University of Nevada, Reno

Representative volume element method for predicting the flow behavior of ferrite-pearlite dual phase steels

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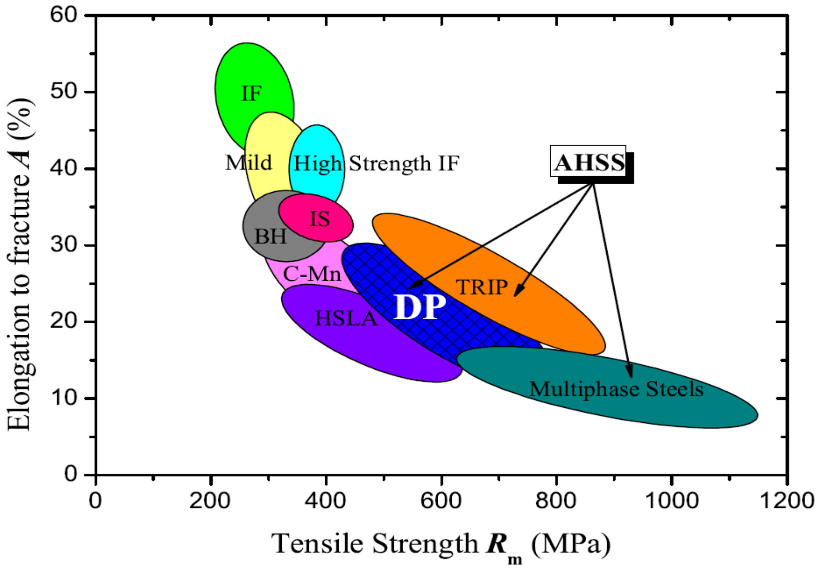
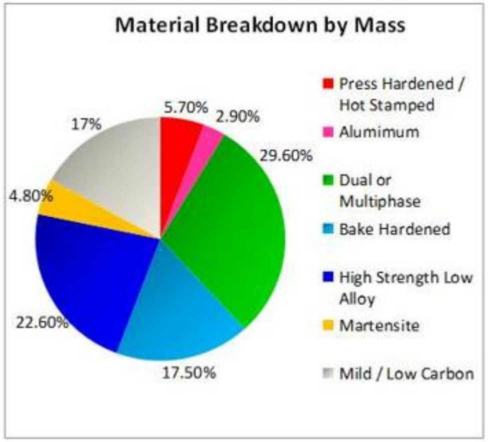
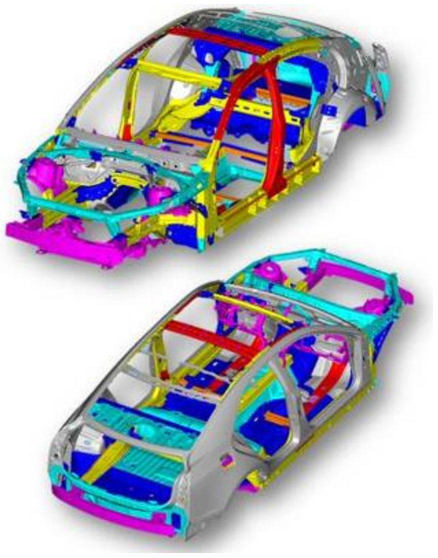
Background: Advanced High Strength Steels (AHSS)







Cadillac ATS

http://www.autosteel.org/research/growth-of-ahss.aspx

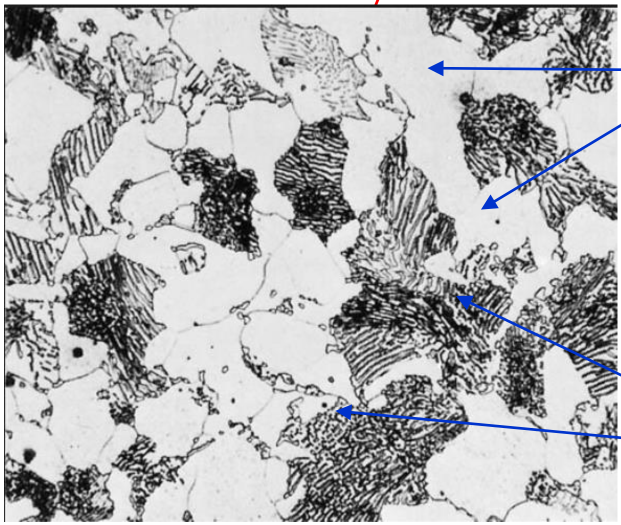
Background: Ferrite-Pearlite Dual Phase Steels

Current Model

Typical DP steels

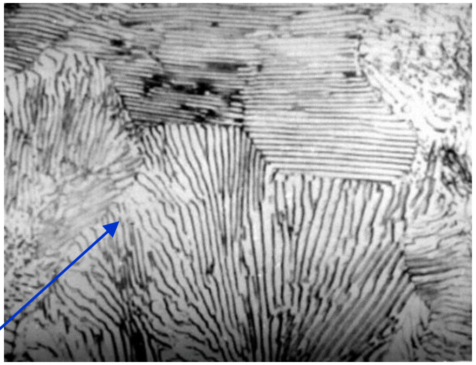
- Ferrite-pearlite steel — Low Cost, High Formability
- Quenched & tempered martensitic steel — High Strength
- Others — for Specific Applications

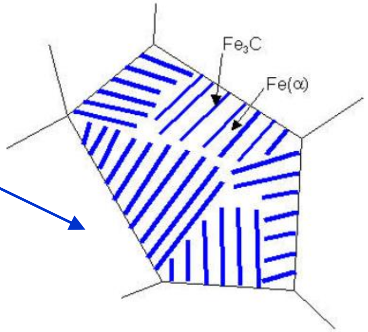
ferrite-pearlite steel



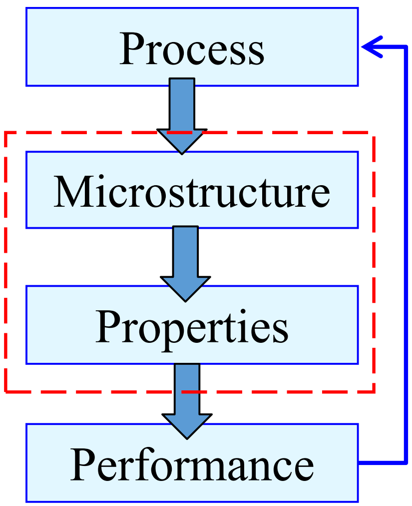
ferrite phase (α-iron, BCC)

pearlite structure (α-ferrite and cementite lamellar structure)





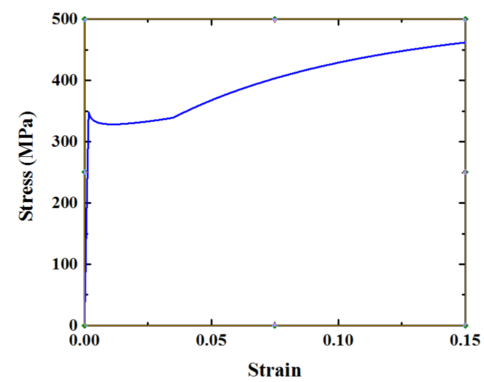
Motivation



To build up relationship between *microstructure* and *mechanical properties*

Challenges

- Current ferrite single phase models are unable to capture the Luders elongation phenomenon
- Empirical rule mixture model for predicting the mechanical properties dose not incorporated the complexity of the microstructure information

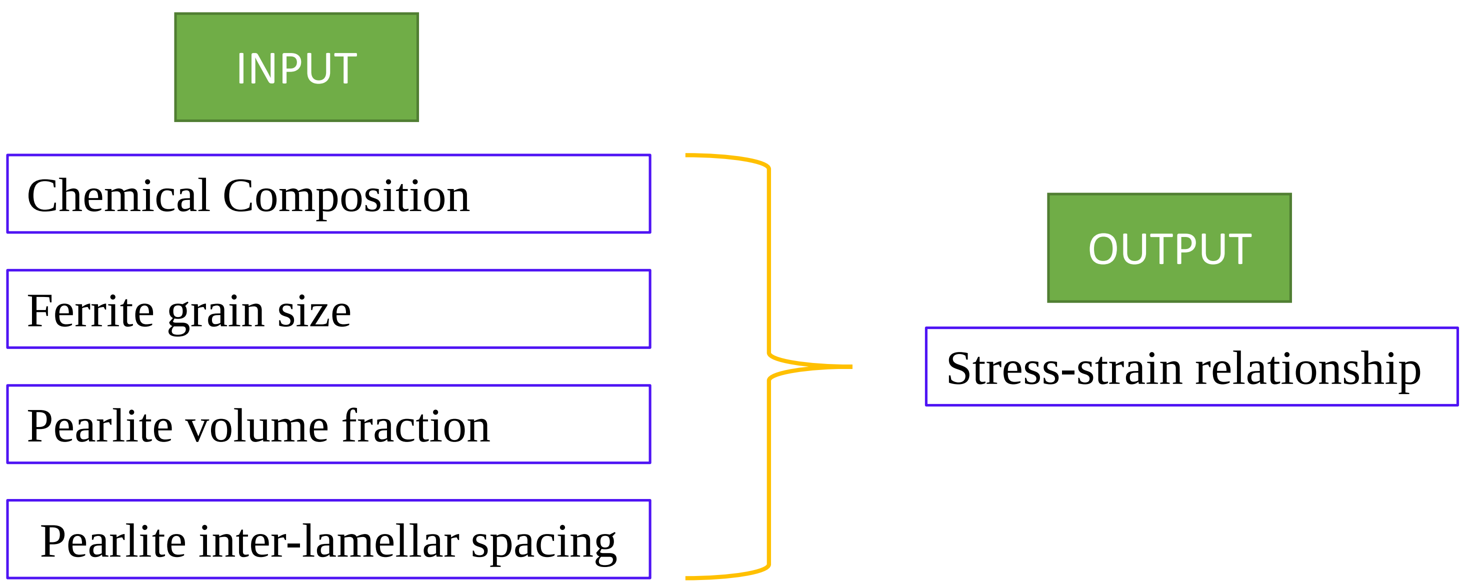


$$E_c = fE_f + (1 - f)\,E_m$$

Objective

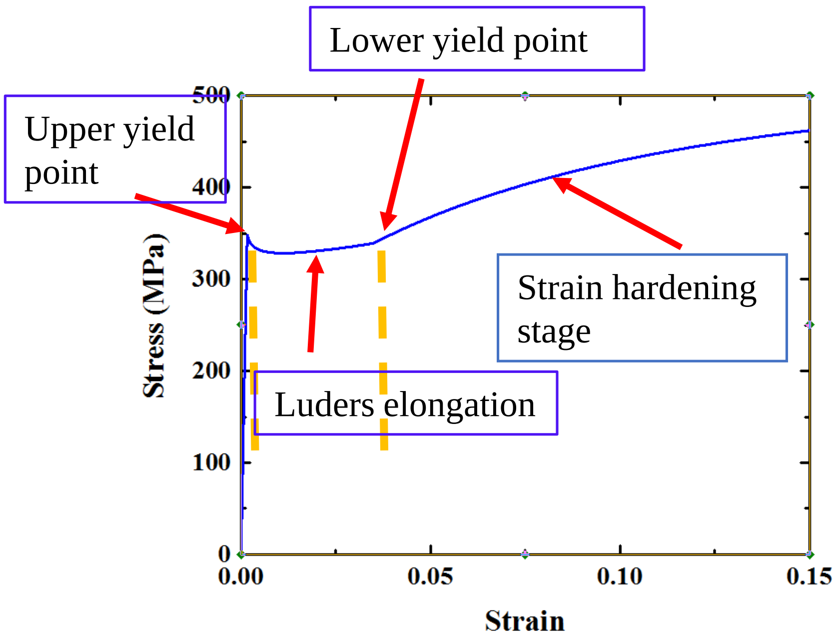
• Build up **microstructure based** ferrite model which is able to capture the Luders elongation phenomenon based on chemical composition, ferrite grain size, and strain rate.

• Build up **microstructure based** representative volume element model and conduct finite element analysis to predict the stress-strain relationship during tensile test based on microstructure



Ferrite Model Development

Correlates the upper yield strength and strain with chemical composition, grain size.



$$\left\{ \begin{aligned} \sigma_{UY} &= \sigma_f + 32\text{Mn} + 678\text{P} + 83\text{Si} + 39\text{Cu} - 31\text{Cr} \\ &\quad + 11\text{Mo} + 5544(\text{N}_{ss} + \text{C}_{ss}) + k_{HP} d^{-0.5} \\ \varepsilon_{UY} &= \sigma_{UY} / E \end{aligned} \right\}$$

For Luders band elongation stage

$$\sigma = \sigma_\varepsilon + 2\tau$$

$$\sigma_\varepsilon = \frac{1}{2} \alpha G M^2 k_1 \varepsilon$$ Linear response

$$\tau = \tau_0 \nu^{1/n}$$ Johnston–Gilman Law for shear stress

dislocation velocity

$$\nu = \dot{\varepsilon} / b\rho(\varepsilon)$$

dislocation density

Ferrite Model Development

Work hardening: the flow stress of work-hardened crystals is defined by the internal stresses due to the presence of forest and mobile dislocations.

$$\rho(\varepsilon) = \rho_0 + \left[M/(bd) - \rho_0 k_2 M\right]\varepsilon$$

Initial dislocation density

Mecking–Kocks theory

$$\frac{d\rho(\varepsilon)}{d\varepsilon} = M\left(\frac{1}{bd} + \frac{k_1}{b}\sqrt{\rho(\varepsilon)} - k_2\rho(\varepsilon)\right)$$

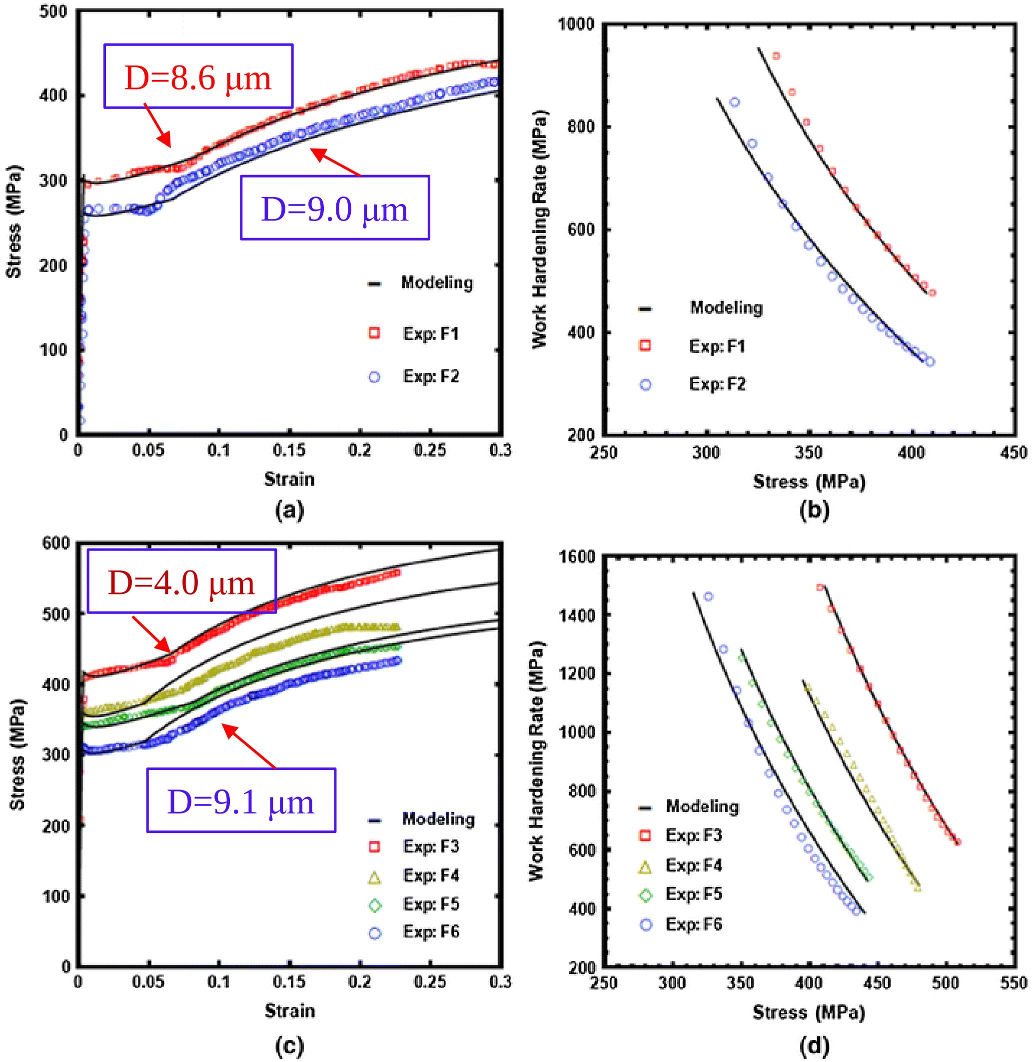
$$\left\{ \begin{aligned} \sigma_{LY} &= \frac{1}{2} p M^2 k_1 G \frac{n+1}{n+\varepsilon_{LY}^{-1}} \\ \sigma(\varepsilon, \dot{\varepsilon}, d) &= \frac{1}{2}\alpha G M^2 k_1 \varepsilon + 2\tau_0 \left[\dot{\varepsilon} \big/ \left(b\rho_0 + M\varepsilon/d\right)\right]^{1/n} \end{aligned} \right\}$$

Lower yield strength

For Strain hardening stage

$$\sigma_\varepsilon \frac{d\sigma_\varepsilon}{d\varepsilon} = \frac{M}{2}\left(k_2 \sigma_{\varepsilon ss}{}^2 + k_1 \sigma_{\varepsilon ss}\sqrt{dk_2/b}\,\sigma_\varepsilon - k_2 \sigma_\varepsilon{}^2\right)$$

Ferrite Model Validation



	C	Mn	Si	P	Al	N	D (µm)
F1	0.004	0.29	0.009	0.01	0.034	0.008	8.6
F2	0.003	0.29	0.007	0.009	0.027	0.005	9
F3	0.09	0.52	0.006	0.017	0.043	0.009	4
F4	0.08	0.45	0.008	0.012	0.04	0.009	6.2
F5	0.06	0.22	0.01	0.01	0.143	0.004	7
F6	0.04	0.26	0.009	0.01	0.1	0.003	9.1

M.M. Petite: Ph.D. Thesis, University of Navarra, Donostia-San Sebastia ´ n, 1999.

R. Rodriguez and I. Gutierrez: Mater. Sci. Forum., 2003, vols. 426–4, pp. 4525–30.

Pearlite Model Description

Hu, Xiaohua, et al. "Modeling work hardening of pearlitic steels by phenomenological and Taylor-type micromechanical models." *Acta materialia* 54.4 (2006): 1029-1040.

Contribution from Ferrite Phase

$$\sigma_{\mathrm{F}} = \begin{cases} E\varepsilon, & \varepsilon < \varepsilon_{\mathrm{F}}^{\mathrm{e}} \\ \sigma_0 + \frac{M\mu b}{\bar{s}} & \varepsilon = \varepsilon_{\mathrm{F}}^{\mathrm{e}} + \varepsilon_{\mathrm{F}}^{\mathrm{p}} \end{cases}$$

$$\bar{s} = \bar{s}_0 \, \mathrm{e}^{-\varepsilon/2}$$

Initial inter-lamellar spacing

Contribution from Cementite Phase

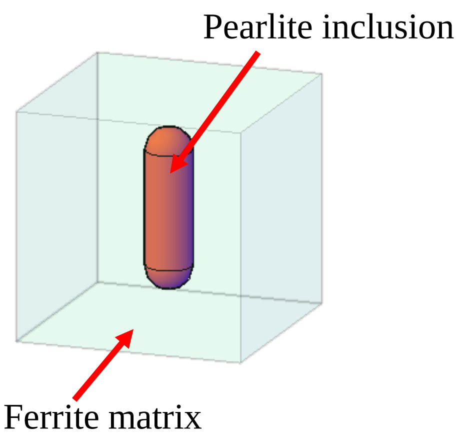
$$\sigma_{\mathrm{C}} = \begin{cases} E\varepsilon, & \varepsilon < \varepsilon_{\mathrm{C}}^{i} \\ \sigma_{\mathrm{C}}^{i} + (\sigma_{\mathrm{C}}^{y} - \sigma_{\mathrm{C}}^{i})\left(1 - \mathrm{e}^{-g(\varepsilon - \varepsilon_{\mathrm{C}}^{i})}\right), & \varepsilon \geqslant \varepsilon_{\mathrm{C}}^{i} \end{cases}, \quad g = E/(\sigma_{\mathrm{C}}^{y} - \sigma_{\mathrm{C}}^{i})$$

Overall stress-strain relationship

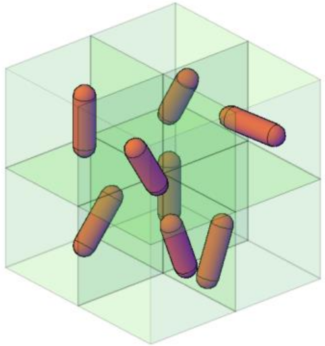
$$\sigma_P = f_F[\sigma_0 + \frac{M\mu b}{S_0 \exp(-\varepsilon/2)}] + (1 - f_F)[\sigma_C^i + (\frac{\sigma_S}{f_C} + \sigma_F^i - \sigma_C^i)(1 - e^{-g(\varepsilon - \varepsilon_C^i)})]$$

$$C\%(f_F \rho_F + (1 - f_F)\rho_C) = (1 - f_F)\rho_C C_{cementite}\%$$

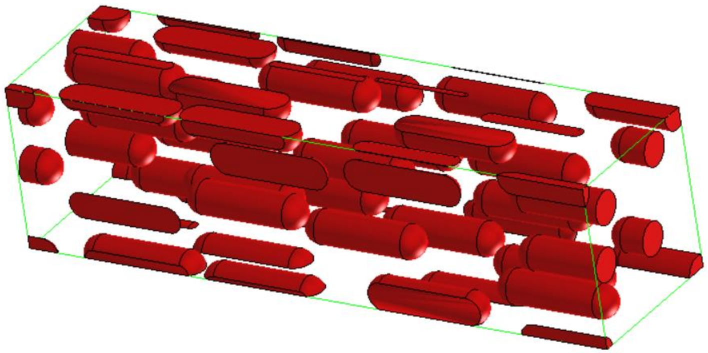
Representative volume element Methods

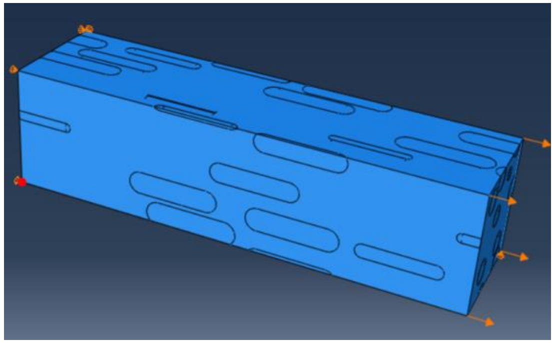


Representative volume
Element unit cell

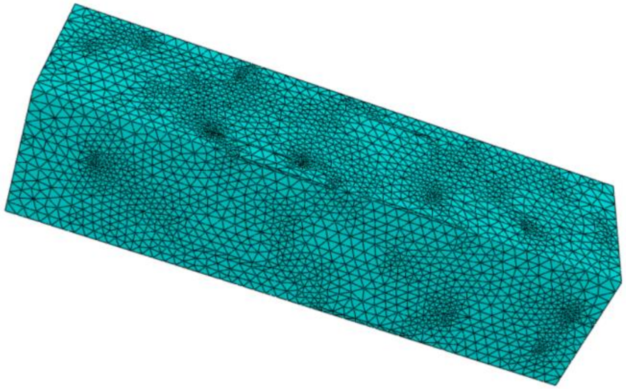


Assembly for Finite Element Analysis





Loading and constraint condition

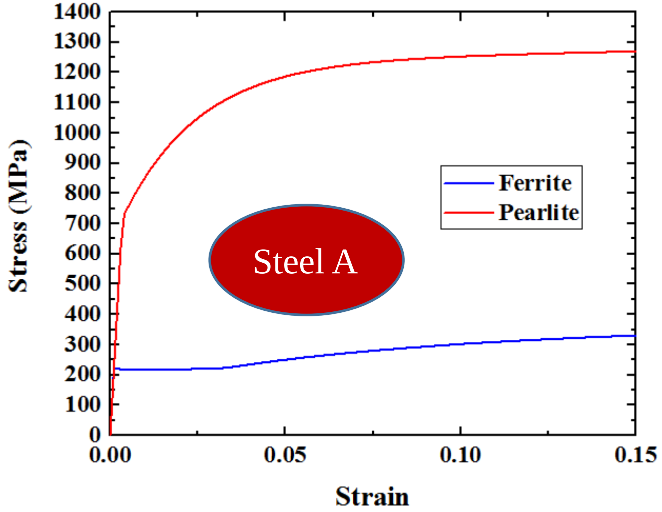


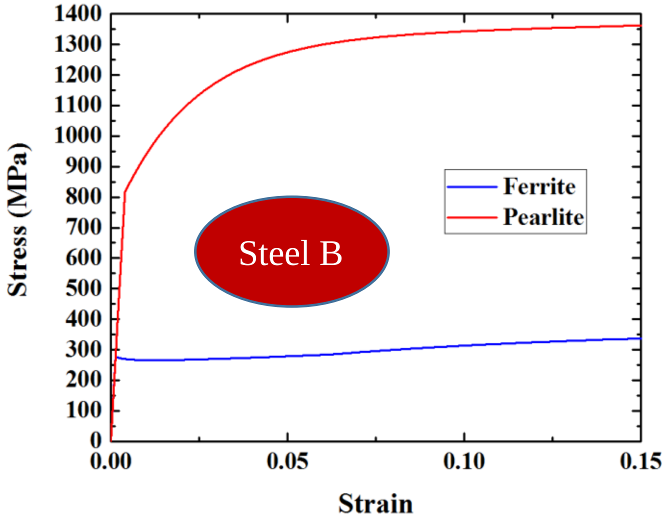
Mesh condition, C3D10M

RVE Model Validation

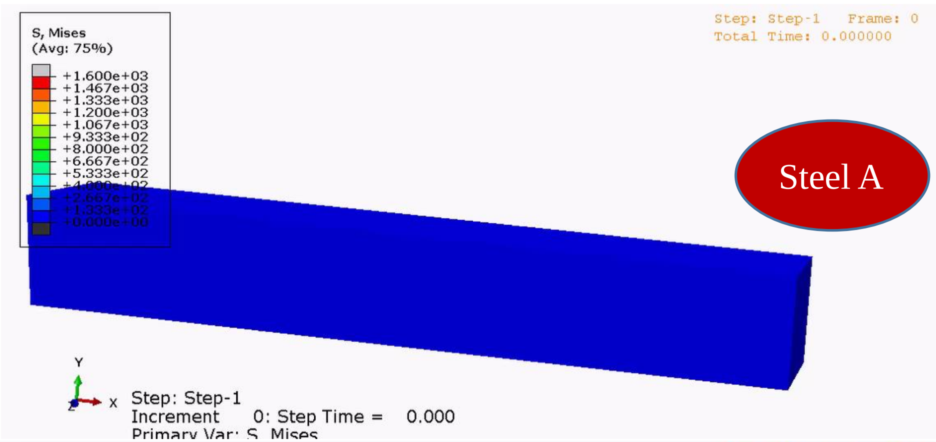
	C	Si	Mn	P	S	Ferrite grain size (μm）	Pearlite inter-lamellar –spacing (nm)	Pearlite Volume Fraction	Pearlite aspect ratio
Steel A	0.15	0.21	0.5	0.012	0.008	23.6	120	0.18	3.8
Steel B	0.15	0.25	1.3	0.012	0.005	20.4	0.10	0.24	6.9

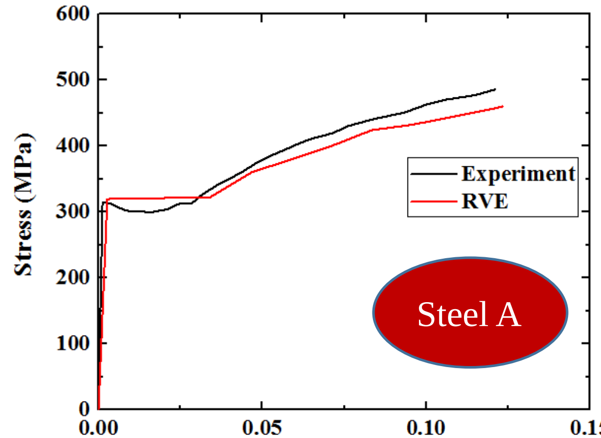
Suh, Dong-Woo, et al. "FEM modeling of flow curves for ferrite/pearlite two-phase steels." *ISIJ international* 41.7 (2001): 782-787.

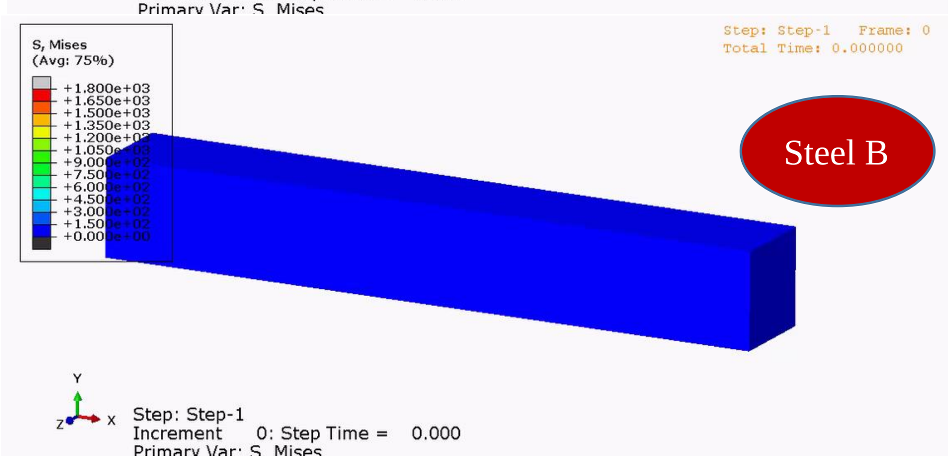


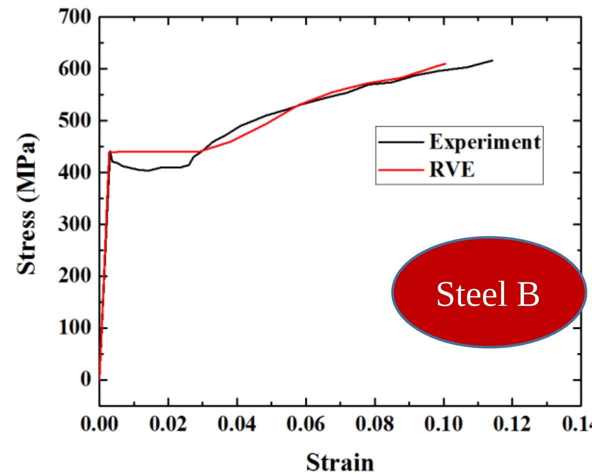


RVE Model Validation





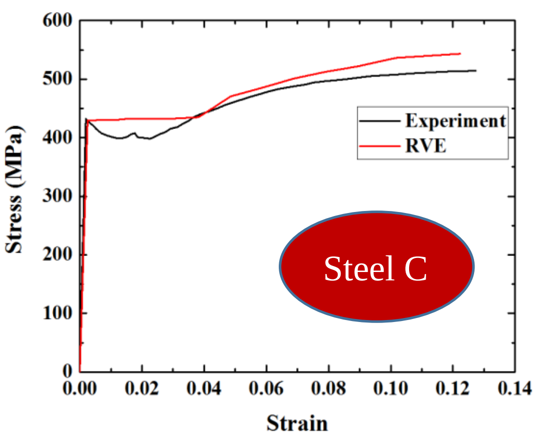


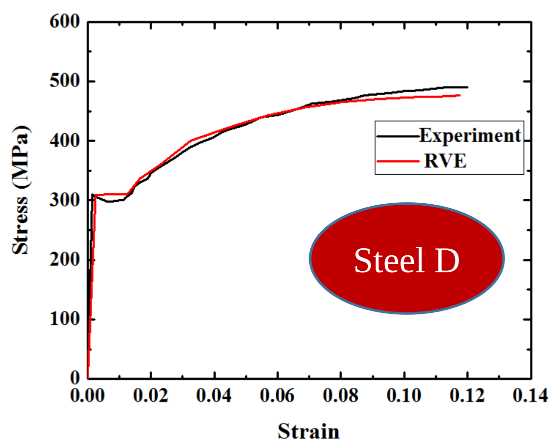


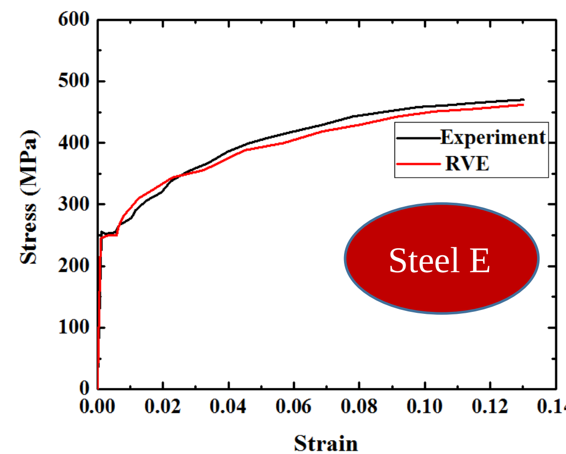
RVE Model Validation

	C	Si	Mn	P	S	Ferrite grain size (μm）	Pearlite inter-lamellar –spacing (nm)	Pearlite Volume Fraction	Pearlite aspect ratio
Steel C	0.15	0.4	1.5	0.014	0.004	3.6	110	0.12	10
Steel D	0.15	0.4	1.5	0.014	0.004	9.8	108	0.12	10
Steel E	0.15	0.4	1.5	0.014	0.004	46.2	105	0.12	10

Tsuchida, N., et al. "Enhanced true stress–true strain relationships due to grain refinement of a low-carbon ferrite–pearlite steel." *Materials Letters* 160 (2015): 117-119.







Conclusions

- The individual ferrite phase model which is able to predict the Luders elongation phenomenon is developed.
- A three dimensional representative model which has the ability to cover the information of distribution and volume fraction of pearlite phase is developed. Finite element analysis is conducted by ABAQUS.
- This model is able to predict the Luders elongation in ferrite-pearlite dual phase steels and has been extensively validated by experimental data.
- Such a model could also be applied on other kinds of dual or complex phase steels to build a database for guiding the manufacturing of AHSS.

Thank you!