

# The Use of Vanadium in High Strength Low Alloy Steels

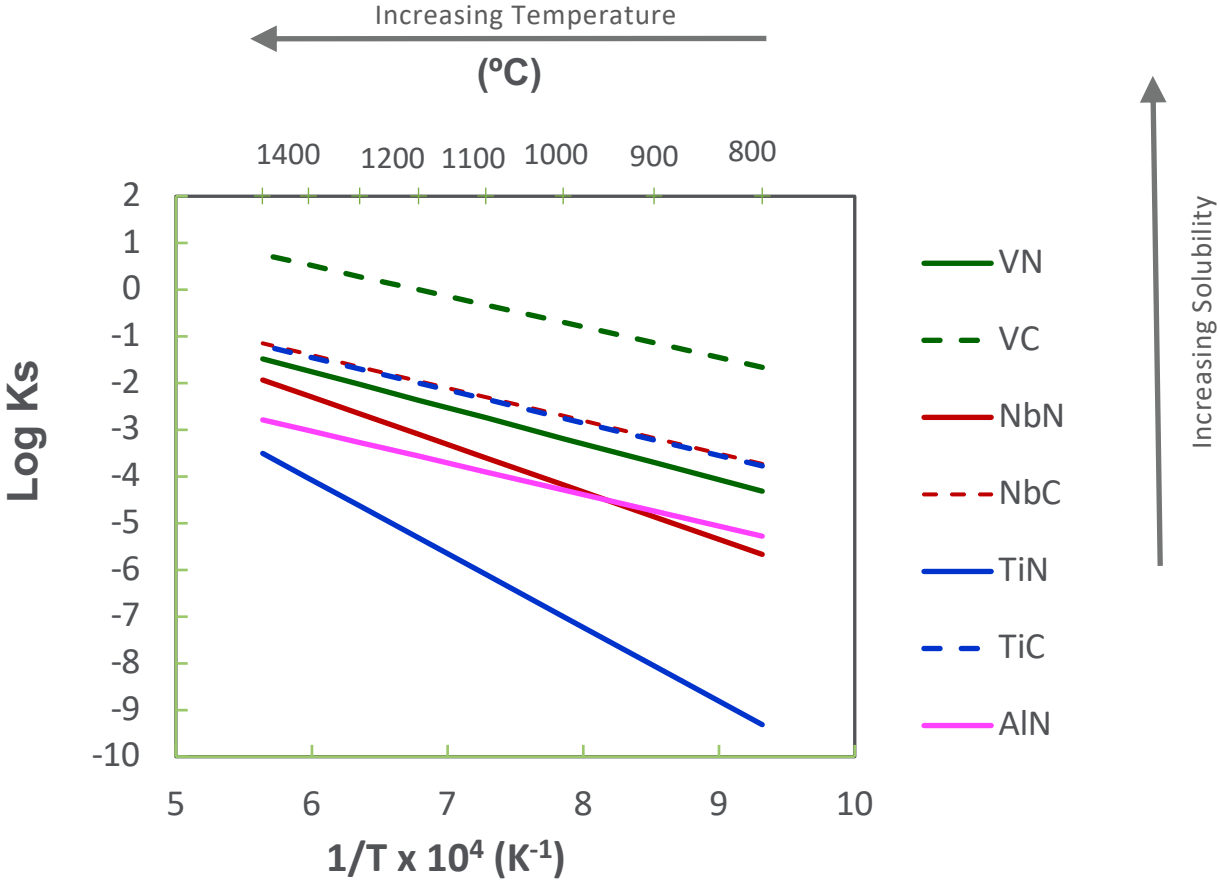
David N. Crowther and Yu Li



# Introduction

- Trends to increased steel strength whilst maintaining ductility and toughness
  - Reduce the amount of steel required, reduced environmental impacts
- HSLA steel properties strongly influenced by microalloy carbide/nitride precipitates  $M(CN)$ 
  - Precipitation strengthening
  - Grain refinement
    - Pinning austenite grain boundaries, nucleation sites for ferrite
- $M(CN)$  precipitate size and volume fraction control strengthening and grain refinement
- $M(CN)$  solubility important in determining formation temperature, and hence size and volume fraction
- $V(CN)$  has a high solubility in austenite and ferrite
- Allows  $V$  to be used in steels with a wide range of  $C$  contents
- Allows  $V$  to be used for a wide range of processing conditions
- In this presentation examples will be given of recent applications of  $V$  in a wide range of HSLA steels processed under a variety of different conditions
- Vanadium – the versatile element

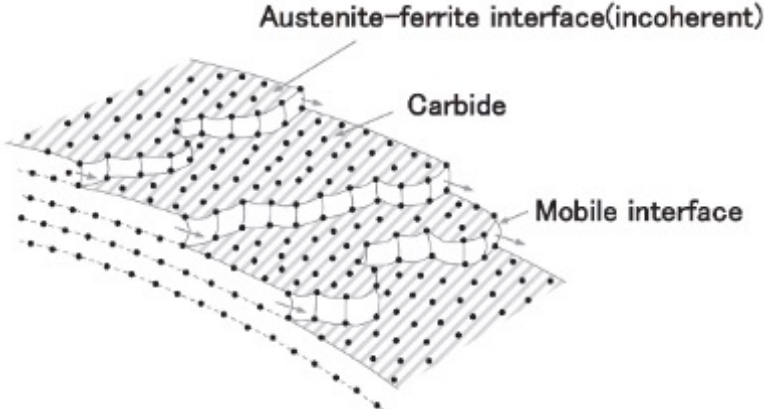
# Microalloy carbide and nitride precipitate solubility in austenite



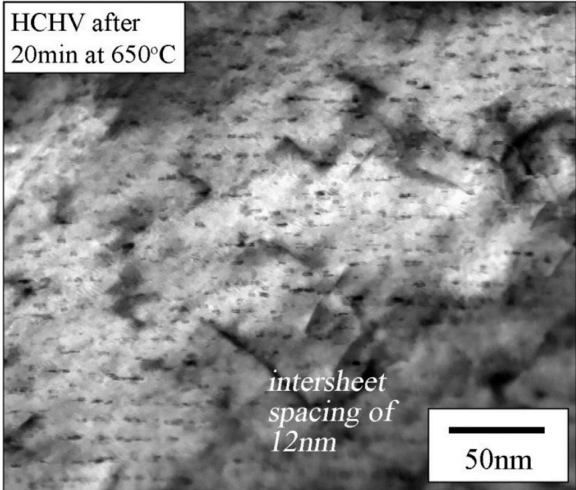
VC and VN have greater solubility than the equivalent carbides and nitrides of Nb and Ti



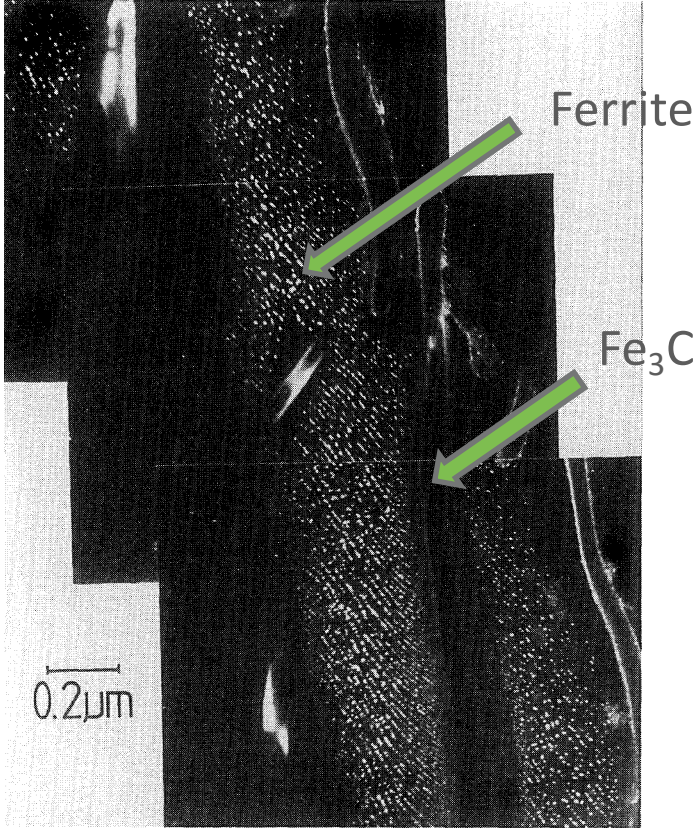
# Vanadium precipitation – interphase precipitation



Schematic precipitation at austenite/ferrite interface

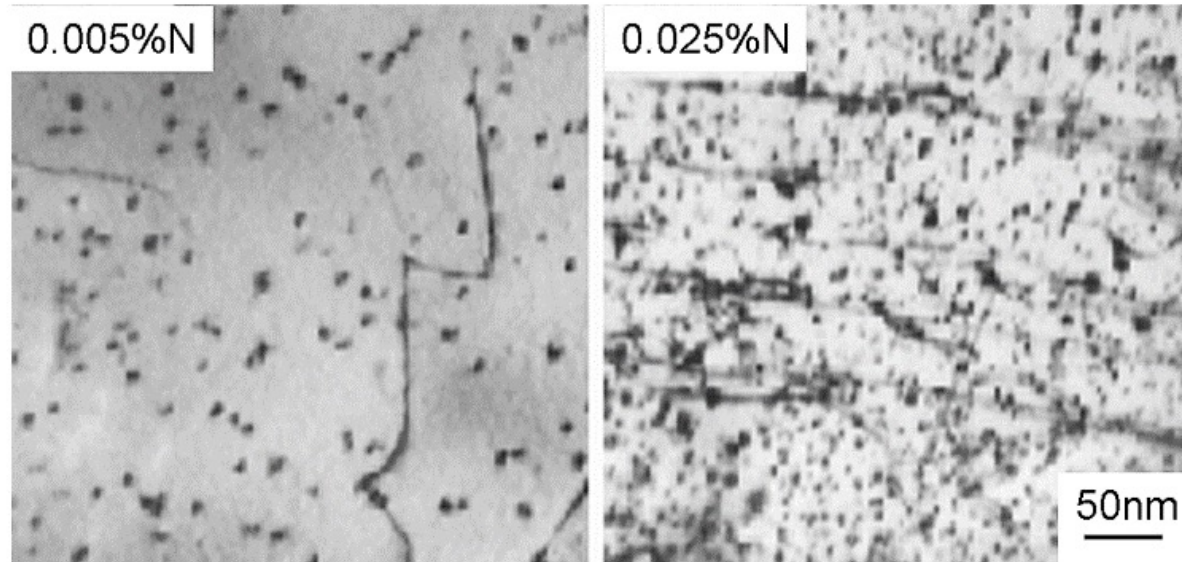


Interphase precipitation in pro-eutectoid ferrite



Interphase precipitation in pearlitic ferrite

## Vanadium precipitation – random precipitation in ferrite



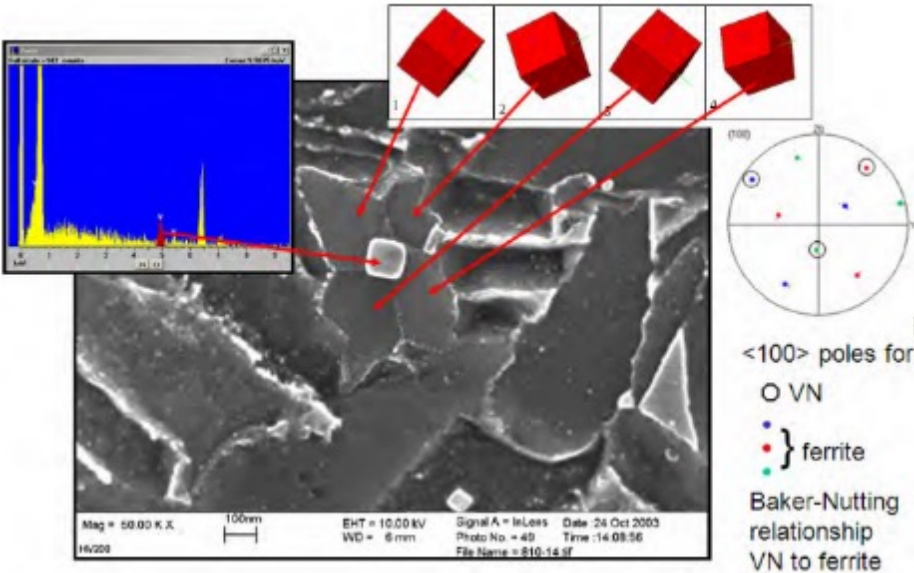
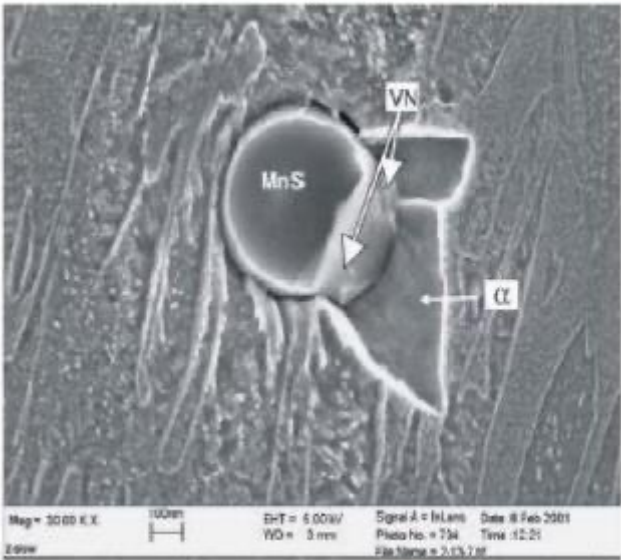
Increased V(C,N) volume fraction with increasing N

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)

# Vanadium precipitation and ferrite grain refinement



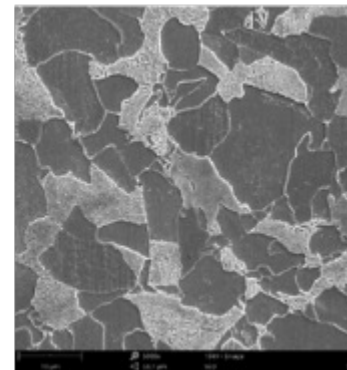
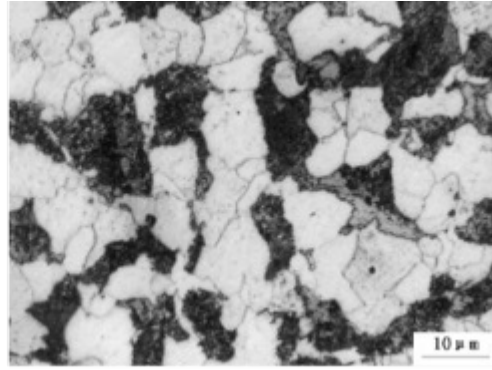
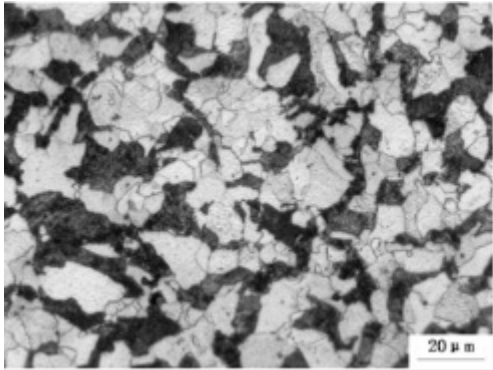
V(CN) can act as a ferrite nucleation site resulting in ferrite grain refinement

## Vanadium in rebar

- Increasing demand for higher strength rebar
- In China, 264Mt rebar was produced in 2020
  - Majority was 400MPa YS, now being replaced by 500 and 600
- Increased C can economically increase strength
- C limited to ~0.25% (500 gr) for weldability and good ductility
- V commonly used in high strength weldable rebar
  - Can use low reheat temperatures – low solution temperatures for V(CN)
  - Low rolling loads – minimal V(CN) precipitation during rolling
  - V(CN) precipitation after rolling – increased strength, consistent properties
  - Resistance to strain ageing due to V(CN) formation
  - Improved low cycle fatigue properties



# Vanadium rebar microstructures

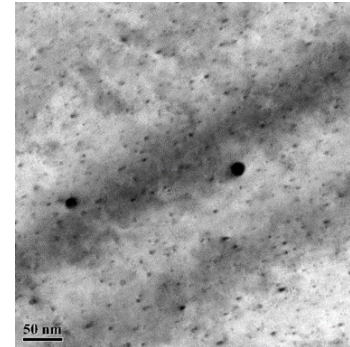


Ferrite grain size 8μm, pearlite = 40%

V additions to rebar increase strength due to:

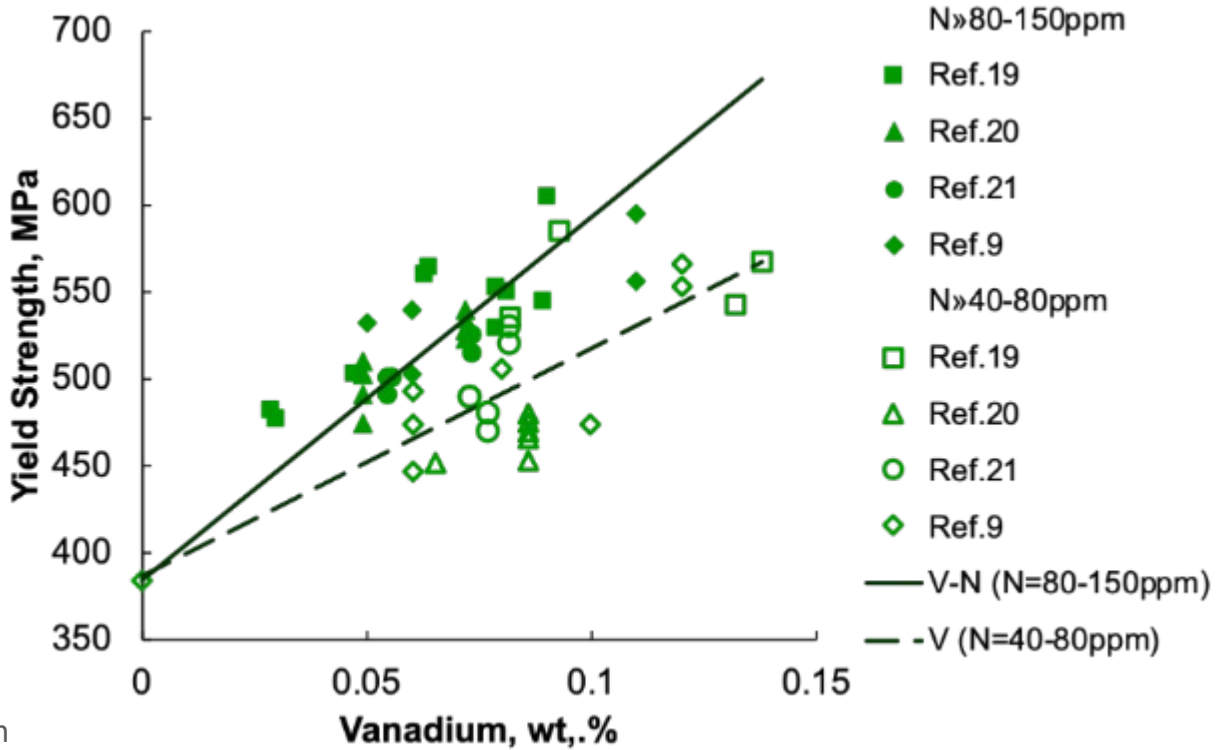
1/Precipitation strengthening

2/Grain refinement



“Random” V(CN) in ferrite

# Influence of V and N on rebar yield strength

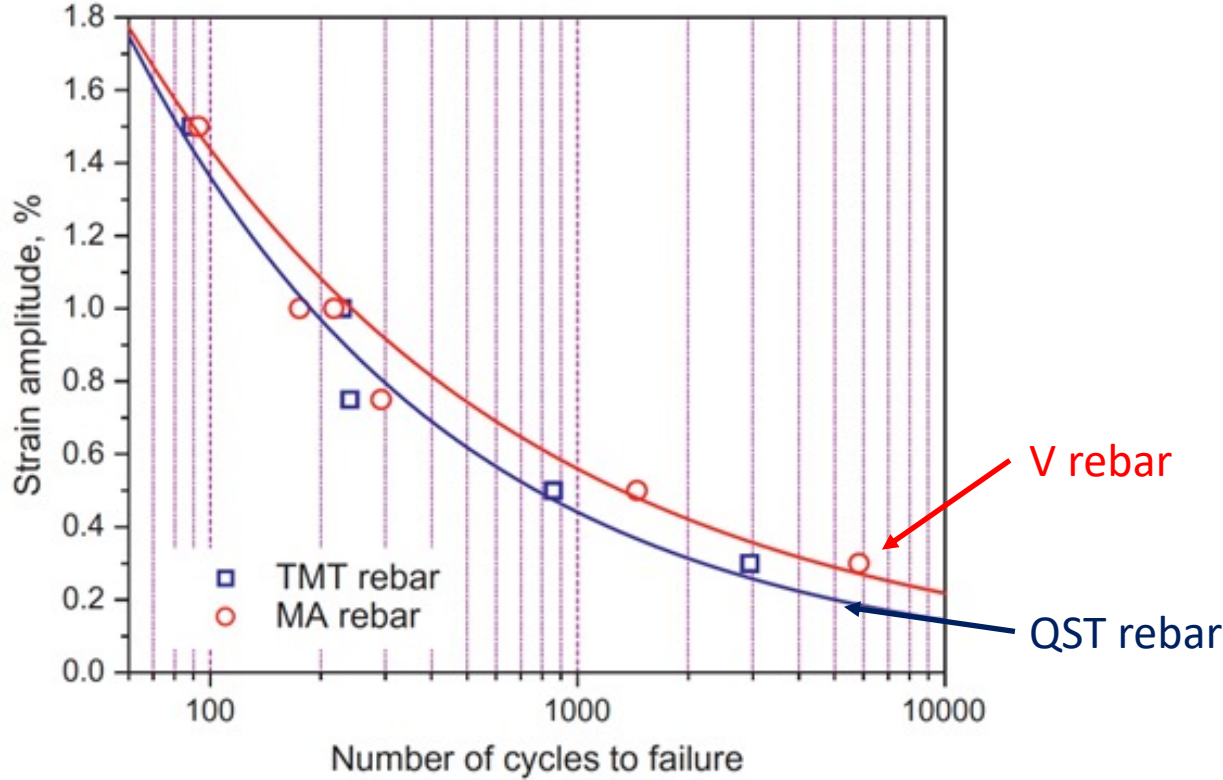


High N content increases V strengthening effect

Strengths up to 600Mpa achievable. Increased N increases strength



# Low cycle fatigue of vanadium containing rebar



V containing rebar shows improved low cycle fatigue compared with quench and self temper rebar  
V containing rebar suitable for seismic zones



After S. K.Paul et. al, Construction and Building Materials, 2014, 54 pp 170-179.

## Vanadium in medium C air cooled forging steels



Crankshaft



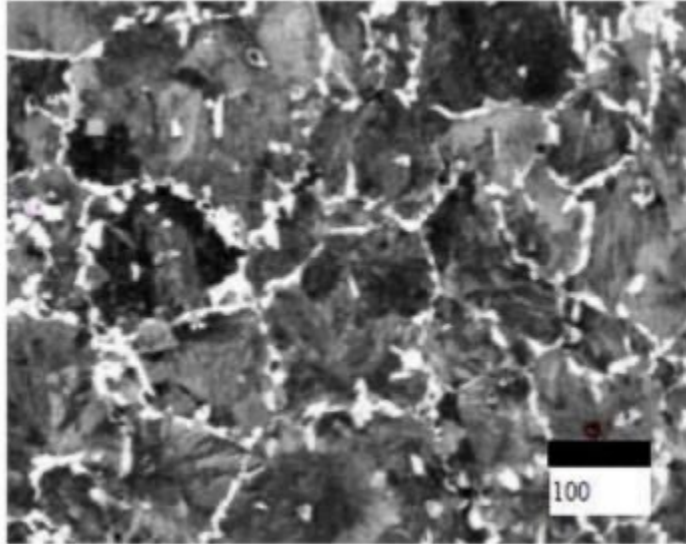
Connecting Rods



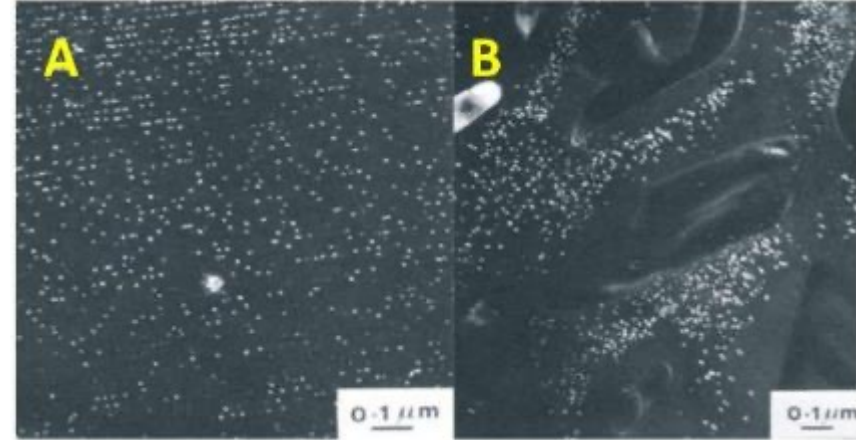
Steering knuckle

- Air cooled forgings used for components such as crankshafts, conrods and steering knuckles
- Air cooled forgings have replaced Q&T forgings
  - Lower costs due to elimination of heat treatment, reduced distortion and easier machining
- V additions increase strength through precipitation and grain refinement
- For C contents of 0.3-0.5%, V is dissolved at normal forging temperatures and precipitates during cooling
- Trends to higher strength (up to 1200MPa), improved fatigue performance
- Bainitic microstructures show improved toughness – V improves hardenability

## Vanadium medium C forgings microstructure



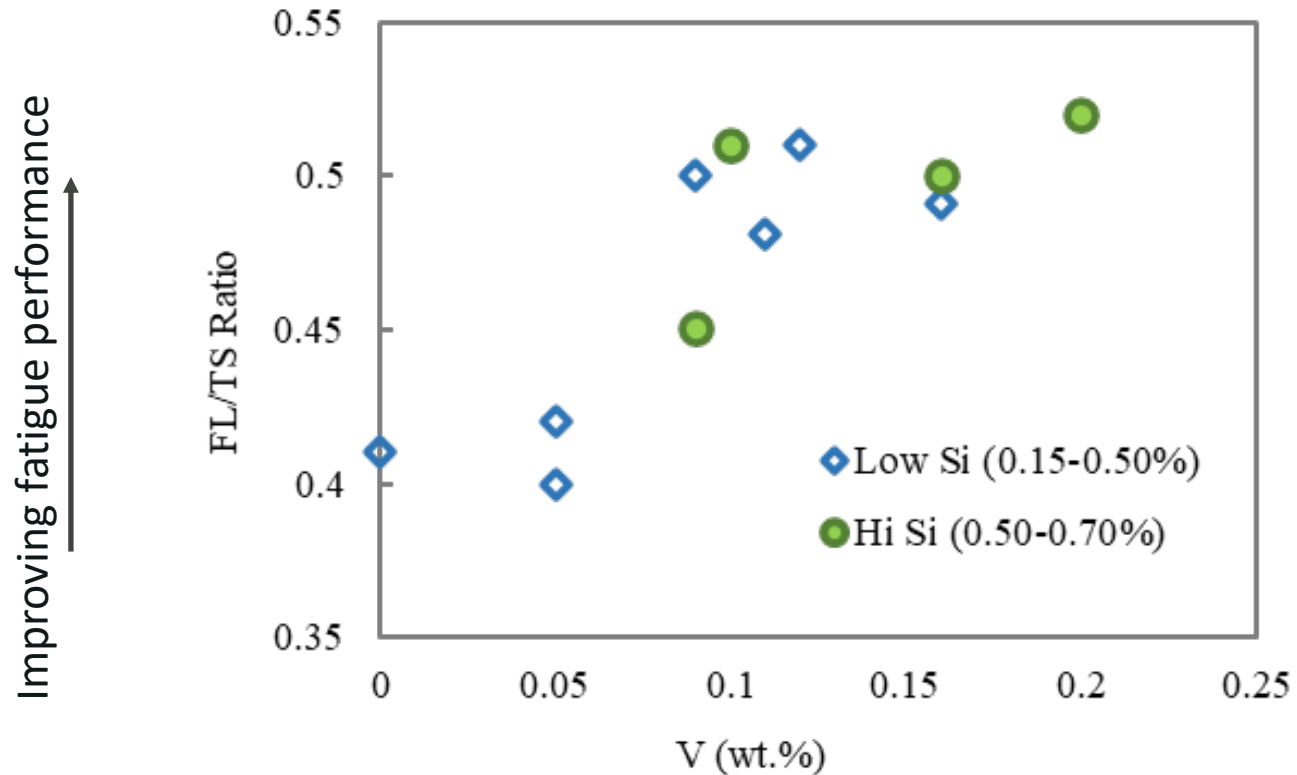
Typical ferrite-pearlite microstructure



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

- Microstructures dominated by pearlite
- V(CN) precipitation strengthening in both pro-eutectoid and pearlitic ferrite

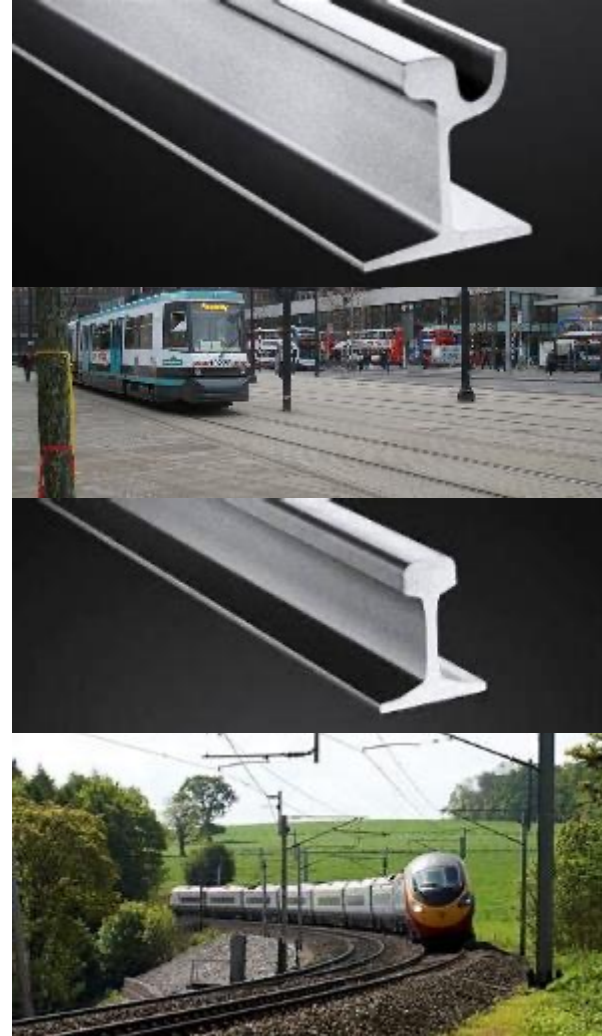
# Fatigue in vanadium containing forgings



- Increased V content improves fatigue performance (fatigue limit (FL)/tensile strength(TS))
- Fatigue crack initiation starts in pro-eutectoid ferrite
- V(CN) precipitation increases strength of pro-eutectoid ferrite

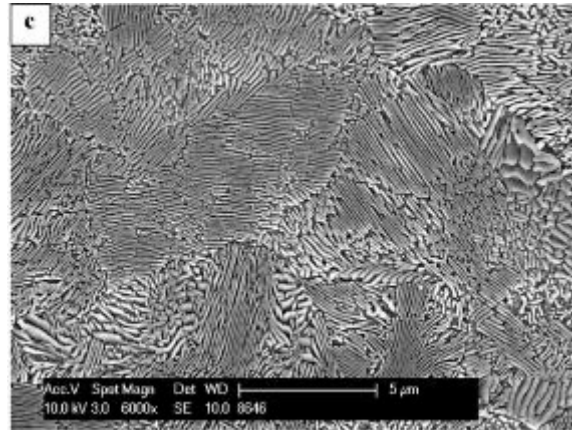
# Vanadium in rail steels

- Increasing demand for rails with improved wear resistance
  - Vignole rails with fully pearlitic microstructure
  - Grooved rails (tramways, light rail) with 0.4-0.6%C
- V additions can increase hardness and improve wear resistance
- In fully pearlitic air cooled rails, hardness in excess of 335 HB can be achieved with  $\sim 0.10\%V$

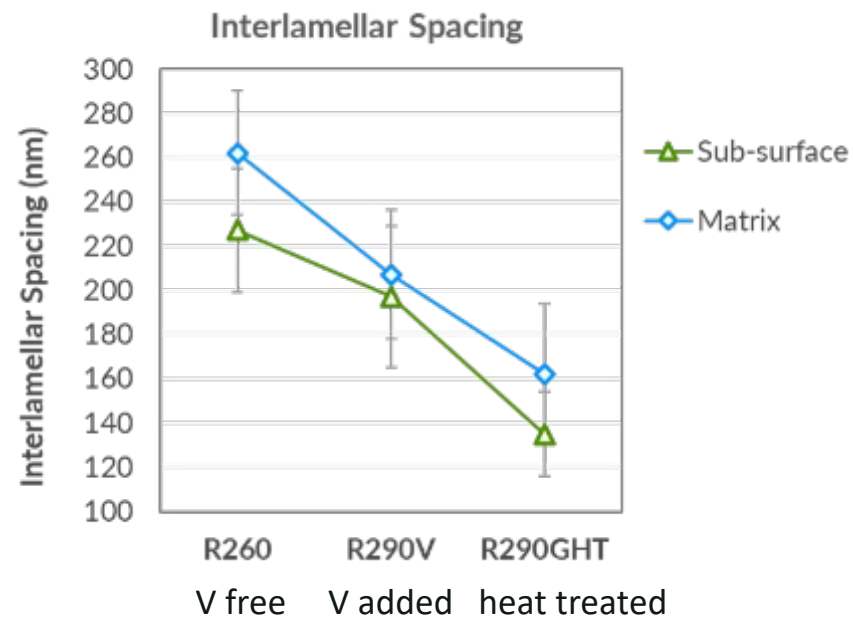
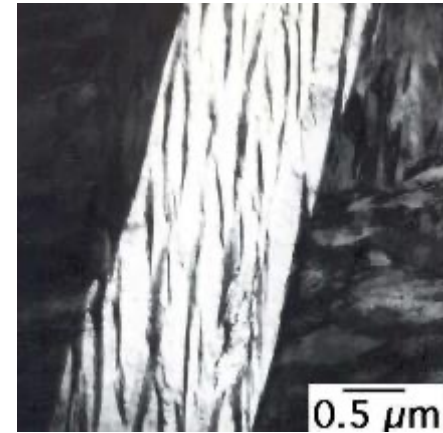


# Vanadium rail steel microstructures

Fully pearlitic rail



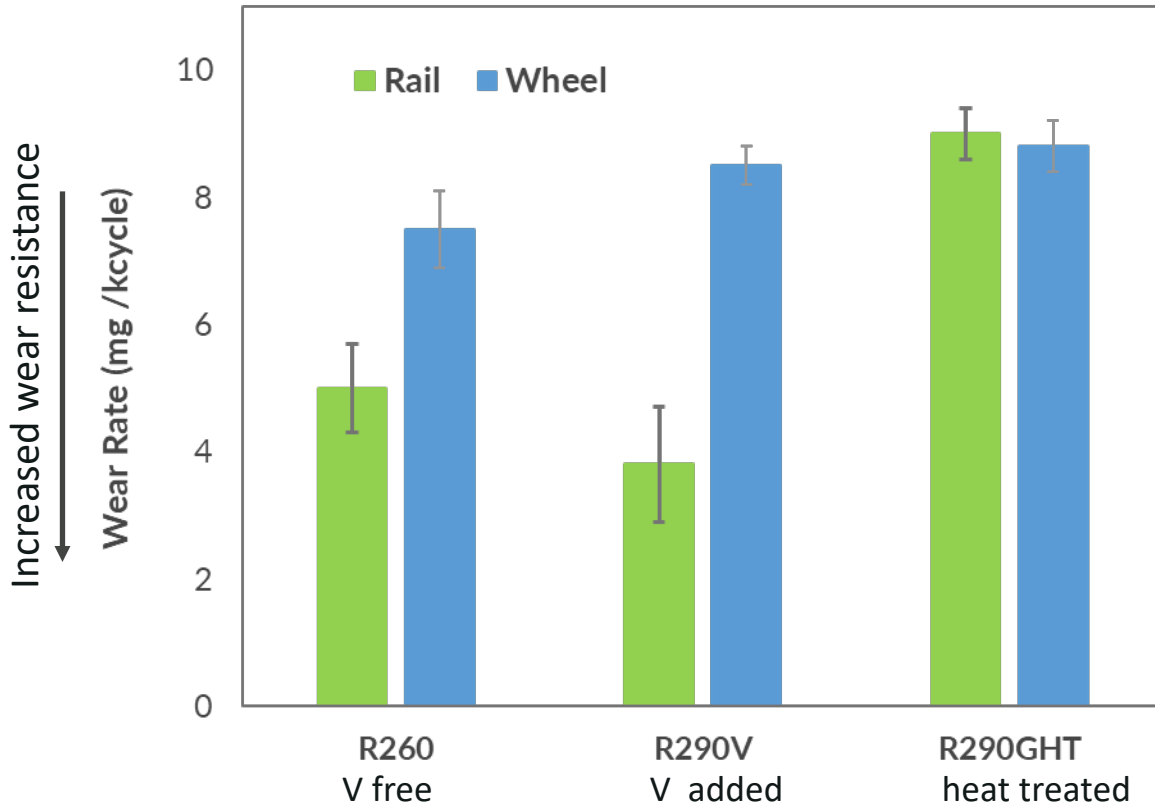
Carbide-free bainitic rail



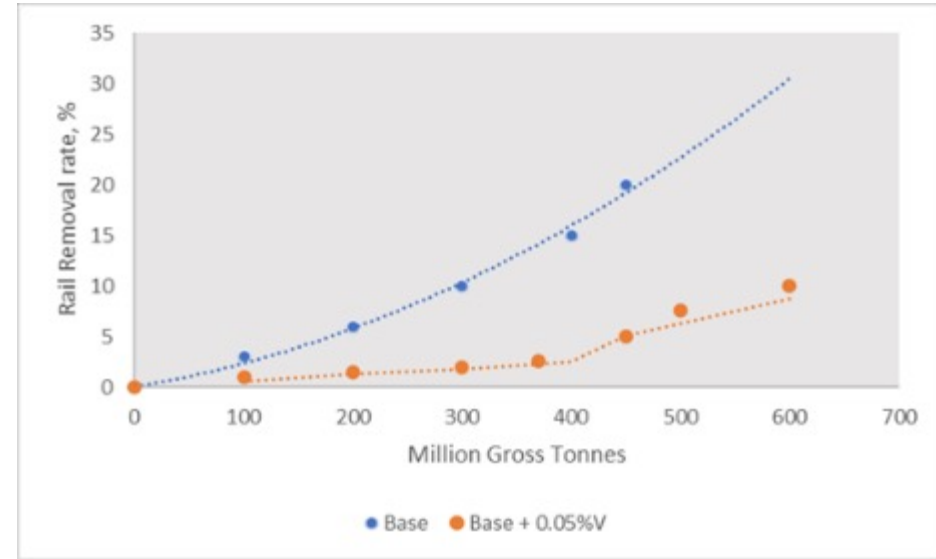
- V additions reduce pearlite interlamellar spacing
- In carbide-free bainitic rails, V additions:
  - reduce rolling contact fatigue
  - reduce temper embrittlement

# Vanadium rail steel wear performance

Effect of Vanadium on Wear Resistance



Result of unlubricated twin disk wear tests that ran for 100,000 cycles at room temperature and 750 MPa of contact pressure using grade R7 for all wheel discs.



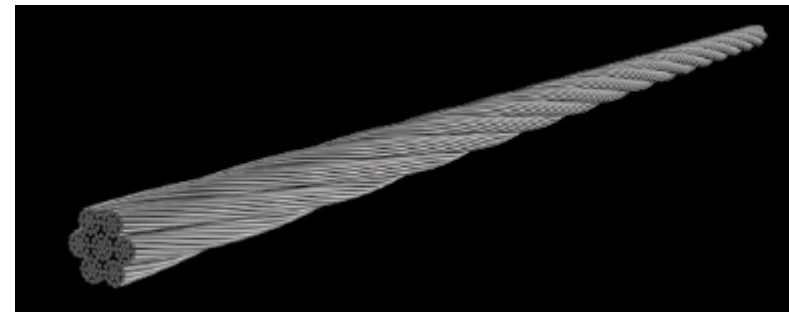
Reduced rail replacement for V containing rail

- V rails show reduced wear rates due to
  - Increased hardness
  - Reduced pearlite interlamellar spacing
  - Precipitation strengthening
- Improved cementite properties



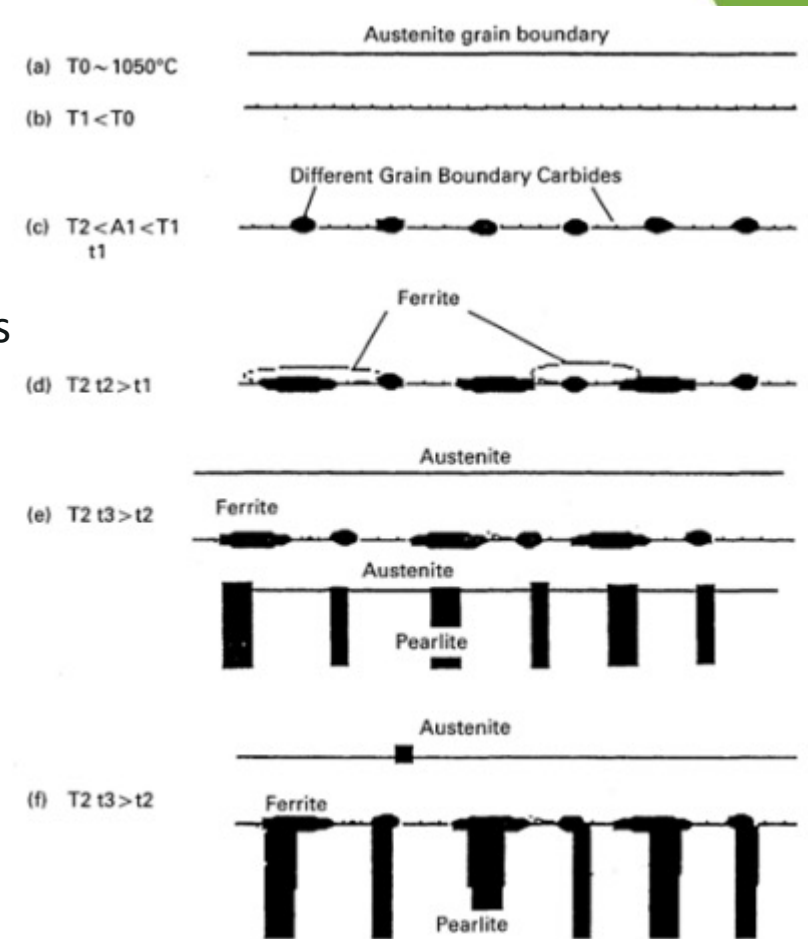
## Vanadium in ultra high strength wire rod

- 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 also 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
  - (b) Formation of fine VC at gamma GBs
  - (c) Formation of fragmented carbides (cementite)
  - (d) Formation of ferrite and VC
  - (e) Pearlite transformation

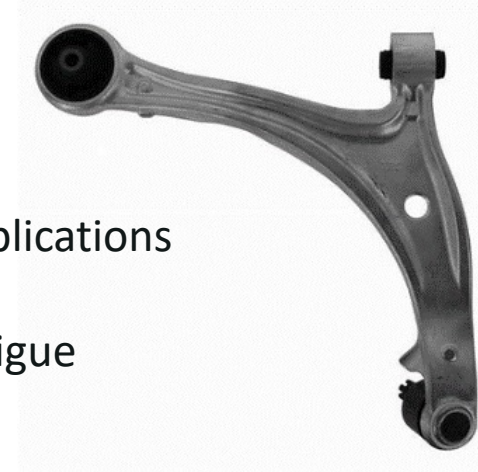


## Vanadium in hot rolled ferritic steels

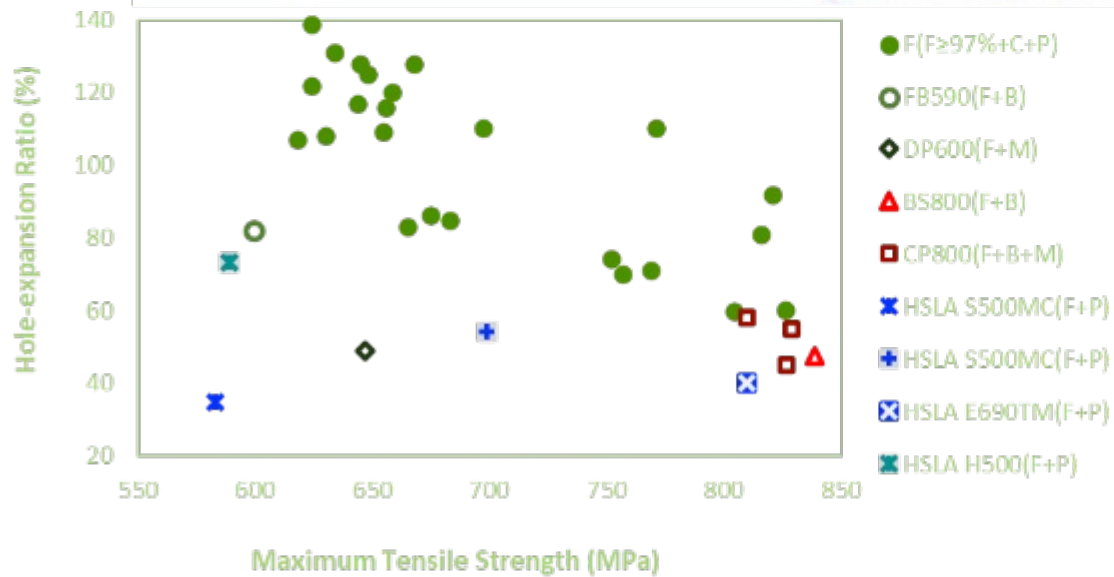
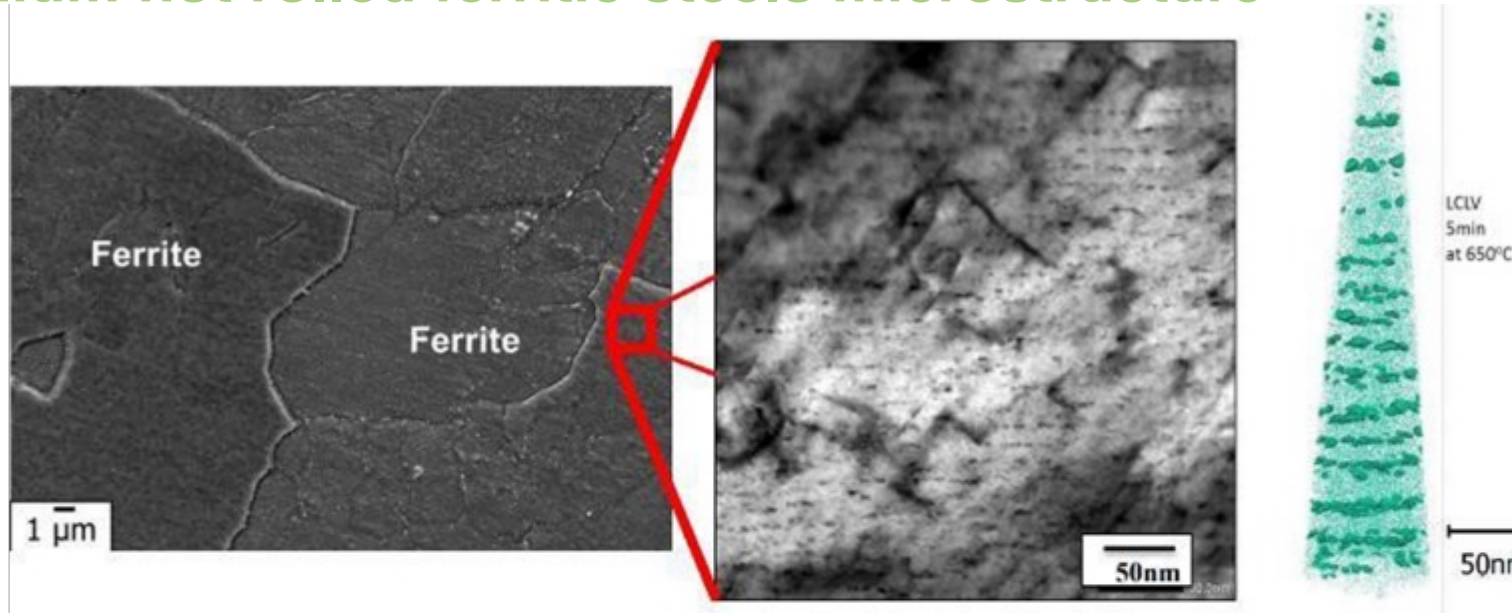
- Increasing demand for advanced high strength steels (AHSS) for automotive applications
- Requirement for increased edge ductility (hole expansion)
- Single phase ferritic microstructure gives high hole expansion and improved fatigue
- Strengthening by extensive V(C,N) precipitation
- Low C and correct choice of V content eliminates pearlite/cementite
- Applications include:
  - Chassis and suspension components,
  - EV crash structures



Hole expansion testing



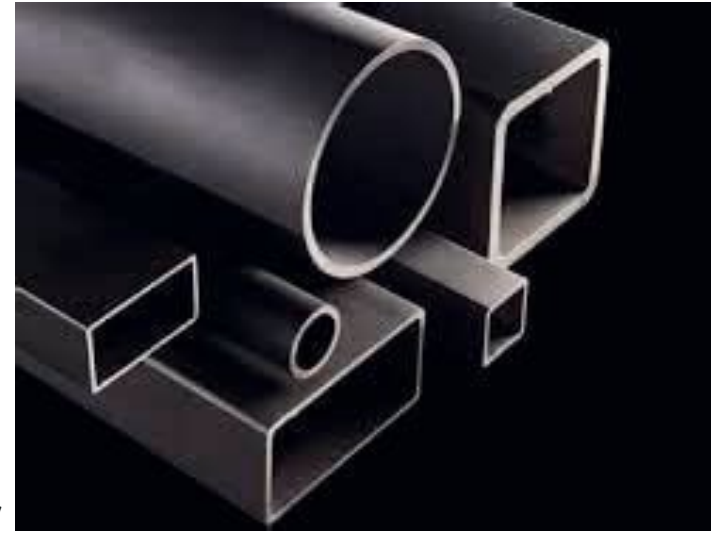
# Vanadium hot rolled ferritic steels microstructure



Improved Hole Expansion compared with other AHSS

## Vanadium in hot formed structural hollow sections

- Structural hollow sections (SHS) used in construction industry
  - Used in multi-axial loading situations
- Hot formed SHS show superior properties to cold formed
  - Hot forming temperature  $\sim 900^{\circ}\text{C}$
- Desire to increase yield strength to 420-460MPa with good weldability
- Solution is to use V with increased N, low Al
- Dual effect of precipitation strengthening and grain refinement
  - High V(CN) solubility allows partial dissolution at hot forming temperatures
  - Un-dissolved V(CN) provides austenite GB pinning
  - Low Al promotes V(CN) formation

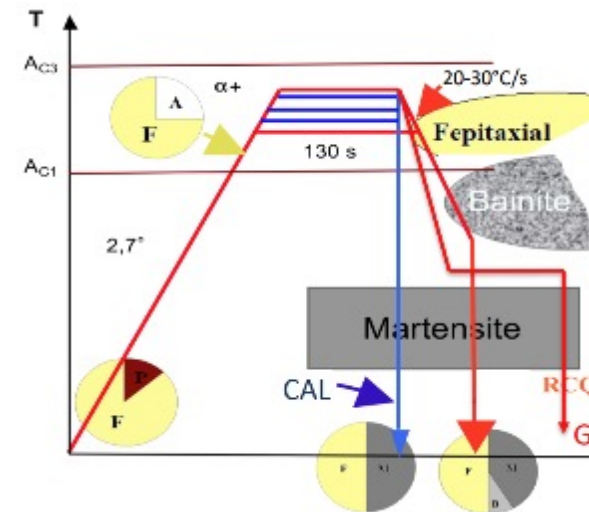
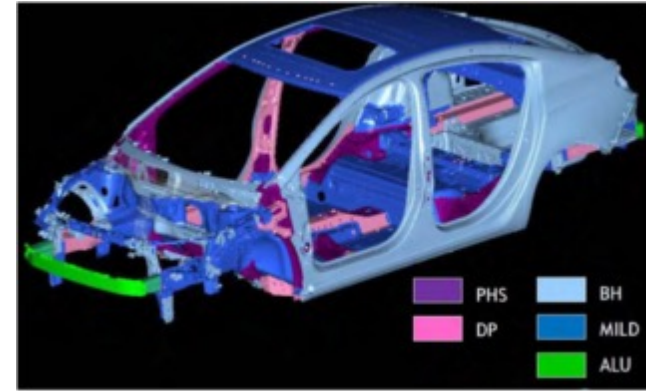


# Vanadium in dual phase steels

- Advanced high strength steels (AHSS) used for automotive applications (body-in white)
- Requirements for increased strength and ductility
- Dual Phase (DP) ferrite-martensite steels widely used
  - Requirement for improved hole expansion (HE) in DP steels
- Cold rolled DP steels produced by inter-critical annealing followed by rapid cooling
- V can be used to improve strength and HE performance



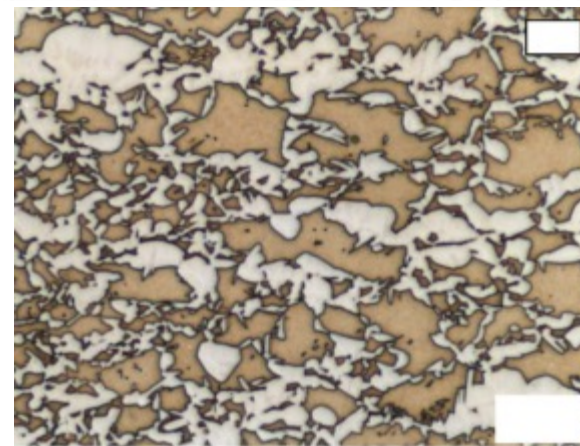
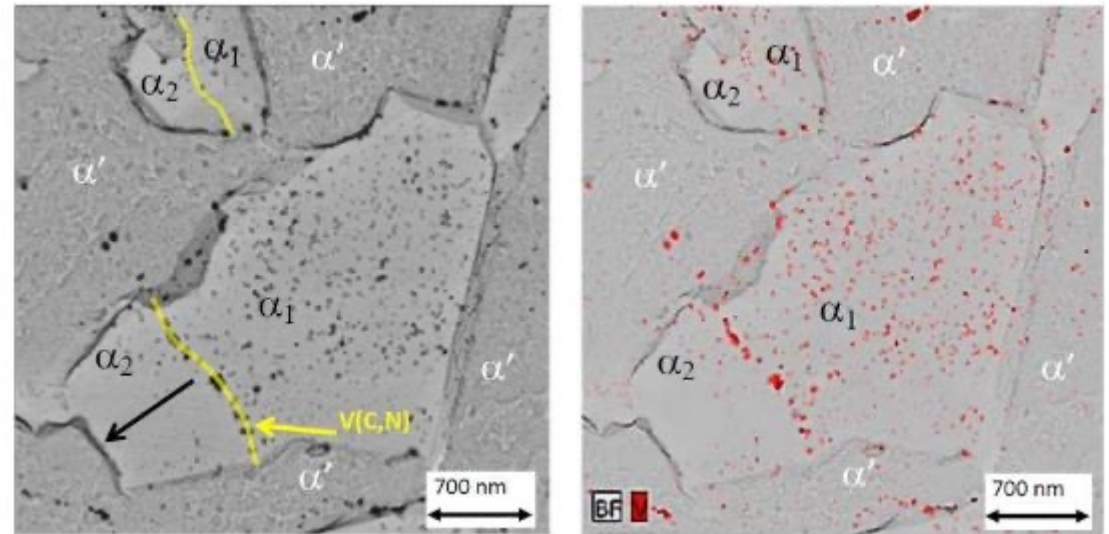
DP microstructure, martensite white, ferrite brown



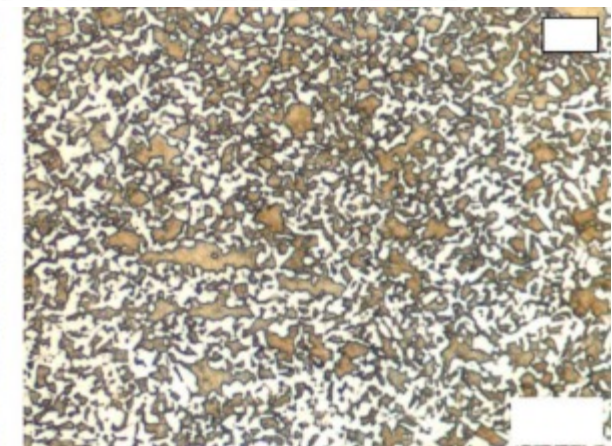
DP annealing cycle

# Vanadium dual phase steels microstructure

- Microstructural refinement associated with V additions
- Extensive V(CN) precipitation
  - V(CN) precipitation concentrated in ferrite ( $\alpha$ )
  - Little precipitation in martensite ( $\alpha'$ )
  - Little precipitation in epitaxial ferrite ( $\alpha_2$ )
- Major strengthening effects associated with V additions
- Decreased hardness difference between  $\alpha'$  and  $\alpha$ 
  - Decreased strain differential between  $\alpha$  and  $\alpha'$
- Improved hole expansion with V additions

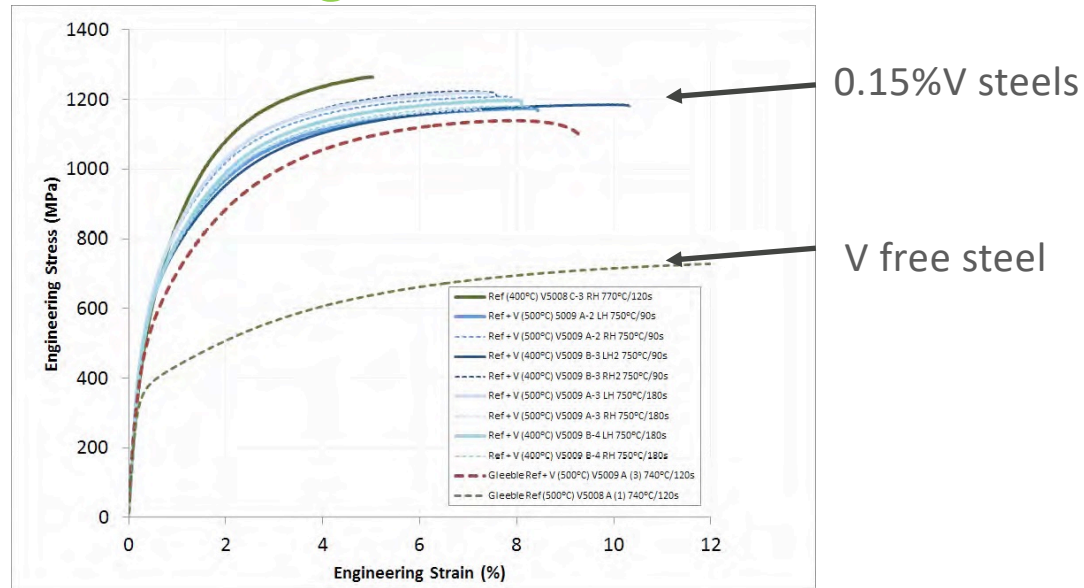


V free

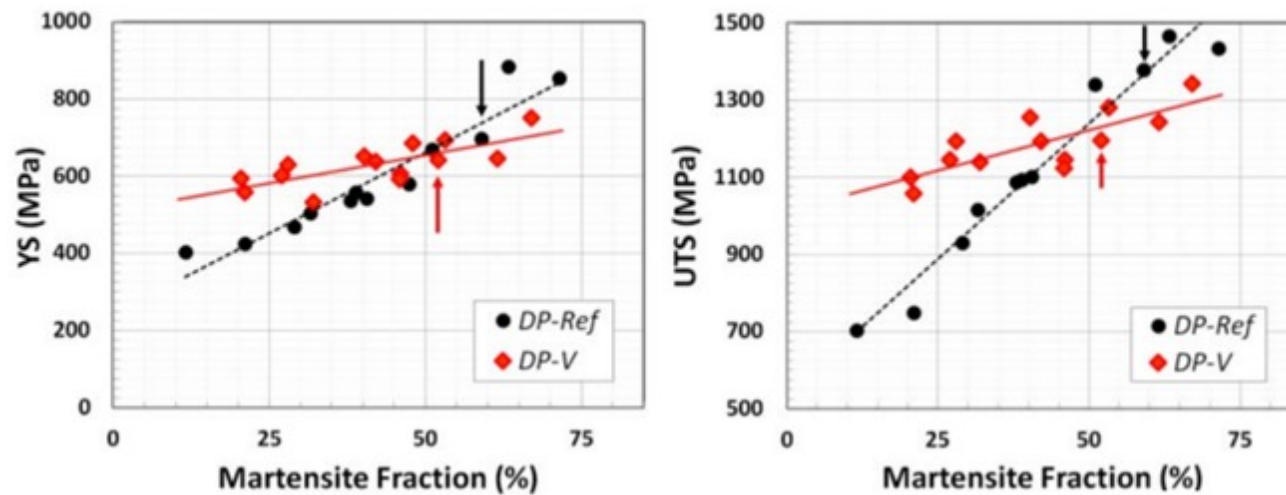


0.15% V

# Vanadium dual phase steel strength



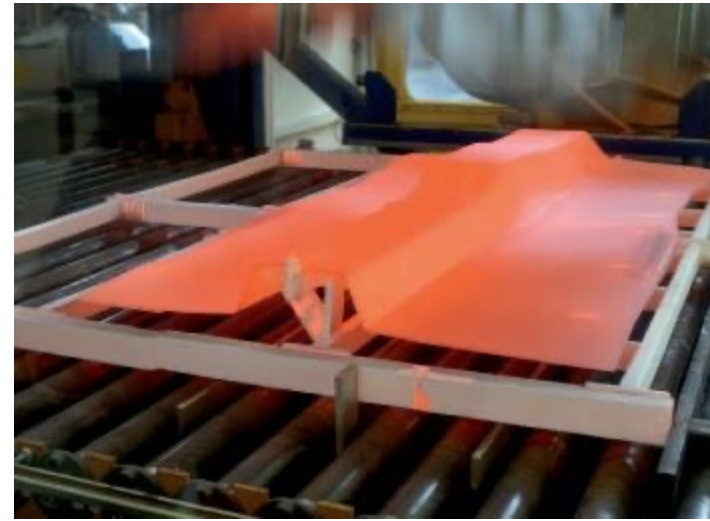
Increasing strength with V additions (0.15%) for various annealing conditions



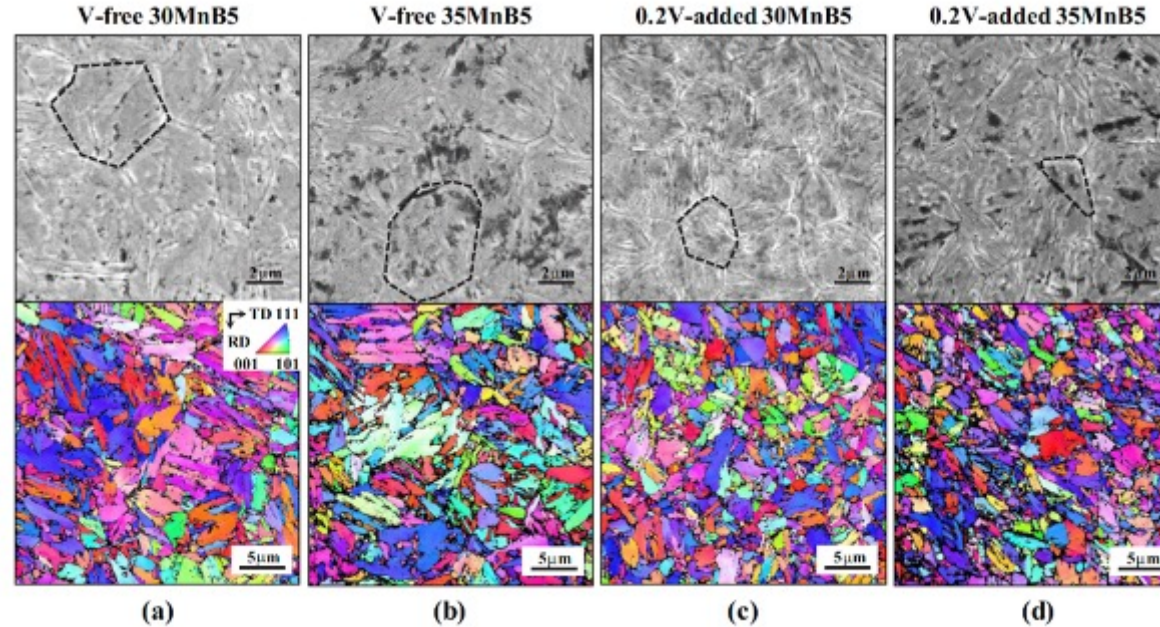
Stable tensile properties for V DP steels

## Vanadium in press hardened steels

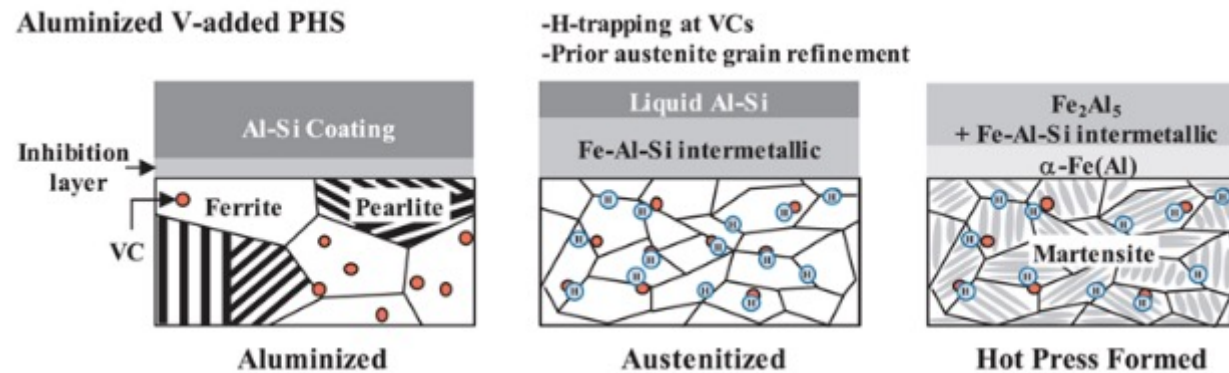
- Ultra-high strength press hardened steels used in automotive industry, e.g. “B” pillars
- Process route:
  - Aluminized for oxidation resistance
  - Full austenitisation
  - Rapid cooling during pressing
  - Fully martensitic microstructure
- Potential problems with hydrogen embrittlement
- V additions can improve properties
- V(CN) pins austenite grain boundaries during austenitising
- V(CN) precipitates act as trapping sites for hydrogen



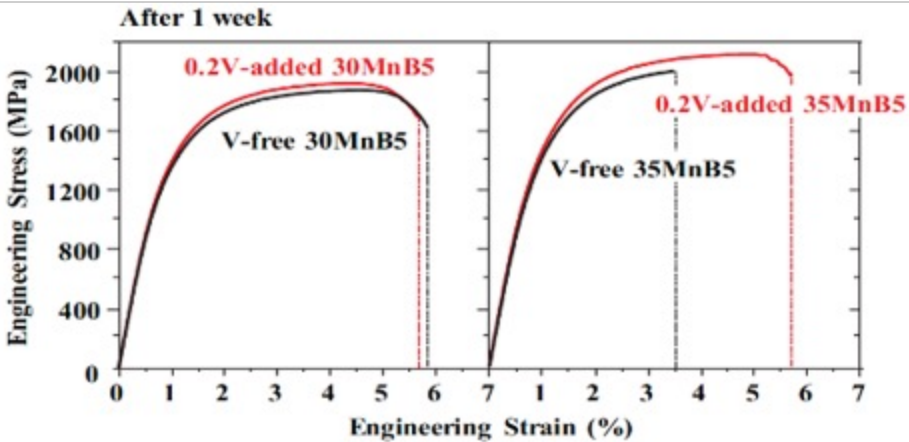
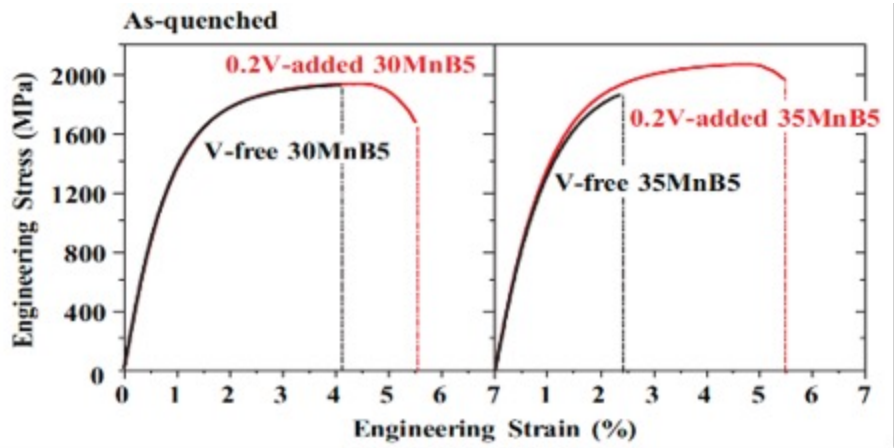
# Vanadium press hardened steels microstructure



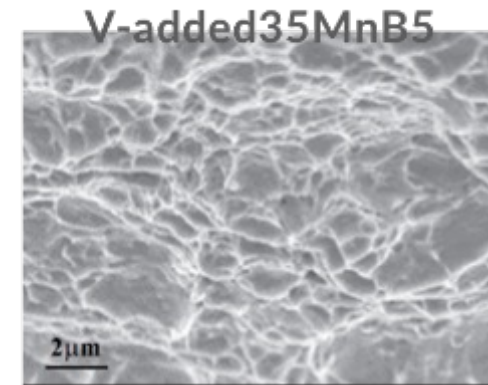
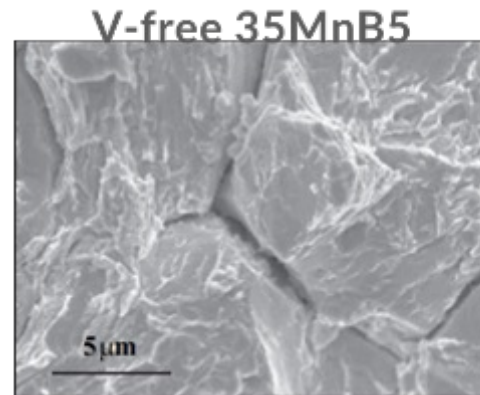
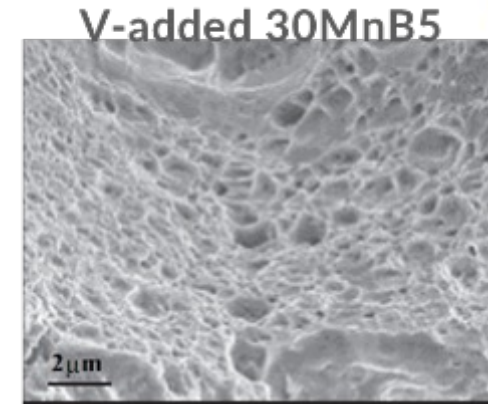
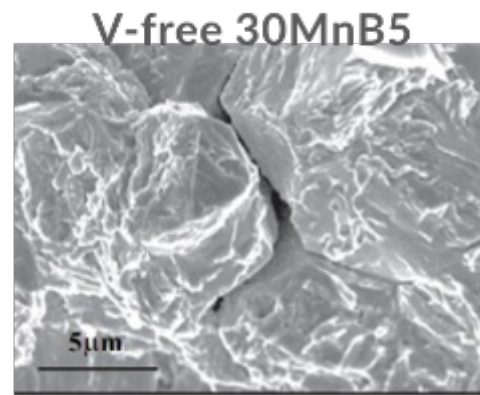
- V refines microstructure
  - V(CN) pins austenite grains during austenitisation
  - Finer martensite packet size
- H introduced during austenitisation
- V reduces hydrogen embrittlement
  - V(CN) act as H trapping sites
  - Refined microstructure reduces HE



# Vanadium press hardened steels tensile properties



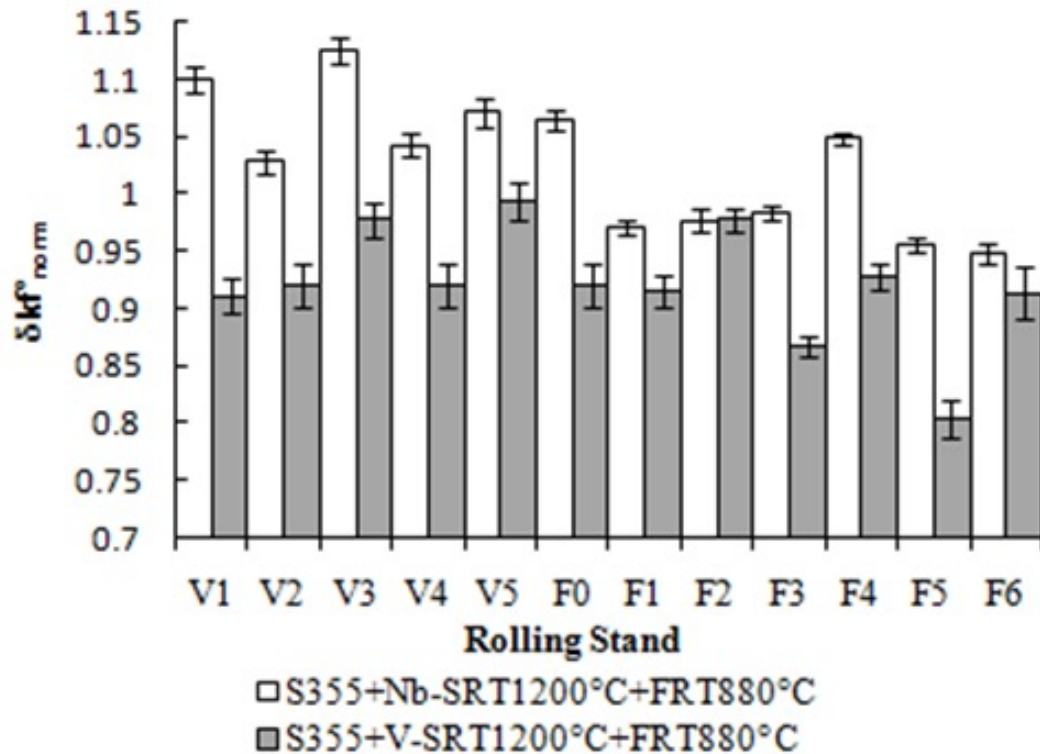
Low elongation values in V free steels



Intergranular failure due to hydrogen embrittlement in V free steels

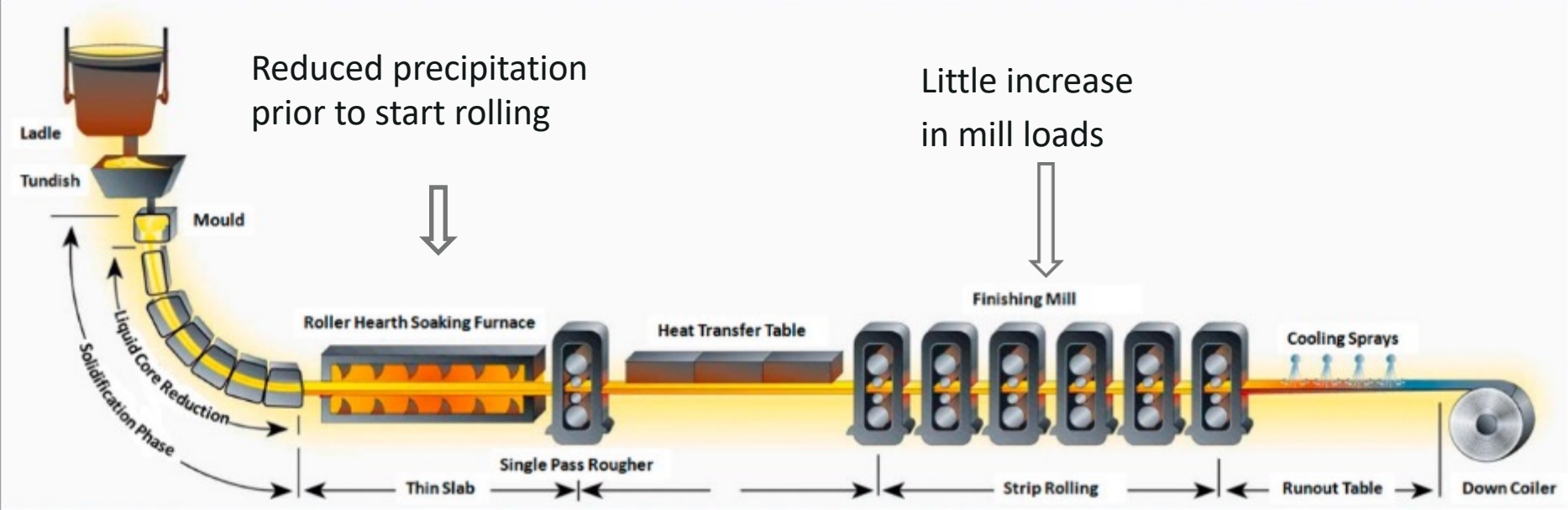
# Rolling of vanadium steels

Limited V(CN) precipitation in austenite allows rapid recrystallisation and low mill loads



Reduced mill loads during hot strip rolling for V steels compared to Nb steels

# Vanadium in thin slab casting & direct rolling



Reduced defects during casting

Rapid austenite recrystallisation

Formation of fine V(CN) to increase strength

# Summary

- Increased demand for higher strength steels with good ductility and toughness
- Vanadium additions can increase strength via precipitation and grain refinement due to V(CN)
- The high solubility of V(CN) allows V to be used in a wide range of steels and under a wide range of processing conditions
- In high and medium C Steels:
  - Rebar, forging steels, rail steels, wire rod
- In low C Steels:
  - Single phase ferritic steels
- Over a wide range of processing conditions:
  - Structural hollow sections, dual phase steels, press hardened steels
- Rolling loads remain low due to limited V(CN) precipitation in austenite
- Vanadium steels suited to thin slab casting/direct rolling



**Thanks for your attention**

**Any questions?**

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