Creep Properties of Lead-free Solder Joints

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Motivation

- High homologous temperature during thermal fatigue means that creep is a major deformation mode.
- Creep behavior of Lead(Pb)-free solder joints in shear must be known to use them reliably in microelectronic applications.

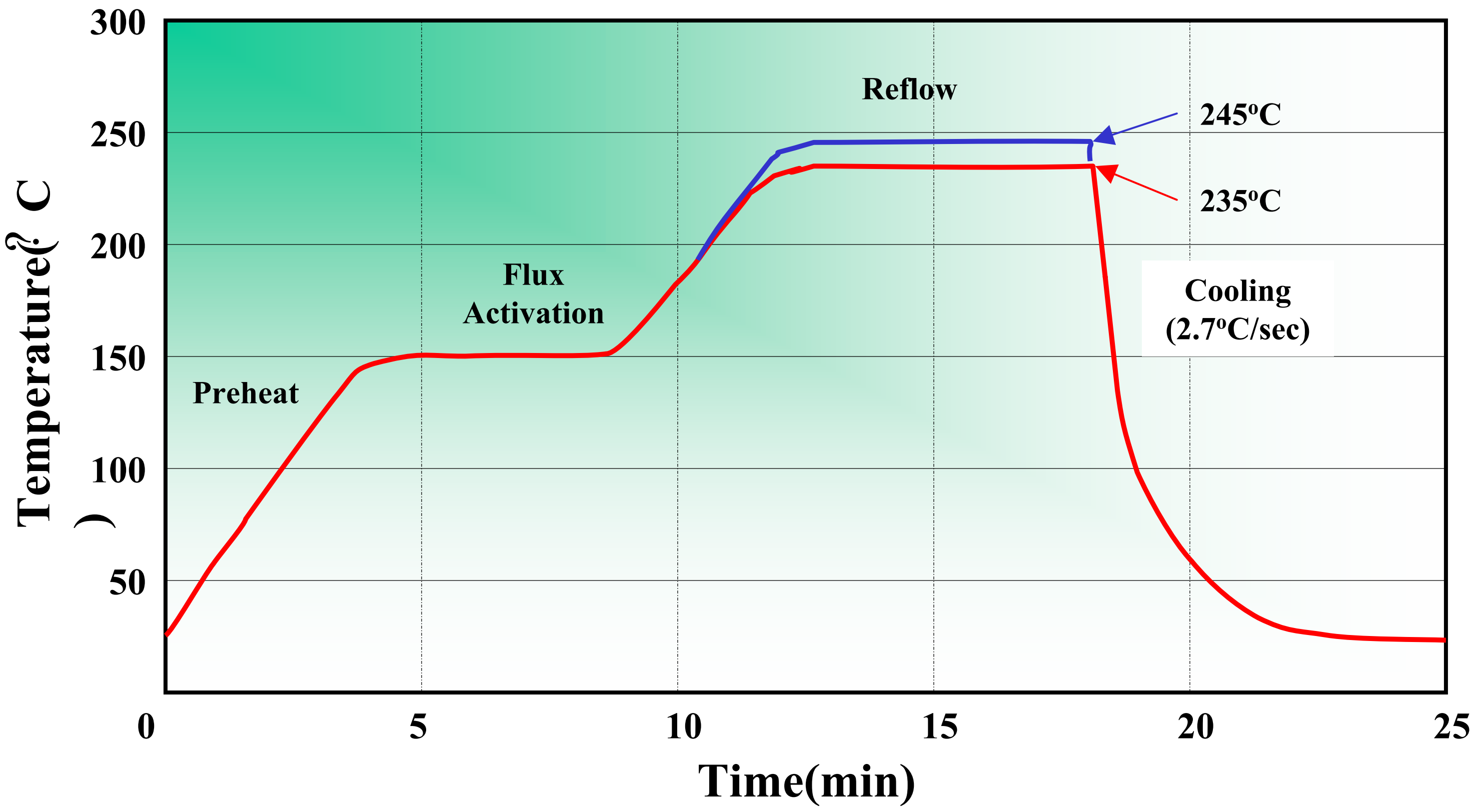
Pb-Free Solders of Interest in This Work

Solder System	M.P.(?C)	Constituent phases	T/T_m at R.T.
Sn-0.7Cu	227	β-Sn, Cu_6Sn_5	0.596
Sn-3.5Ag	221	β-Sn, Ag_3Sn	0.603
Sn-10In-3.1Ag	204	β-Sn, Ag_2In, γ-InSn	0.625
Sn-3Ag-0.5Cu	218	β-Sn, Ag_3Sn, Cu_6Sn_5	0.607

Experimental Procedure

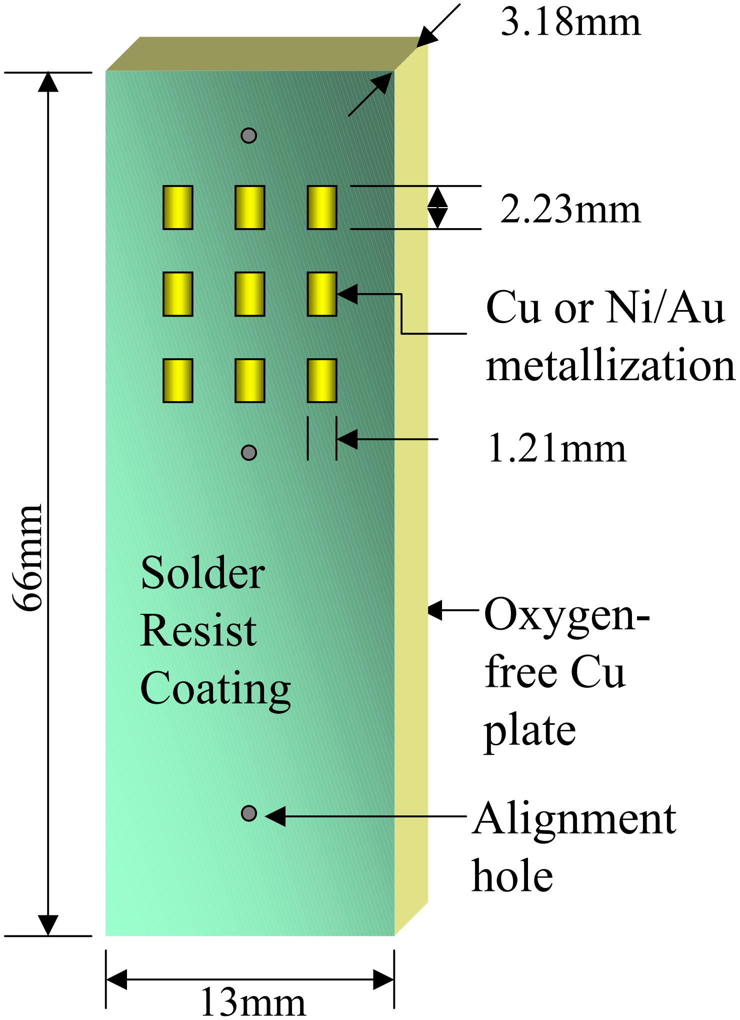
- Solder alloy manufacturing
  - Alloyed by vacuum arc melting
  - Rolled to make foil after homoginization
  - Punched to get the constant volume of solder
- Test specimen manufacturing
  - Manufactured solder masked Cu coupons with 9 pads
  - Assembled to single-shear specimens with bare Cu and electroless Ni/immersion Au plated coupons
  - Reflow and annealing
- Creep tests
  - Performed at 60, 95, 130?C under constant load conditions

Reflow Profile (at N_2 atmosphere)



- Reflow peak temperature of 235°C for SnAg, SnInAg, SnAgCu and 245°C for SnCu
- Followed by aging at 160°C for 4 hours.

Geometry of Single-Shear Specimen



3.18mm

2.23mm

Cu or Ni/Au metallization

1.21mm

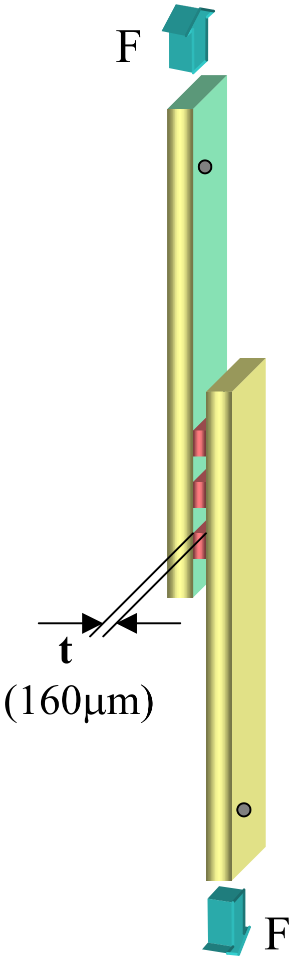
Solder Resist Coating

Oxygen-free Cu plate

Alignment hole

66mm

13mm



F

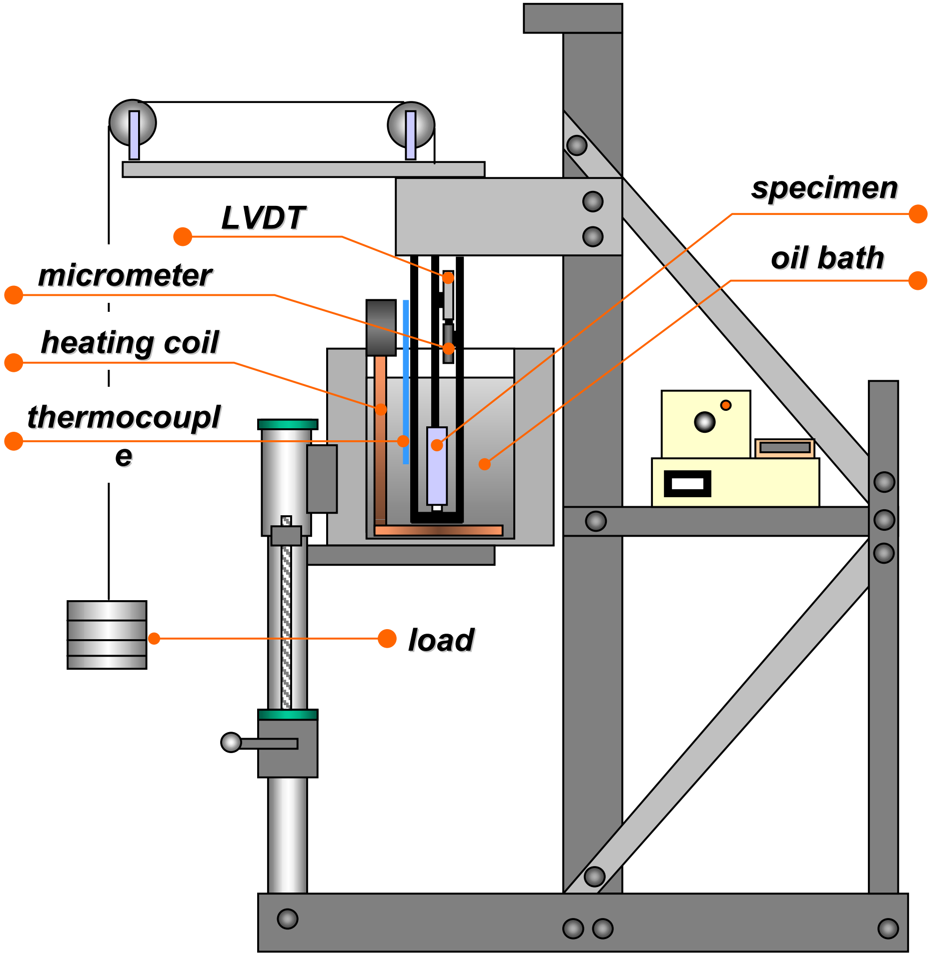
t (160μm)

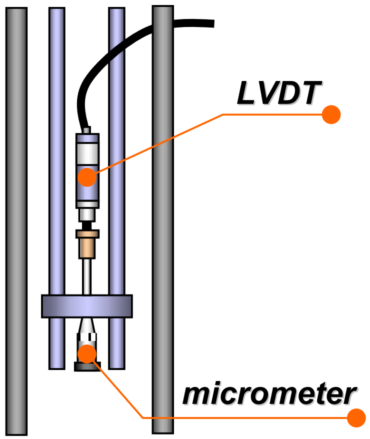
F

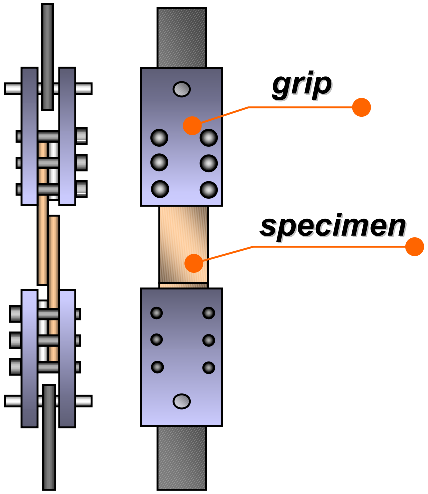
- One coupon has Cu pads

  One coupon has electroless Ni / immersion Au pads.

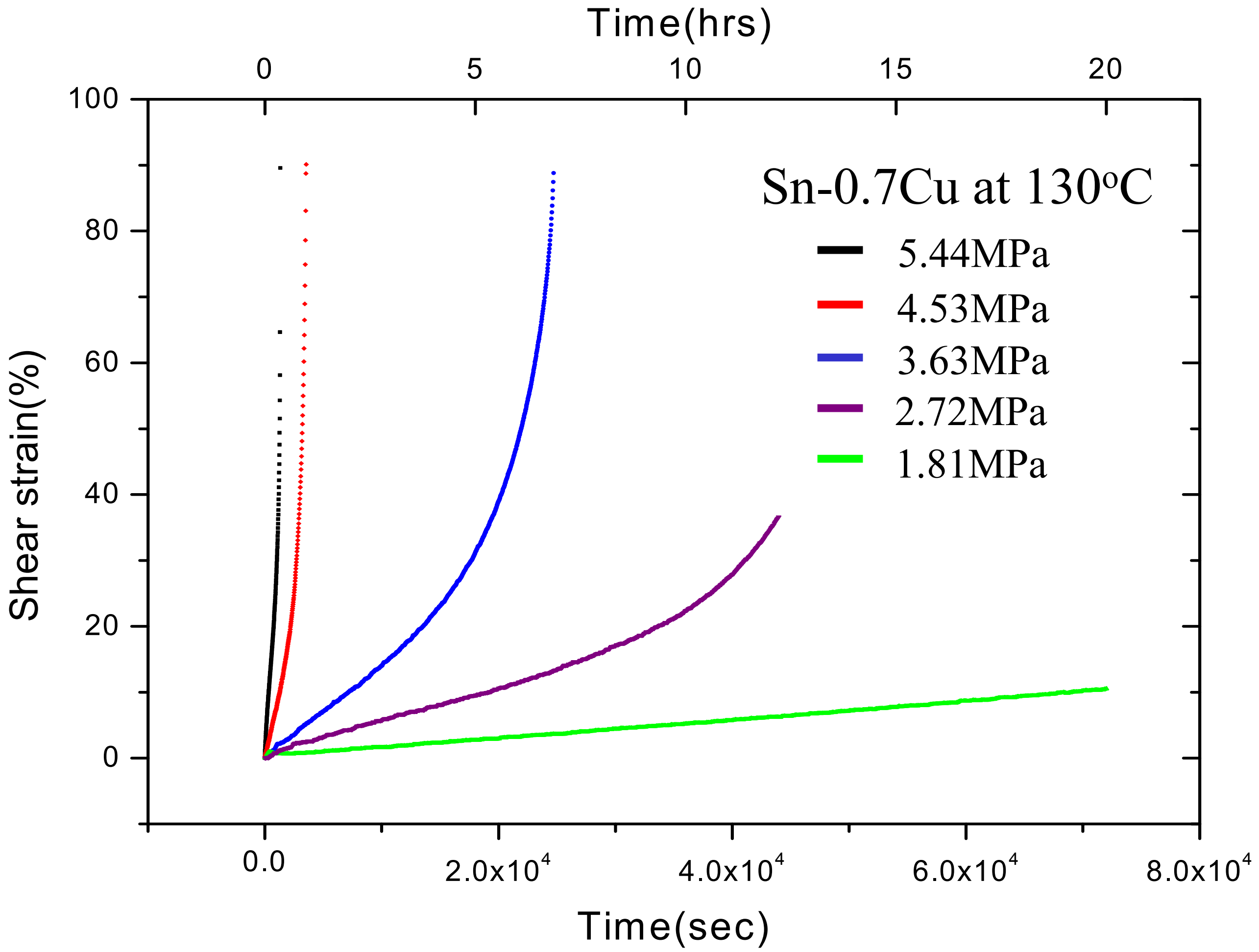
Creep Test Apparatus



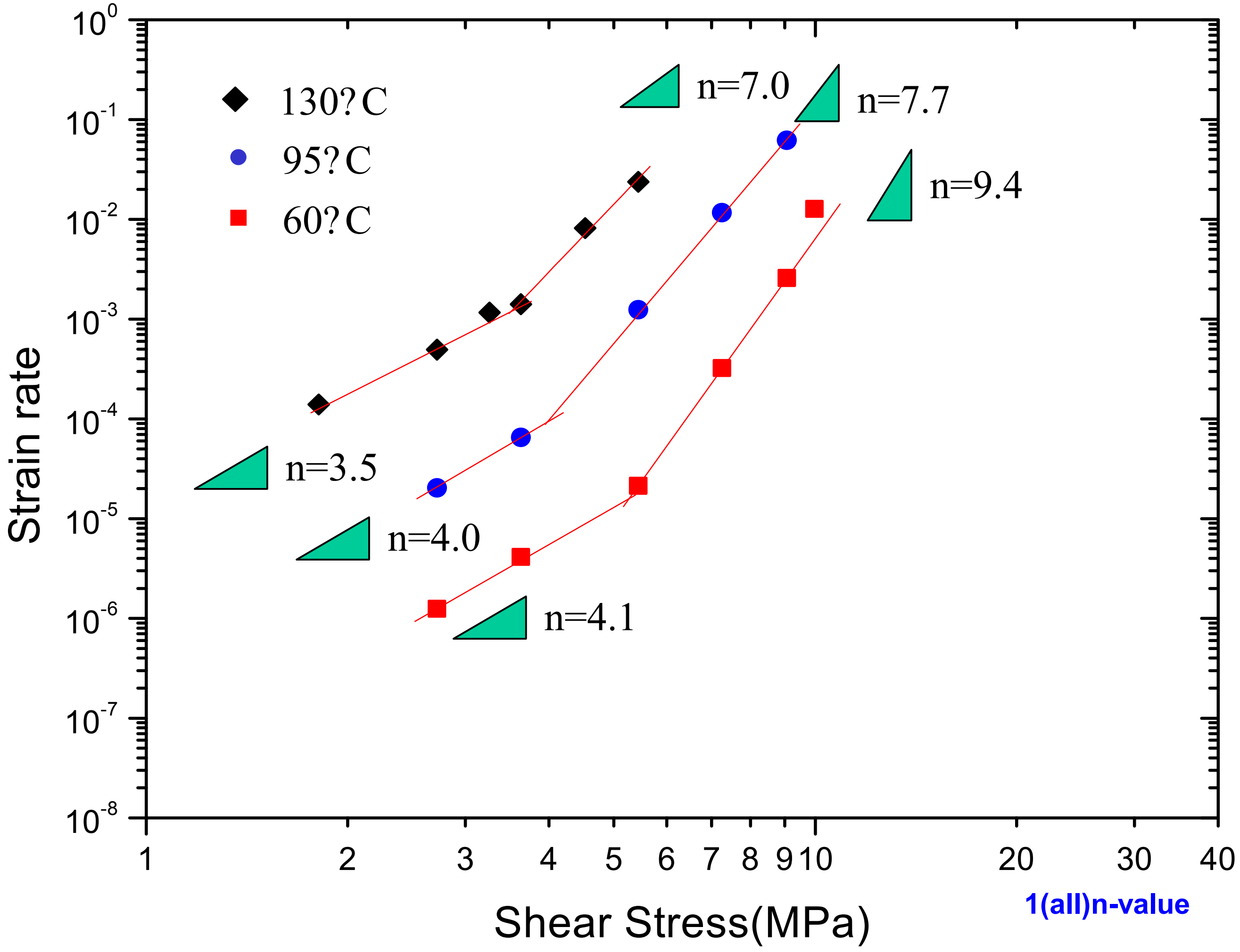




Typical Creep Curves of Solder Joints

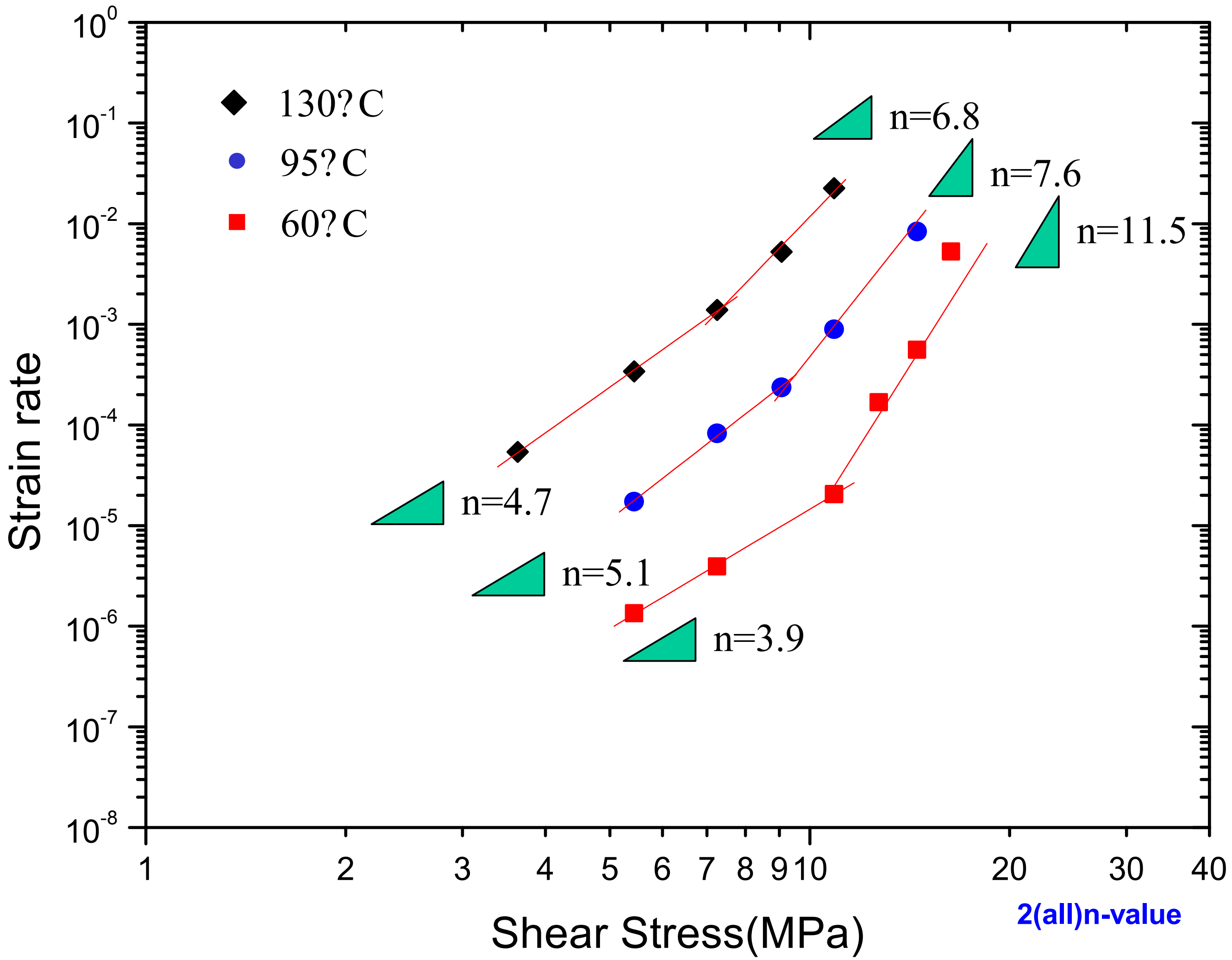


SnCu: Shear Stress vs. Shear Strain rate



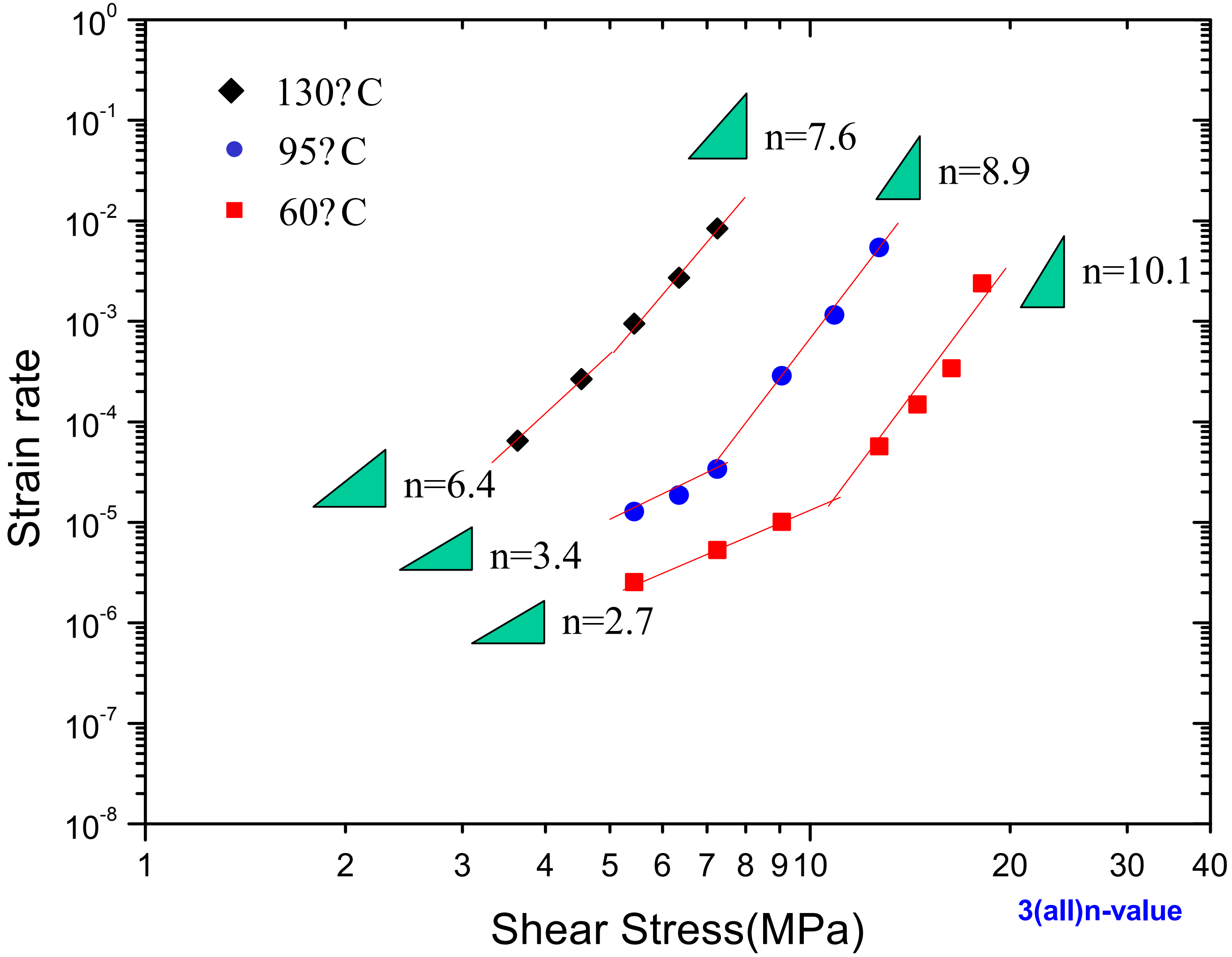
1(all)n-value

SnAg: Shear Stress vs. Shear Strain rate



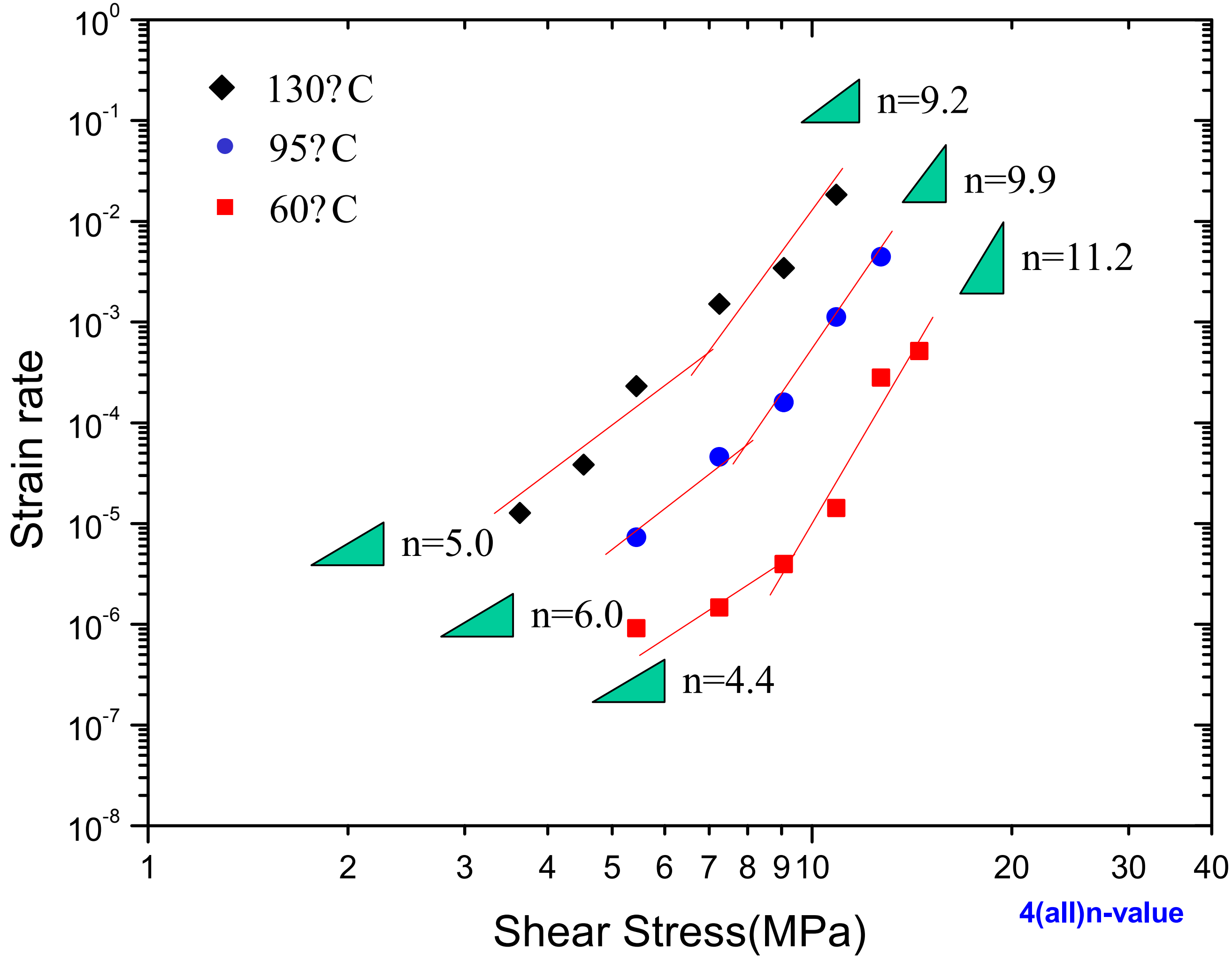
2(all)n-value

SnInAg: Shear Stress vs. Shear Strain rate



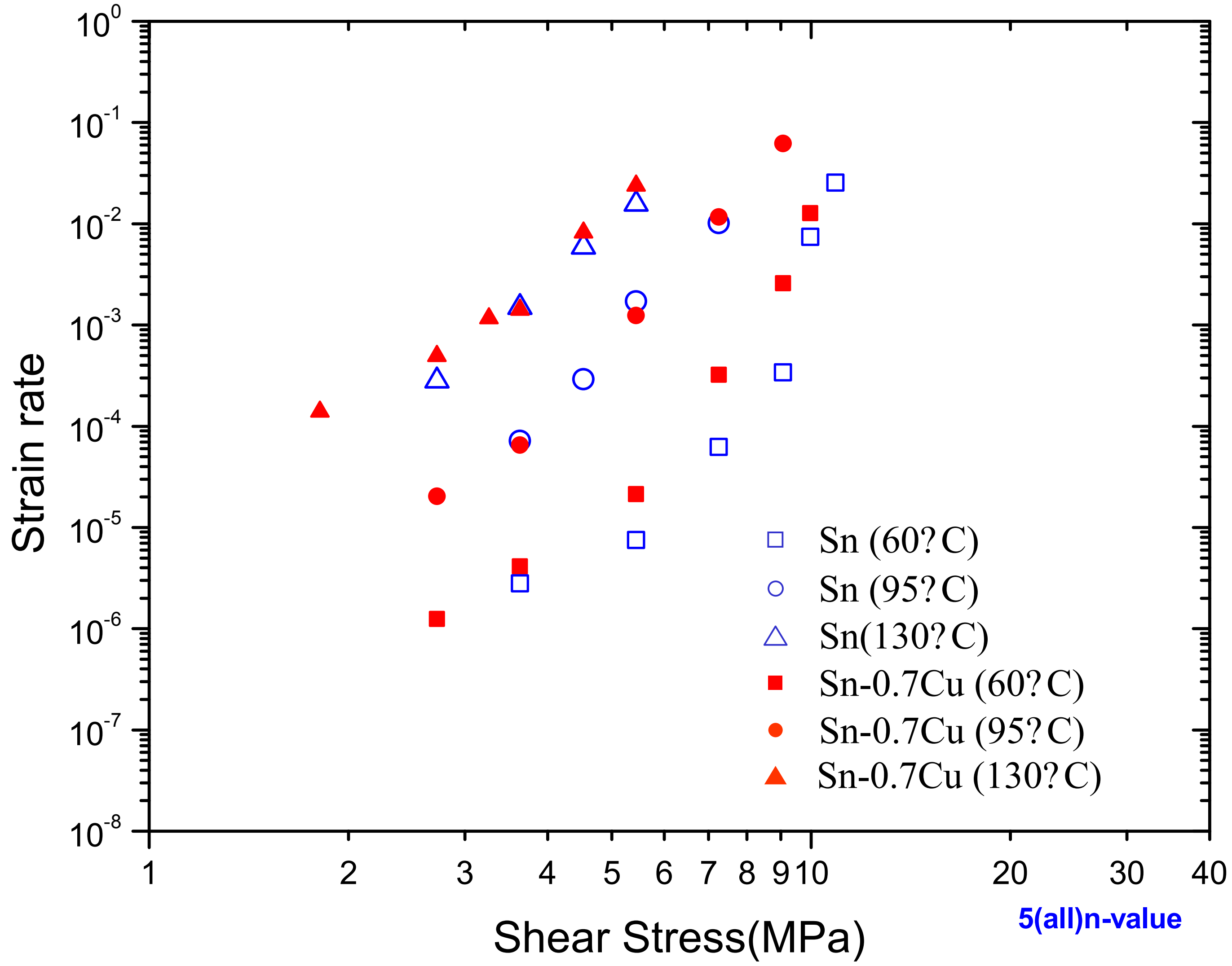
3(all)n-value

SnAgCu: Shear Stress vs. Shear Strain rate



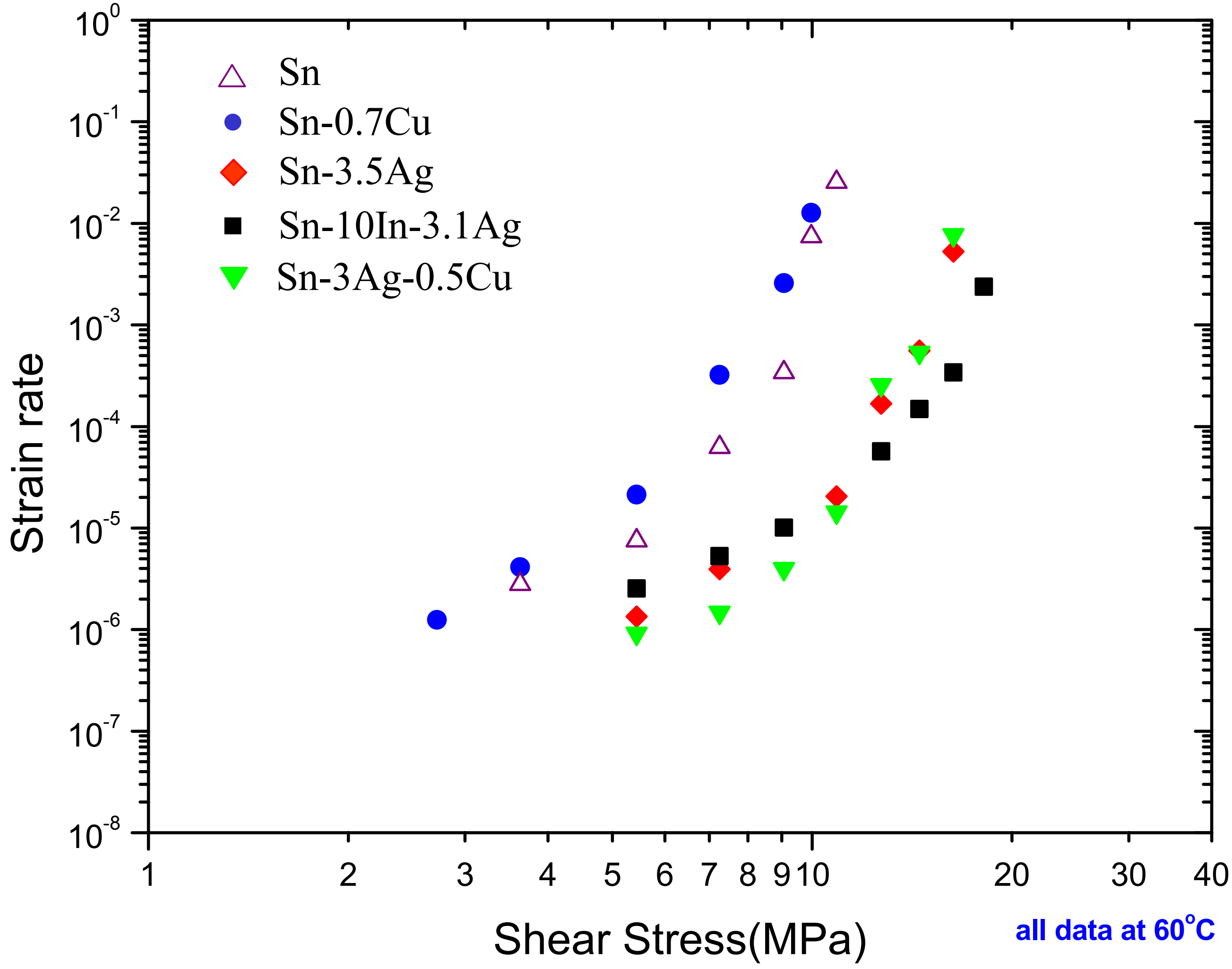
4(all)n-value

Sn Joints vs. Sn-0.7Cu Joints



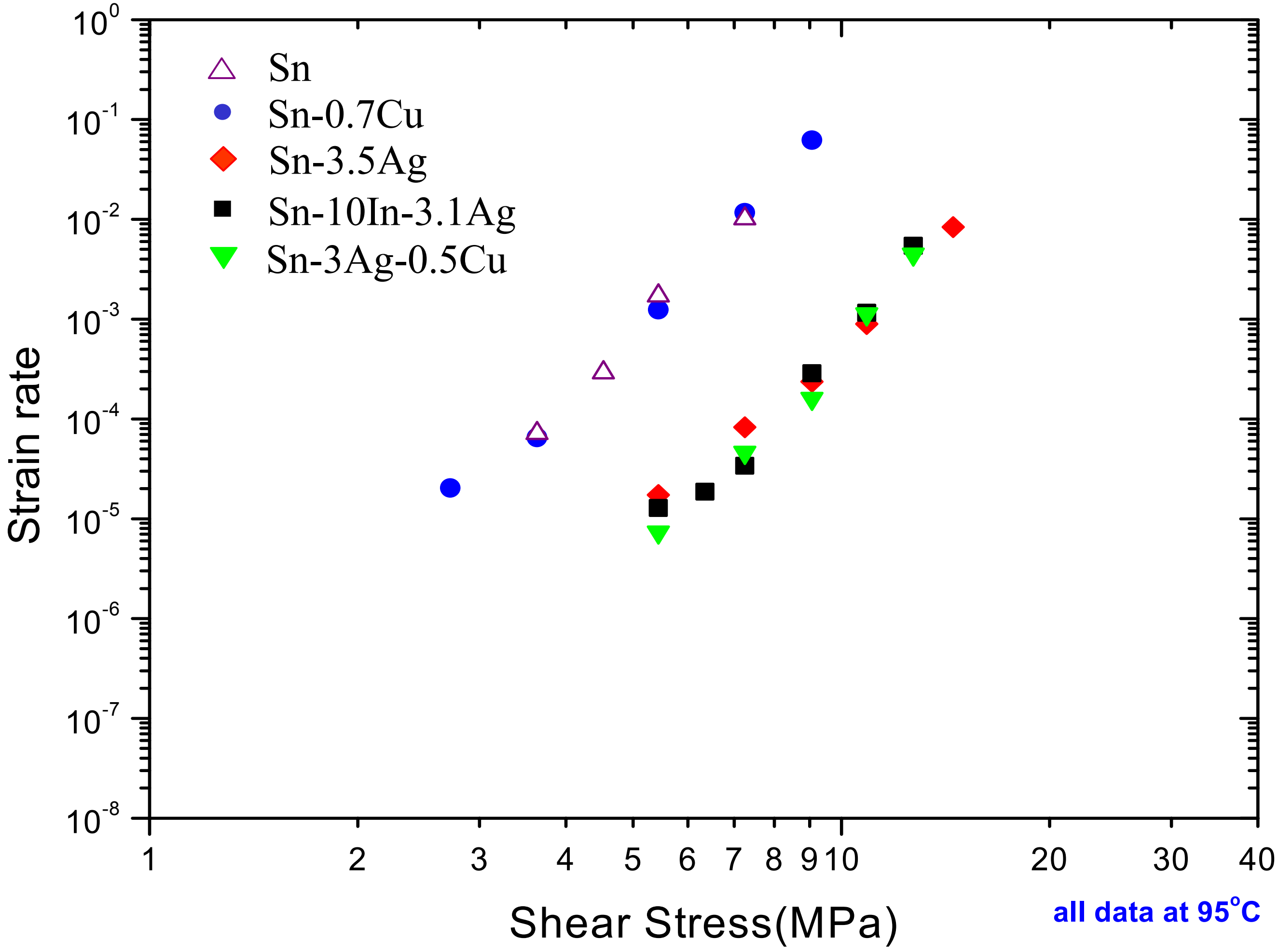
5(all)n-value

Stress vs. Strain rate at 60°C



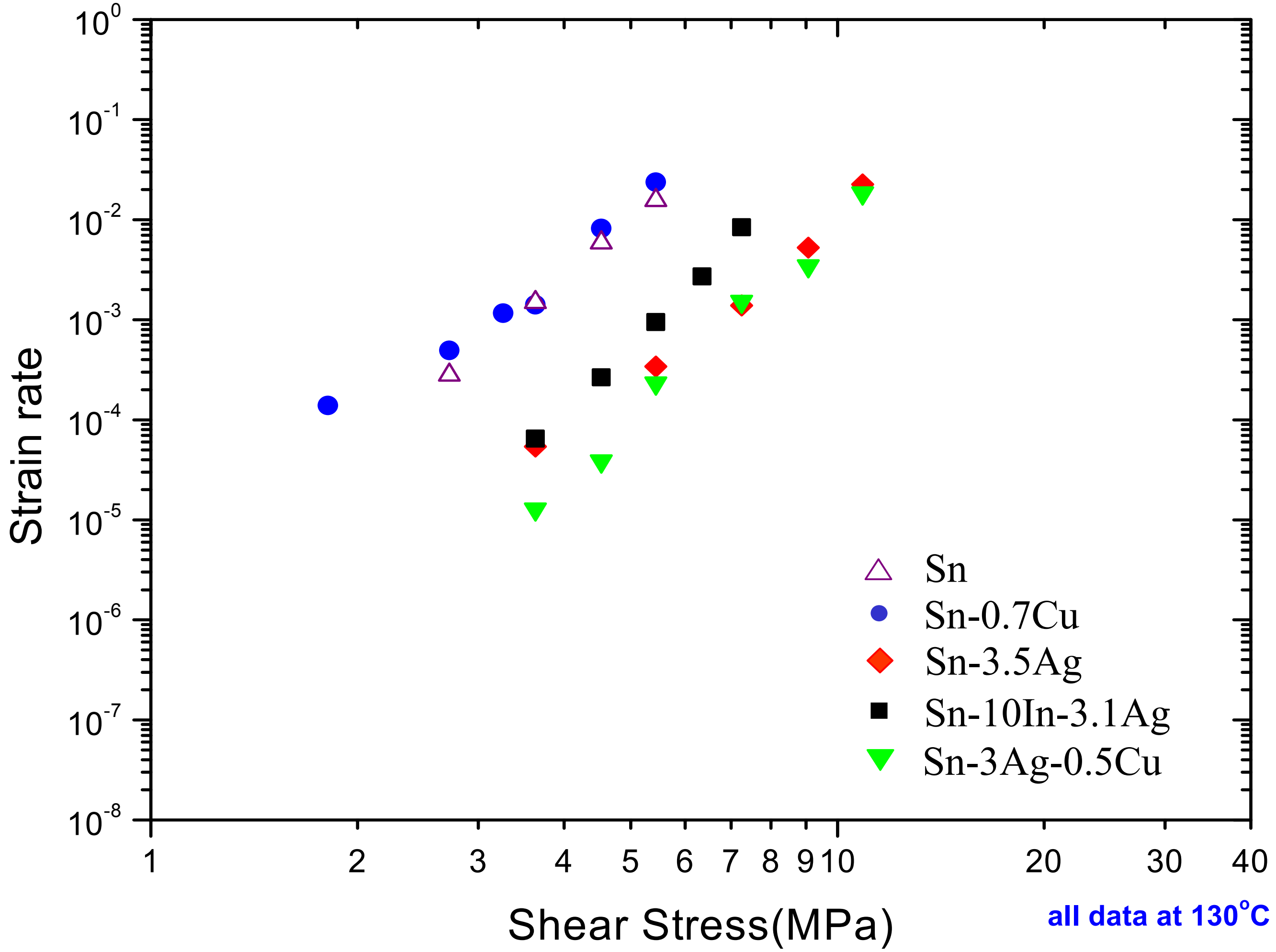
all data at 60°C

Stress vs. Strain rate at 95°C



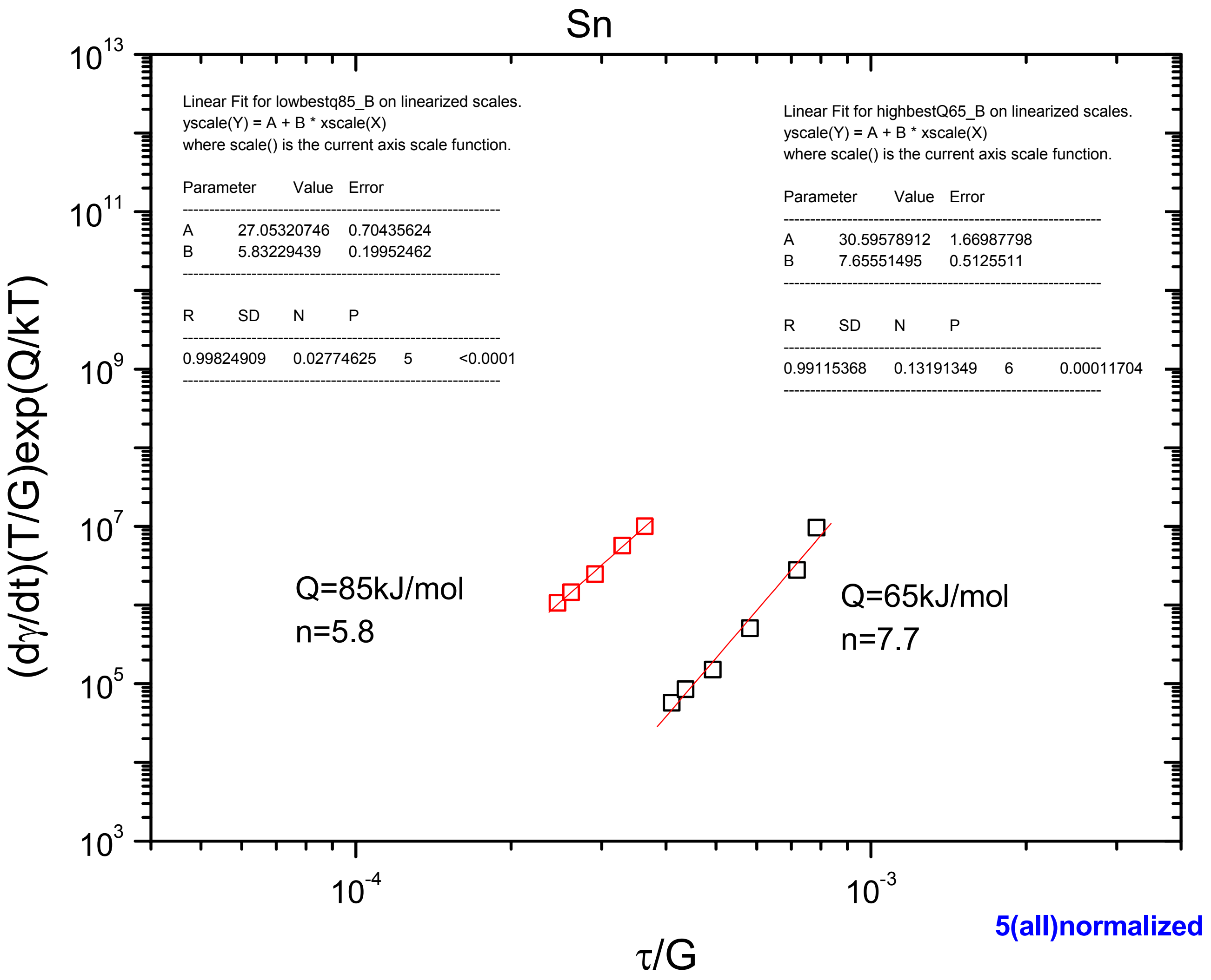
all data at 95°C

Stress vs. Strain rate at 130°C



all data at 130°C

Sn: Data normalized separately for high and low stress



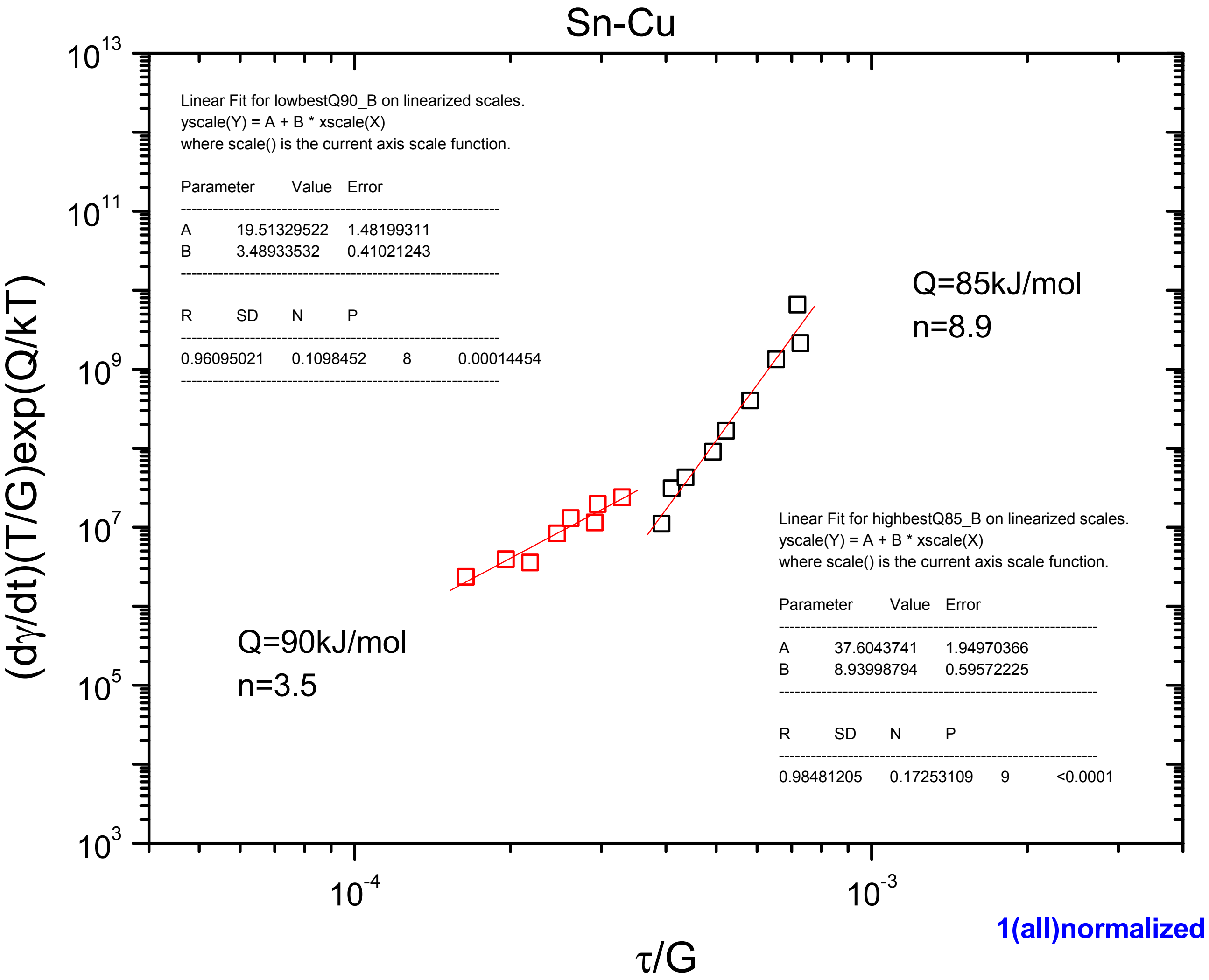
```
Linear Fit for lowbestq85_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter       Value   Error
------------------------------------------------------------
A          27.05320746    0.70435624
B          5.83229439     0.19952462
------------------------------------------------------------

R          SD          N          P
------------------------------------------------------------
0.99824909      0.02774625      5          <0.0001
------------------------------------------------------------
```

```
Linear Fit for highbestQ65_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter       Value   Error
------------------------------------------------------------
A          30.59578912    1.66987798
B          7.65551495     0.5125511
------------------------------------------------------------

R          SD          N          P
------------------------------------------------------------
0.99115368      0.13191349      6          0.00011704
------------------------------------------------------------
```

* G=16302-40.5T(ºC)

*ignore abnormal three data points in the middle of 60ºC data

SnCu: Data normalized separately for high and low stress

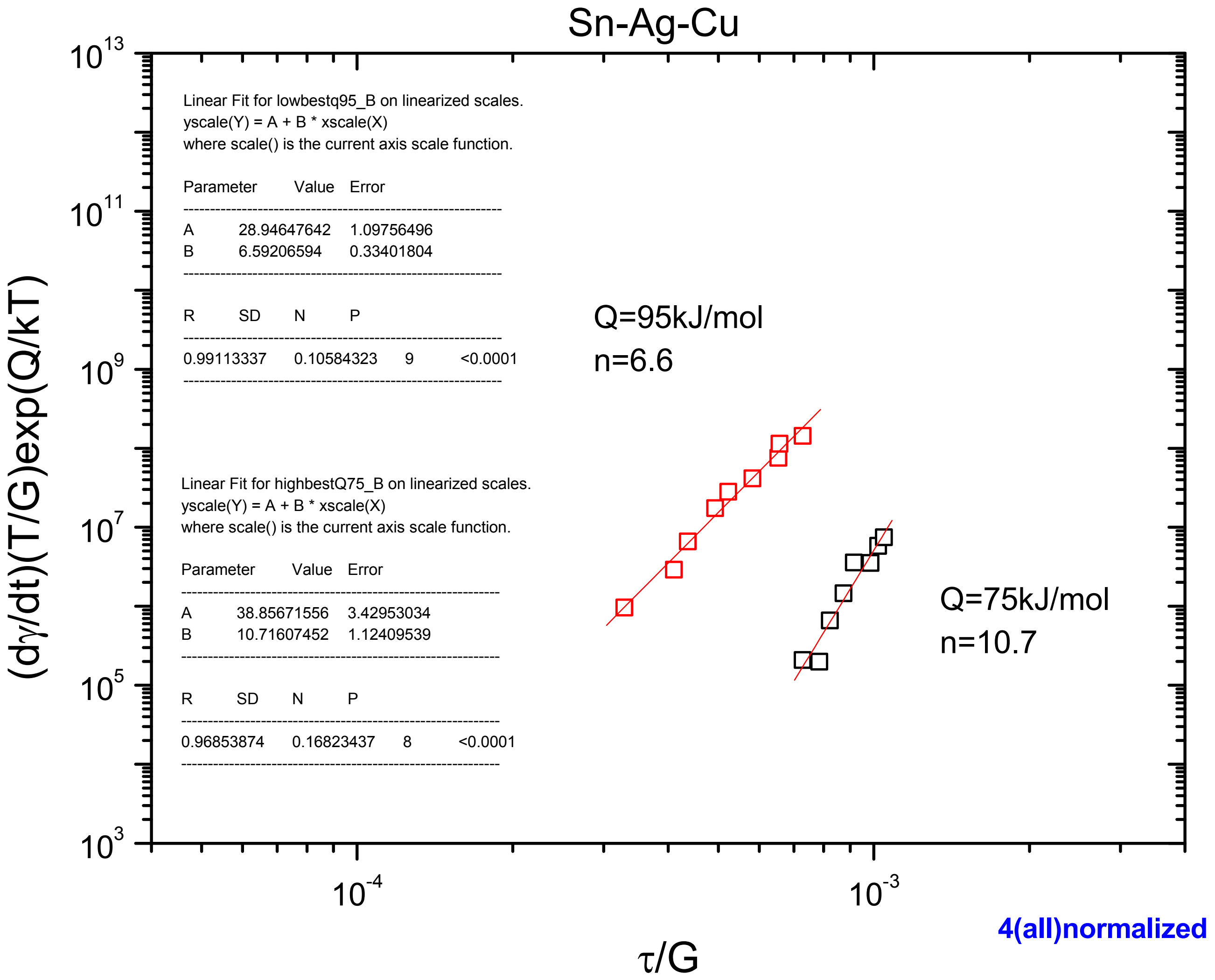


```
Linear Fit for lowbestQ90_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          19.51329522    1.48199311
B          3.48933532     0.41021243
------------------------------------------------------------

R          SD          N          P
------------------------------------------------------------
0.96095021    0.1098452    8    0.00014454
------------------------------------------------------------
```

```
Linear Fit for highbestQ85_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          37.6043741     1.94970366
B          8.93998794     0.59572225
------------------------------------------------------------

R          SD          N          P
------------------------------------------------------------
0.98481205    0.17253109    9    <0.0001
```

* G=16302-40.5T(°C)

SnAgCu: Data normalized separately for high and low stress

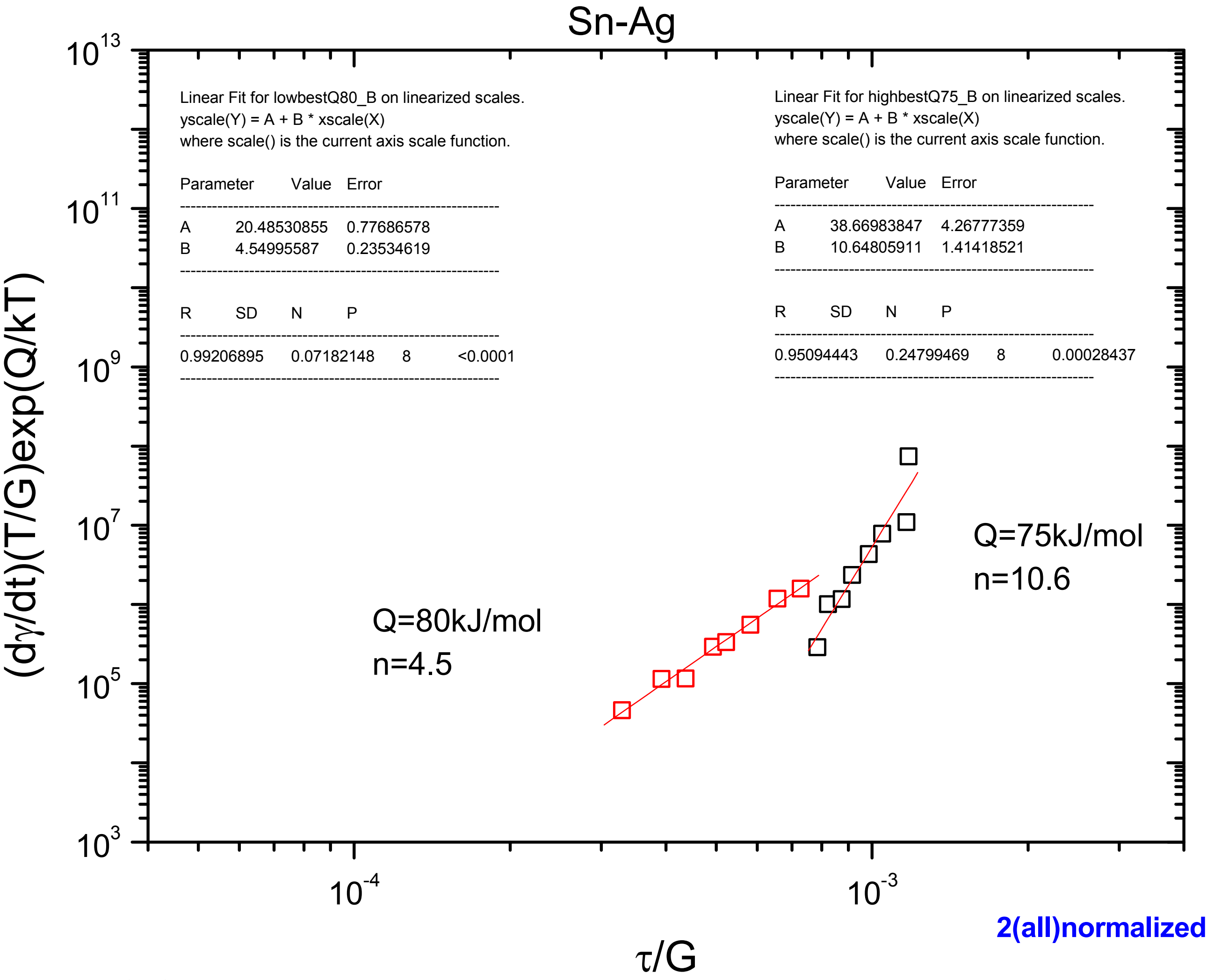


```
Linear Fit for lowbestq95_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value     Error
------------------------------------------------------------
A         28.94647642    1.09756496
B         6.59206594     0.33401804
------------------------------------------------------------

R         SD          N         P
------------------------------------------------------------
0.99113337     0.10584323     9          <0.0001
------------------------------------------------------------
```

```
Linear Fit for highbestQ75_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value     Error
------------------------------------------------------------
A         38.85671556    3.42953034
B         10.71607452    1.12409539
------------------------------------------------------------

R         SD          N         P
------------------------------------------------------------
0.96853874     0.16823437     8          <0.0001
------------------------------------------------------------
```

* G=16302-40.5T(^{o}C)

SnAg: Data normalized separately for high and low stress



```
Linear Fit for lowbestQ80_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter       Value   Error
------------------------------------------------------------
A         20.48530855    0.77686578
B         4.54995587     0.23534619
------------------------------------------------------------

R         SD         N         P
------------------------------------------------------------
0.99206895      0.07182148      8         <0.0001
------------------------------------------------------------
```

```
Linear Fit for highbestQ75_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter       Value   Error
------------------------------------------------------------
A         38.66983847    4.26777359
B         10.64805911    1.41418521
------------------------------------------------------------

R         SD         N         P
------------------------------------------------------------
0.95094443      0.24799469      8         0.00028437
------------------------------------------------------------
```

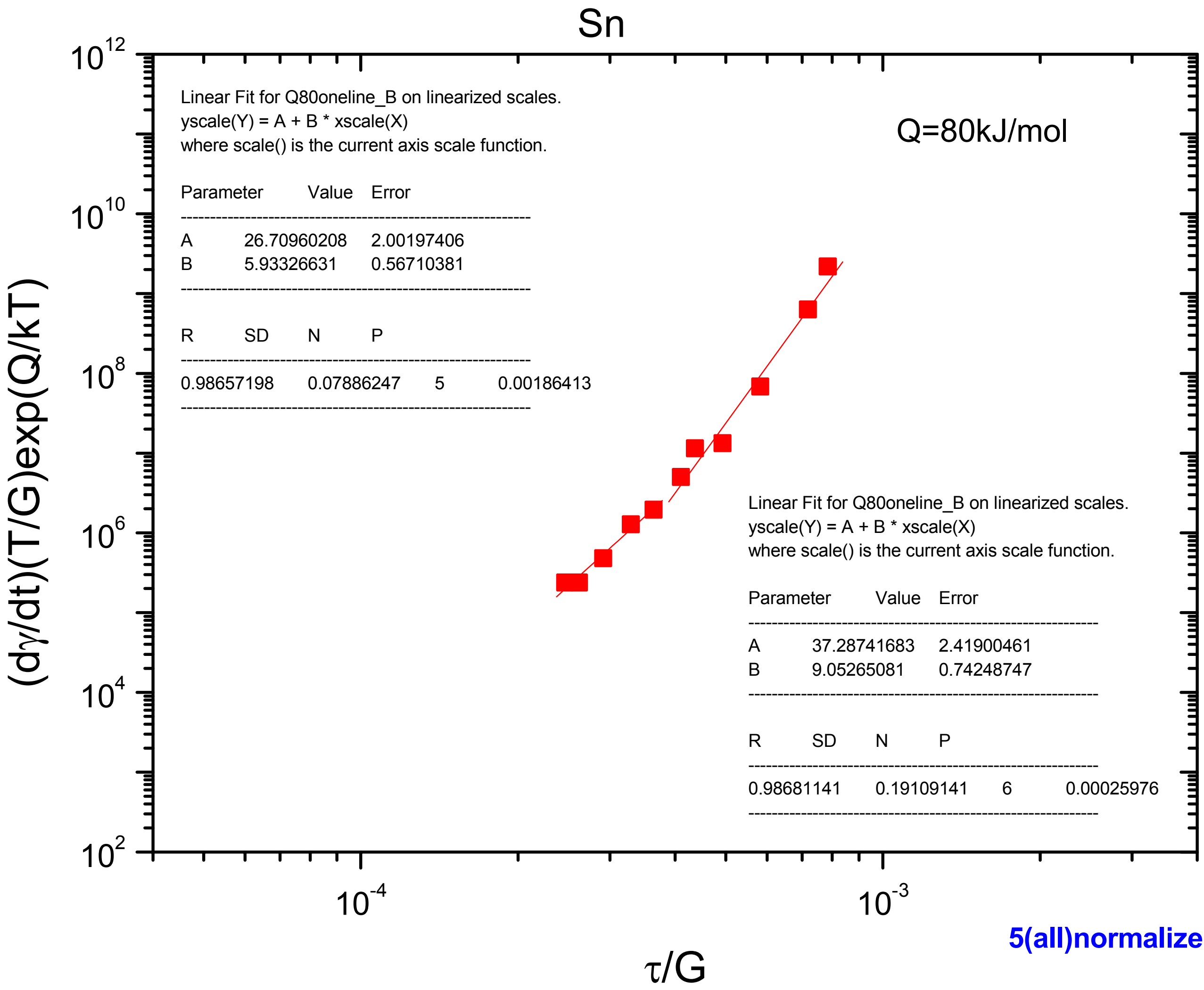
* G=16302-40.5T(°C)

Q-n Values from Normalized data

Solders	n		Q(KJ/mole)		τ/G at transition
	low	high	low	high	
Sn-Cu	3.5	8.9	90	85	$3\sim4 \times 10^{-4}$
Sn-Ag	4.5	10.6	80	75	$7\sim8 \times 10^{-4}$
Sn-In-Ag	5.4	9.5	100	115	$6\sim7 \times 10^{-4}$
Sn-Ag-Cu	6.6	10.7	95	75	$7\sim8 \times 10^{-4}$
Sn	5.8	7.7	85	65	$3\sim4 \times 10^{-4}$

* Based on Shear Modulus for Pure Sn, G=16302-40.5T(°C)

Sn: Normalized data(when Q=80KJ/mole)



```
Linear Fit for Q80oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          26.70960208    2.00197406
B          5.93326631     0.56710381
------------------------------------------------------------

R          SD         N          P
------------------------------------------------------------
0.98657198       0.07886247       5          0.00186413
------------------------------------------------------------
```

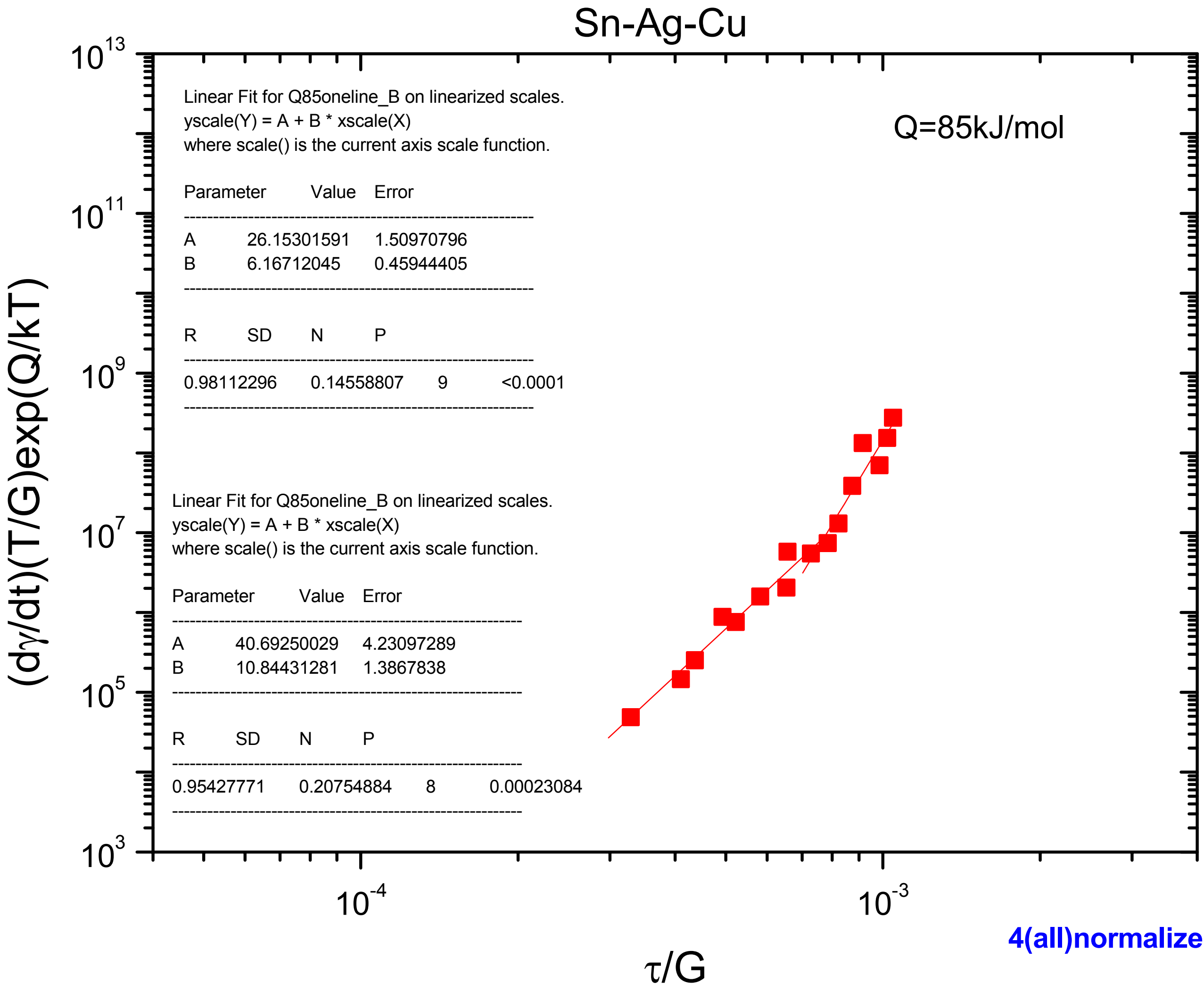
```
Linear Fit for Q80oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          37.28741683    2.41900461
B          9.05265081     0.74248747
------------------------------------------------------------

R          SD         N          P
------------------------------------------------------------
0.98681141       0.19109141       6          0.00025976
------------------------------------------------------------
```

5(all)normalized

* G=16302-40.5T(ºC)

*ignore abnormal three data points in the middle of 60ºC data

SnAgCu: Normalized data(Q=85KJ/mole)



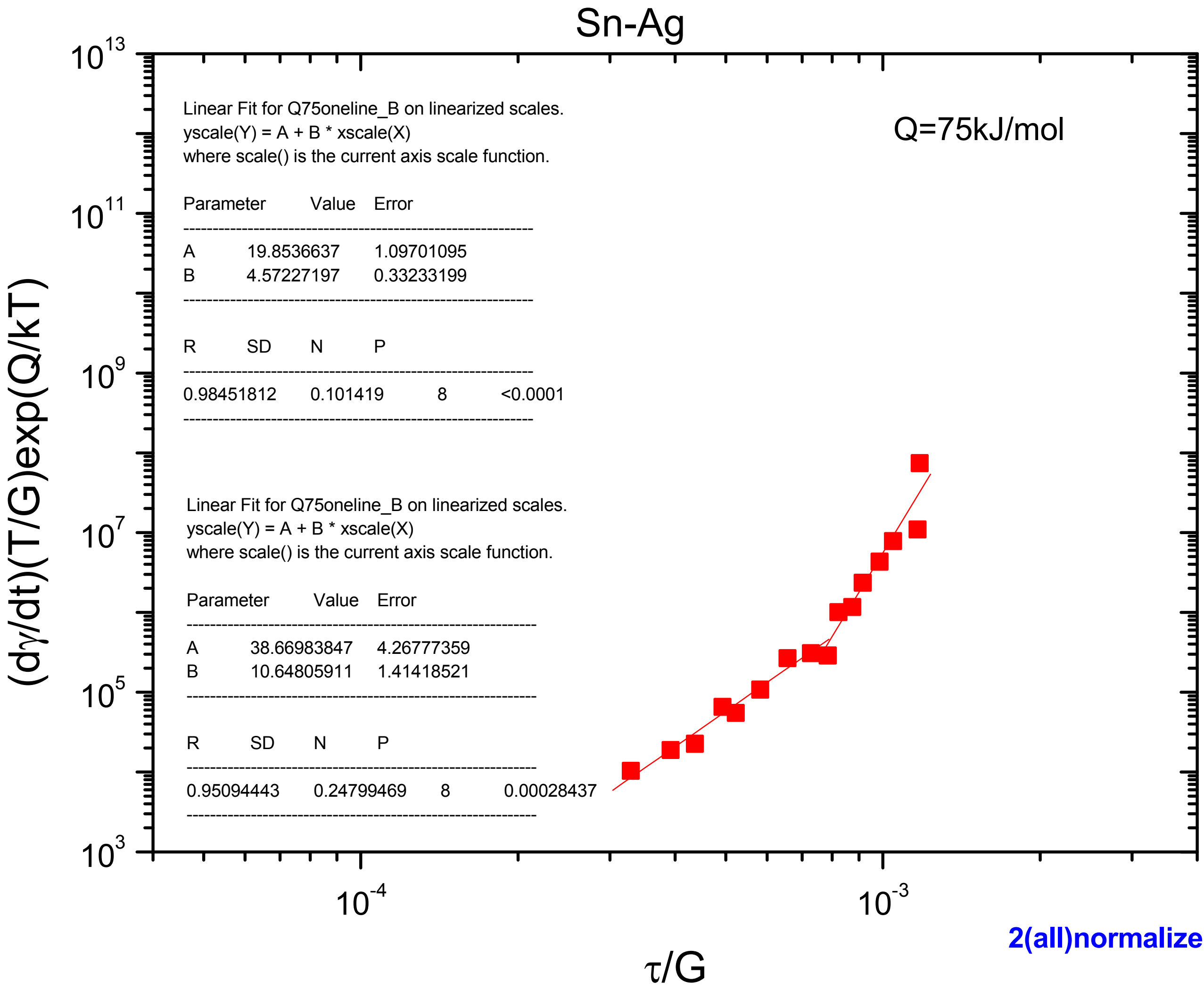
```
Linear Fit for Q85oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A         26.15301591    1.50970796
B         6.16712045     0.45944405
------------------------------------------------------------

R         SD         N         P
------------------------------------------------------------
0.98112296     0.14558807     9          <0.0001
------------------------------------------------------------
```

```
Linear Fit for Q85oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A         40.69250029    4.23097289
B         10.84431281    1.3867838
------------------------------------------------------------

R         SD         N         P
------------------------------------------------------------
0.95427771     0.20754884     8          0.00023084
------------------------------------------------------------
```

4(all)normalized

* G=16302-40.5T(°C)

SnAg: Normalized data(when Q=75KJ/mole)



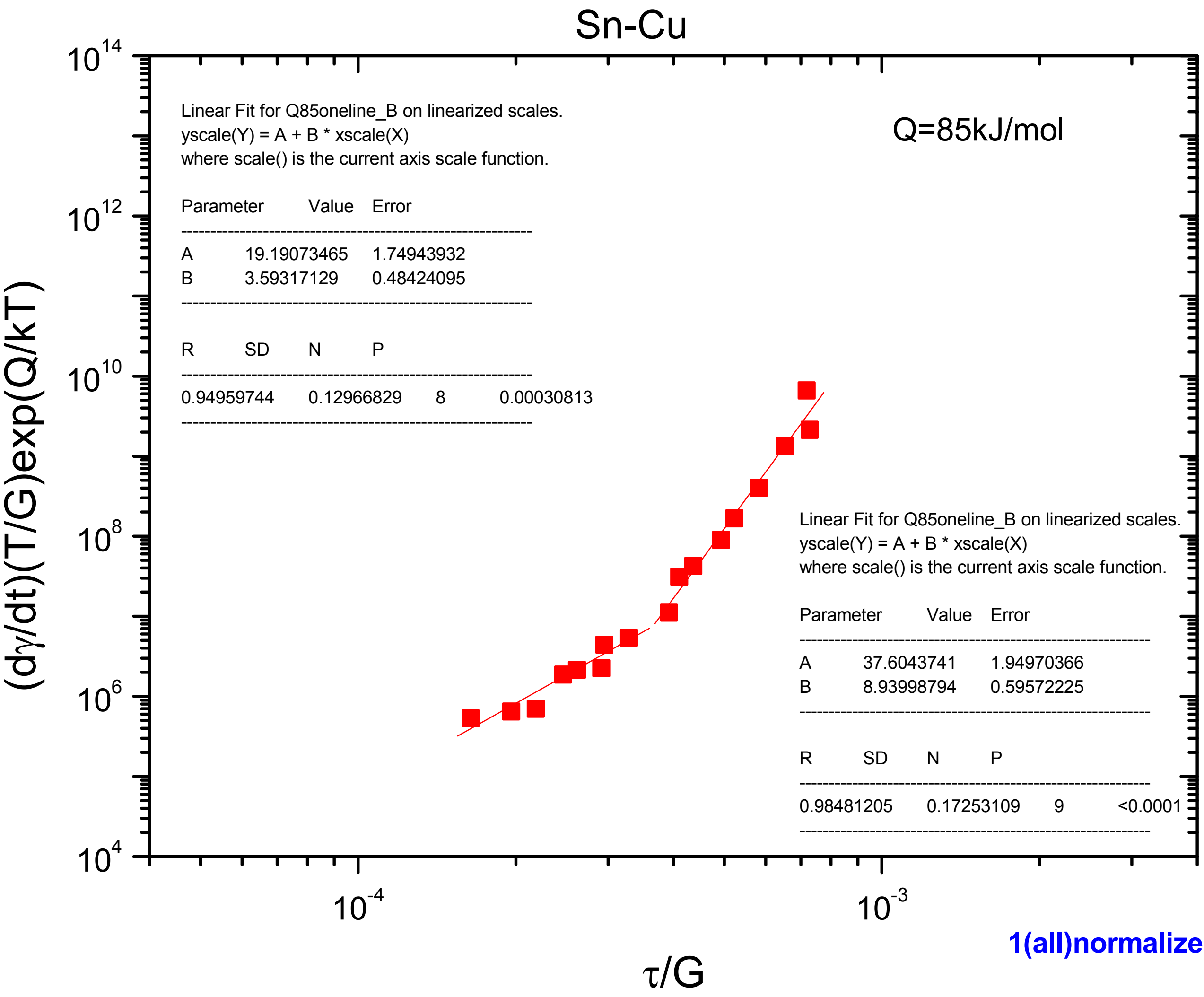
```
Linear Fit for Q75oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          19.8536637      1.09701095
B          4.57227197      0.33233199
------------------------------------------------------------

R          SD         N          P
------------------------------------------------------------
0.98451812       0.101419        8          <0.0001
------------------------------------------------------------
```

```
Linear Fit for Q75oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          38.66983847    4.26777359
B          10.64805911    1.41418521
------------------------------------------------------------

R          SD         N          P
------------------------------------------------------------
0.95094443       0.24799469       8          0.00028437
------------------------------------------------------------
```

2(all)normalized

* G=16302-40.5T(°C)

SnCu: Normalized data(when Q=85KJ/mole)



```
Linear Fit for Q85oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value       Error
------------------------------------------------------------
A           19.19073465     1.74943932
B           3.59317129      0.48424095
------------------------------------------------------------

R           SD          N           P
------------------------------------------------------------
0.94959744      0.12966829      8           0.00030813
------------------------------------------------------------
```

```
Linear Fit for Q85oneline_B on linearized scales.
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value       Error
------------------------------------------------------------
A           37.6043741      1.94970366
B           8.93998794      0.59572225
------------------------------------------------------------

R           SD          N           P
------------------------------------------------------------
0.98481205      0.17253109      9           <0.0001
------------------------------------------------------------
```

1(all)normalized

* G=16302-40.5T(°C)

Conclusion

- Sn-rich solders show two regimes of steady-state creep behavior
  - $n_L \sim 3.5\text{-}6.5$ at low stress
  - $n_H \sim 8\text{-}11$ at high stress
  - Break at $\tau/G \sim 4\text{x}10^{-4}$ (Sn,SnCu), $7\text{x}10^{-4}$ (SnAgX)
- The high-stress exponent (n_H) increases dramatically near room temperature
  - due to dominant Sn constituent
- Nonetheless, overall creep behavior is reasonably well fit by two-stage curve with Q ~ 80 KJ/mole