

# The Use of Vanadium in Steels

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# ABOUT VANITEC

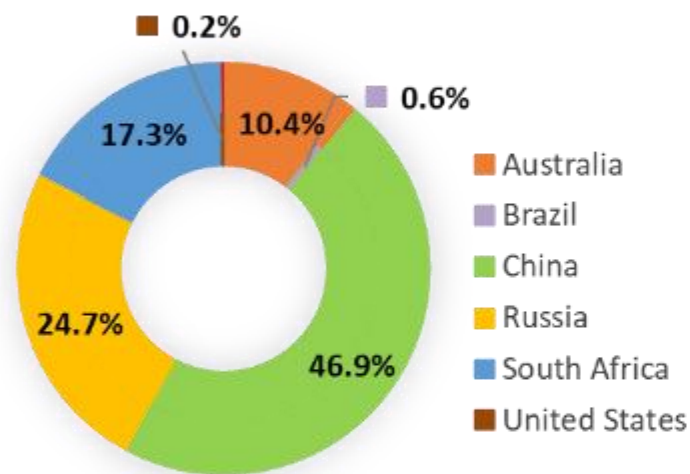


- **Vanitec** is the only not-for-profit international global member organisation whose objective is to promote the use of vanadium bearing materials and thereby to increase the consumption of vanadium.
- Founded in 1972, registered in UK
- Its members include all the world's major vanadium producers as well as vanadium users and those involved in vanadium energy storage.
- Vanitec members benefit by the organisation representing the interests of its members in technical, market development and HSE issues. It offers a forum for collaboration to understand and promote the uses of vanadium at a global level.

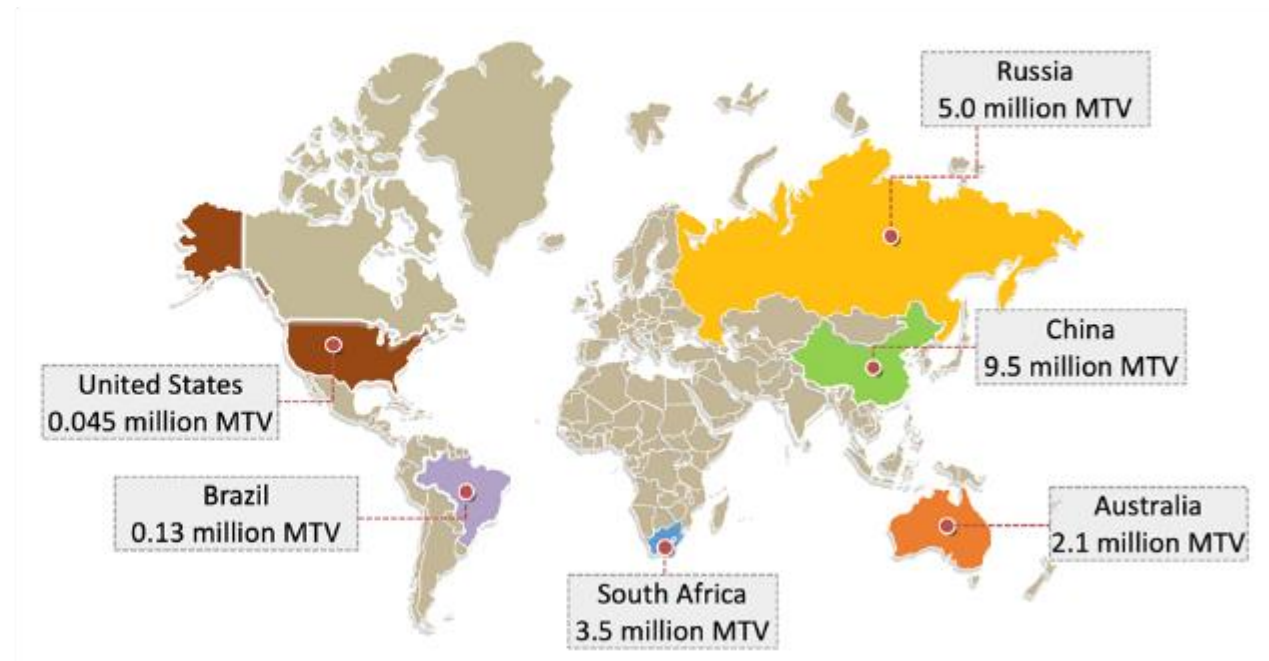
# WORLD VANADIUM RESOURCES AND RESERVES

- World vanadium resources are estimated to be > 63 million metric tons.
- World total vanadium reserves are estimated to be ~20 million metric tons.
- Vanadium reserves are sufficient to meet current market demands for more than 150 years.

## Vanadium Reserves

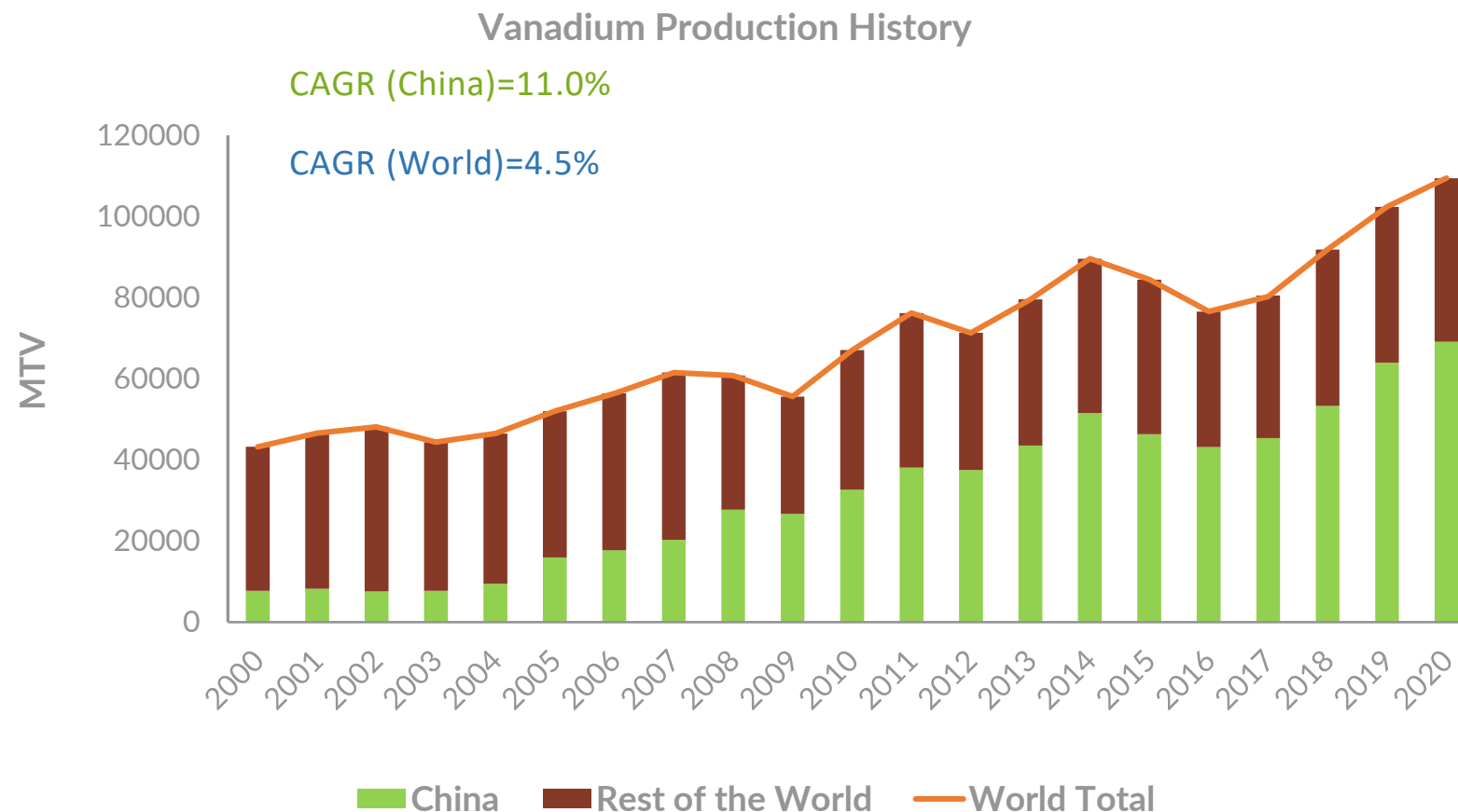


Source: US Geological Survey (USGS)



# WORLD VANADIUM PRODUCTION

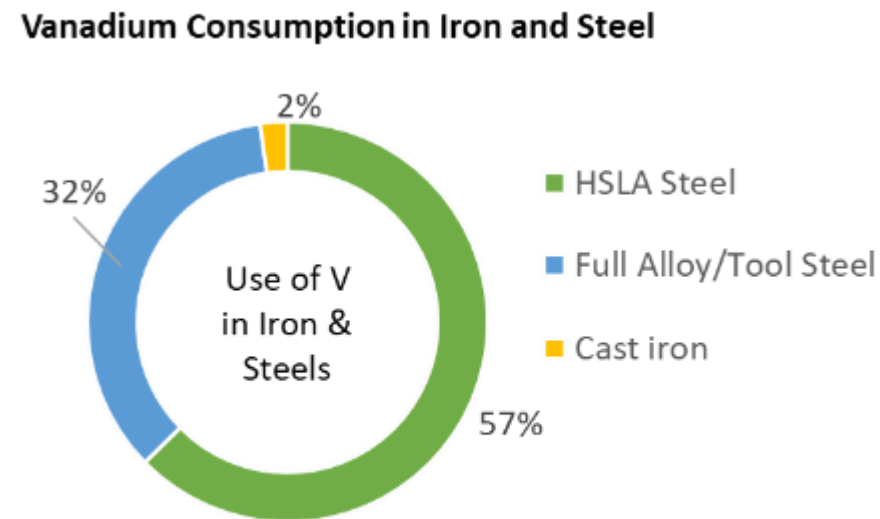
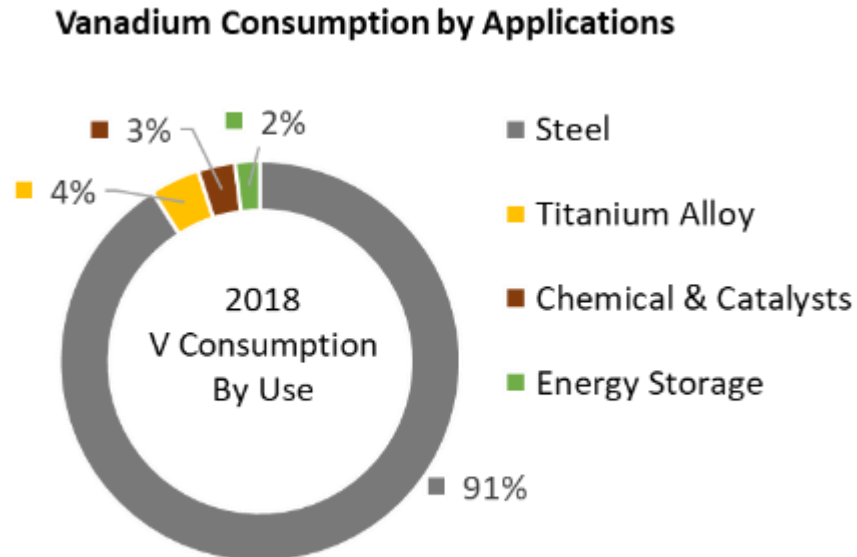
- In the past two decades, the growth of world vanadium production was mainly due to the growth of China's vanadium production.
- In 2000, China's vanadium production accounted for ~18% of the world's vanadium production and increased to ~50% in 2011 and ~63% in 2020.



Source: Vanitec + Pangang

# VANADIUM APPLICATIONS

- Vanadium consumption is heavily influenced by steel production, especially the production of high-strength steels, which are increasingly used in the construction, energy, and transportation industries to maximize the strength and to minimize the weight of their products.
- The steel industry accounts for >90% of total vanadium consumption.

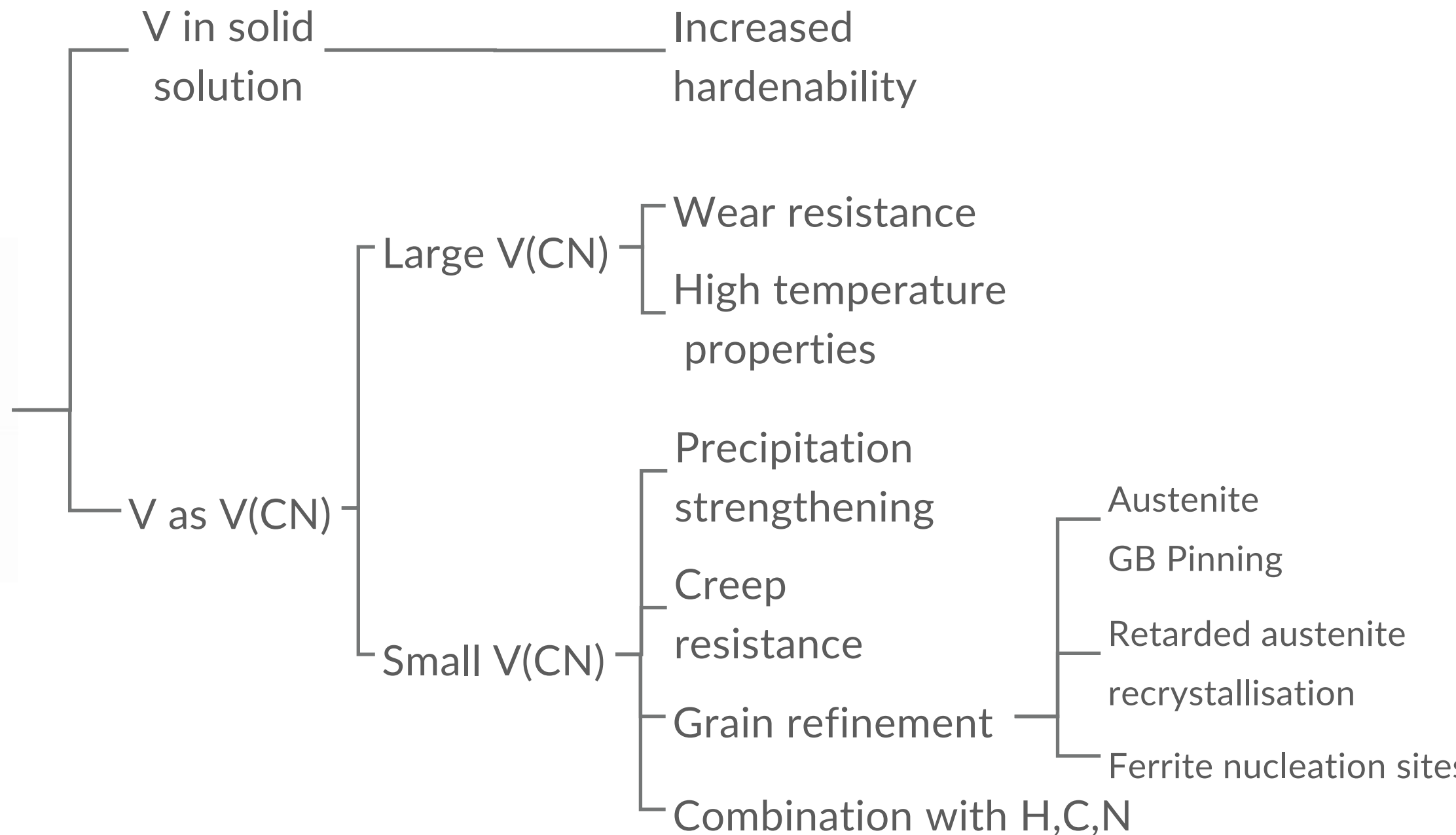




# VANADIUM – THE VERSATILE ELEMENT

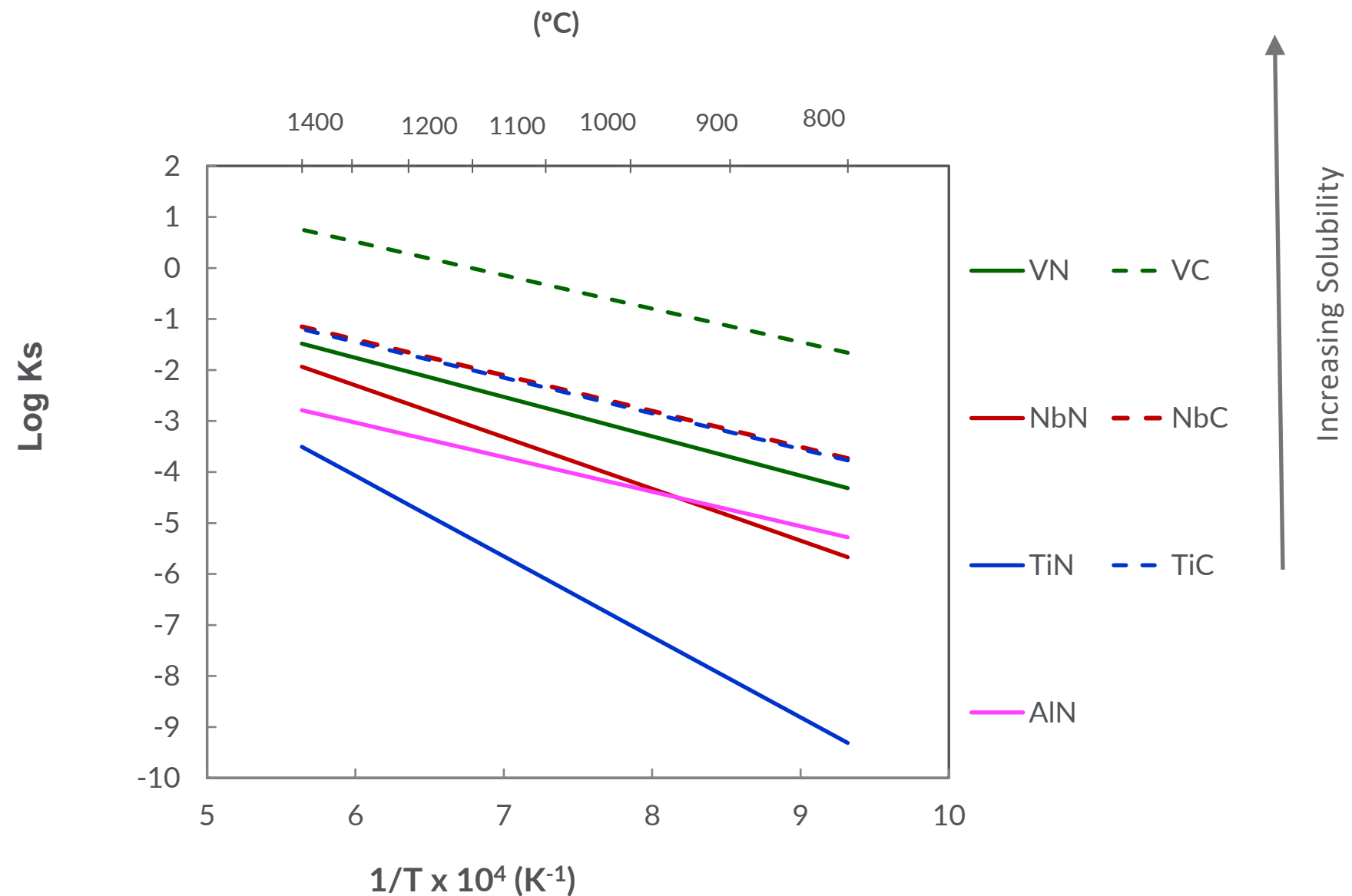


# VANADIUM STEEL METALLURGY



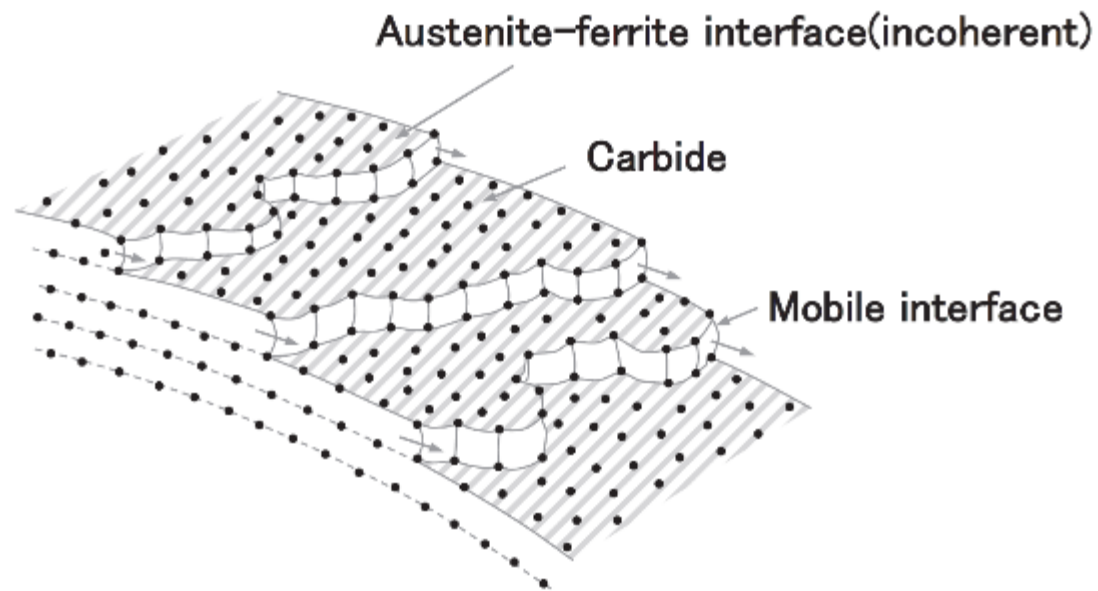


# MICROALLOY CARBIDE AND NITRIDE PRECIPITATE SOLUBILITY IN AUSTENITE

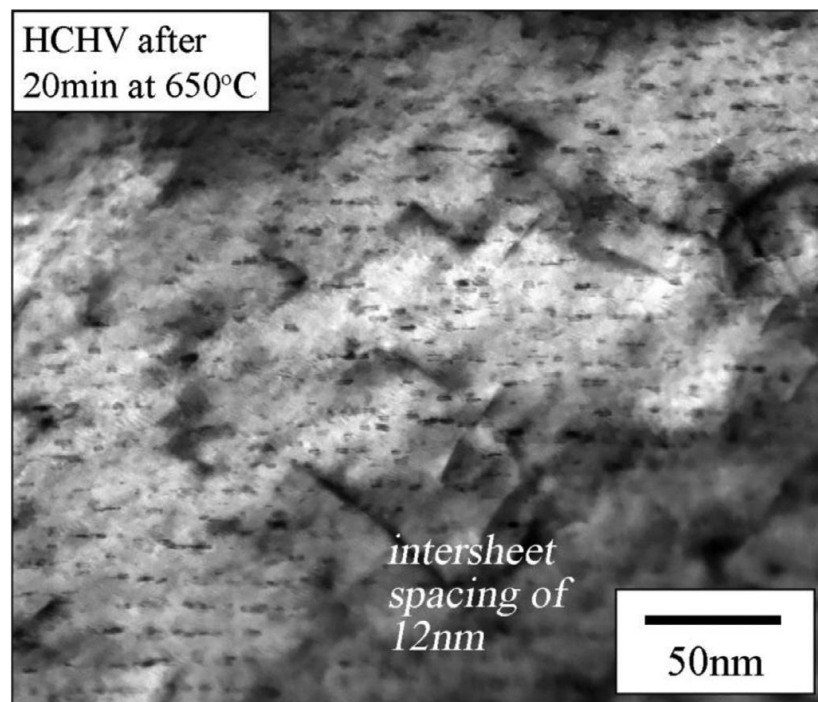


VC and VN have greater solubility than the equivalent carbides and nitrides of Nb and Ti

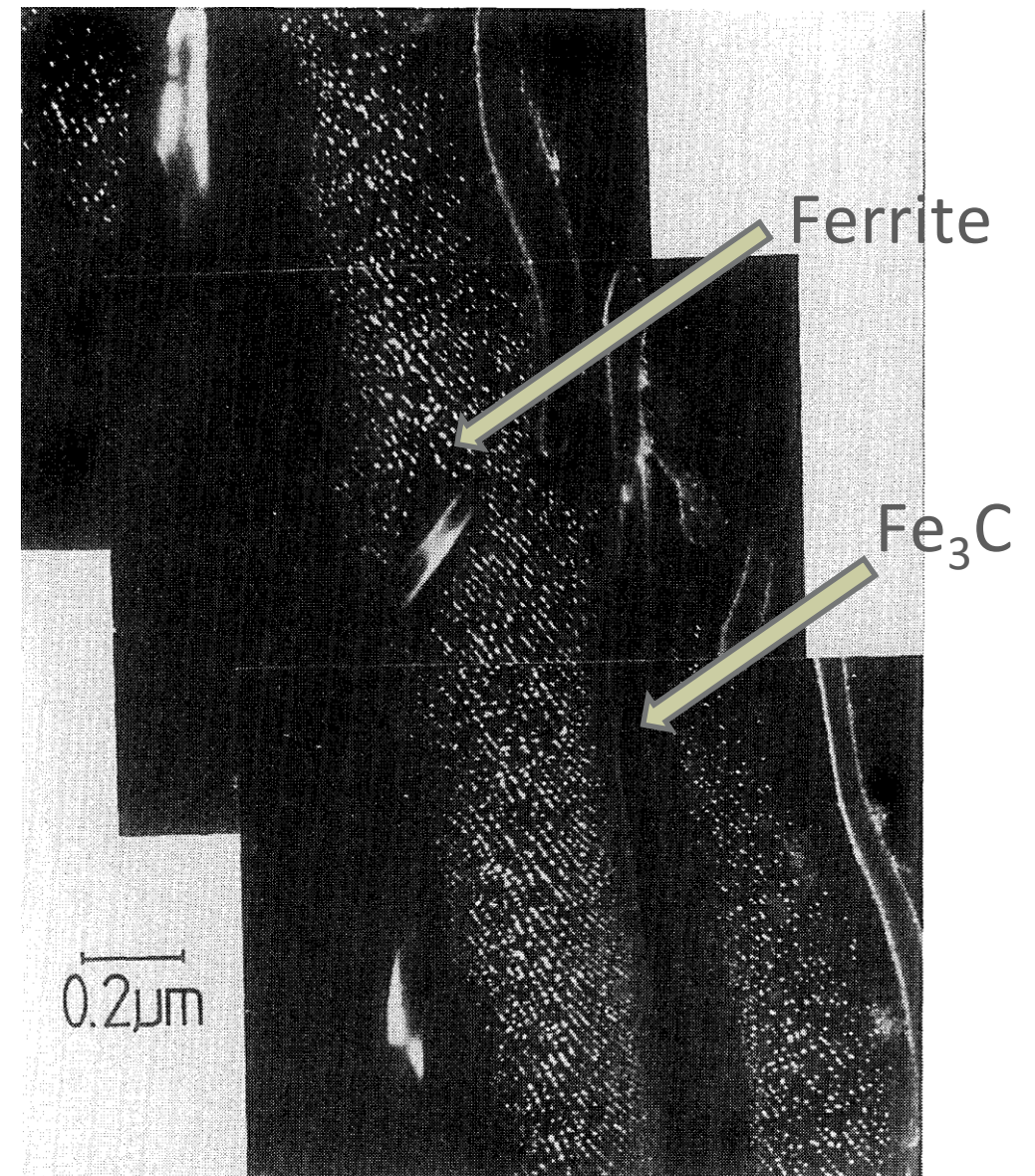
# VANADIUM PRECIPITATION – INTERPHASE PRECIPITATION



Schematic precipitation at austenite/ferrite interface



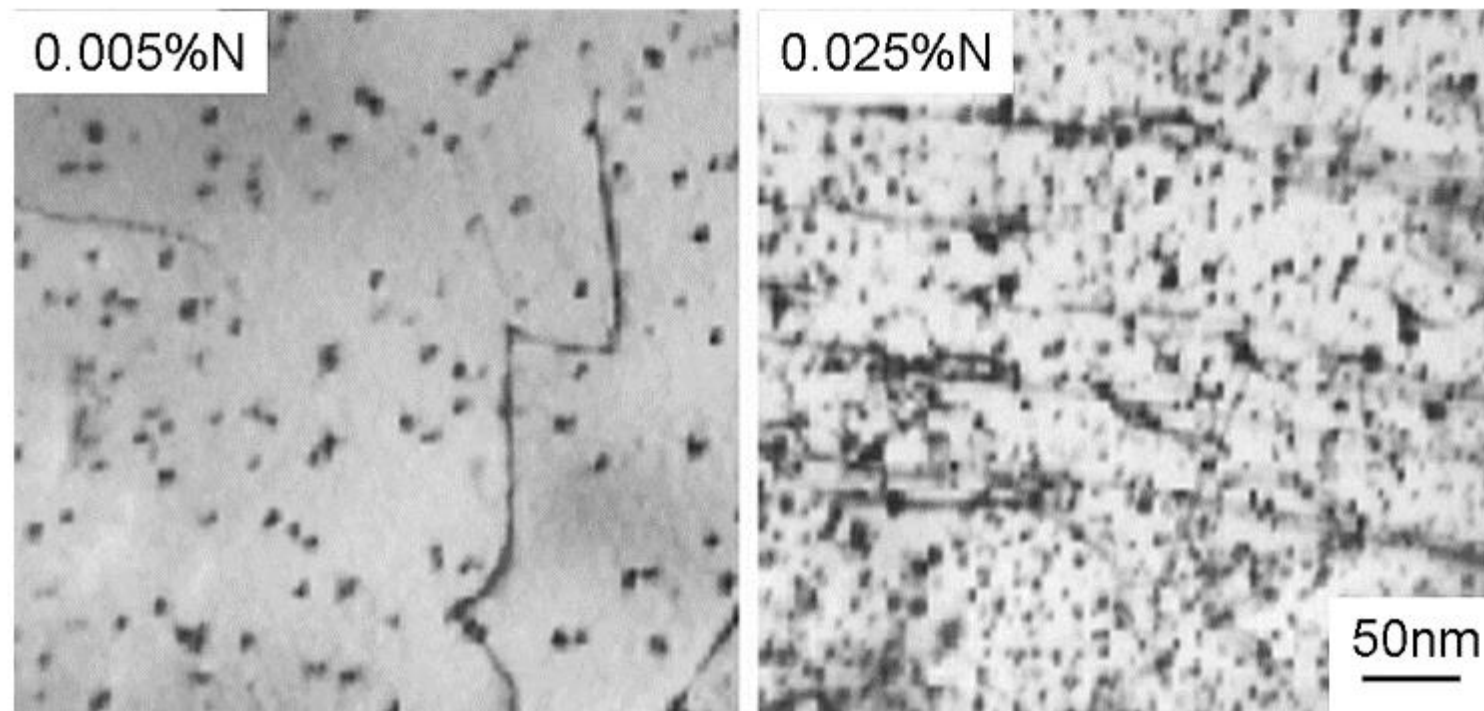
Interphase precipitation in pro-eutectoid ferrite



Interphase precipitation in pearlitic ferrite



# VANADIUM PRECIPITATION – RANDOM PRECIPITATION IN FERRITE



Increased V(C,N) volume fraction with increasing N

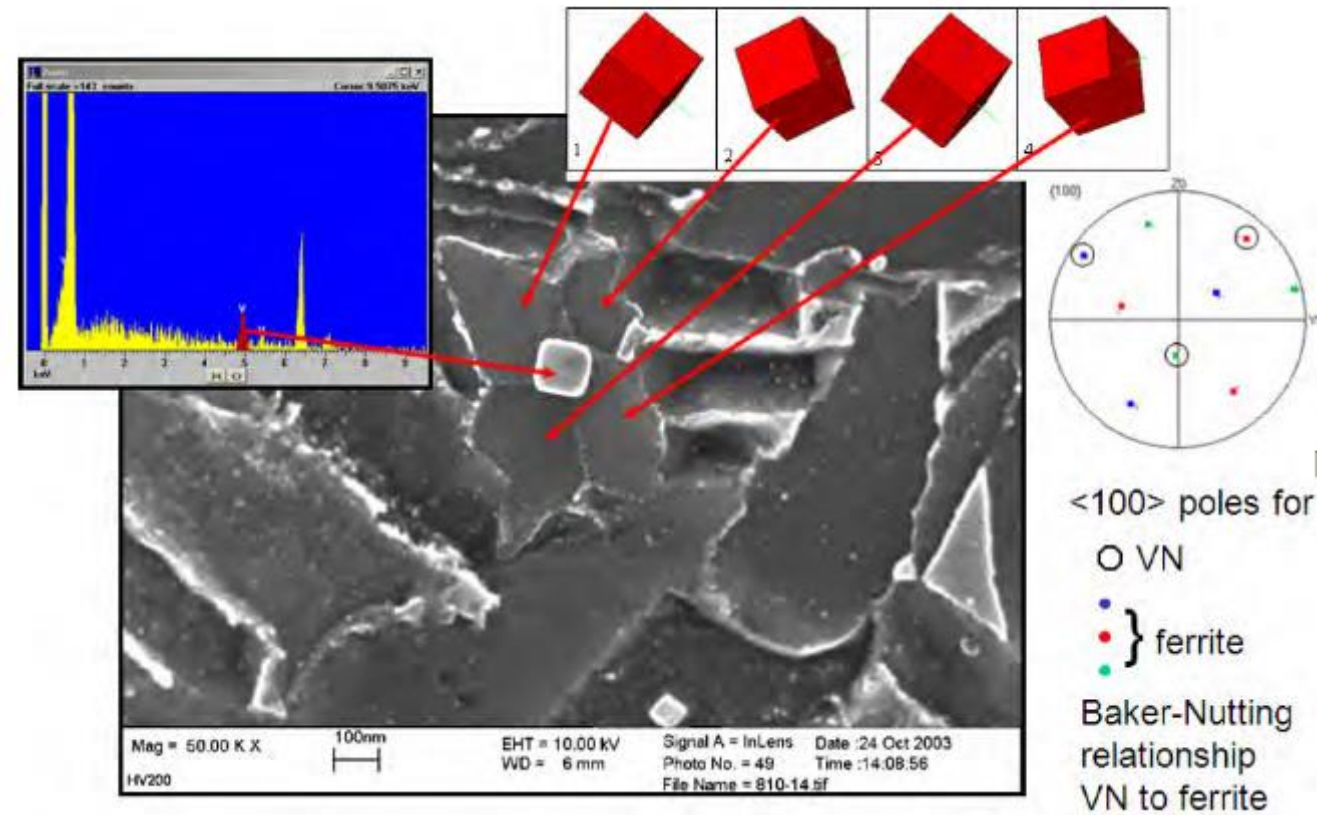
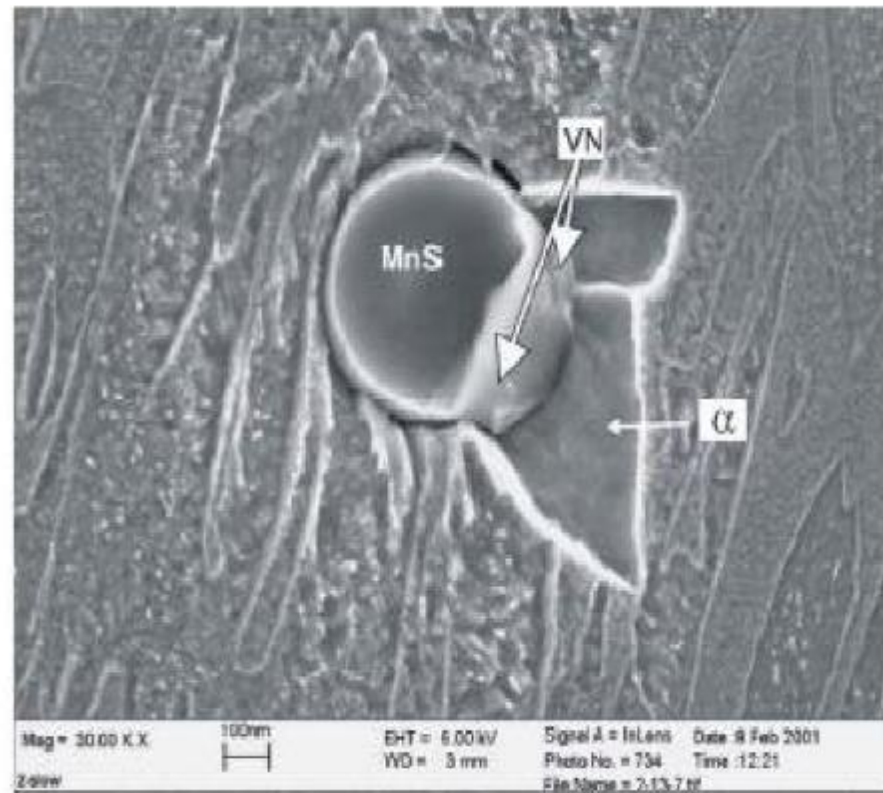
Baker-Nutting Orientation relationship between V(C,N) and ferrite

$(100)_a // (100)_{VCN}$  ,  $\langle 011 \rangle_a // \langle 010 \rangle_{VCN}$

(Single variant observed for IP precipitation, multiple variants for precipitation in ferrite)

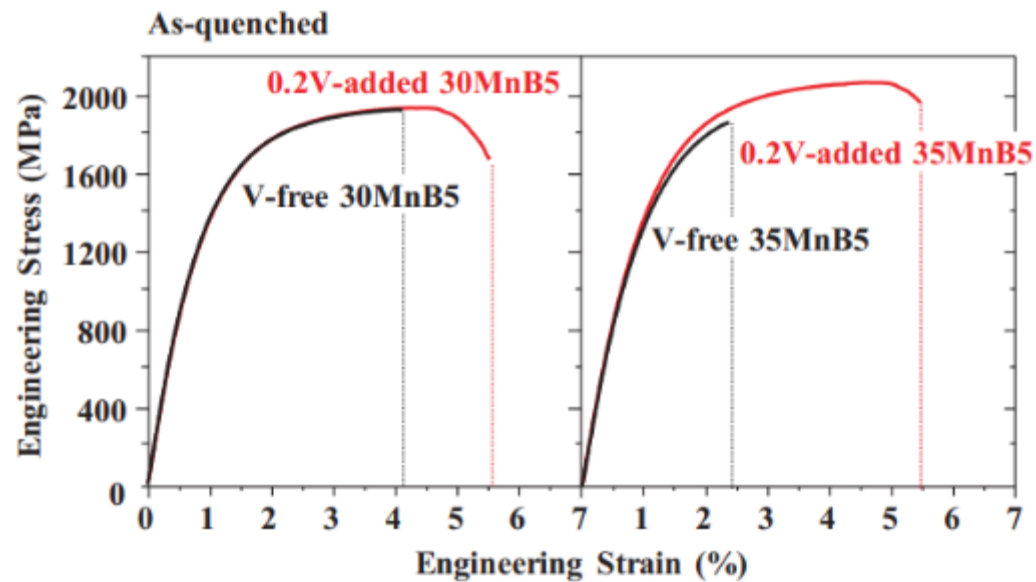


# FERRITE GRAIN REFINEMENT



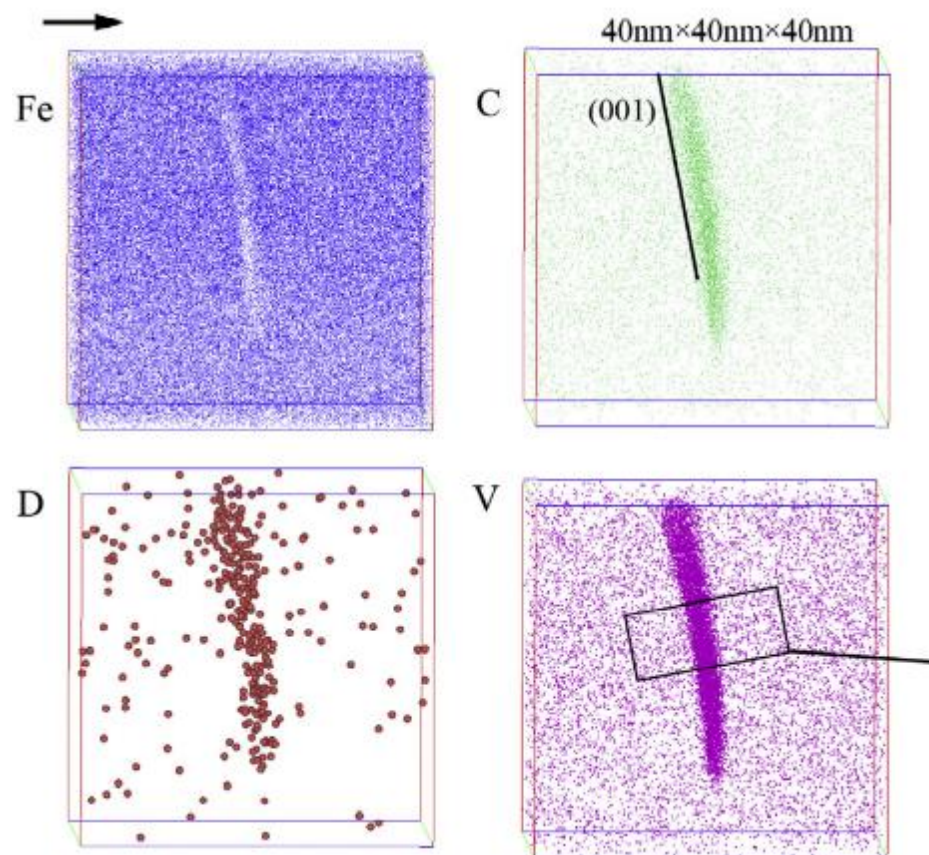
V(CN) can act as a ferrite nucleation site resulting in ferrite grain refinement

# VANADIUM AND HYDROGEN EMBRITTLEMENT



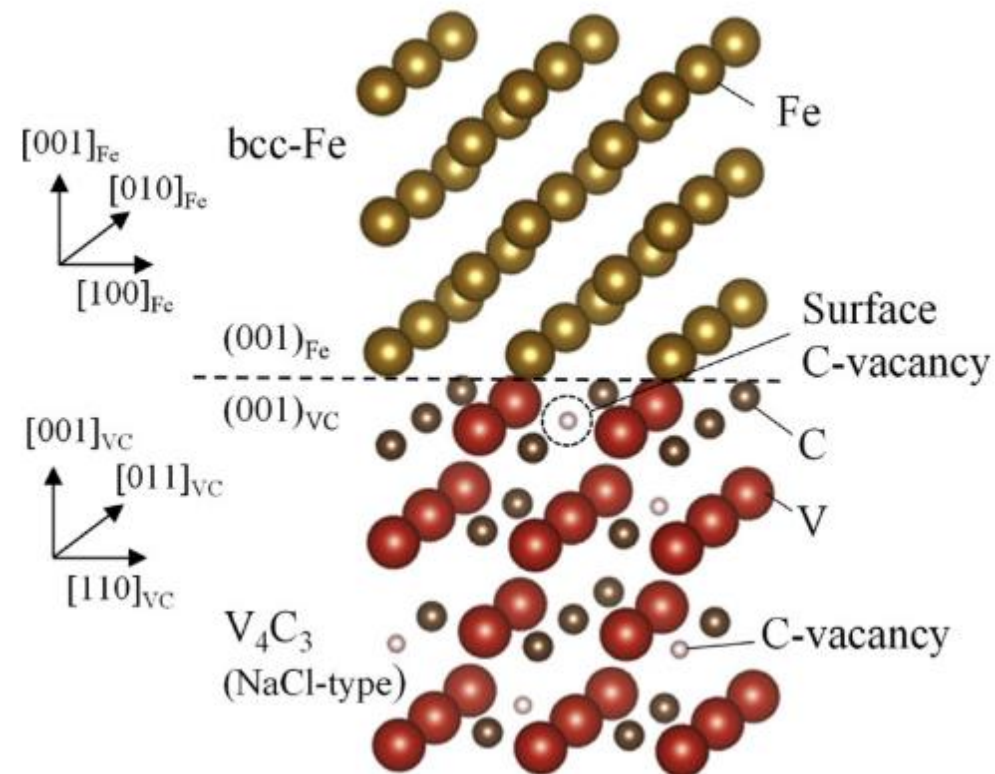
After Cho et al, Mat. Sci and Eng. A 2018

V can reduce hydrogen embrittlement by refining microstructure and trapping hydrogen (VC)



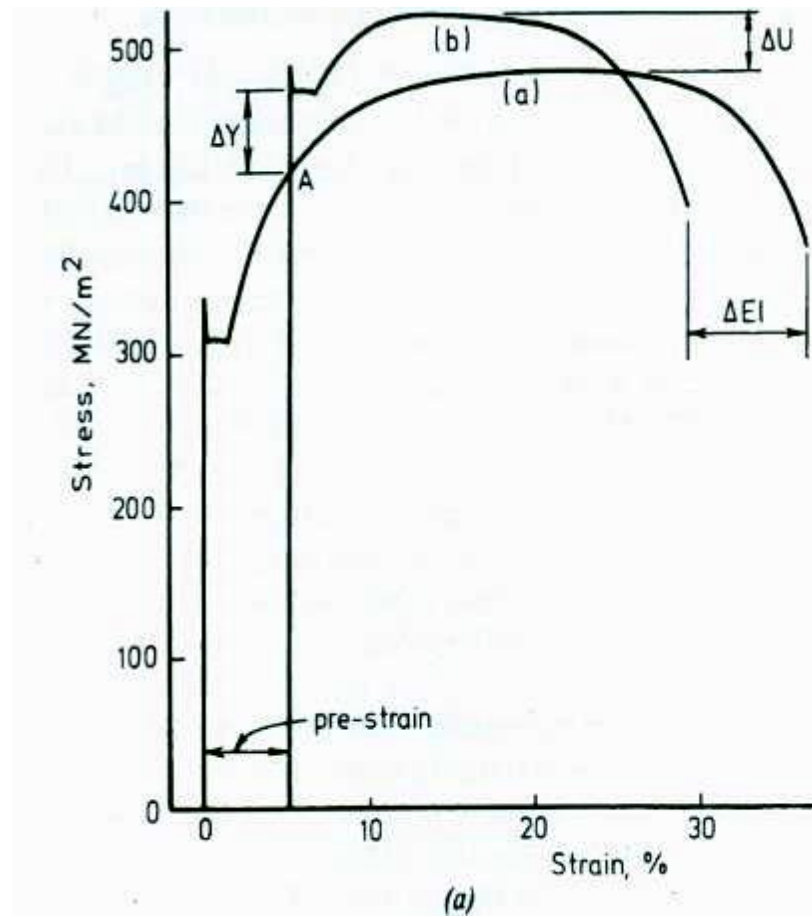
APT showing deuterium associated with V precipitate

After Takahashi et. al., Acta. Mat. 2018

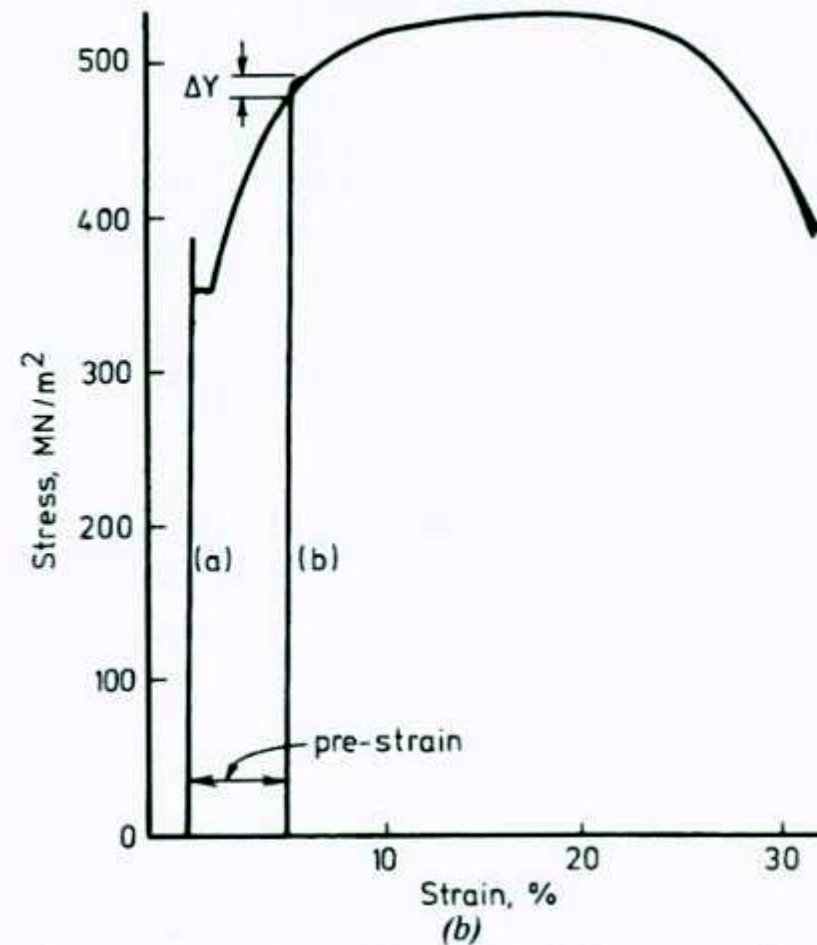


H trapping site at C vacancy at precipitate-matrix interface

# STRAIN AGEING



C-Mn Steel



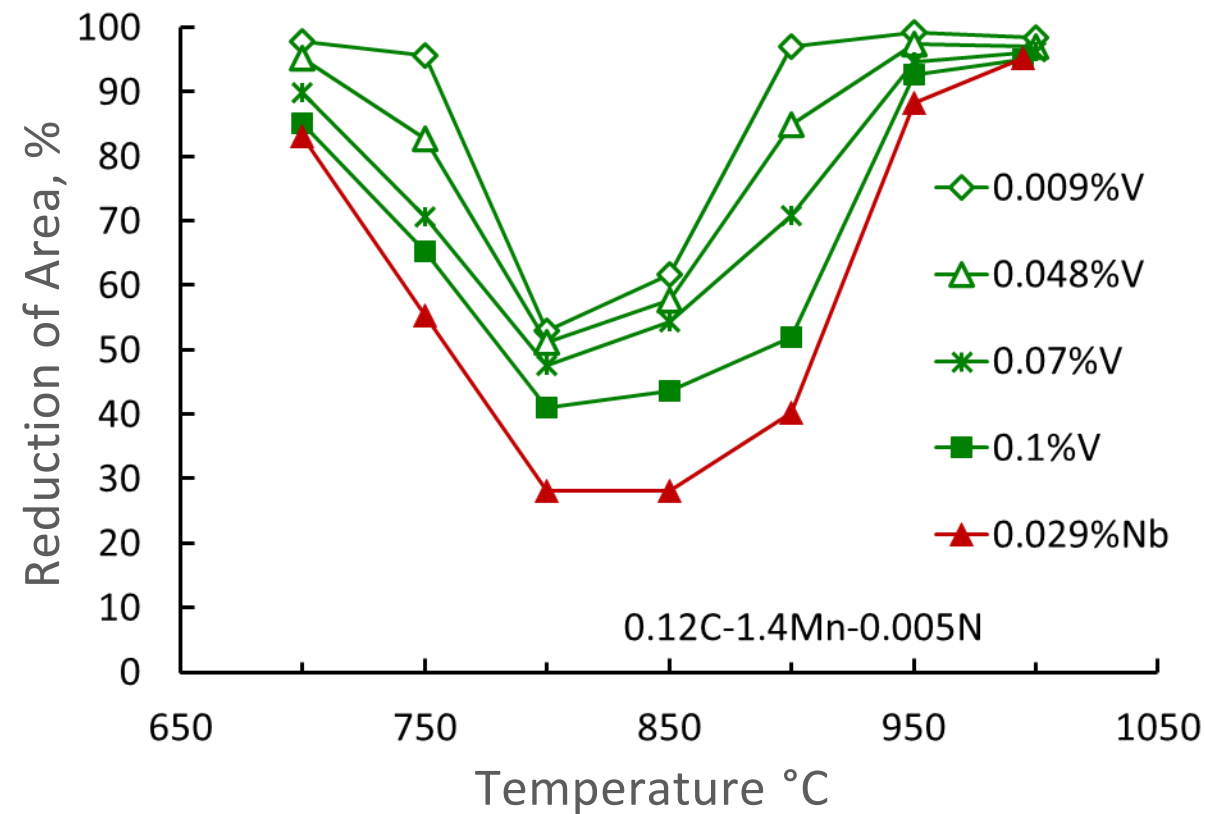
0.06%V Steel

Strain ageing eliminated by V addition of 0.06%

N content 0.006%



# CONTINUOUS CASTING

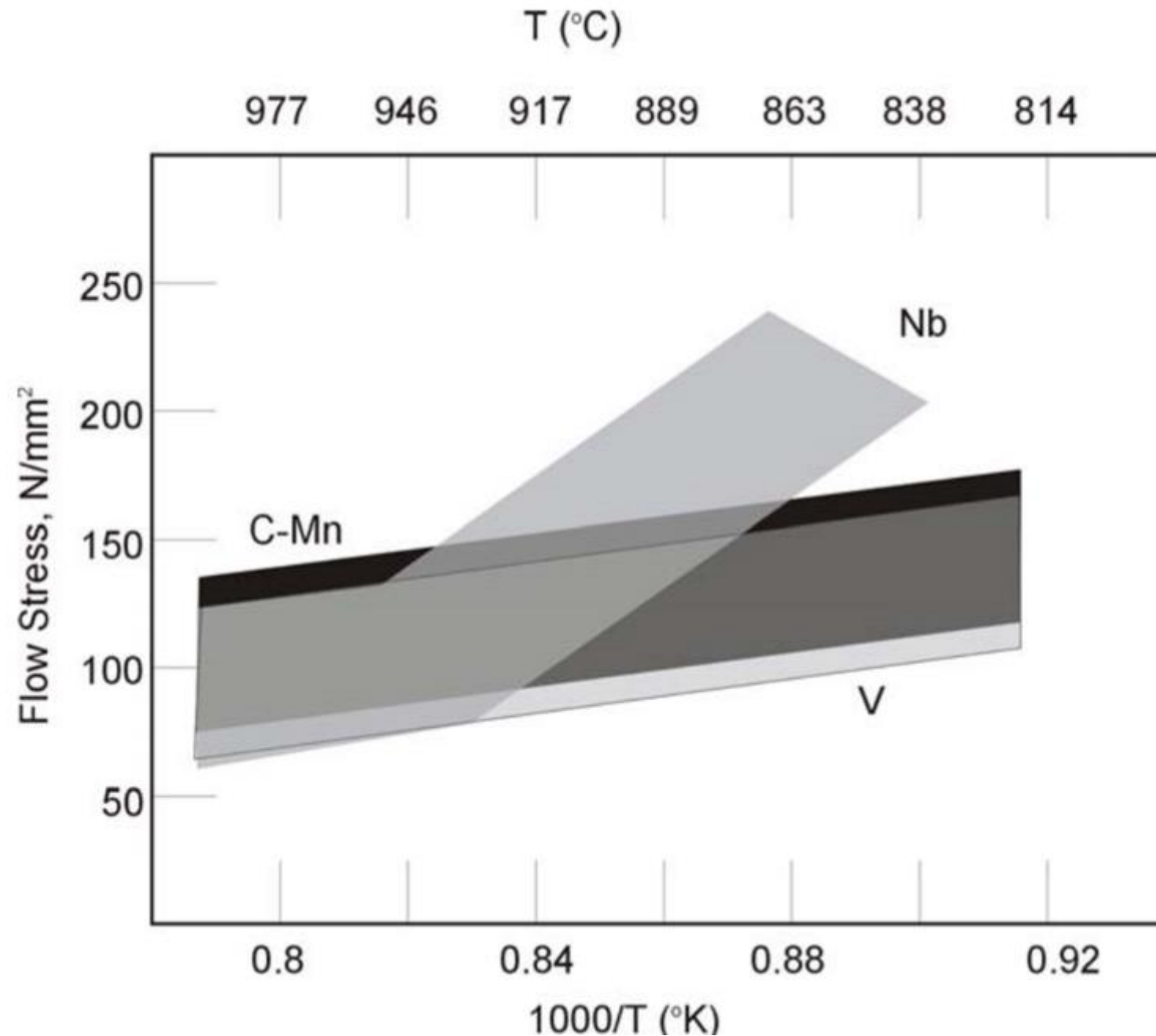


V steels show higher ductility at high temperatures than Nb steels.

As a result V steels show reduced cracking during continuous casting in comparison with Nb steels.

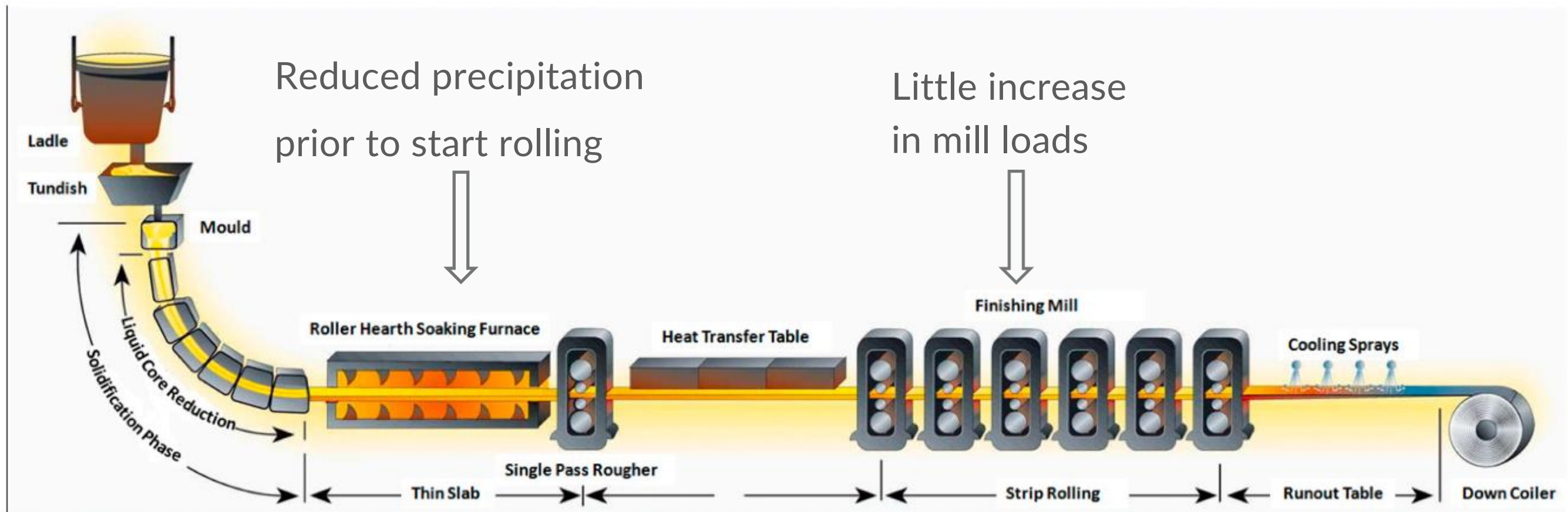


# VANADIUM AND HOT FLOW STRESS



Vanadium has little influence on hot flow stress and hence little influence on rolling loads

# VANADIUM, THIN SLAB CASTING & DIRECT ROLLING



Reduced defects during casting

Rapid austenite recrystallisation

Formation of fine V(CN) to increase strength



# VANADIUM STEEL FOR CONSTRUCTION

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- More than 50% of world steel production was used for construction in 2021
- Vanadium is the most widely used alloying element for strengthening steels employed in buildings and bridges.
- Vanadium microalloyed steel is the best choice for making high strength reinforcing bars, which counted more than half of steel used for construction in 2021.
- Vanadium is also used in hot rolled steel plates, sections and tubes for construction.



Birds Nest (Beijing)



Beijing Daxing Airport



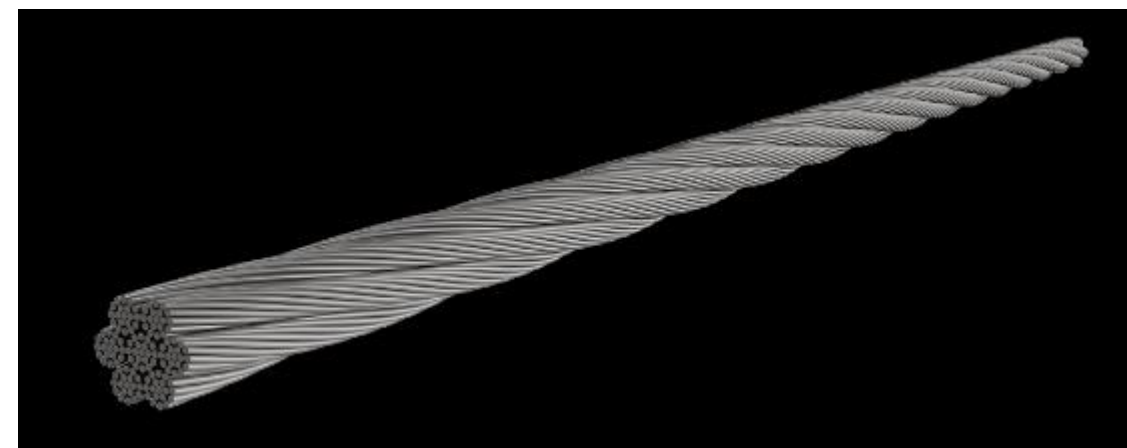
Reinforcing Bar



Bridge Construction

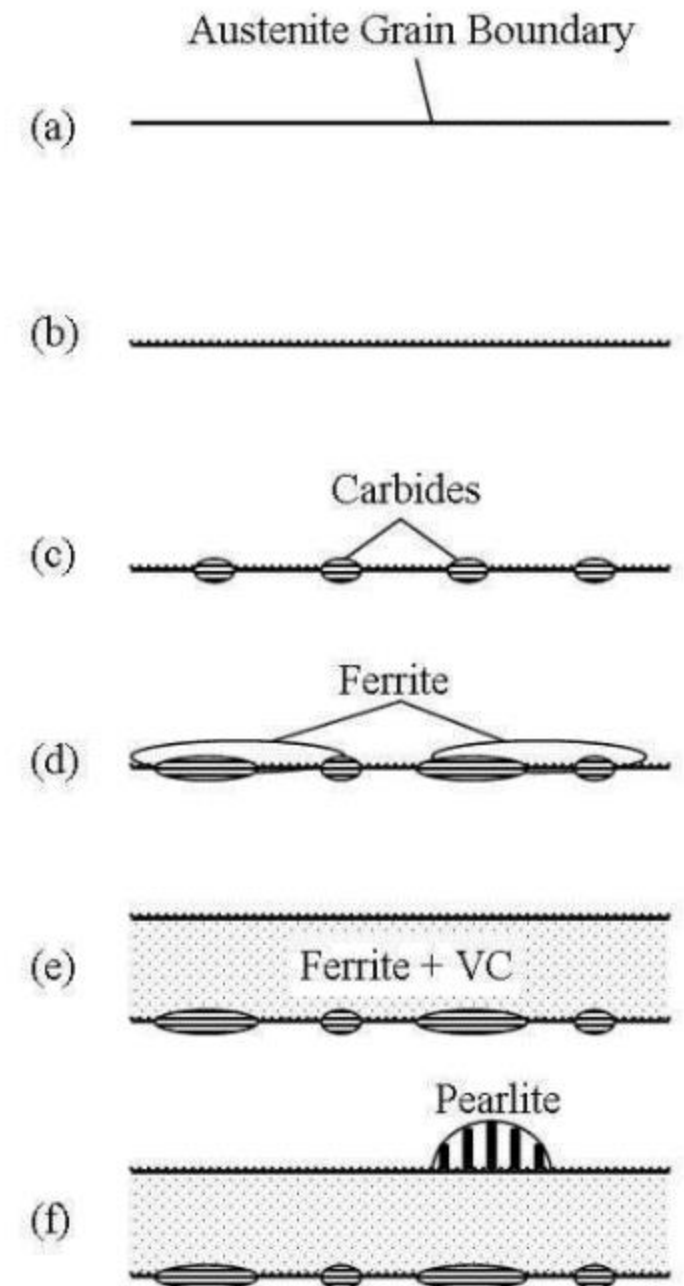
# VANADIUM IN WIRE ROD

- High strength rod required for wire drawing applications such as bridge wire and mooring cables
- Wire strengths  $>2\text{GPa}$  are under development
- Ultra-high strengths are achieved by using hyper-eutectoid C in combination with alloying with V, Si and Cr
- V alloying gives precipitation strengthening in pearlitic ferrite
- Strength increases in the rod are maintained after wire drawing
- V alloying improves ductility



# VANADIUM IMPROVES DUCTILITY IN HYPER-EUTECTOID STEELS

- V alloying modifies the pearlite transformation in hyper-eutectoid steels and improves ductility
- V alloying prevents the formation of coarse grain boundary cementite (Fe carbides)
  - (b) Formation of fine VC at gamma GBs
  - (c) Formation of fragmented carbides (cementite)
  - (d) Formation of ferrite and VC
  - (e) Pearlite transformation



Reproduced from Han et al.  
**VANITEC**  
TRANSFORMING POSSIBILITIES

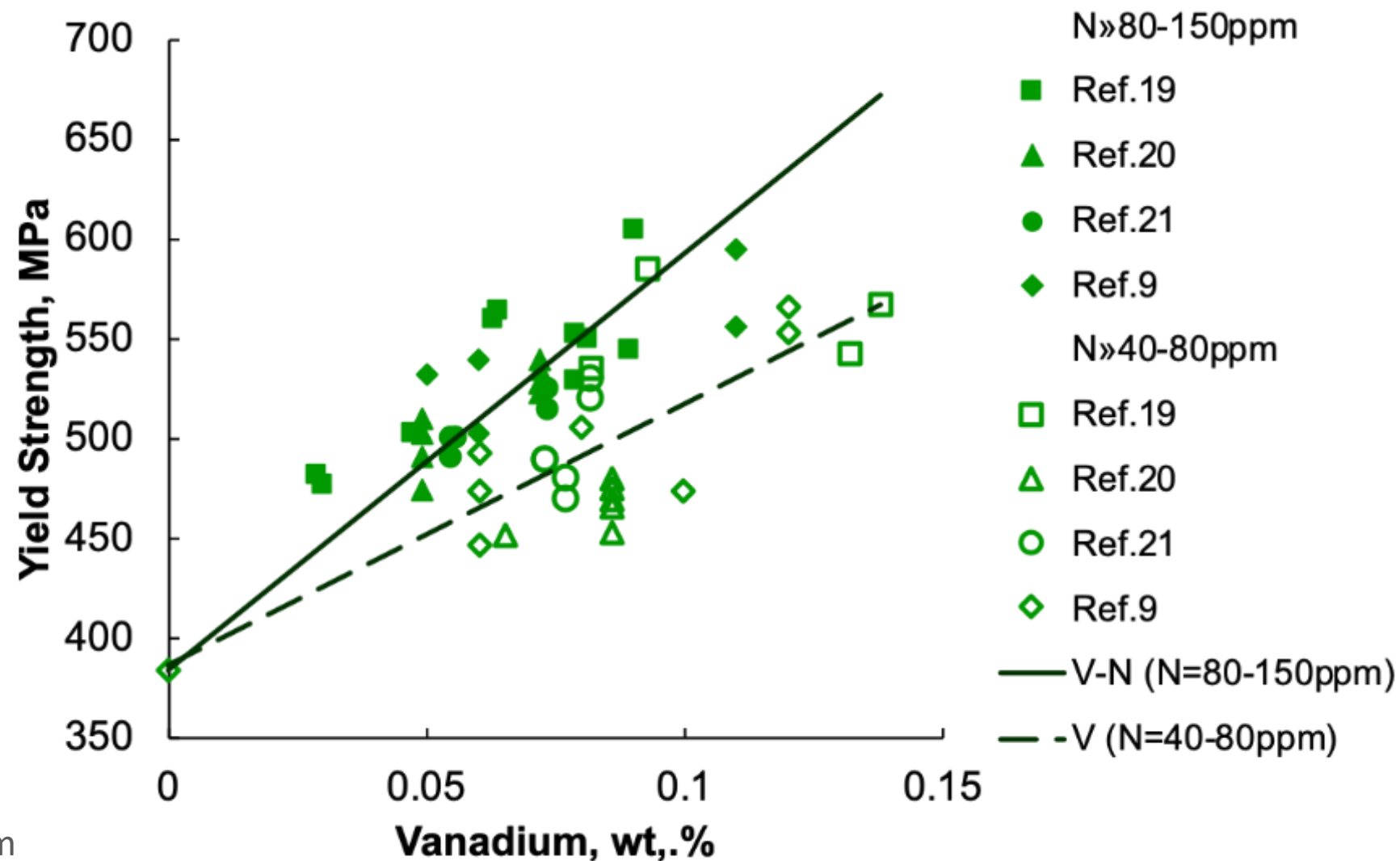


# VANADIUM IN REBAR

- V commonly used in high strength weldable rebar
- Suitable for use in seismic zones
- Easy to dissolve V(CN) precipitates prior to rolling
- Can use low reheat temperatures
- Consistent properties, low rolling loads
- Excellent bending, resistance to strain ageing
- Weldable
- Improved low cycle fatigue properties



# INFLUENCE OF V AND N ON REBAR YIELD STRENGTH

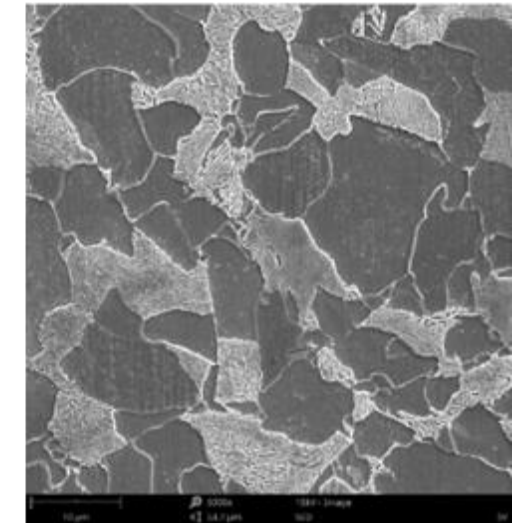
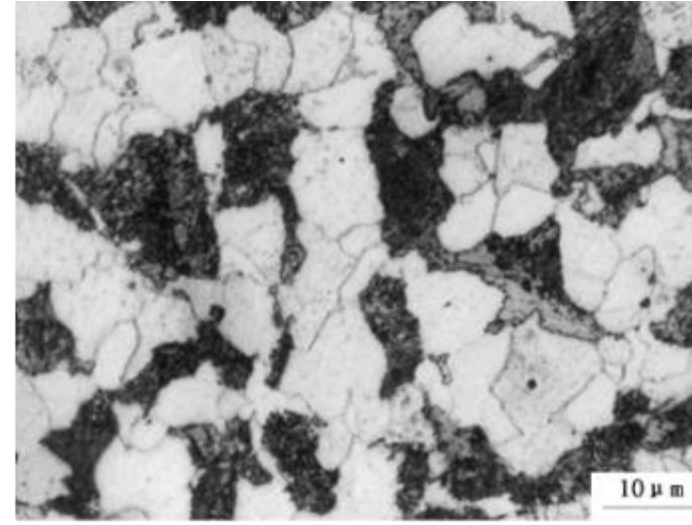
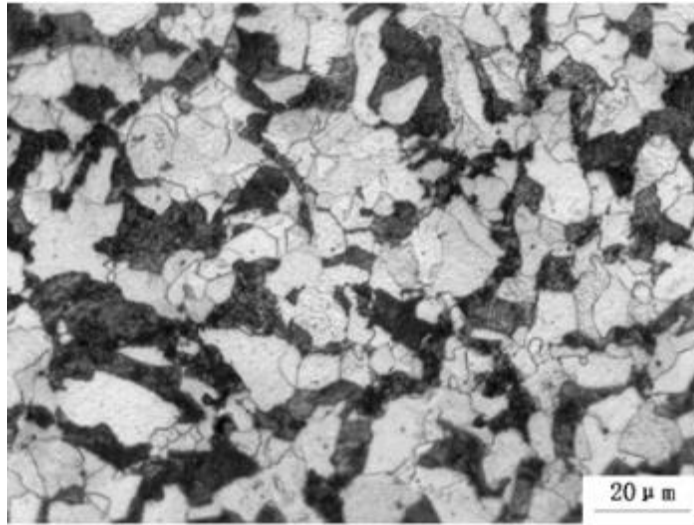


Diameter 8-40mm

Strengths up to 600Mpa achievable. Increased N increases strength



# TYPICAL REBAR MICROSTRUCTURES

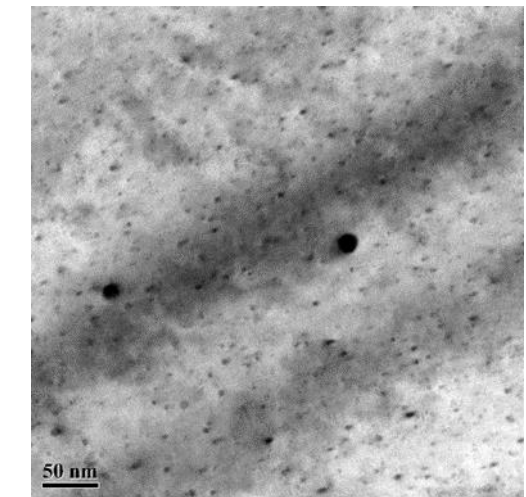


Ferrite grain size 8μm, pearlite = 40%

V additions to rebar increase strength due to:

1/Precipitation strengthening

2/Grain refinement



“Random” V(CN) in ferrite

25mm diameter gr 500: 0.23%C 0.44%Si 1.4%Mn 0.092%V 0.010%N



# VANADIUM STEEL FOR TRANSPORTATION

- Vanadium is used in steel strips and plates for transportation to improve strength, reduce product weight and increase payloads.
- Vanadium microalloyed steel plates are often preferred for shipbuilding as vanadium steels are free from the casting and other problems associated with alternative steels. Vanadium also promotes a microstructure in the heat affected zone of welds associated with higher toughness.
- The addition of vanadium to rail steels increases hardness and improves toughness, and thereby increase the wear resistance of the rails.



Railway wagons



Rails



Ship Building Plate



Sheet piling

# VANADIUM IN RAIL STEELS

- Vanadium increases hardness in both medium carbon and high carbon rails
  - Grooved rails
  - Vignole rails
- Hardness greater than 335HB can be achieved in air cooled rails
- Due to reduced wear, reduced rolling contact fatigue and reduced corrugations, rail life increased by a factor greater than 3





# VANADIUM STEELS FOR AUTOMOTIVE APPLICATIONS

- Vanadium is the most widely used microalloying element in high strength air-cooled forgings for critical automotive components in the drivetrain and chassis of modern cars and trucks, such as crankshafts, connecting rods and steering knuckles.



Crankshaft



Connecting Rods



Steering knuckle

- Vanadium is used in automotive hot and cold rolled strips to increase strength and improve formability, thereby reducing weight and fuel consumption.

U Bolts



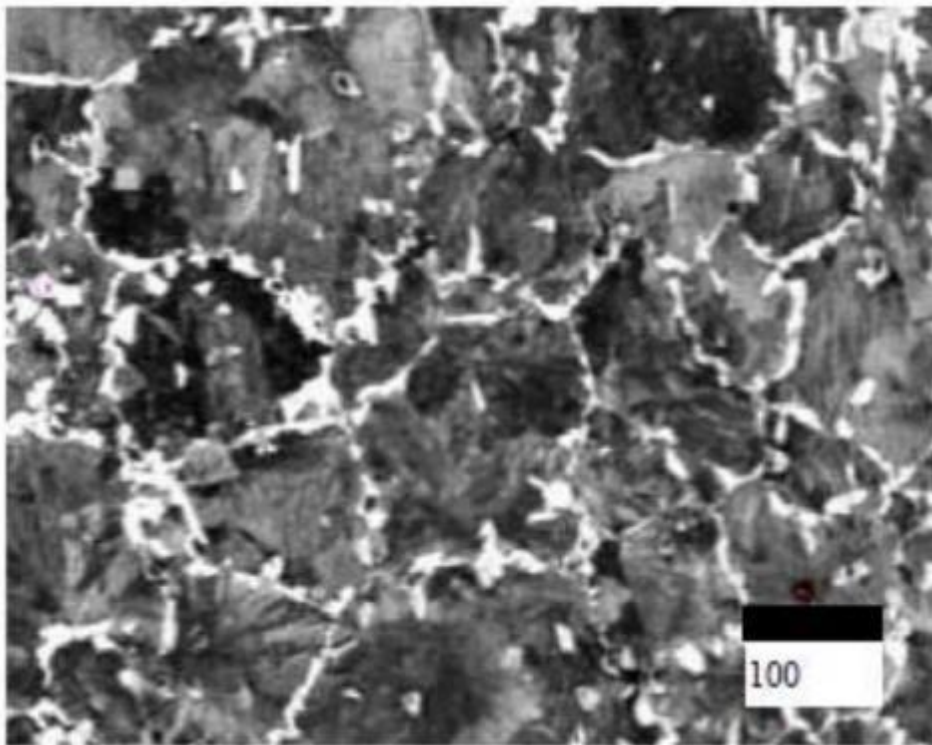
Coil Springs



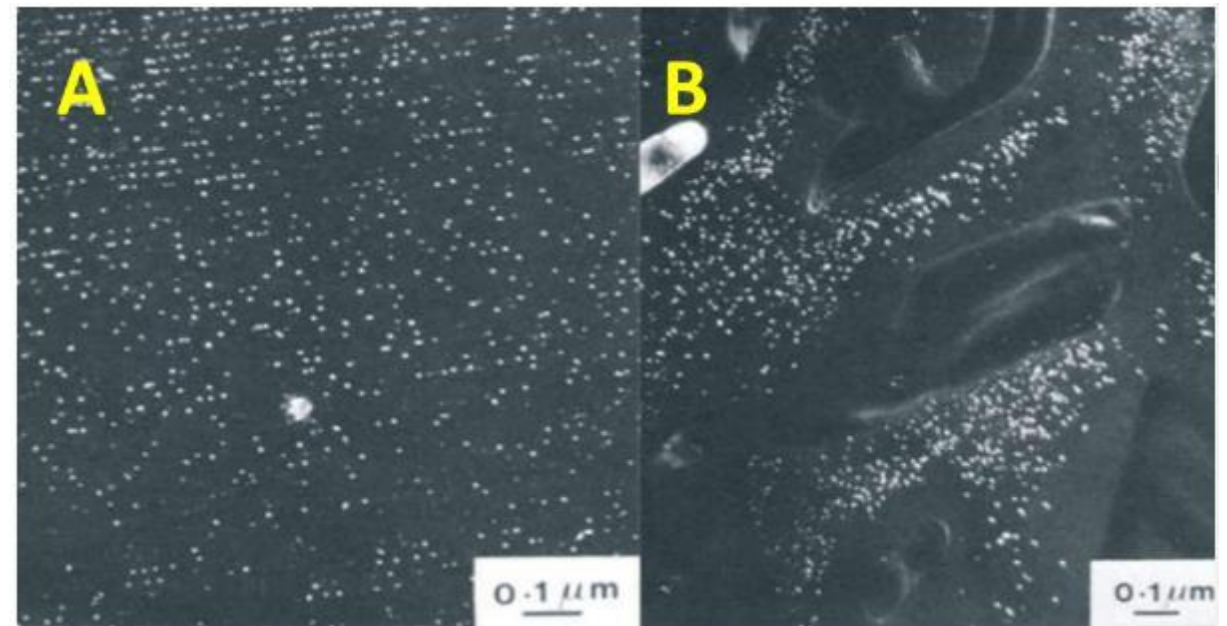


# VANADIUM IN MEDIUM C AIR COOLED FORGINGS

- Forgings for applications such as crank shafts and con rods
- Air cooled V microalloyed forgings have replaced Q&T products
  - Tensile strengths up to 1200MPa
  - Reduced production costs
  - Improved machinability



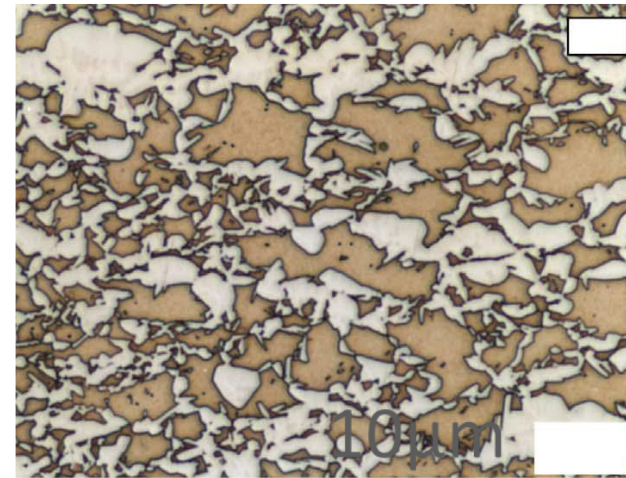
Typical ferrite-pearlite microstructure



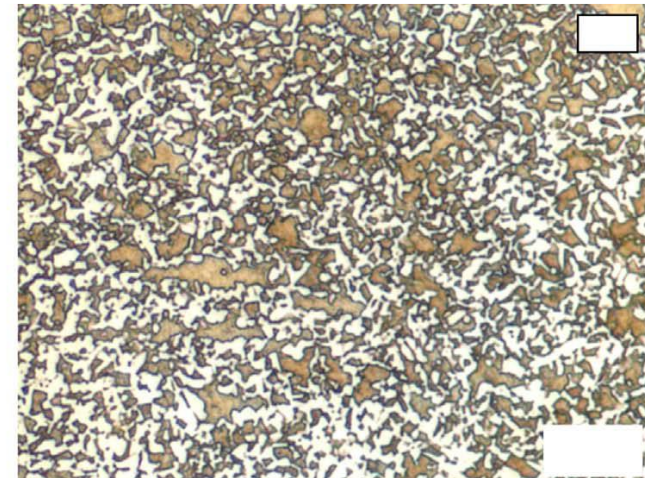
V(CN) precipitation in ferrite (A) and Pearlite (B)

# VANADIUM IN DUAL PHASE STEELS

- Dual Phase ferrite-martensite steels are the most common AHSS
- DP steels have high strength and high ductility
- V additions to DP steels increase strength
  - 1/ Grain refinement
  - 2/ Selective precipitation in ferrite



Ref 750°C/120s



Ref+0.14%V 750°C/180s

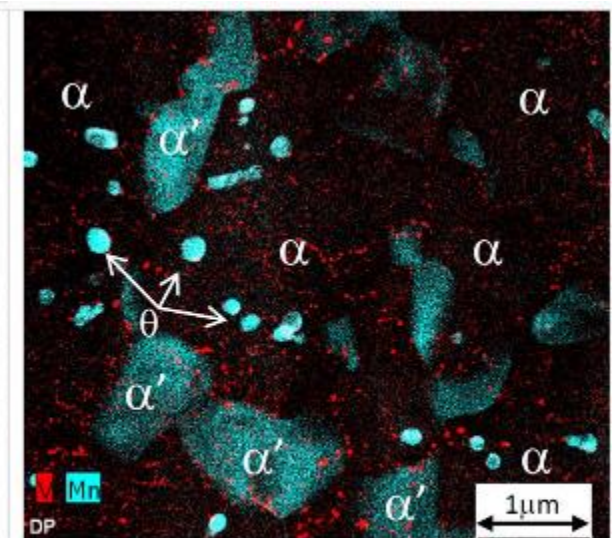
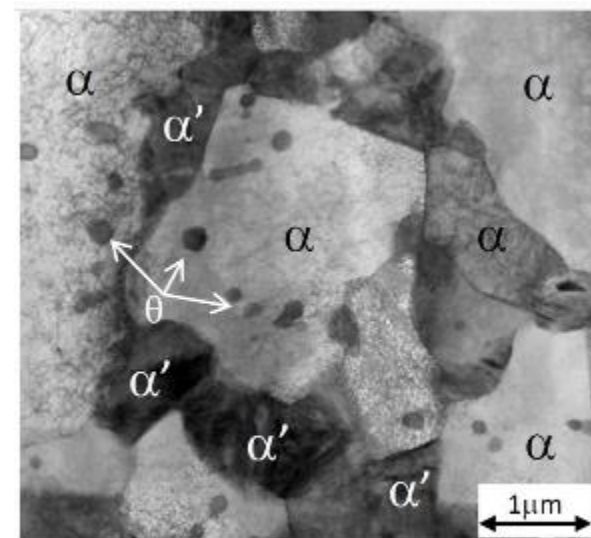
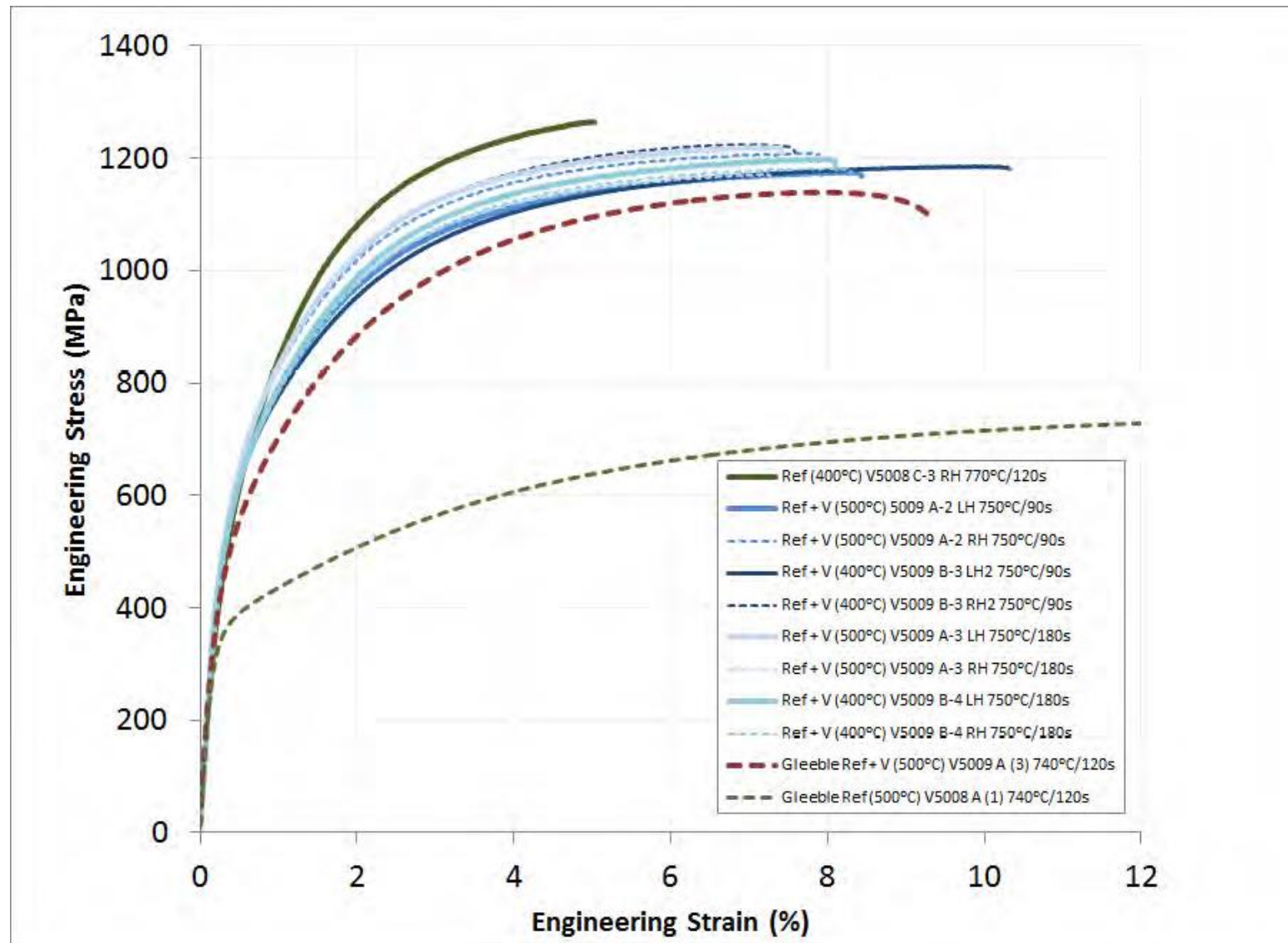


Figure 7: a) Thin foil BF STEM image of the Ref+V alloy after annealing at 740 °C / 120s and die quenching. b) Composite EDX chemical map of the same region showing Mn (blue) and V (red).



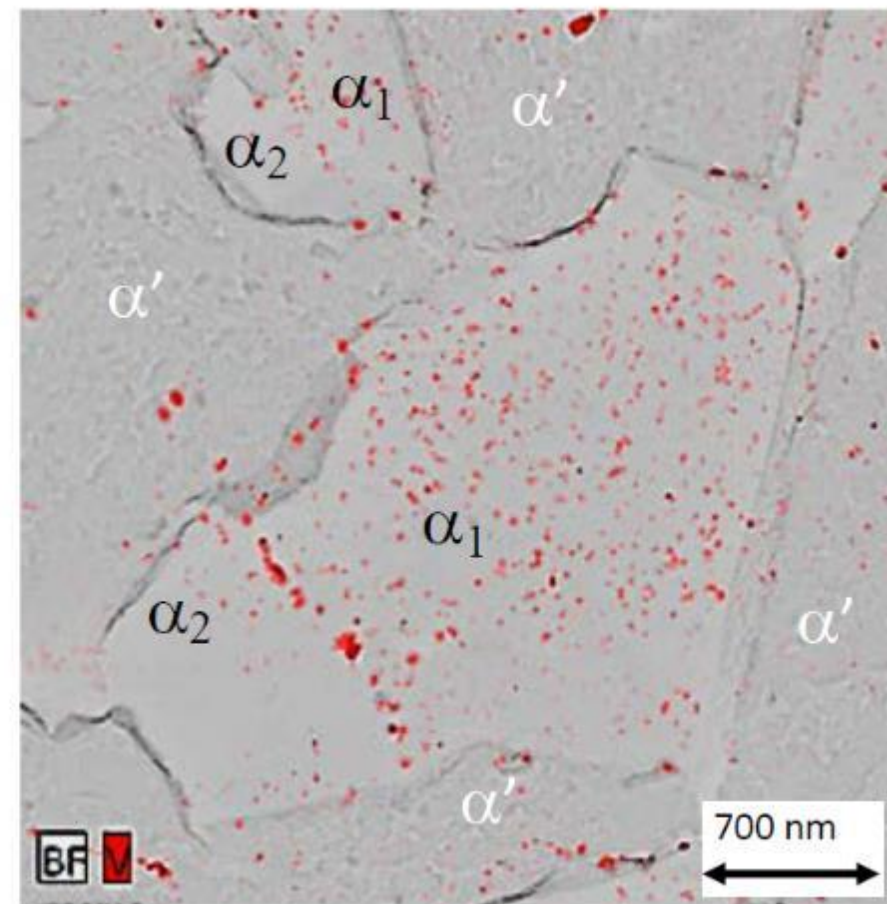
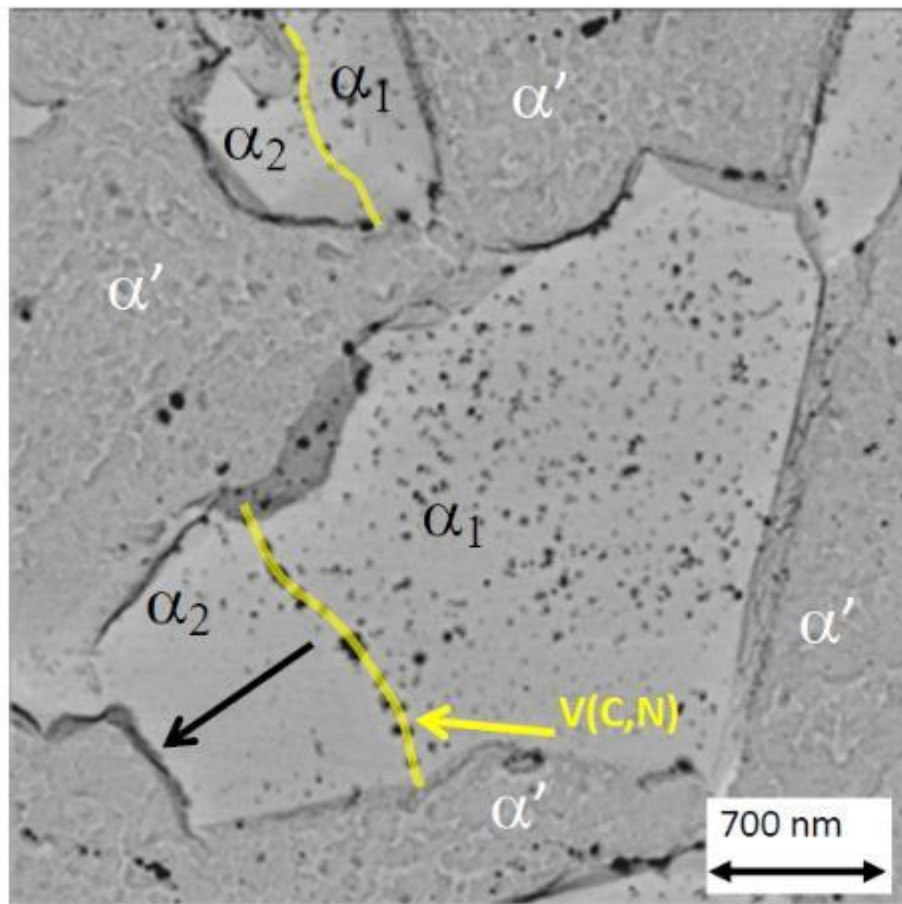
# DUAL PHASE STEELS – V STRENGTHENING EFFECT, COLD ROLLED AND ANNEALED



Increasing strength with V additions (0.15%) and increasing annealing temperature



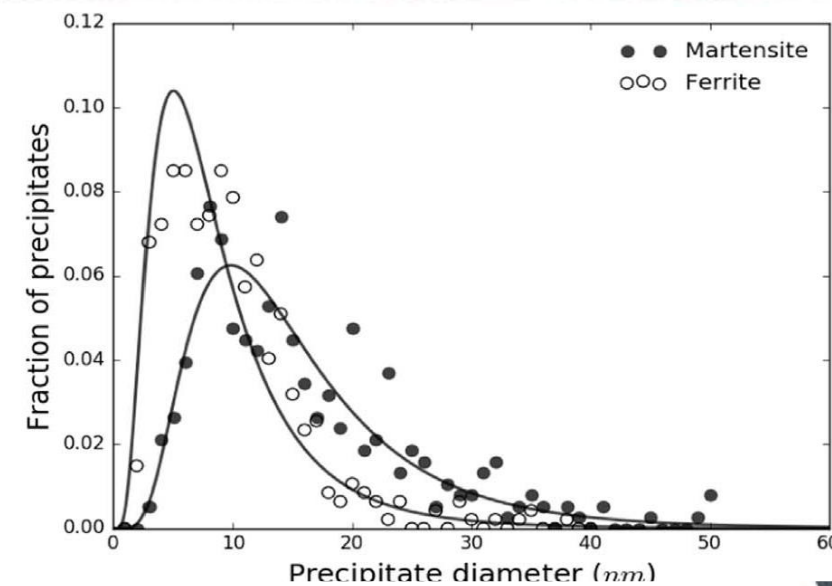
# DUAL PHASE STEELS - MICROSTRUCTURE



Reduced V precipitation in M and epi ferrite

Reduced V precipitate size in ferrite

Decreased hardness difference between M and ferrite

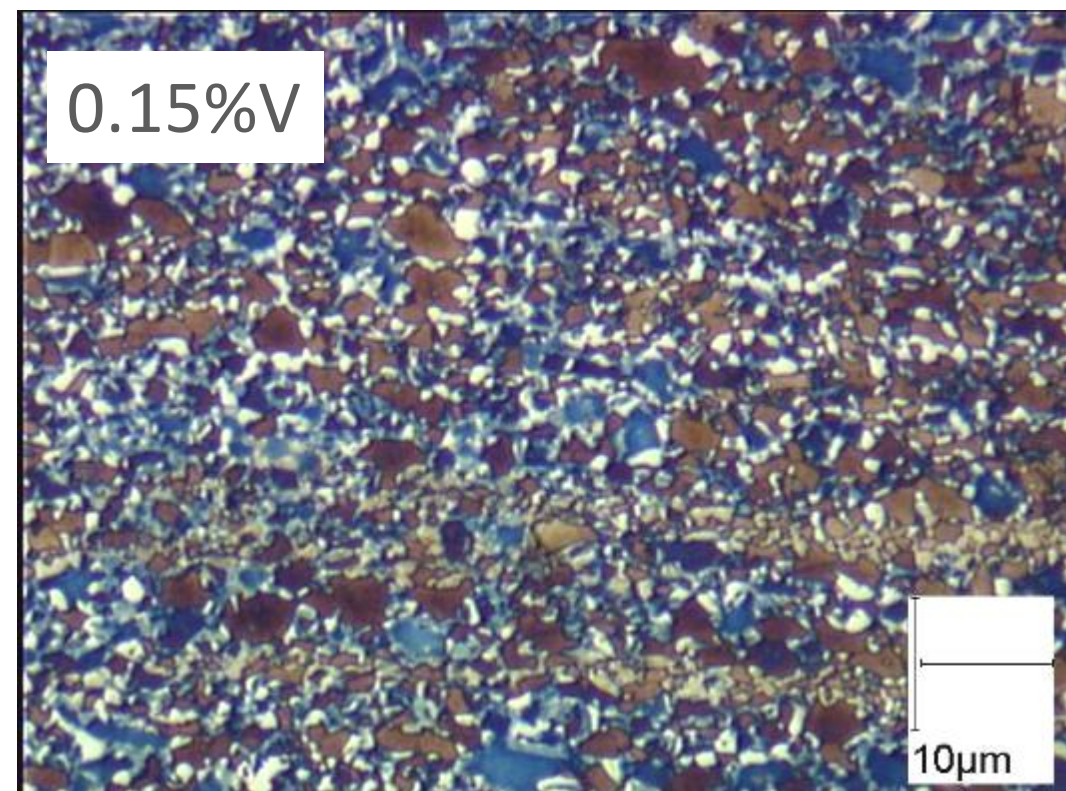
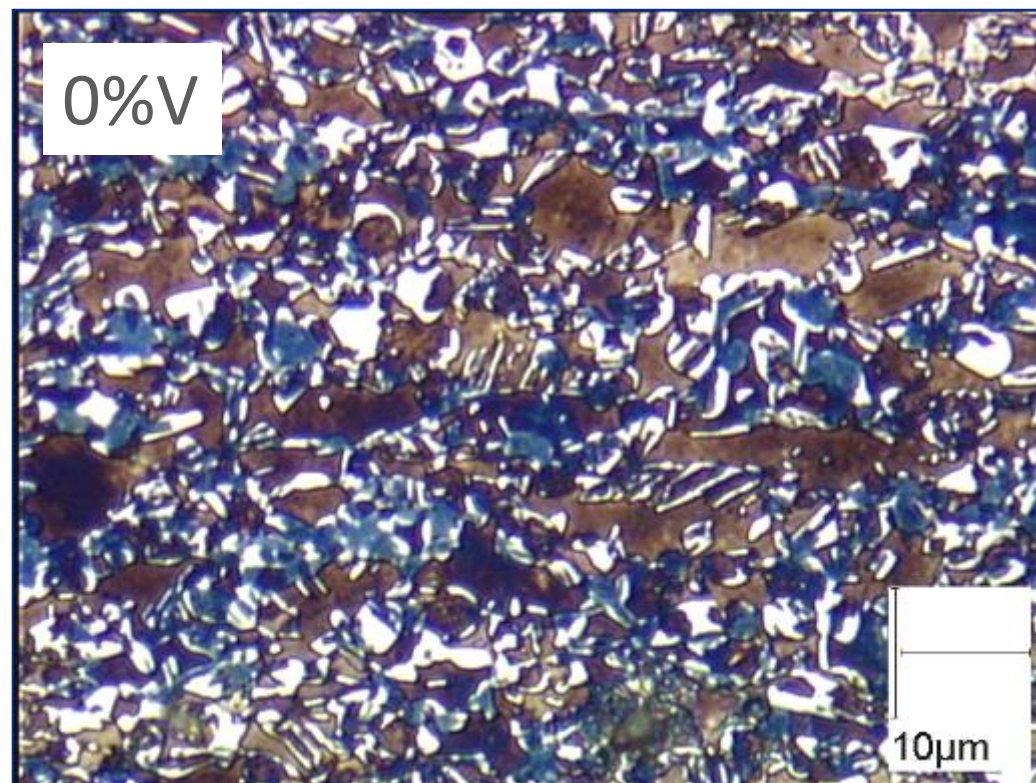




# VANADIUM IN TRIP STEELS

## Cold Rolled and Annealed TRIP Steels

Steel	C	Si	Mn	Ti	V	N
V-Free	0.221	1.59	1.60	0.0022	0.0050	0.0015
0.15% V	0.225	1.60	1.58	0.0025	0.155	0.0090



Microstructure (ferrite, bainite and retained austenite) after continuous annealed for 180 s/775°C then cooled at 20°C/s and overaged for 300 s/400°C.

# VANADIUM IN HOT ROLLED FERRITIC STEELS

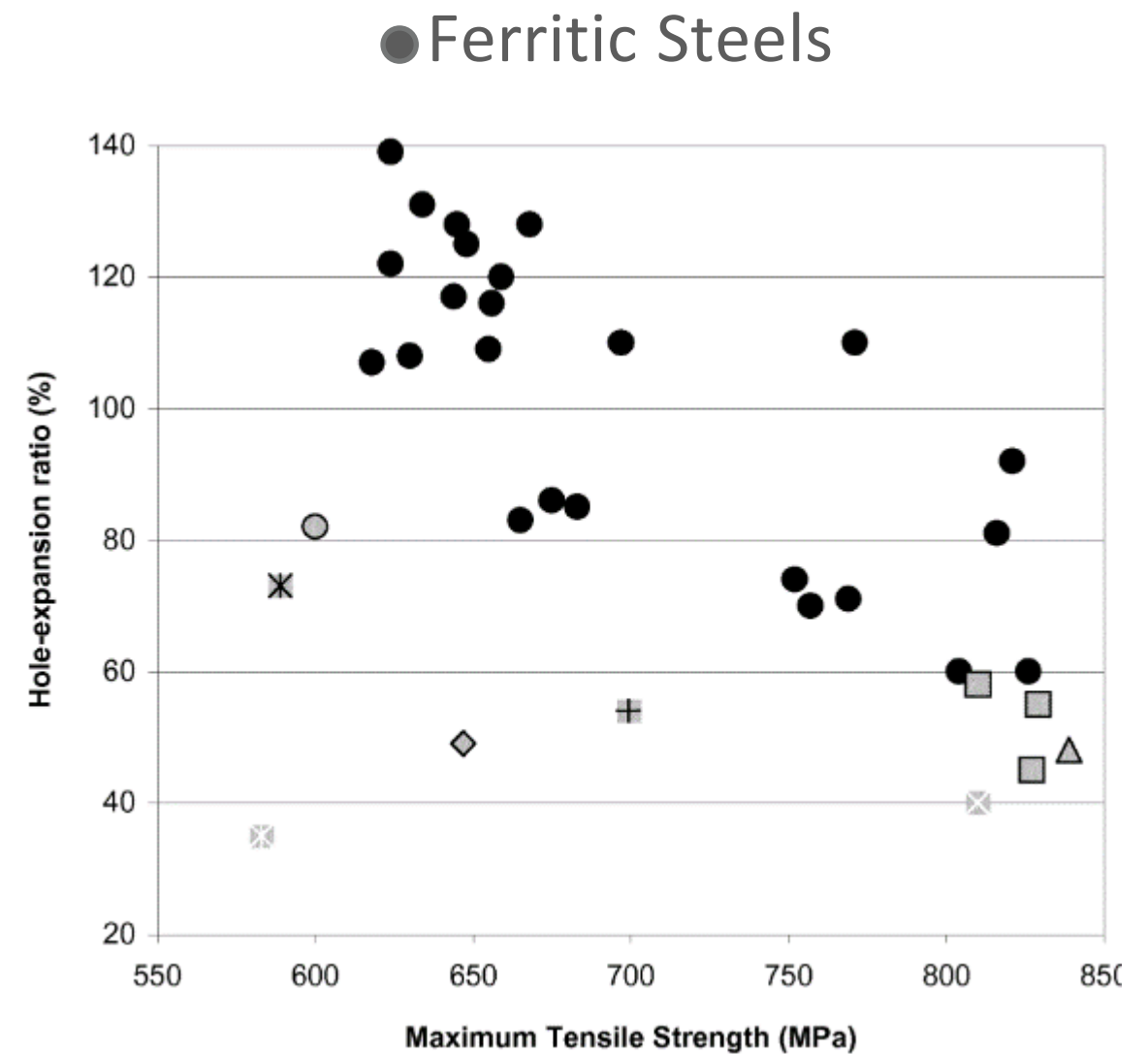
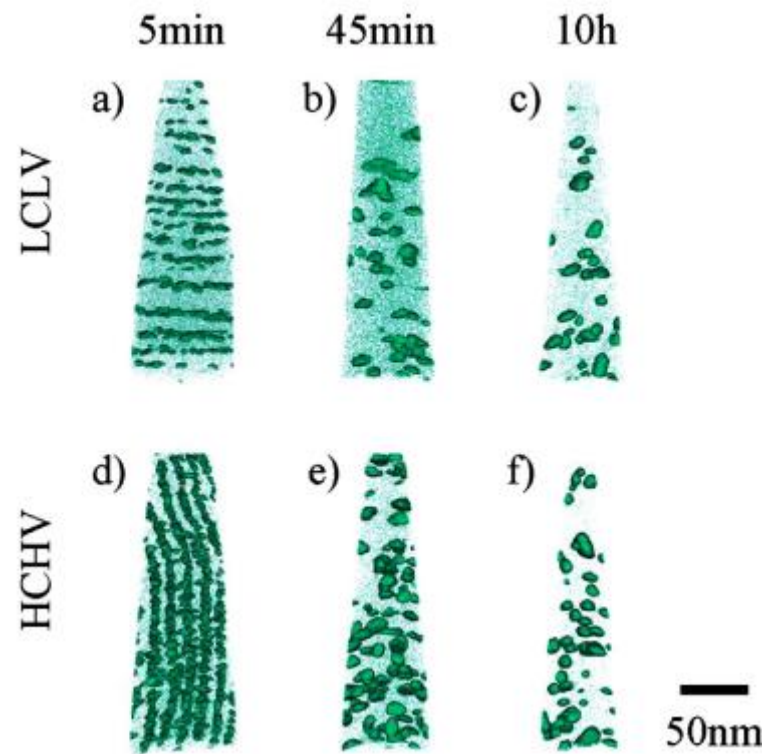
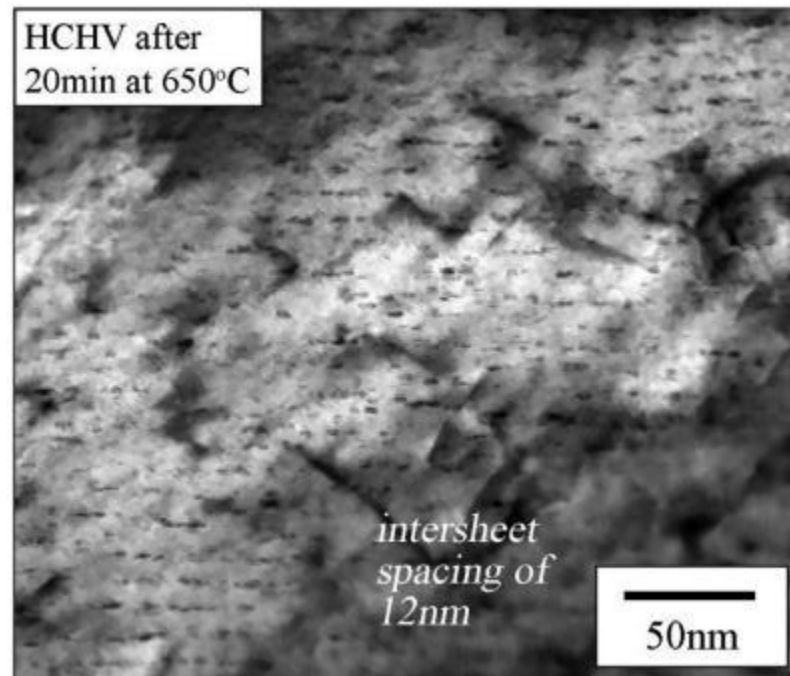
- Hot rolled single phase (Ferritic) steels
  - Single phase gives high hole expansion
  - Single phase gives improved fatigue performance
- Strengthening by extensive V(C,N) precipitation
- Low C and correct choice of V content eliminates pearlite/cementite
- Applications include:
  - Chassis and suspension components,
  - EV crash structures





# FERRITIC STEEL PRECIPITATION AND HOLE EXPANSION

V interphase precipitation



Improved hole expansion

# SUMMARY

- Vanitec
  - Represents vanadium producers and users and promotes vanadium
- Vanadium resources and production
  - Wide geographic distribution, increasing production
- Vanadium the Versatile Element
  - Used in a wide range of steels (Ti alloys, batteries)
- Vanadium Steel Metallurgy
  - V(CN) precipitation, strengthening, grain refinement
- Production of Vanadium containing steels
  - Ease of casting, rolling
- Vanadium Containing Steels in Construction
  - Wire rod, rebar
- Vanadium Containing Steels in Transportation
  - Rail, automotive applications



**Thanks for your attention**

**Any questions?**

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