Deformation mechanism of TWIP steels at high strain rates

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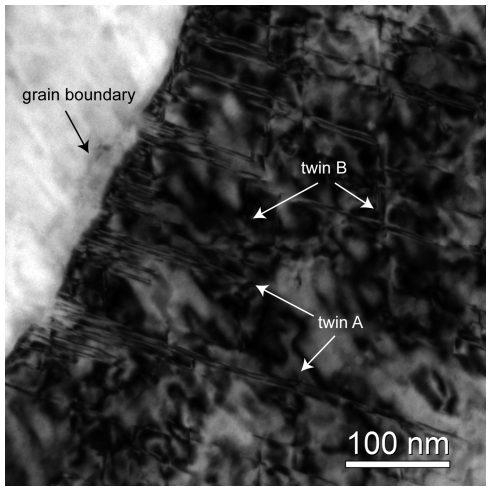
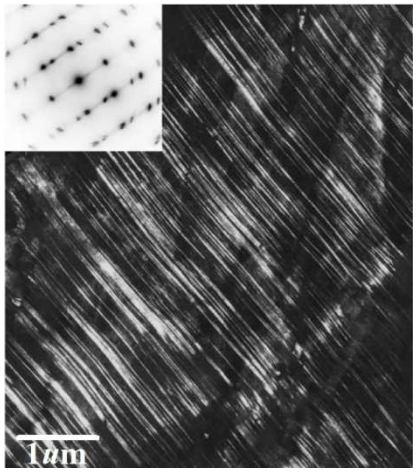
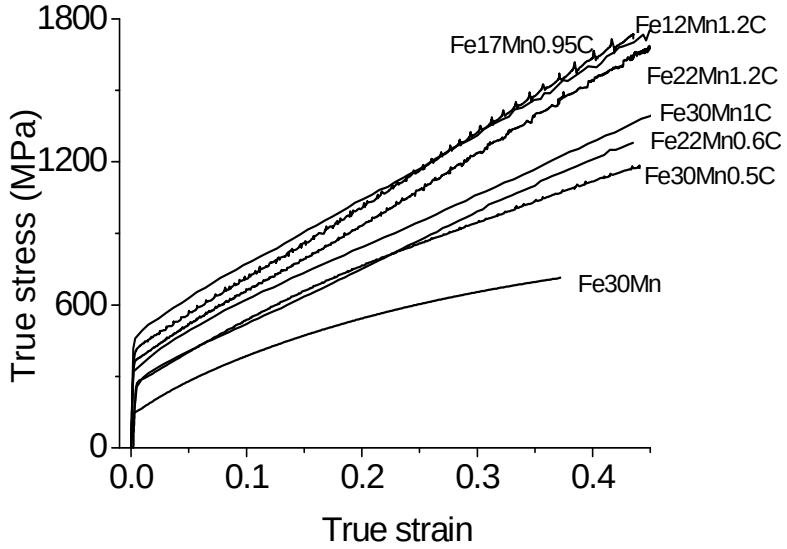
Automotive steel workshop 2014

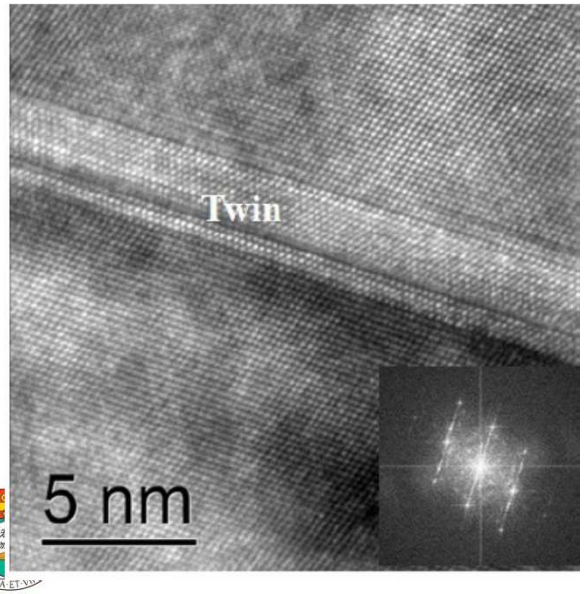
Introduction

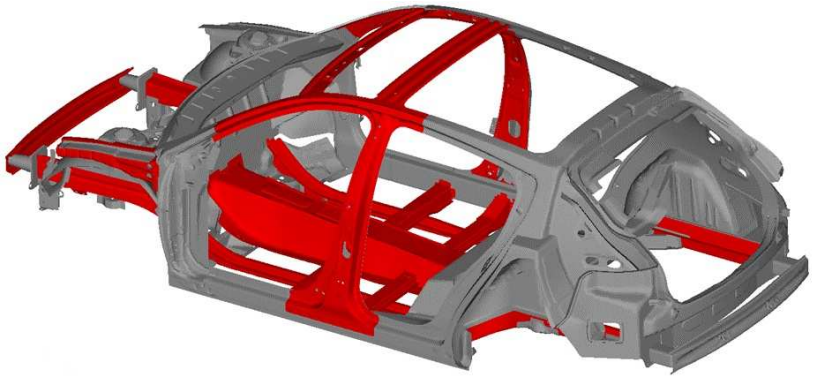
Deformation twinning TWIP steels





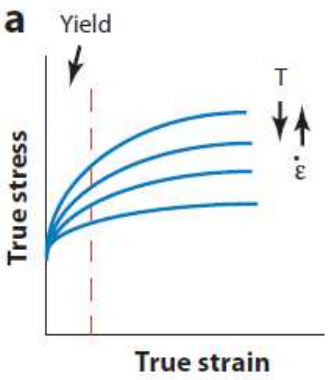


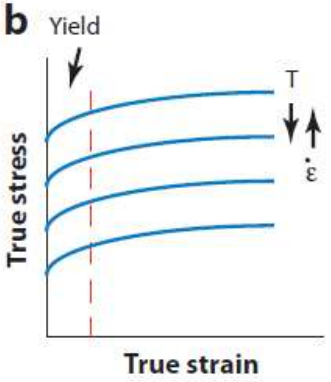


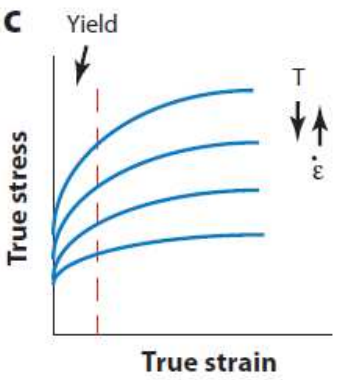


TWIP steels for automotive applications

Review on strain rates effects







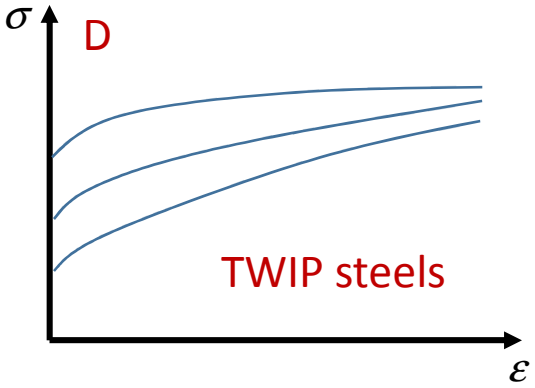
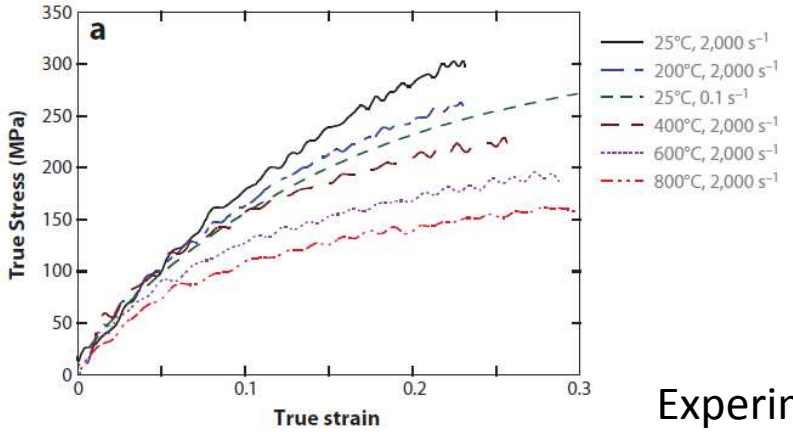


Figure 1

Schematic representations of the influence of temperature and strain rate on the yield and strain-hardening response of (*a*) annealed pure FCC metals such as Ni, Al, and Cu, (*b*) BCC and HCP metals at lower temperature and/or high strain rate, and (*c*) FCC alloys such as 304 stainless steel and/or BCC or HCP metals at higher temperatures and/or BCC or HCP metals for which deformation encompasses both dislocation slip and deformation twinning.



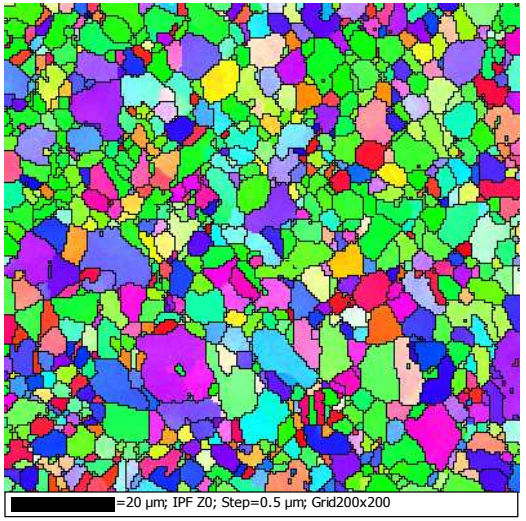
Experimental data for pure Cu

Gray Annu. Rev. Mater. Res. 2012. 42:285–303

Experiments

- Material

	Fe	Mn	C	Al	Si
wt (%)	Bal.	18	0.6	1.5	0.8

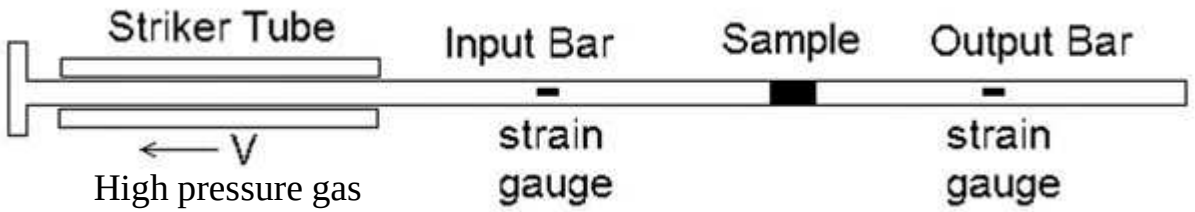


20 um

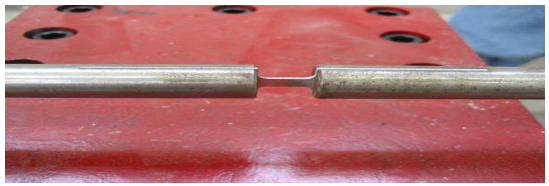
- Mechanical tests

  Quasi-static tensile tests (10^{-3} to 10^{-2} s^{-1})

  High strain rate tensile tests (10^{1} to 10^{3} s^{-1}): Split Hopkinson bar system



http://what-when-how.com/dynamic-behavior-of-materials



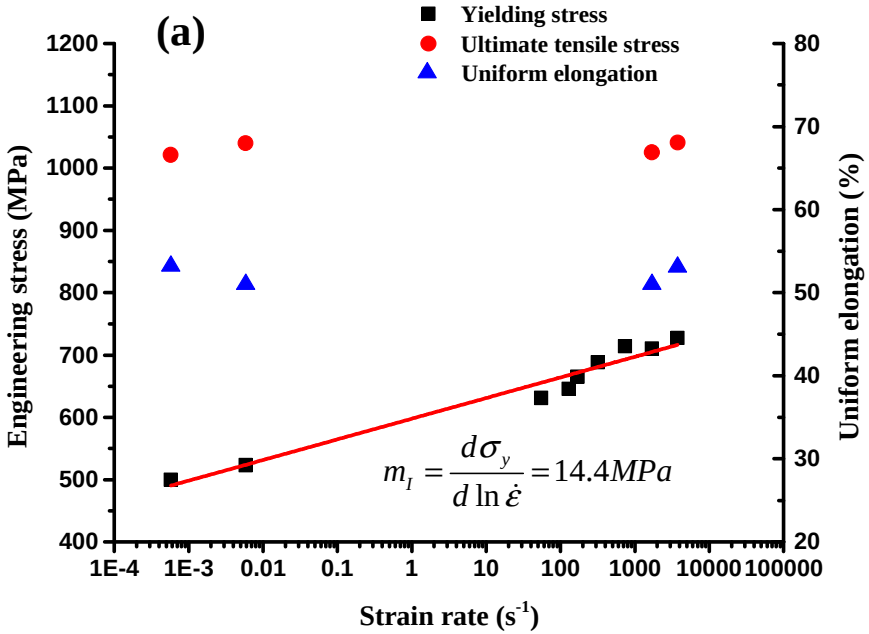
- Microstructure characterization

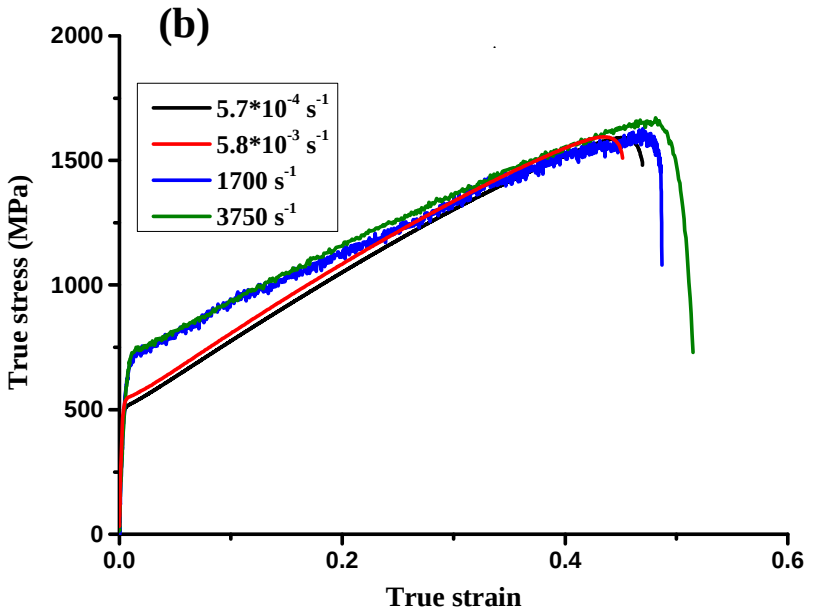
  TEM for observing the dislocations and deformation twins

  Synchrotron X-ray diffraction for measuring the dislocation and twin density

Mechanical properties

Strain rate: 5.7×10^{-4} to 3750 s^{-1}





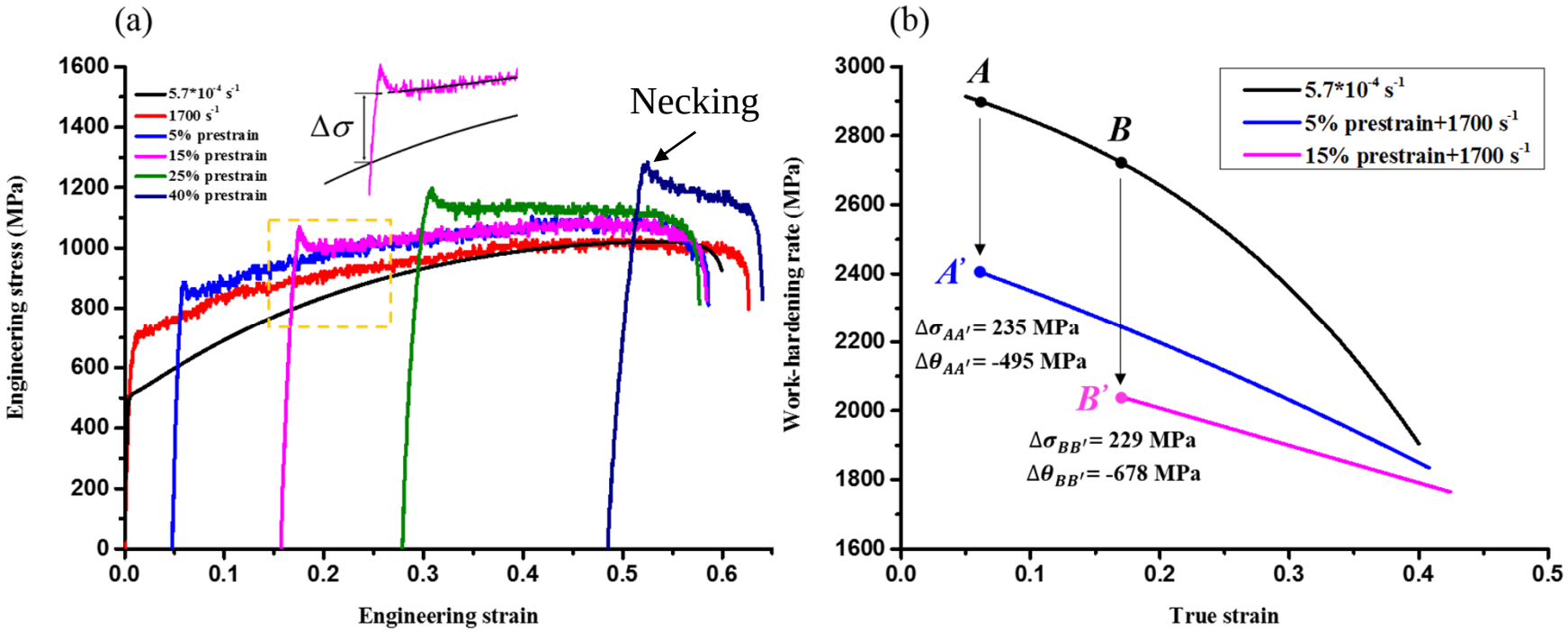
➢ Significant instantaneous strain rate sensitivity $m_I = 14.4MPa$

➢ Similar UTS obtained regardless of the strain rate

Possible explanations for similar UTS:

1. Instantaneous effect weakens with strain
2. Weakened work-hardening at higher strain rate

Strain rate jump tests

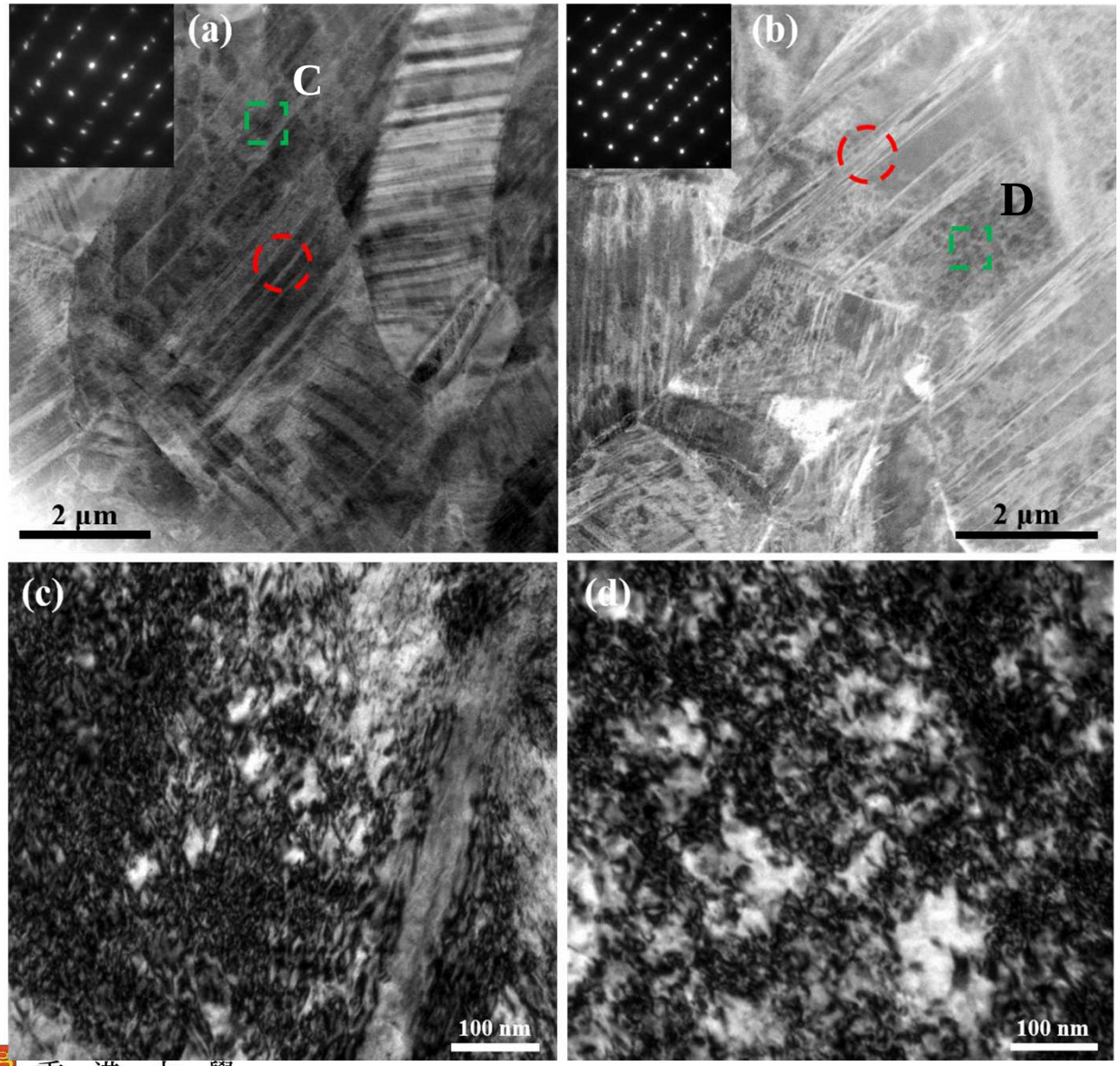


Prestrain at 5.7×10^{-4} s^{-1} to different levels
Unload and reload at 1700 s^{-1} until fracture

Prestrain	0%	5%	15%	25%
Δσ (MPa)	210	235	229	241

- Instantaneous effect stay relatively constant with strain
- Weaker work-hardening rate at higher strain rate
- Lower density of defects developed at higher strain rate

TEM characterization



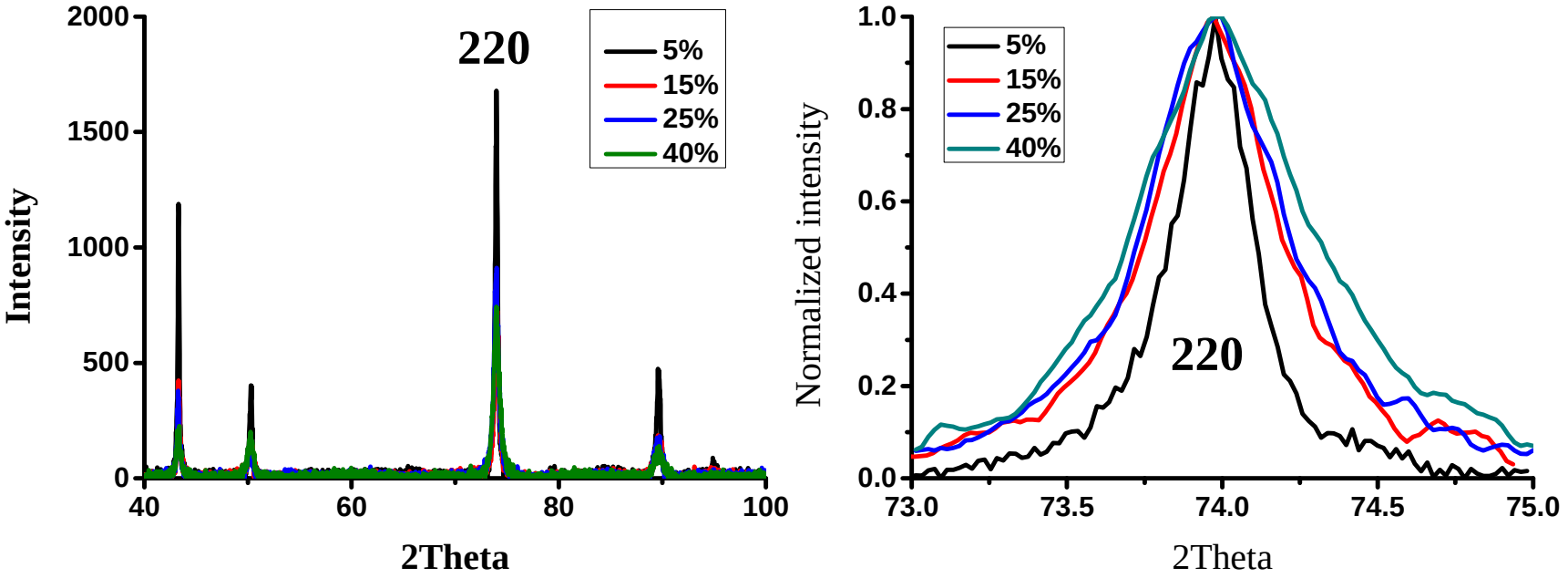
(a) 5.7×10^{-4} s^{-1}
STEM dark field
(b) 1700 s^{-1}
STEM dark field
(c) 5.7×10^{-4} s^{-1}
TEM bright field
(d) 1700 s^{-1}
TEM bright field

Massive deformation twins and dislocation found in specimen strained at both low and high strain rate

Difference in defects density is difficult to detect in TEM

XRD tests

Defects in crystal will cause peak broadening in the X-ray diffraction

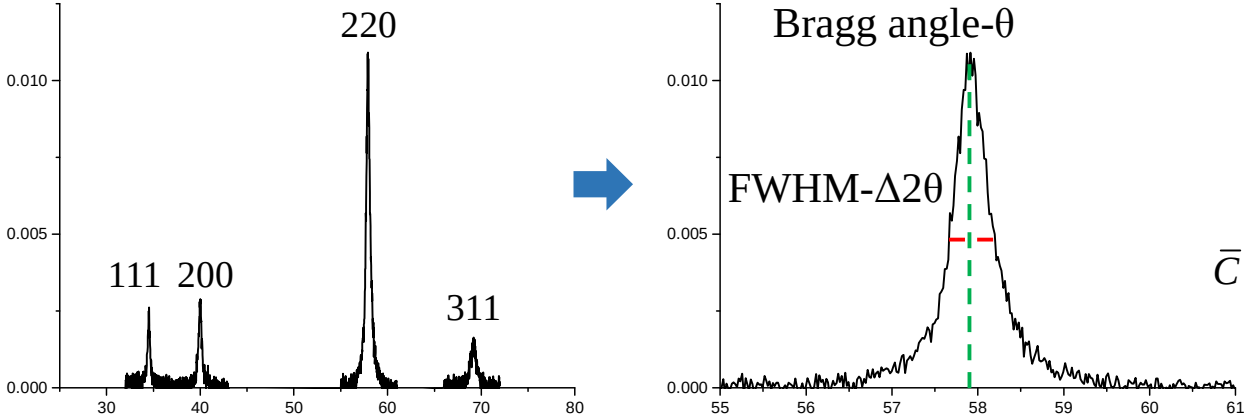


Modified Williamson-Hall method-the peak broadening can be linked to the crystal size, dislocation density and population of twin boundaries & stacking faults as:

$$\Delta K = 0.9/d + (\pi A'^2 b^2/2)\cdot\rho^{1/2}\cdot K^2\bar{C} + \beta' W(K) + O(K^4\bar{C}^2)$$

Modified W-H plot

$$\Delta K = 0.9/d + (\pi A'^2 b^2/2)\cdot\rho^{1/2}\cdot K^2\bar{C} + \beta' W(K) + O(K^4\bar{C}^2)$$



$$\Delta K = \cos\theta(\Delta 2\theta)/\lambda$$

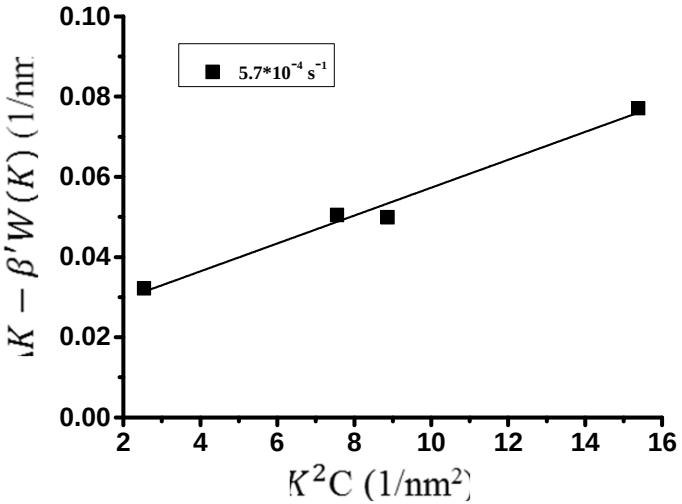
$$K = 2\sin\theta/\lambda$$

$$\bar{C} = C_{h00}\left[1 - q\left(\frac{h^2k^2 + k^2l^2 + l^2h^2}{h^2 + k^2 + l^2}\right)\right]$$

$$\Delta K - \beta' W(K) = 0.9/d + (\pi A'^2 b^2/2)\cdot\rho^{1/2}\cdot K^2\bar{C} + O(K^4\bar{C}^2)$$

$$y = n + m\cdot K^2 C$$

	K^2C	ΔK	W(K)
111	2.5	0.021	0.43
200	7.6	0.036	1
220	8.9	0.037	0.71
311	15.4	0.058	0.45



$$m = (\pi A'^2 b^2/2)\cdot\rho^{1/2}$$

$$n = 0.9/d$$

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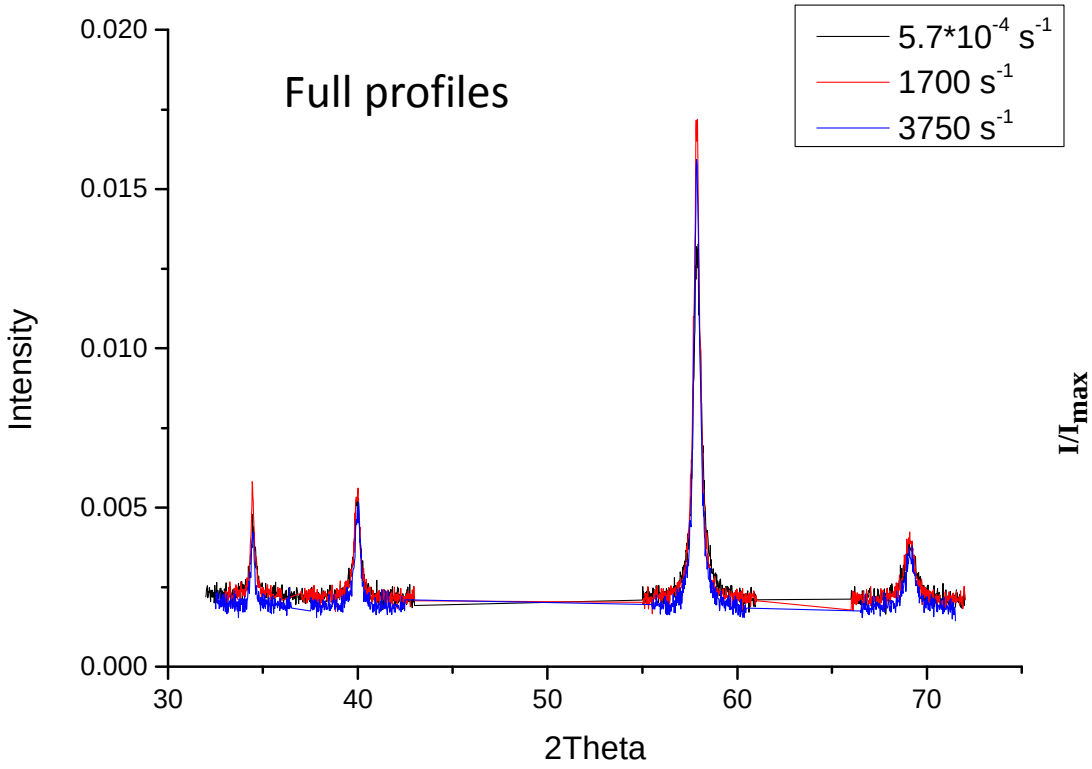
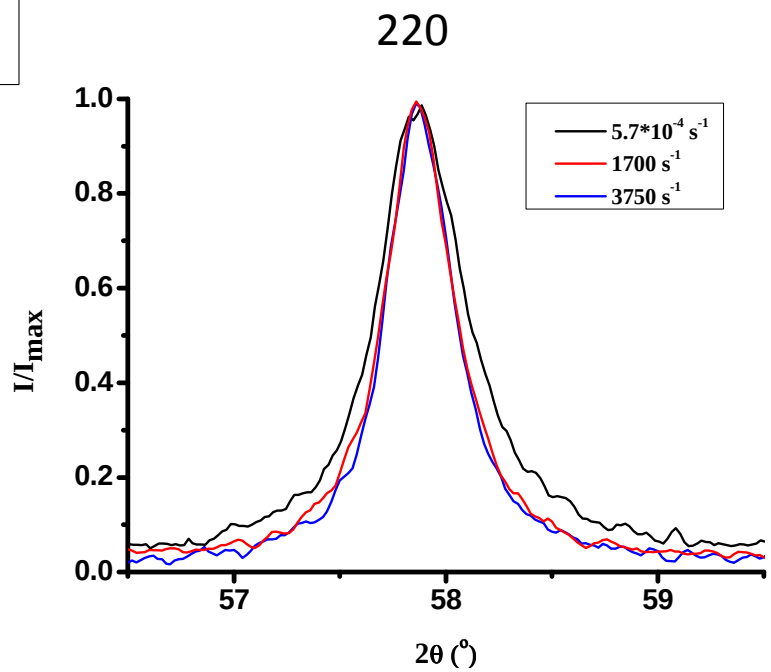
Synchrotron XRD





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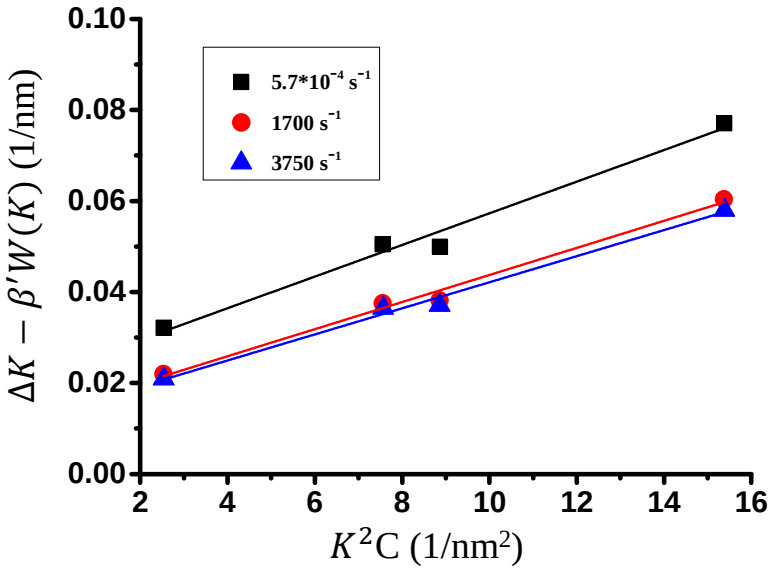
Modified Williamson-Hall plot



$\dot{\varepsilon}$ (s^{-1})	ρ (m^{-2})	β' (%)	d (nm)
5.7×10^{-4}	1.16×10^{15}	0.35	39.5
1700	8.68×10^{14}	0.24	64.6
3750	7.99×10^{14}	0.23	66.6

$\dot{\varepsilon}$ ↑ ρ & β' ↓

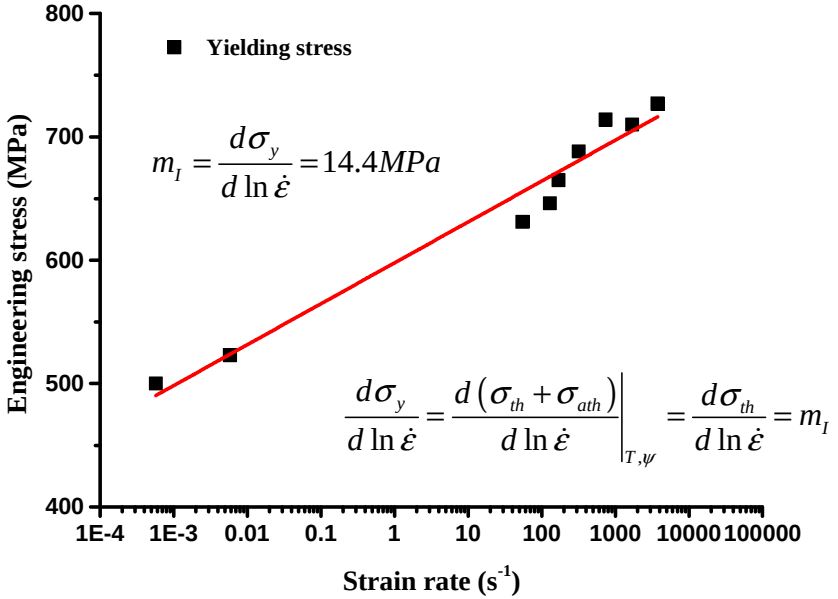
Negative rate sensitivity of work-hardening

Modelling

$\sigma = \sigma_{th} + \sigma_{ath}$ Thermal and athermal stress

$$\dot{\varepsilon} = \rho_m b \Lambda \nu_0 \exp\left(\frac{\Delta G_0 - \Delta V \cdot \sigma_{th} / M}{kT}\right) \Rightarrow \sigma_{th} = \frac{MkT}{\Delta V} \ln \dot{\varepsilon} + \frac{M}{\Delta V}\left(\Delta G_0 - kT \ln \rho_m b \Lambda \nu_0\right) = m_I \ln \dot{\varepsilon} + \sigma_0$$

$$\sigma_{ath} = M \alpha G b \sqrt{\rho} + \frac{K_{HP}}{\sqrt{L}}$$



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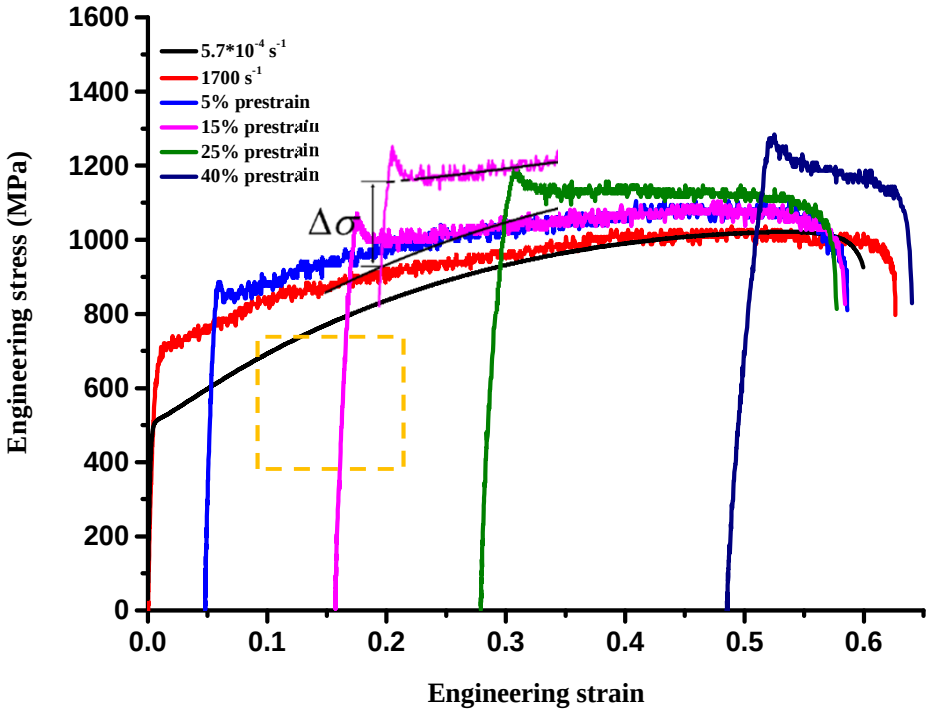
Thermal stress



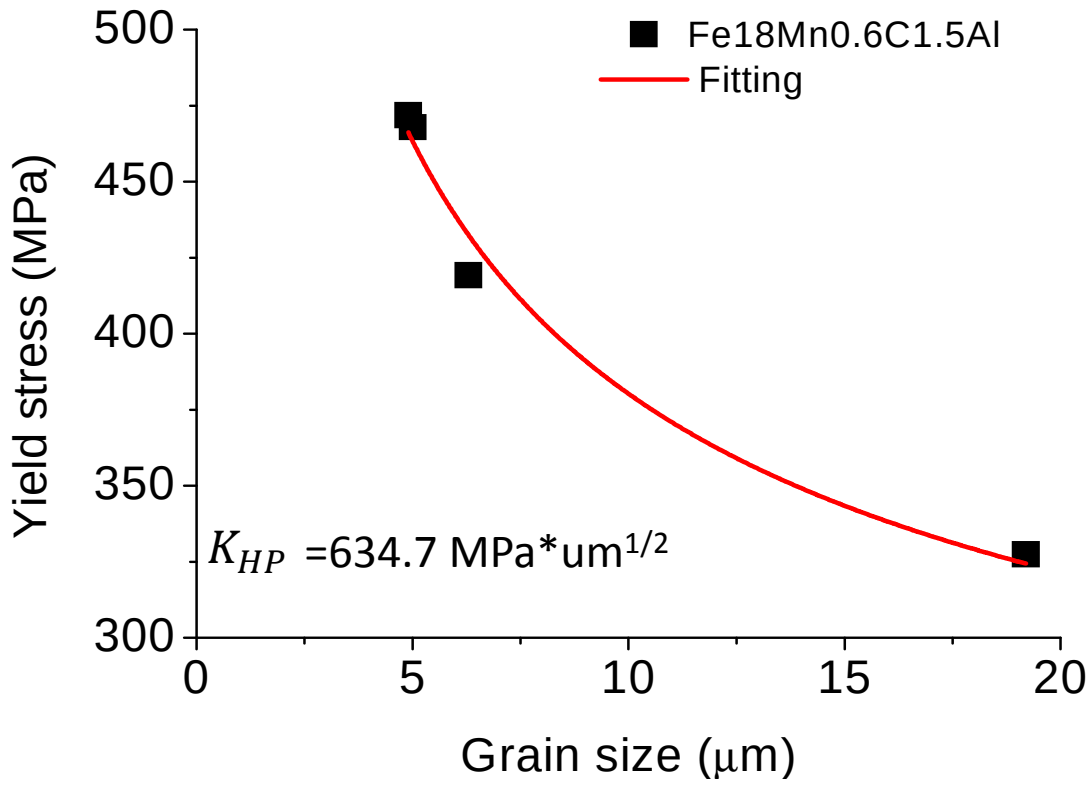
Prestrain	0%	5%	15%	25%
Δσ (MPa)	210	235	229	241

Conclusion :Thermal stress does not change with dislocation and twin density, and should be constant during straining.

Athermal stress

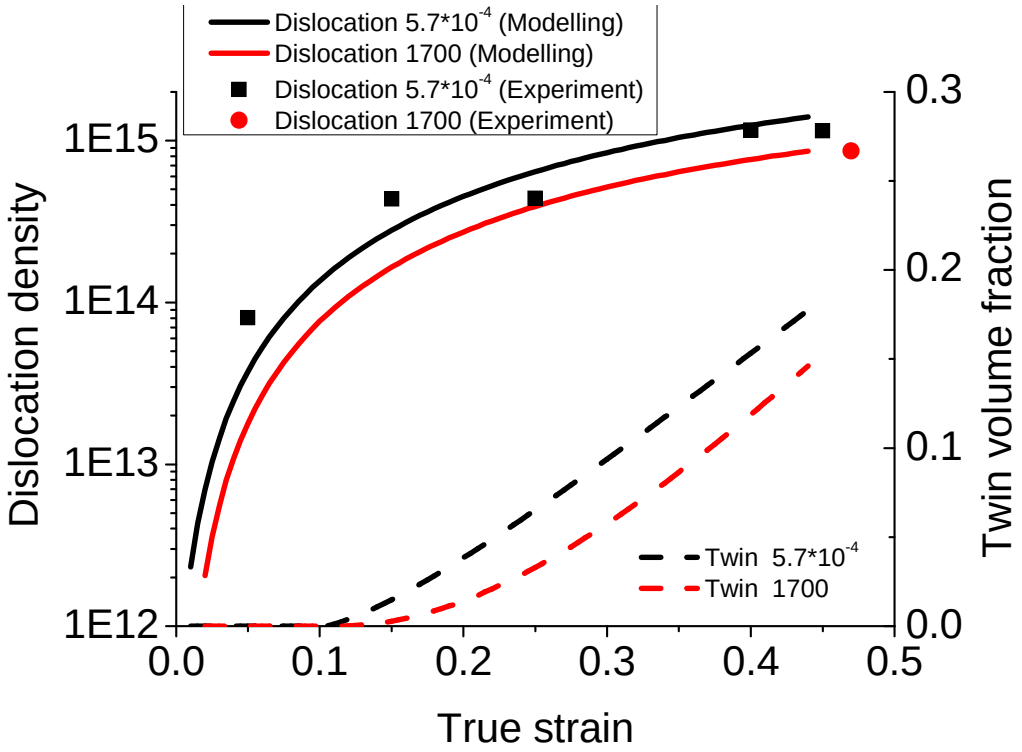
$$\sigma_{ath} = M\alpha Gb\sqrt{\rho} + \frac{K_{HP}}{\sqrt{L}}$$

(a function of strain because of dislocation density and twin volume fraction)



Dislocation and Twin evolution

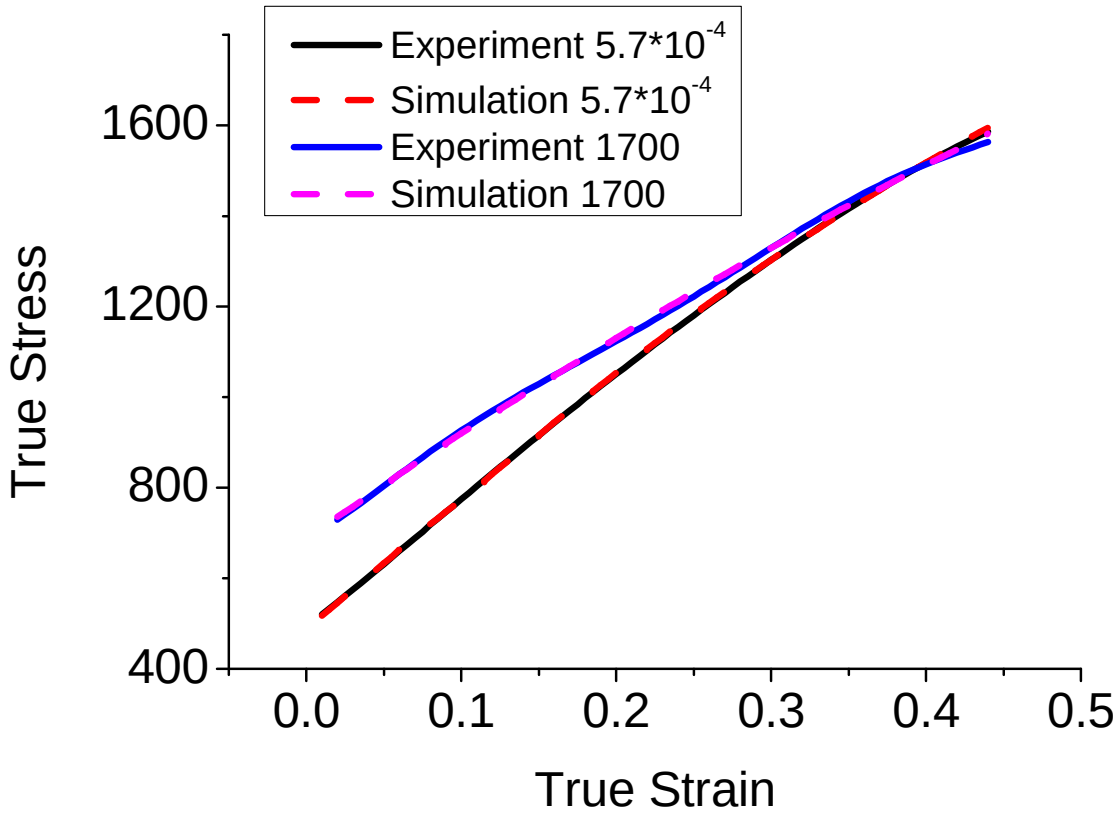
$$\frac{d\rho}{d\varepsilon} = M\left(\frac{k_a}{b}\sqrt{\rho} - f\rho\right) \qquad F = 1 - e^{-\chi(\varepsilon-\varepsilon_{init})^n}$$



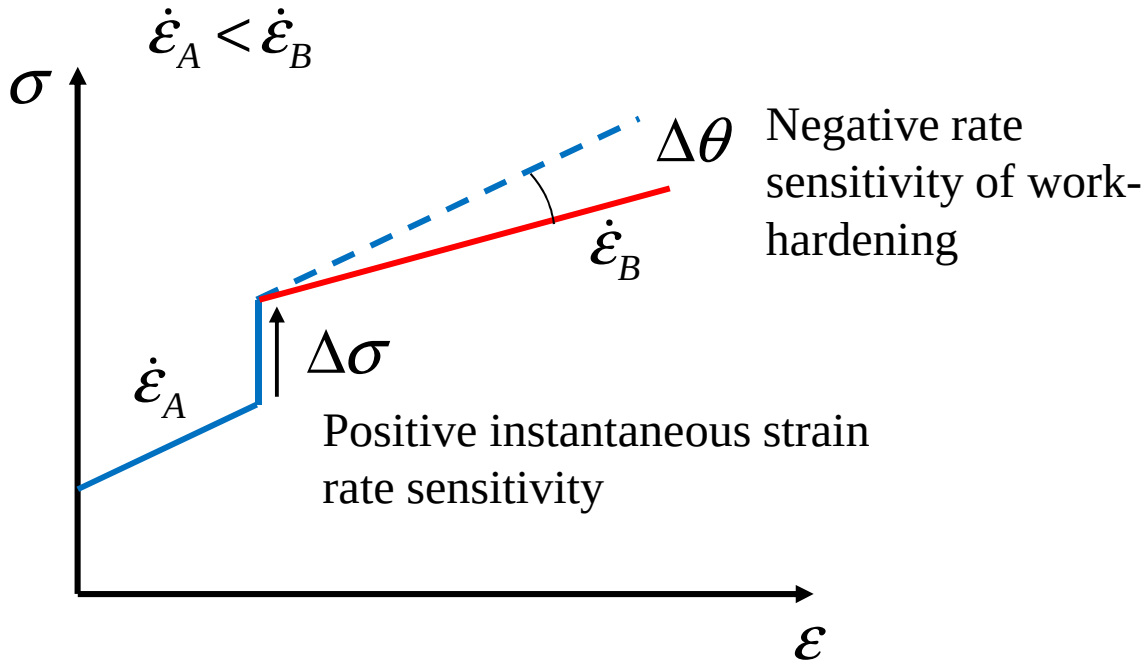
	5.7*10^{-4}	1700
k_a	0.0222	0.0180
f	1.45	1.53
χ	0.965	1.50
ε_{init}	0.103	0.112
n	1.35	2.03
i_c	0.1	0.1

$\dot{\varepsilon}\uparrow \rightarrow k_a\downarrow \; f\uparrow \rightarrow \rho\downarrow$ $\qquad$ $\dot{\varepsilon}\uparrow \rightarrow F\downarrow$

Stress-strain curves



Conclusions



Yield stress increases with strain rates.
UTS remains the same for various strain rates.
Higher strain rates leads to lower dislocation density and twin volume fraction. The average glide distance is higher at higher strain rate due to its higher stress.