GREAT DESIGNS IN STEEL

TWENTY YEARS

EVOLVING THE STEEL STRENGTH - DUCTILITY DIAGRAM: TEMPERATURE AND RATE EFFECTS ON NEW AHSS

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ACKNOWLEDGEMENT

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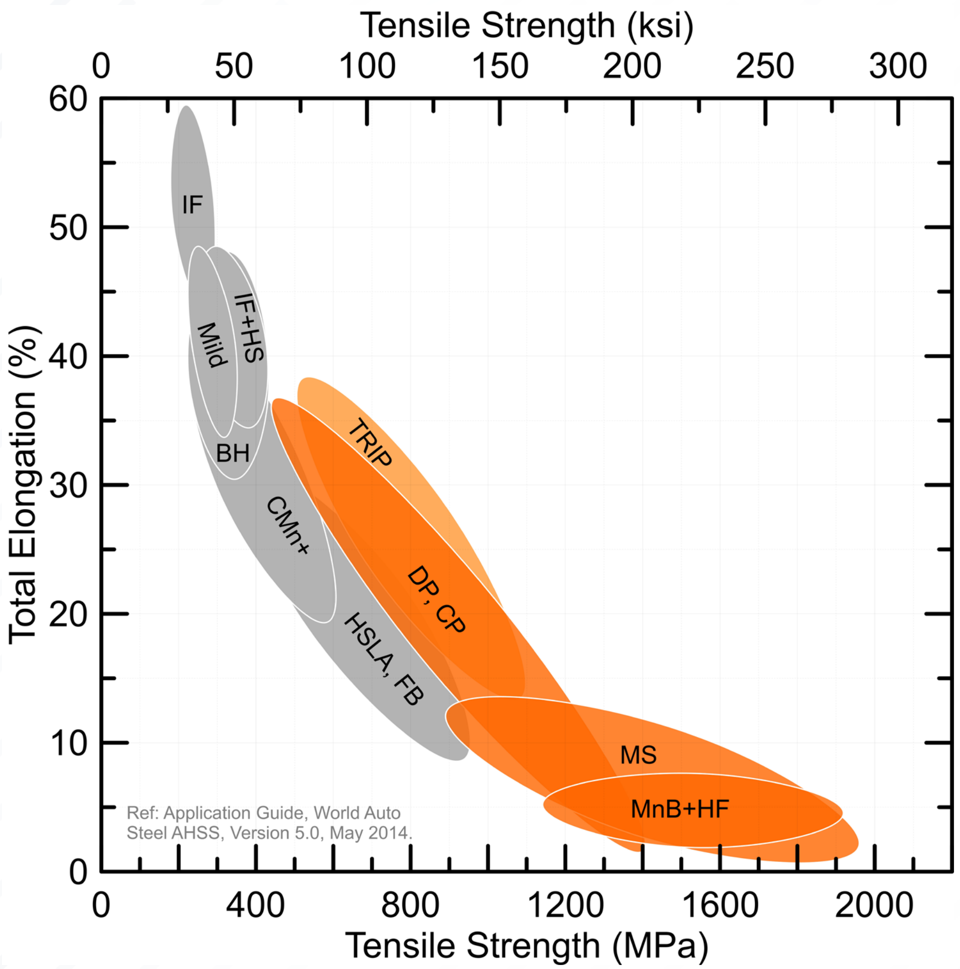
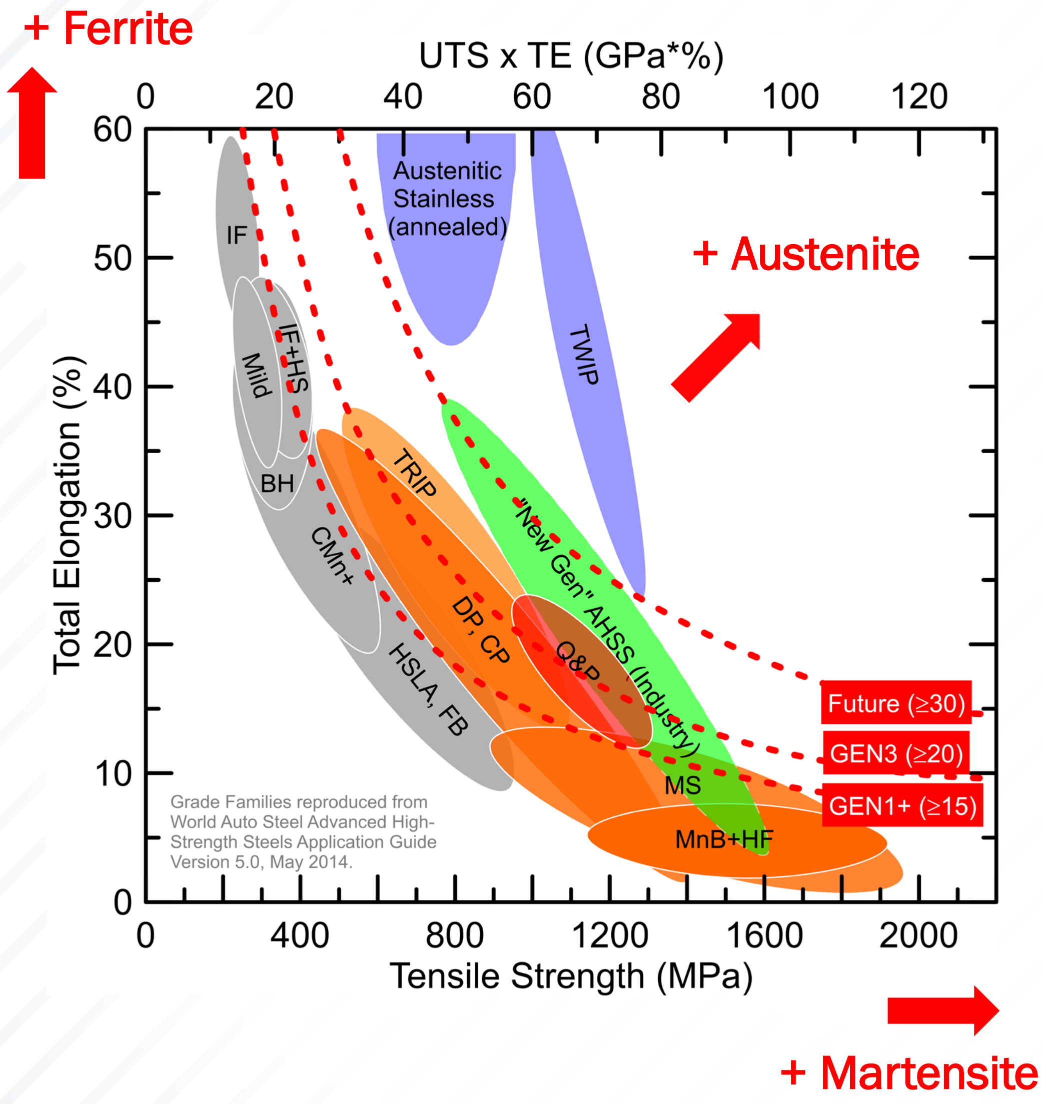
THE STRENGTH-DUCTILITY DIAGRAM



- ‘Strength-Ductility Chart/Diagram’
- The initial version: total elongation (TE) vs. yield strength (YS) (Shaw *et al.*, 2002)
- The abscissa evolved to ultimate tensile strength (UTS) (Matlock and Speer, 2006)
- The TE values are obtained using ASTM E8 test samples or converted based on the ISO 2566 standard (Matlock *et al.*, 2010)
- Based on quasi-static tensile test results at room temperature (RT)

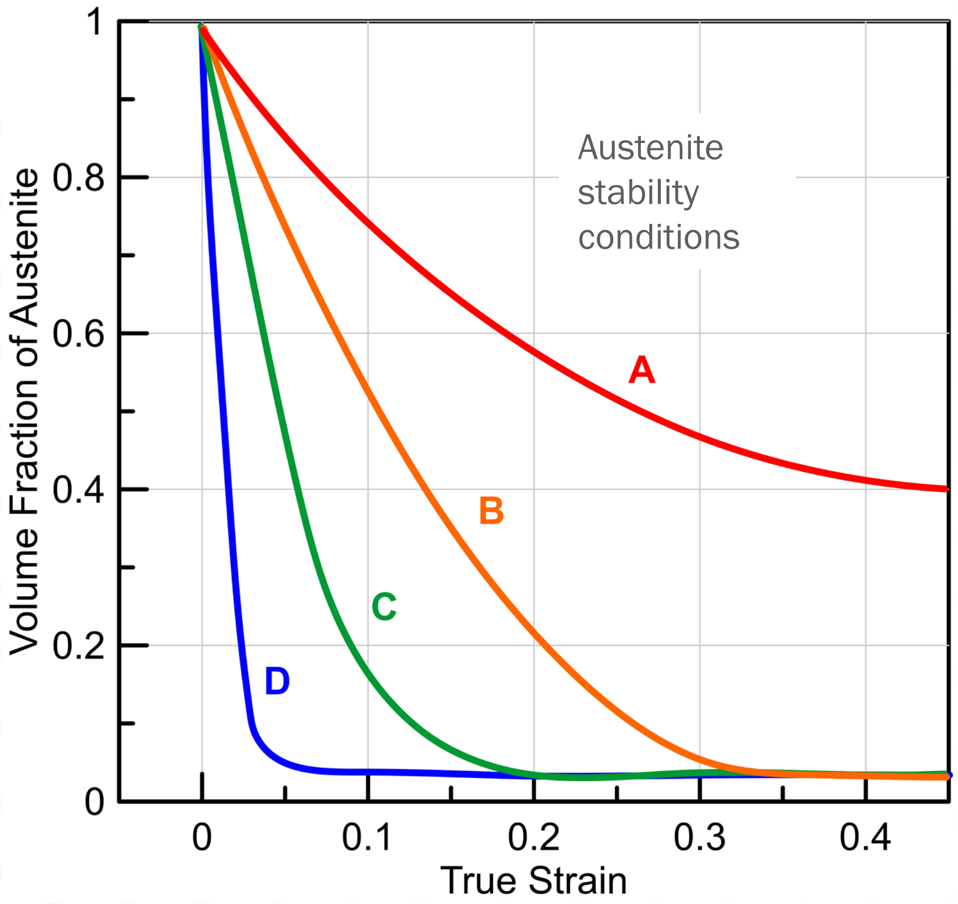
AHSS IN THE DIAGRAM

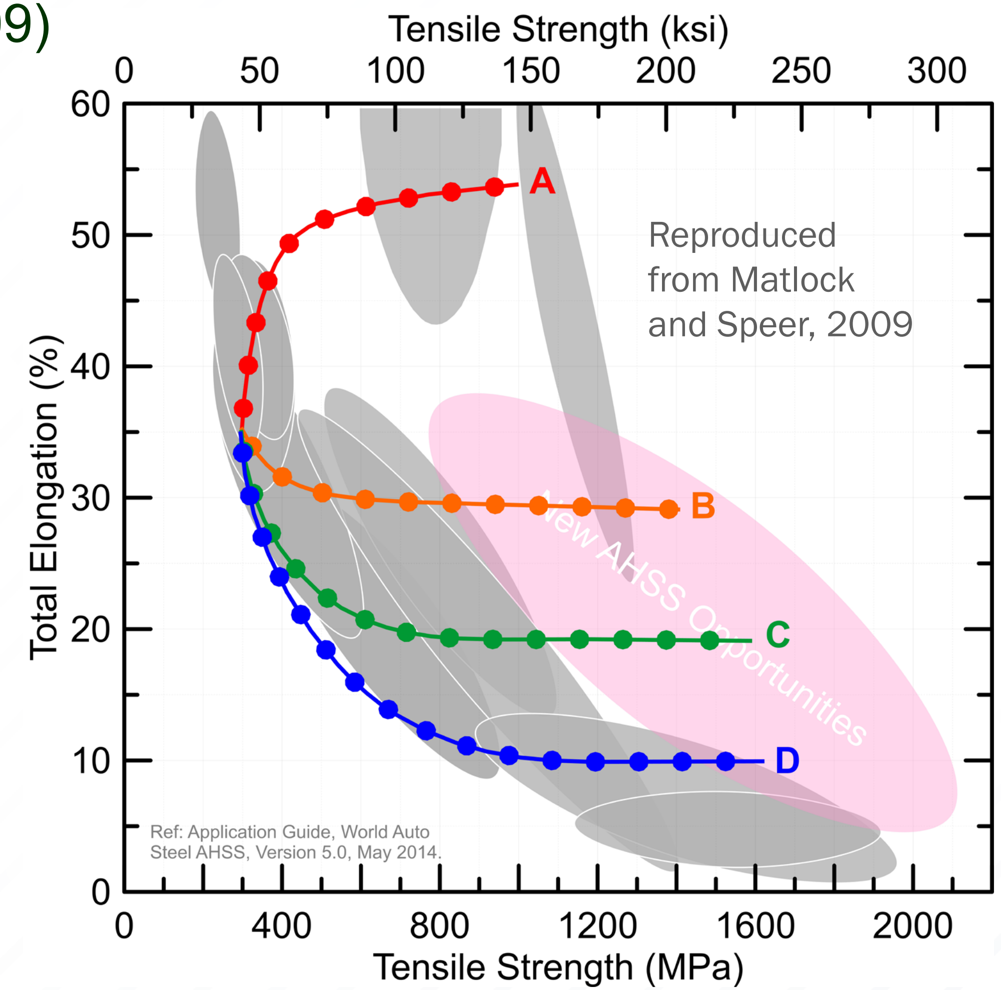


- 1st generation (**GEN1**) band: ferrite + martensite dominant microstructure, a trade-off between TE and UTS
- 2nd generation (**GEN2**): good TE + UTS, yet limited by cost and joining challenges
- New generation opportunities: De Moor *et al*. (2010) and Fonstein (2015) suggested DP+, TRIP+, Q&P, TWIP+, Med-Mn, and CFB/TBF steels
- Categorization based on UTS x TE values (Davenport, 2017)

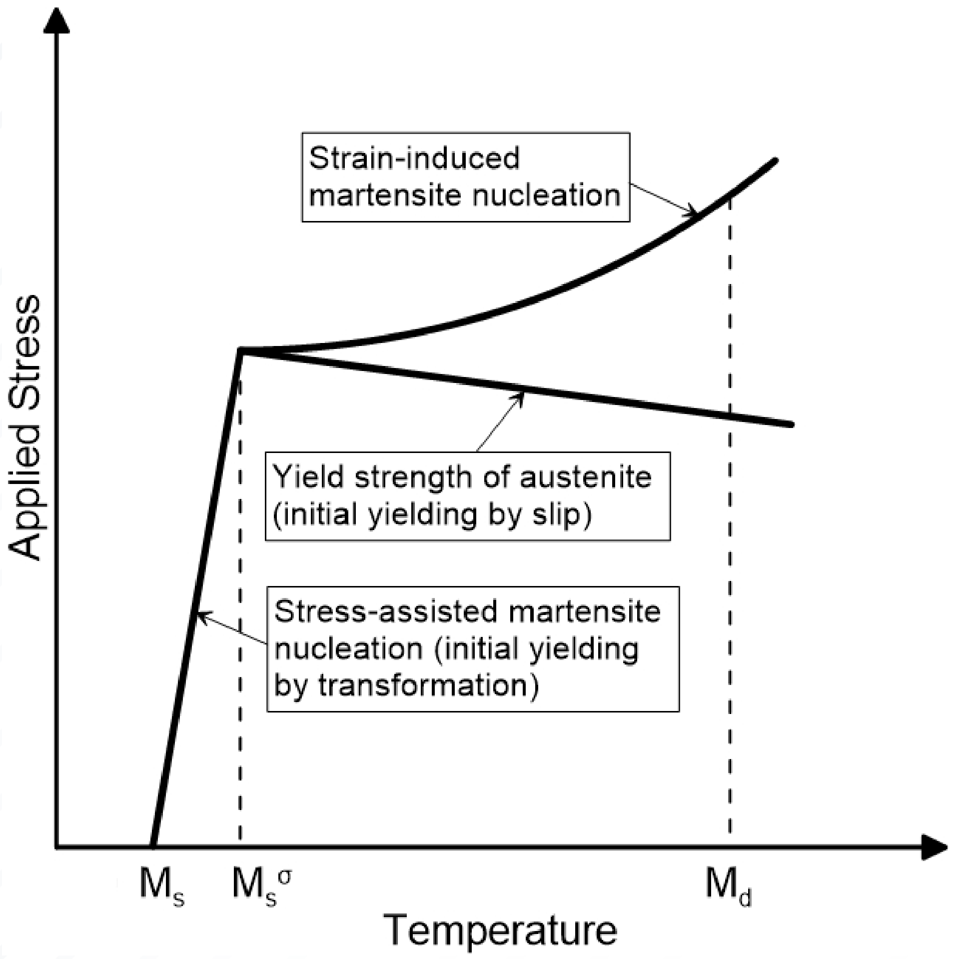
NEW AHSS DEV. STRATEGY

- Controlling austenite stability conditions can achieve various strength-ductility combinations (Matlock and Speer, 2009)





TEMPERATURE SENSITIVITY



Reproduced from Olson and Cohen, 1972

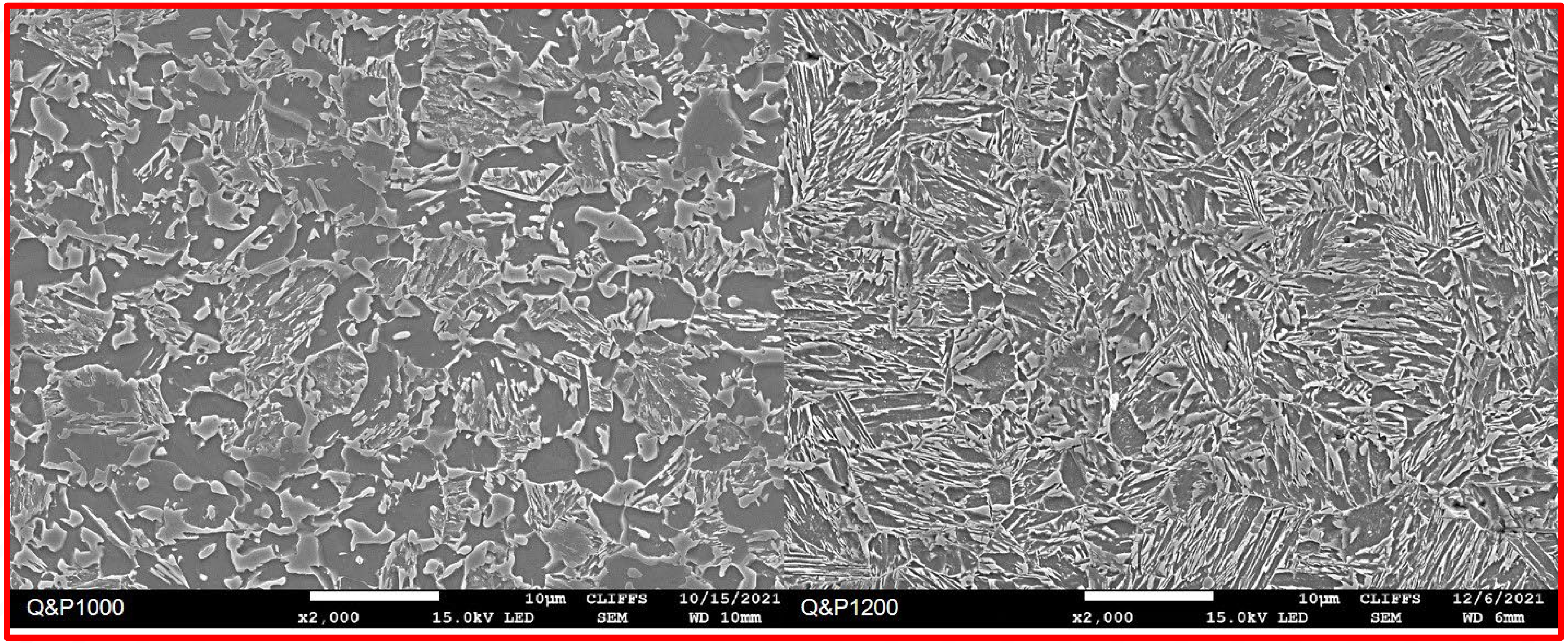
- Olson-Cohen theory (1972)
- $M_s < T < M_s^\sigma$ (typically subzero): stress-assisted martensite nucleation
- $M_s^\sigma < T < M_d$ (for general applications): strain-induced martensite nucleation
- $T > M_d$ (for some applications): transformation stops because the critical stress exceeds the material strength

RESEARCH MOTIVATION

- Tool temperature when stamping DP780: ~180˚C (Pereira and Rolfe, 2014)
- Highest temperature of tensile testing on Q&P1180 at 0.5 s^{-1} exceeded 230˚C (Hu and Raghavan, 2018)
- Either stamping rate (order of 10^1 s^{-1}) or crashing rate (order of 10^3 s^{-1}) is much higher than the laboratory testing rate (order of 10^{-3} s^{-1})
- To study the temperature and strain rate effects on the tensile properties of the selected AHSS grades and illustrate such changes in the Steel Strength-Ductility Diagram

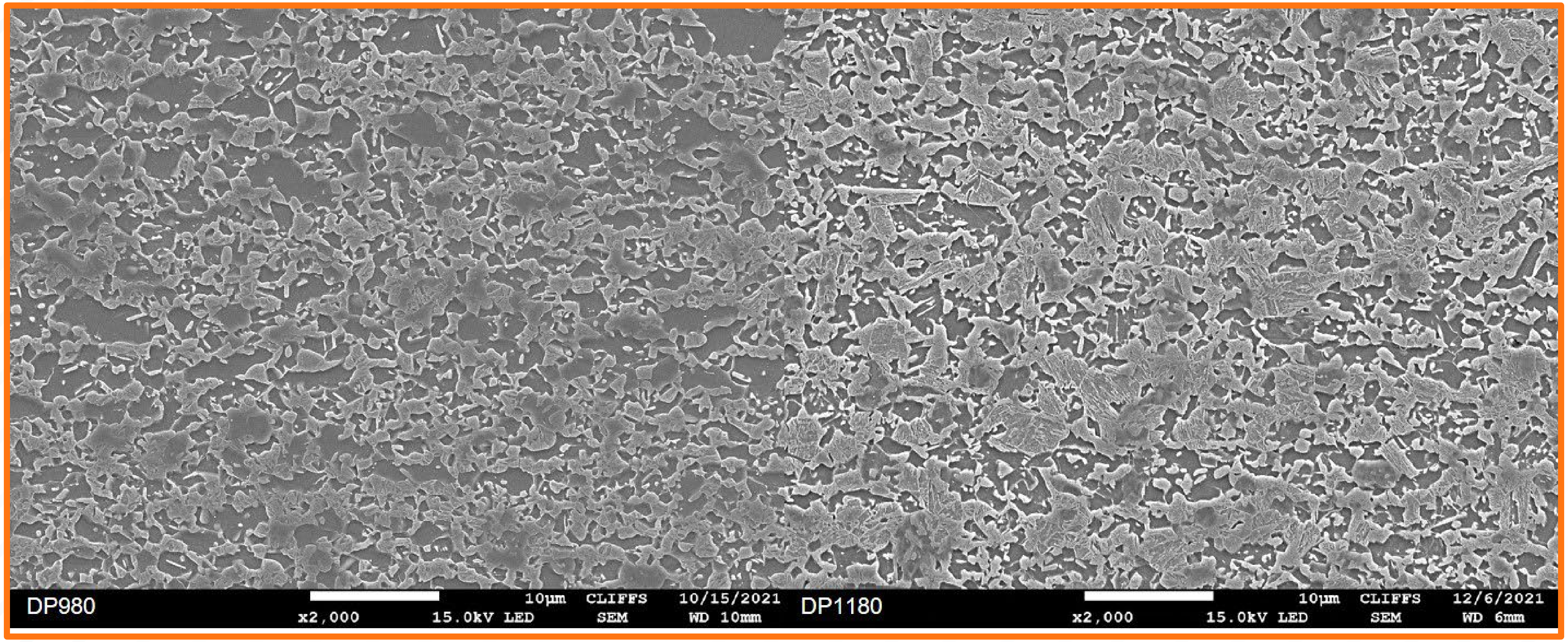
TARGET GROUP

- **Q&P1000 (left) and 1200 (right)**, each containing ~14% retained austenite



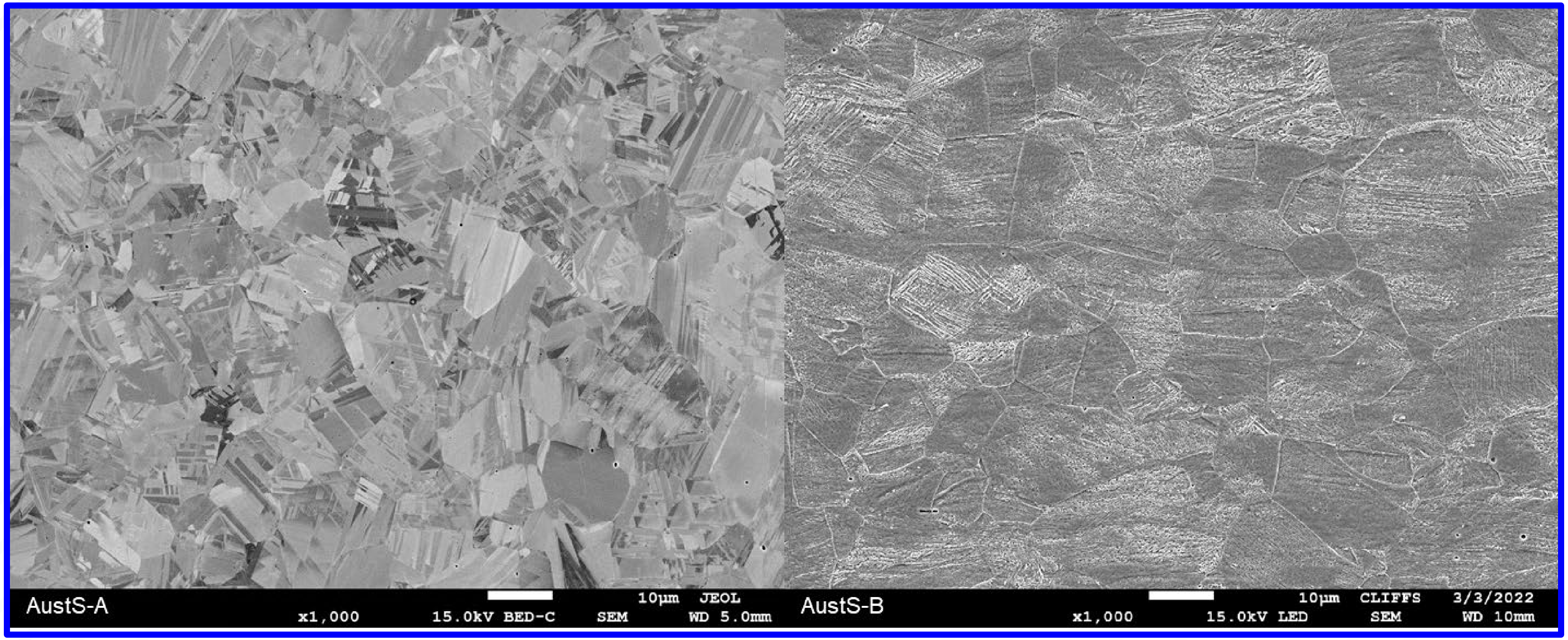
COMPARISON GROUP (1)

- **DP980 (left) and 1180 (right)**, with conventional ferrite + martensite microstructure



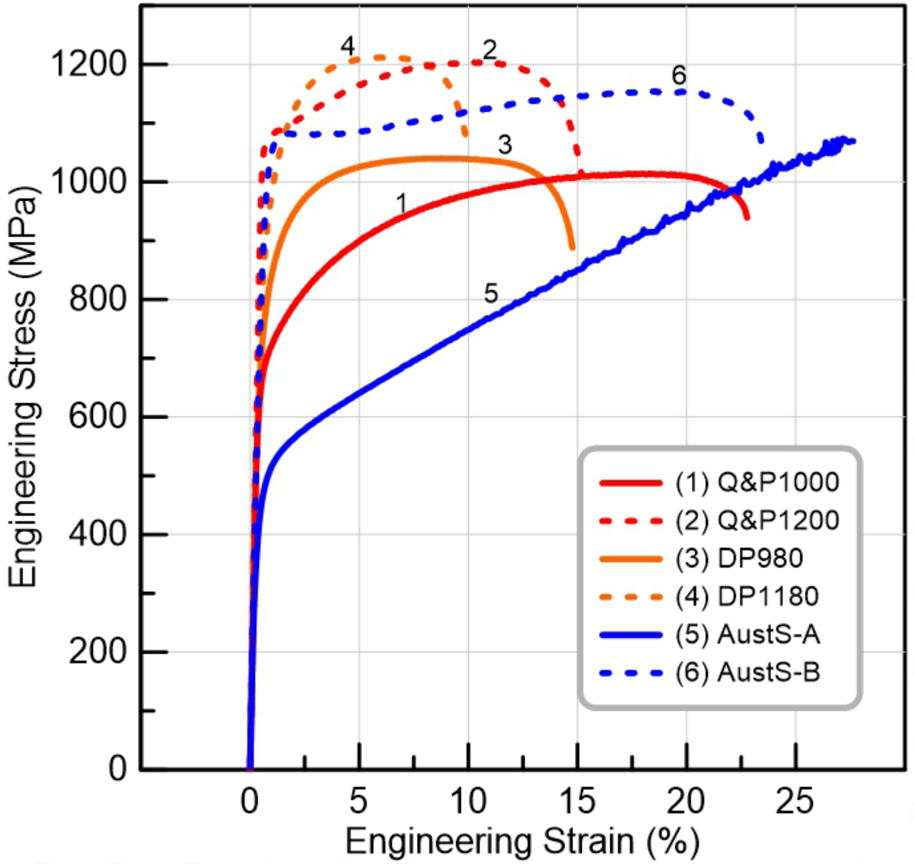
COMPARISON GROUP (2)

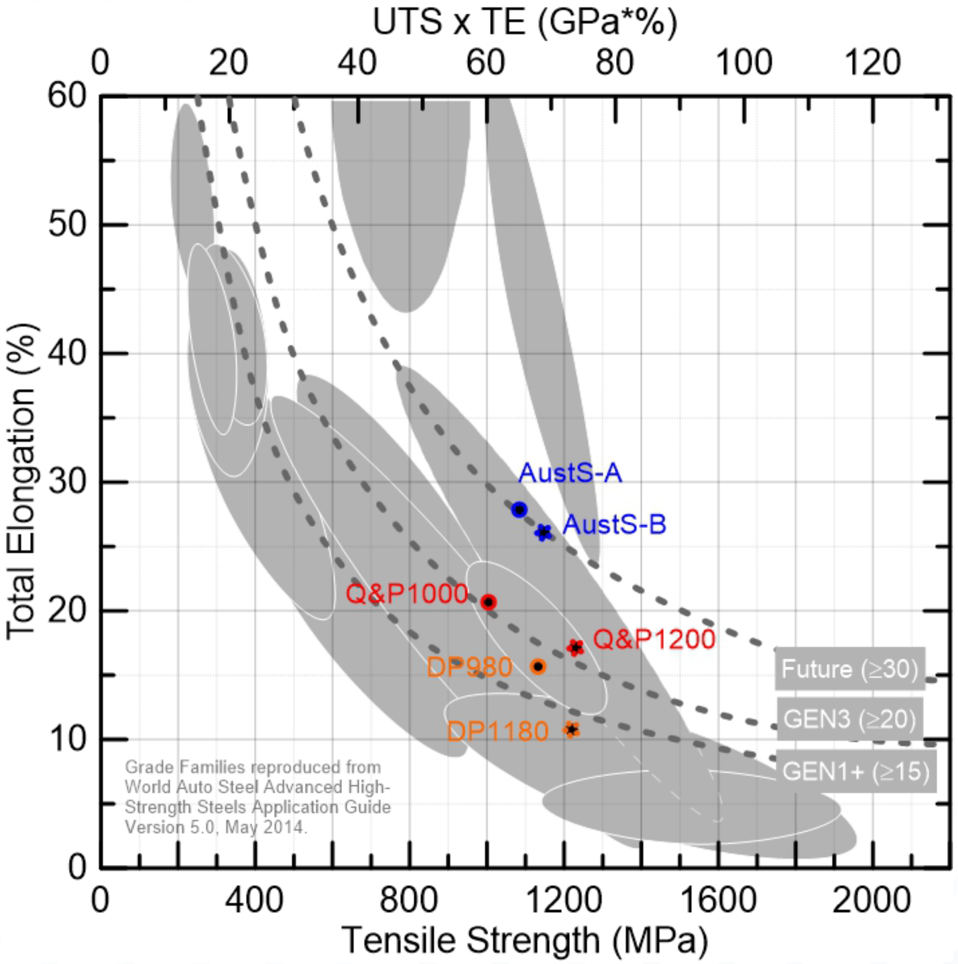
- 2 austenitic steels, coded as **AustS-A and -B**, 90% austenite yet of different stability



TENSILE PROPERTIES OVERVIEW

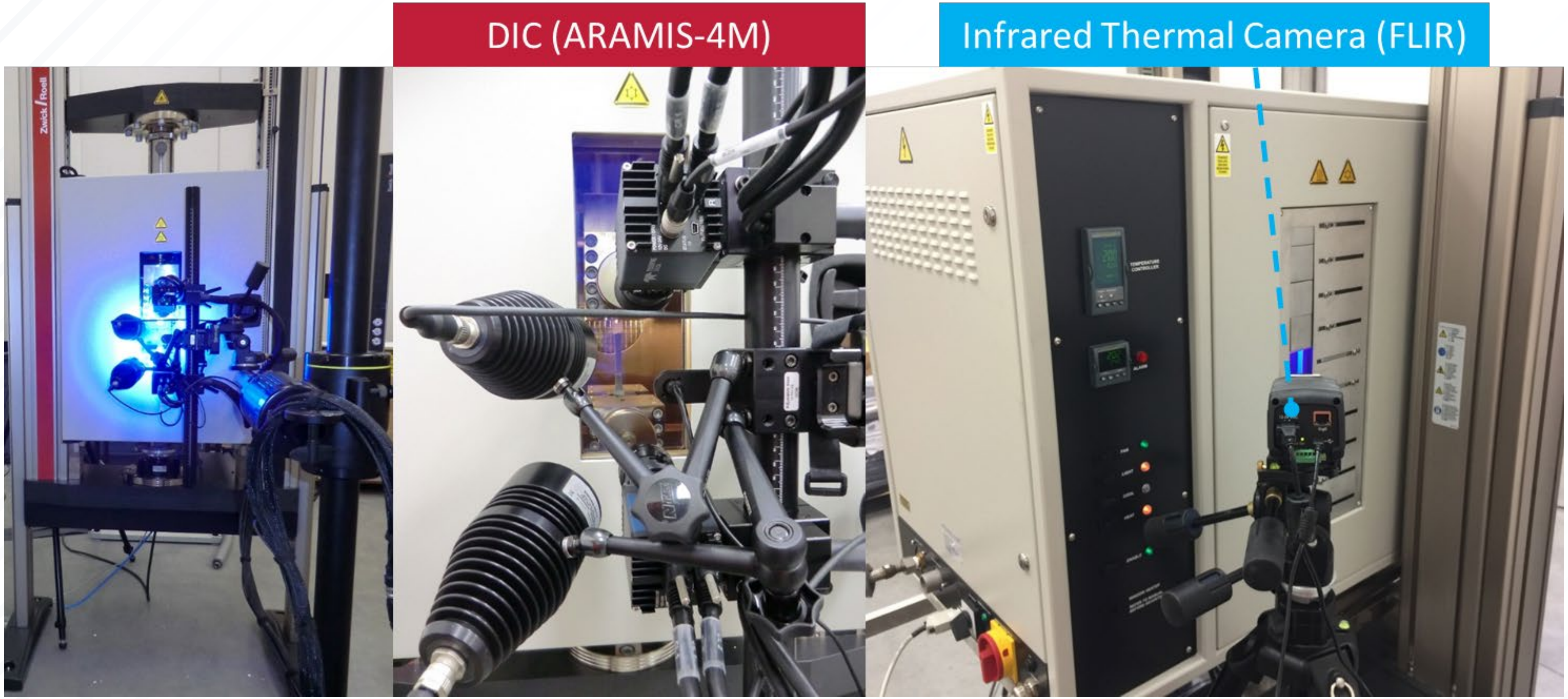
- Representative tensile properties of the six selected AHSS grades



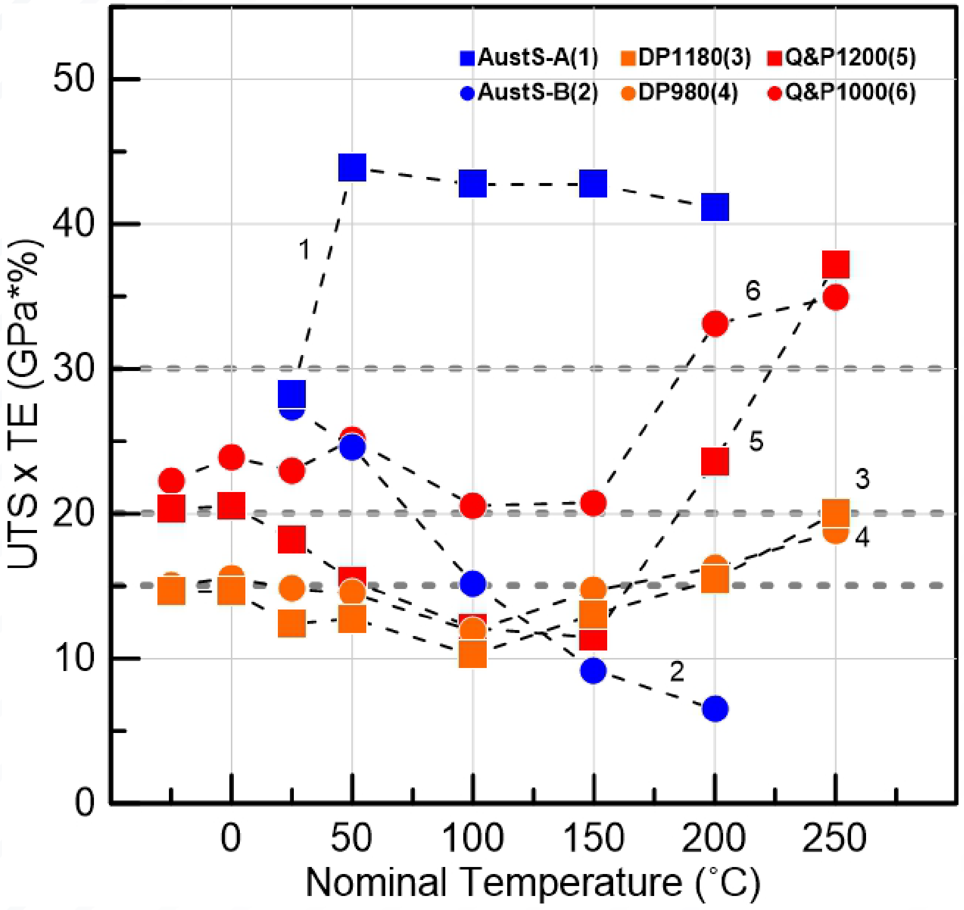


TEMP. EFFECTS: TEST SETUP

- Quasi-isothermal heating, tensile testing at 0.001 s^{-1} nominal strain rate

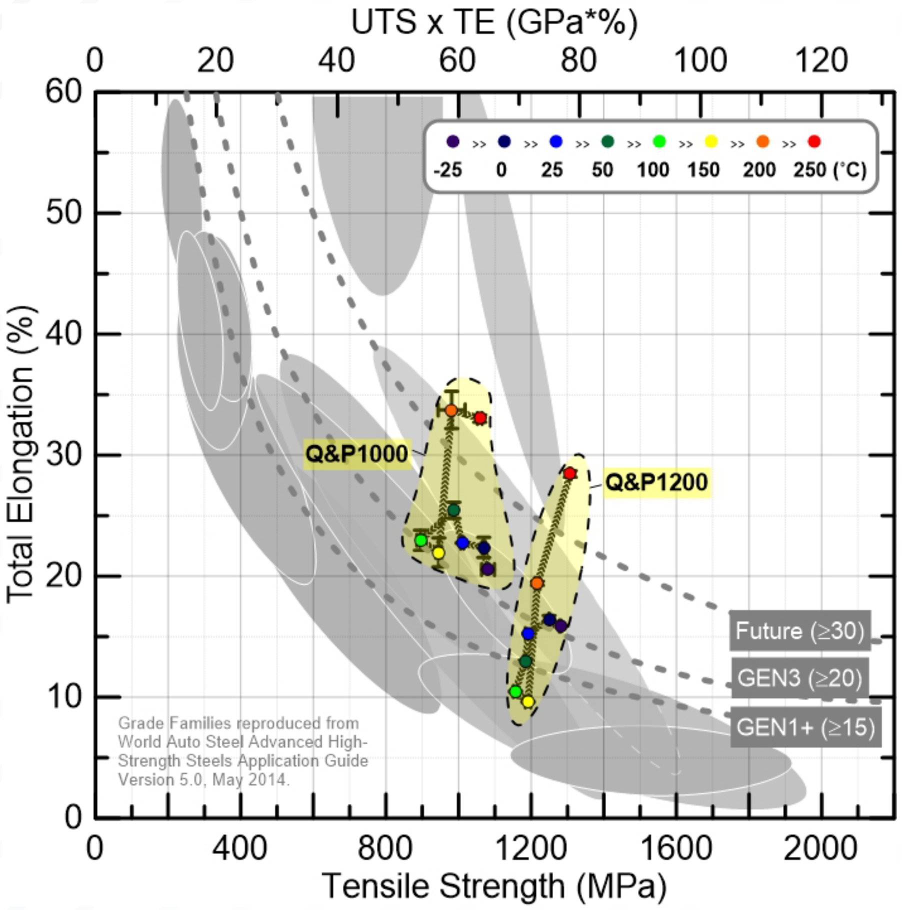


TEMP. EFFECTS: RESULTS OVERVIEW



- The grades with austenite in the microstructure are more sensitive to the temperature change
- Both Q&P grades exhibit wavy tensile properties with the temperature change
- Both DP grades exhibit comparatively more stable tensile properties
- The 2 AustS grades exhibit completely discrepant temperature dependency due to the different austenite stability

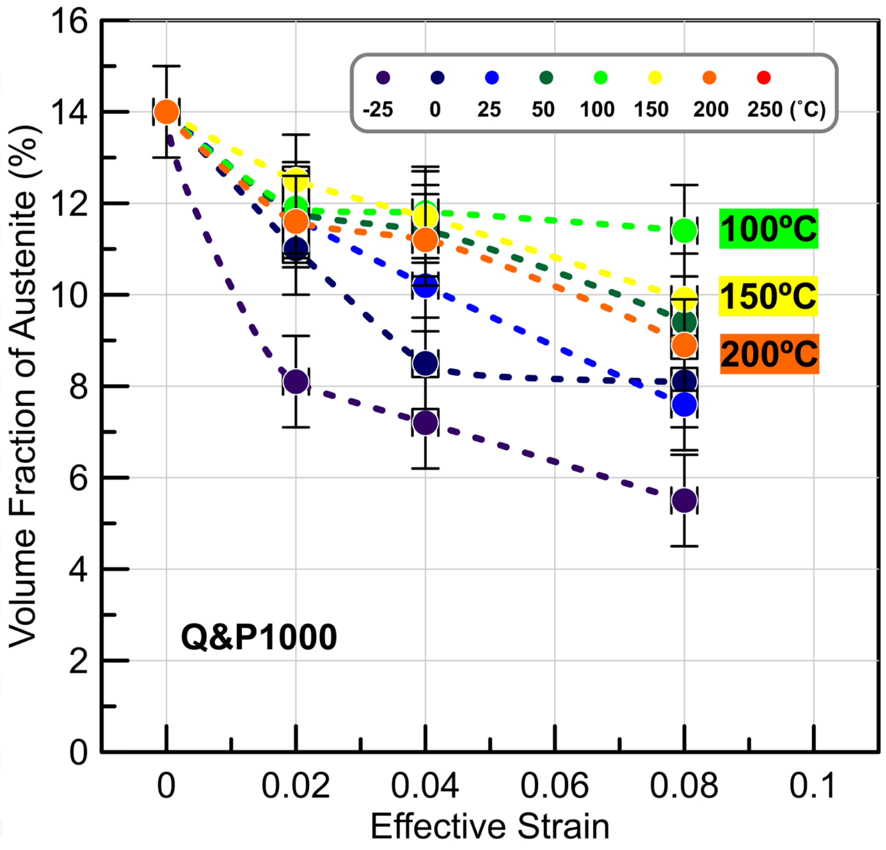
TEMP. EFFECTS: TARGET GROUP

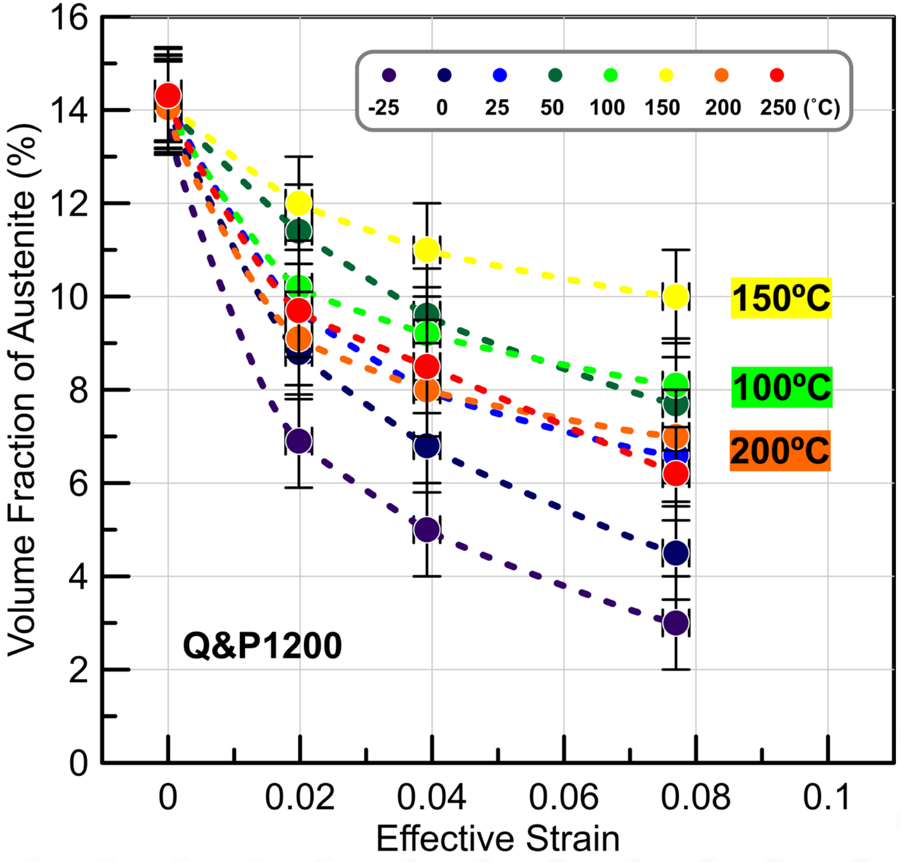


- Q&P1200 is more temperature-sensitive than Q&P1000
- Multiple effects, either opposing or favoring, contribute to such sensitivity:
  - Martensitic transformation: +TE, +UTS
  - Dynamic strain aging (DSA): -TE, +UTS
  - Thermal softening: +TE, -UTS
- The martensitic transformation becomes gradually inactive from 25 to 100˚C, but then reactivated from 150 to 250˚C

TEMP. EFFECTS: TARGET GROUP

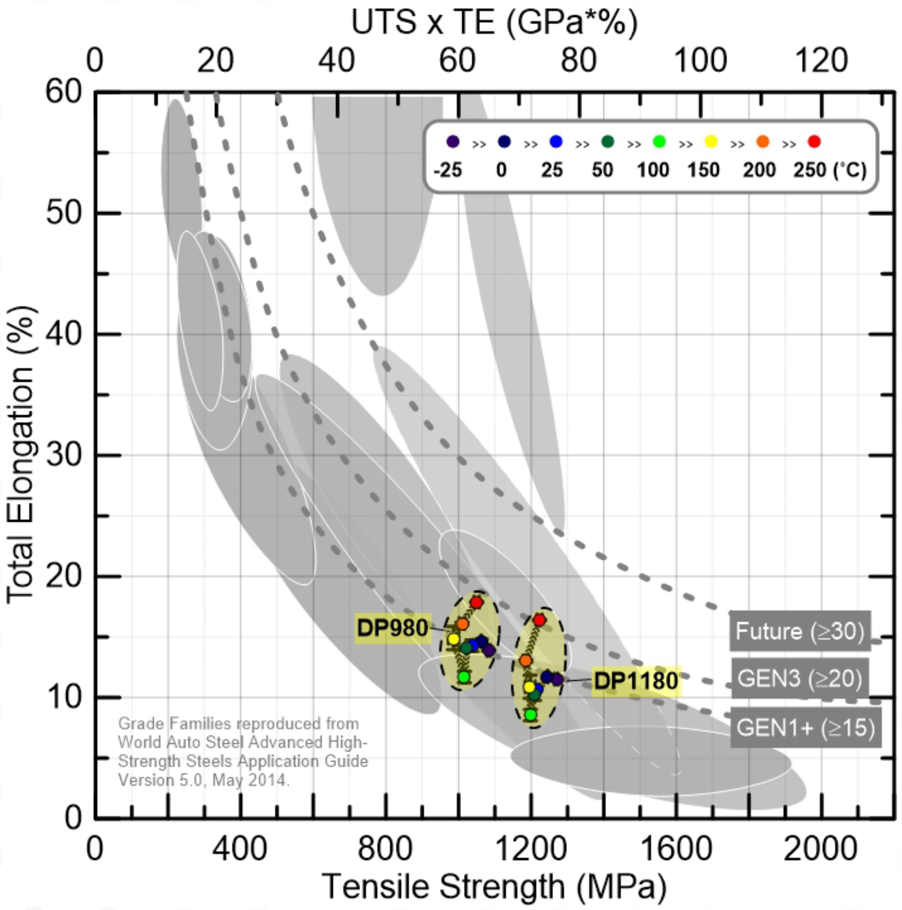
- Similar observations were reported from other Q&P and TRIP steels (Coryell *et al.*, 2013, Min *et al.*, 2016, Zhang *et al.*, 2019), yet the mechanism is still unclear.

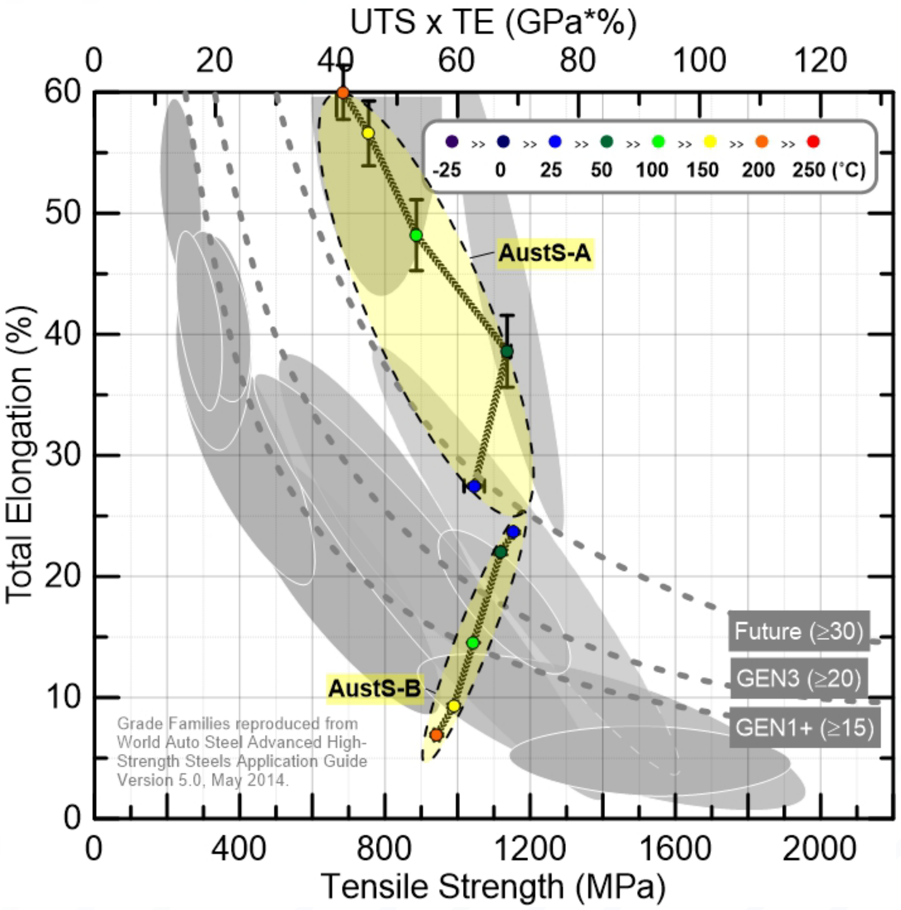




TEMP. EFFECTS: COMPARISON GROUP

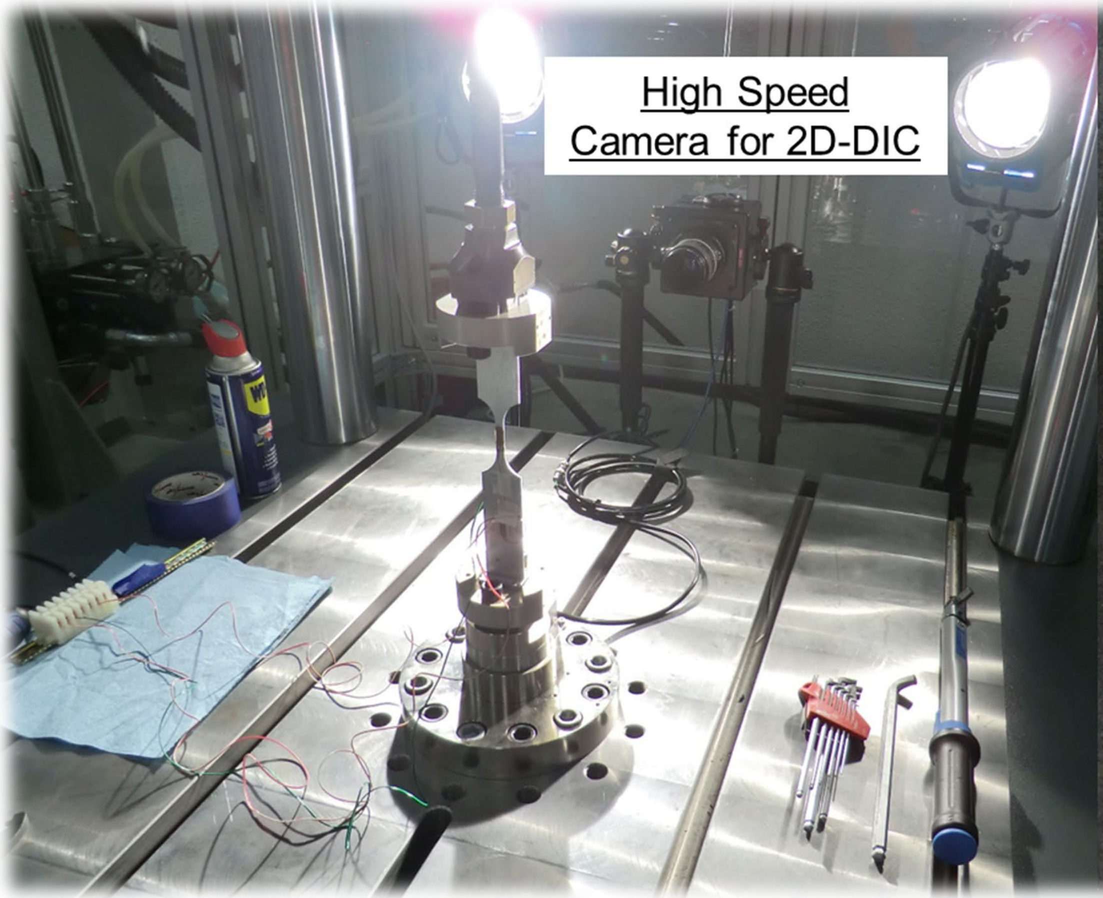
- DP grades: the TE drops around 100˚C is due to the DSA effects
- AustS-A: deformation mechanism evolves; AustS-B: follows the Olson-Cohen theory

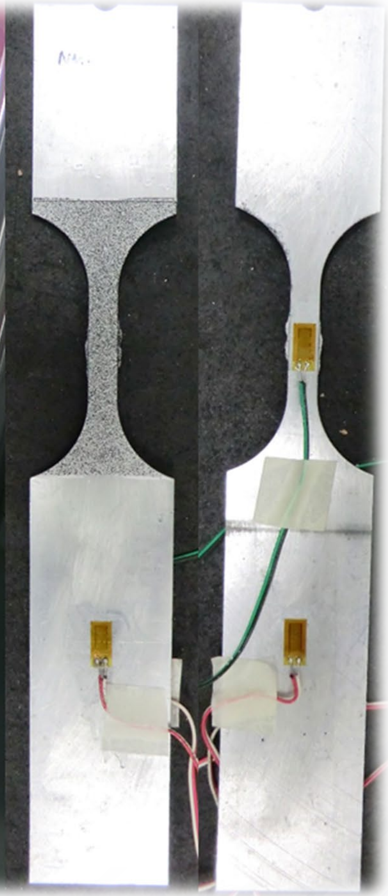




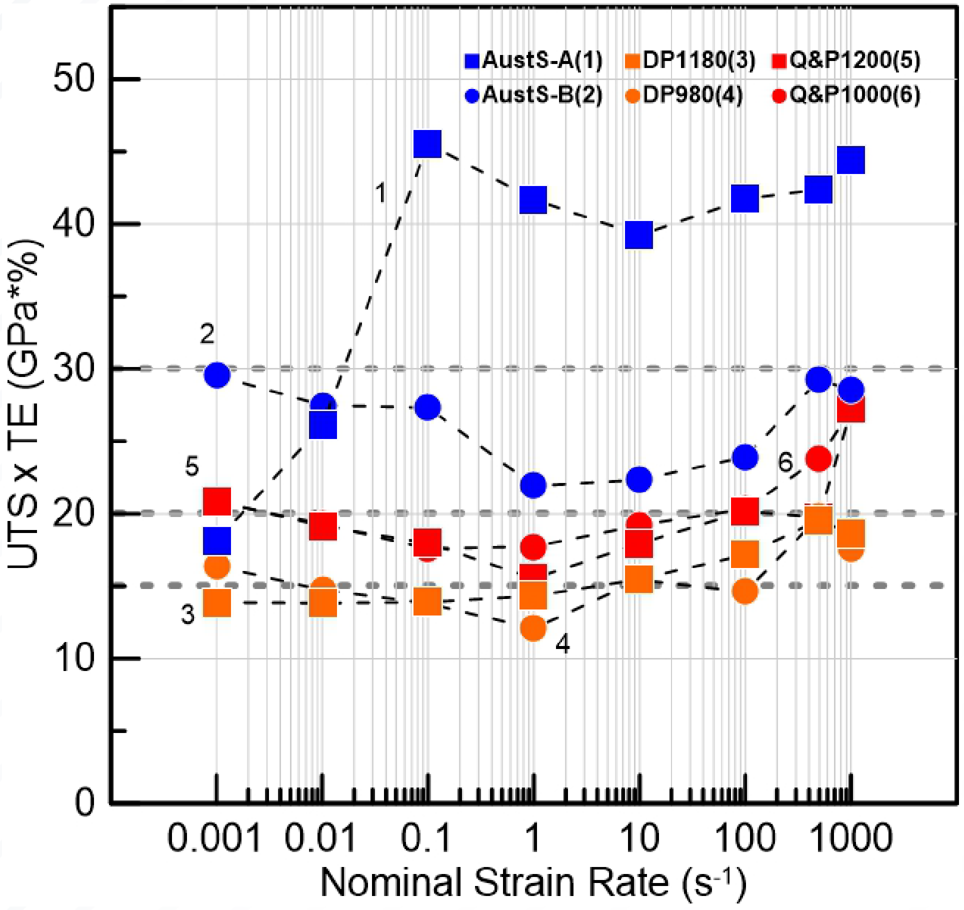
RATE EFFECTS: TEST SETUP

- For tensile tests at nominal strain rates 1 – 1000 s^{-1}



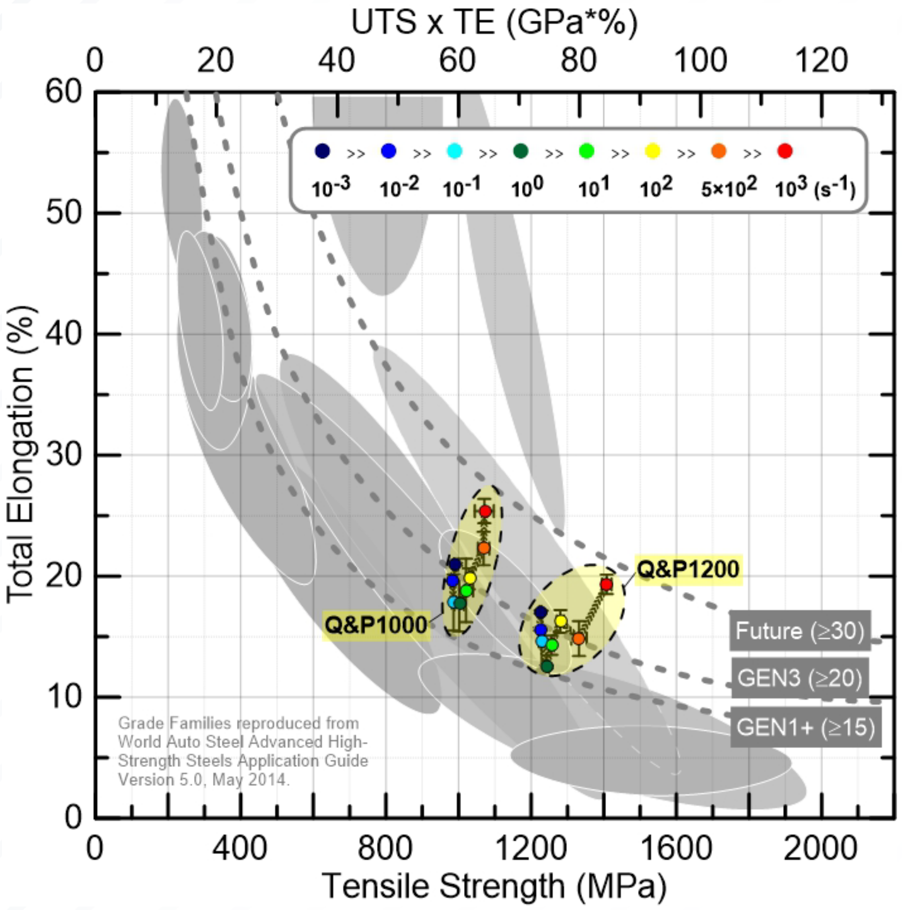


RATE EFFECTS: RESULTS OVERVIEW



- Adiabatic heating at elevated strain rates particularly affects the grades with austenite
- Both Q&P grades exhibit a similar UTS x TE valley at 1 s^{-1}
- Both DP grades exhibit comparatively more stable tensile properties
- The 2 AustS grades exhibit completely discrepant rate dependency due to the different austenite stability

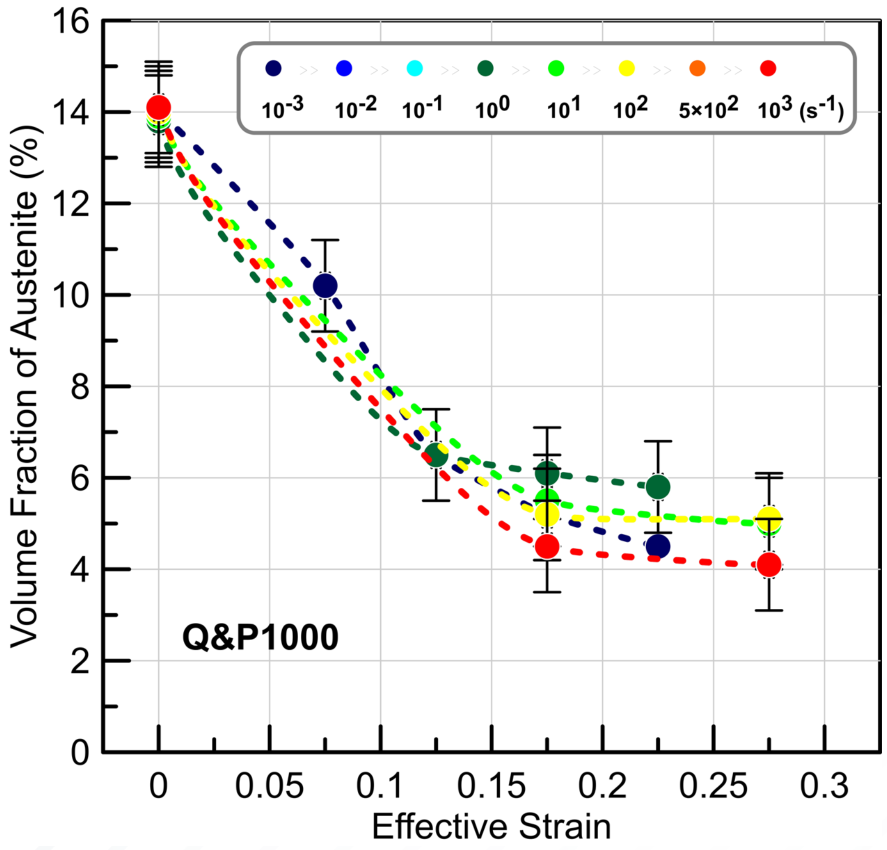
RATE EFFECTS: TARGET GROUP

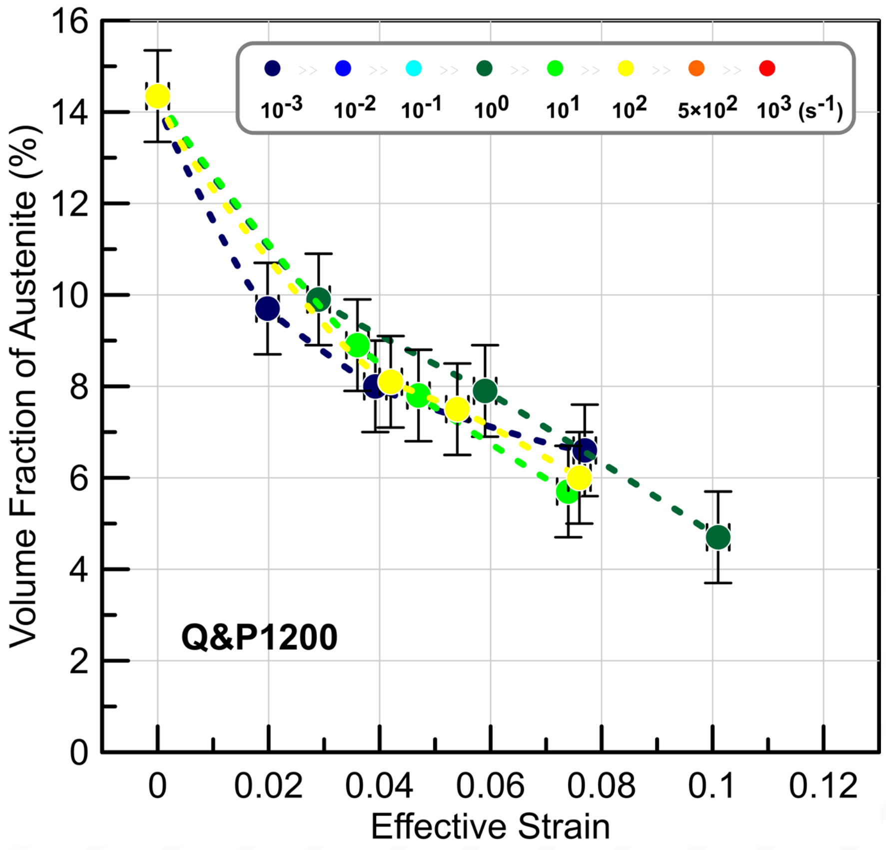


- Both Q&P grades exhibit very similar rate-dependency
- With the strain rate increasing, the adiabatic heat has less time to dissipate, which elevates the temperature more rapidly: +-TE, +-UTS, while the dislocations have less time to pass through obstacles: -TE
- Above 1 s^{-1}, in the ‘dynamic-low’ range, additional forces are needed to overcome the inertial forces in the material: +UTS

RATE EFFECTS: TARGET GROUP

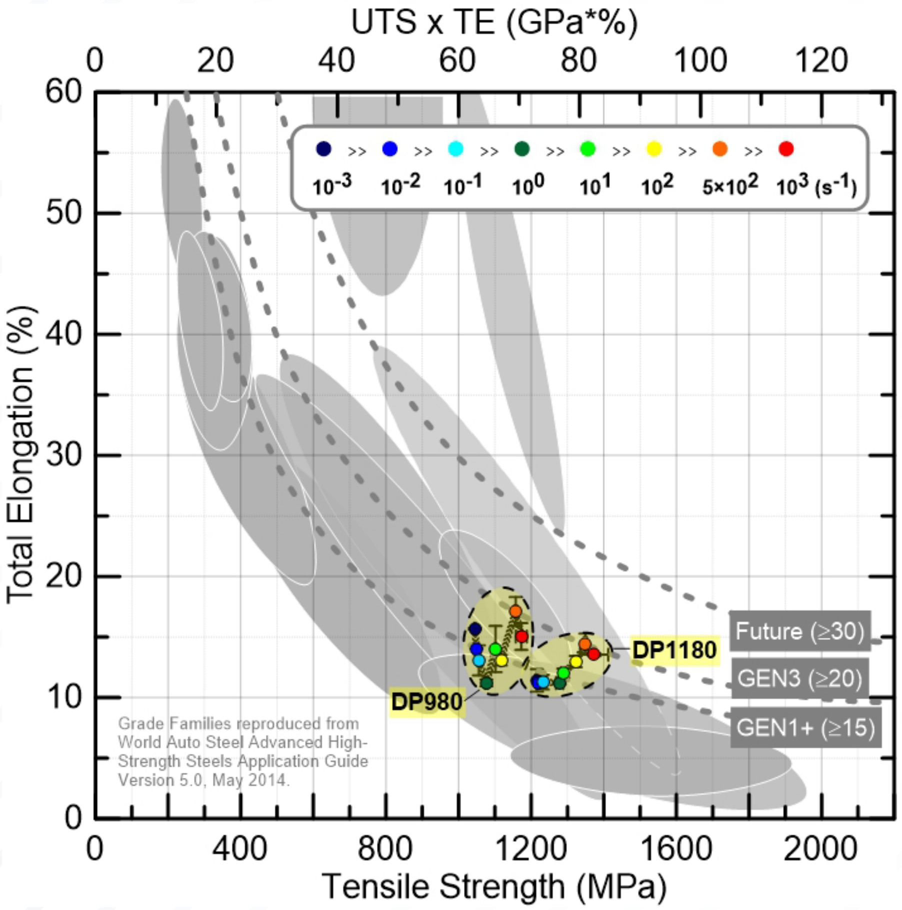
- The retained austenite in the Q&P grades has finished transformation before the adiabatic heat accumulates. Similar observation was reported by Choi *et al.* (2006).

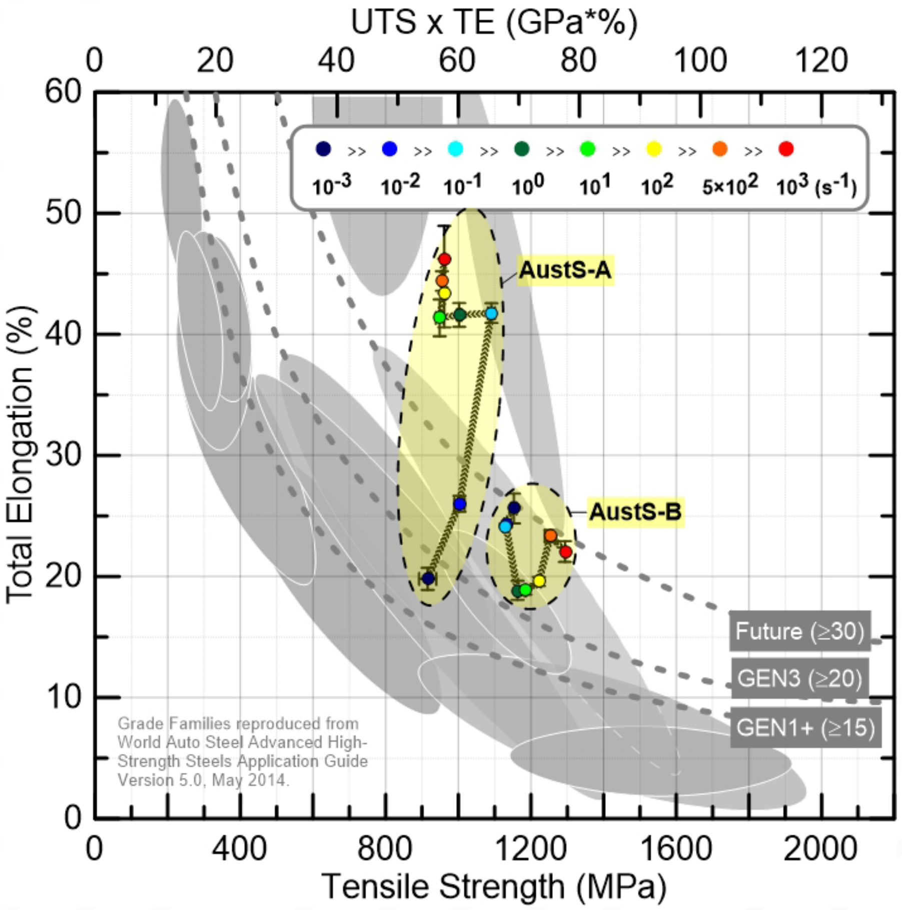




RATE EFFECTS: COMPARISON GROUP

- DP grades: similar yet less accentuated effects as the Q&P grades
- The martensitic transformation in AustS-A is more exothermic than that in AustS-B





CONCLUSIONS

- The critical role of the Steel Strength-Ductility Diagram in categorizing and developing the new AHSS grades is acknowledged.
- The laboratory test results are limited in representing the evolving tensile properties of the new AHSS grades, especially those with austenite in their microstructures, under the practical thermal and strain-rate conditions.
- Focusing on the two Q&P steels and comparing with the selected DP and austenitic steels, this work illustrated in the Steel Strength-Ductility Diagram how diverse the temperature and strain-rate dependencies of different AHSS grades can be.
- Multiple material effects were highlighted, although some of them, such as the martensitic transformation reactivation, have not been yet fully understood.

FOR MORE INFORMATION

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ADVANCED HIGH-STRENGTH STEELS

Evolving the "Banana Chart": Temperature and Strain Rate Effects on Tensile Properties of New-Generation Advanced High-Strength Steels