Comparison of 1500 MPa Ultra-High-Strength Steels (UHSSs) for Automotive Applications

Jun Hu, PhD

Cleveland-Cliffs Inc.

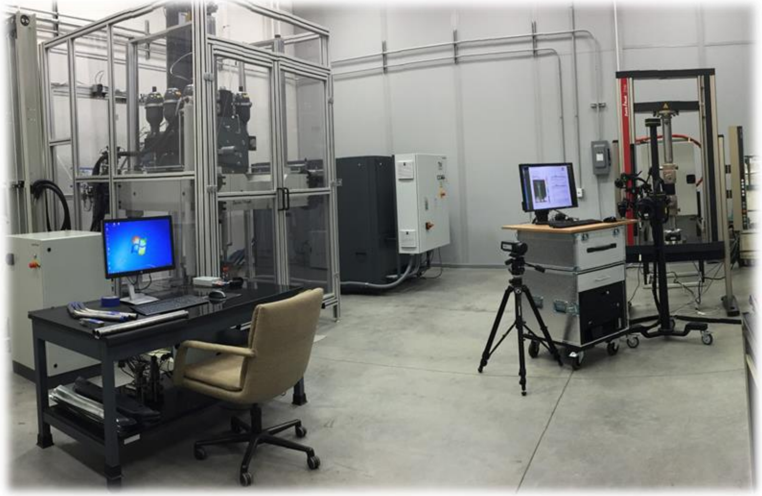
CLIFFS

GREAT DESIGNS IN STEEL™

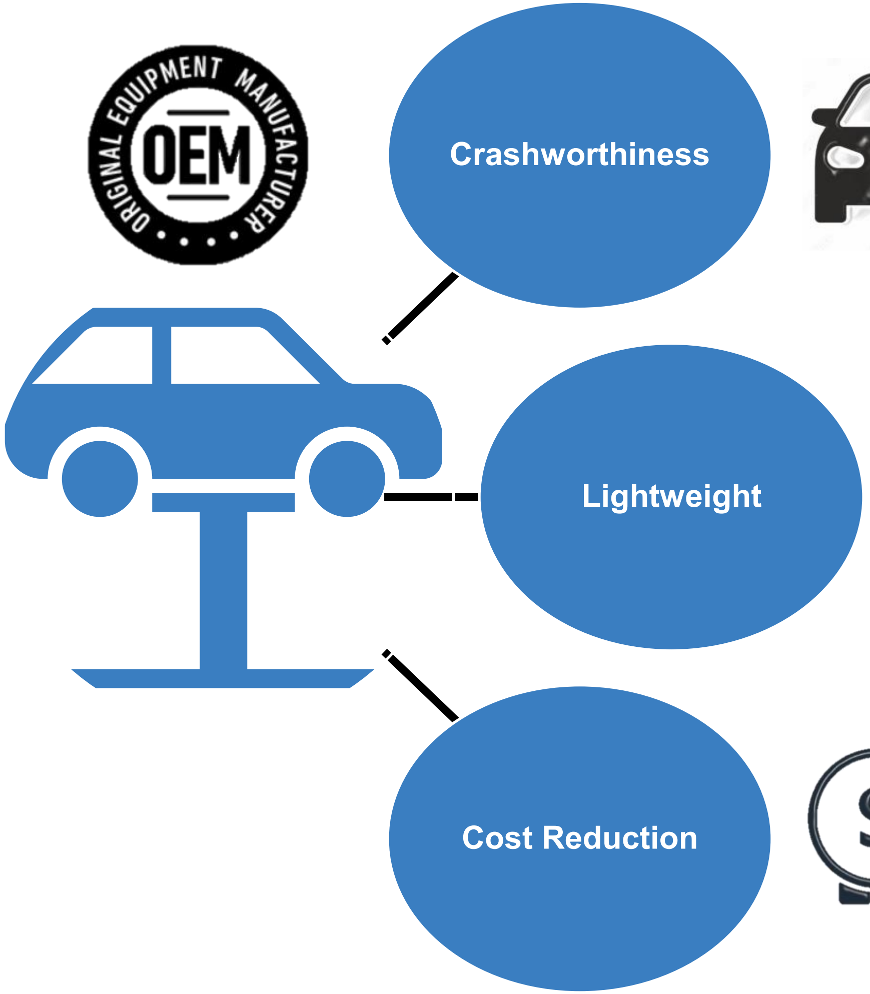
Acknowledgements

The presenter wishes to acknowledge Yeting Sun (University of Central Florida), Tobi Oriola (University of Cincinnati), Eliseo Hernandez-Duran, Timothy Gustafson, Eizo Yoshitake, Fred Sun, Chris Copeland, Steven Walls, Reuben Felsheim, Chris Walker, Jason Wymer, Dana Lentz, Laura Burroughs, Grant Thomas, and many other colleagues for their efforts and/or discussions in this and preceding work. The support from Cleveland-Cliffs Inc. management is greatly appreciated as well.

Additionally, the coordination efforts by Brain Esterberg and Hesham Ezzat at AISI are also acknowledged.



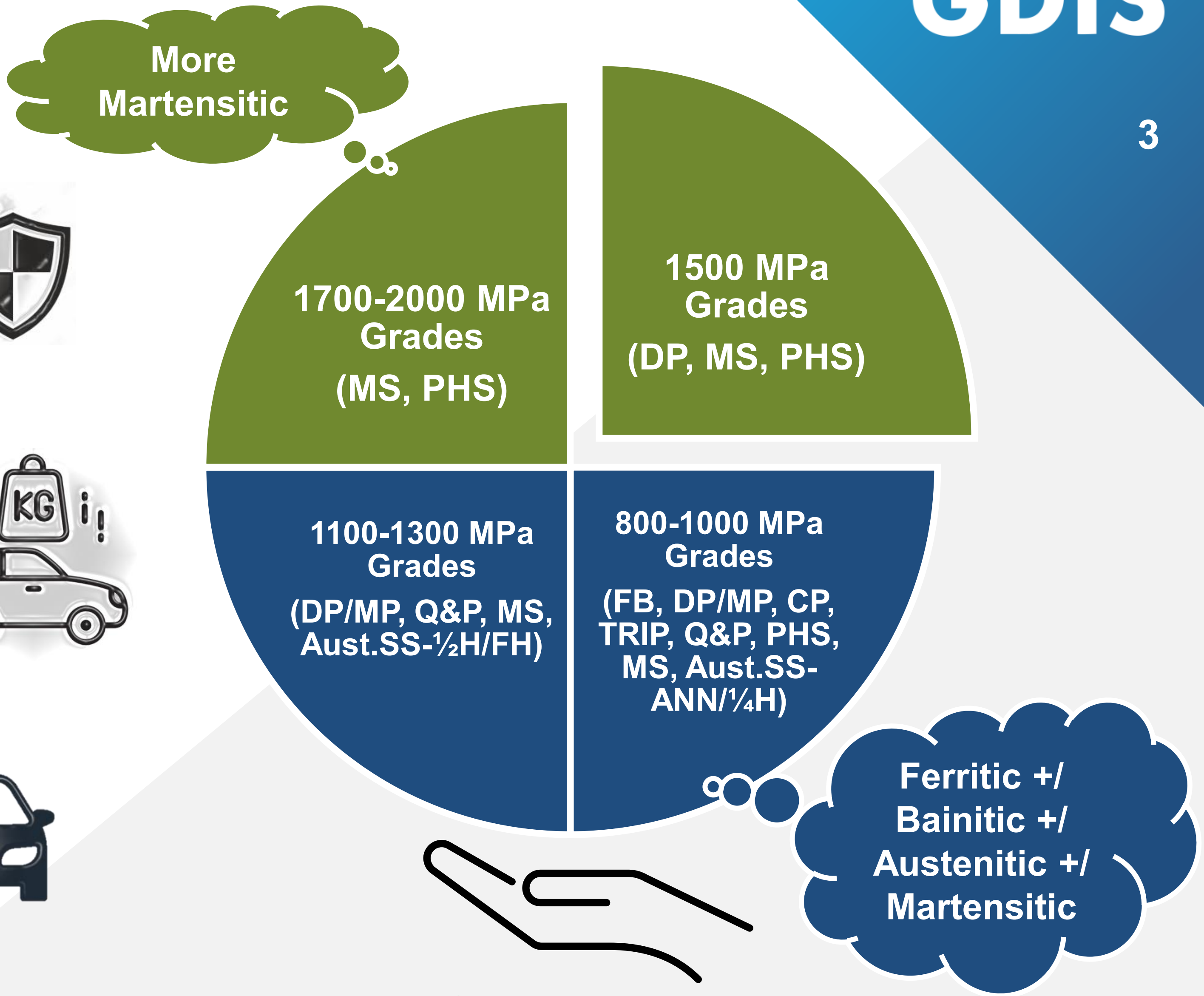
Needs and Offers



Crashworthiness

Lightweight

Cost Reduction



More Martensitic

1700-2000 MPa Grades
(MS, PHS)

1500 MPa Grades
(DP, MS, PHS)

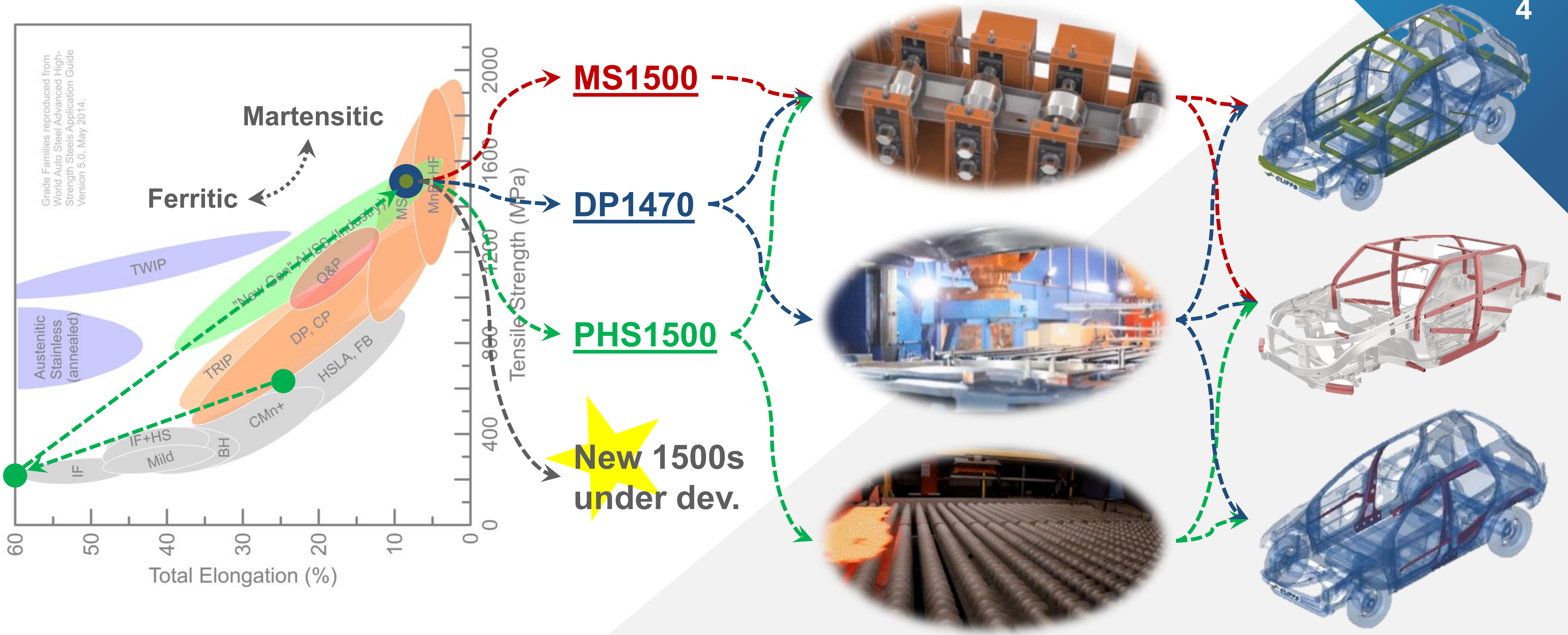
1100-1300 MPa Grades
(DP/MP, Q&P, MS, Aust.SS-½H/FH)

800-1000 MPa Grades
(FB, DP/MP, CP, TRIP, Q&P, PHS, MS, Aust.SS-ANN/¼H)

Ferritic +/
Bainitic +/
Austenitic +/
Martensitic

CLIFFS

1500 MPa Grades Overview



Grade Families reproduced from World Auto Steel Advanced High-Strength Steels Application Guide Version 5.0, May 2014.

MS1500

DP1470

PHS1500

New 1500s under dev.

CLIFFS 1500 MPa Grades Protect EVs

GDIS

HOME > ARTICLE > END MARKET > AUTOMOTIVE

Stamping a One-Piece TWB Battery Tray

February 11, 2025

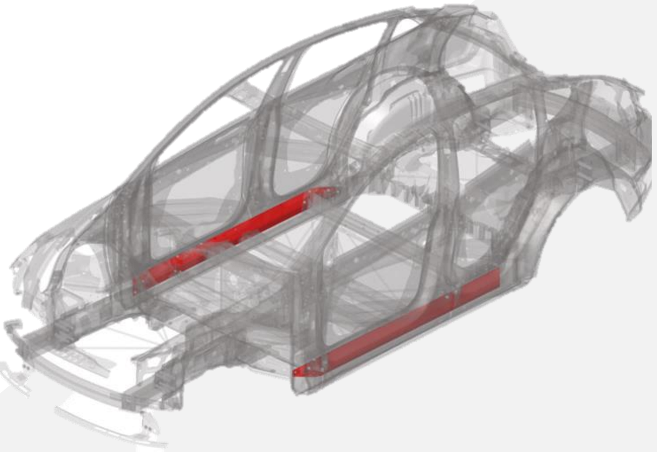
0 COMMENTS

Simulation proves out creation of a tailor-welded blank for an EV battery tray, combining AHSS and lower-strength steel to develop unique blank configurations.

A battery pack typically represents 20 to 25% of the overall weight of an electric vehicle (EV). Though driven by the battery technology selected and the energy-capacity needs of each vehicle model, weight savings clearly can be had in the architecture of the battery enclosure.

The choice of material, gauge and manufacturing process for enclosure and assembly components represents opportunities to realize weight and cost savings, balanced against the imperative to protect the battery tself.

n constructing battery trays, vehicle manufacturers have used a variety of material and manufacturing-process combinations, with steel and aluminum dominating applications for the top-cover and bottom-tray components.



CLIFFS

C-STAR^{TM} PROTECTION

Cleveland-Cliffs' Steel: The Only Choice

Which Do You Want Protecting Your Battery?

C-STAR™ Protection offers scalable solutions.
With 10% higher mass, it outperforms the baseline 6000 series extruded aluminum.

- In peak force by 33%
- In energy absorption by more than 50%

Scope of Work

Comparative studies based on mechanical properties:

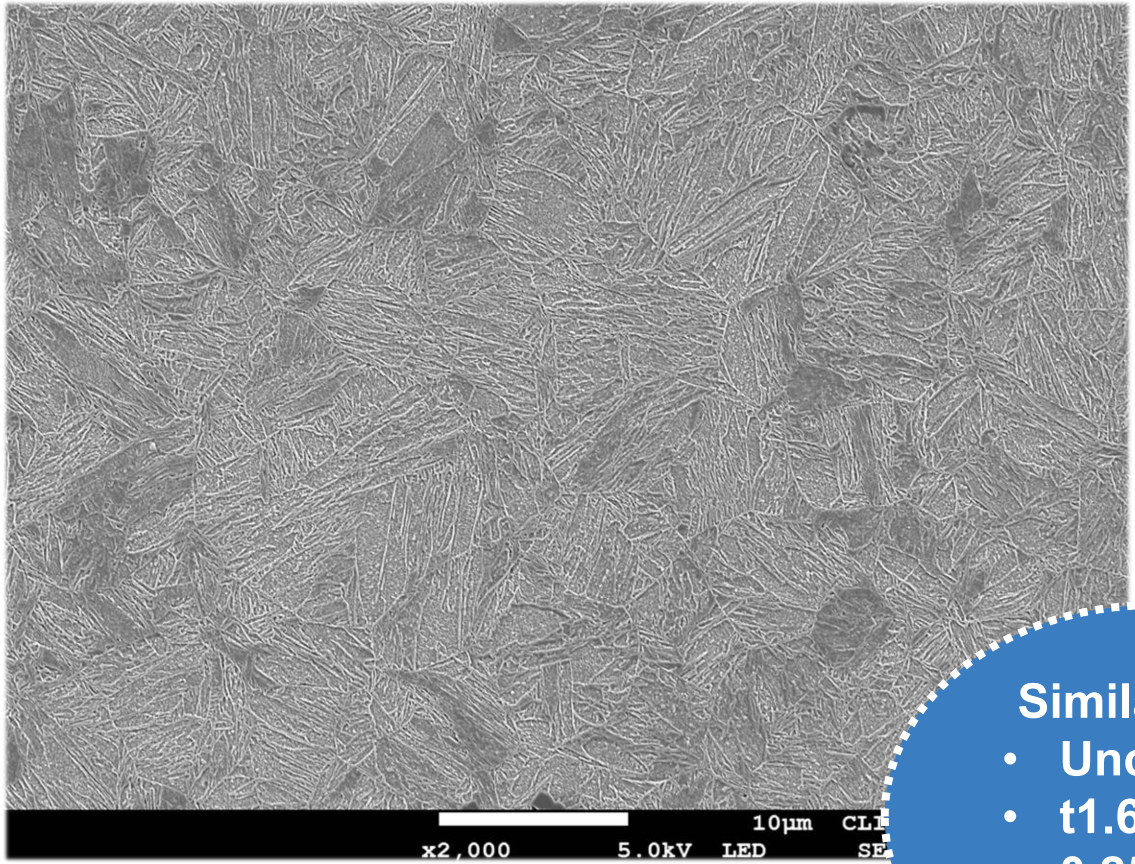
I. Cold-forming 1500 MPa grades: MS1500 vs. DP1470
  - Monotonic phase (all hard phase) vs. dual/multi phases (hard + soft phases)?
  - Pro fracture resistance (local ductility) vs. pro cold forming (global ductility)?
  - → to discuss future UHSS microstructure design strategies

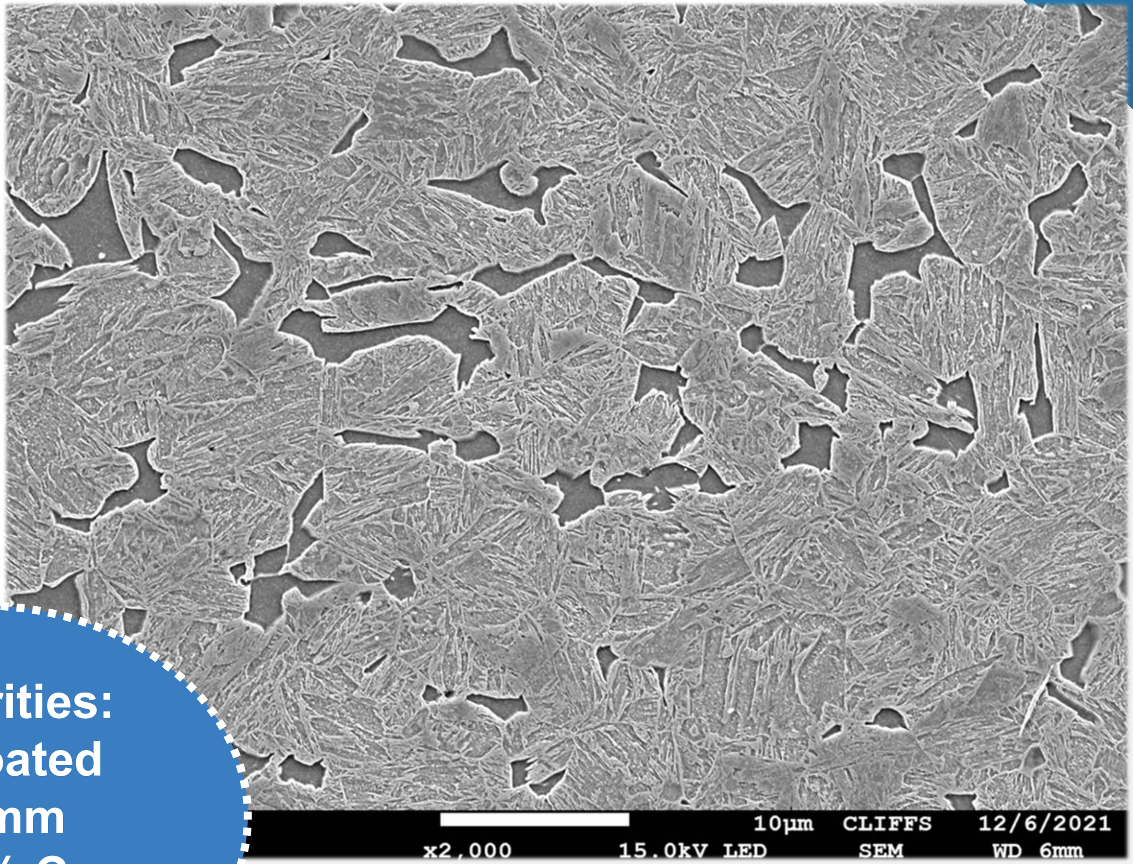
II. Cold- vs. hot-forming 1500 MPa grades
  - M vs. D vs. PHS1500 vs. AA7075T6
  - Steels vs. aluminum alloy
  - → to discuss future UHSS automotive application potentials

Part I: Cold-Forming 1500 Grades

Microstructure Comparison

- **MS1500**: fully **martensitic**
- **DP1470**: mainly **martensitic + ferritic**

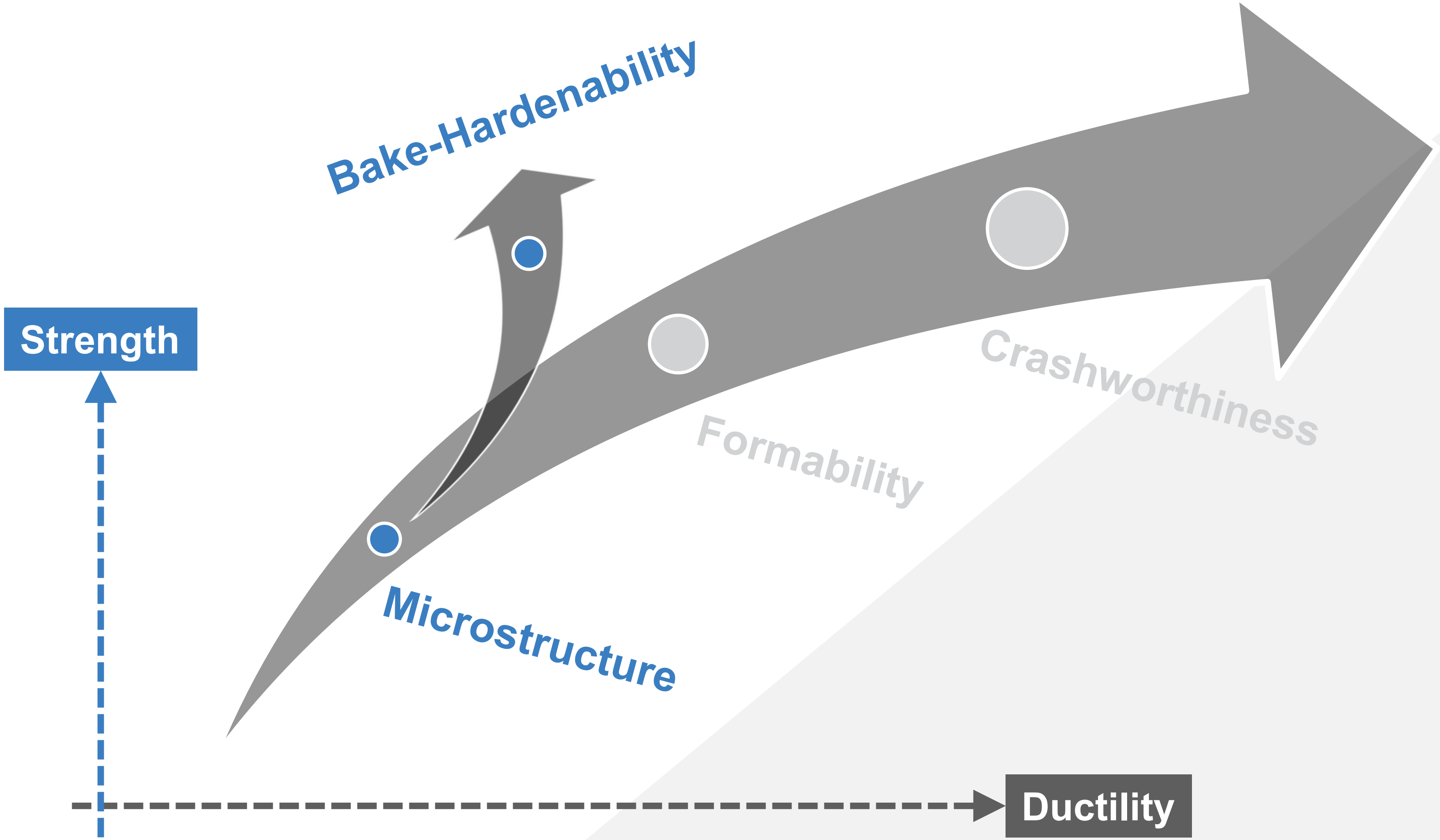




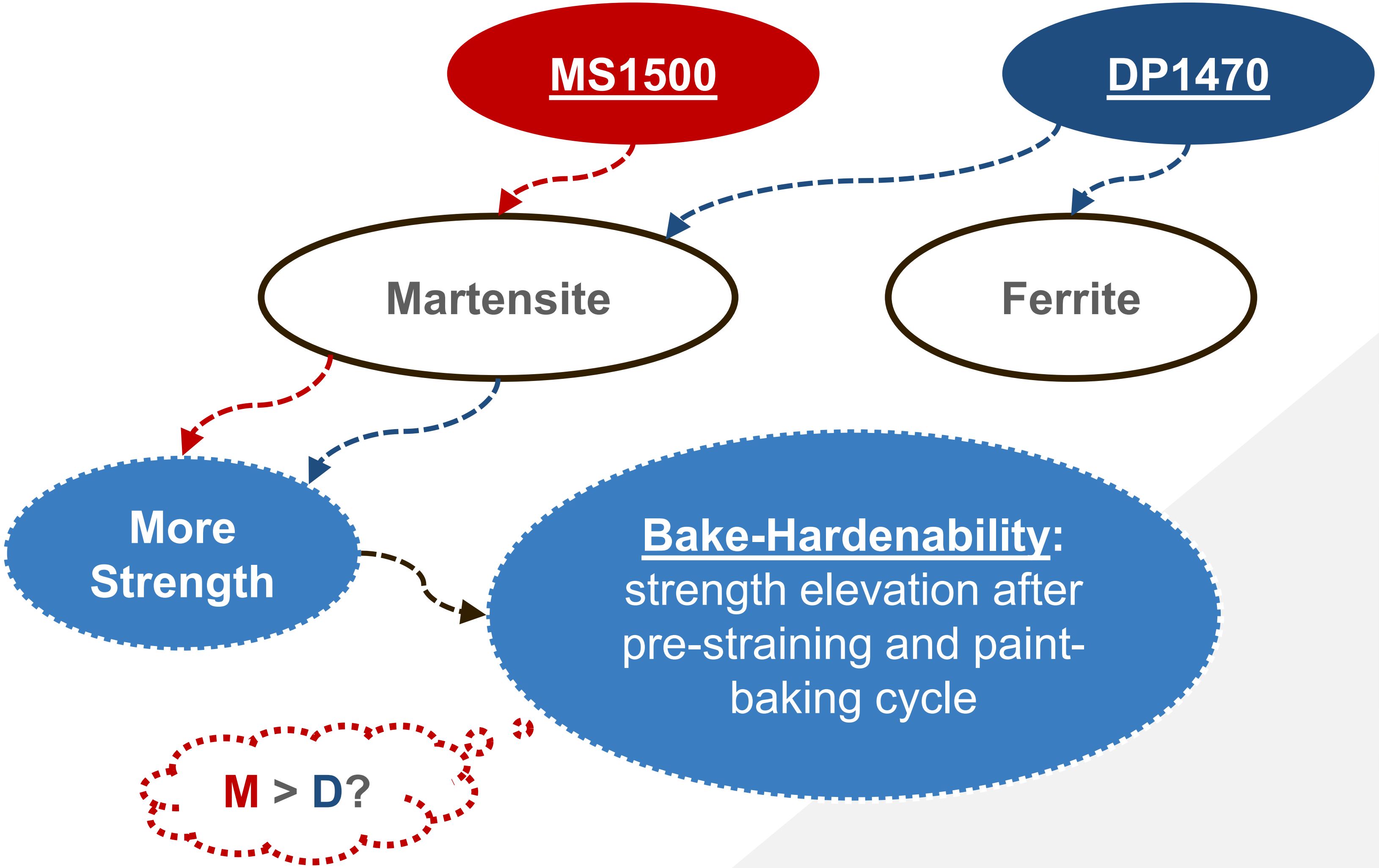
Similarities:

- **Uncoated**
- **t1.6 mm**
- **0.25% C**
- **Grain size**

MS1500 vs. DP1470: Overview



Microstructure → Bake-Hardenability



MS1500

DP1470

Martensite

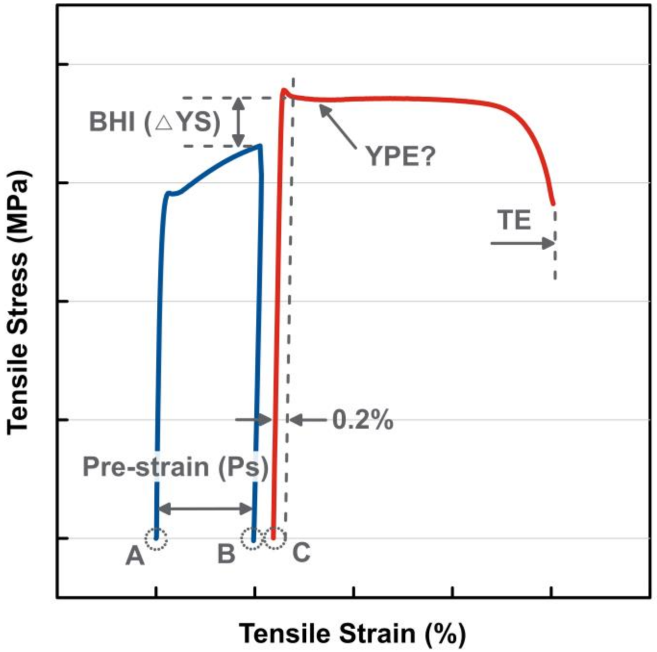
Ferrite

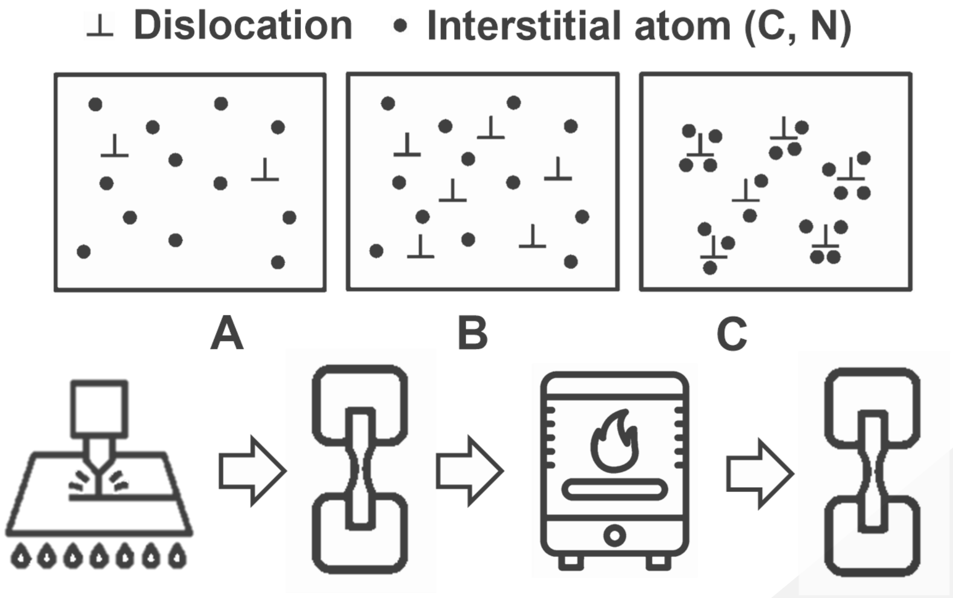
More Strength

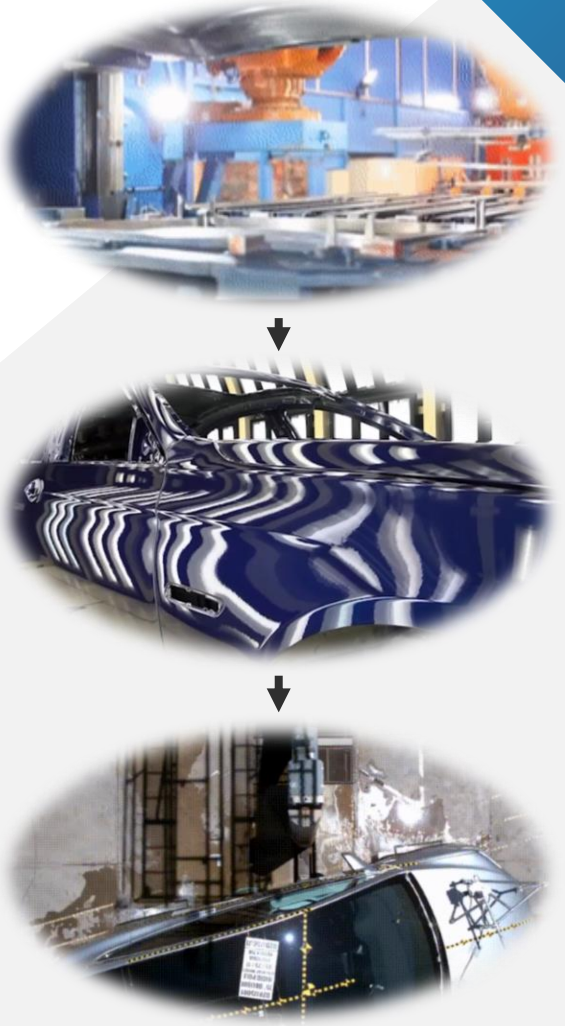
Bake-Hardenability: strength elevation after pre-straining and paint-baking cycle

M > D?

Bake-Hardening Testing Overview



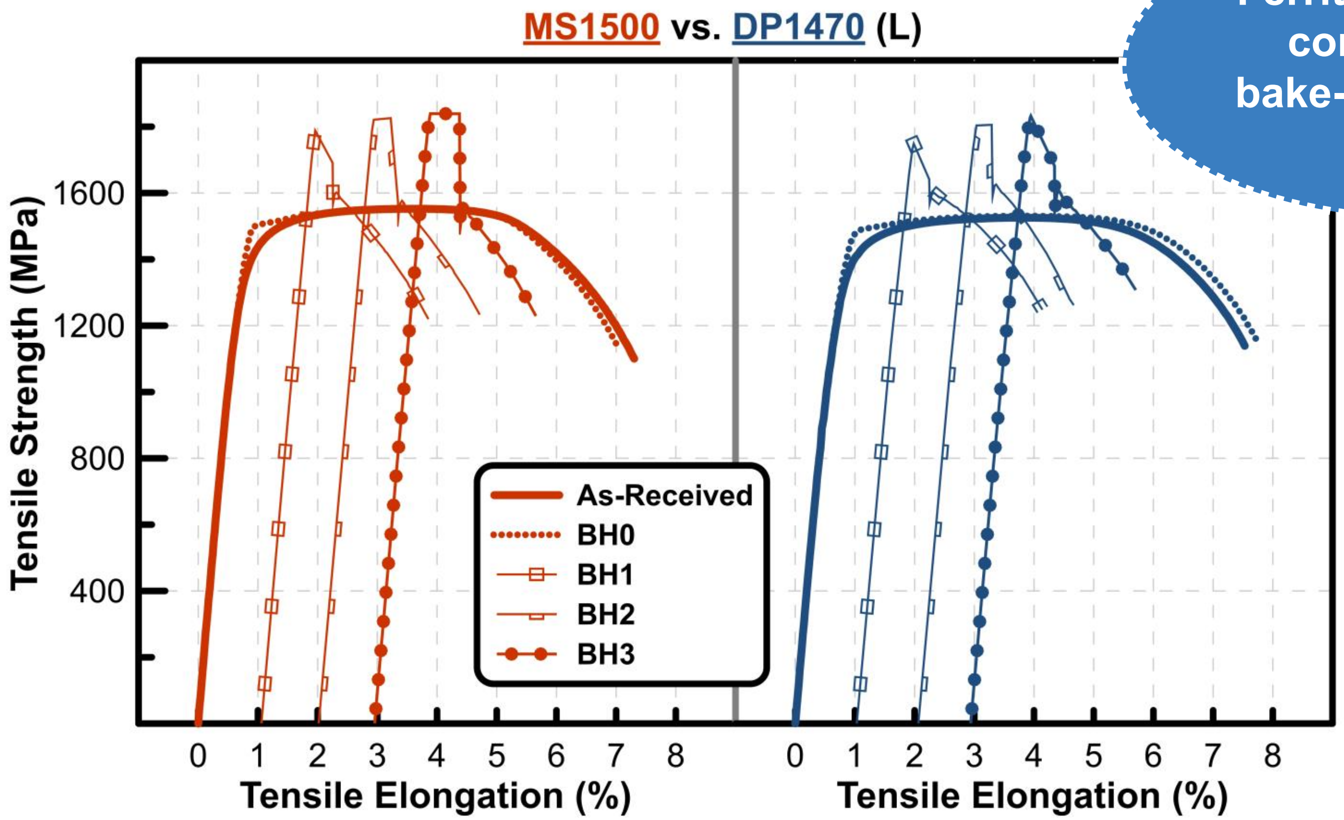




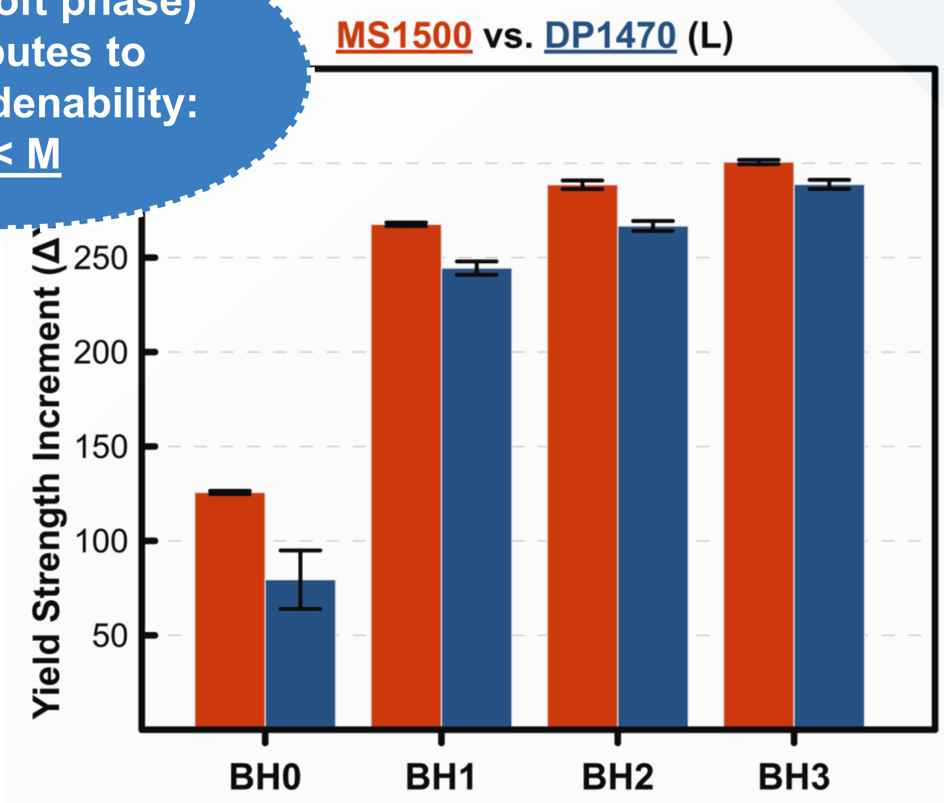
- ASTM E8 Standard tensile test sample geometry
- **Plastic pre-strain levels: 0/1/2/3%** under DIC real-time control
- **Baked at 170˚C for 20 min.** monitored by an infrared camera
- Mechanisms: ‘**Cottrell atmosphere**,’ stress relief, carbide precipitation, ...
- Tensile stress was calculated based on the **nominal cross-sectional area** (discrepant with the DIN EN 10325 Standard)

MS1500 vs. DP1470: Bake-Hardenability

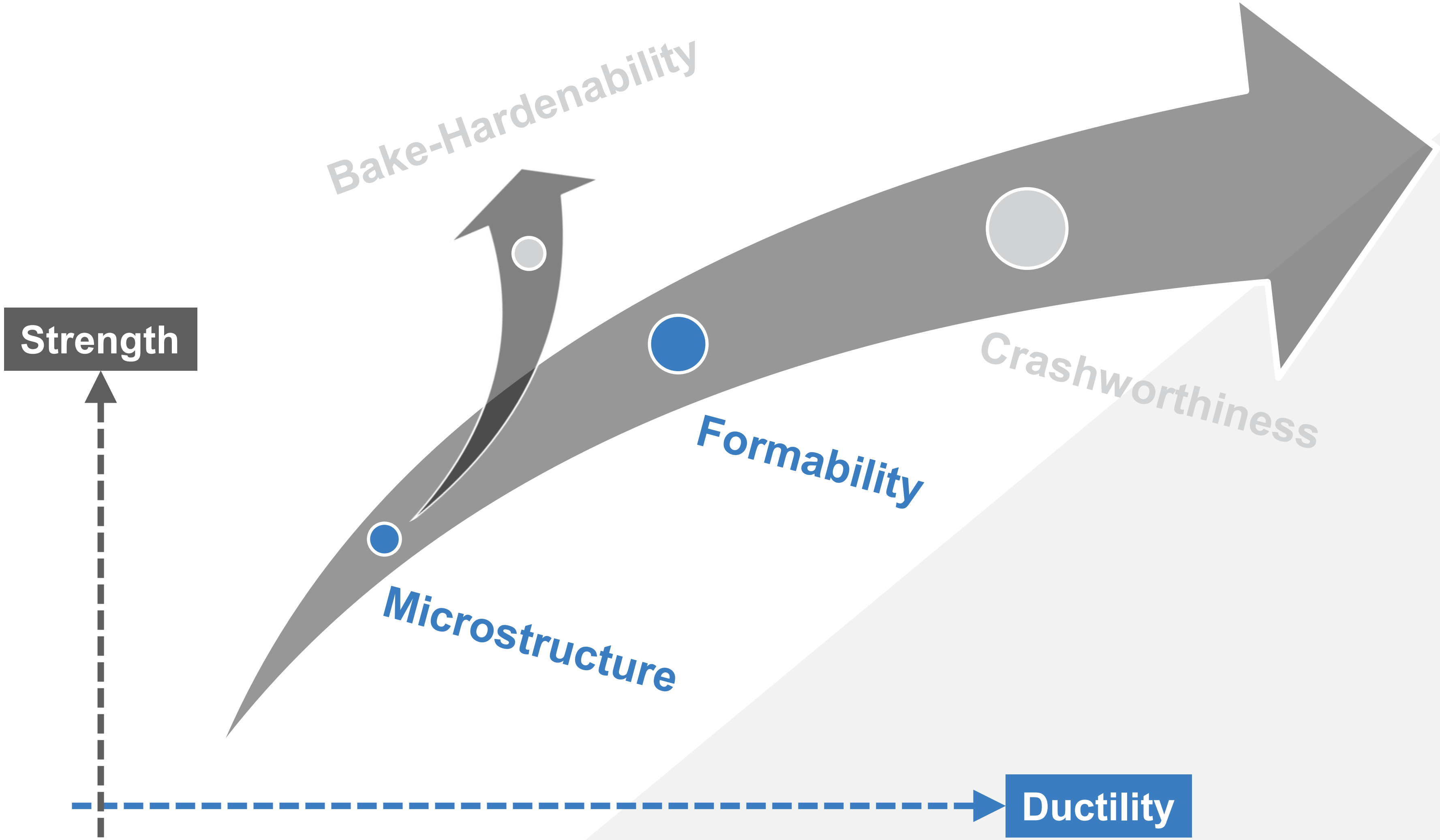
Bake-hardening index **(BHI) = ΔYS** after pre-strain → baking



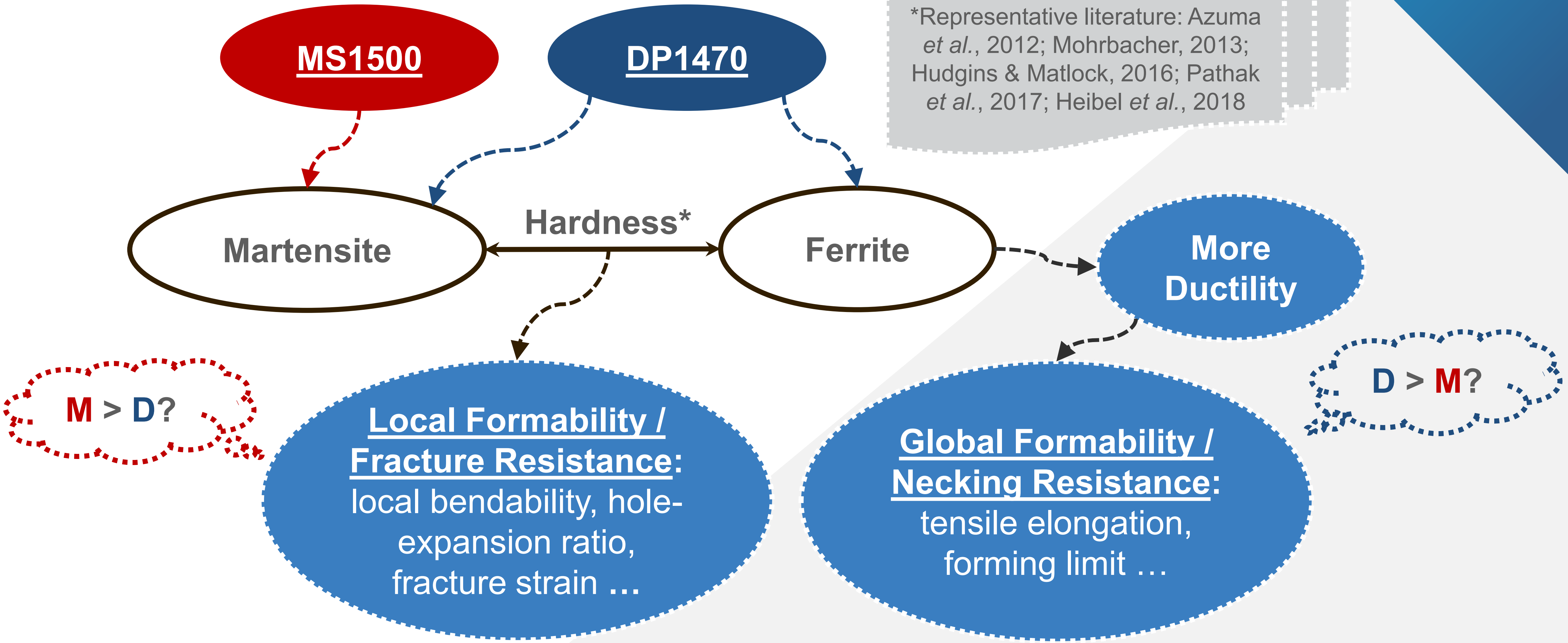
Ferrite (soft phase) contributes to bake-hardenability:
D < M



MS1500 vs. DP1470: Overview



Microstructure → Formability

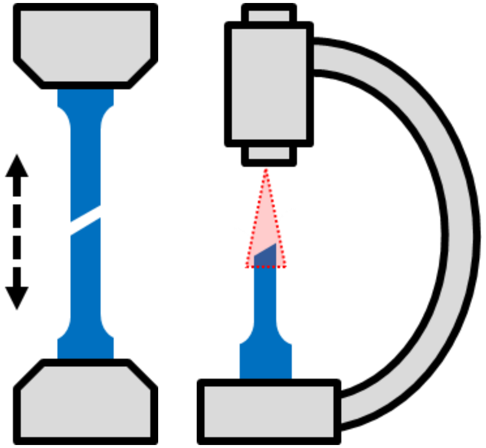


Local Formability / Fracture Resistance: local bendability, hole-expansion ratio, fracture strain …

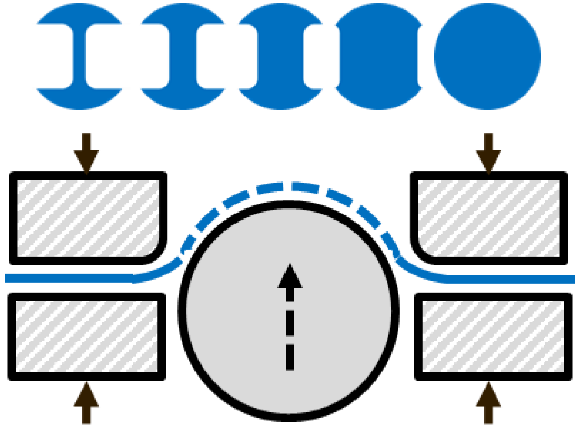
Global Formability / Necking Resistance: tensile elongation, forming limit …

*Representative literature: Azuma *et al.*, 2012; Mohrbacher, 2013; Hudgins & Matlock, 2016; Pathak *et al.*, 2017; Heibel *et al.*, 2018

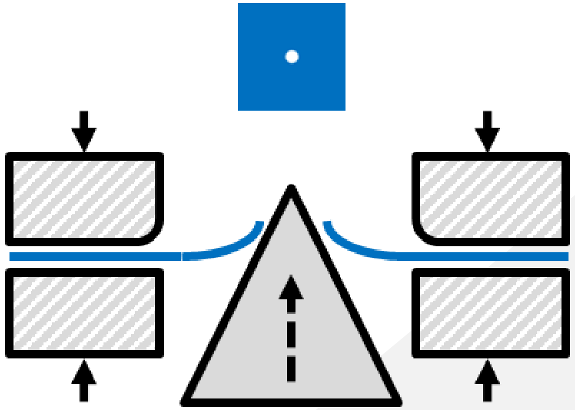
Formability Testing Overview



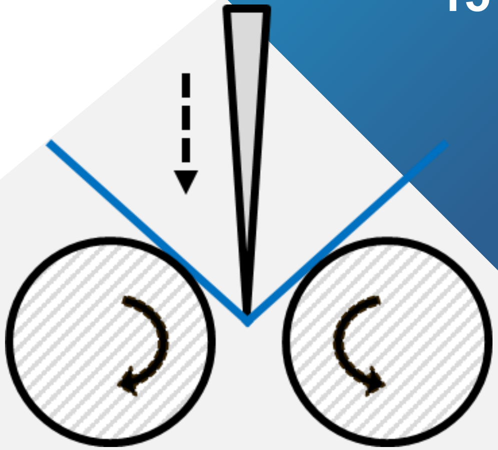
- ASTM E8 Standard



- ISO12004-2 Standard



- ISO16630 Standard

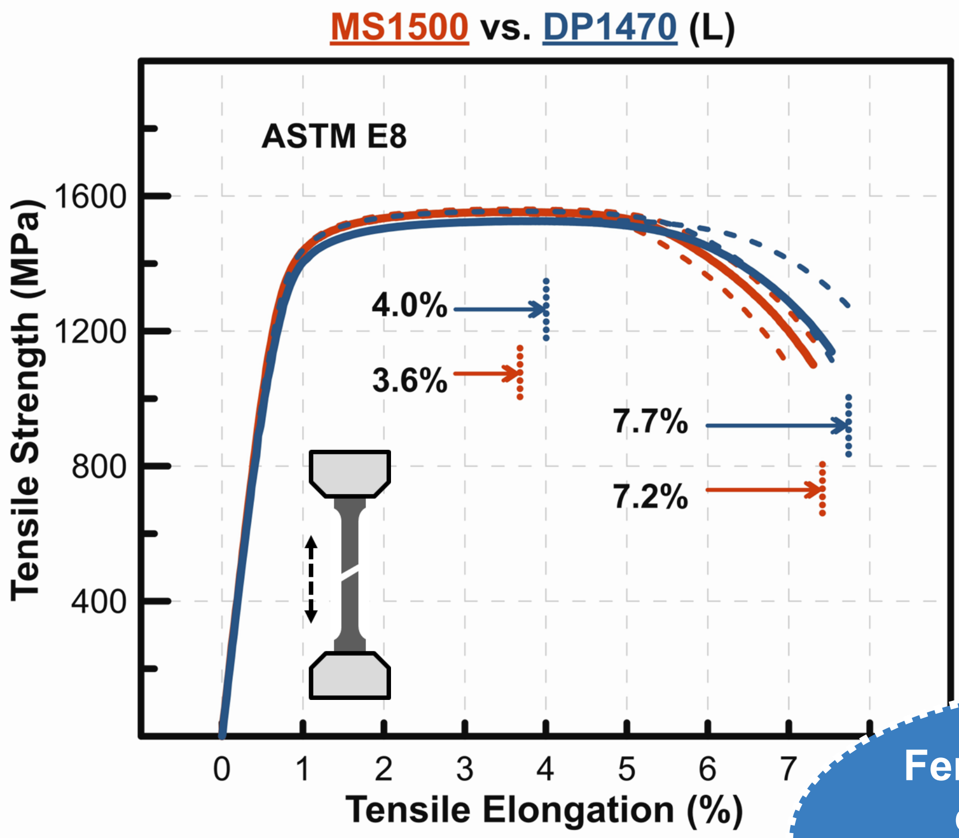


- VDA238-100 Standard

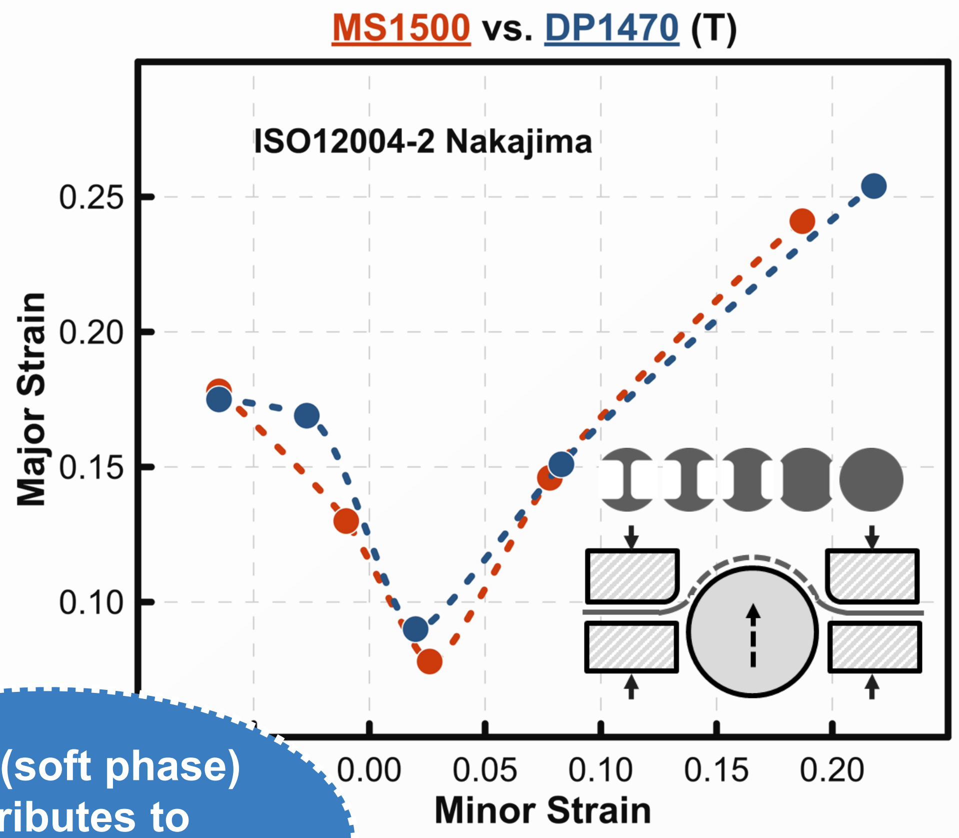
- VDA238-110 Standard
- **Fracture strain (ε_f) measurement: hybrid method** (Hu *et al.*, SAE 2022)
  - DIC measures 2 planar strain components ($\varepsilon_{1,2}$)
  - Microscope measures thickness strain (ε_t) at fracture
  - **ε_f = sqrt(2/3*(ε_{1f}^2+ ε_{2f}^2+ ε_{tf}^2))**
  - **Fracture strain ≠ tensile elongation**

MS1500 vs. **DP1470**: Global Formability

- Tensile elongation (TE):



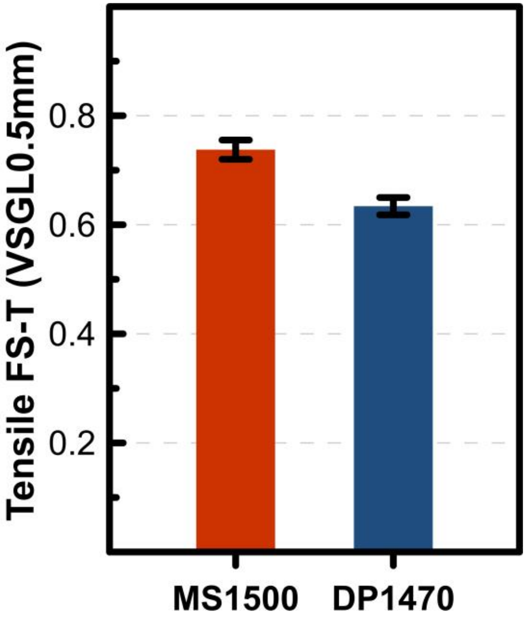
- Forming limit curve (FLC):

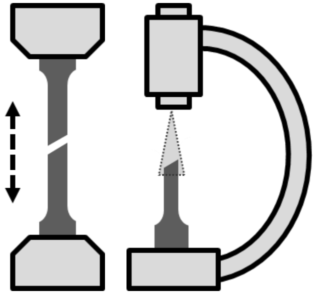


Ferrite (soft phase) contributes to global formability:
D > M

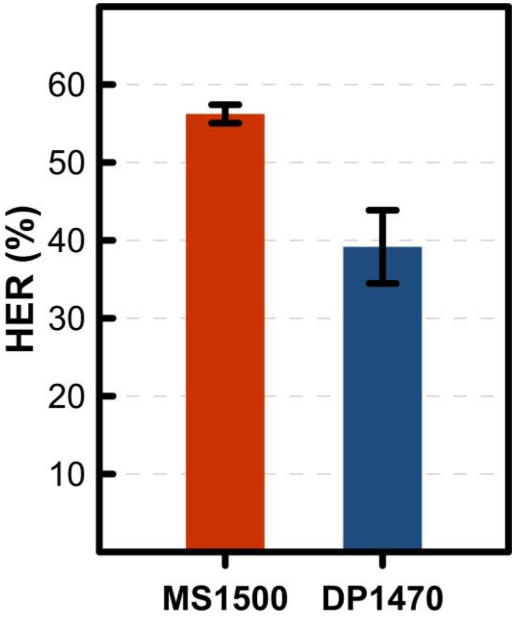
MS1500 vs. **DP1470**: Local Formability

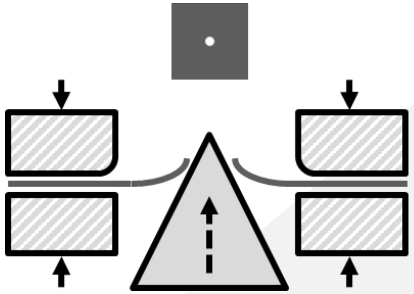
- Tensile fracture strain:



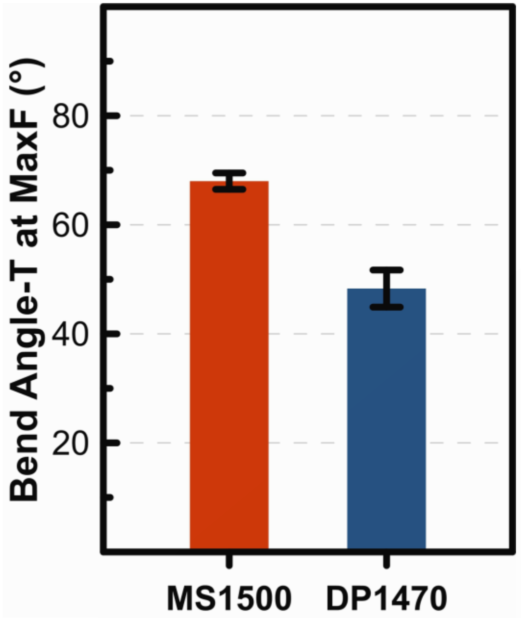


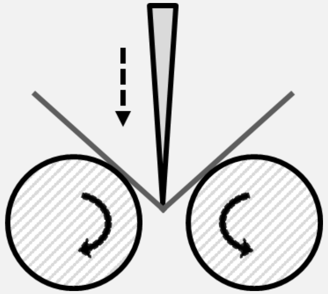
- Hole expansion ratio (HER):





- Local bending angle:



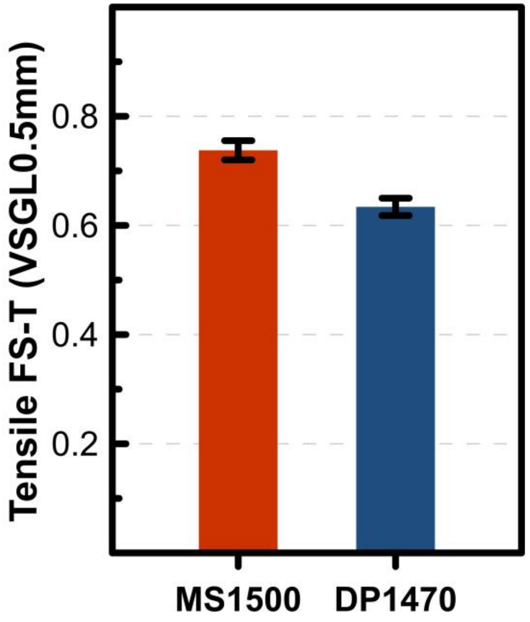


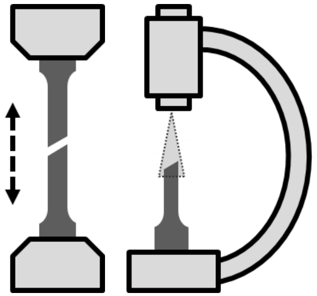
Soft + hard phases decrease the local formability: D < M

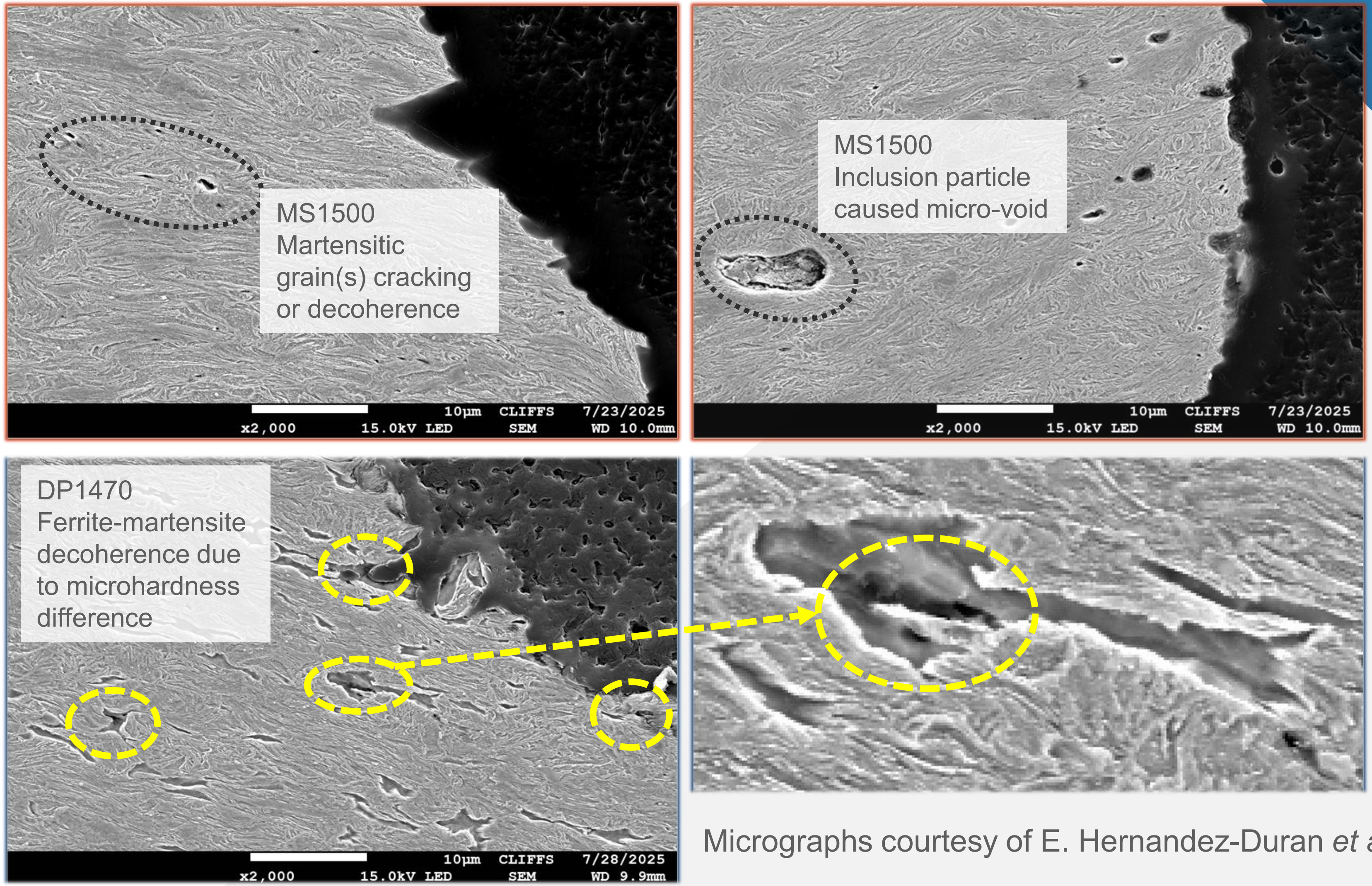
← micro-hardness difference between ferrite and martensite tends to cause early micro-voids that eventually evolve to fracture

M vs. D: Local Formability & Micro-voids

- Tensile fracture strain:







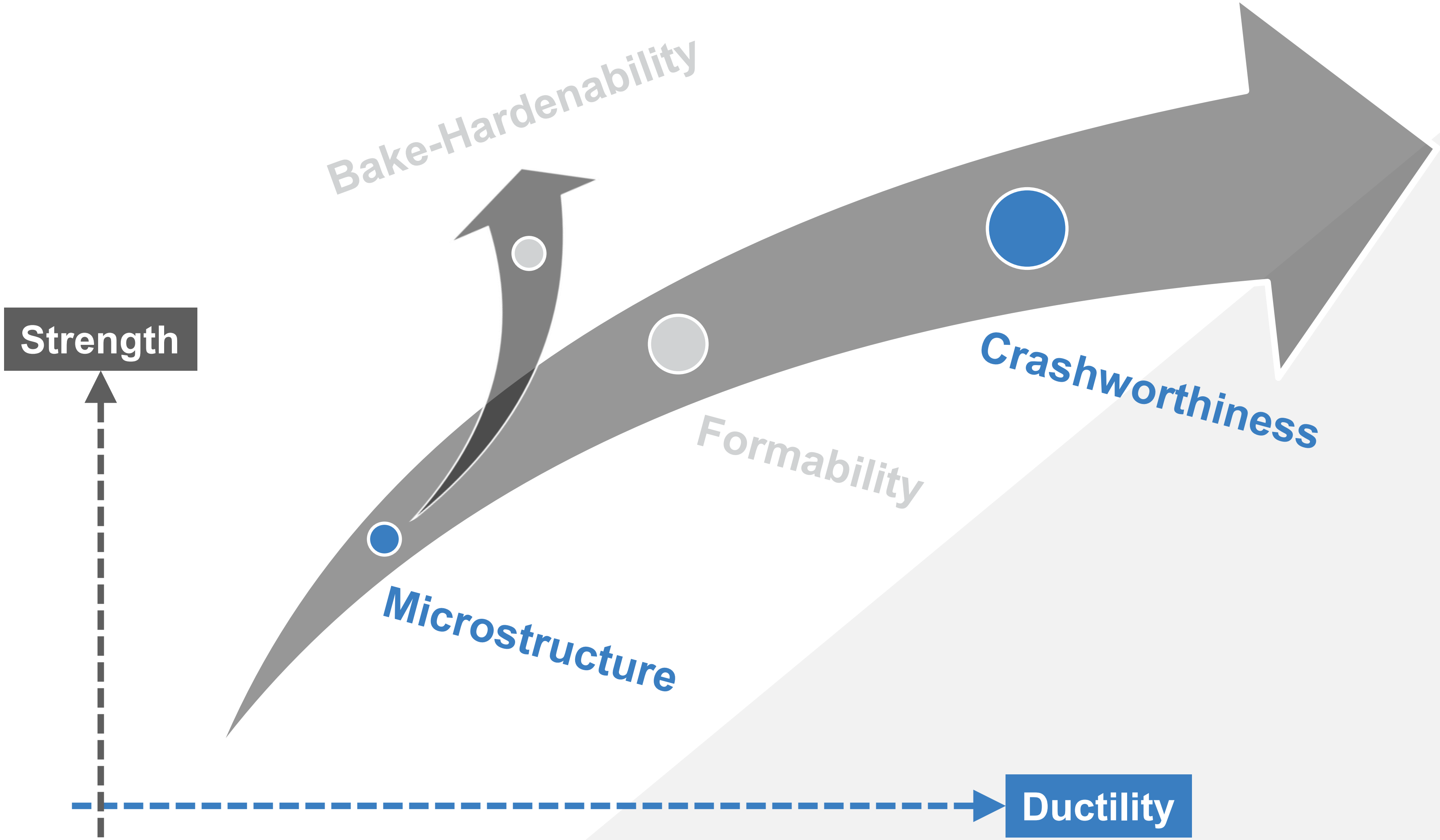
MS1500
Martensitic grain(s) cracking or decoherence

MS1500
Inclusion particle caused micro-void

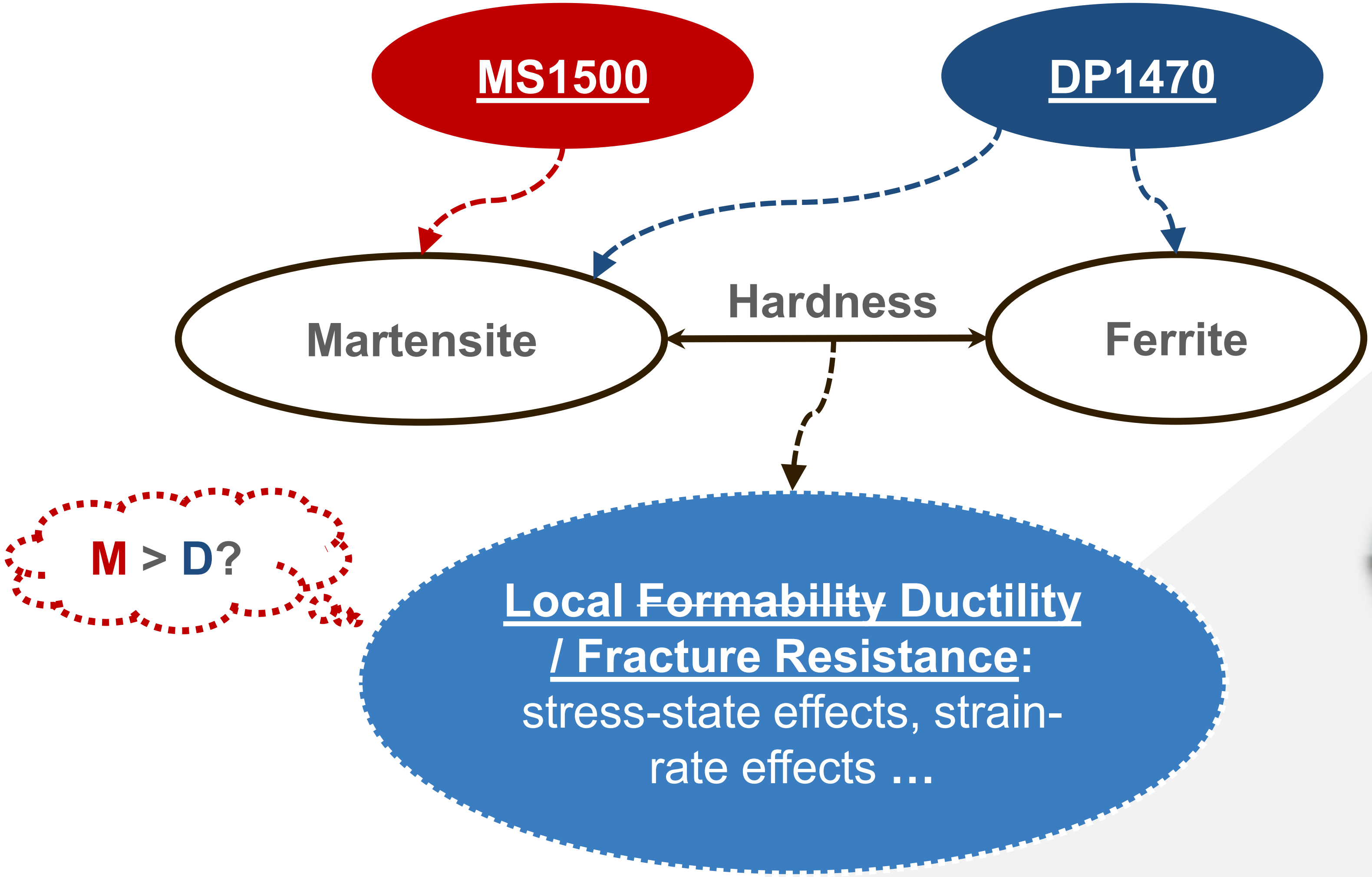
DP1470
Ferrite-martensite decoherence due to microhardness difference

Micrographs courtesy of E. Hernandez-Duran *et al.*

MS1500 vs. DP1470: Overview



Microstructure → Crashworthiness



MS1500

DP1470

Martensite

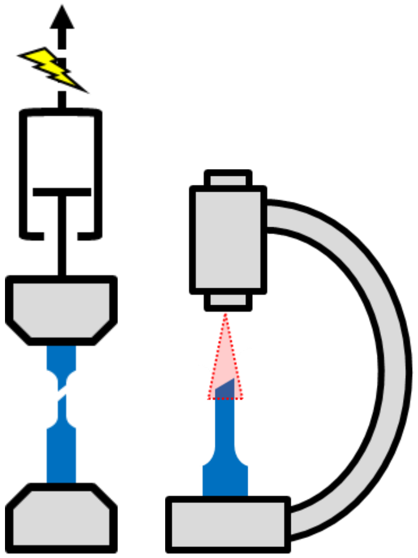
Hardness

Ferrite

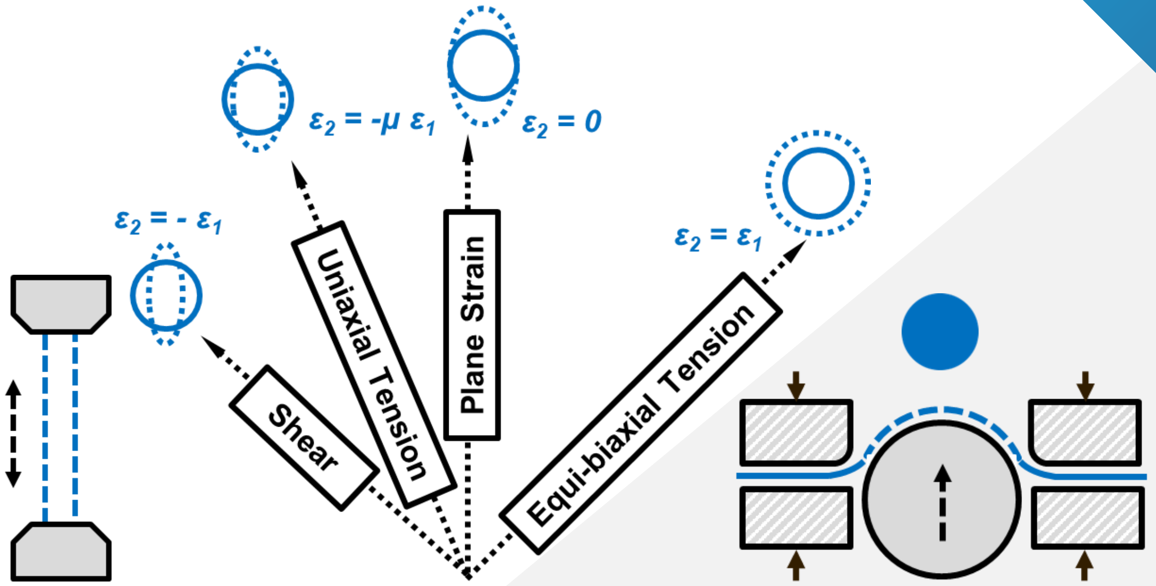
M > D?

Local ~~Formability~~ Ductility / Fracture Resistance:
stress-state effects, strain-rate effects …

Rate- / Stress-State-Dep. Testing Overview



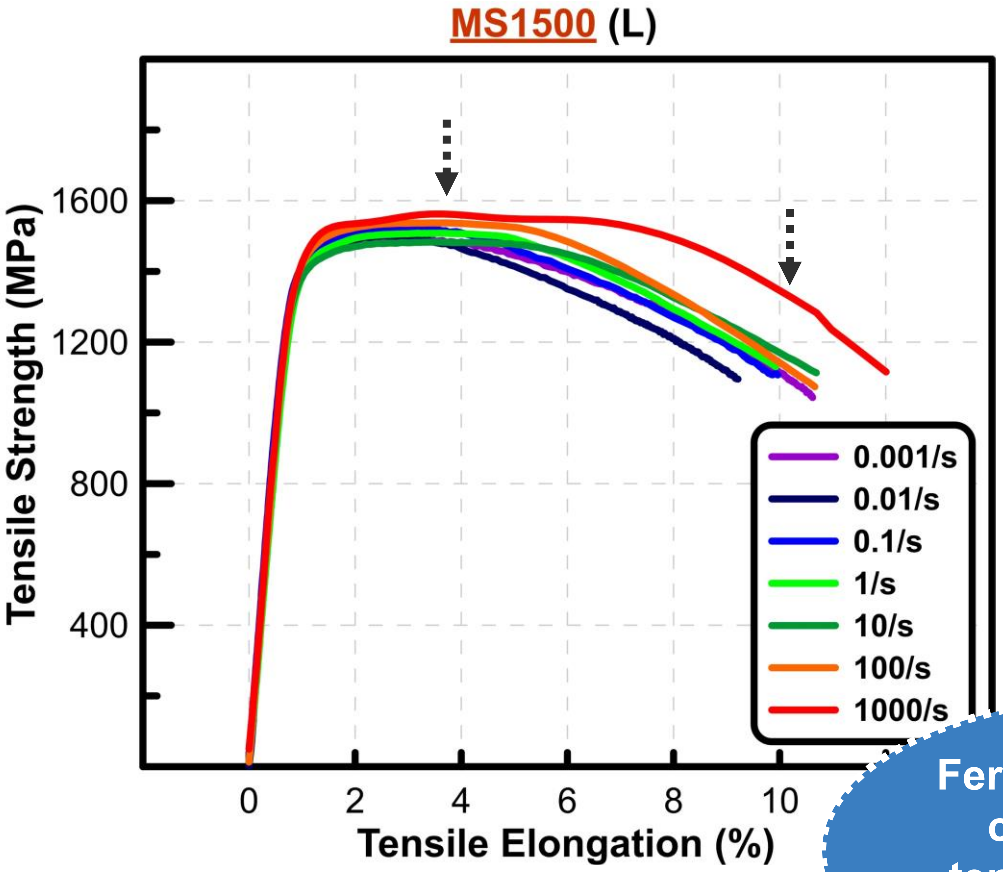
- ISO 26203-2 Standard
- VDA 238-110 Standard
- Fracture strain measurement: hybrid method (Hu *et al.*, SAE 2022)
- Nominal strain rates (**10^{-3} – 10^{3} s^{-1}**)

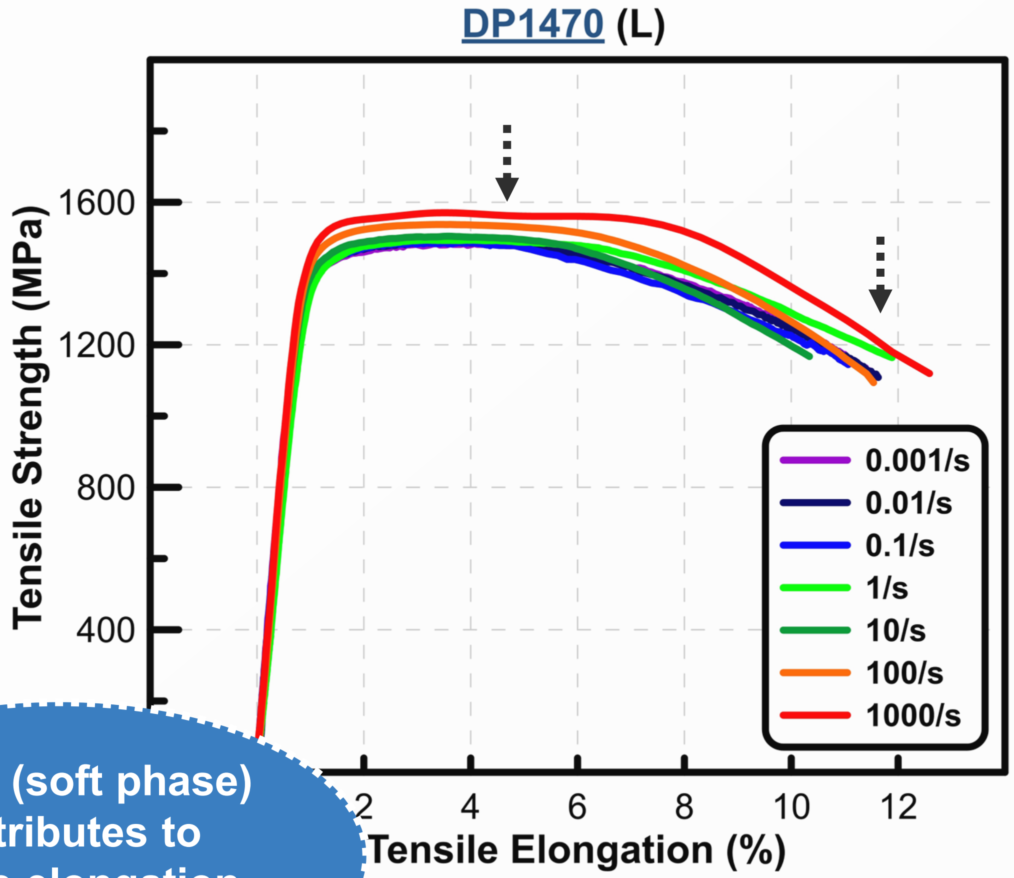


- **4 representative testing conditions at 0.001 s^{-1}** effective strain rate for MMC calibration (Hu *et al.*, SAE WCX 2023)
- Fracture strain measurement: hybrid method (Hu *et al.*, SAE 2022)
- Fracture locus interpolation based on the **Modified Mohr-Colomb (MMC)** model (Bai & Wierzbicki, 2010)

MS1500 vs. DP1470: Rate-Dep. Tensile Properties

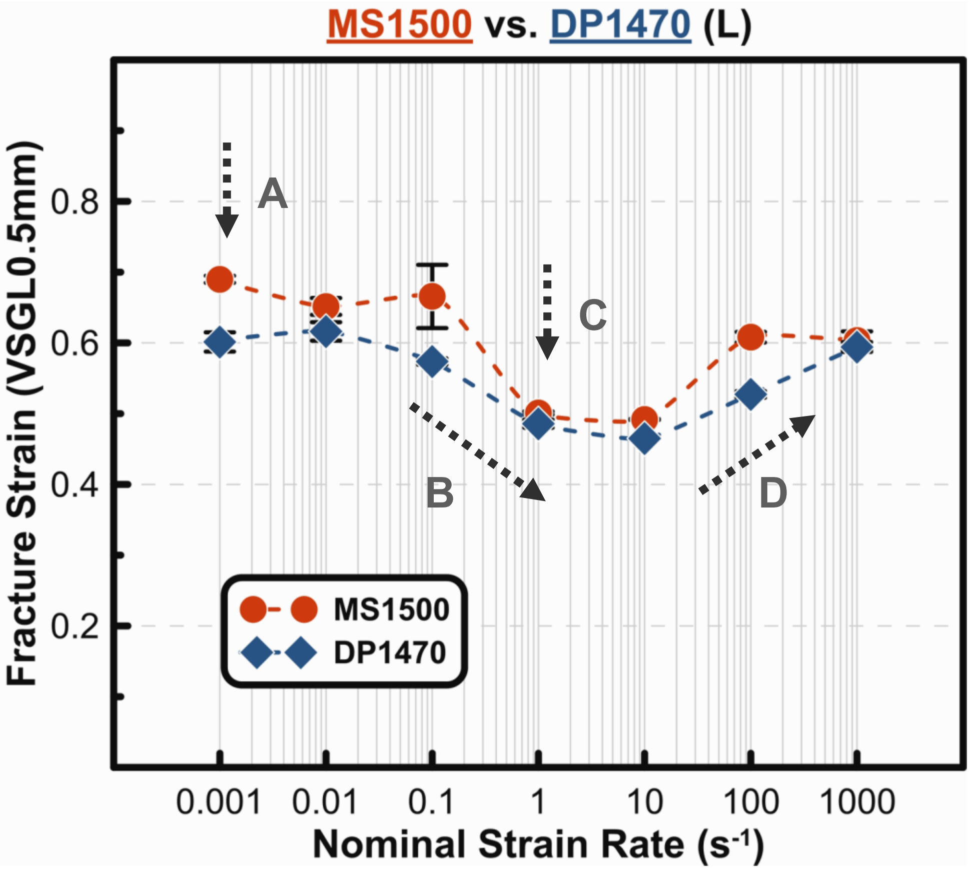
Rate-dependent tensile testing at nominal strain rates of $10^{-3} – 10^{3}$/s





Ferrite (soft phase) contributes to tensile elongation at all rates: D > M

MS1500 vs. DP1470: Rate-Dep. Fracture Strain



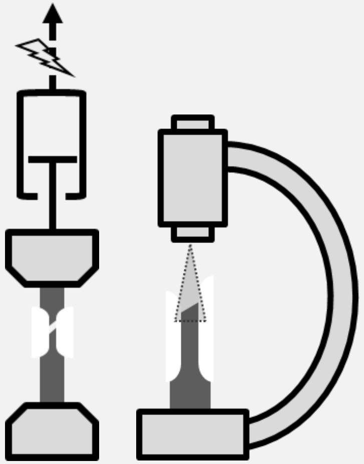
A. Sub-sized samples of elevated triaxiality ratio ($\downarrow\varepsilon_f$)

B. Positive rate-dependent strain-hardening + adiabatic heating ($\downarrow\varepsilon_f$)

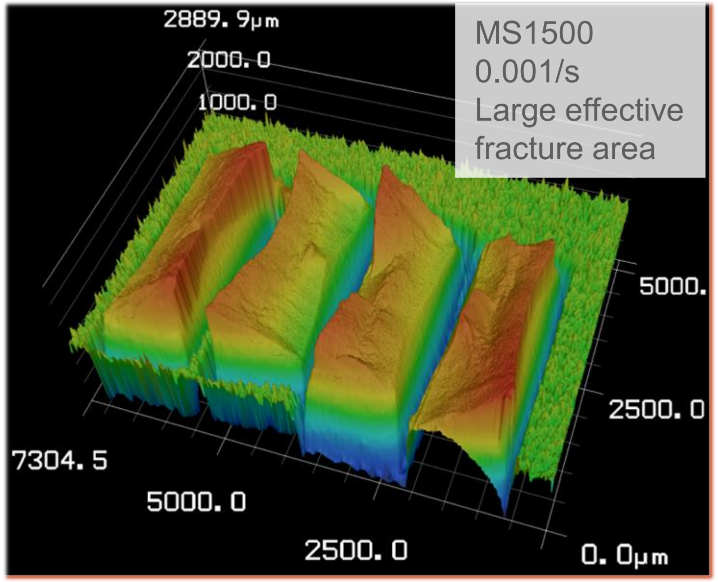
C. Faster hardening rate of ferrite mitigated the $\downarrow\varepsilon_f$ **of DP1470**

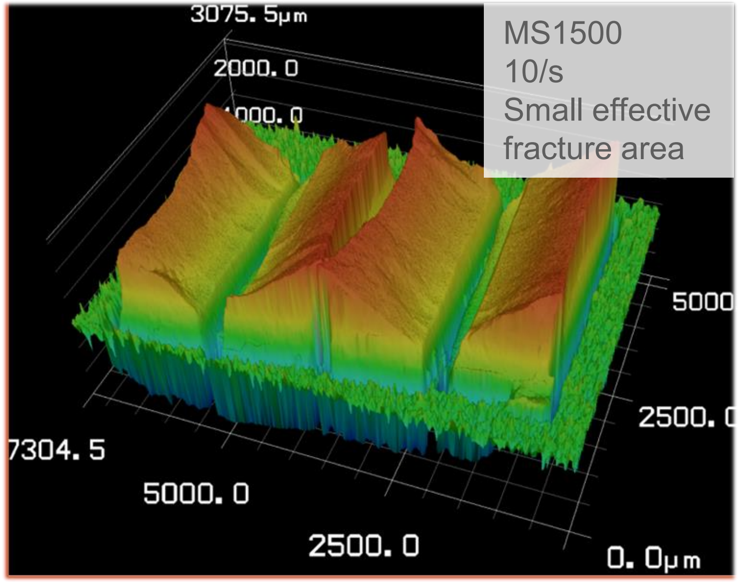
D. Rapid adiabatic heating ($\uparrow\varepsilon_f$)

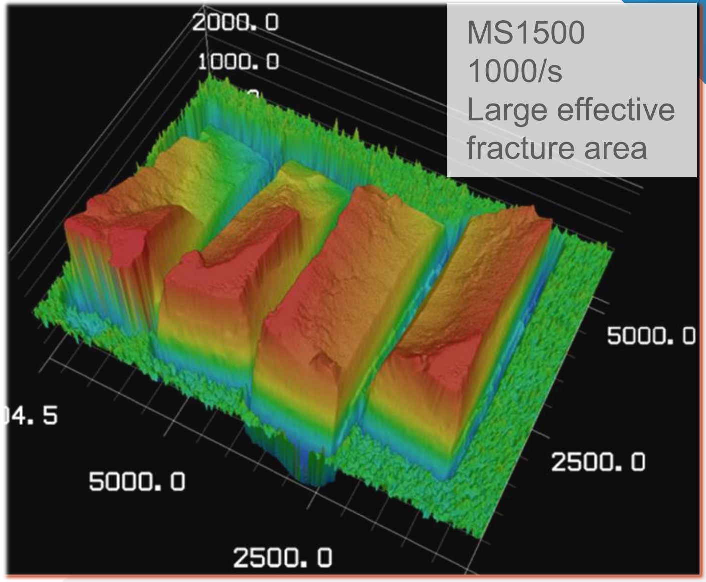
Soft + hard phases decrease the fracture strain at all rates: D < M

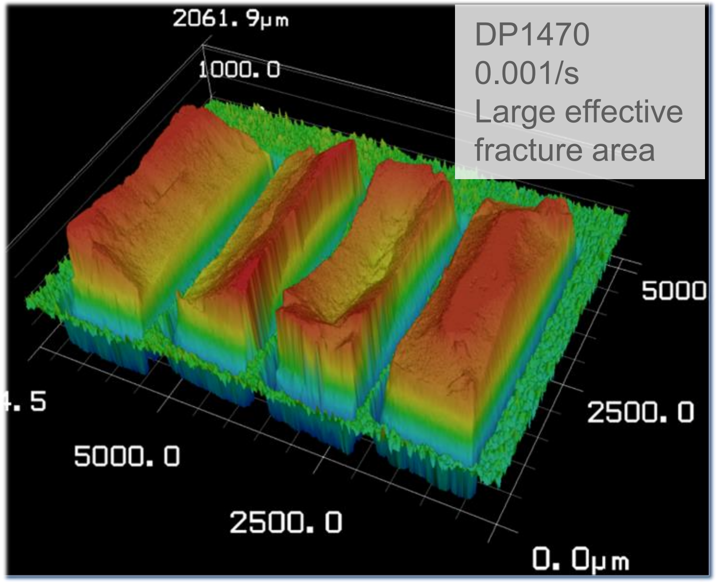


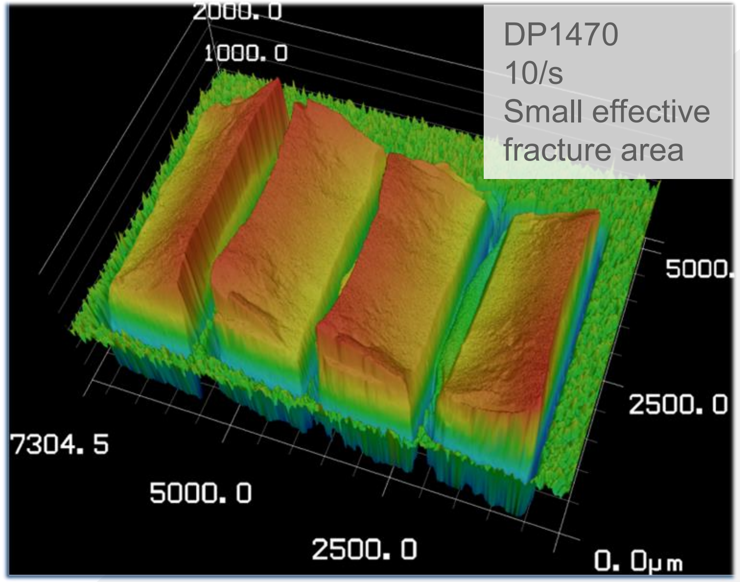
M vs. D: Rate-Dep. Fracture Morphology

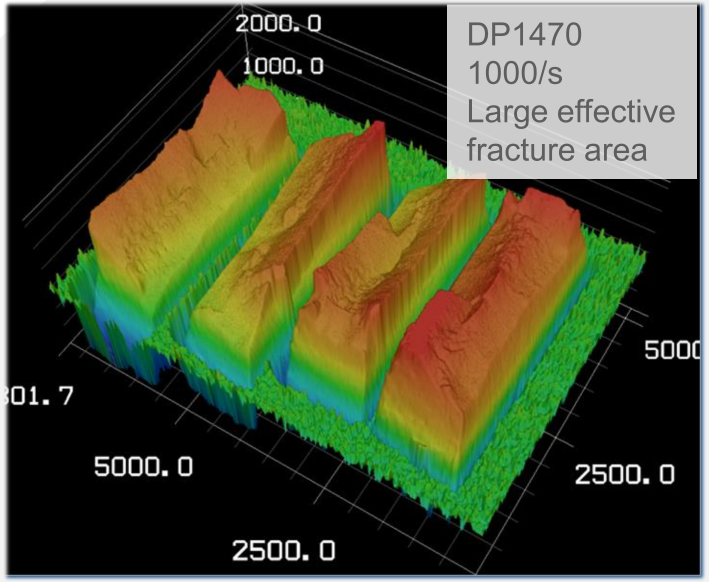

MS1500
0.001/s
Large effective fracture area

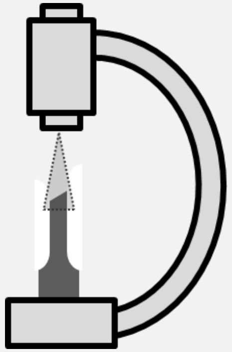

MS1500
10/s
Small effective fracture area


MS1500
1000/s
Large effective fracture area

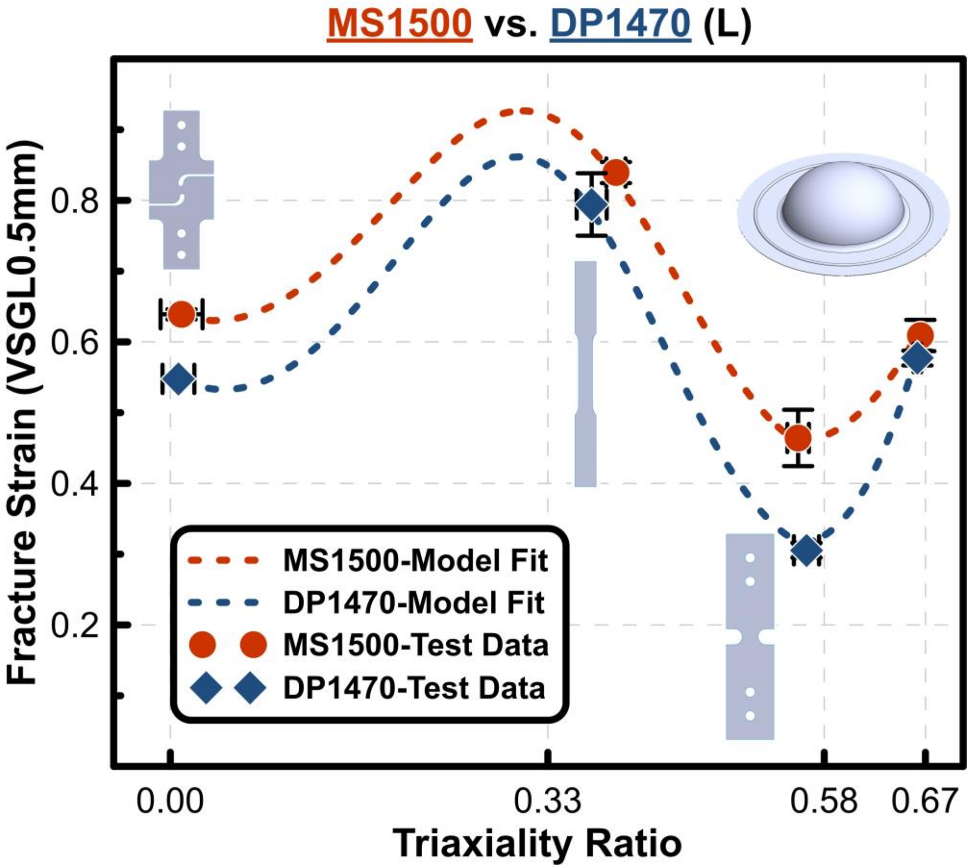

DP1470
0.001/s
Large effective fracture area


DP1470
10/s
Small effective fracture area


DP1470
1000/s
Large effective fracture area

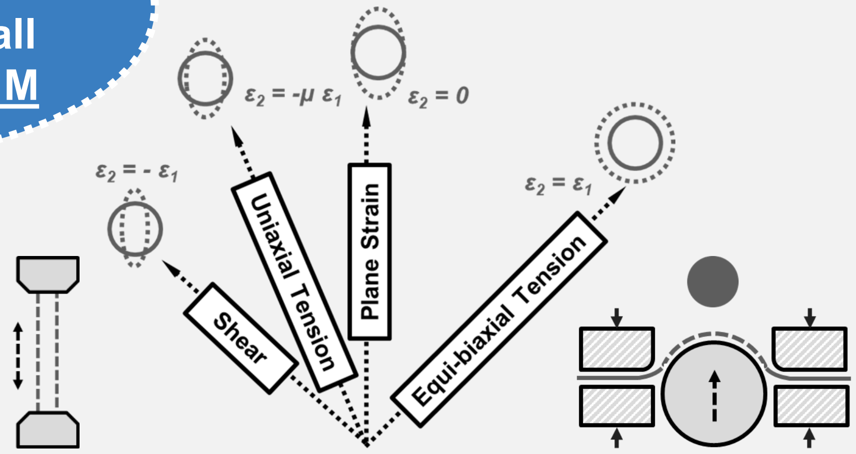


MS1500 vs. DP1470: Stress-State-Dep. Fracture

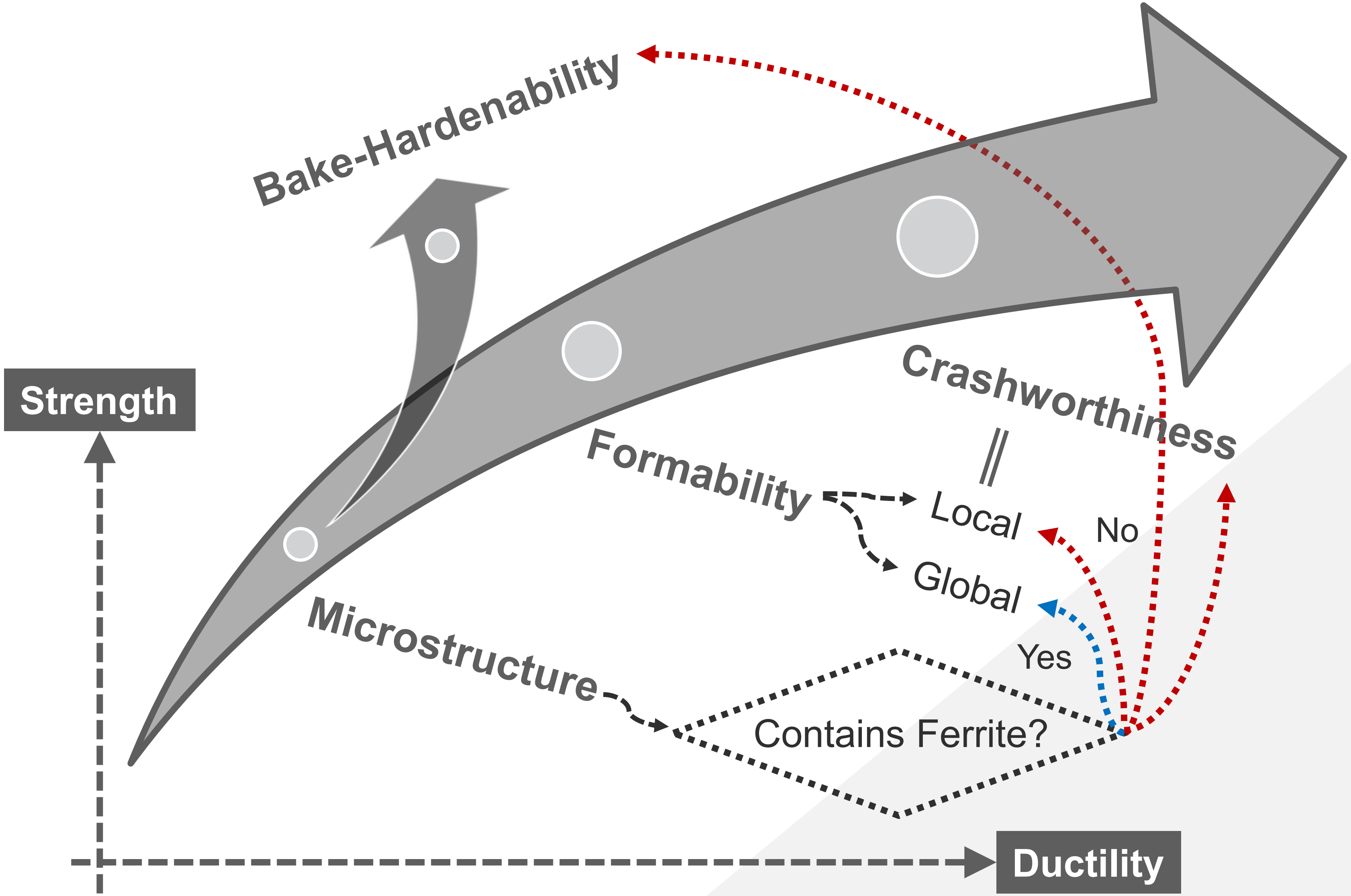


- Quasi-static simple shear, uniaxial tension, plane strain, and equi-bixial testing
- Work-in-progress: rate- + stress-state-dependent testing fixtures

Soft + hard phases decrease the fracture strain at all stress states: D < M



MS1500 vs. DP1470: Summary

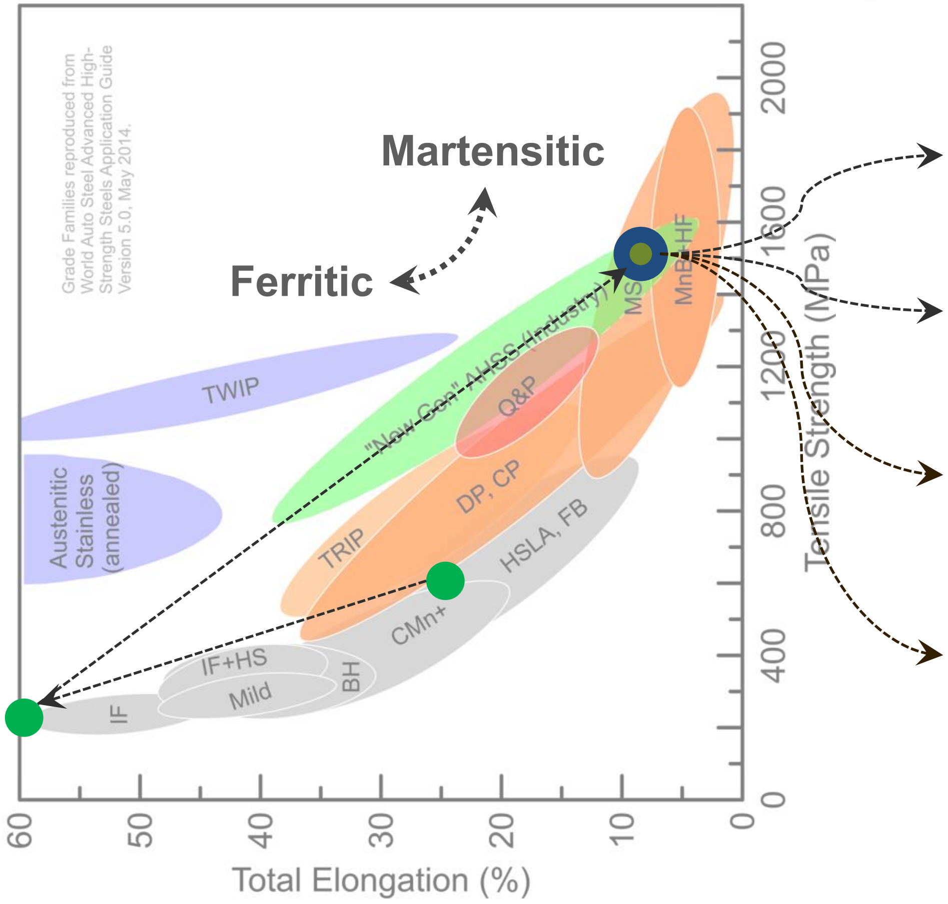


	Testing	M	D
Strength	Bake-Hardenability	X	
Ductility	Tensile Elongation		X
	Tensile ε_f	X	
	Forming Limit		X
	Hole Exp. Ratio	X	
	Local Bending	X	
	Rate-Dep. Tensile E		X
	Rate-Dep. Tensile ε_f	X	
	Stress-State-Dep. ε_f	X	

Part II: Cold- vs. Hot-Forming 1500 Grades

MS1500 vs. DP1470 vs. PHS1500 vs. AA7075T6

CLIFFS



Grade Families reproduced from World Auto Steel Advanced High-Strength Steels Application Guide Version 5.0, May 2014.

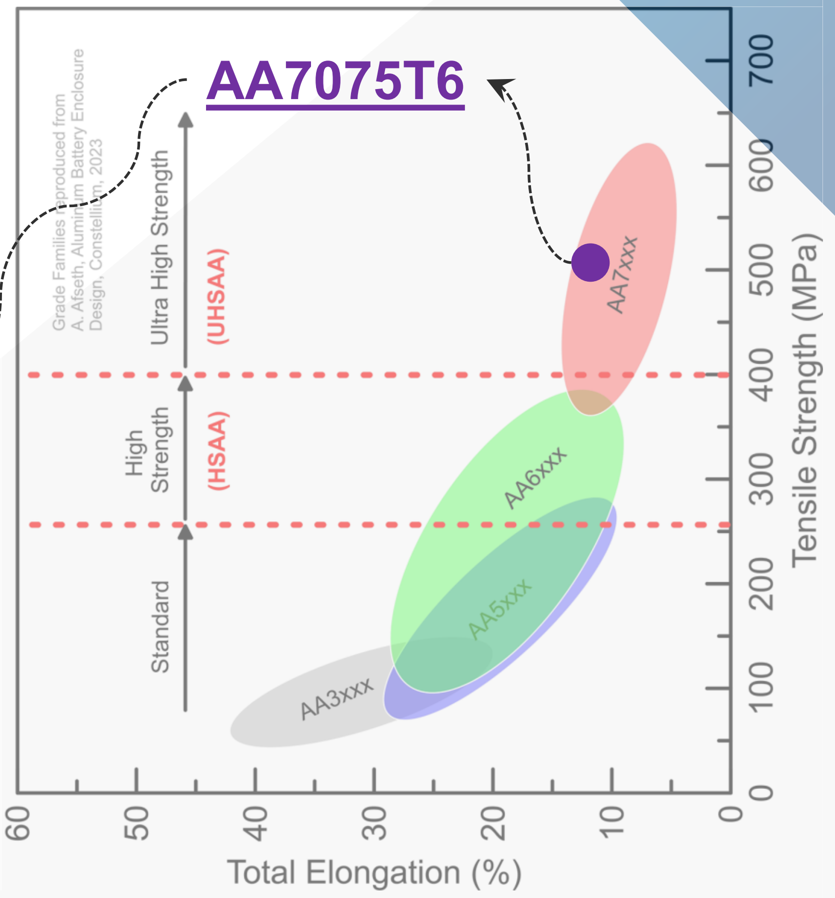
MS1500

DP1470

PHS1500

New 1500s under dev.

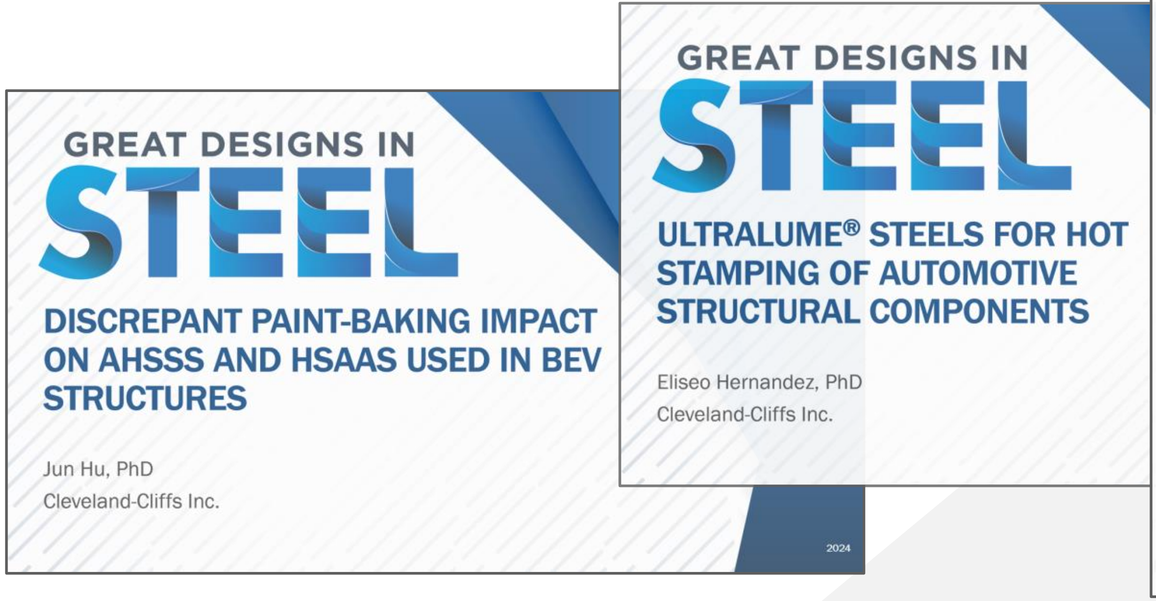
Equivalent strength by Steel-to-AA density ratio (≈ 3)



Grade Families reproduced from A. Afseth, Aluminium Battery Enclosure Design, Constellium, 2023

Keynotes of Previous Studies on PHS1500

- **Evolving phase** during automotive manufacturing: ferritic (as-received) → austenitic (annealed) → fresh martensitic (as-quenched) → tempered martensitic (paint-baked) (AIST 3rd ASIC 2025)
- Excellent formability and trivial spring-back when austenitized (hot stamping) or ferritic (roll forming)
- **ε_f after quenching: uncoated > Al-Si coated PHS** (AIST 3rd ASIC 2025)
- **↑ε_f (with yield strength and energy absorption) after baking** due to martensite tempering at all rates and stress states (CHS^2 2024, GDIS 2024)



GREAT DESIGNS IN STEEL

DISCREPANT PAINT-BAKING IMPACT ON AHSSS AND HSAAS USED IN BEV STRUCTURES

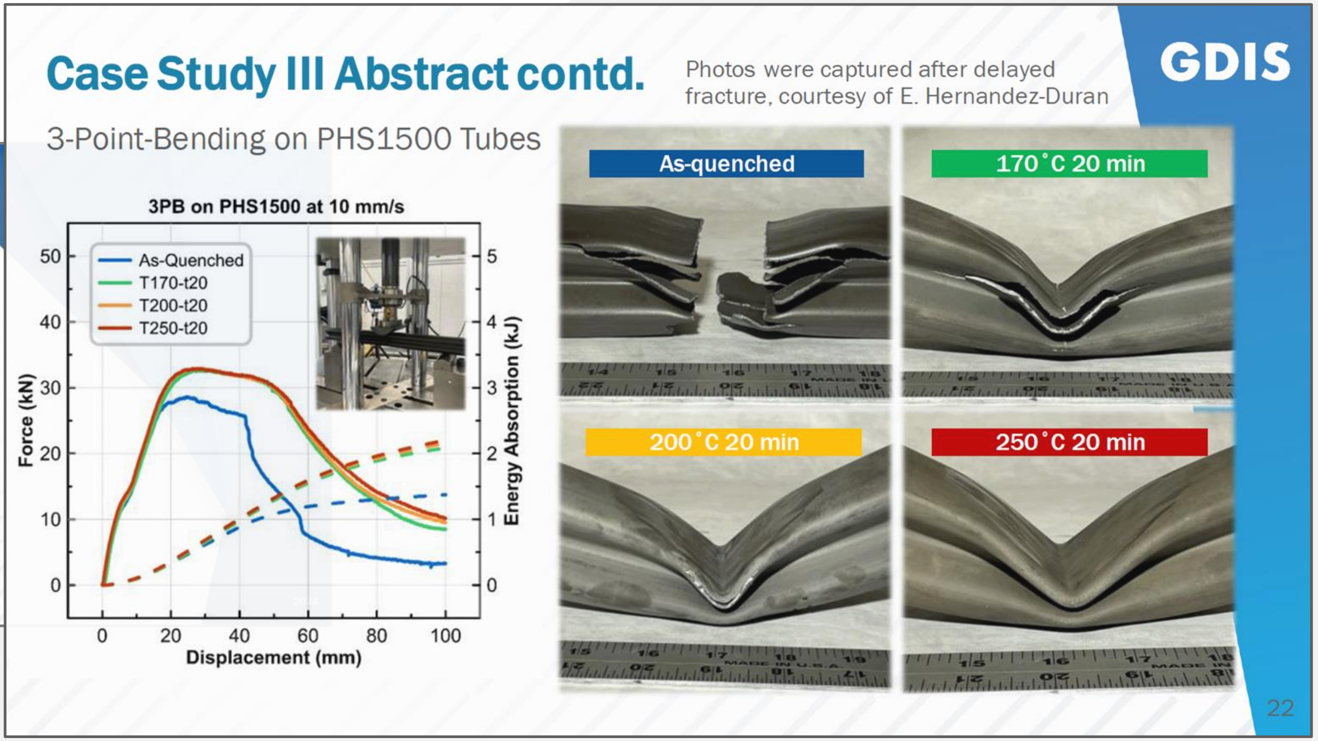
Jun Hu, PhD
Cleveland-Cliffs Inc.

GREAT DESIGNS IN STEEL

ULTRALUME® STEELS FOR HOT STAMPING OF AUTOMOTIVE STRUCTURAL COMPONENTS

Eliseo Hernandez, PhD
Cleveland-Cliffs Inc.

2024



Case Study III Abstract contd.

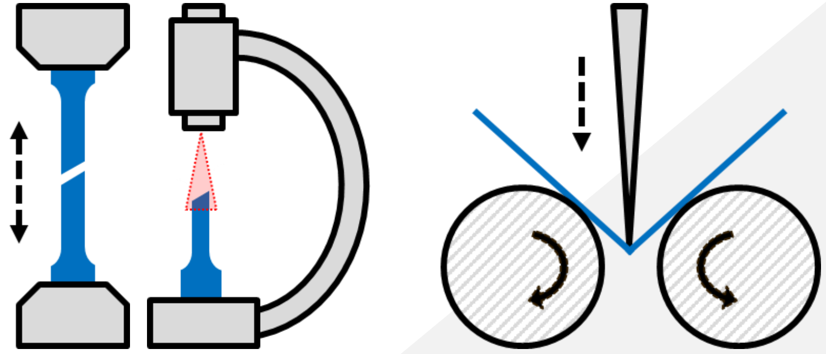
Photos were captured after delayed fracture, courtesy of E. Hernandez-Duran

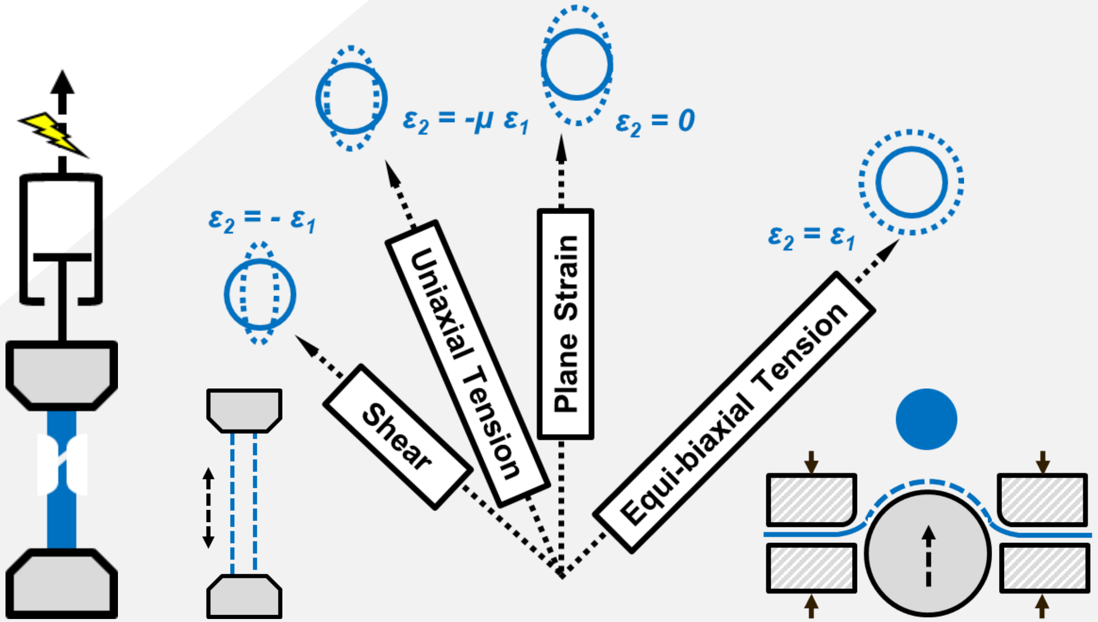
3-Point-Bending on PHS1500 Tubes

M vs. D vs. P vs. A: Scope of Testing

Only **cold-rolled uncoated fully treated** samples are studied in this comparison:

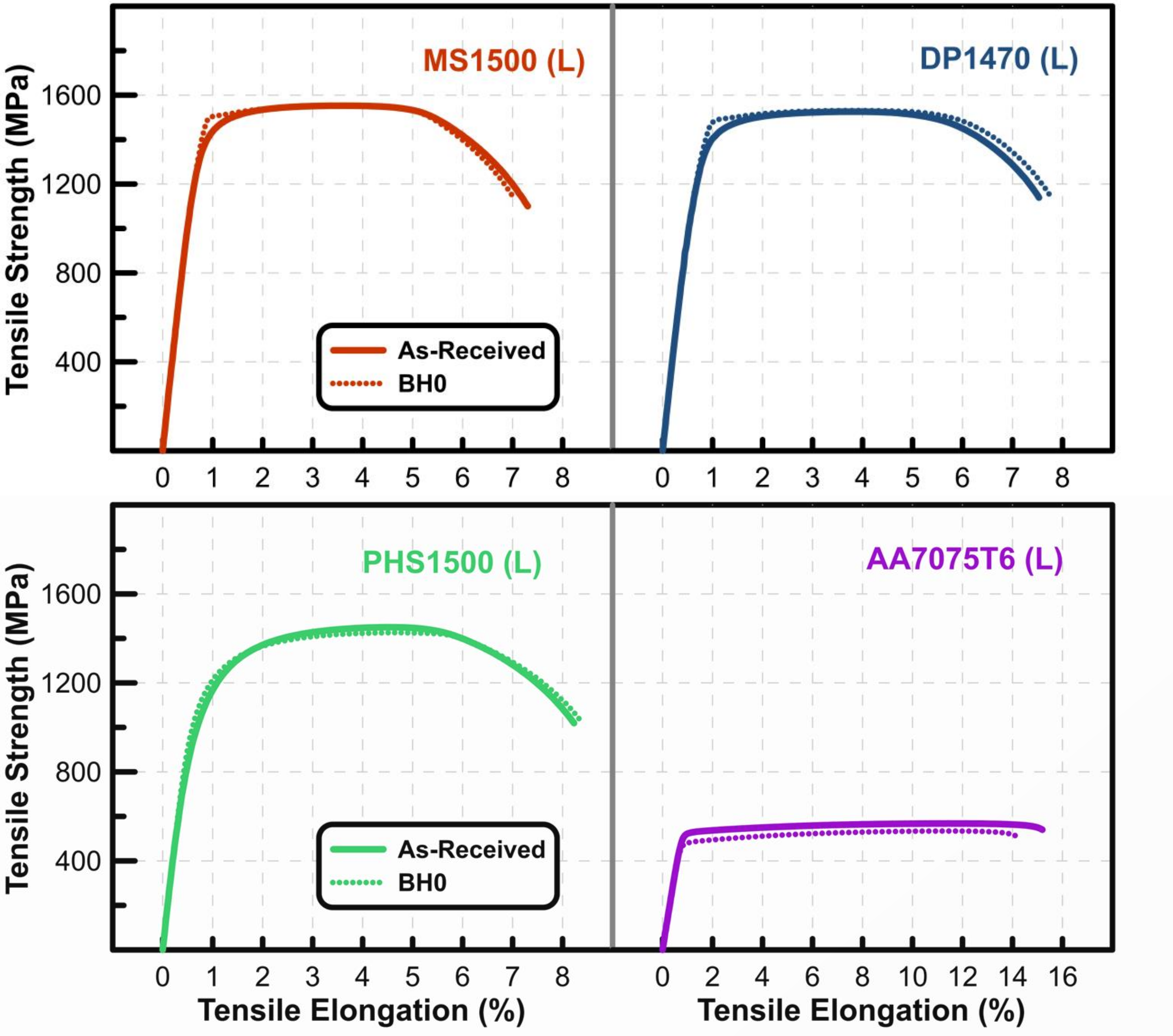
	Testing	M	D	P	A
Strength	Bake-Hardenability				
Ductility	Tensile Elongation				
	Tensile ε_f				
	~~Forming Limit~~		X		
	~~Hole Exp. Ratio~~	X			
	Local Bending				
	Rate-Dep. Tensile E				
	Rate-Dep. Tensile ε_f				
	Stress-State-Dep. ε_f				

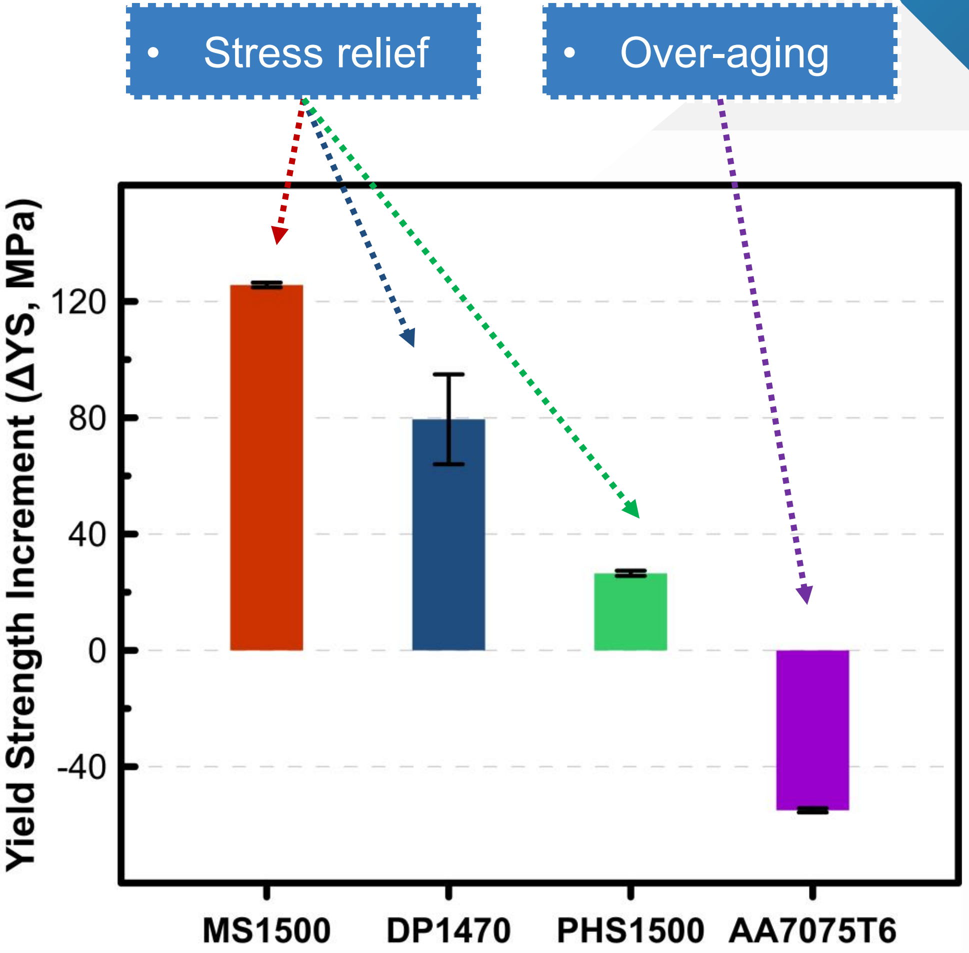




M vs. D vs. P vs. A: Bake-Hardenability

No pre-strain **(BH0)**, baked at 170˚C for 20 min.

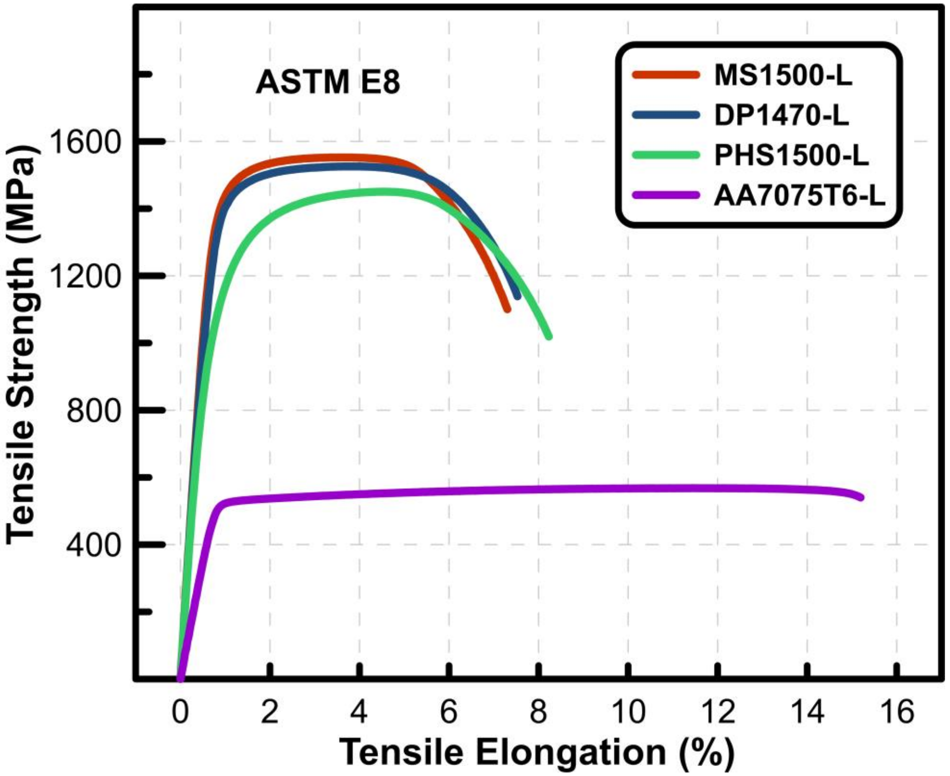


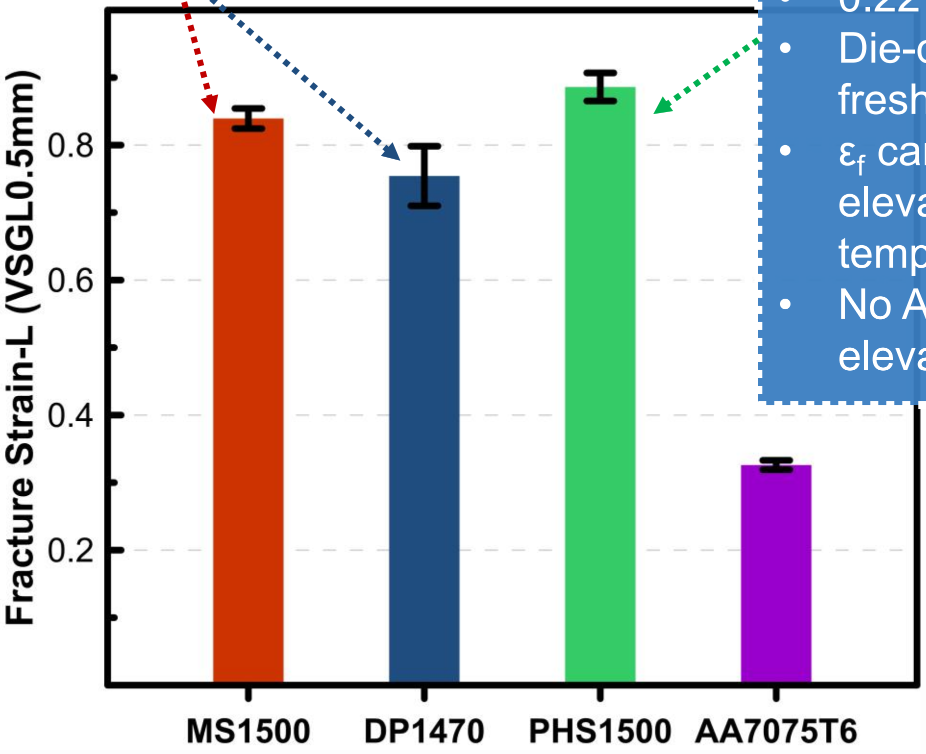

- Stress relief
- Over-aging

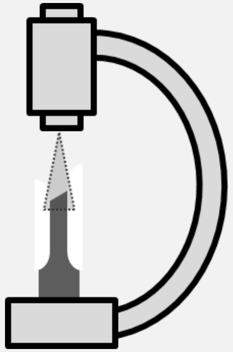
M vs. D vs. P vs. A: Quasi-Static Tensile Properties

- 0.25% C
- Tempered martensite during production

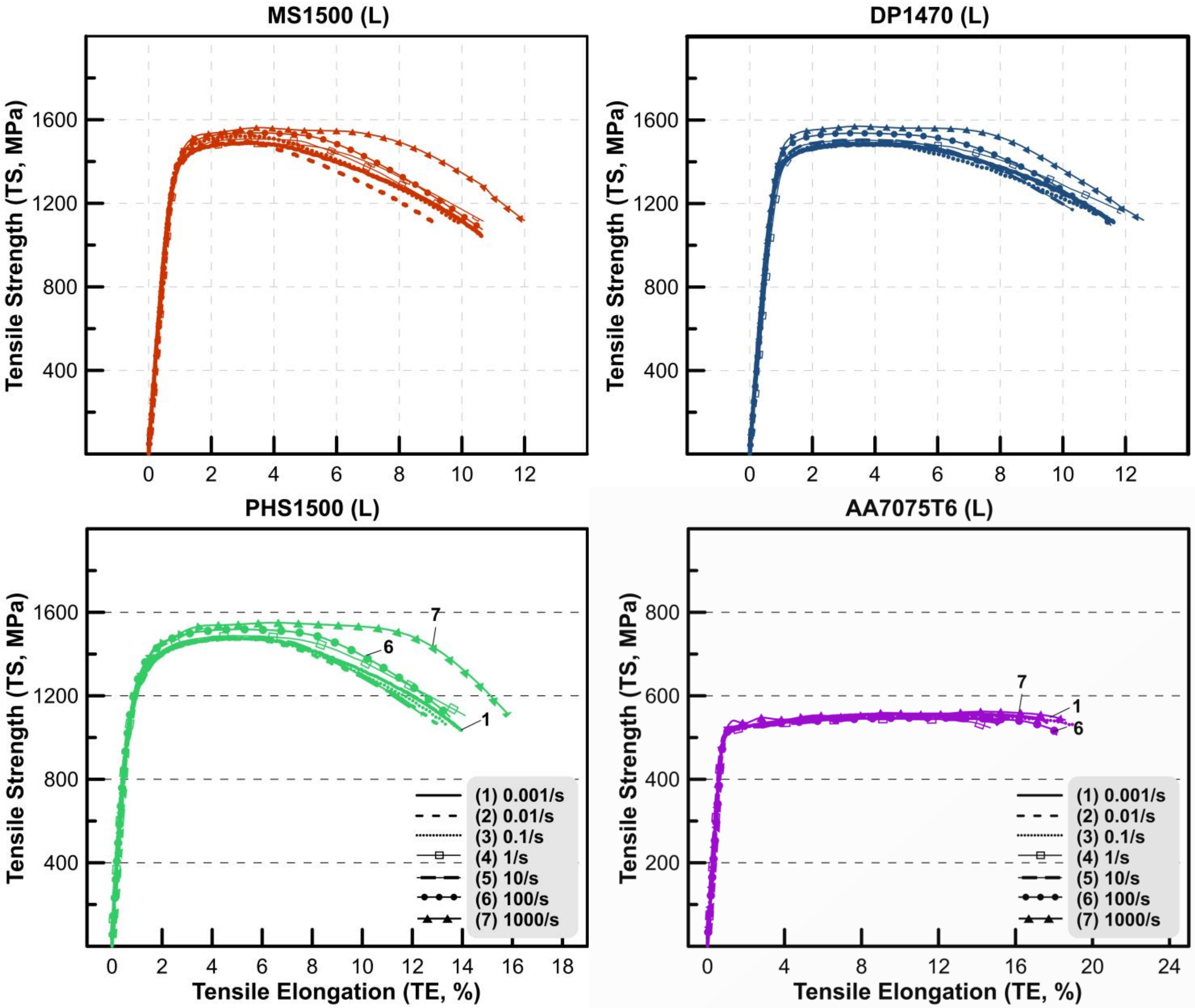
- 0.22% C
- Die-quenched fresh martensite
- ε_f can be further elevated by tempering
- No Al-Si coating elevates ε_f

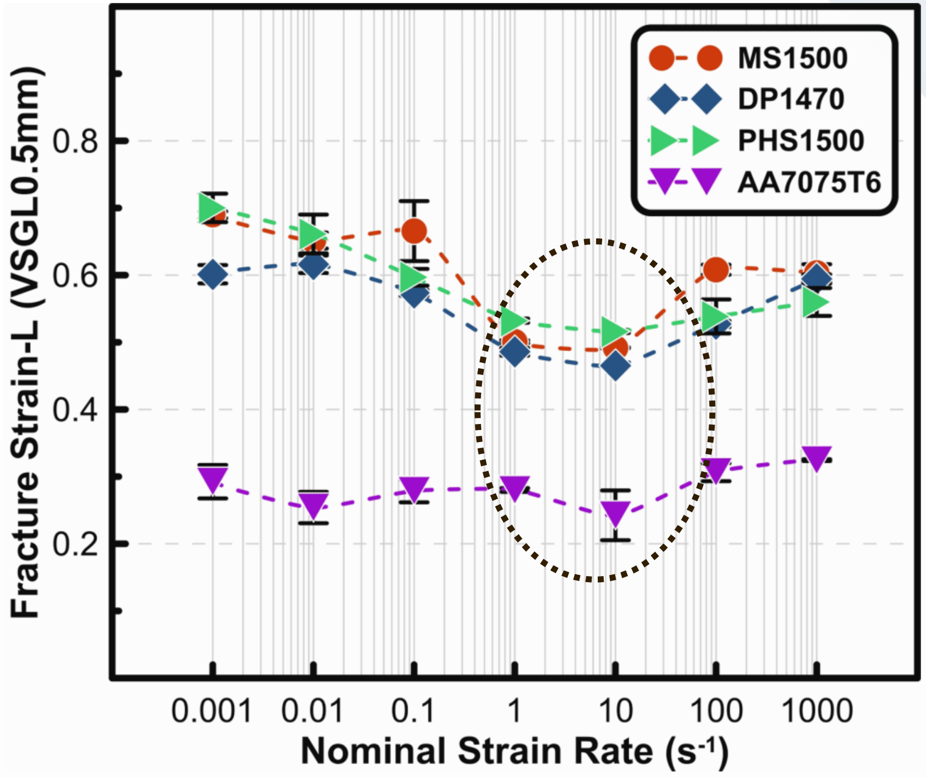




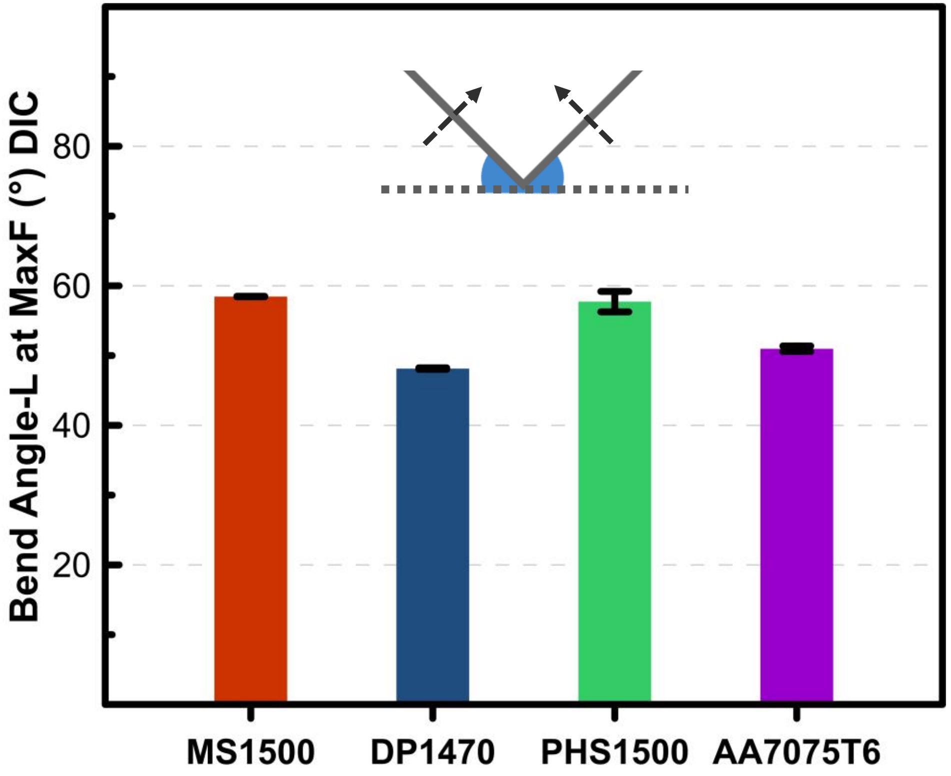


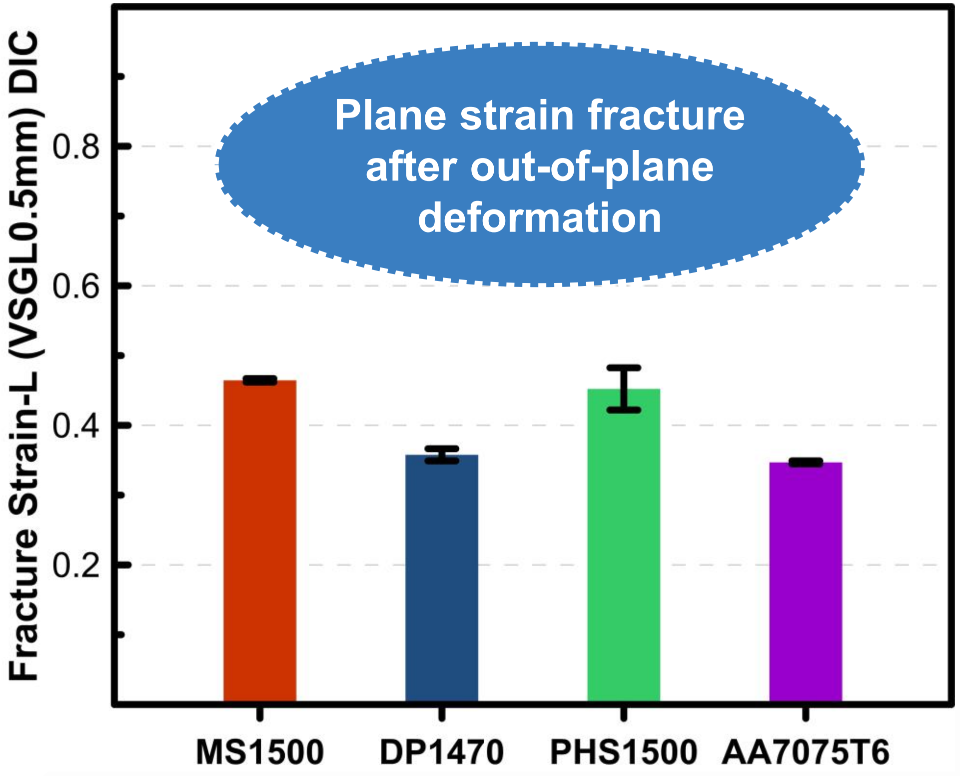
M vs. D vs. P vs. A: Rate-Dep. Tensile Properties



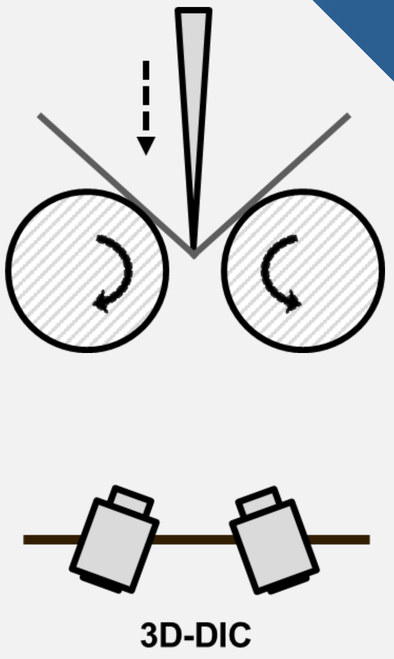


M vs. D vs. P vs. A: Local Bendability



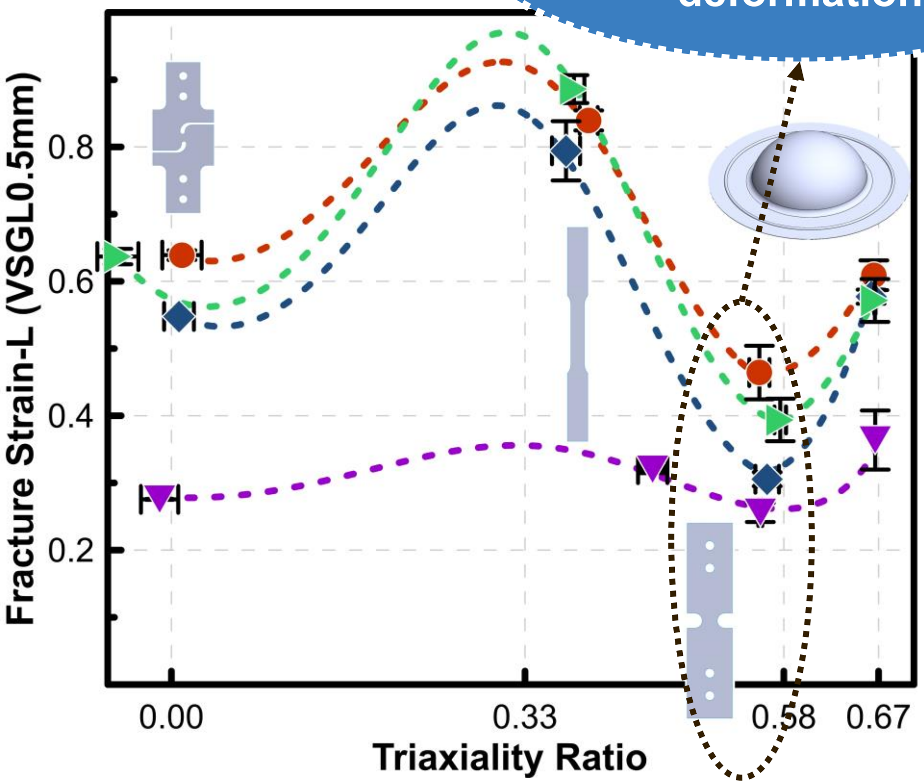


Plane strain fracture after out-of-plane deformation

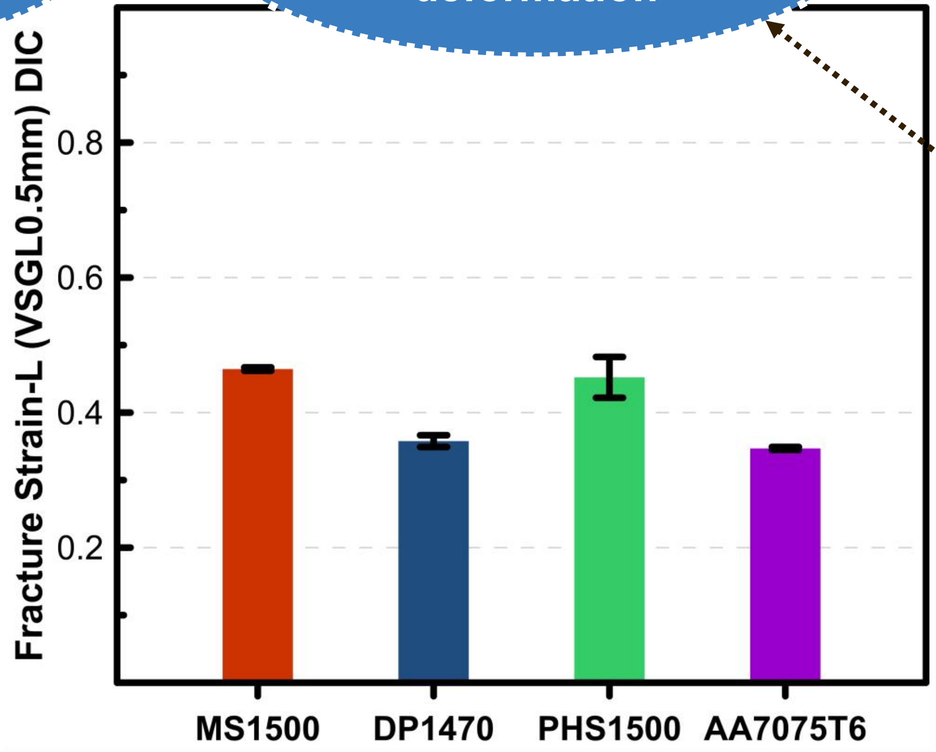


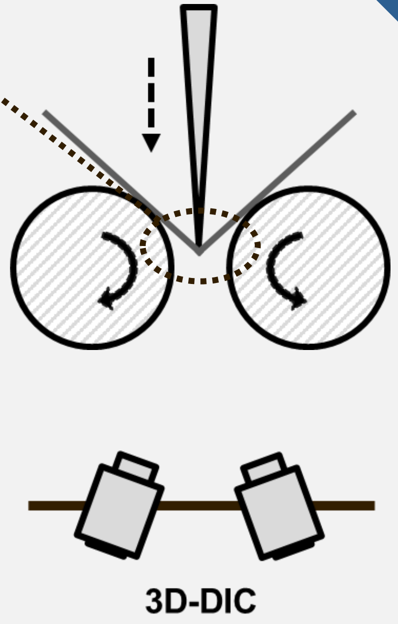
M vs. D vs. P vs. A: Stress-State-Dep. Fracture

Plane strain fracture after in-plane deformation



Plane strain fracture after out-of-plane deformation

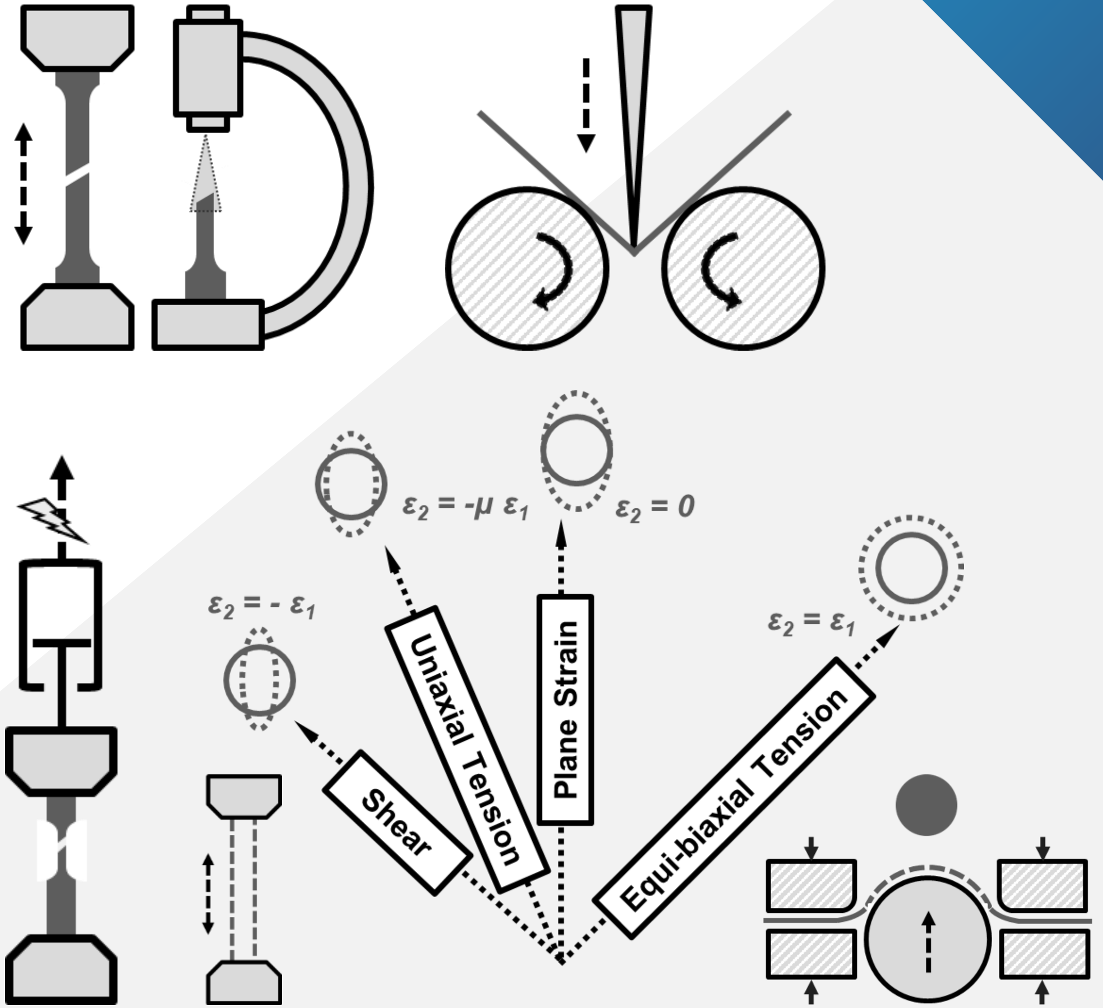




M vs. D vs. P vs. A: Summary

Only **cold-rolled uncoated fully treated** samples are studied in this comparison:

	Testing	M	D	P	A
Strength	Bake-Hardenability	X			
Ductility	Tensile Elongation				X
	Tensile ε_f			X	
	~~Forming Limit~~		X	╲	╲
	~~Hole Exp. Ratio~~	X		╲	╲
	Local Bending	X			
	Rate-Dep. Tensile E				X
	Rate-Dep. Tensile ε_f	X		X	
	Stress-State-Dep. ε_f	X		X	



Conclusions

1. Compared the 2 cold-forming 1500MPa grades (MS1500 vs. DP1470):
    - Microstructure: martensite vs. martensite + ferrite.
    - The ferrite (soft phase) in DP1470 contributes to ↓BHI, ↑global formability, ↓local formability and ↓fracture resistance under the practical conditions.
    - Based on the microstructure, the mechanical properties can be postulated.
    - Single or dual/multi phase(s) in the future UHSS development?
2. Compared the cold- vs. hot-forming 1500MPa grades (M vs. D vs. P vs. A):
    - PHS1500: lower strength yet similar fracture resistance with MS1500 before being further improved by tempering the fresh martensite.
    - The fracture resistance of all the 3 studied UHSSs > AA7075T6.
    - Many factors need to be considered in the automotive material selection.

THANK YOU!

For More Information

→ → →

Jun Hu, PhD
Jun.Hu@clevelandcliffs.com

Laura Burroughs
Laura.Burroughs@clevelandcliffs.com

Grant Thomas, PhD
Grant.Thomas@clevelandcliffs.com

Relative publications:

- **On Fracture Resistance of Ultra-High-Strength Press-Hardened Steels**, AIST 3rd Auto Steel Int. Conf. 2025
- **On Local Formability/Ductility of New Advanced High-Strength Steels: Temperature, Bake Hardening, and Strain Rate Effects**, AIST Transactions 2024
- **True Fracture Strain Measurement and Derivation for Advanced High-Strength Steel Sheets**, SAE 2022, GDIS 2023