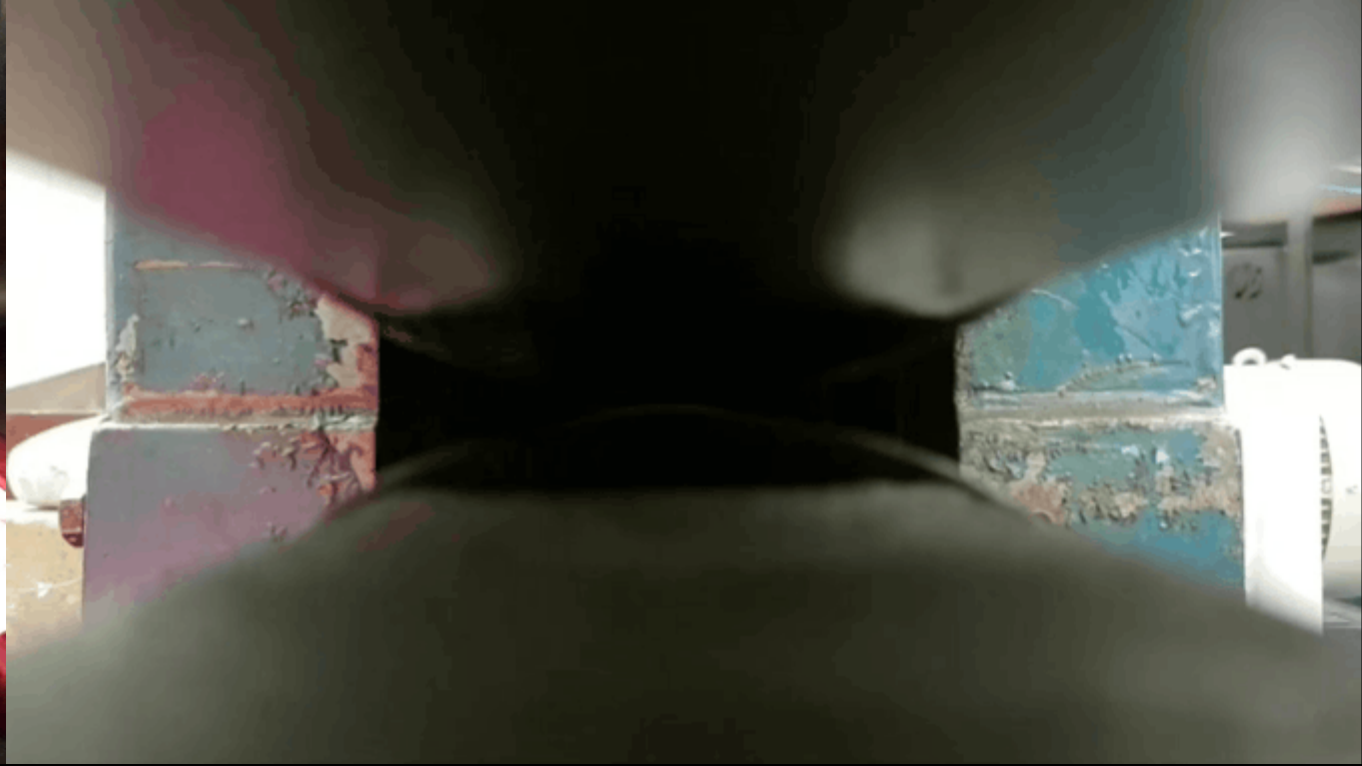
Imperial College
London



How low can you go?
The medium manganese limbo

Thomas Kwok, Xin Xu, David Dye

Collaborators:
Gong Peng (University of Sheffield)
Carl Slater, Claire Davis (Warwick Manufacturing group)

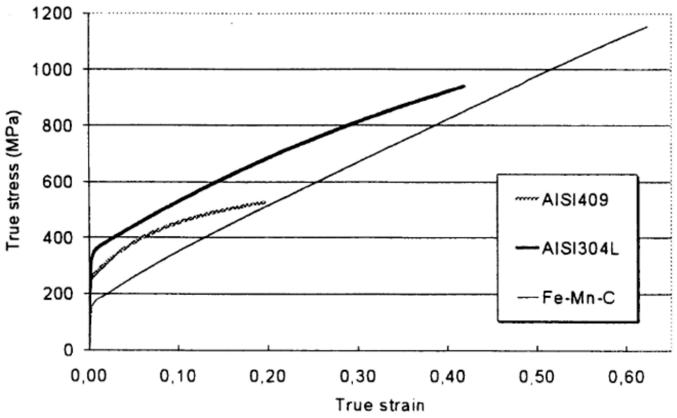
SINGAPORE

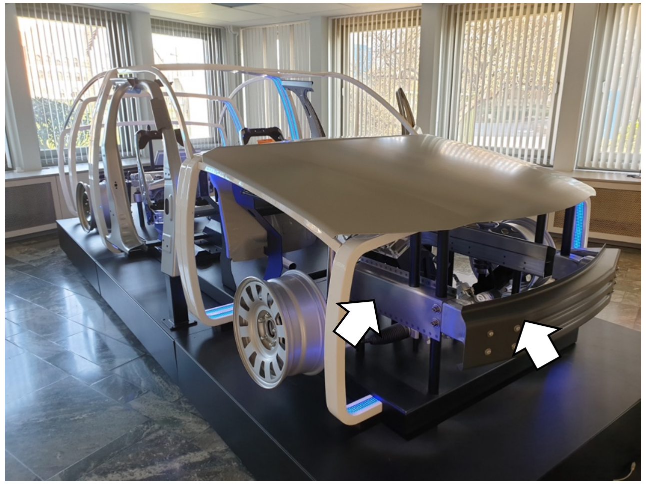
High Manganese steels

When added in large amounts (>15 wt%) together with >0.4 wt% C, Twinning Induced Plasticity (TWIP) effect is active in the γ phase.

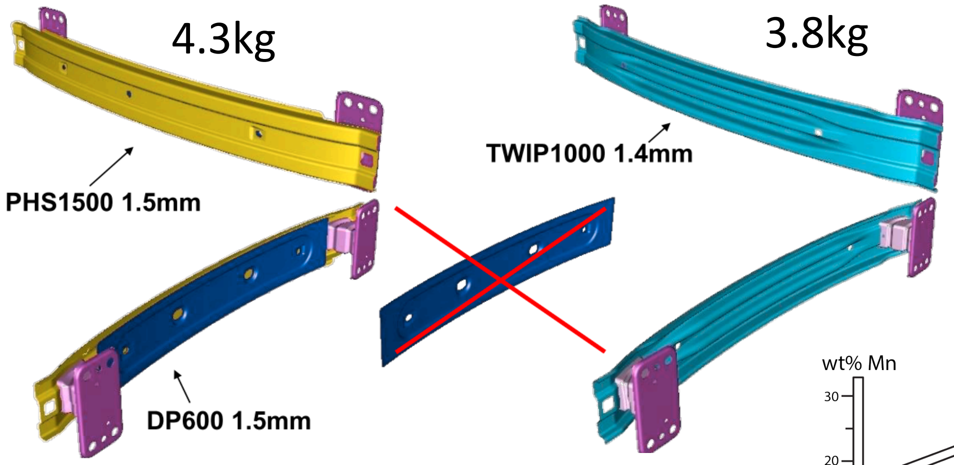
High ductility (>50%) and strain hardening rate (~3 GPa) very attractive for energy absorbing applications.

Stronger steel also offers greater lightweighting opportunities through down-gauging.

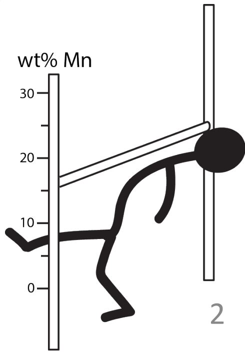




Blast tested TWIP steel



Fiat Panda front crash beam



Rahman, K. M., Vorontsov, V. A. and Dye, D. (2014) 'The dynamic behaviour of a twinning induced plasticity steel', *Materials Science and Engineering A*. 252–261.
Bouaziz, O. & Guelton, N. Modelling of TWIP effect on work-hardening. Mater. Sci. Eng. A ***319–321****, 246–249 (2001).*
D'Aiuto, F. (2016) Innovative materials and solutions for automotive components. Available at: http://s6prod.s3.amazonaws.com/DAiuto.pdf.

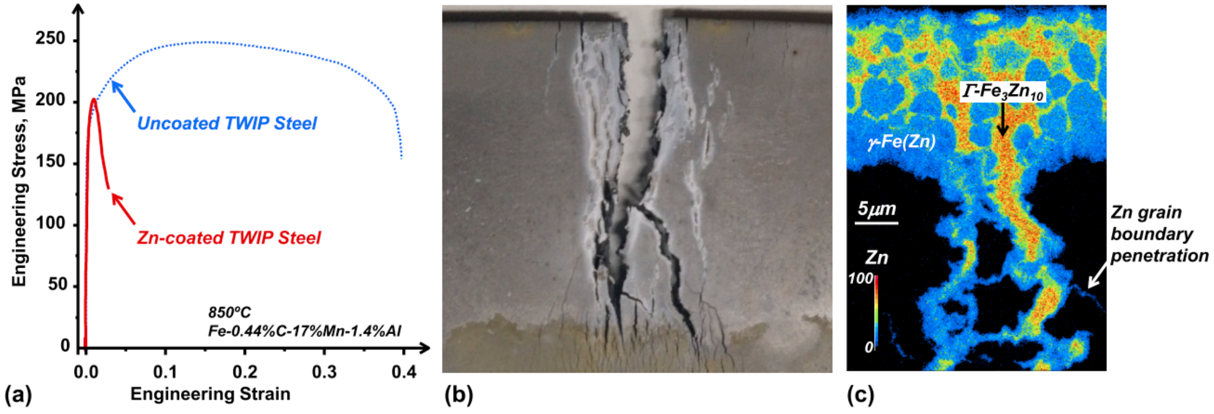
High Manganese steels – Problems

- Susceptible to H-cracking
- Liquid metal embrittlement during galvanizing
- Mn microsegregation in ingots
- Edge cracking during hot rolling
- Difficulty in adding >15wt% of alloying elements during secondary steel melting
- **COST**

posco

thyssenkrupp

Scientific question: How much Mn can you take out before losing TWIP-like properties?

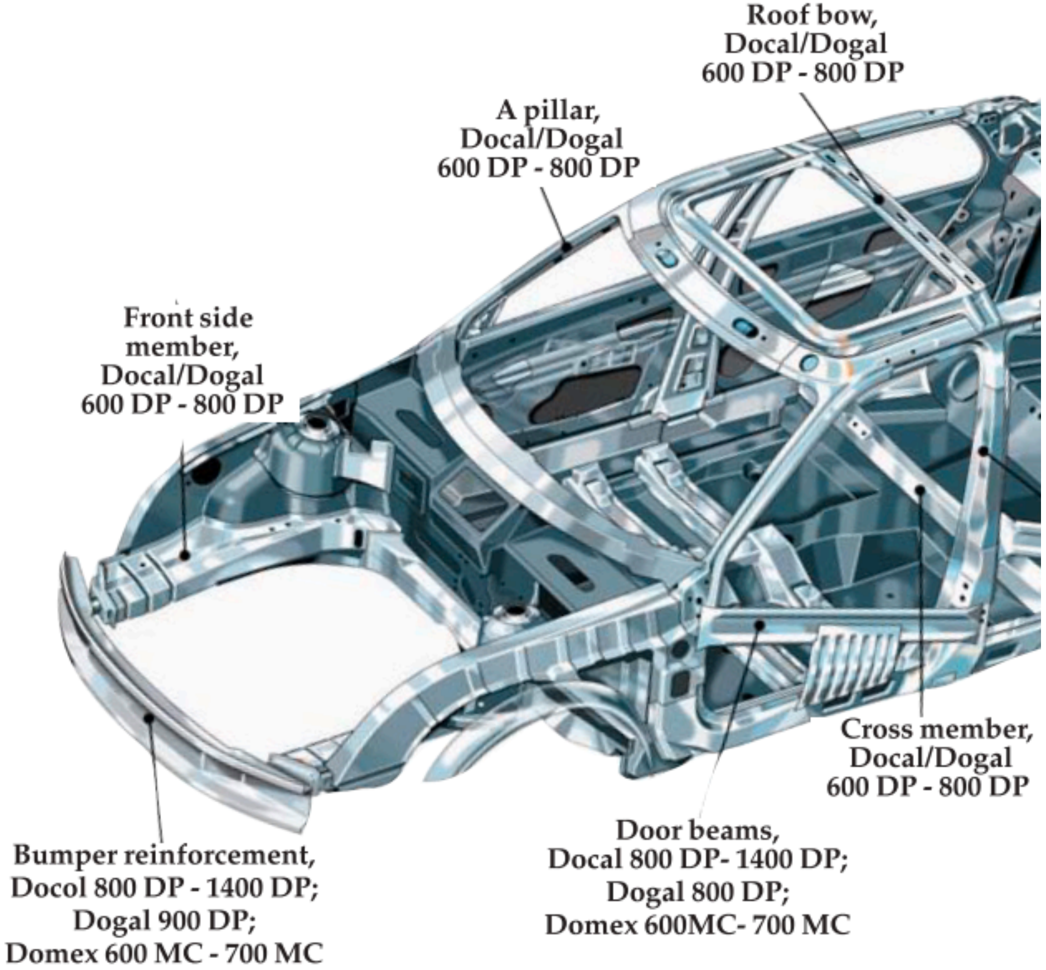


B. C., Estrin, Y. & Kim, S. K. Twinning-induced plasticity (TWIP) steels. Acta Mater. **142**, 283–362 (2018).
Bausch, M. et al. Ultra high-strength and ductile FeMnAlC light-weight steels. (2013).

Medium Mn steels

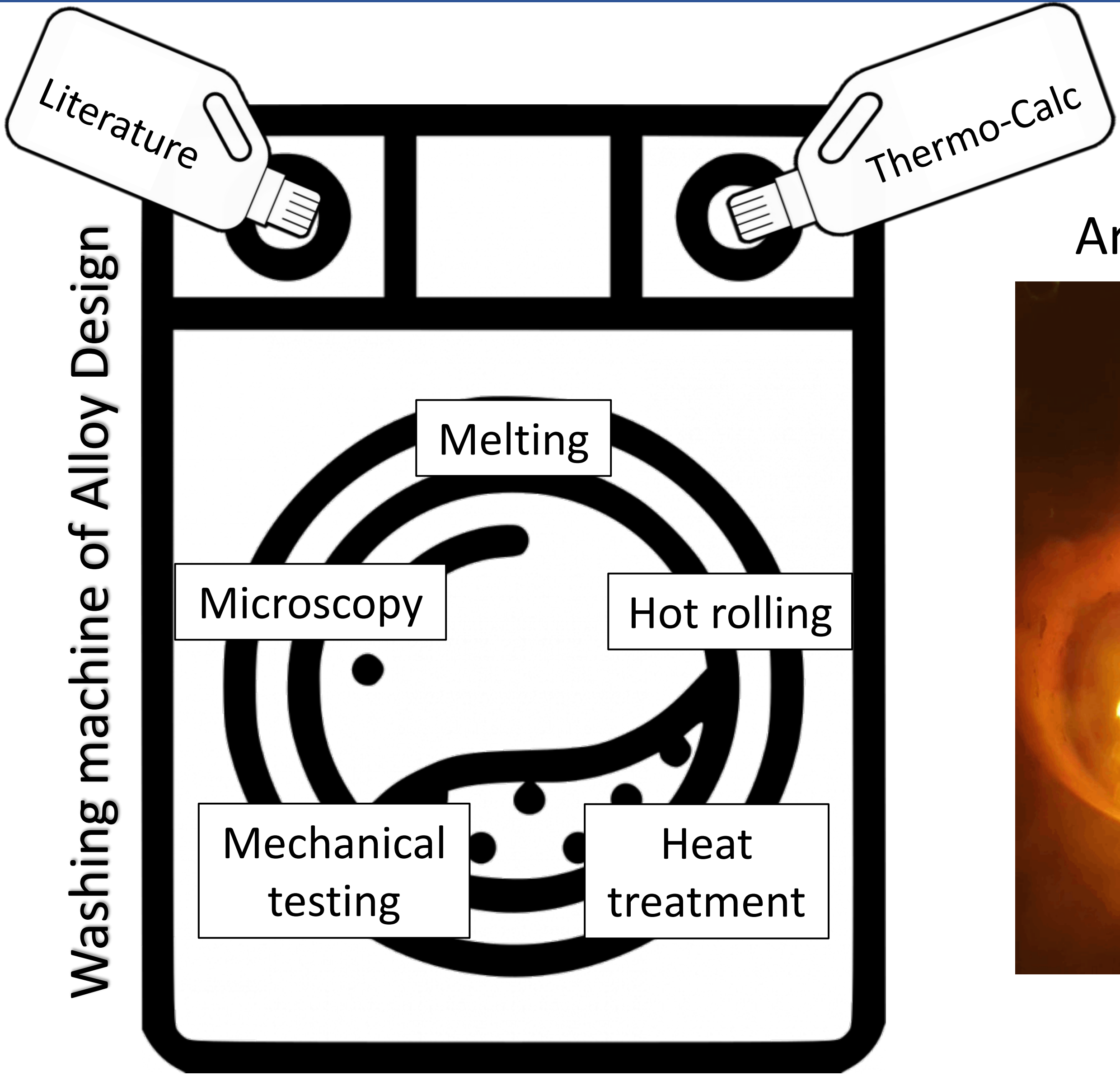
Design requirements

- Significantly reduced Mn content (≤ 12 wt% Mn)
- Strong (≥ 1 GPa YS) and ductile (~ 30% ductility)
- Conventional steel processing methods
- Similar cost level to current steels (DP800)



Olsson, K. et al. (2006) 'Microalloyed high-strength', Advanced Materials and Processes, (8), pp. 44–46.

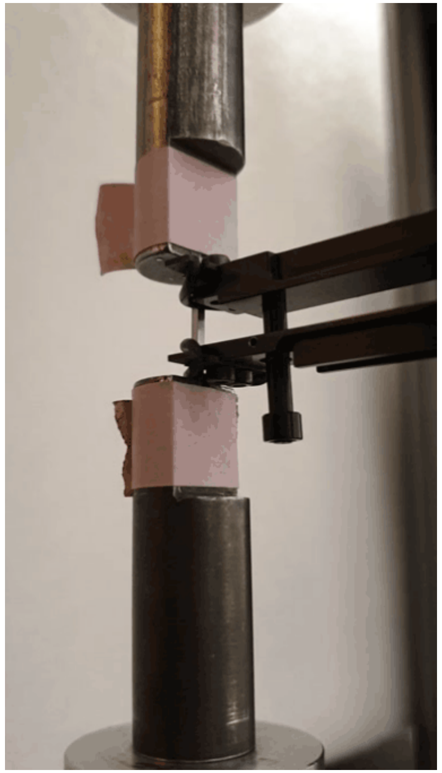
Medium Mn steel – Alloy design



Arc melting

Hot rolling

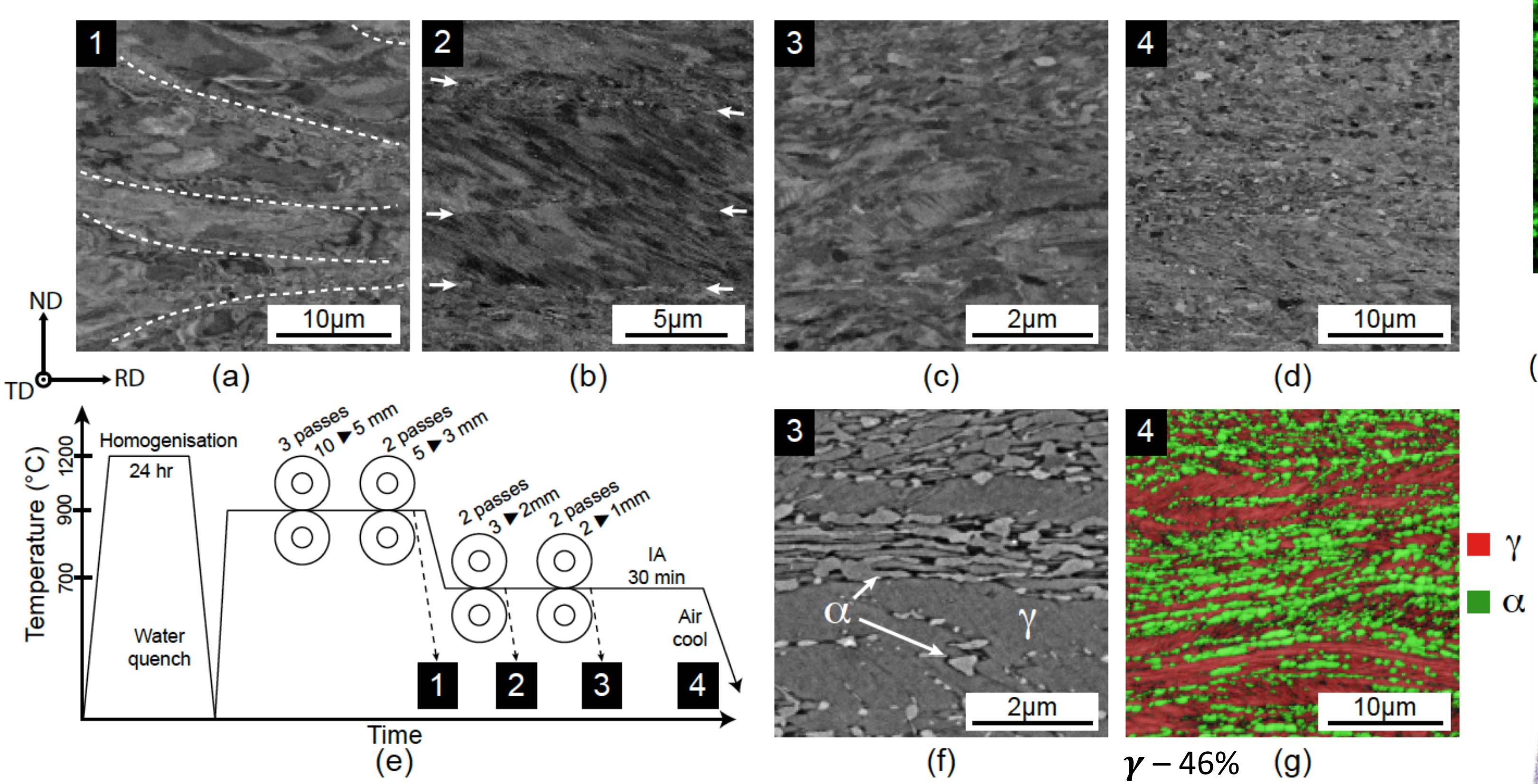
Tensile test



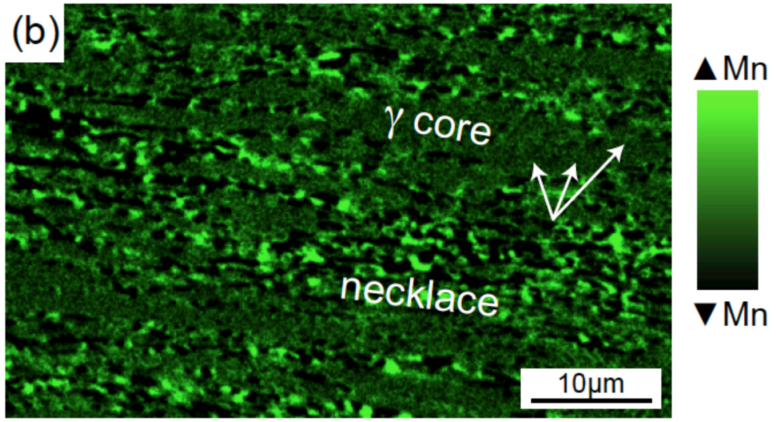
DP-TWIP – 12 wt% Mn

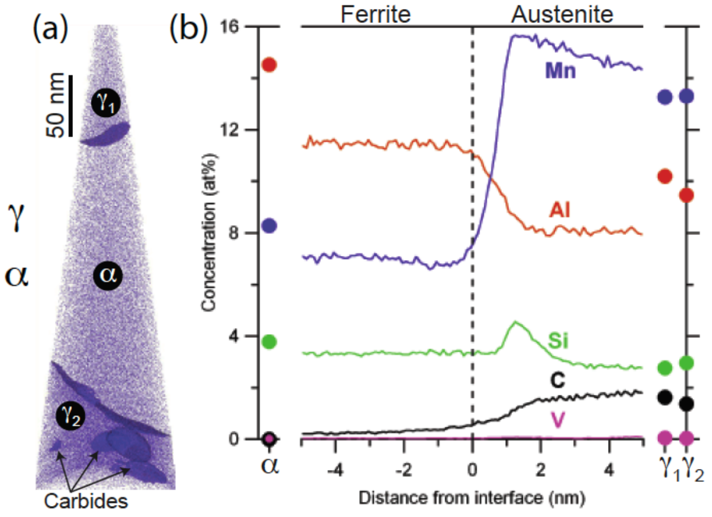
Kwok, T. W. J. *et al.* (2020) 'Design of a High Strength, High Ductility 12 wt% Mn Medium Manganese Steel With Hierarchical Deformation Behaviour', *Materials Science & Engineering A*, (782).

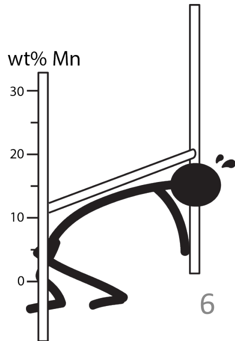
Fe - 12Mn - 4.8Al - 2.0Si - 0.3C - 0.3V



γ – 46%
α – 38%
NI – 16%







DP-TWIP – 12 wt% Mn

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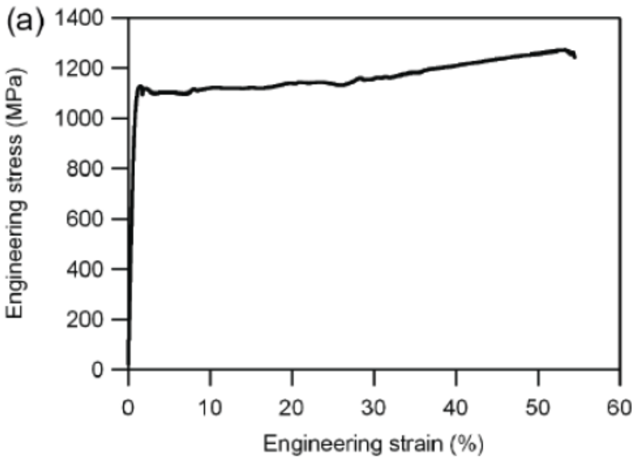
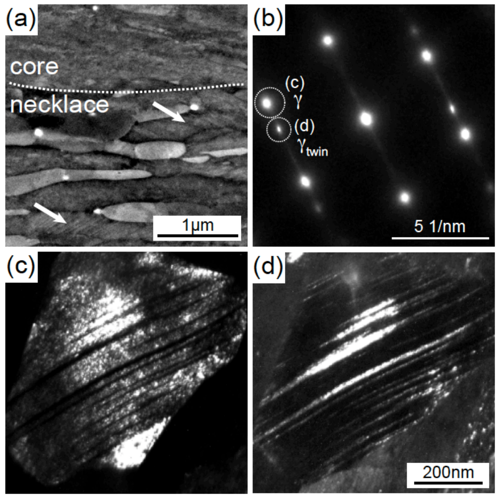
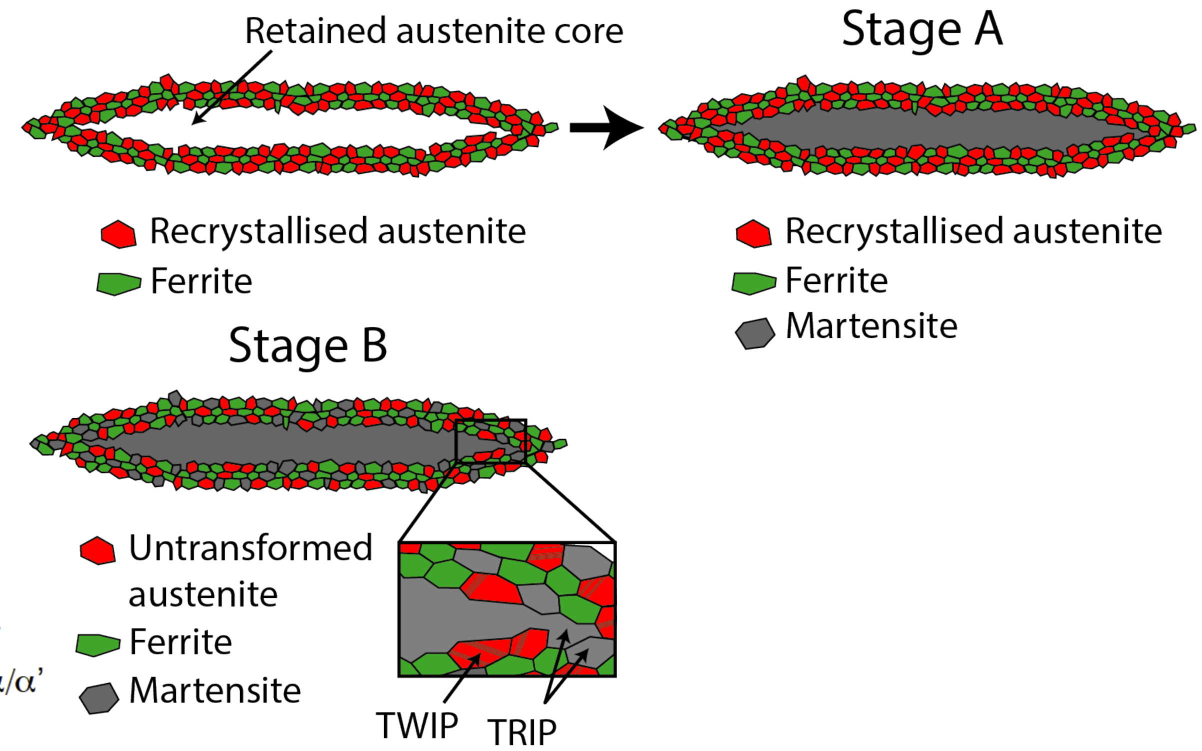
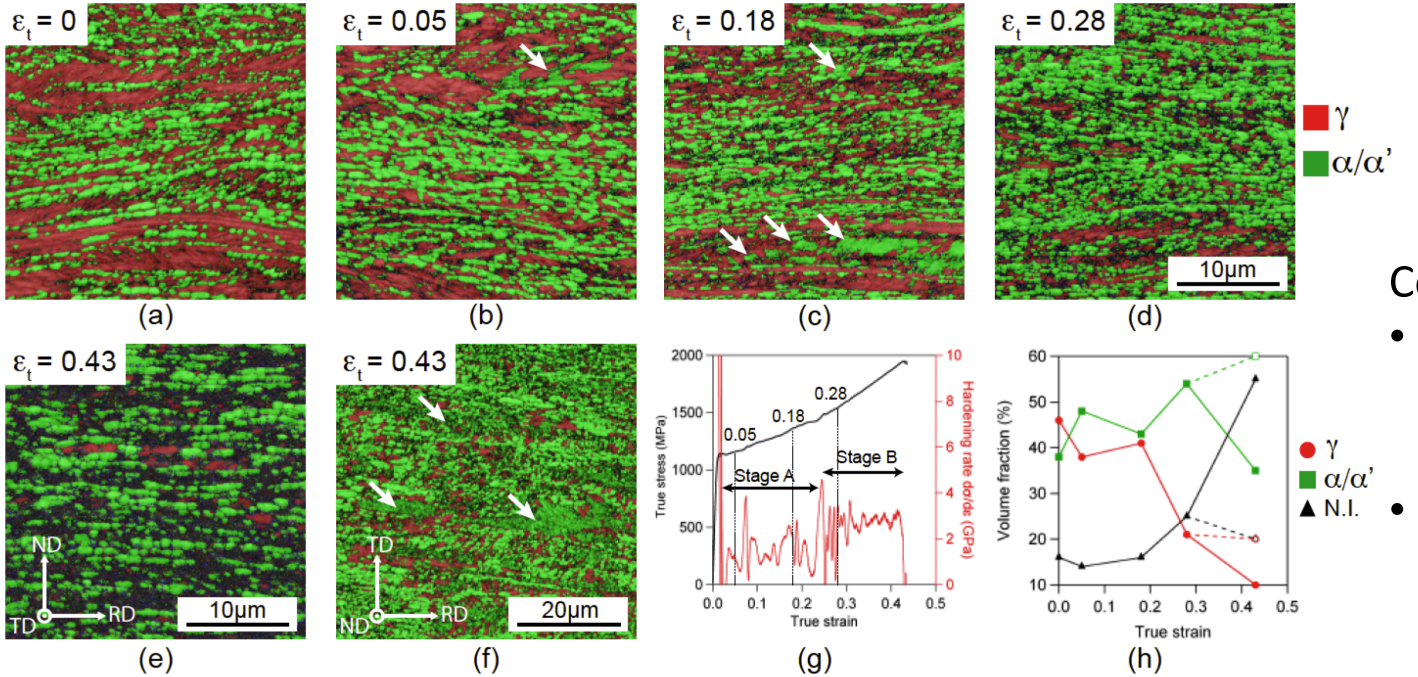


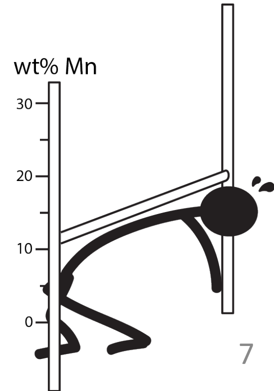






Conclusions

- Evolution of microstructure affects partitioning of Mn and therefore SFE/stability.
- Sequential activation of different deformation mechanisms (TWIP/TRIP) can lead to large elongations.

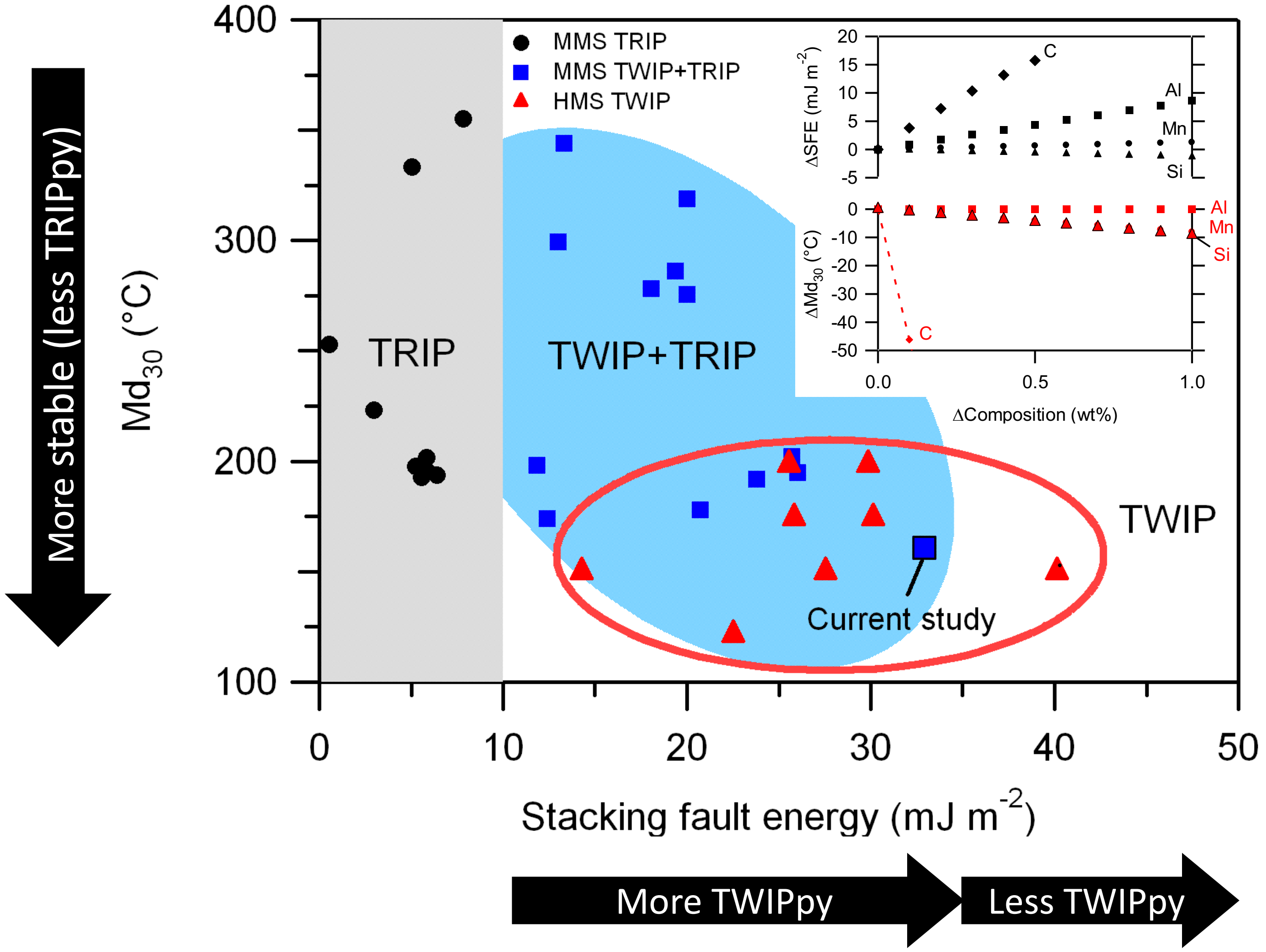


TWIP+TRIP in a single grain

Paper in preparation with University of Sheffield

TWIPpiness: Stacking Fault Energy (mJ m^{-2})

TRIPpiness: Stability against transformation, Md_{30} (˚C)

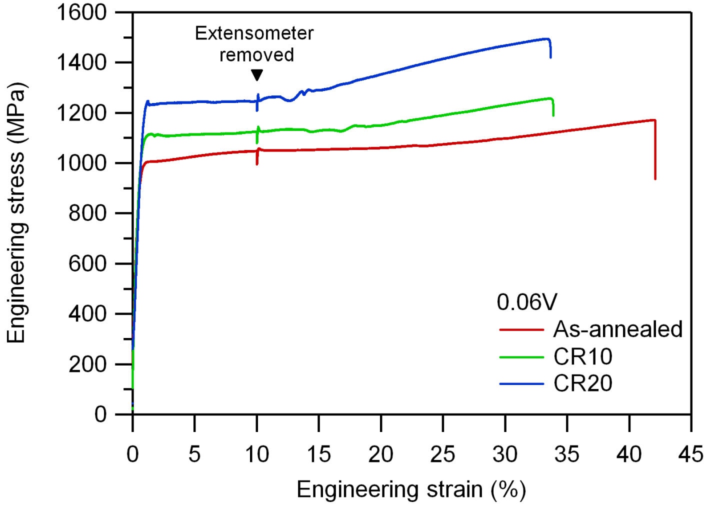


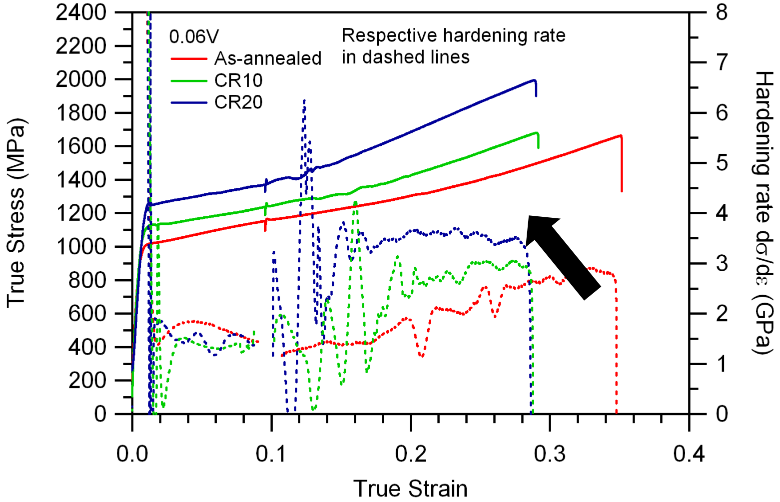
Comparison of SFE and Md_{30} of the austenite phase in several Medium Mn steels (MMS) and High Mn TWIP steels (HMS) in the literature. Inset: Changes in SFE and Md30 with different additions to austenite with an initial composition of Fe-6.55Mn-1.33Al-1.19Si-0.48C

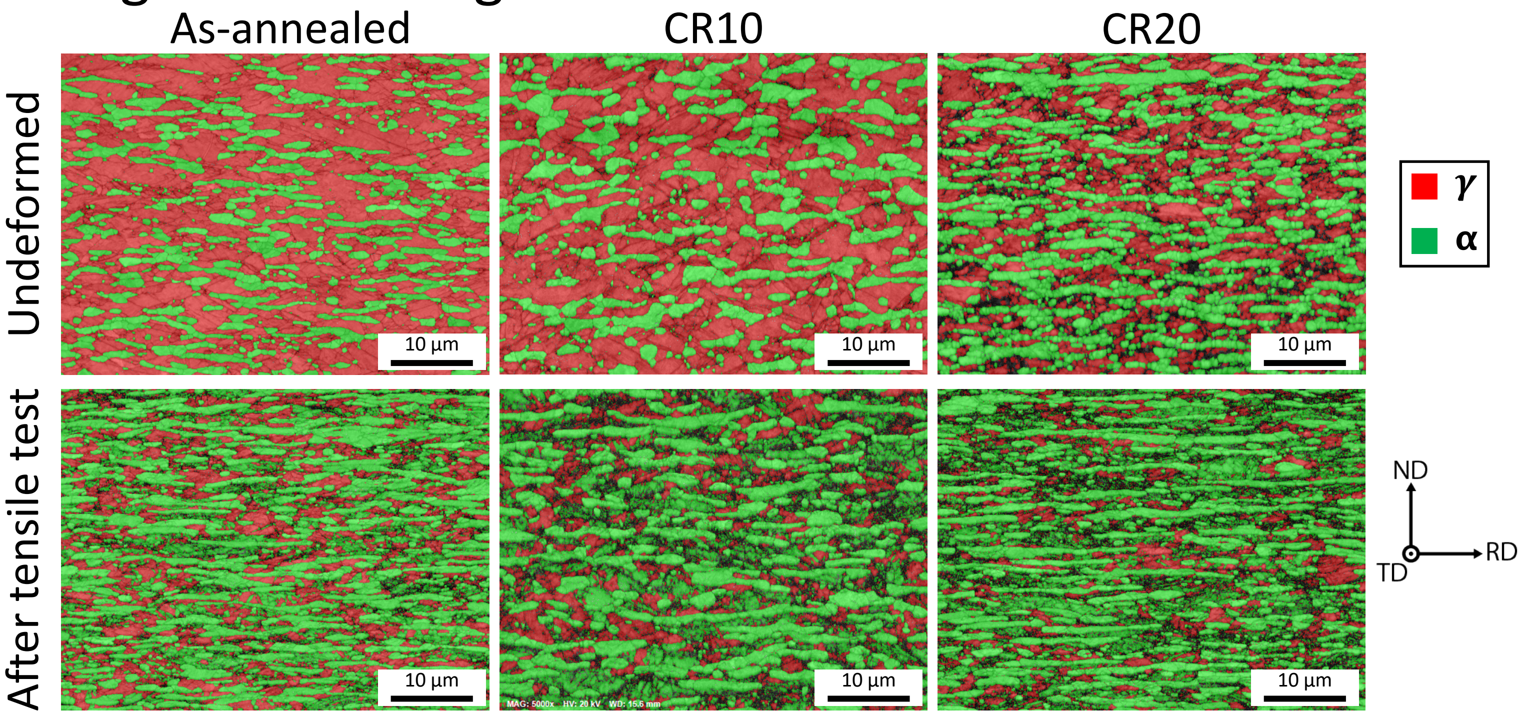
Novalloy – 8 wt% Mn

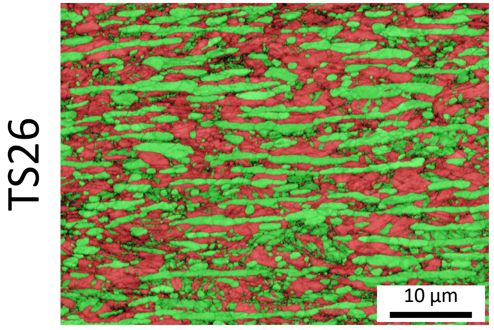
Paper in preparation with University of Sheffield

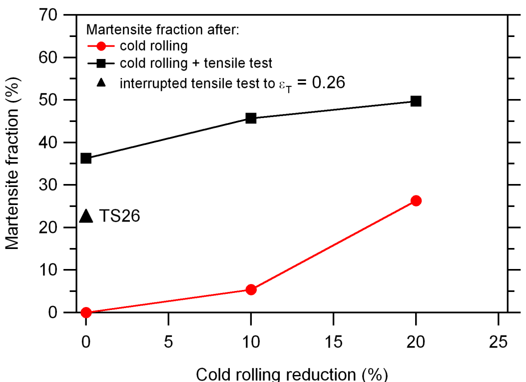
Hot rolling – Intercritical annealing – Cold rolling

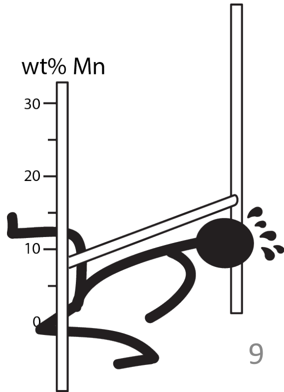








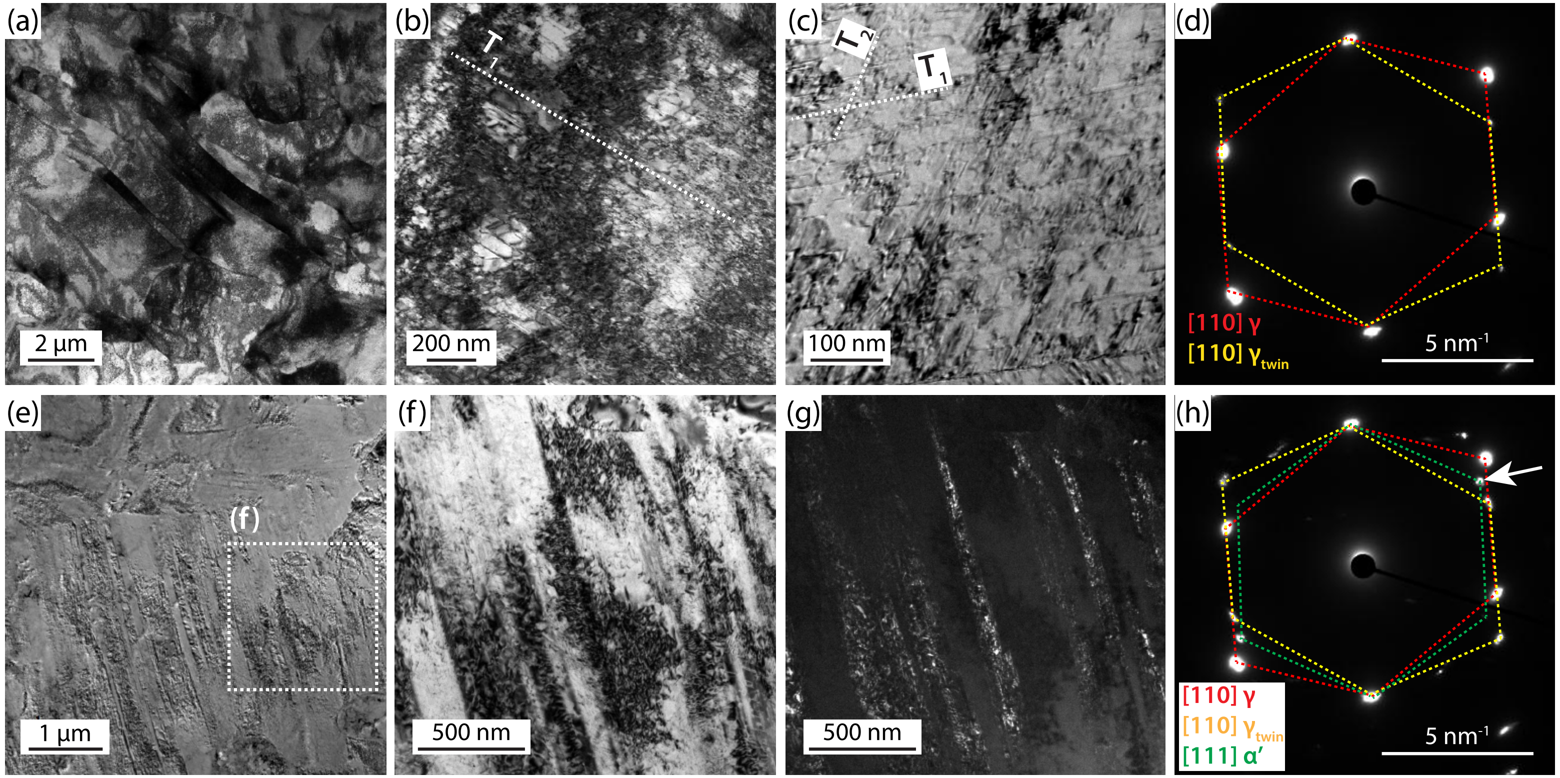




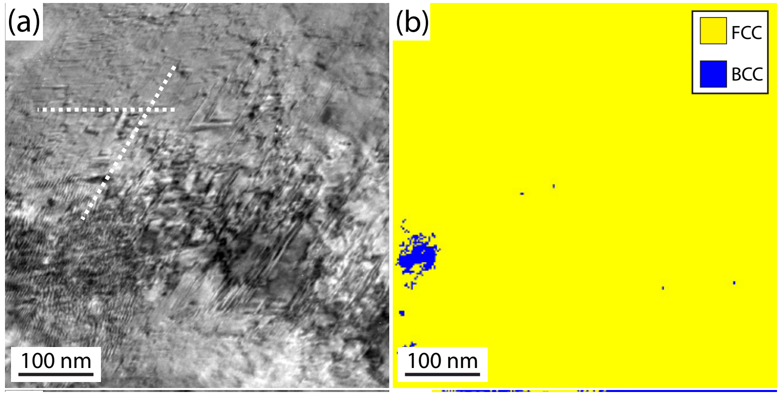
Novalloy – 8 wt% Mn

Paper in preparation with University of Sheffield

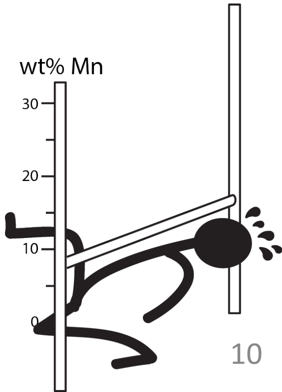
CR20 sample – before tensile testing



Deformation structures in CR20 sample with beam direction parallel to [110]**γ**. (a) STEM-BF micrograph of the general microstructure. (b) STEM-BF micrograph showing one active twinning system and surrounding high dislocation density. (c) STEM-BF micrograph of a region with two active twinning systems. (d) Diraction pattern obtained from region in (b). (e) TEM-BF micrograph of an austenite grain showing long lath-structures. (f) Magnified TEM-BF micrograph from (e). (g) TEM-Dark Field (DF) obtained from martensite spot indicated by white arrow in (h). (h) Diraction pattern obtained from (f).



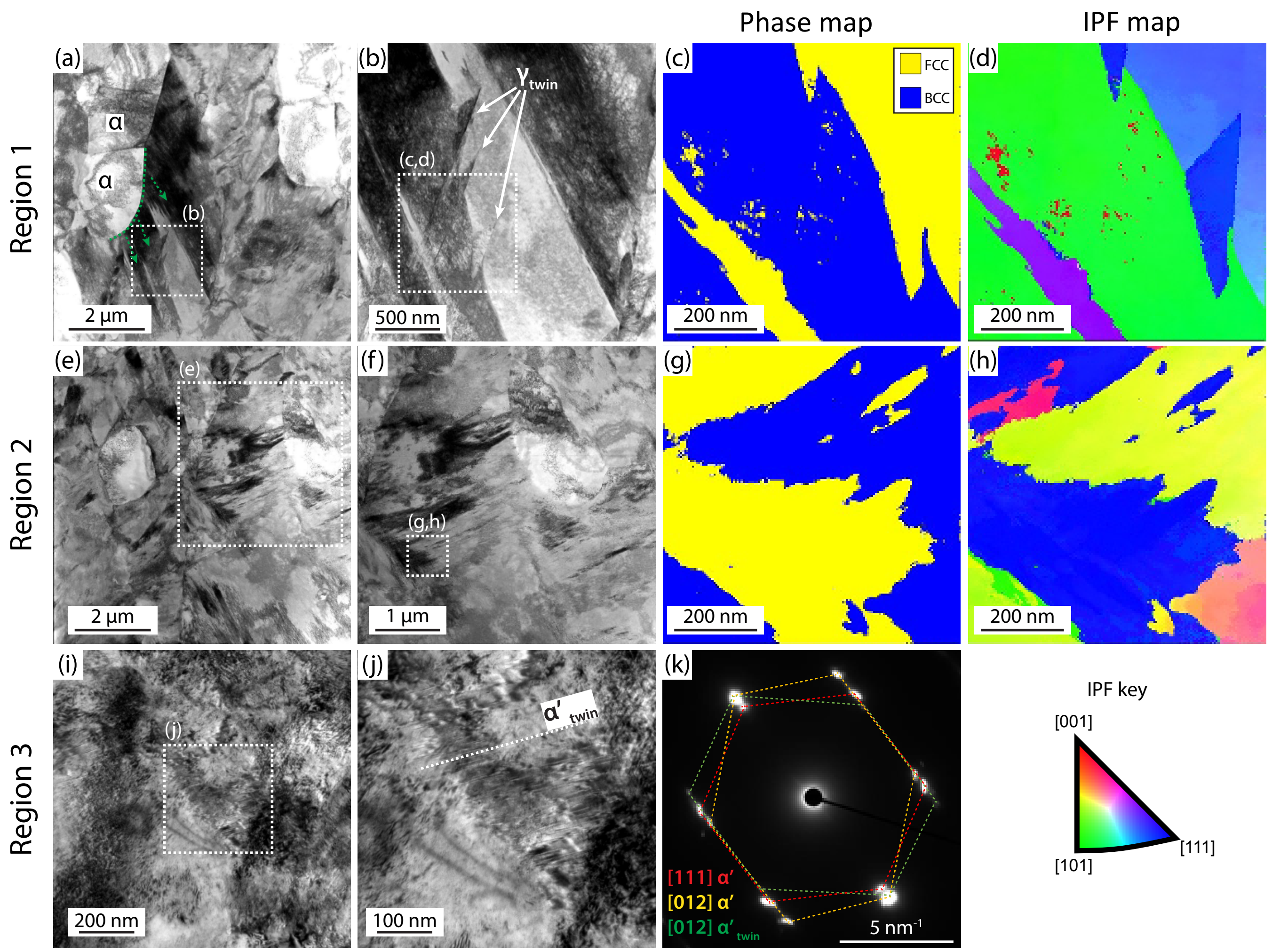
Strain-induced martensite in CR20 sample (a) TEM-BF of two twinning systems and (b) corresponding NanoMegas phase map. Beam direction parallel to [110]**γ**.



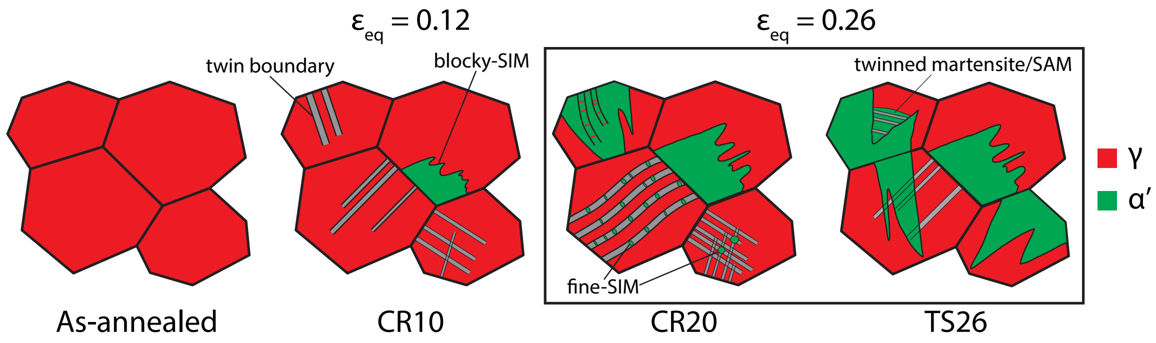
Novalloy – 8 wt% Mn

Paper in preparation with University of Sheffield

TS26 sample – same equivalent strain as CR20



Deformation structures in TS26 sample. From region 1, (a) general microstructure (STEM-BF), (b) magnified view showing martensite and austenite twins (STEM-BF), NanoMegas (c) phase map and (d) IPF from red square in (b). From region 2, (e) general microstructure (STEM-BF), (b) magnified view of austenite and martensite regions (STEM-BF), NanoMegas (g) phase map and (h) IPF from red square in (f). From region 3, TEM-BF micrograph of (i) entirely martensitic region, (j) magnified view showing martensitic twins and (k) diffraction pattern from (j).

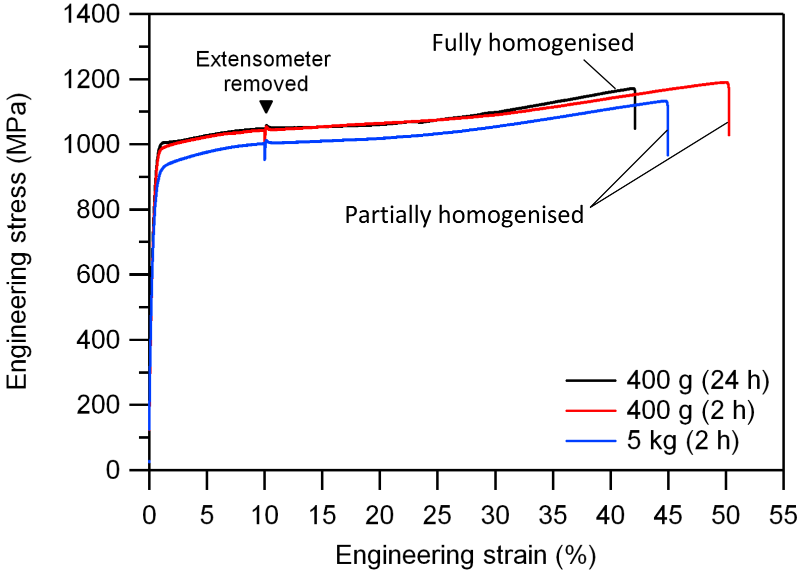


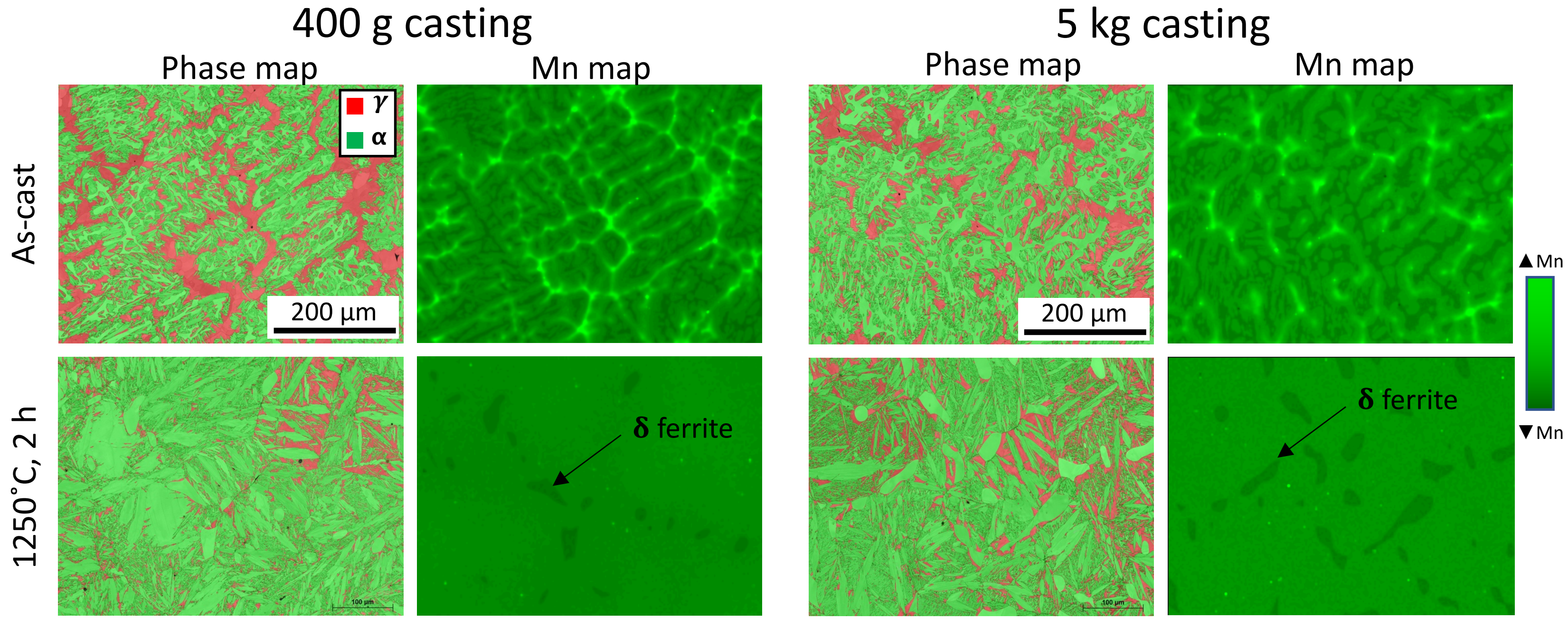
Conclusions

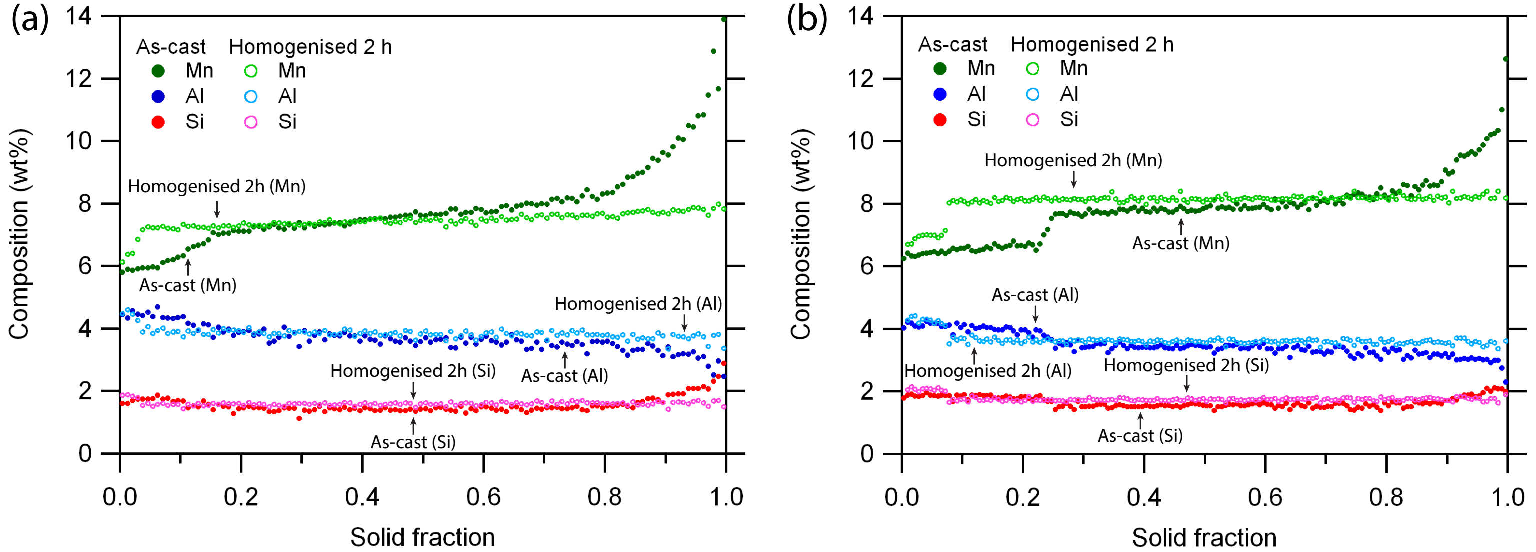
- Microstructure evolution is strain path dependent
- Defects introduced by cold rolling promotes the formation of fine-SIM which leads to an increased strain hardening rate (enhanced TRIP effect) during subsequent tensile tests.

Novalloy – scale up

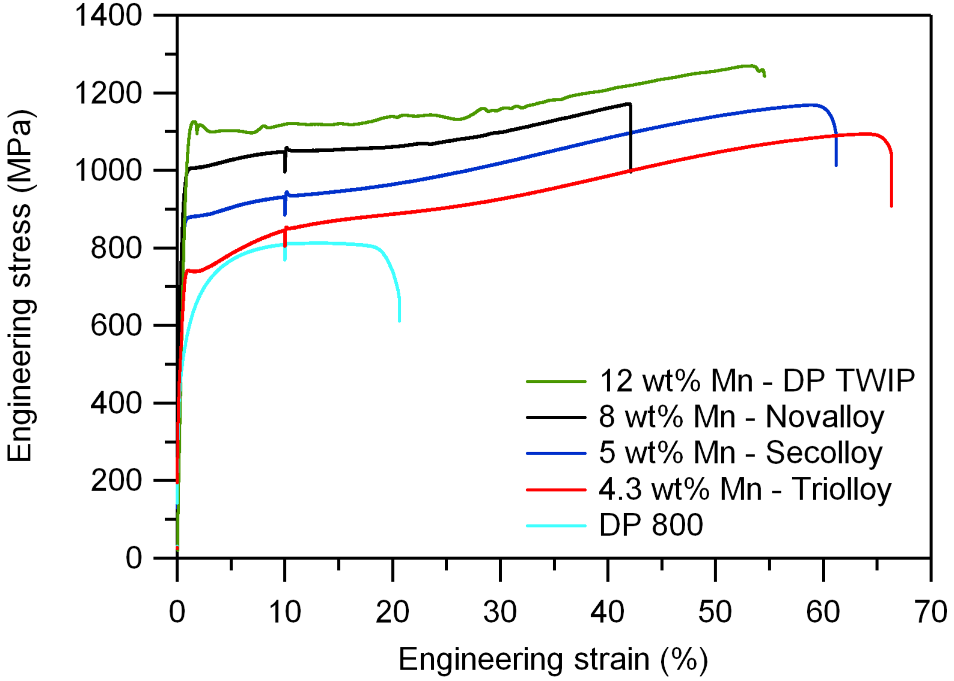
Paper in preparation with WMG

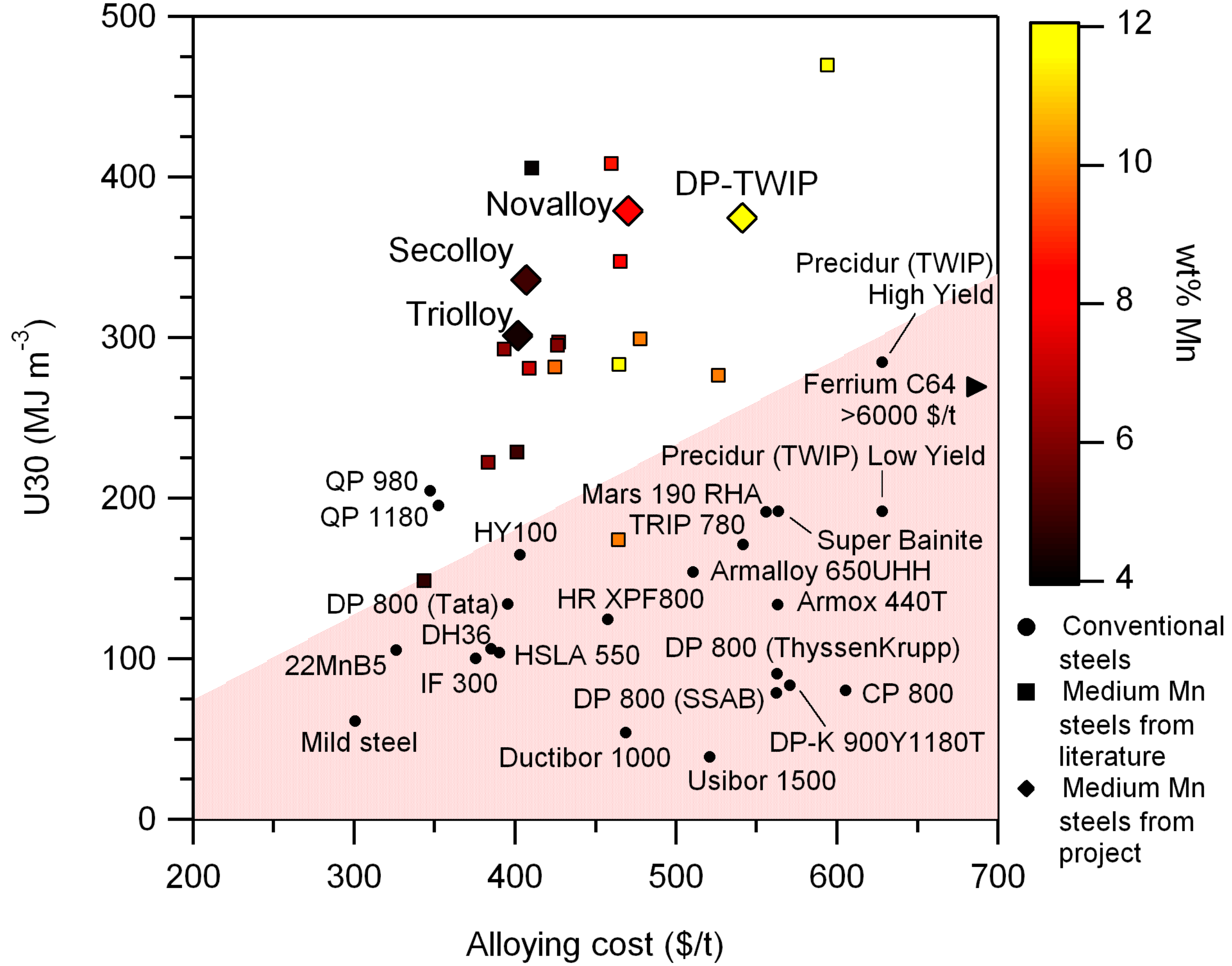






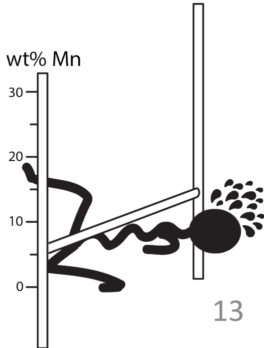
Future work + industrial benchmarking





Energy absorption parameter U30:

$$U30 = \frac{\sigma_y + \sigma_{UTS}}{2}\,\varepsilon_{0.3}$$



Acknowledgements

Dye Group (CAA 2018)

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Dr Carl Slater
Prof Claire Davis

Sheffield University
Dr Gong Peng

Conclusions

- The TWIP+TRIP effect in medium Mn steels can be tailored and engineered.
- Composition, microstructure and strain path significantly influence the deformation behaviour in medium Mn steels.
- Medium Mn steel is a promising replacement to high Mn TWIP steels and a strong competitor to current steels in the market.