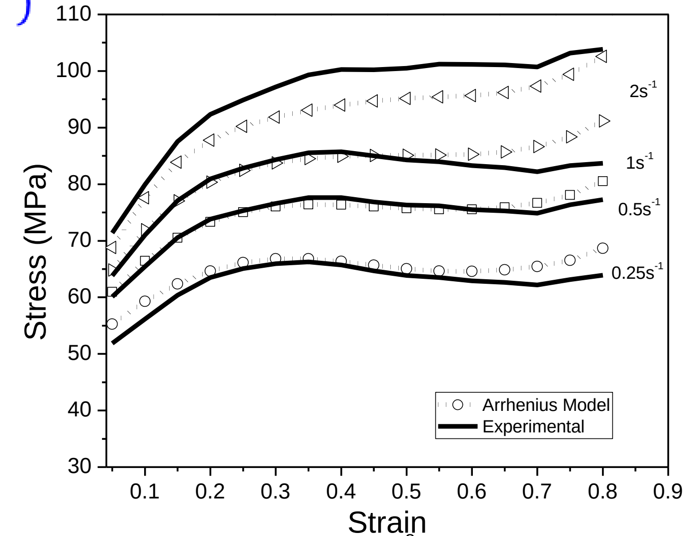
## Predicted Values

$$\sigma = \frac{1}{\alpha} \times \ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\}$$

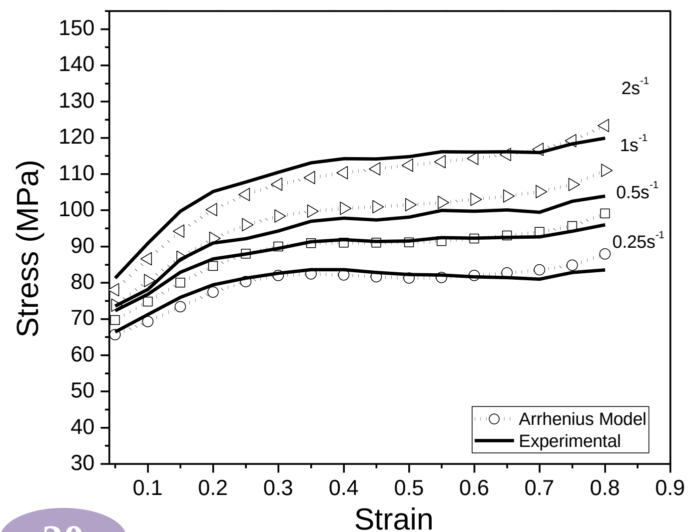
1200°C



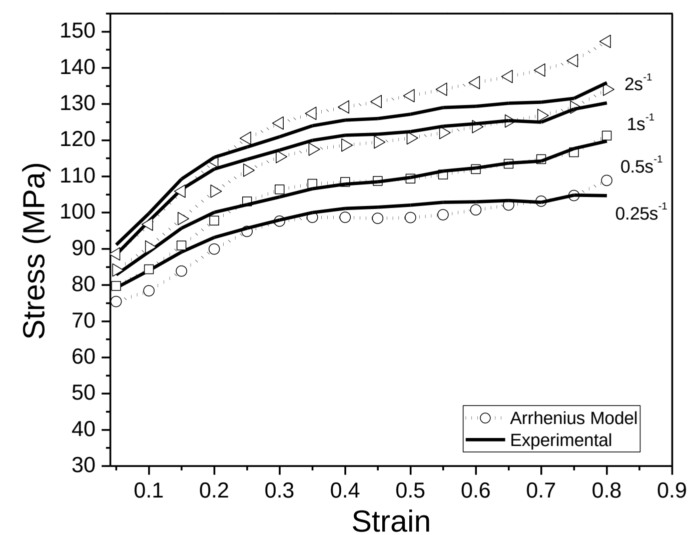

1150°C




1100°C



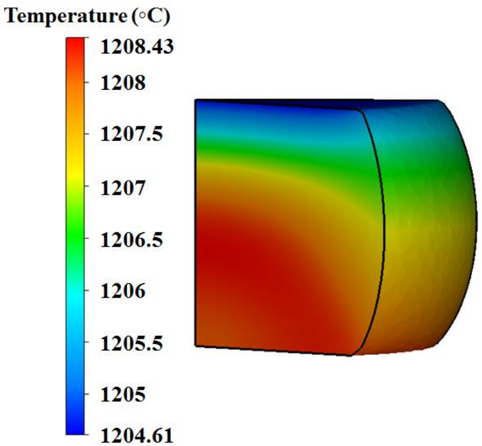

1050°C



# ❑ FEM Simulation

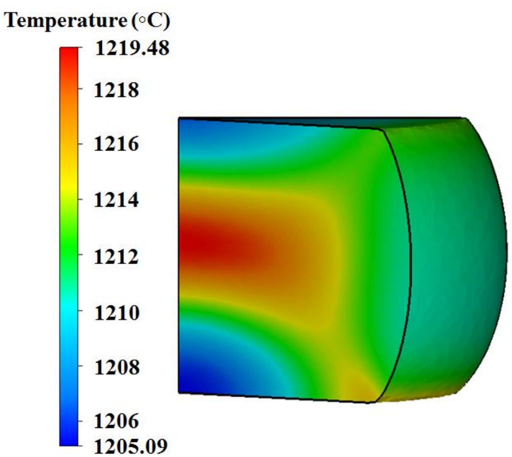
## Adiabatic Heating

$$\Delta T_{Adiabatic} = \frac{0.95 \int \sigma \, d\varepsilon}{\rho \, C_p}$$




Temperature 1200 ˚C ,Strain Rate $0.25 s^{-1}$

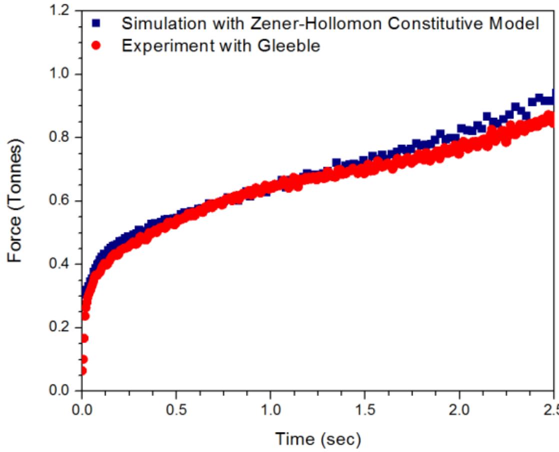
Simulated Adiabatic heating: 1208.4 ˚C
Theoretical Adiabatic Heating: 1208.24 ˚C



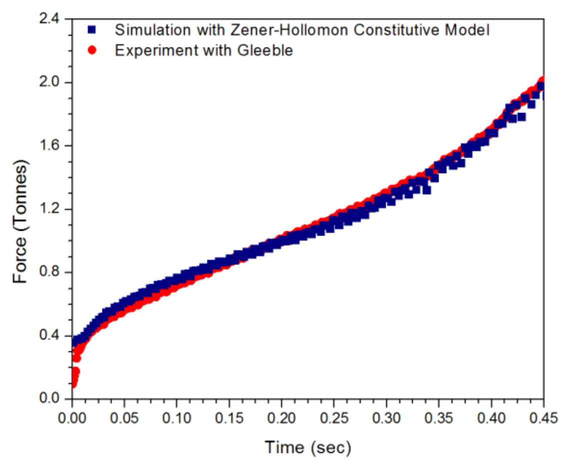

Temperature 1200 ˚C ,Strain Rate $2 s^{-1}$

Simulated Adiabatic heating: 1219.4 ˚C
Theoretical Adiabatic Heating: 1214.5 ˚C

## Force Calculation




Difference ~4%




Difference ~1%

## ❑ Conclusions

- ✓ **Hot compression of as-cast 42CrMo alloy reveals that at low strain rates, dynamic recrystallization occurs, whereas at low strain rate recovery occurs.**
- ✓ **Arrhenius model significantly predicts the flow curves. It is not only able to predict softening of flow stress due to dynamic recrystallization but takes into account the frictional effect at the end of deformation.**
- ✓ **Simulation results reveal that the model is able to predict the adiabatic heating during deformation at a slow strain rate, but not there is large variation in the values at higher strain rates. It can significantly predict the force with the time at both strain rates.**

# ❑ Acknowledgement

Industrial Research Chair in Forming Technologies of High Strength Alloys

*Thanks for Your Attention*

✓ **Question?**