Developing of a Material Card for FE Simulation

Contents

Aims and Objectives

Aims:

- Develop a **Material Card** for Aluminium 6111, for FE simulations, of a high temperature sheet metal forming process

Objectives

- Determine appropriate constants for constitutive equations to generate the material card:
  - $K_0, k_0, n_0, B_0, A_0, C_0, E_0, Q_K, Q_k, Q_n, Q_B, Q_A, Q_C$ *and* Q_E
- Produce a cost analysis, highlighting the benefit of the material card
- Evaluate the sustainability affects of the material card

Data Provided

Uniaxial tensile test data for constant strain rate and constant temperature

Constant Temperature

Temperature (°C)	Strain rate (s^{-1})
300	0.1
	3.0
	5.0
535	0.1
	3.0
	5.0

Constant Strain Rate

Temperature (°C)	Strain rate (s^{-1})
200	1
250	1
300	1
350	1
400	1
450	1
500	1
535	1

Fundamentals

Fundamental Principles

ε_p *Plastic Strain*

R *Universal Gas Constant*

$\dot{\rho}$ *Dislocation Density*

Aluminium alloys are elastic-plastic materials so mechanical properties are dependent on both **temperature (T)** and **strain rate (SR).**

At high Ts and SRs, material displays visco-plastic behaviour which is modelled using the constitutive equations:

Isotropic hardening

$$\dot{R} = 0.5B\bar{\rho}^{-0.5}\dot{\bar{\rho}}$$

Viscoplastic flow rule

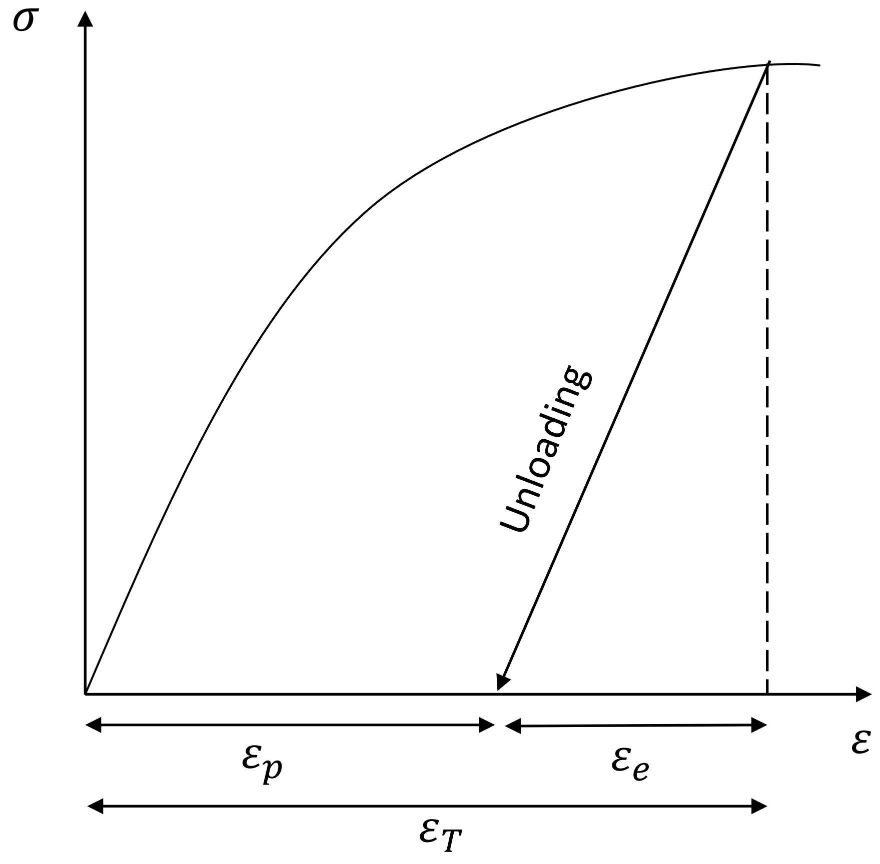
$$\dot{\varepsilon}_p = \left(\frac{\bar{\sigma} - R - k}{K}\right)^{n_1}$$

Rate of change of normalised dislocation density

$$\dot{\bar{\rho}} = A(1 - \bar{\rho})\dot{\varepsilon}_p - C\bar{\rho}^{n_2}$$

Flow stress

$$\bar{\sigma} = E(\varepsilon_t - \varepsilon_p)$$



These models can only be used to predict yielding and hardening or softening as they do not predict the failure of the material.

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Fundamental Principles

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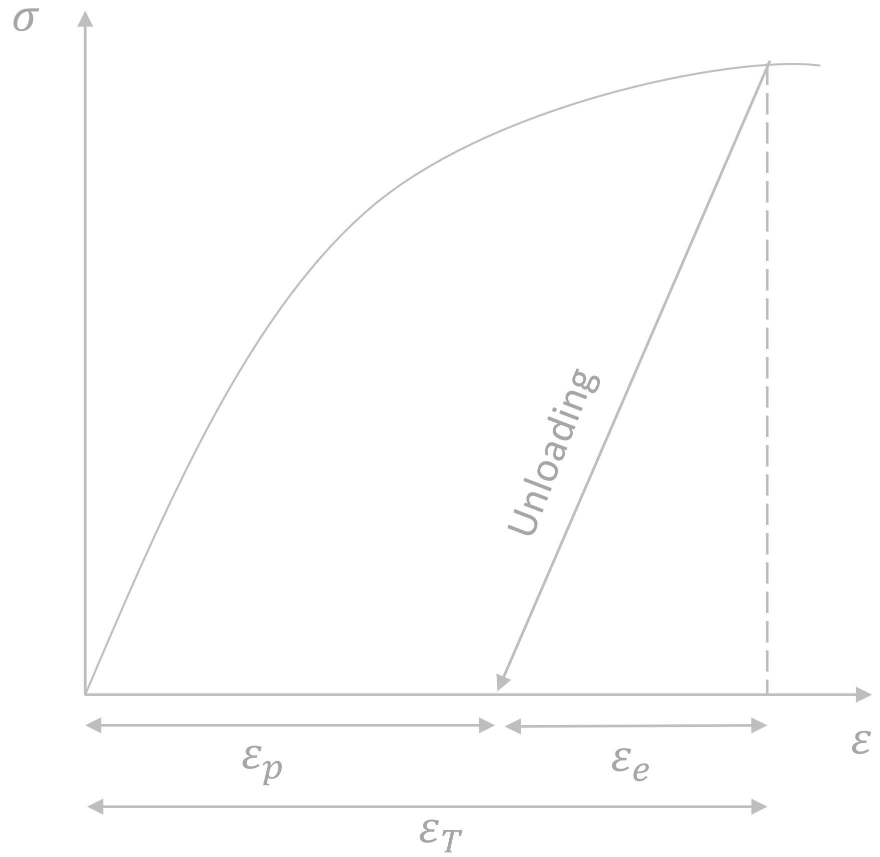

These models can only be used to predict yielding and hardening or softening as they do not predict the failure of the material.

Temperature Dependencies

Q_x	$Activation\ Energy$
x_0	$Temp.\ Dependent\ Constant$
T	$Temperature\ (K)$

The temperature dependent constants follow the Arrhenius relationship.

General form

$$x = x_0 e^{\left(\frac{Q_x}{RT}\right)}$$

$$K = K_0 e^{\left(\frac{Q_K}{RT}\right)}$$

$$k = k_0 e^{\left(\frac{Q_k}{RT}\right)}$$

$$B = B_0 e^{\left(\frac{Q_B}{RT}\right)}$$

$$C = C_0 e^{\left(\frac{Q_C}{RT}\right)}$$

$$E = E_0 e^{\left(\frac{Q_E}{RT}\right)}$$

$$n_1 = n_{1_0} e^{\left(\frac{Q_{n_1}}{RT}\right)}$$

The Approach

Data Cleaning & Filtration

Clean and filter the data so it is in an appropriate form for model fitting

Model Fitting

Find material constants in each situation and fit models using appropriate methods.

Regenerate constants

Find Arrhenius constants and regenerate fitted curves based on them (Constant SR only)

Error Analysis

Conduct error analysis to determine the validity of generated models.

Material Card Creation

Create a material card that is ready to use within FE models.

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Data Cleaning

Data Cleaning Process

1. Average Data

Use all the repeats for the same experiments to form an average for each of the tensile tests.

2. Cut Data

Cut the data beyond the ultimate tensile strength (UTS) point of curves so that model is appropriate for FE.

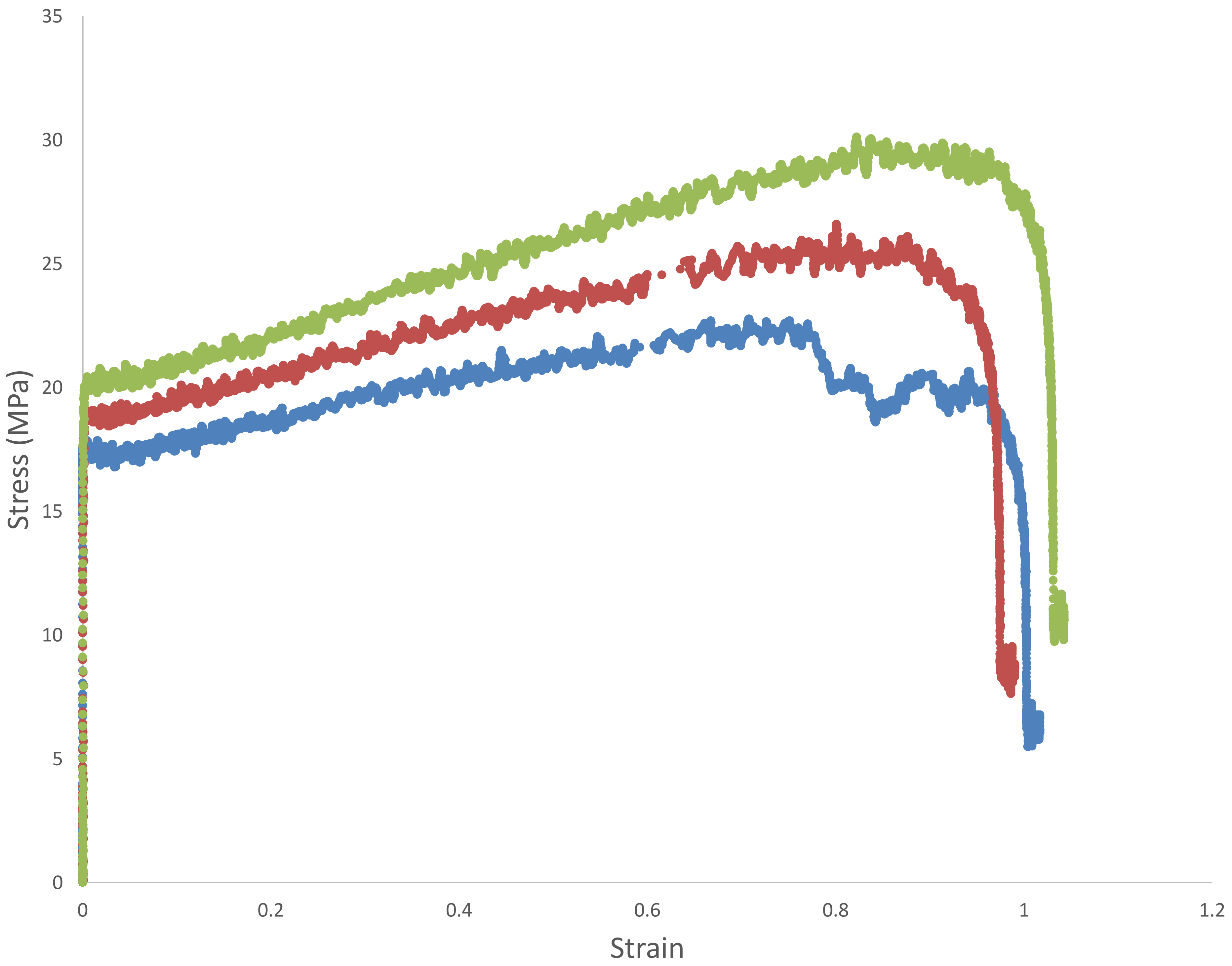
3. Smoothen Data

Eliminate the fluctuations by smoothing the data with the use of Origin smoothing software.

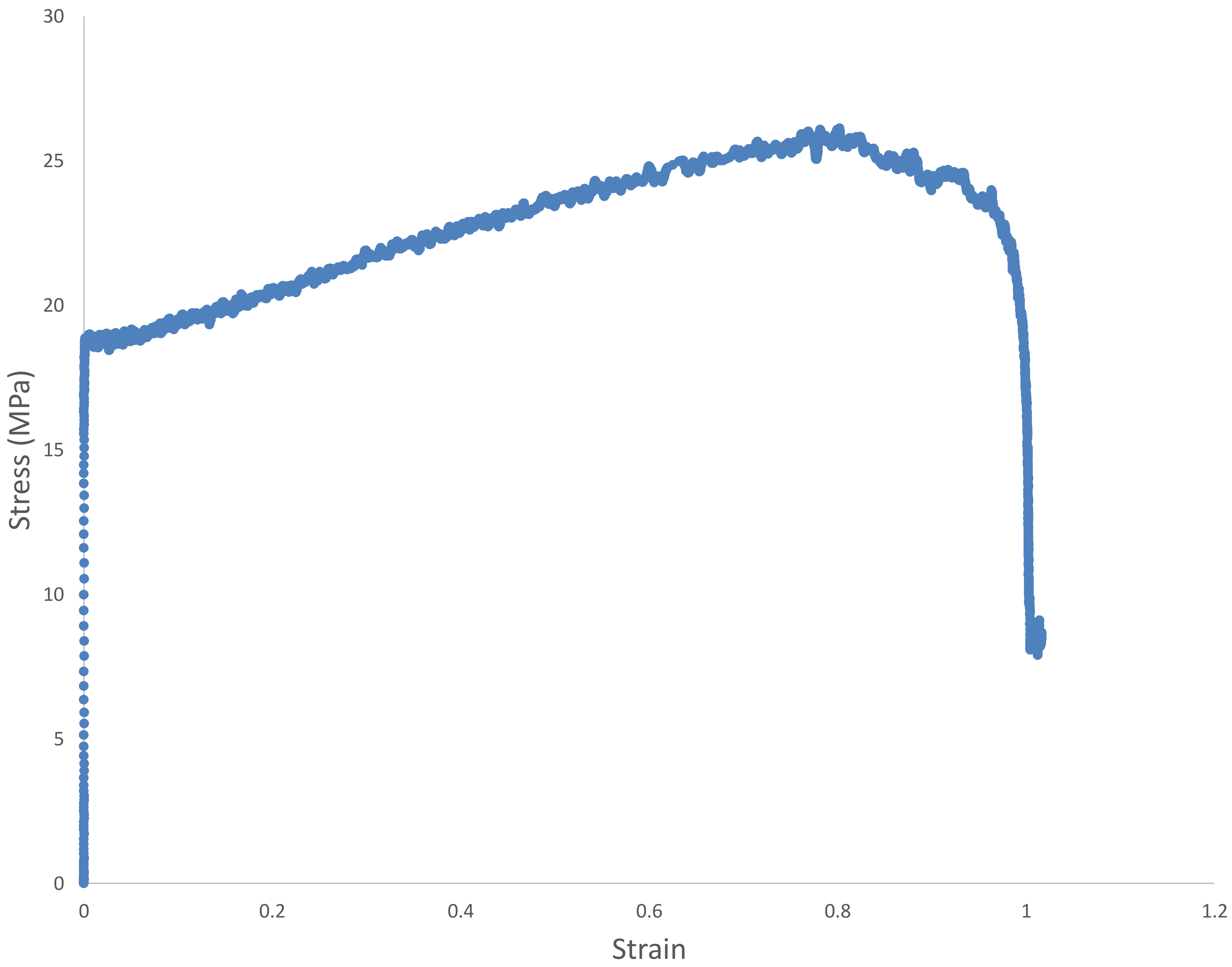
4. Data Elimination

Reduce the number of data points to prepare base to which model is fitted.

Data Cleaning Example



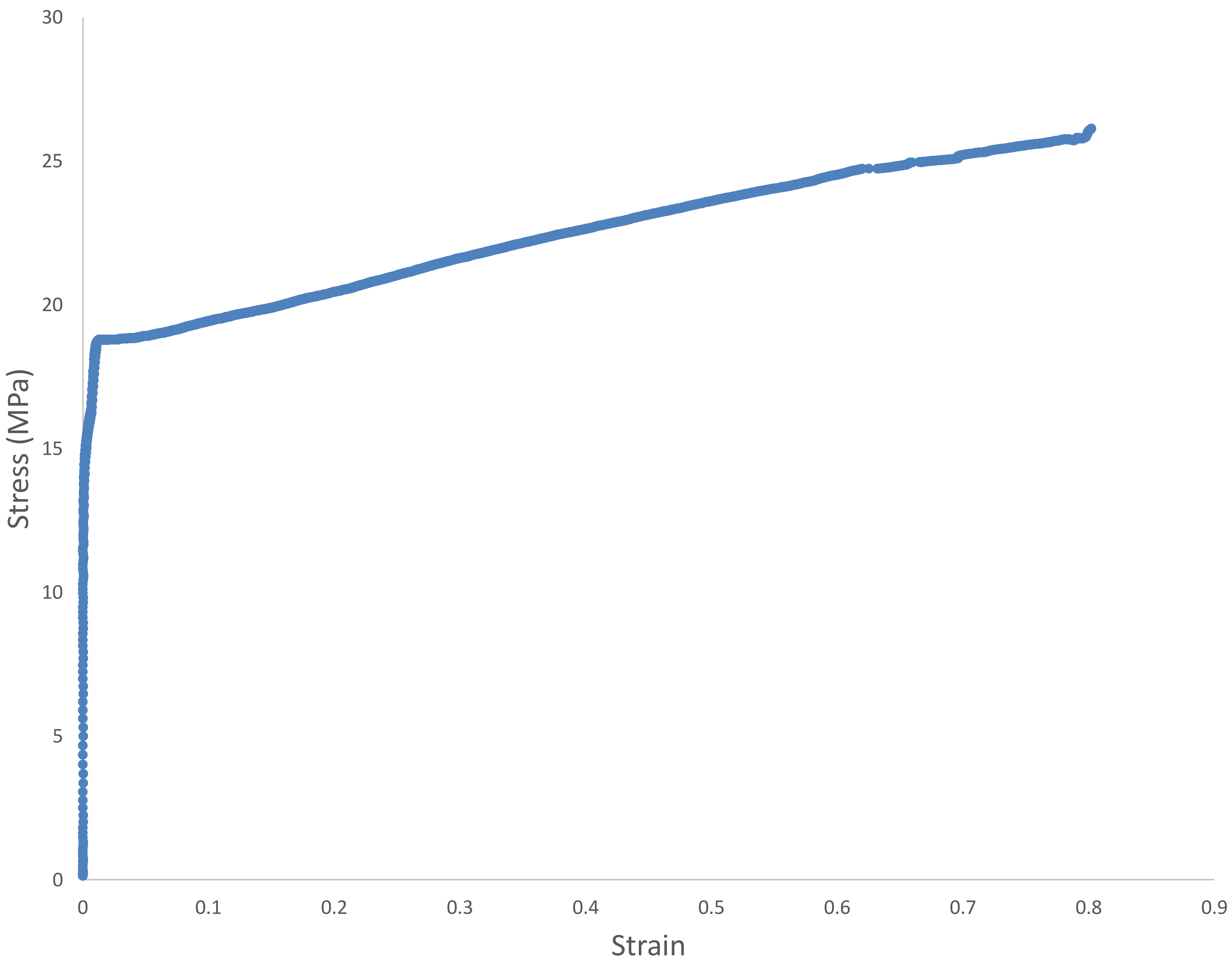
Export Data



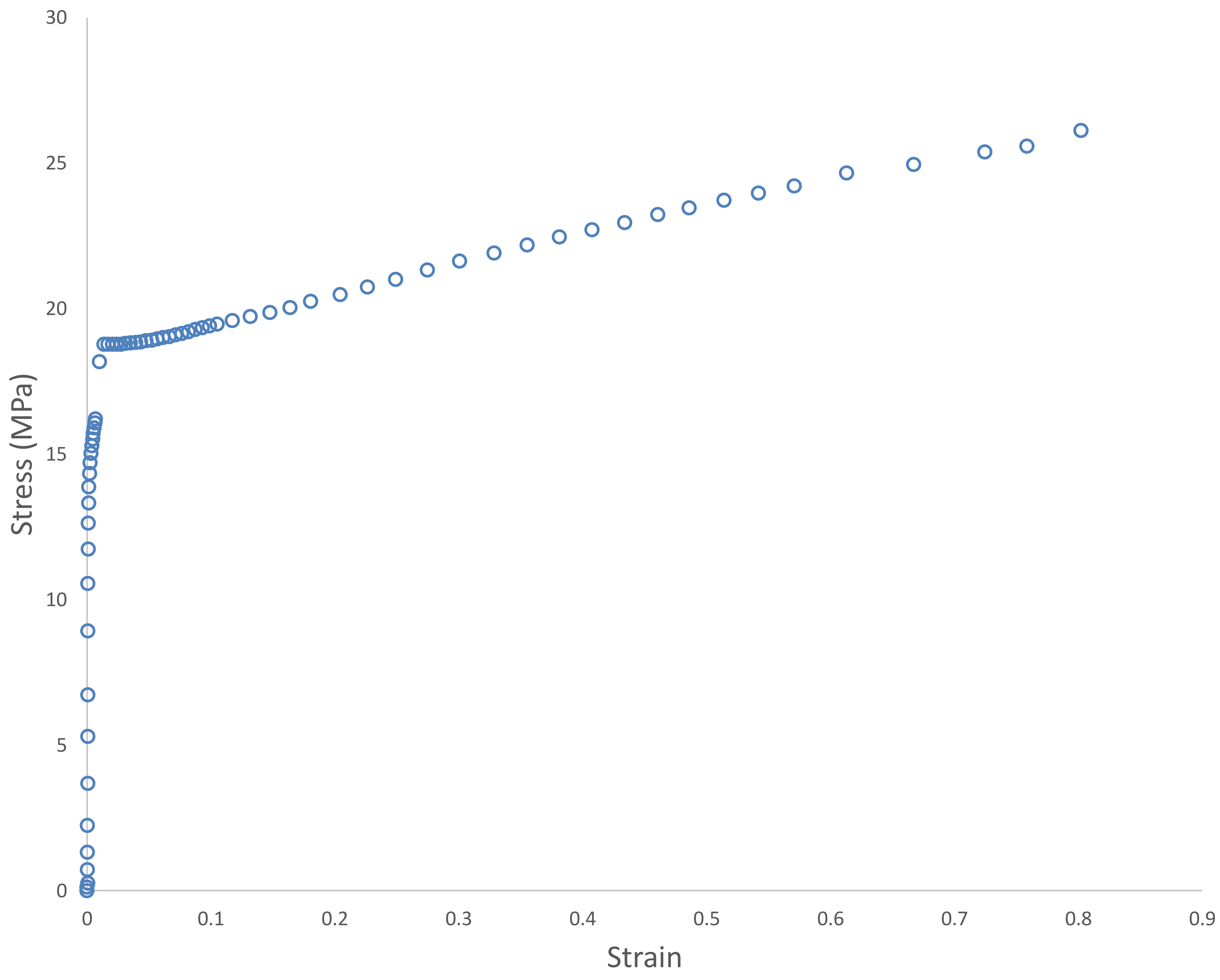
Average Data

Data: SR0.1 Temp 535 deg

Data Cleaning Example



Cut-off and Remove fluctuations



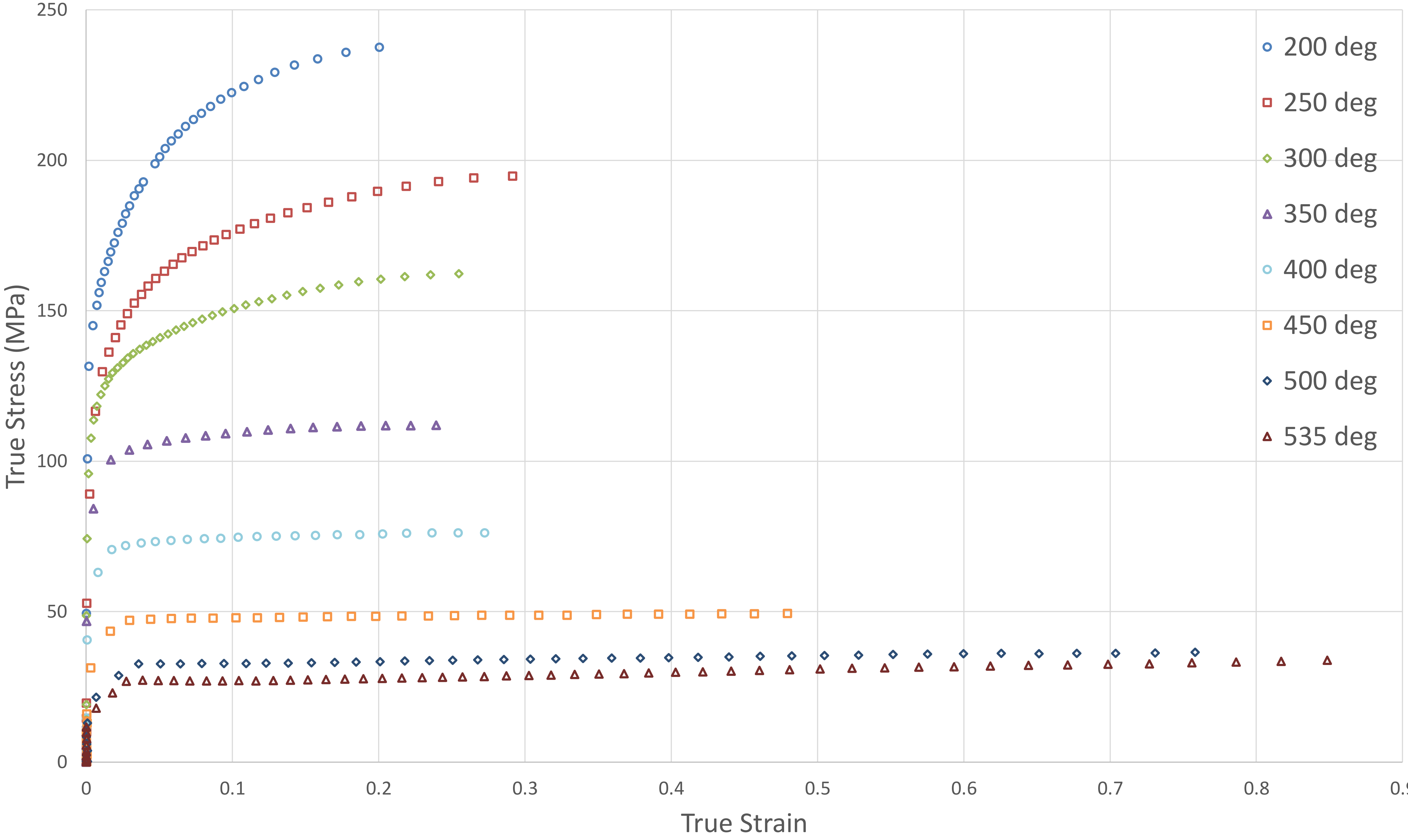
Reduce Data points

2

Model Fitting

Model Fitting (1)

- Plotted reduced data on stress-strain curves
- Temperature example shown



Model Fitting (2) – Integration Method

Forward Euler integration method used as:

- Quick and easy to implement
- Stable for a range of Arrhenius constants
- Computationally efficient

INPUT

Temperature dependent Arrhenius constants:

- K
- k
- B
- C
- E
- η_1
- η_2
- A
- n_1

Temperature independent:

- n_2
- T – time step

OUTPUT

- Stress
- Strain

Model Fitting (2) – Integration Method

ε_p *Plastic Strain*

R *Universal Gas Constant*

$\dot{\rho}$ *Dislocation Density*

Assign an appropriate time step

Initialise variables to 0

Use Forward Euler to find the next value of variables

Iterate to max strain value

Plot on a stress-strain curve

$$\dot{R}_i = 0.5B\sqrt{\bar{\rho}_{i-1}}$$

$$\dot{\varepsilon}_{p_i} = \left|\frac{\bar{\sigma}_{i-1} - R_{i-1} - k}{K}\right|^{n_1}$$

$$\dot{\rho}_i = A(1 - \bar{\rho}_{i-1})\dot{\varepsilon}_{p_{i-1}} - C\bar{\rho}_{i-1}{}^{n_2}$$

$$\varepsilon_{p_i} = \varepsilon_{p_{i-1}} + \dot{\varepsilon}_{p_{i-1}}\Delta t$$

$$\rho_i = \rho_{i-1} + \dot{\rho}_{i-1}\Delta t$$

True Strain: $\varepsilon_{T_i} = \dot{\varepsilon}_t t$

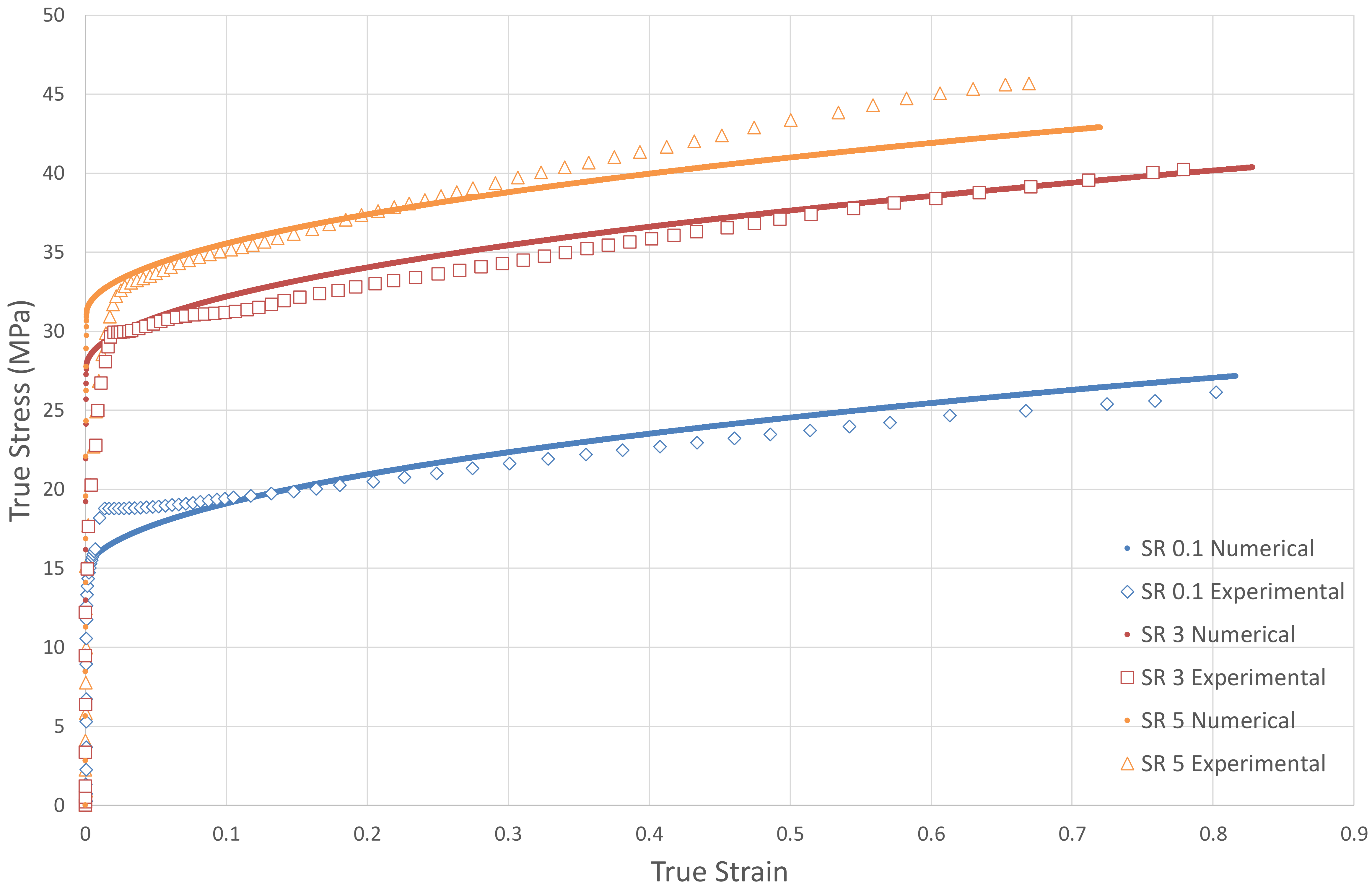
True Stress: $\bar{\sigma}_i = E(\varepsilon_{T_i} - \varepsilon_{p_i})$

Model Fitting (2) – Integration Method

Constant	Increasing Constant
K	Shifts the curve upwards
k	Shifts the curve upwards (smaller effect than K)
B	Increases the steepness of the strain hardened section and shifts curve upwards
C	Shifts the end of the curve downwards
E	Young's modulus does not affect the curve hugely, decreases slightly with temperature
A	Increases the initial curvature/bend of the resulting curve
n1	Increases strain rate sensitivity, but little effect on curve
n2	Temperature independent, increases gradient of the graph

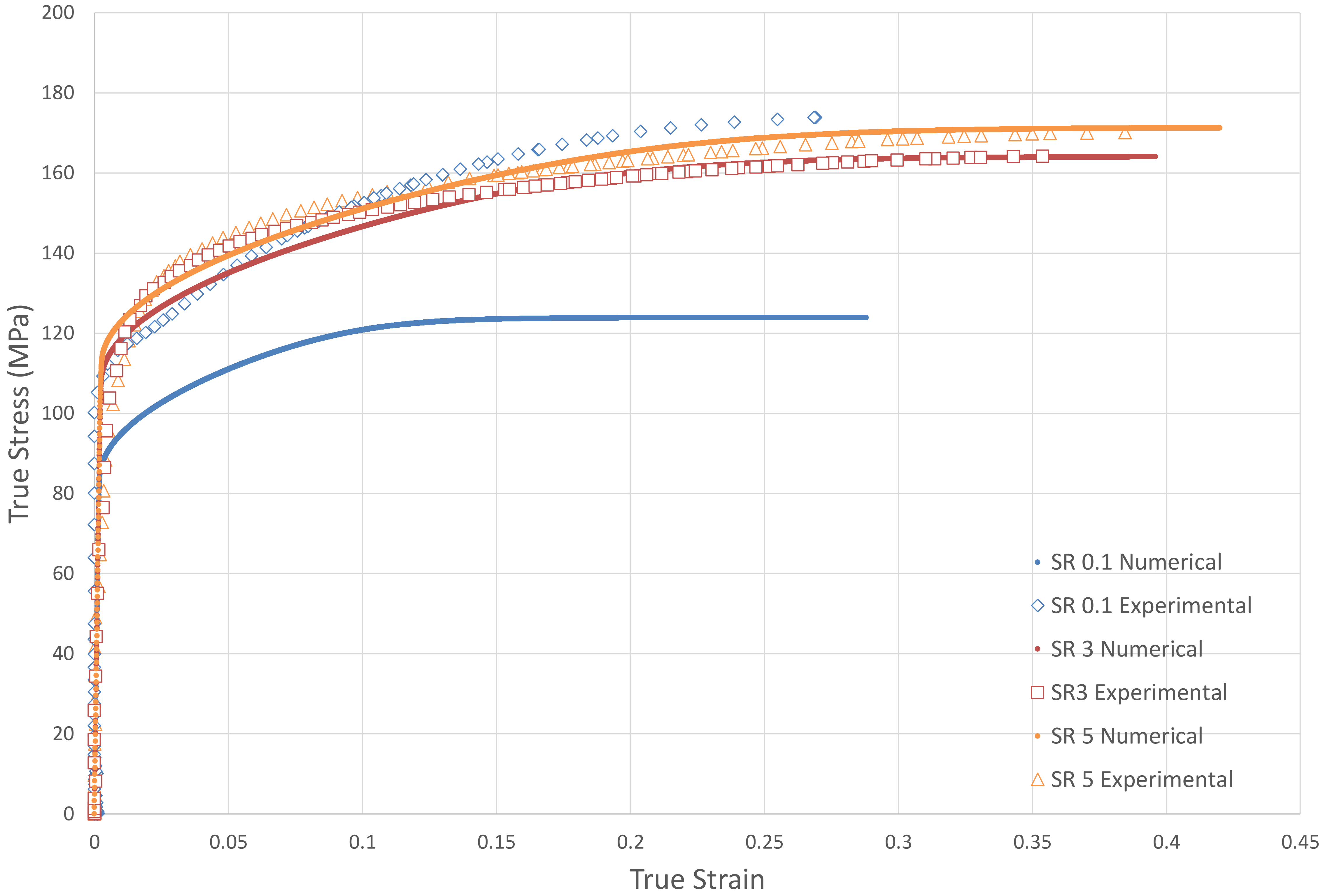
Model Fitting (3) – Manual Fitting (Strain)

- The model was fitting to various strain values at 535°C



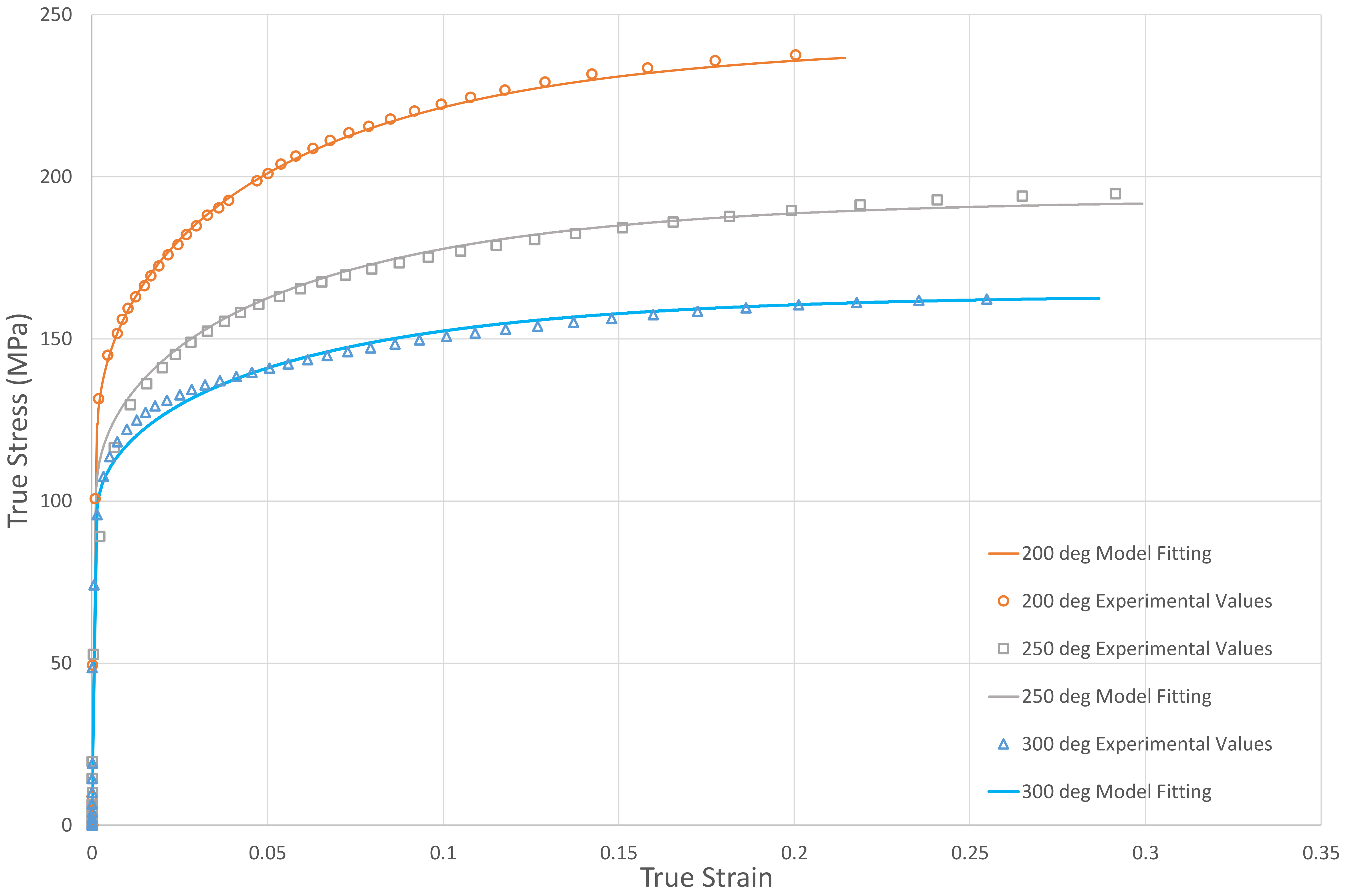
Model Fitting (3) – Manual Fitting (Strain)

- The model was fitting to various strain values at 300°C



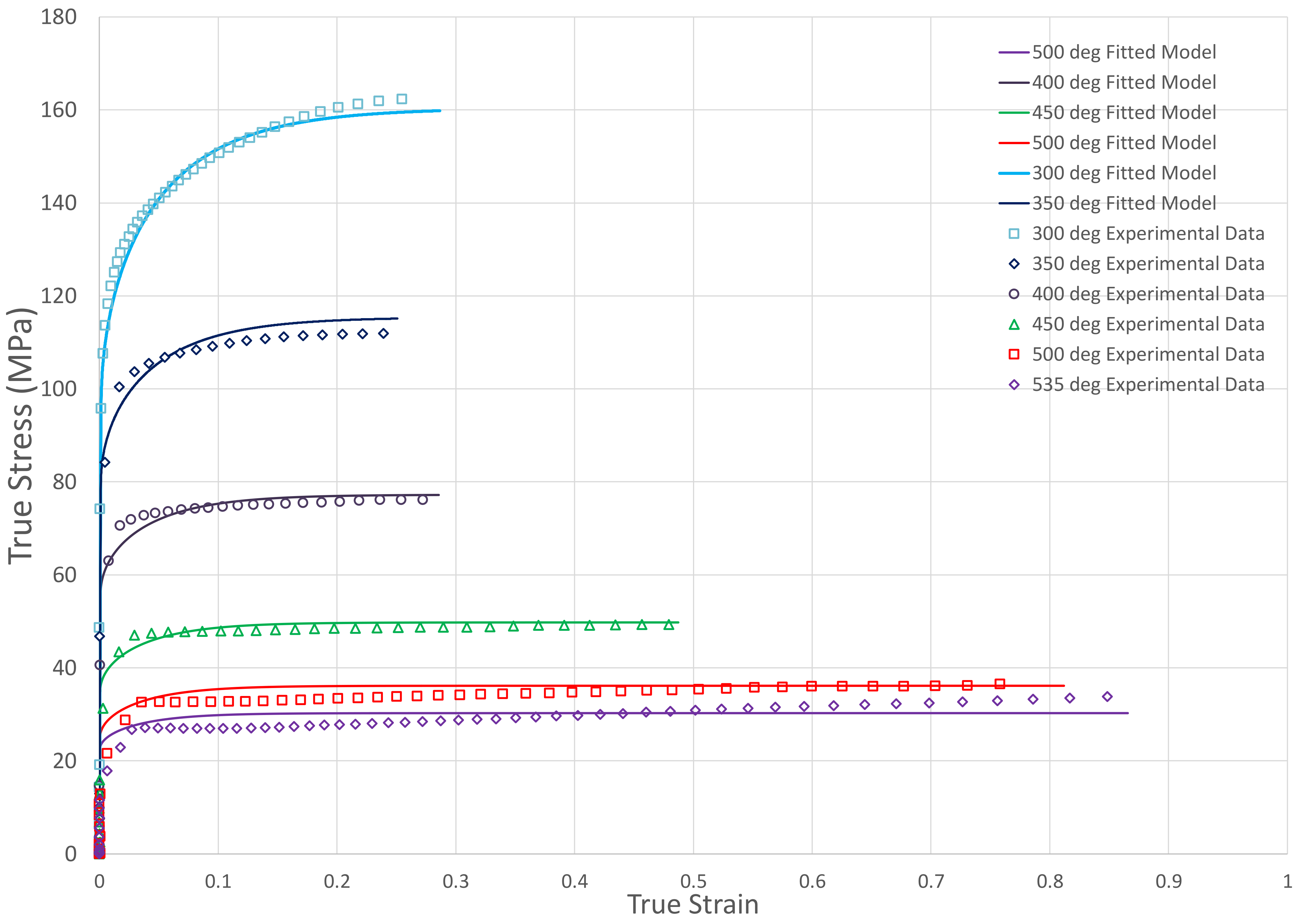
Model Fitting (3) – Manual Fitting (Temp)

- The model was fitted to temperature values between 200°C - 300°C at a strain rate of 1.



Model Fitting (3) – Manual Fitting (Temp)

- The model was fitted to temperature values between 300ºC - 535ºC at a strain rate of 1.



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Regenerate Constants

Arrhenius Fits

We expect the temperature dependent constants to follow the Arrhenius form:

$$x = x_0 e^{\left(\frac{Q_x}{RT}\right)} \longrightarrow \ln(x) = \ln(x_0) + \frac{Q_x}{R} * \frac{1}{T}$$

The two requirements:

- Fit curves of flow stress well
- Follow the expected relationship

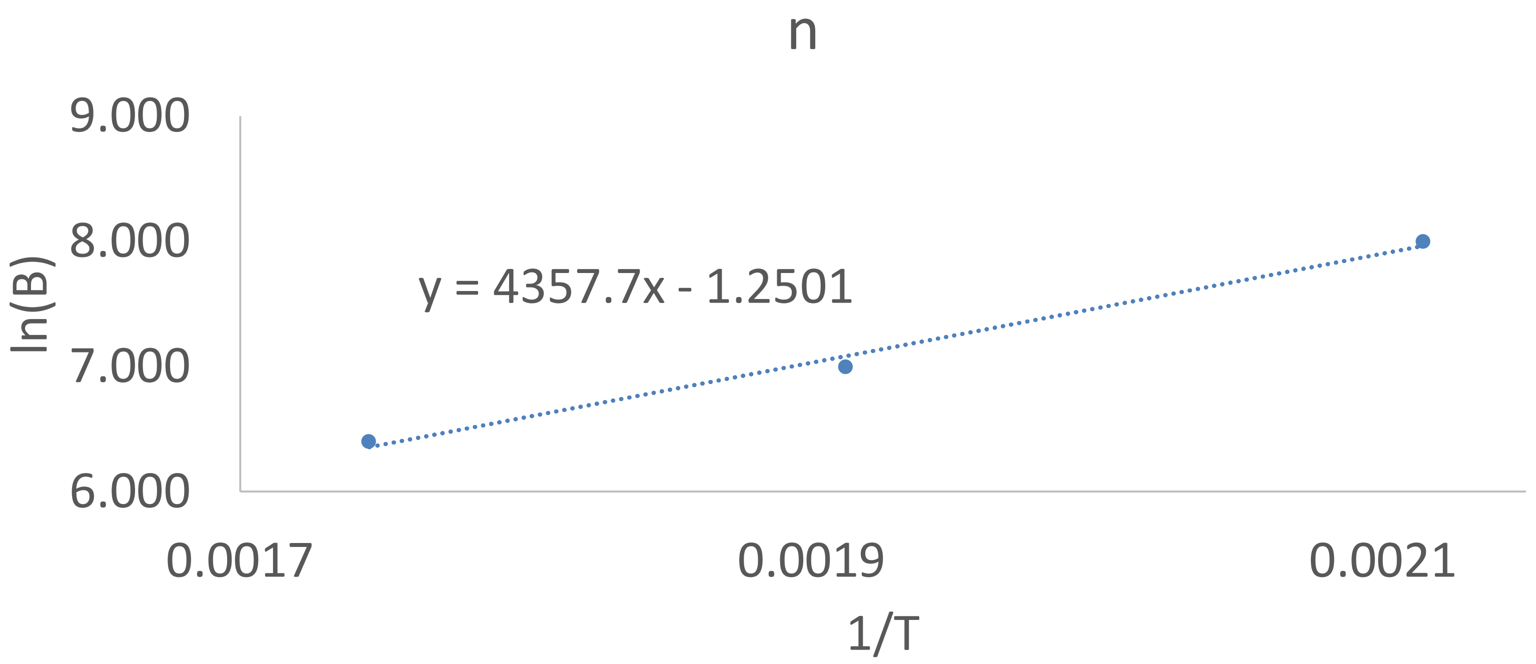
Expected relationship

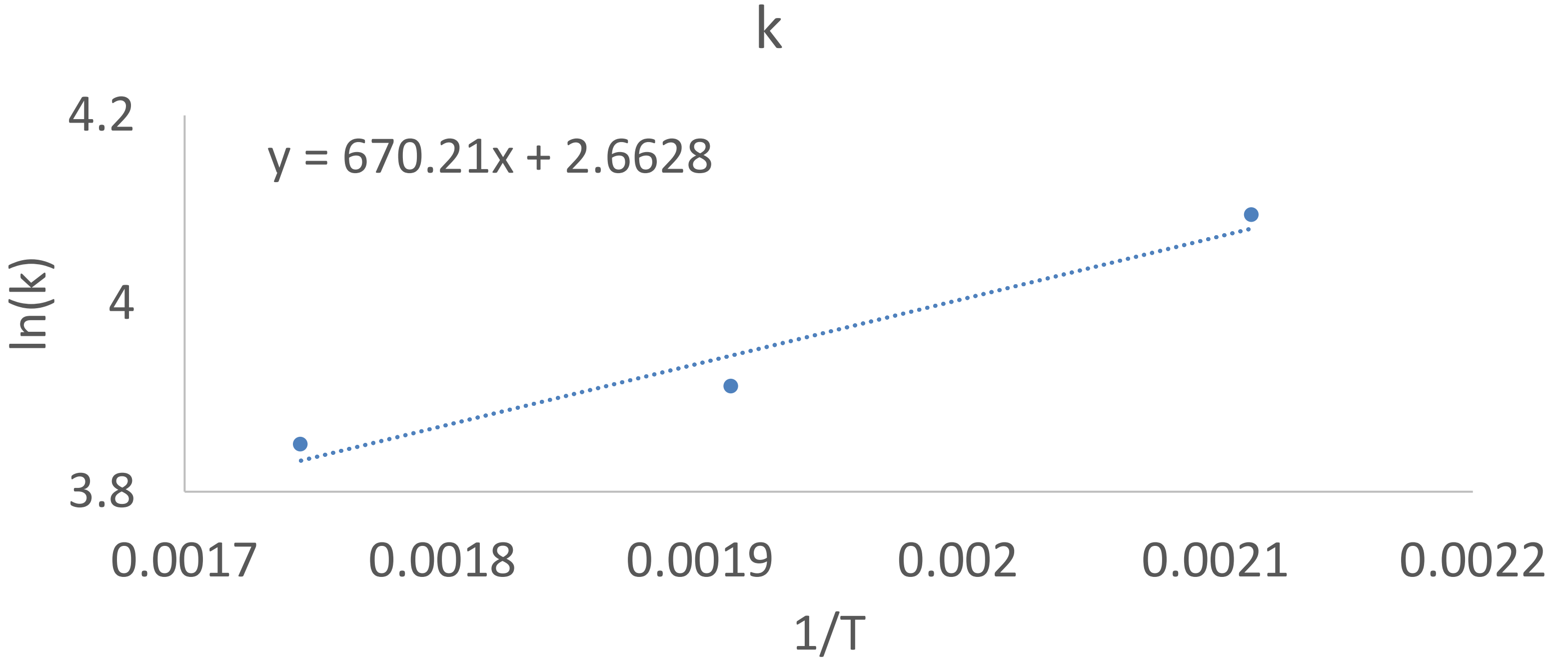
Therefore, for each constant we have found (under constant strain rate), we expect to find that the constant is a function of 1/T.

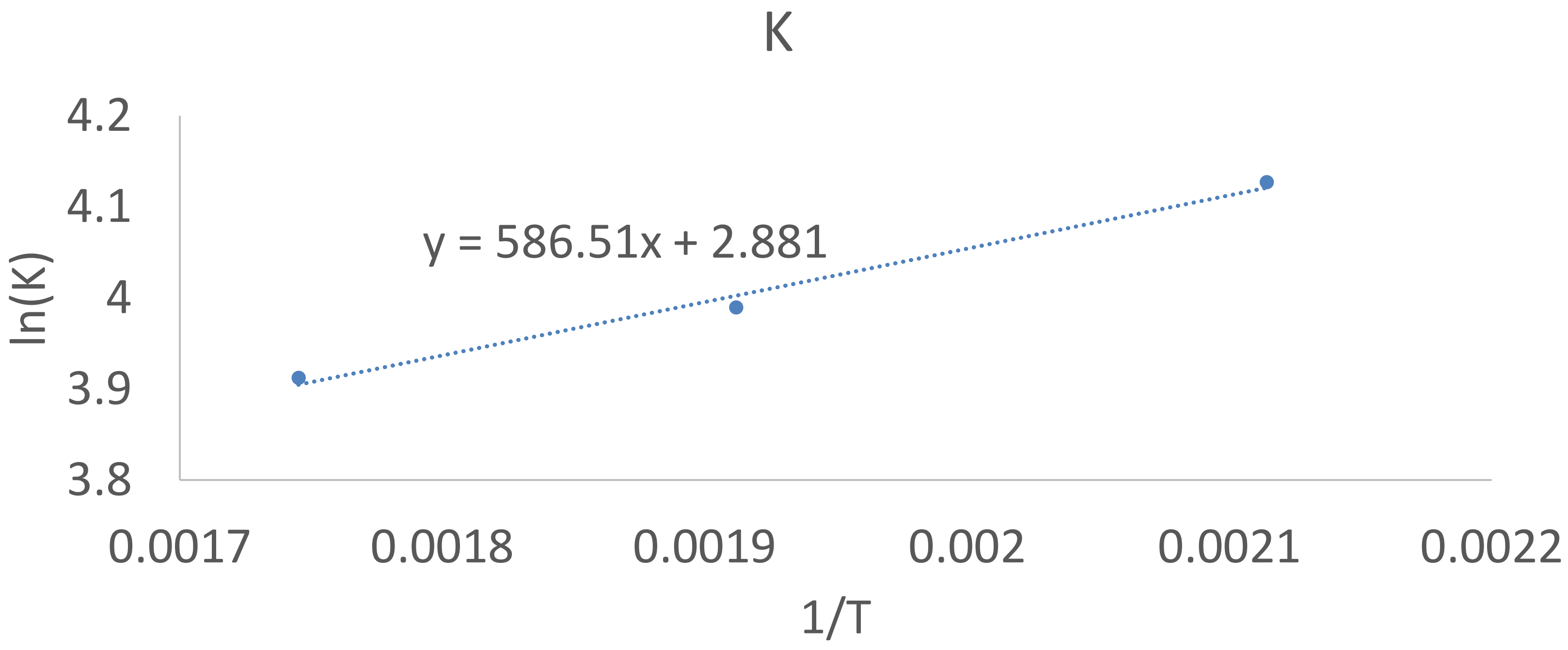
We noticed a **difference in sensitivity between 200-300ºC and 300-535ºC**.

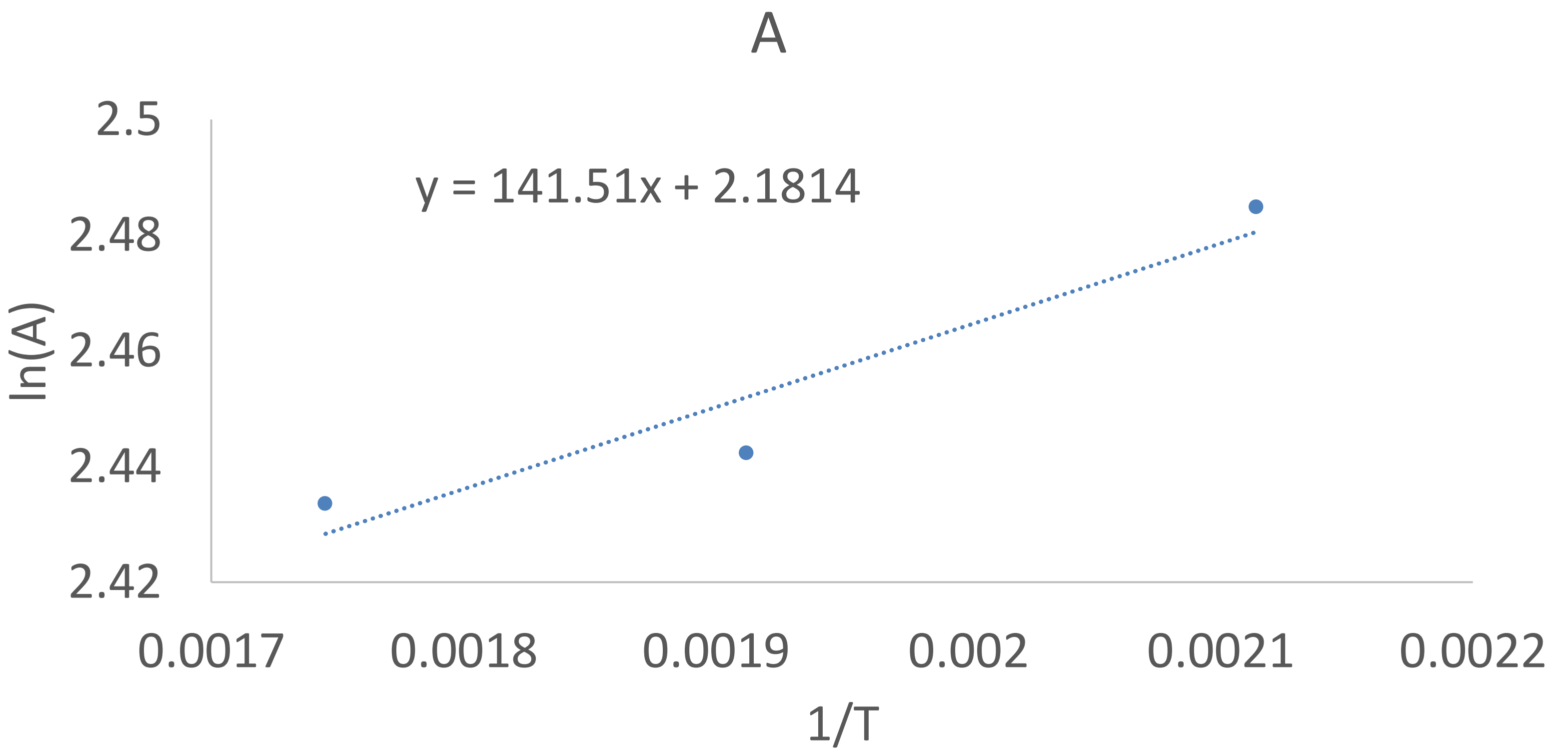
This is explained due to **viscoplastic nature of material**, and so we provide two sets of Arrhenius constants

Arrhenius Fits (200-300°C)

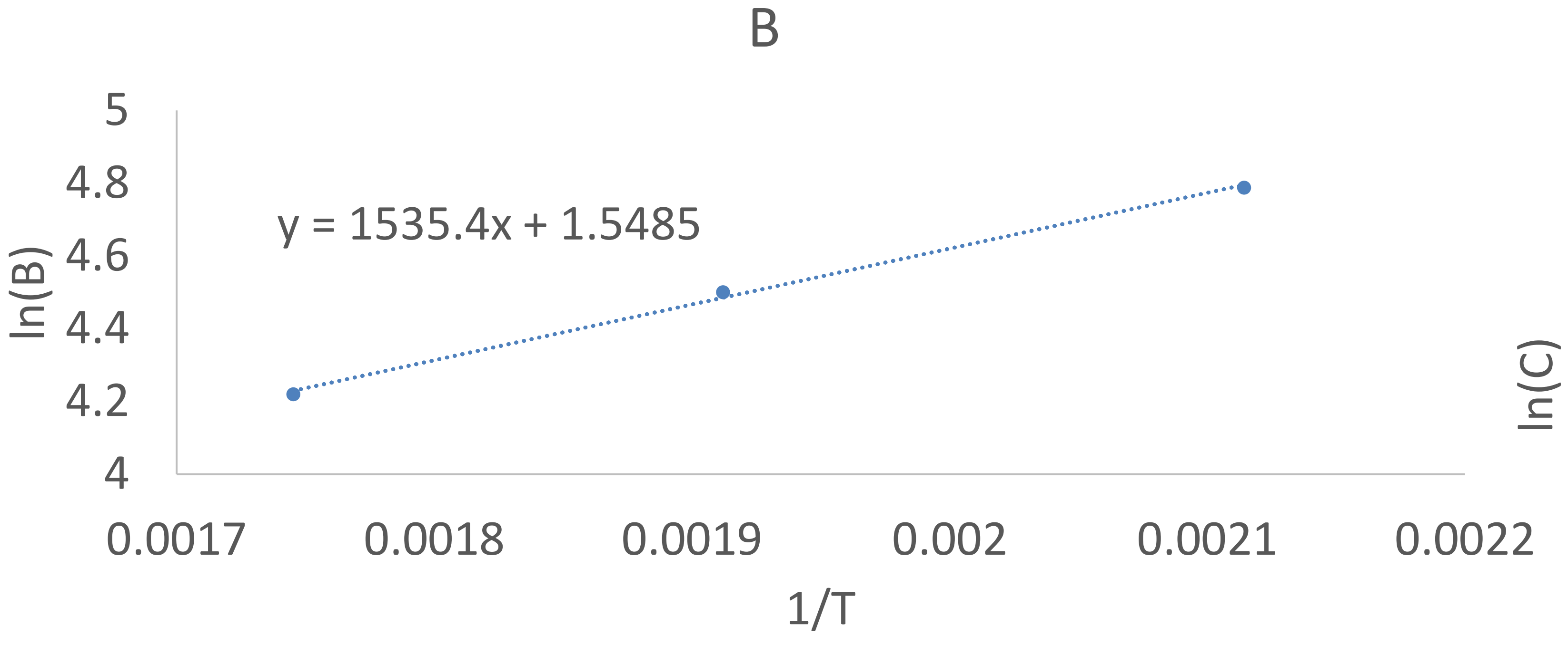


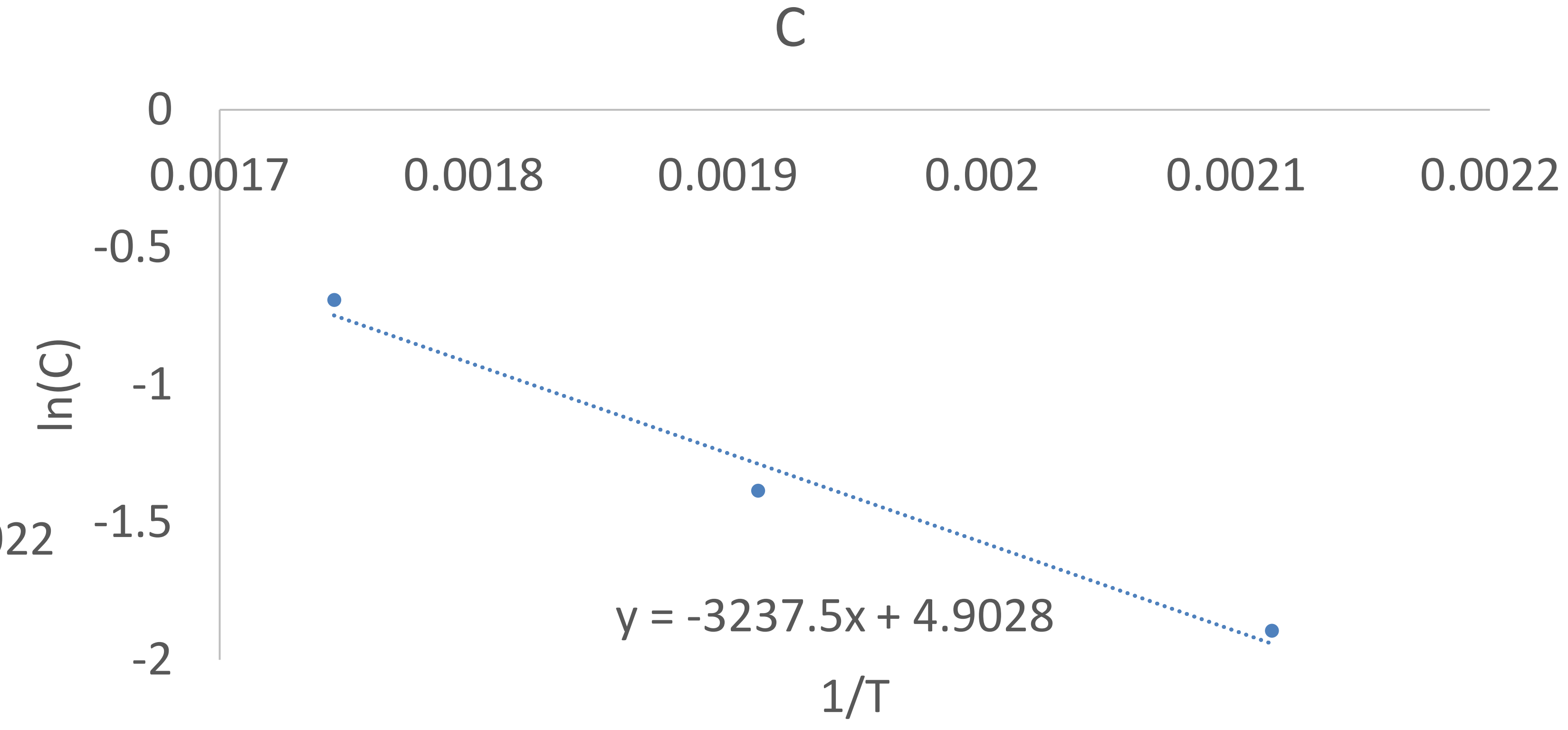


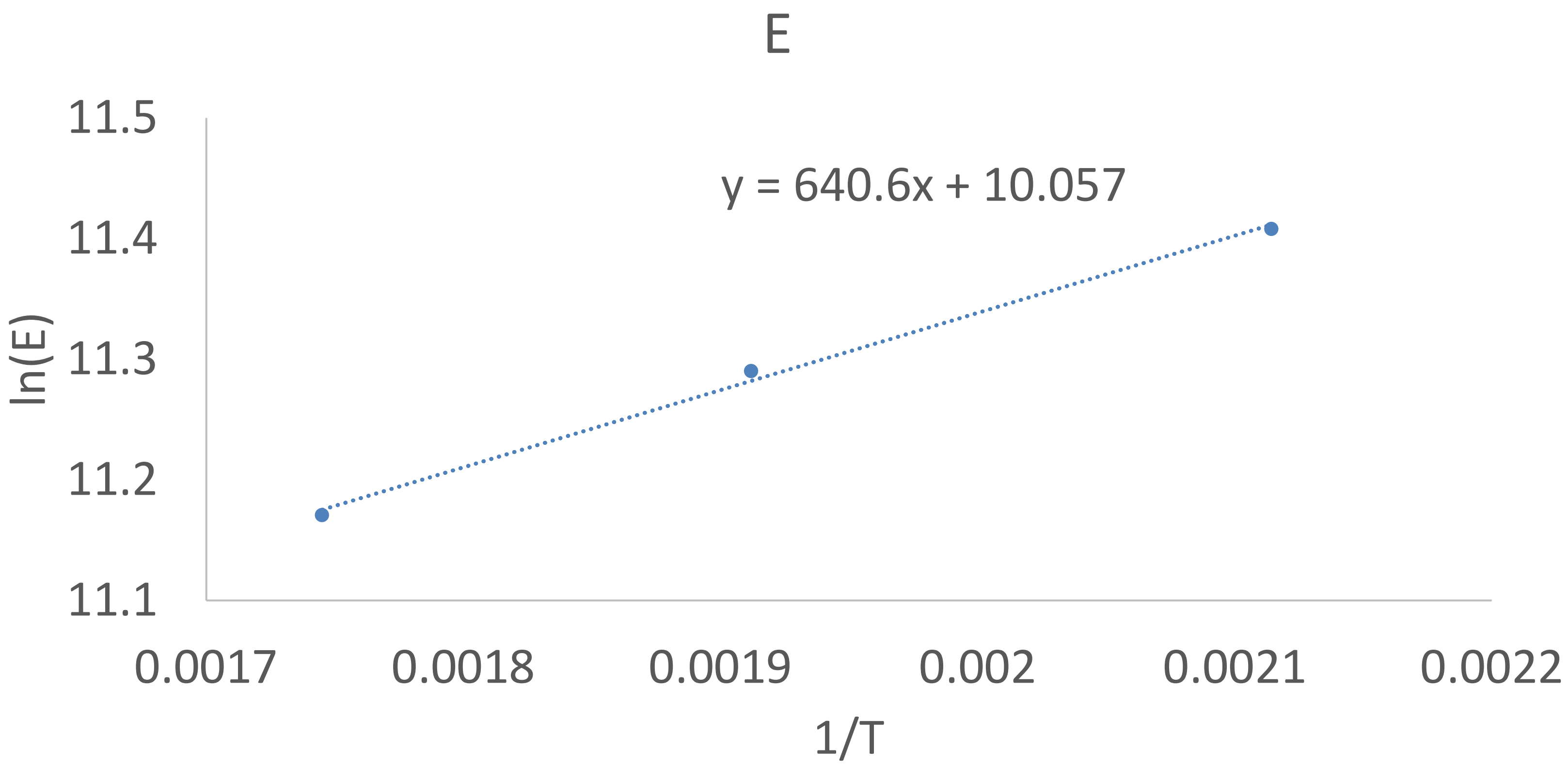




Arrhenius Fits (200-300°C)



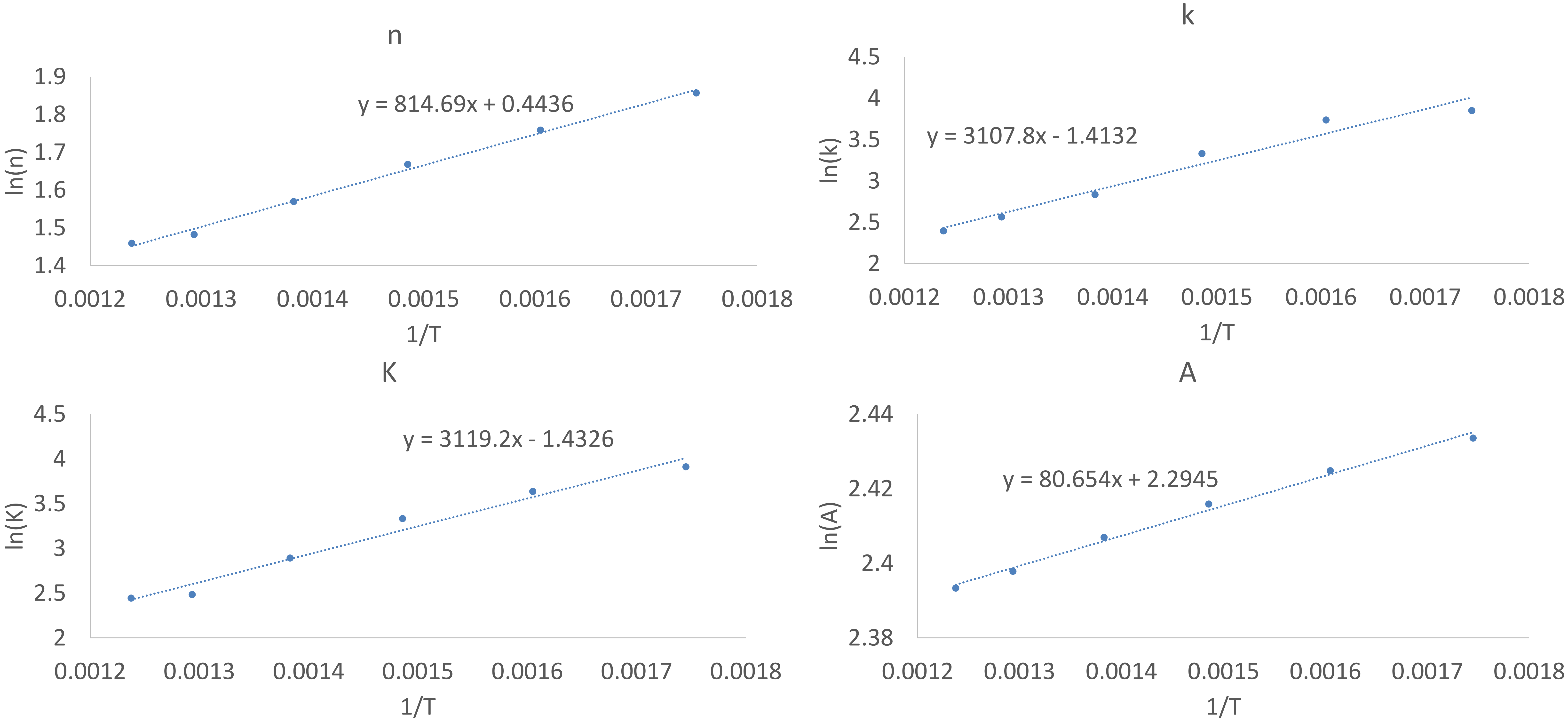




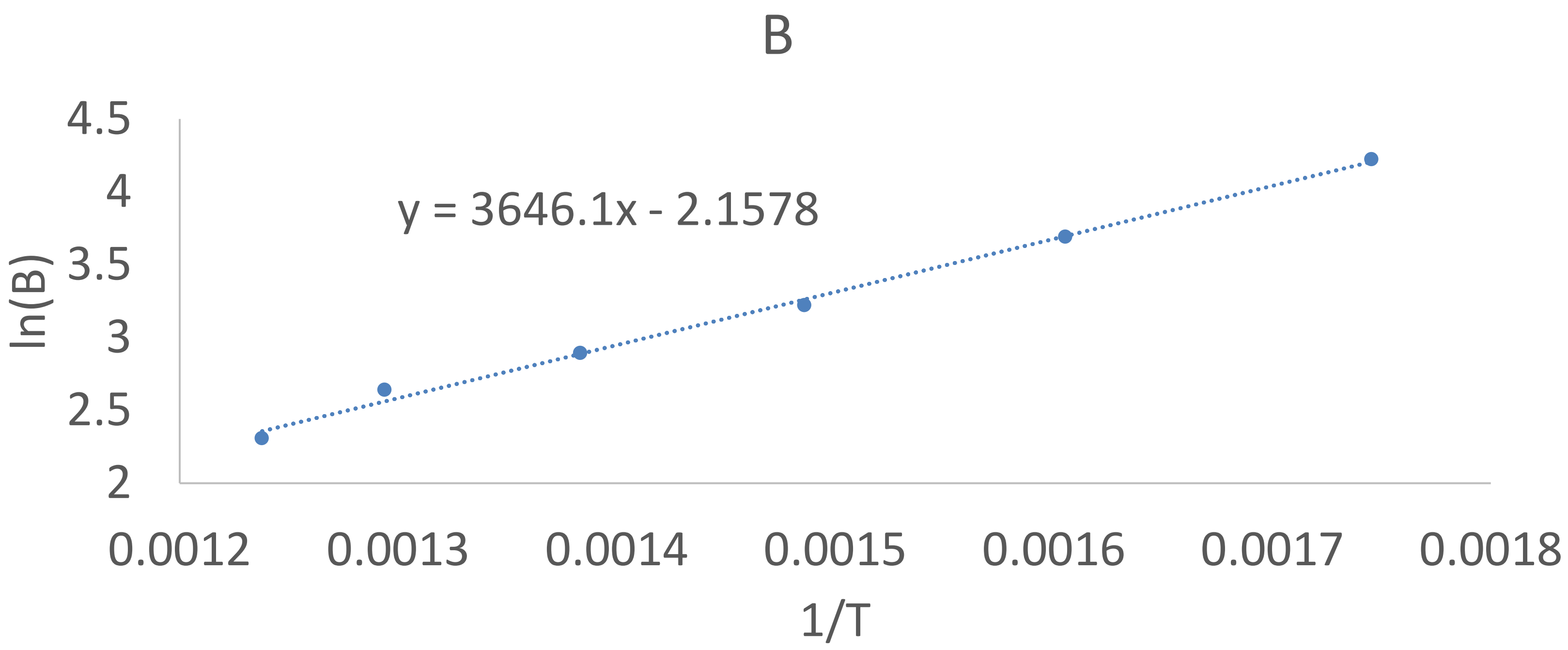
Constant	Correlation (%)
n	99.83
B	99.89
C	-98.89
E	99.83
K	99.42
k	97.54
A	95.27

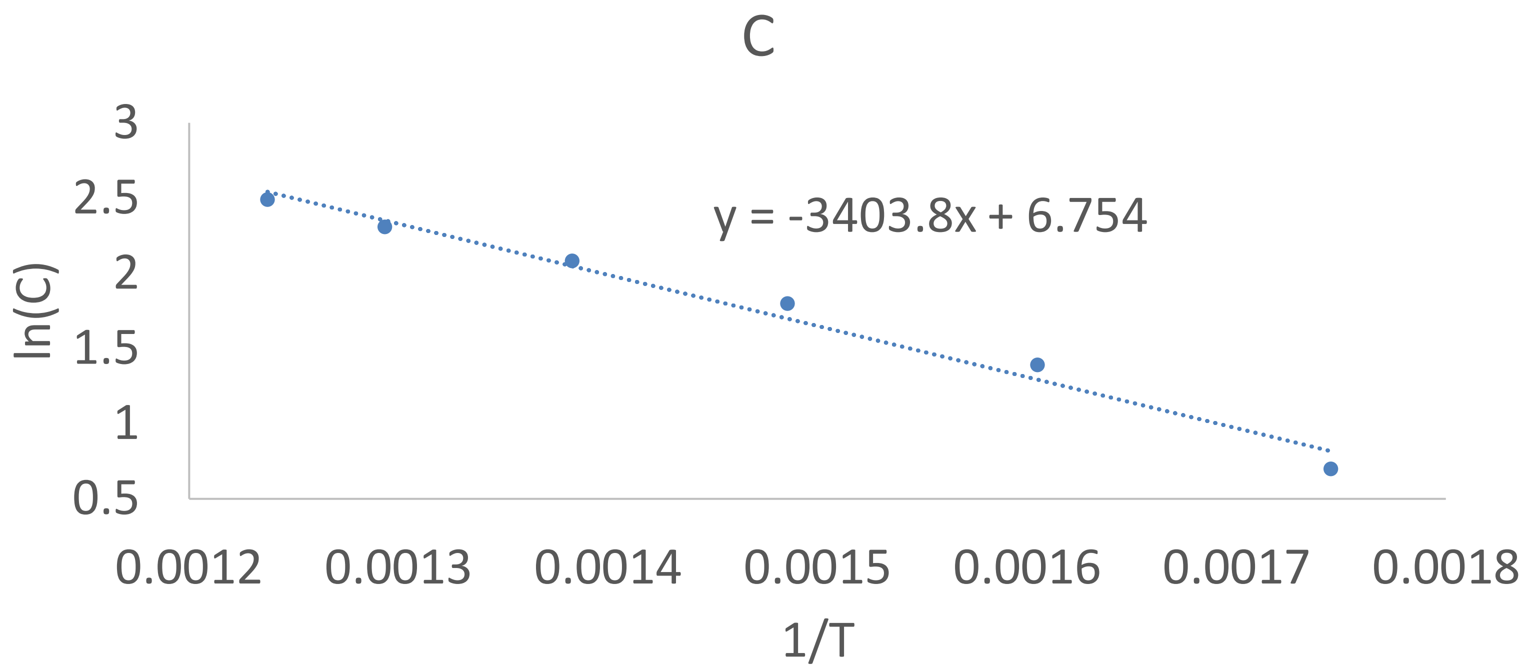
High correlations with all T-dependent material constants within specified range

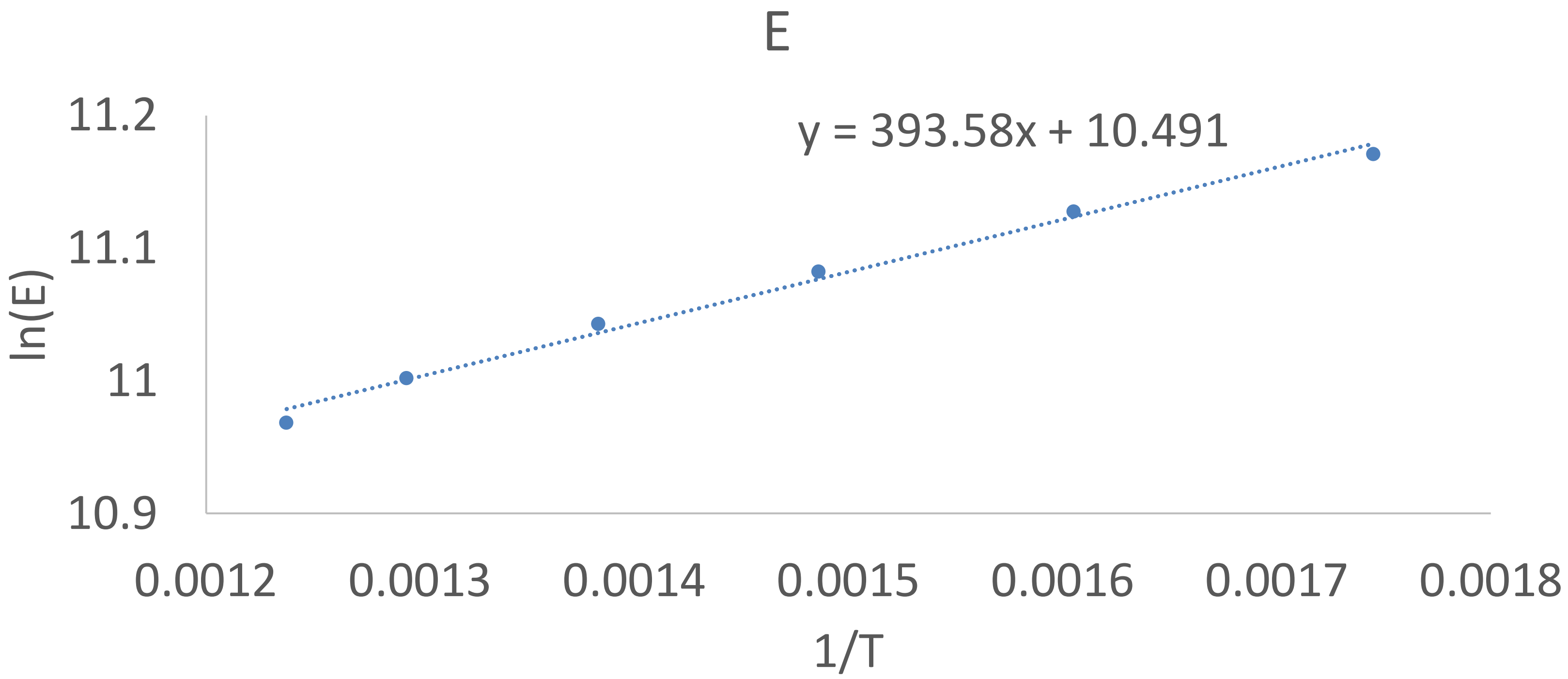
Arrhenius Fits (300-535°C)



Arrhenius Fits (300-535°C)





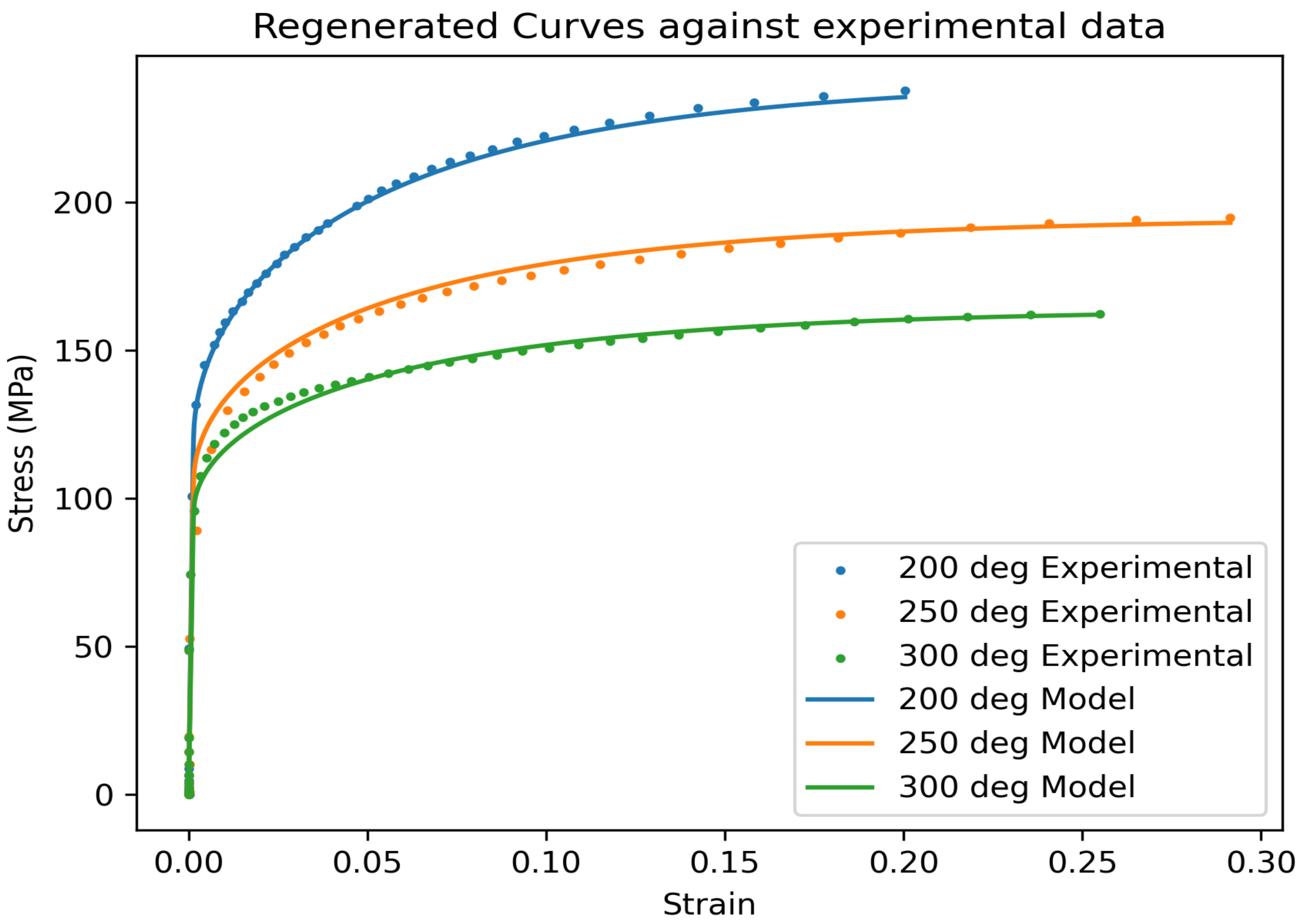


Constant	Correlation (%)
n	99.74
B	99.85
C	-88.25
E	99.80
K	98.40
k	97.17
A	99.62

High correlations with all T-dependent material constants within specified range

Regenerated Curve – (200-300°C)

- New constants found using the Arrhenius Constants
- This was between 200 and 300 °C



Regenerated Curve – (300-535°C)

- New constants found using the Arrhenius Constants
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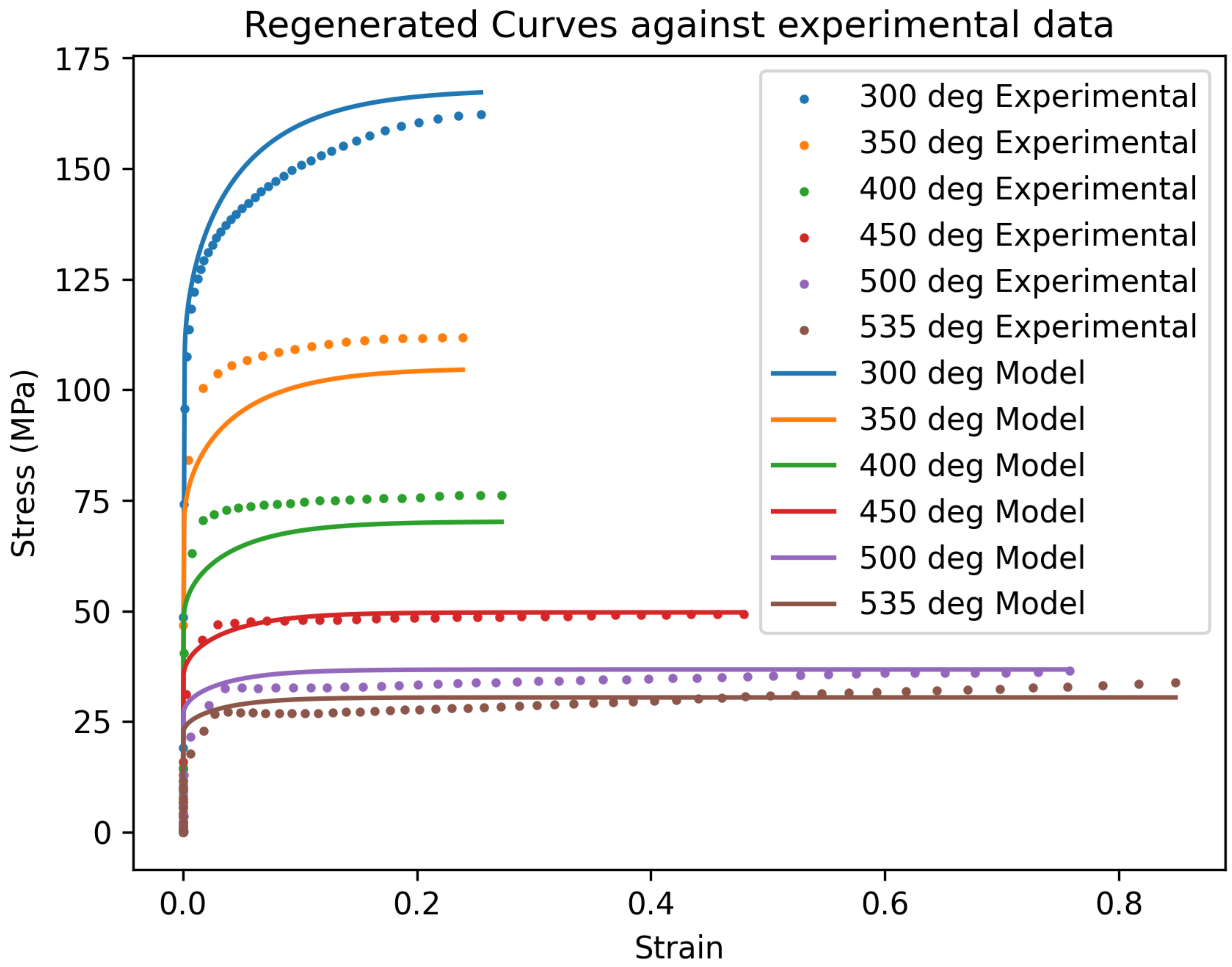

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Error Analysis

Constant strain rate errors

To conduct error analysis, we compared the experimental values to our generated models.

300˚C Error Analysis

	SR0.1	SR3	SR5
Max Error (%)	28.8	5.6	5.9
Mean Error (%)	19.9	1.9	1.9
Pass/Fail	F	P	P

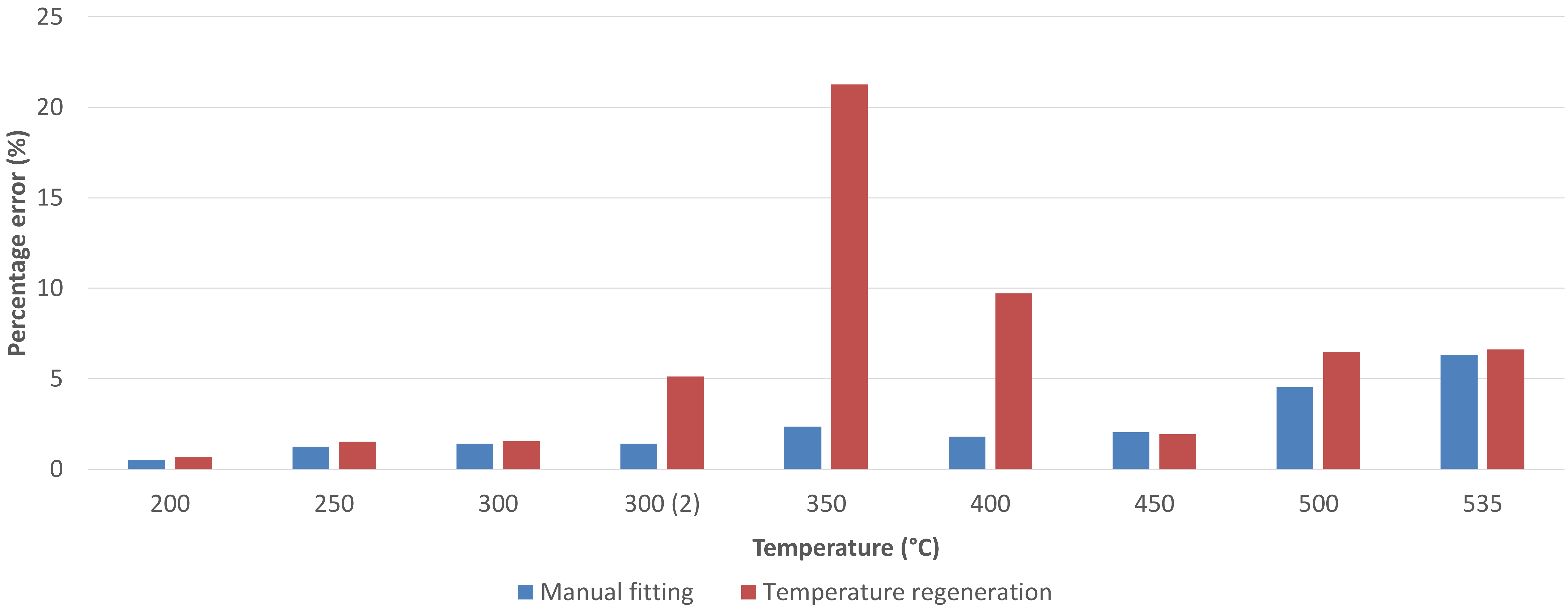
535˚C Error Analysis

	SR0.1	SR3	SR5
Max Error (%)	26.9	4.7	7.1
Mean Error (%)	4.9	2.0	2.6
Pass/Fail	P	P	P

- High correlations between experimental and model data
- Pass rate is defined as ~ 5%
- The derived constants were unsuitable for **SR0.1, 300°C**
  - Repeats at different strain rates should be taken

Constant strain rate errors

To conduct error analysis, we compared the experimental values to our generated models.



Constant strain rate errors - Sources

We then investigated the sources of the disparity in the errors between manual and Arrhenius fits.

	n	B	C	E	K	k	A
200	0.34%	0.71%	4.37%	0.36%	0.61%	1.45%	0.43%
250	0.75%	1.55%	10.39%	0.80%	1.36%	3.28%	0.97%
300	0.41%	0.86%	5.27%	0.44%	0.74%	1.75%	0.53%
350	0.65%	0.59%	9.15%	0.40%	6.15%	14.99%	0.09%
400	1.35%	4.19%	9.11%	0.58%	12.19%	11.98%	0.16%
450	0.18%	0.51%	3.28%	0.70%	0.87%	5.35%	0.09%
500	1.61%	7.69%	4.92%	0.14%	12.49%	4.32%	0.09%
535	0.67%	5.36%	5.80%	1.05%	1.44%	3.58%	0.09%

% Change between the manually inputted constants vs the regenerated constants

Reasons:

- Linear regressions very sensitive
  - Particularly between 300-535˚C
- Large changes to K and k values for 350 & 400˚C
  - Causing large shifts to graphs

Future Improvements: Conduct more tests at smaller temperature intervals

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Material Card

Material Constants

We found the following material constants at the following temperatures, from the constants

	300°C	535°C
K	75	15
k	24	7
B	200	46
C	350000	80
E	47000	47000
A	0.4	0.095
n1	10	3.4
n2	5	5

Material Constants (Arrhenius)

We found the following material constants at the following temperatures, from the constants

	Q_x	x_0
K	0.23868	25920.8
k	0.243372	25825.67
B	0.115582	30299.34
C	857.4684	-28285.9
E	36007.81	3270.687
A	9.919039	670.2345
n1	1.55832	6770.07
n2	2	0

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Costs

Facility Operating cost

Electricity cost (£/kWh)	0.27
Power consumption (kWh/month)	58352
Power consumption (kWh/hr)	243.13
Emissions (kgeCO2/kWh)	0.337

Gleeble 3800 Power Consumption = 58352 kWh per month = 243.13 kWh per hour

Required **Testing Duration** = 1.5 months

Translates to an **operational time** of 252 hours (8 hours per day, 5 days per week)

Total Energy Consumption = 243.13 * 252 = 61269.60 kWh

Electricity Cost = £0.27 per kWh

Gleeble 3800 **Operating Cost** = 61269.60 * 0.27 = £16542.79

Operating cost of computing equipment is negligible (£4.54)

Materials Characterisation	Facility required	Facility investment (£)	Lifetime (years)	Lifetime (hours)	Duration (months)	Operational time (hours)	Depreciation cost (£)	**Total Energy Consumption (kWh)**	**Operating Cost (£)**	Staff required	Hourly cost (£/hr)	Labour costs (£)	
Uniaxial compression tests	Gleeble 3800	1000000	15	131400	1.5	252	1917.81	**61269.60**	**16542.79**	Senior Lab Engineer	20	5040	
Fitting material models	Computing equipment	1000	4	35040	0.5	84	2.40	**0.1**	**2.27**	Junior Engineer	16	1344	
CAE analysis		1000	4	35040	0.5	84	2.40	**0.1**	**2.27**	Senior CAE Engineer	22.5	1890	
Total							1922.60		16547.33			8274	26743.93

Facility Depreciation cost

Electricity cost (£/kWh)	0.27
Power consumption (kWh/month)	58352
Power consumption (kWh/hr)	243.13
Emissions (kgeCO2/kWh)	0.337

Gleeble 3800 Upfront Investment = £1,000,000

Required Testing Duration = 1.5 months

Translates to an operational time of 252 hours (8 hours per day, 5 days per week)

Estimated Lifetime = 15 years = 131400 hours

Gleeble 3800 **Depreciation Cost** = 1,000,000 * (252 / 131400) = £1917.81

Degradation cost of computing equipment is negligible (£4.80)

Assume that the **salvage value after 15 years is £0**, hence true depreciation will be lower

Materials Characterisation	Facility required	Facility investment (£)	Lifetime (years)	Lifetime (hours)	Duration (months)	Operational time (hours)	Depreciation cost (£)	Total Energy Consumption (kWh)	Operating Cost (£)	Staff required	Hourly cost (£/hr)	Labour costs (£)	
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Labour Cost

Staff Required – Senior Lab Engineer, Junior Engineer, Senior CAE Engineer

Respective Hourly Costs – £20, £16, £22.5

Required Computing Duration for Each Task = 0.5 months

Translates to an operational time of 84 hours (8 hours per day, 5 days per week)

Multiply hourly cost by operational time for each task

Total **Labour Cost** = **£8274**

Labour Costs		
Staff	Salary (£/year)	Hourly cost (£/hr)
Senior Lab Engineer	40000	20
Junior Engineer	32000	16
Senior CAE Engineer	45000	22.5

Materials Characterisation	Facility required	Facility investment (£)	Lifetime (years)	Lifetime (hours)	Duration (months)	Operational time (hours)	Depreciation cost (£)	Total Energy Consumption (kWh)	Operating Cost (£)	**Staff required**	**Hourly cost (£/hr)**	**Labour costs (£)**	
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Total							**1922.60**		**16547.33**			**8274**	26743.93

Sustainability and CO2 Analysis

Electricity cost (£/kWh)	0.27
Power consumption (kWh/month)	58352
Power consumption (kWh/hr)	243.13
Emissions (kgeCO2/kWh)	0.337

Gleeble 3800 Power Consumption = 58352 kWh per month = 243.13 kWh per hour

Required Testing Duration = 1.5 months

- Translates to an operational time of 252 hours (8 hours per day, 5 days per week)

Total Energy Consumption = 243.13 * 252 = 61269.60 kWh

Carbon Emissions = 0.337 kgeCO2 per kWh

Total CO2 Emissions = 61269.60 * 0.337 = 20647.86 kgeCO2

- Carbon emissions of computing equipment is negligible

Conclusion

- We generated a material card, with low costs and CO_2 emissions for the customer
- Accurate results for derived constants for varying strain rates at an average error of 2.7% (excluding the anomaly)
- We successfully fit graphs for the 200-300°C and were able to generate accurate Arrhenius constants within this range
- Successfully fit graphs for the 300-535°C but were unable to generate accurate Arrhenius constants within this range

Future Work:

- The derived constants were unsuitable for SR0.1, 300°C, so repeats at strain rates of smaller intervals should be taken to see if the constants are appropriate
- Regenerated curves for 350 and 450 °C were not suitable, so conduct repeats at smaller temperature intervals.