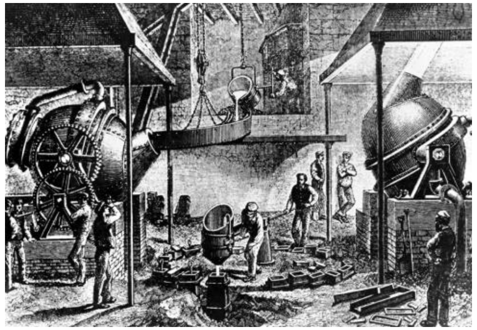
Innovative Approaches to Boost Steel Performance Under Extreme Conditions

Why steel ?

- One of the oldest materials used by humankind
- Excellent properties were achieved in steel already in middle ages (Damascus steel)
- Industrial manufacturing process has been continuously improved
  - 1856, Henry Bessemer developed effective and inexpensive method of producing steel
  - XX, Environmentally friendly Electric Arc Furnaces were developed



Why steel ?

Steel is a very versatile material

1. Excellent mechanical properties
2. Excellent wear, fatigue and fracture resistance
3. Excellent electrical and magnetic properties
4. Customizability (via alloy and process design, post-processing, etc.)
5. Availability and cost effectiveness
6. Durability
7. Endless recyclability
8. ….

Material of choice for applications at extreme conditions

Why steel ?

Material of choice for applications at extreme conditions

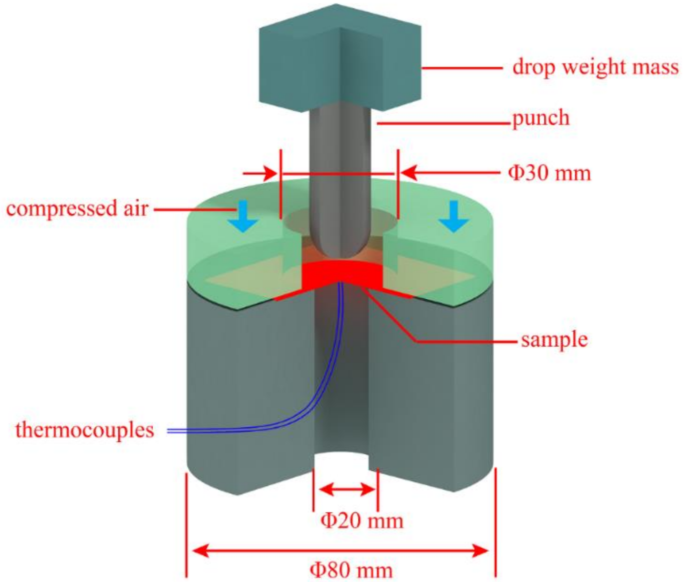
Extreme conditions

1. High impact loads
2. Extreme stress cycles
3. High or cryogenic temperatures
4. Temperature fluctuations (thermal fatigue)
5. Aggressive (corrosive) environments
6. Extreme abrasive environments
7. High pressure
8. Radiation exposure
9. ....




Impact resistance (energy absorption capability)

Impact testing



Strain rate： 1 - 10^2 s^{-1}
Impact energy: up to 700 J

Drop weight impact test system (INSTRON CEAST 9350)

Diameter of impactor: Φ 16 mm
Specimen size: 50*50*1 mm

High strain rate testing

Split Hopkinson Tensile Bar testing

Strain rate： 10^2 - 10^5 s^{-1}

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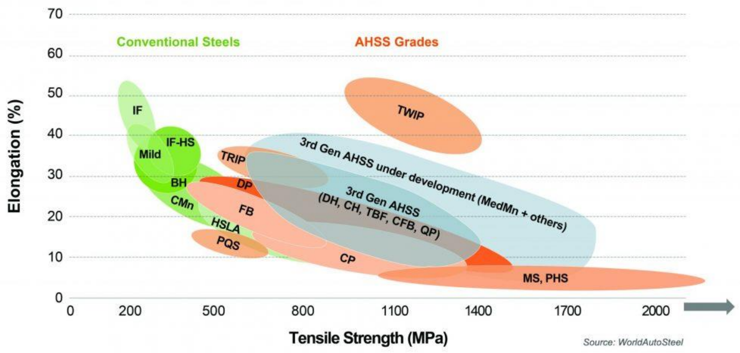
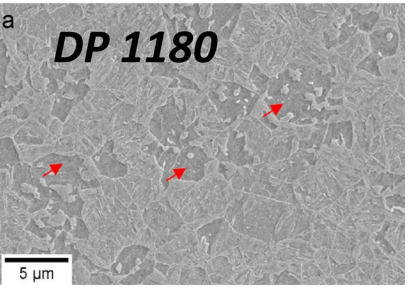
Impact resistance (energy absorption capability)

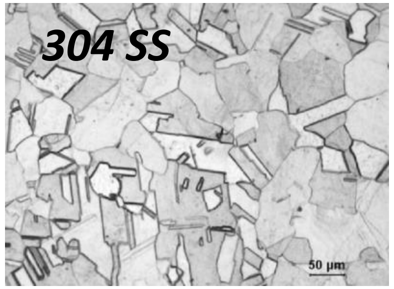
3 generations of advanced high strength steels (AHSS)

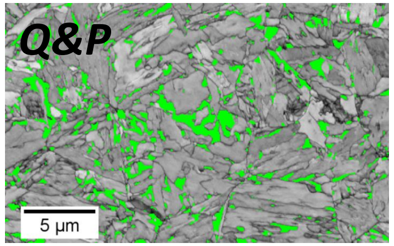


Chemical composition (wt.%) of the studied steels (1 mm thickness)

steel	generation of AHSS	C	Mn	Si	Al	Cr	Ni	Nb
Dual phase steel (DP 1180)	1st	0.12	2.48	0.28	0.035	0.59	-	0.023
304 stainless steel (304 SS)	2nd	0.08	2	1	-	18	9	-
Quenching and partitioning steel (Q&P)	3rd	0.25	3.0	1.5	0.023	0.015	-	-



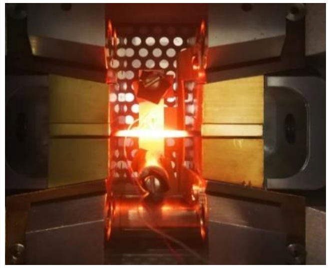


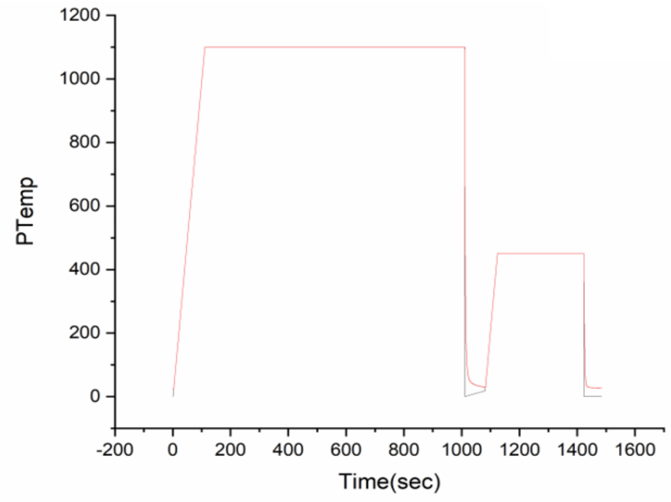


Microstructure and basic mechanical properties of the studied steels

steel	microstructure	yield strength (MPa)	tensile strength (MPa)	fracture elongation (%)
Dual phase steel (DP 1180)	Martensite (75%) + Ferrite (25%)	1062	1244	8.2
304 stainless steel (304 SS)	Austenite (100%)	342	818	97.7
Quenching and partitioning steel (Q&P)	Austenite (18%) + Martensite (82%)	1175	1305	26.4

Advanced heat treatments: Quenching and Partitioning process (carbon steels, stainless steels)

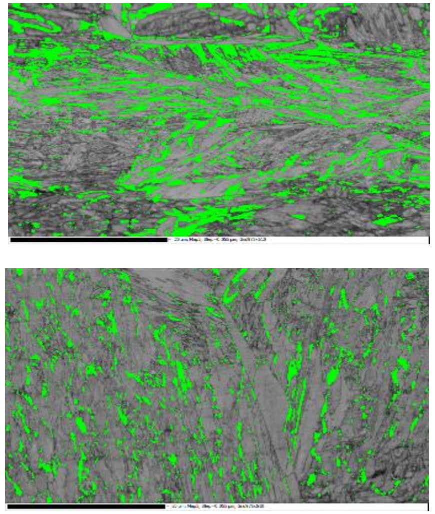


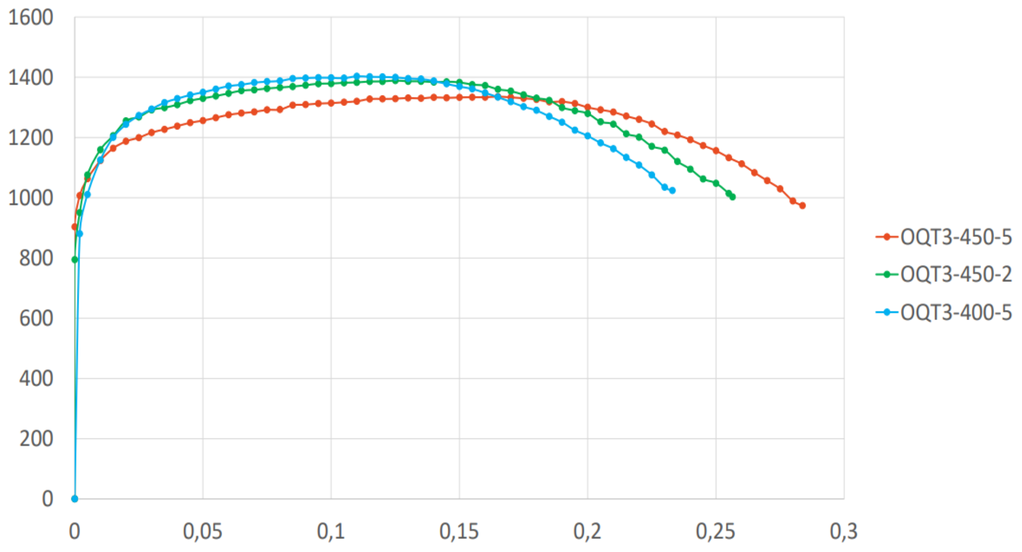


Left: A Q&P treatment in a GLEEBLE chamber;

Right: a typical Q&P thermal cycle. Varying Q&P parameters:

- **Quenching temperature**
- **Partitioning temperature**
- **Partitioning time**





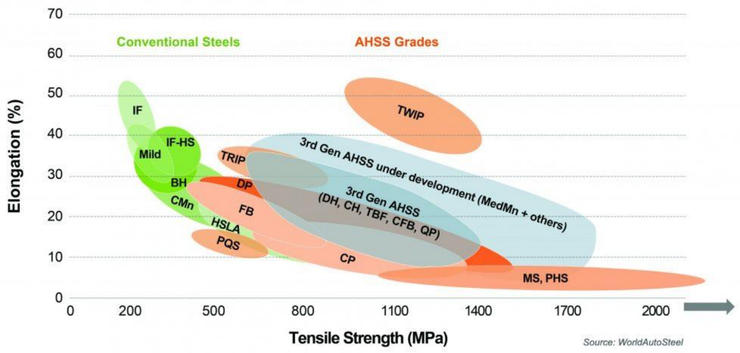
Left: the effect of chemistry on a microstructure of a Q&P treated stainless steel (retained austenite is in green, fresh martensite in dark gray, tempered martensite in gray);

Right: tensile stress – strain curves for the steel after different Q&P treatments.

A. Sierra-Soraluce, G. Li, M. Santofimia, J.M. Molina-Aldareguia, A. Smith, M. Muratori, I. Sabirov. *MSEA*, 2023.

Impact resistance (energy absorption capability)

3 generations of advanced high strength steels (AHSS)



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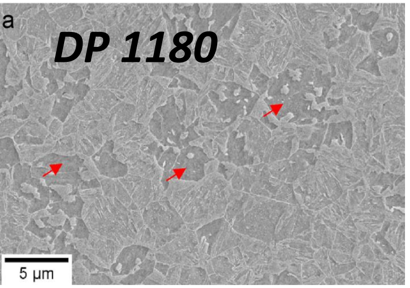

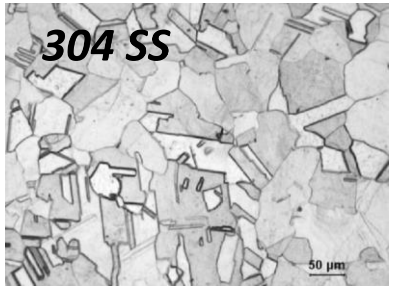

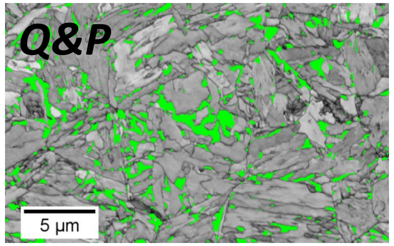

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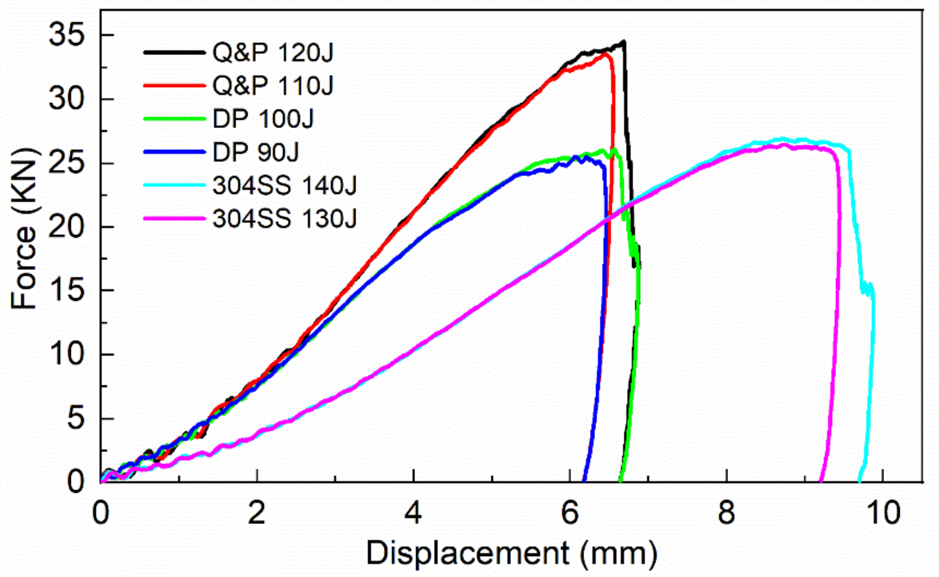
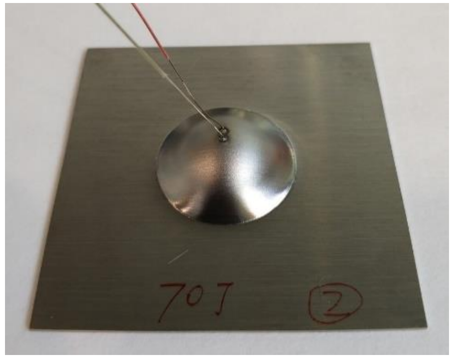
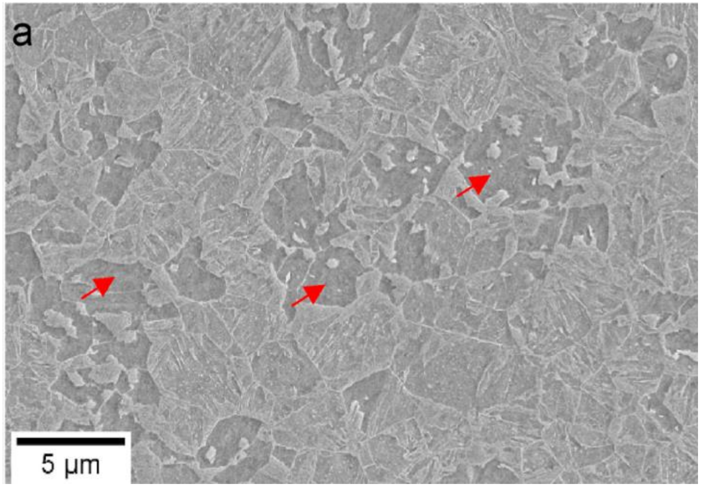
Impact resistance (energy absorption capability)

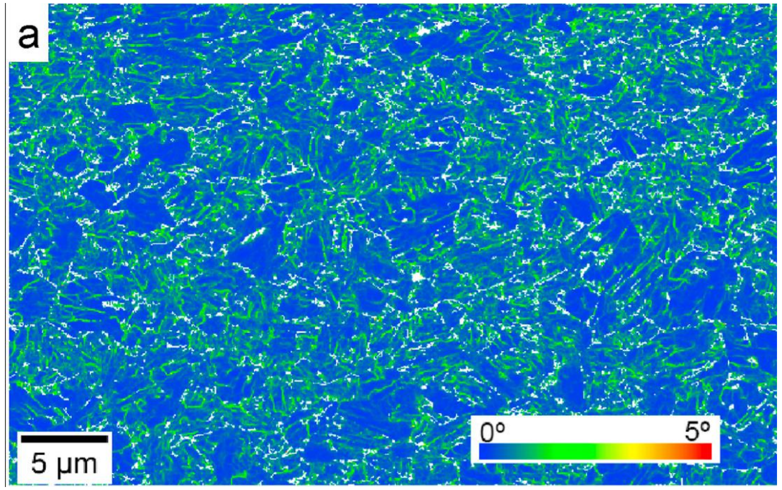


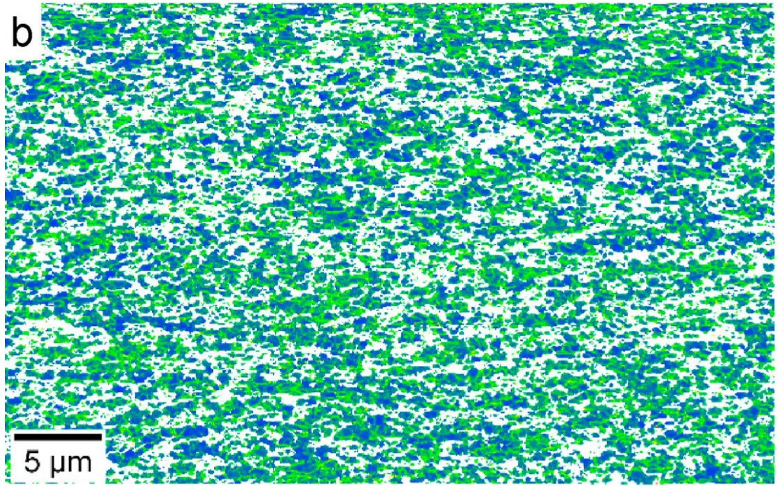


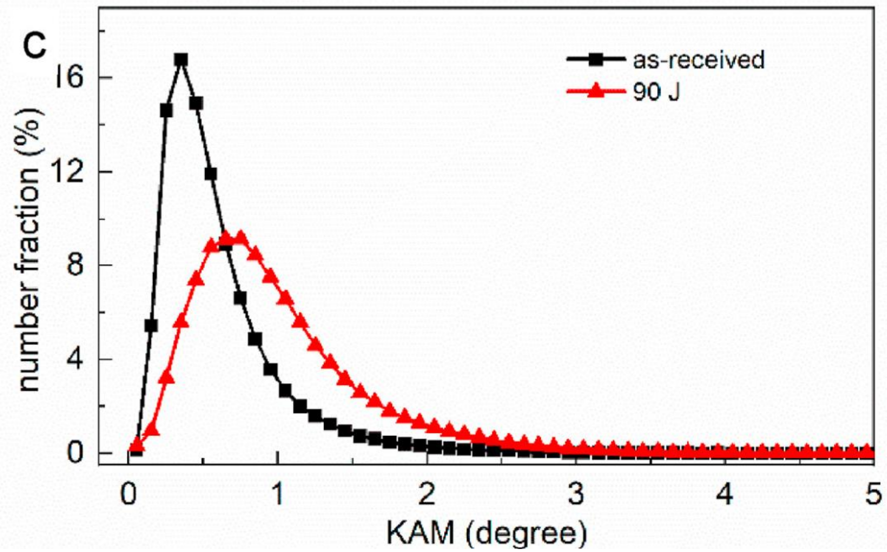
Generation	Steel	yield strength (MPa)	tensile strength (MPa)	fracture elongation (%)	Impact resistance [J]
1st	DP 1180	1062	1244	8.2	80
2nd	304 SS	342	818	97.7	140
3rd	Q&P	1175	1305	26.4	110

Impact performance of DP1180 (1st generation)





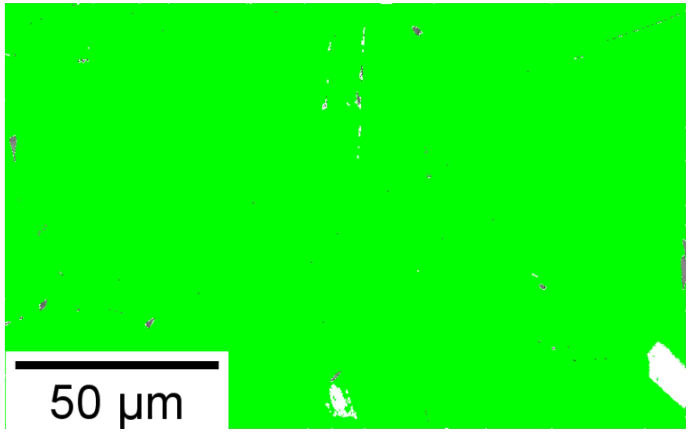




Dislocation glide

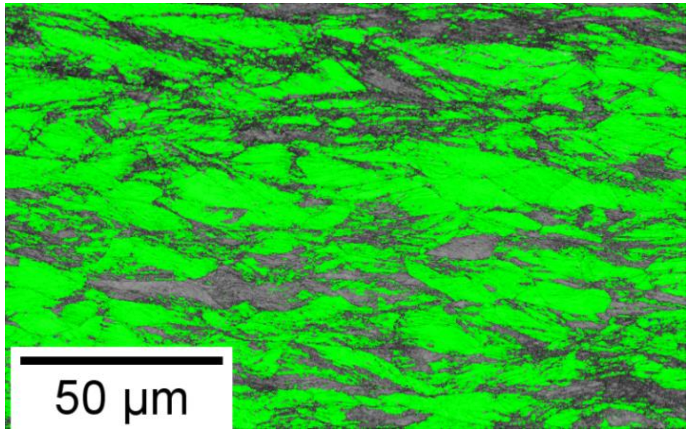
P. Xia, M.S. Palomar, I. Sabirov. *MSEA*, 2020.

Enhanced impact performance of SS304 (2nd generation)

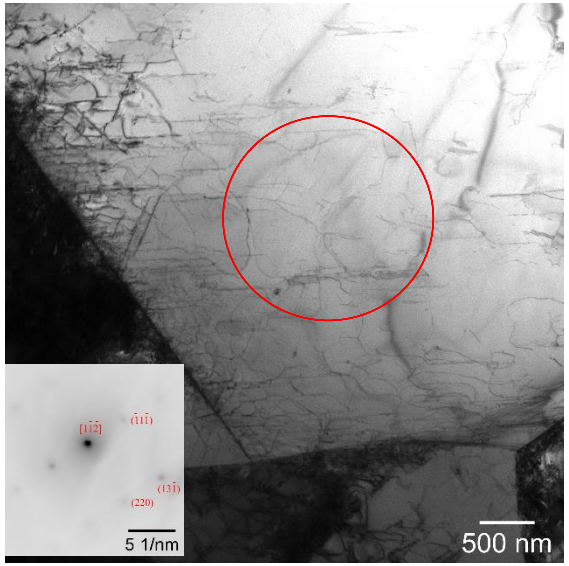


304SS, 0 J

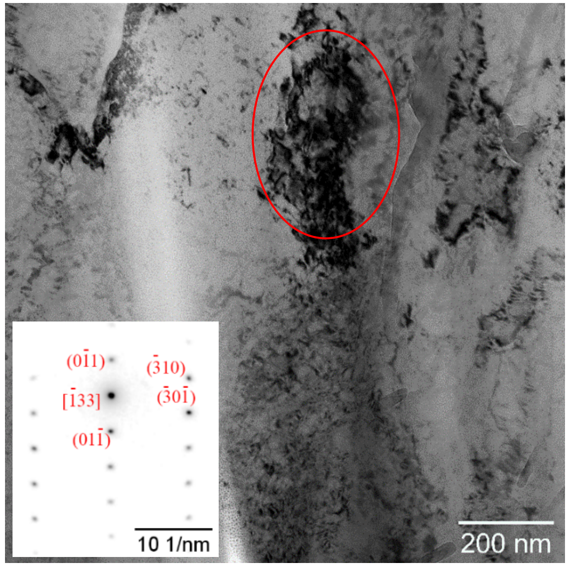
fcc bcc



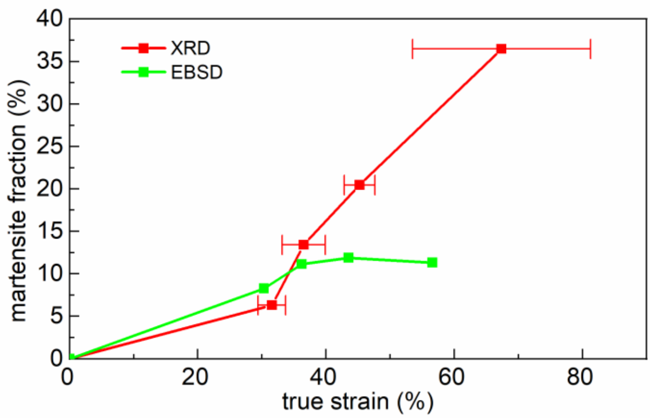
304SS, 81.16% true strain, 140 J



Austenite in undeformed 304 SS

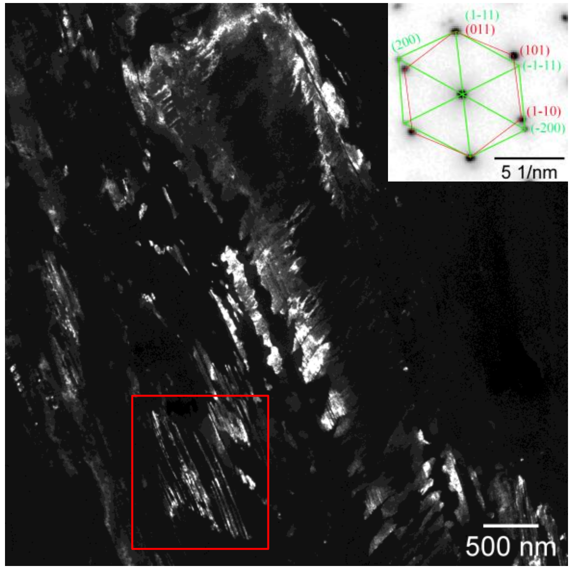


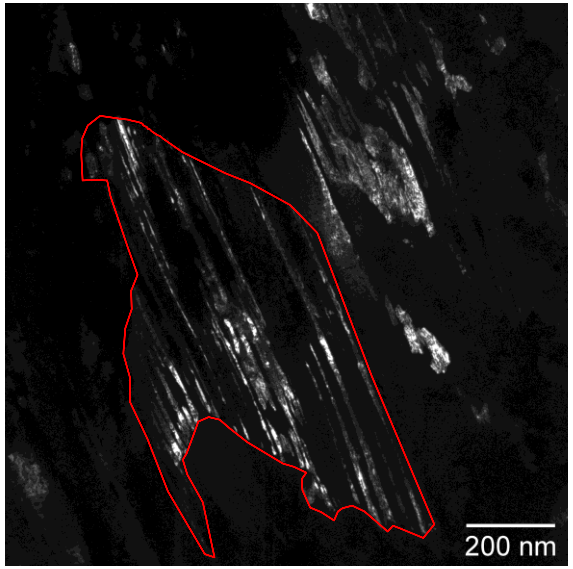
Martenste in 140 J impacted 304 SS

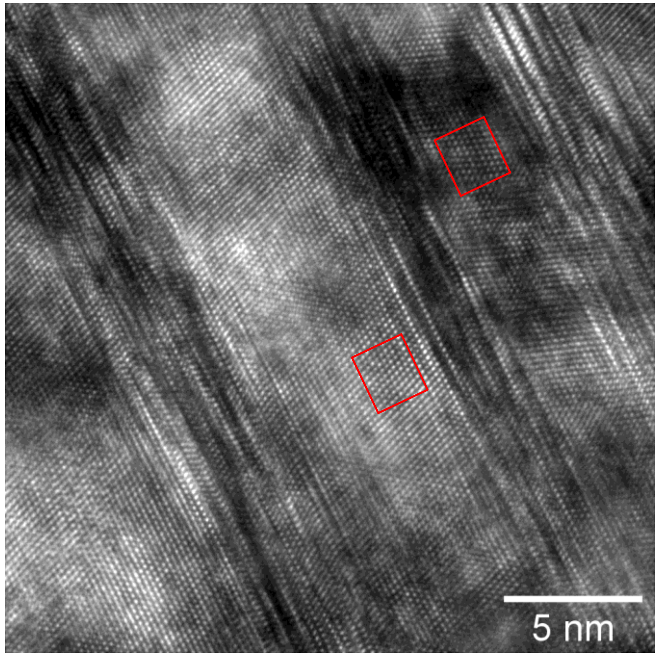


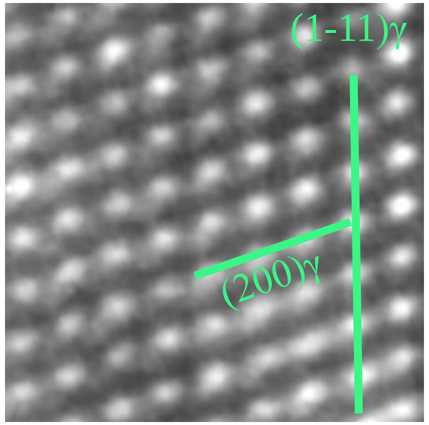
A => M phase transformation
TRIP effect + dislocations

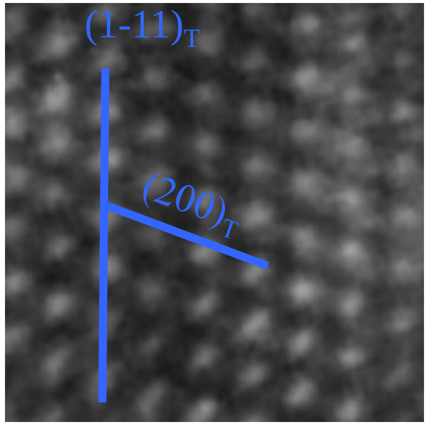
Enhanced impact performance of SS304 (2nd generation)







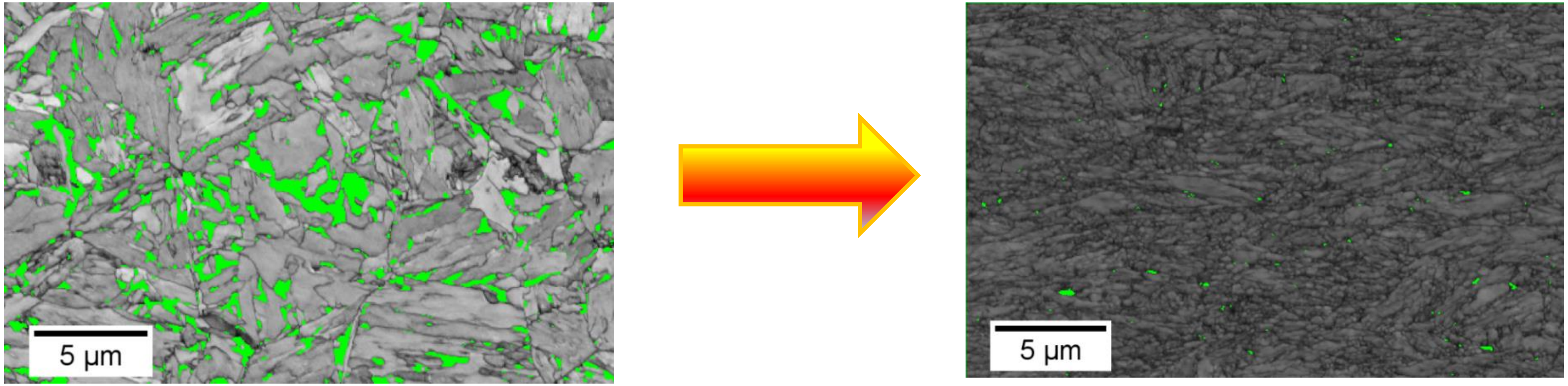




Extensive twinning

P. Xia, F.J. Canillas Rodriguez, I. Sabirov. *MSEA*, 2020.

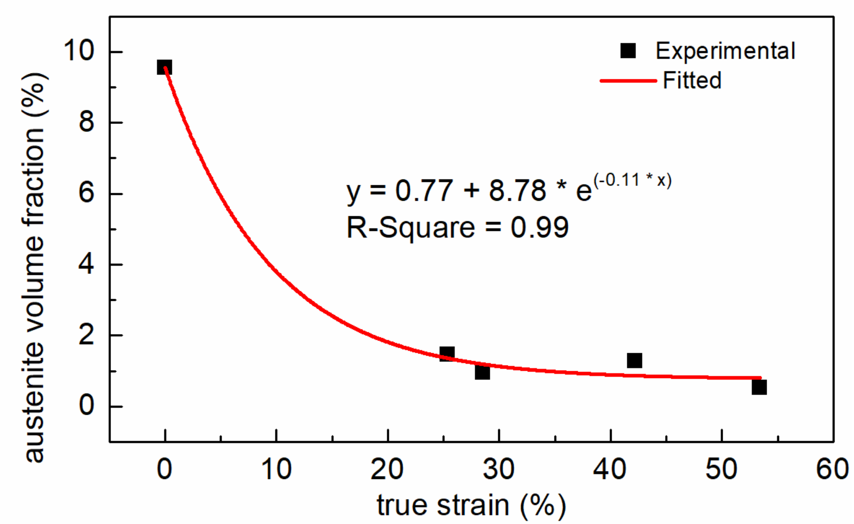
Impact performance of Q&P steel (3rd generation)



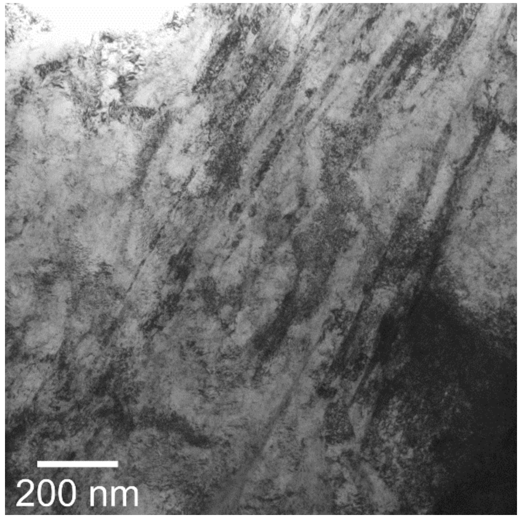
Q&P, 0 J

fcc bcc

Q&P, 53.40% true strain, 110 J



Austenite fraction evolution



Martensite in 110 J impacted Q&P steel

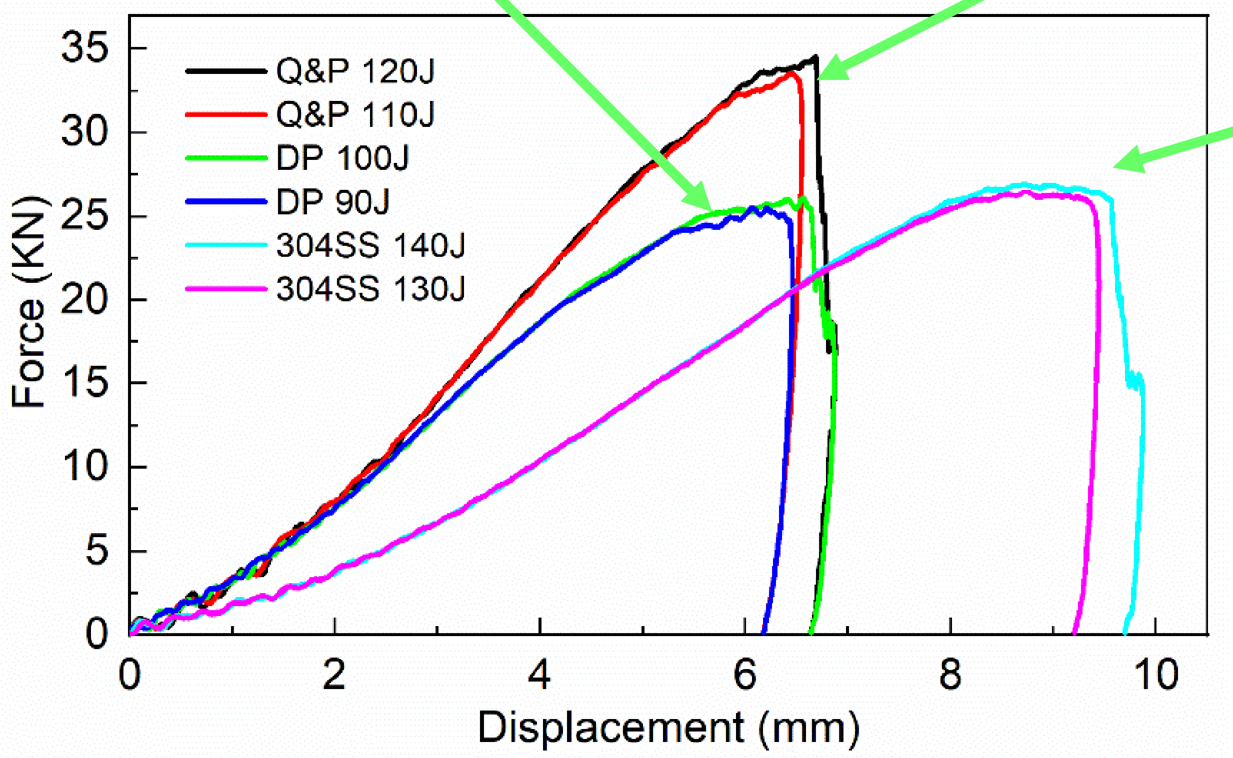
Dislocation glide + TRIP effect

Impact performance of AHSS

DP: Dislocations
80 J

Q&P: TRIP+dislocations
110 J

304SS: TRIP+twins+dislocations
140 J

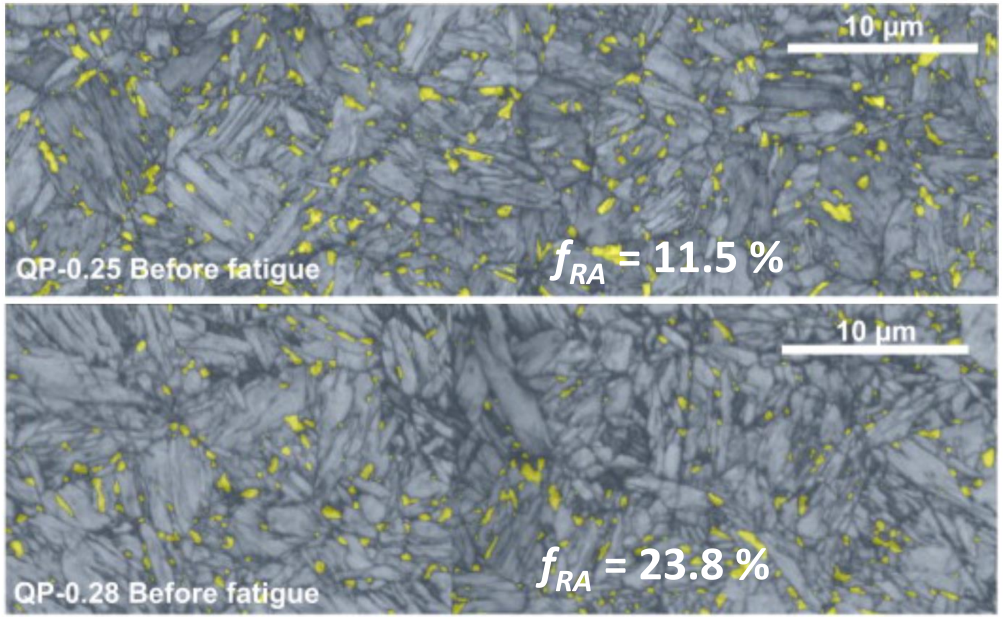


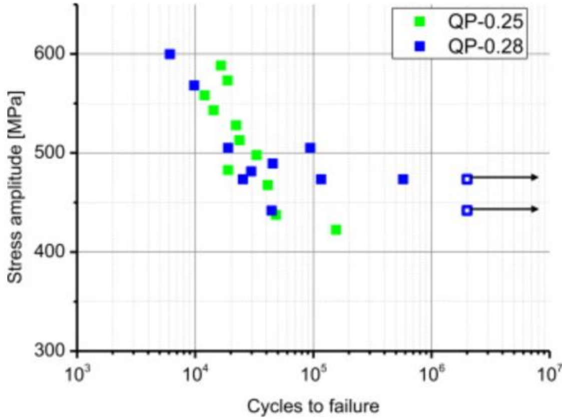
Dislocation glide and twinning along with TRIP effect result in enhanced impact resistance of 304 SS steel (140 J).

Dislocation glide and TRIP effect provide enhanced impact resistance in Q&P steel.

Fatigue behaviour of AHSS

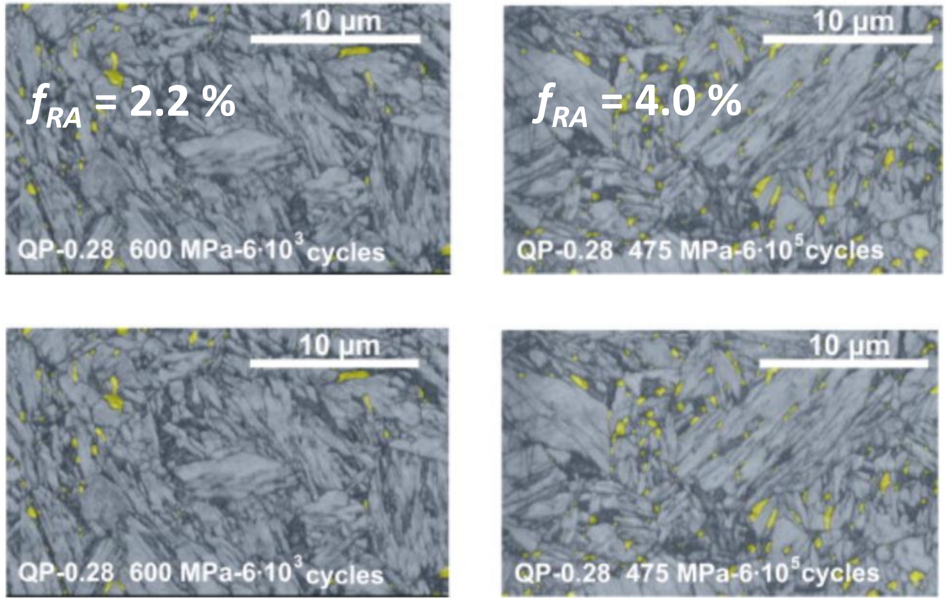
Q&P carbon steels with retained austenite





0.25 wt.%C 445 MPa

0.28 wt.%C <420 MPa



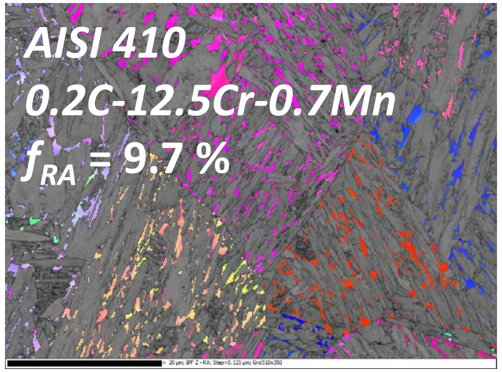
- *Higher carbon content => higher fraction of RA => higher fatigue limit.*
- *There is a RA=>M transformation during fatigue. Size and orientation of RA control stability of RA.*

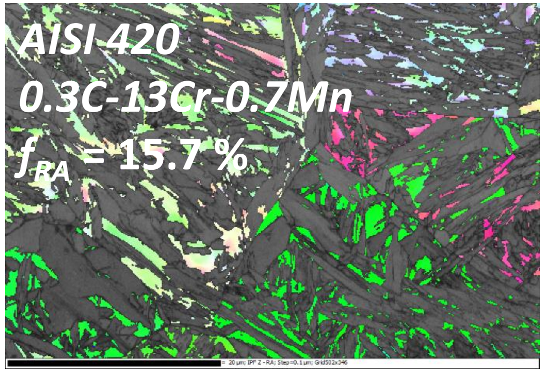
I. Diego-Calderon, P. Rodriguez, A. Lara, J.M. Molina-Aldareguia, R. Petrov, D. De Knijf, I. Sabirov. *Materials Science and Engineering A*. 641 (2015) 215.

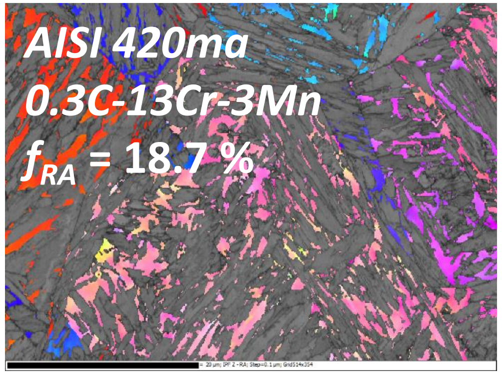
Fatigue behaviour of AHSS

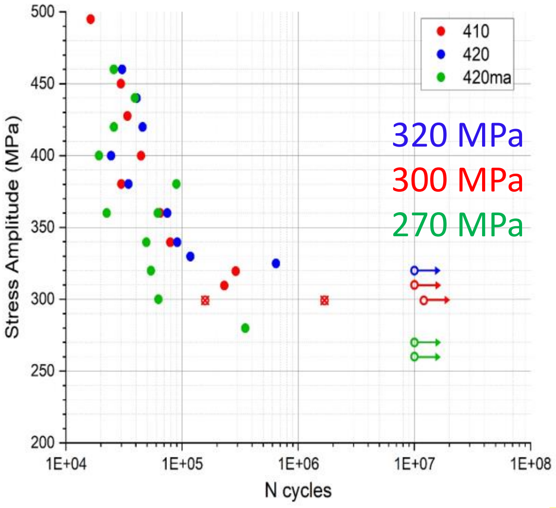
OPINOX Development of New Martensitic Stainless Steels for Automotive Lightweight Structural Applications

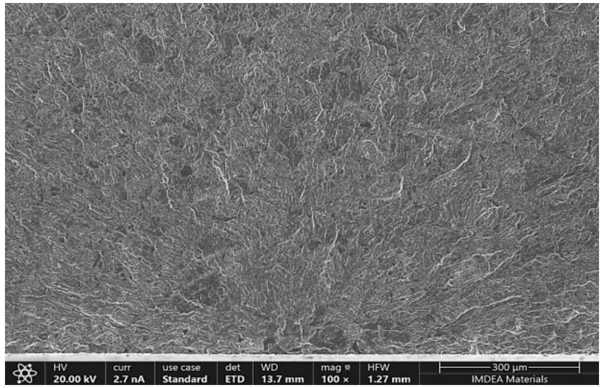
Q&P martensitic stainless steels with retained austenite

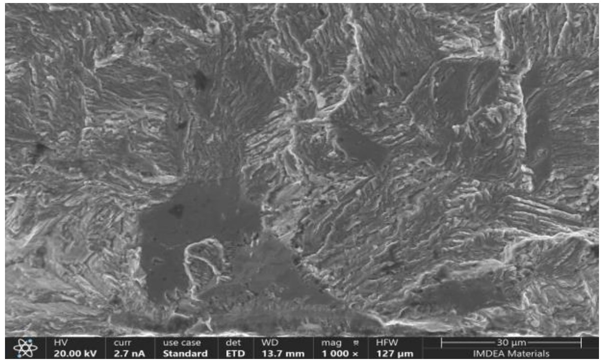










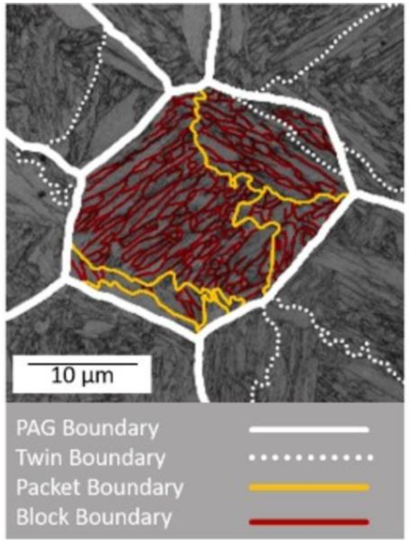


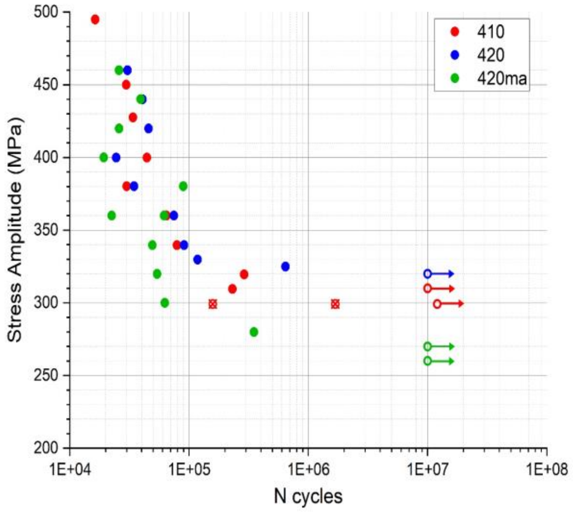
- *Fatigue cracks are formed on the surface in transgranular mode in dependently on applied stress values.*
- *Fatigue cracks grow also in transgranular mode.*

A. Sierra-Soraluce, G. Li, A. Lara, M.J. Santofimia, J. Molina, A. Smith, M. Muratori, I. Sabirov.
Materials and Design. 233 (2023) 112286.

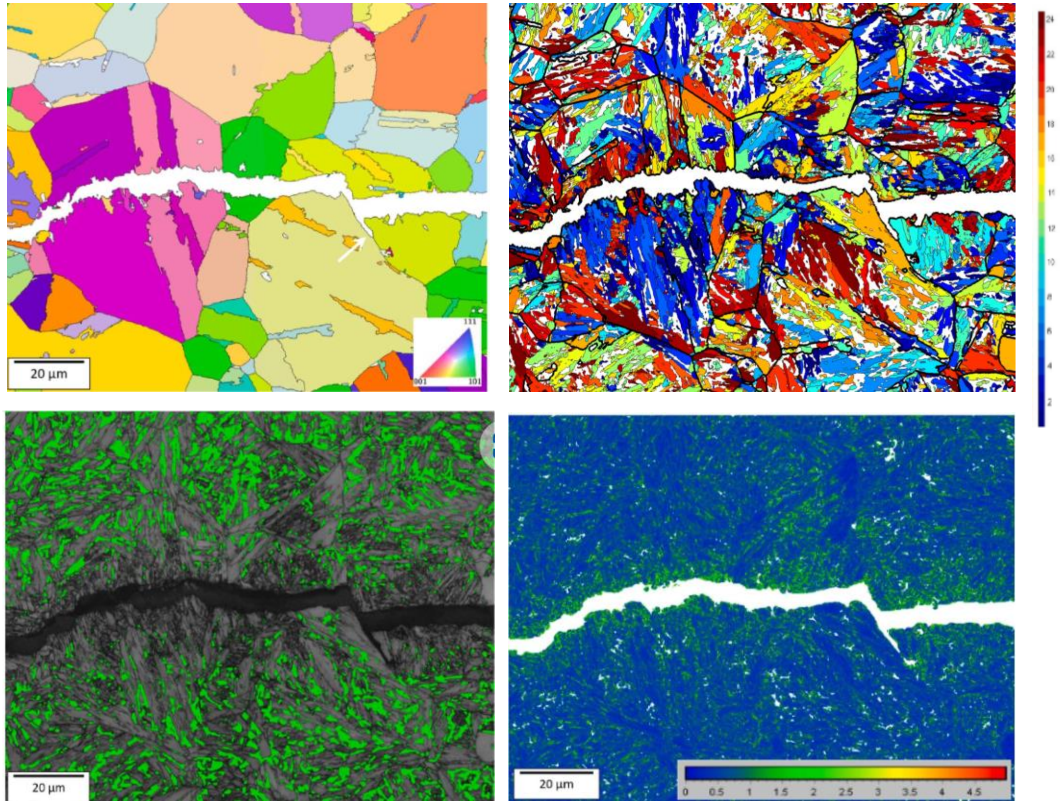
Fatigue behaviour of AHSS

OPINOX Development of New Martensitic Stainless Steels for Automotive Lightweight Structural Applications





	PAGS [µm]	Packet size [µm]	Block size [µm]	RA size [µm]	f_{RA} [%]
410	38.3	21.6	3.8	0.7	9.7
420	29.4	11.9	3.5	0.9	15.7
420ma	20.4	8.4	2.7	0.8	18.7

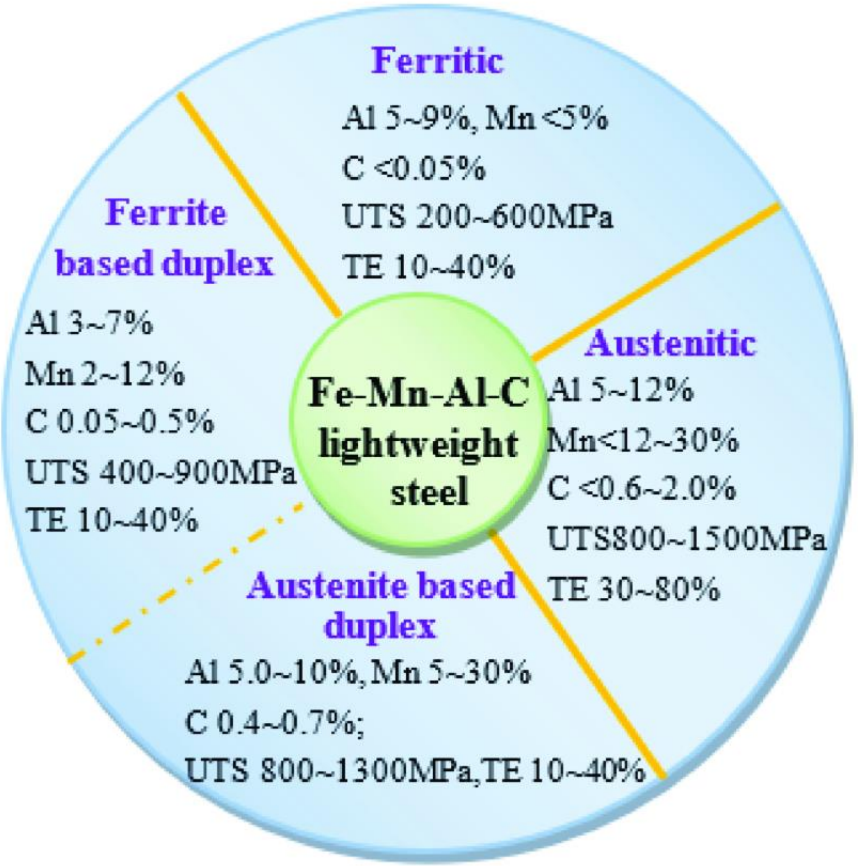


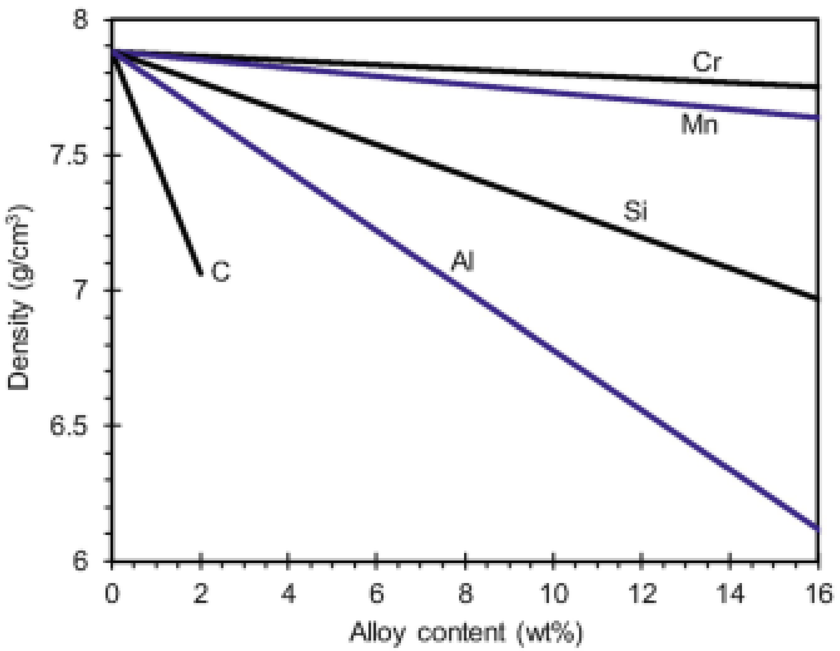
- *Fatigue cracks are formed and grow predominantly along martensite block boundaries.*
- *Fatigue strength is determined by complex microstructure.*

A. Sierra-Soraluce, G. Li, A. Lara, M.J. Santofimia, J. Molina, A. Smith, M. Muratori, I. Sabirov. *Materials and Design*. 233 (2023) 112286.

Fatigue behaviour of AHSS

Lightweight austenitic Fe-30Mn-9Al-1C steel



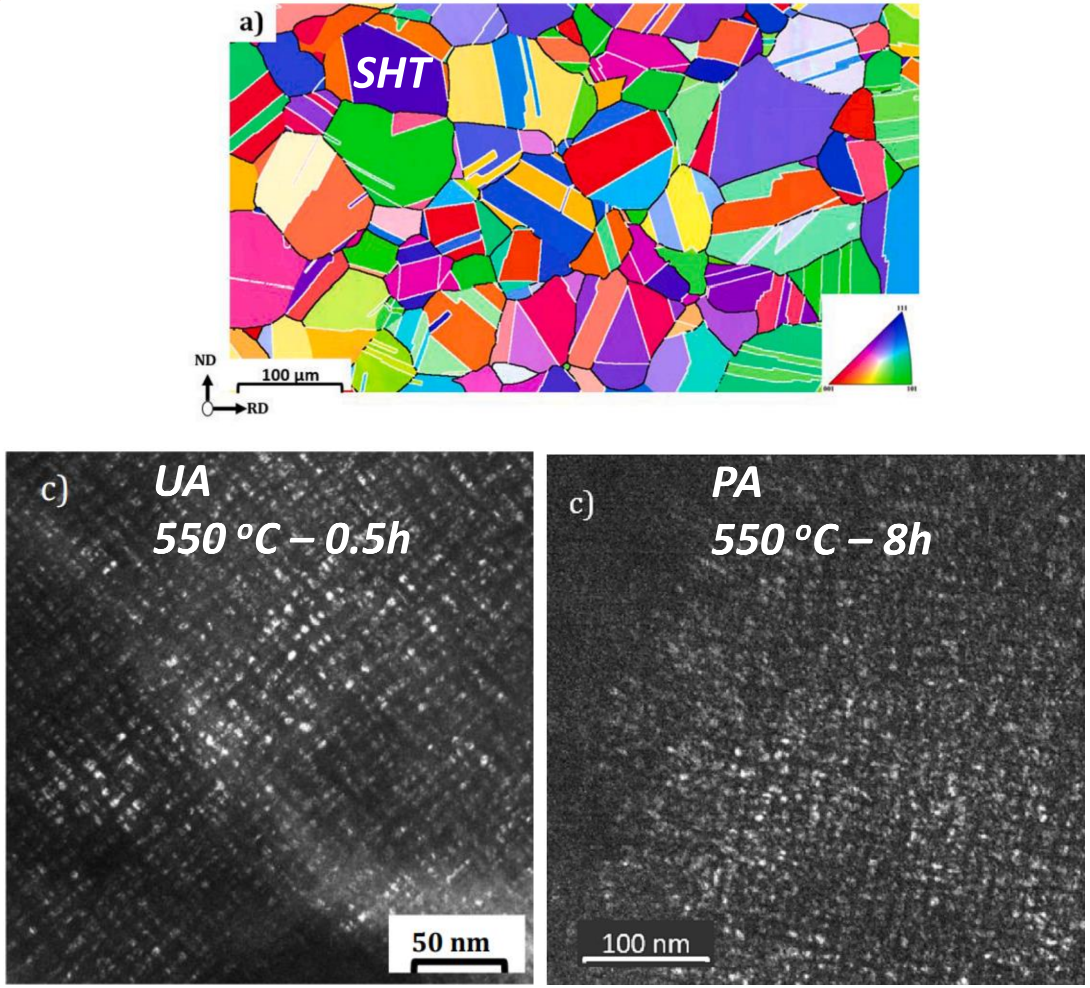


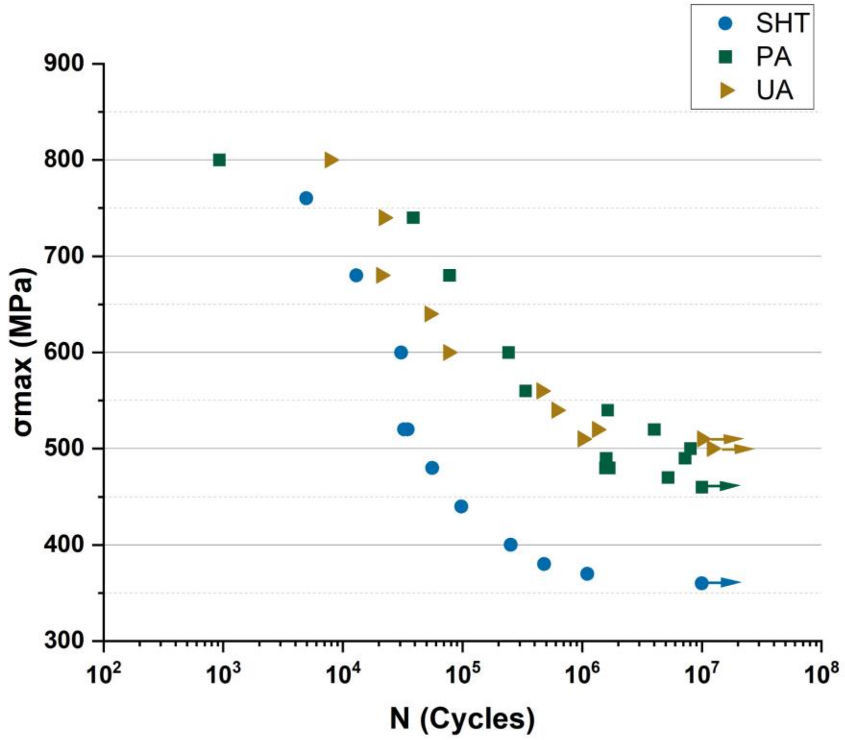
- ***Significant reduction of steel density***
- ***Significant improvement of specific strength: σ_y/ρ***

A. Gomez, A. Banis, M. Avella, J.M. Molina-Aldareguia, R.H. Petrov, A. Dutta, I. Sabirov. International Journal of Fatigue. 184 (2024) 108306.

Fatigue behaviour of AHSS

Lightweight austenitic Fe-30Mn-9Al-1C steel (6.8 g/mm^3)





- ***Significant improvement of fatigue limit after under-aging (UA)***

A. Gomez, A. Banis, M. Avella, J.M. Molina-Aldareguia, R.H. Petrov, A. Dutta, I. Sabirov. International Journal of Fatigue. 184 (2024) 108306.

Fatigue behaviour of AHSS

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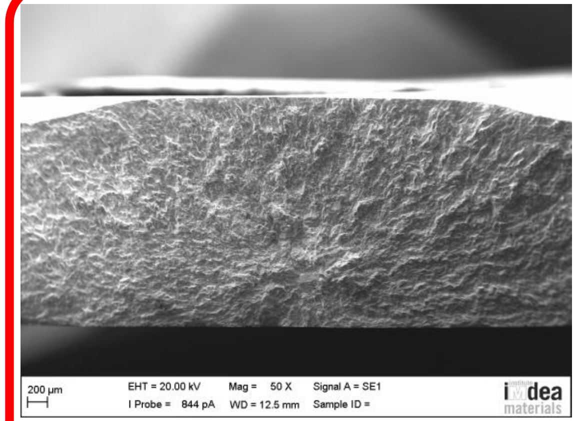
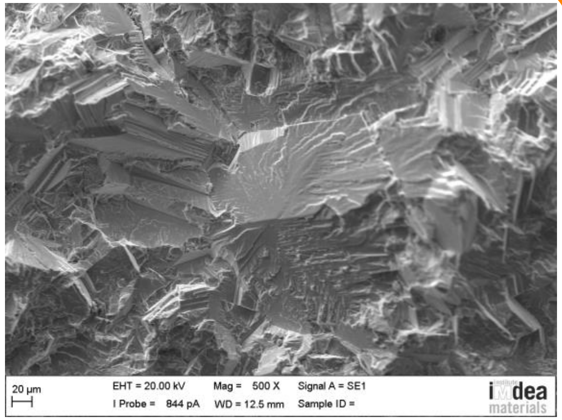
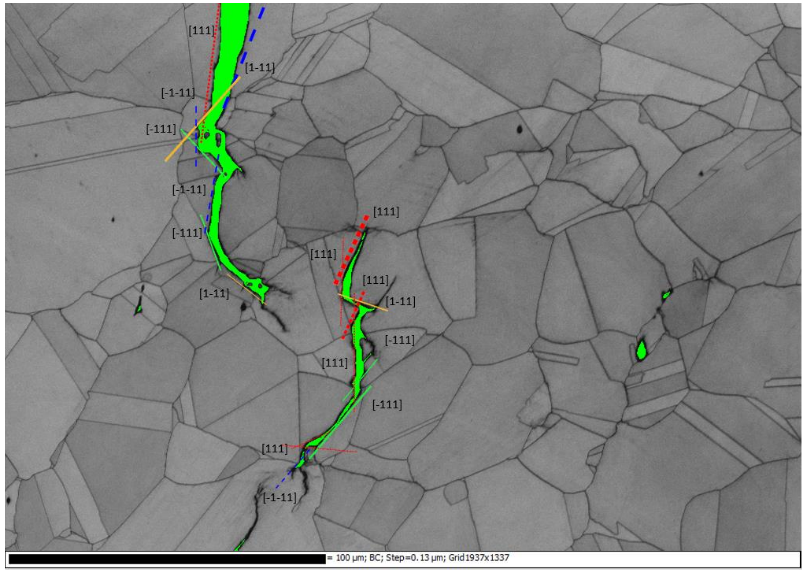
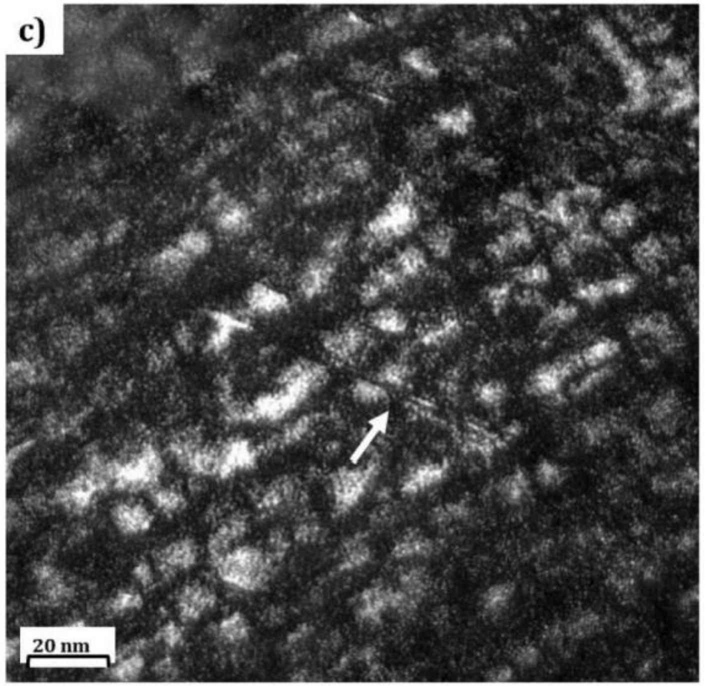






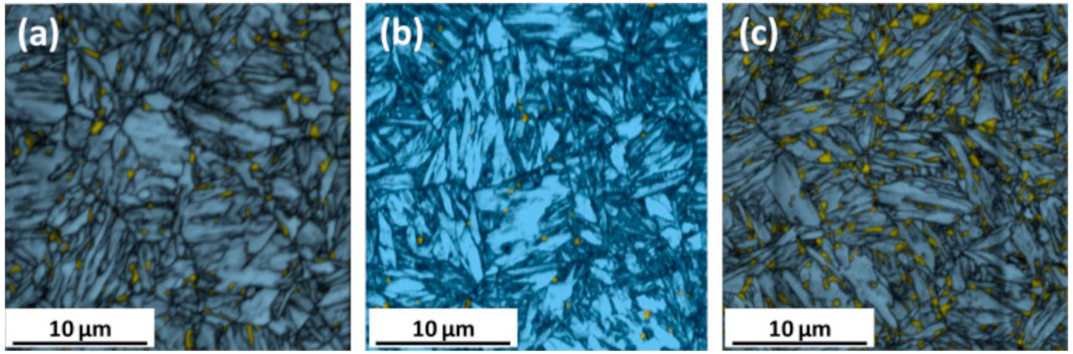
- *Fatigue cracks are formed and grow along <111> plane.*

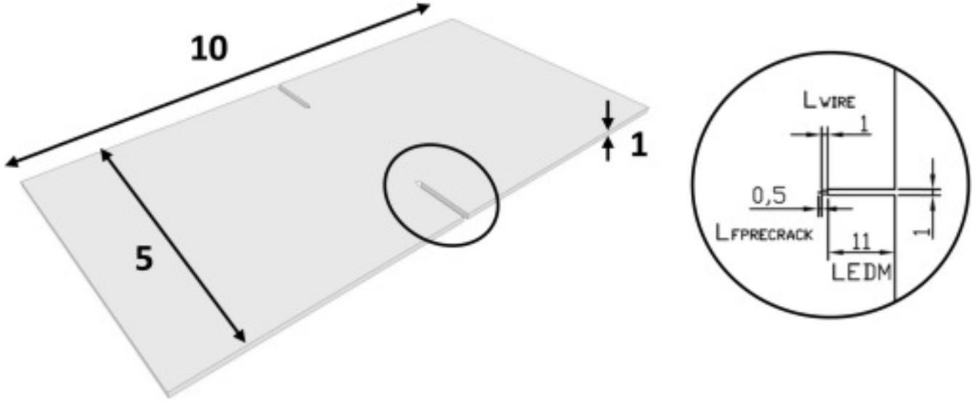


- *Kappa-carbides delay the formation of persistent slip bands (e.g. fatigue crack) due to the additional energy barrier associated with the shearing of κ-carbides.*
- *The resistance of the κ-carbides to shearing is determined by their size, volume fraction, and antiphase boundary energy.*

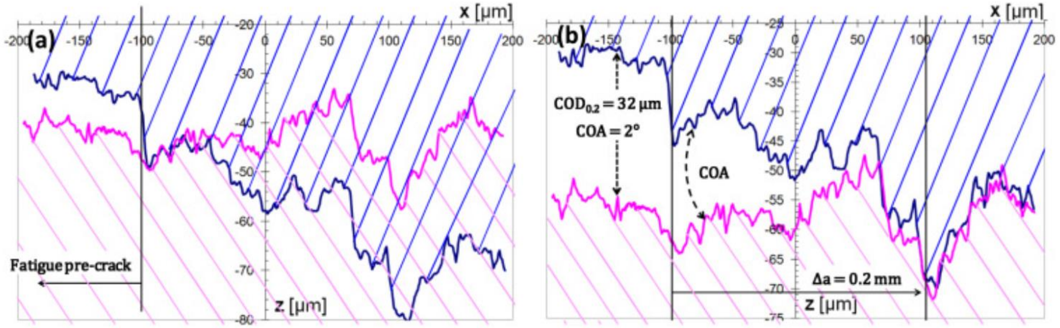
Fracture behavior of advanced high strength steels

Quenched and partitioned carbon steels





Specimen	K_Q (MPa $m^{1/2}$)	COD_i–δ_t (μm)	J_i (kJ/m^2)	$COD_{0.2}$–$\delta_{0.2}$ (μm)	$J_{0.2}$ (kJ/m^2)	CTOA (deg)	R_{tot} (kJ/m^2)
PT-280	73.17±0.14	2.8±0.6	9.3	9.3±0.8	31.3	1	49.7
PT-400	148.8±5.9	4±0.7	8.7	15.7±0.7	34.1	3.7	92.3
PT-450	117.17±8.99	4.1±1.5	10.1	22±3.1	54.2	3	124.1



- *Retained austenite can be effectively used to improve total crack growth resistance of material.*

I. de Diego-Calderón, I. Sabirov, J.M. Molina-Aldareguia, C. Föjer, R. Thiessen, R.H. Petrov. Materials Science and Engineering A. 657 (2016) 136-146.

Colaborators

IMDEA Materials Institute
Dr. Peikang Xia, Dr. Andres Sierra Soraluce, Andrea Gomez, Prof. Jon Molina-Aldareguia

Ghent University
Prof. Patricia Verleysen, Prof. Roumen Petrov

TU Delft
Prof. Maria Jesus Santofimia

CSM RINA
Dr. Ali Smith

ArcelorMittal
Dr. Irene de Diego-Calderon, Dr. Aniruddha Dutta, Dr. Cecilia Fojer

ACERINOX
Marta Muratori

Thank you!