

Solidification and phase transformations in welding

Subjects of Interest

Part I: Solidification and phase transformations in carbon steel and stainless steel welds

- Solidification in stainless steel welds
- Solidification in low carbon, low alloy steel welds
- Transformation hardening in HAZ of carbon steel welds

Part II: Overaging in age-hardenable aluminium welds

Part III: Phase transformation hardening in titanium alloys



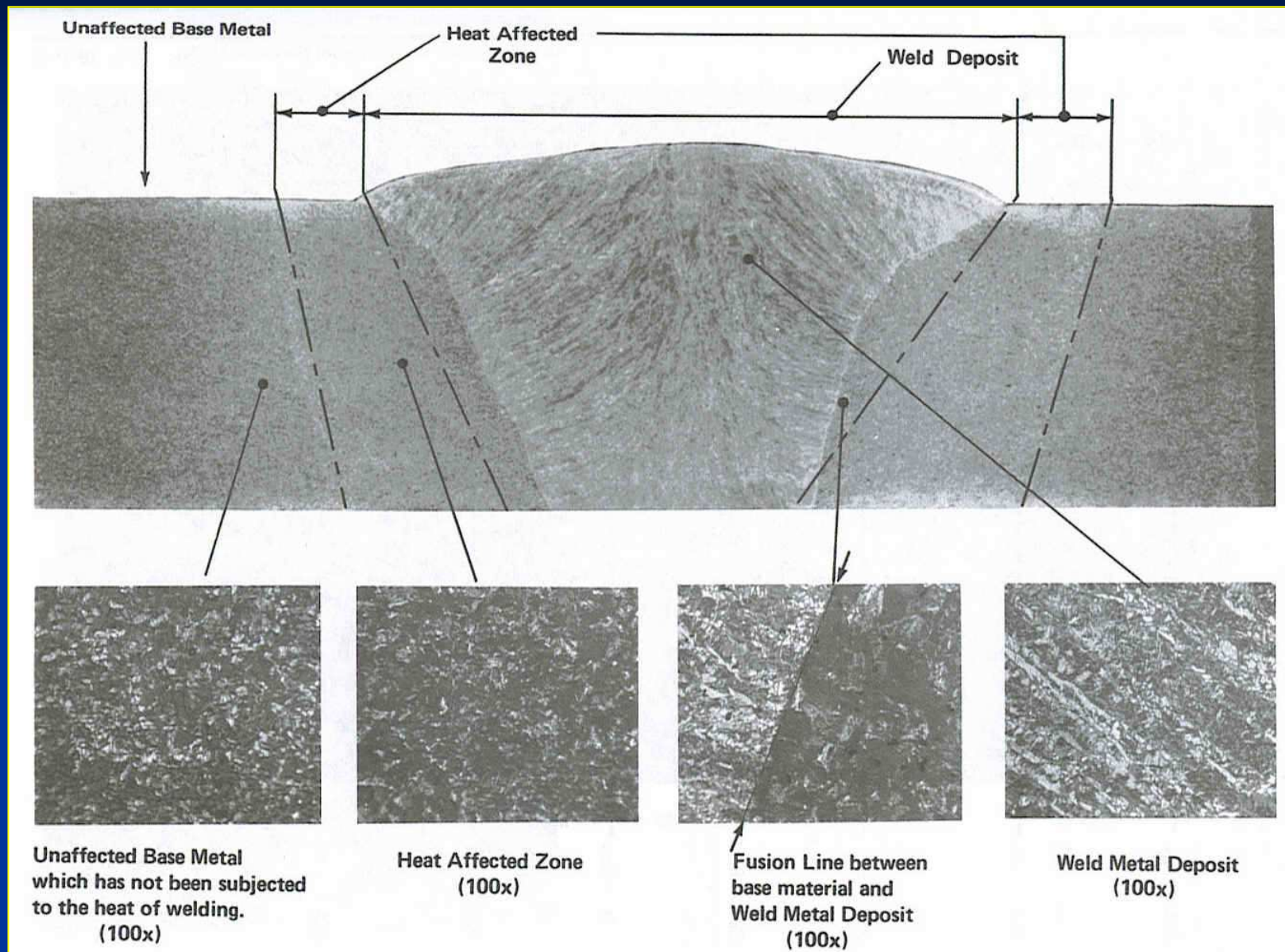
Objectives

This chapter aims to:

- Students are required to understand solidification and phase transformations in the weld, which affect the weld microstructure in carbon steels, stainless steels, aluminium alloys and titanium alloys.

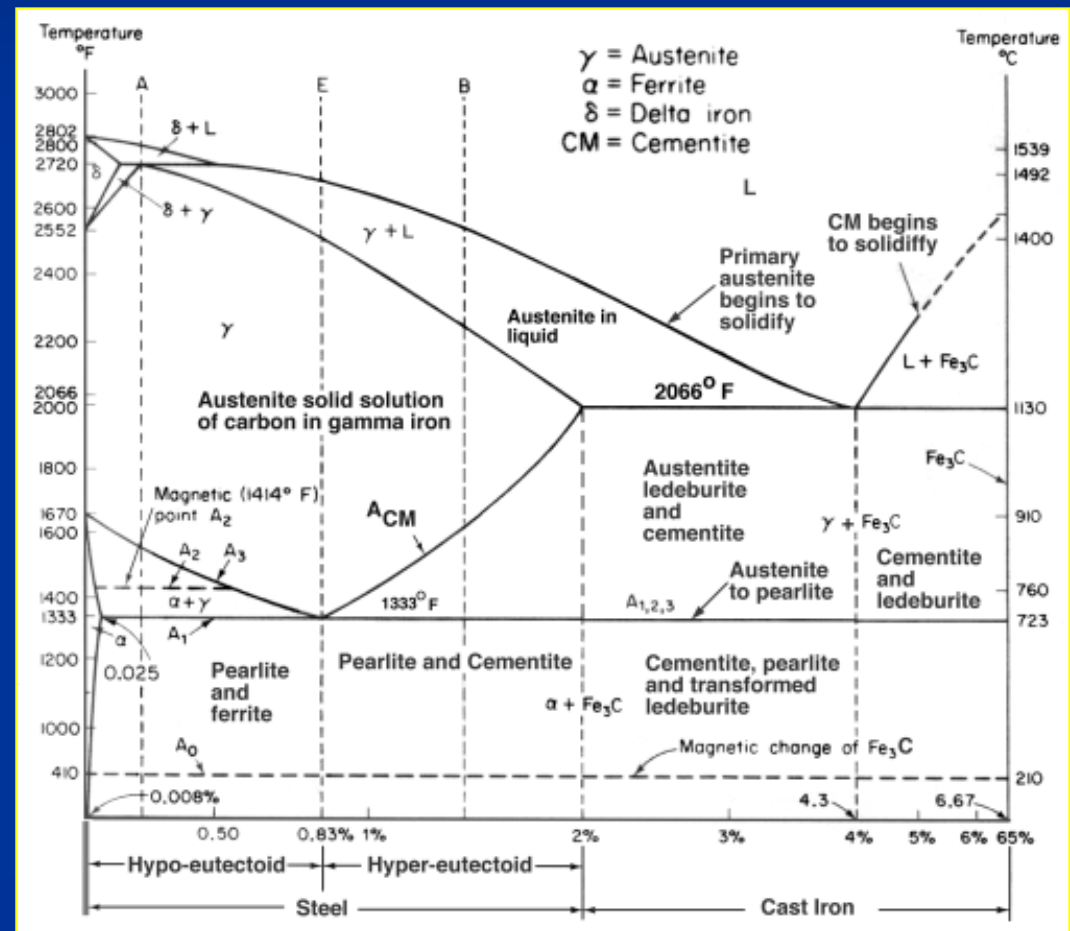


Introduction



Part I: Solidification in carbon steel and stainless steel welds

- **Carbon and alloy steels** are more frequently welded than any other materials due to their **widespread applications and good weldability**.
- Carbon and alloy steels with **higher strength levels are more difficult to weld** due to the risk of hydrogen cracking.
- Austenite to ferrite transformation in **low carbon, low alloy steel welds**.
- Ferrite to austenite transformation in **austenitic stainless steel welds**.
- **Martensite transformation** is not normally observed in the **HAZ** of a **low-carbon steel**.

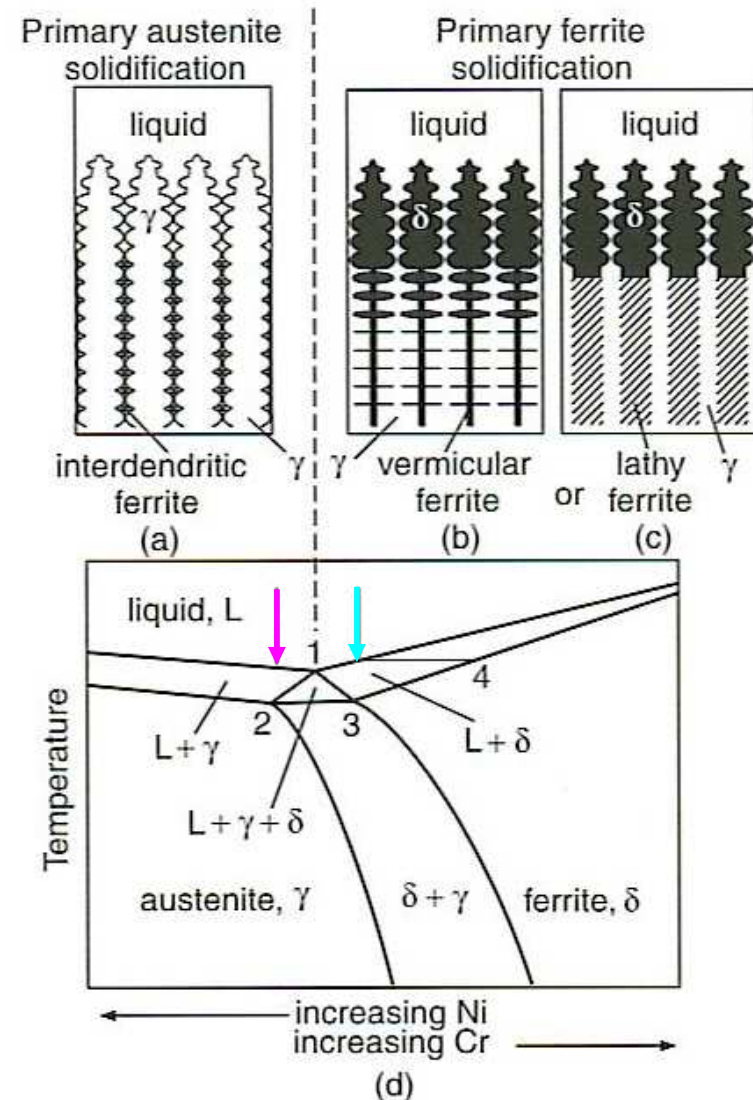


Fe-C phase binary phase diagram.

Solidification in stainless steel welds

- **Ni rich stainless steel** first solidifies as primary dendrite of γ **austenite** with interdendritic δ **ferrite**.
- **Cr rich stainless steel** first solidifies as primary δ **ferrite**. Upon cooling into $\delta + \gamma$ region, the outer portion (having less **Cr**) transforms into γ **austenite**, leaving the core of dendrite as **skeleton** (**vermicular**).
- This can also transform into **lathly ferrite** during cooling.

Solidification and post solidification transformation in Fe-Cr-Ni welds
(a) interdendritic ferrite,
(b) vermicular ferrite (c) lathly ferrite
(d) section of Fe-Cr-Ni phase diagram

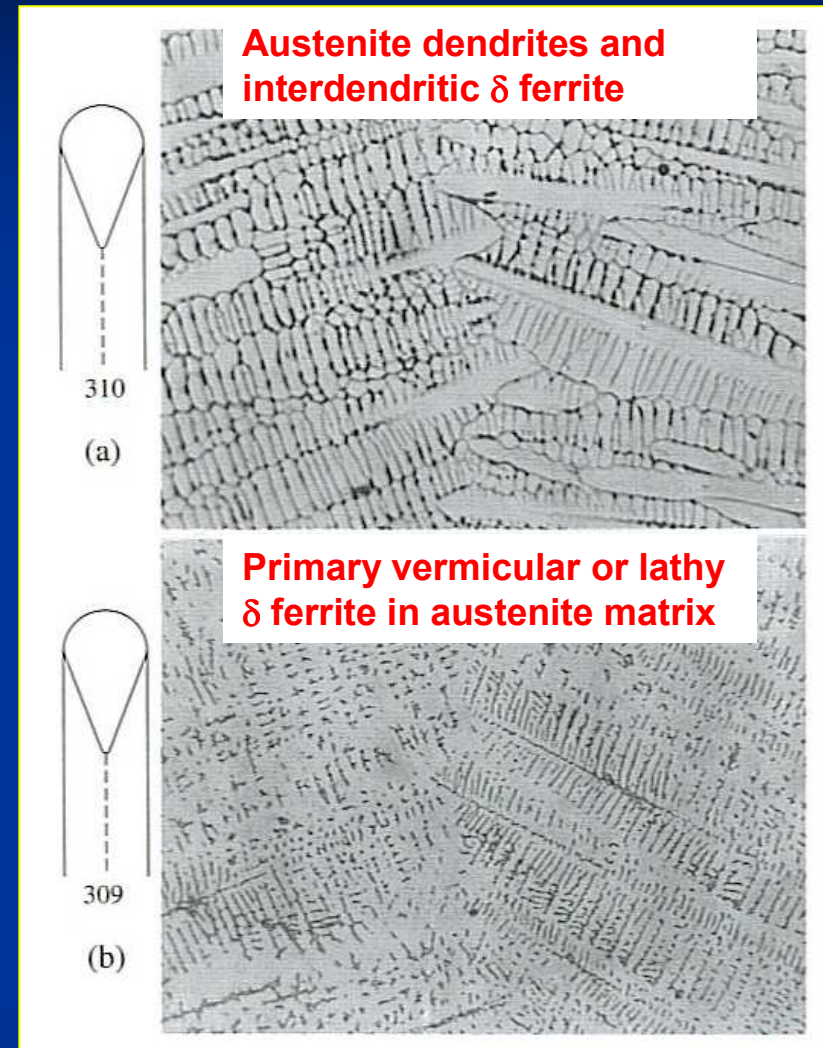


Solidification in stainless steel welds

- Weld microstructure of **high Ni 310 stainless steel** (25%Cr-20%Ni-55%Fe) consists of primary **austenite dendrites** and **interdendritic δ ferrite** between the primary and secondary dendrite arms.

- Weld microstructure of **high Cr 309 stainless steel** (23%Cr-14%Ni-63%Fe) consists of primary **vermicular or lathy δ ferrite** in an **austenite matrix**.

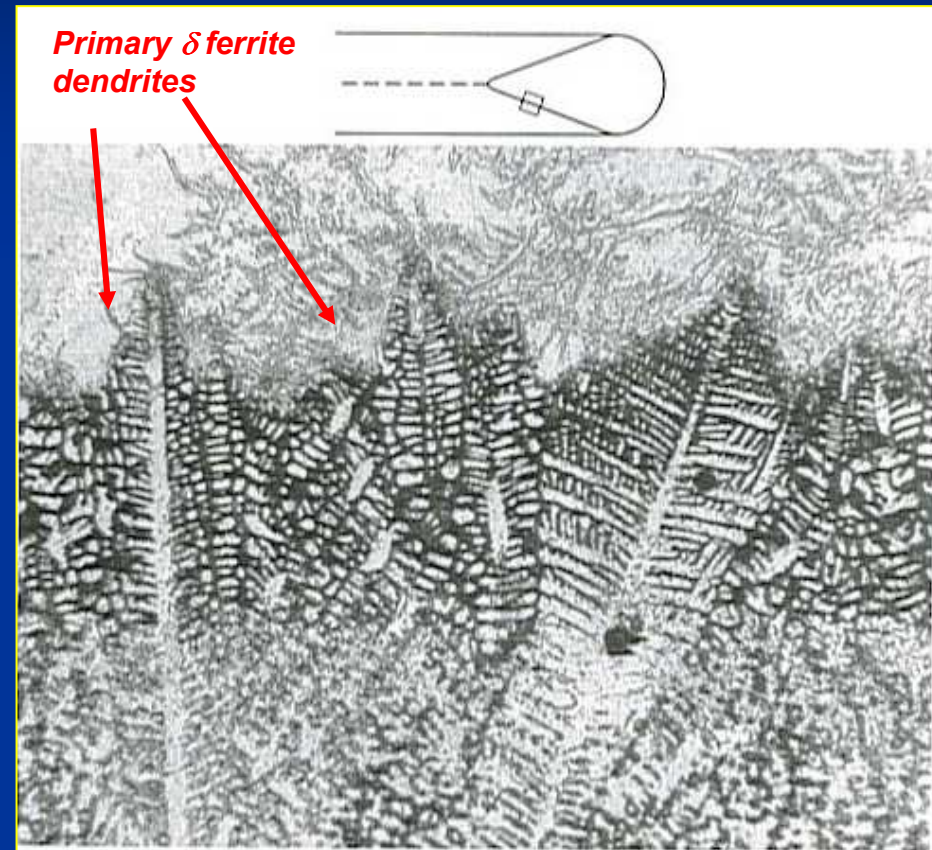
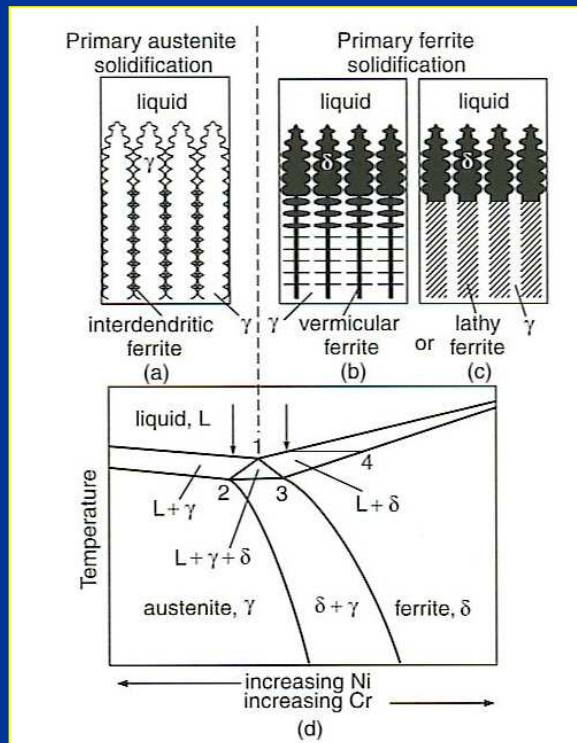
- The columnar dendrites in both microstructures grow in the direction perpendicular to the tear drop shaped weld pool boundary.



Solidification structure in (a) 310 stainless steel and (b) 309 stainless steel.

Solidification in stainless steel welds

- A **quenched structure** of ferritic (309) stainless steel at the weld pool boundary during welding shows **primary δ ferrite dendrites** before transforming into vermicular ferrite due to $\delta \rightarrow \gamma$ transformation.



Quenched solidification structure near the pool of an autogenous GTA weld of 309 stainless steels



Mechanisms of ferrite formation

- The **Cr: Ni ratio** controls the amount of vermicular and lathy ferrite microstructure.

Cr : Ni ratio

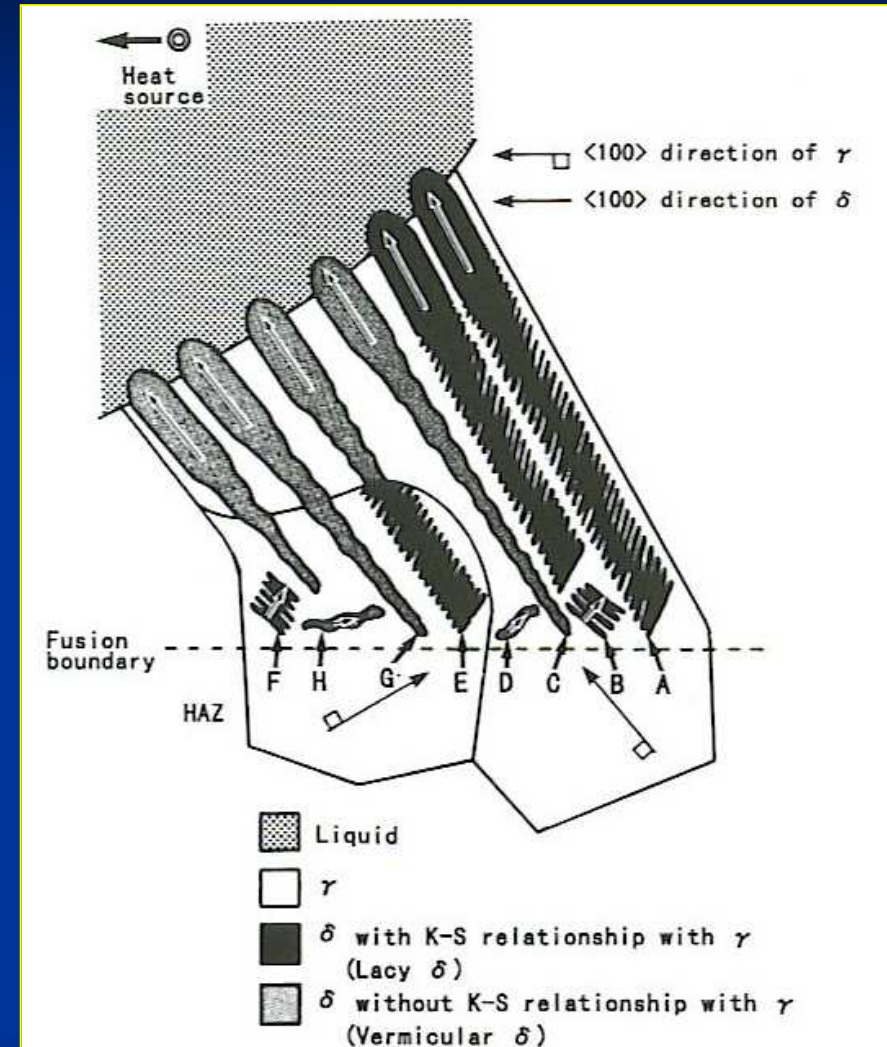
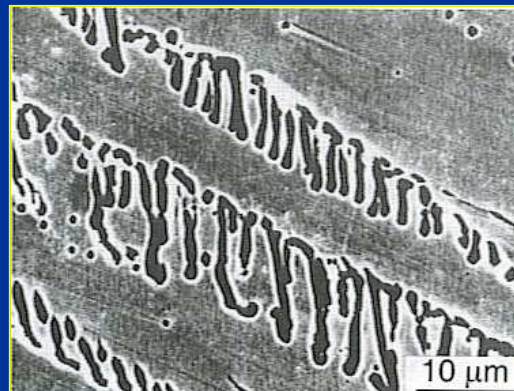


Vermicular & Lathy ferrite



- Austenite** first grows epitaxially from the unmelted austenite grains at the fusion boundary, and **δ ferrite** soon nucleates at the solidification front in the preferred **$\langle 100 \rangle$ direction**.

Lathy ferrite in an autogenous GTAW of Fe-18.8Cr-11.2Ni.

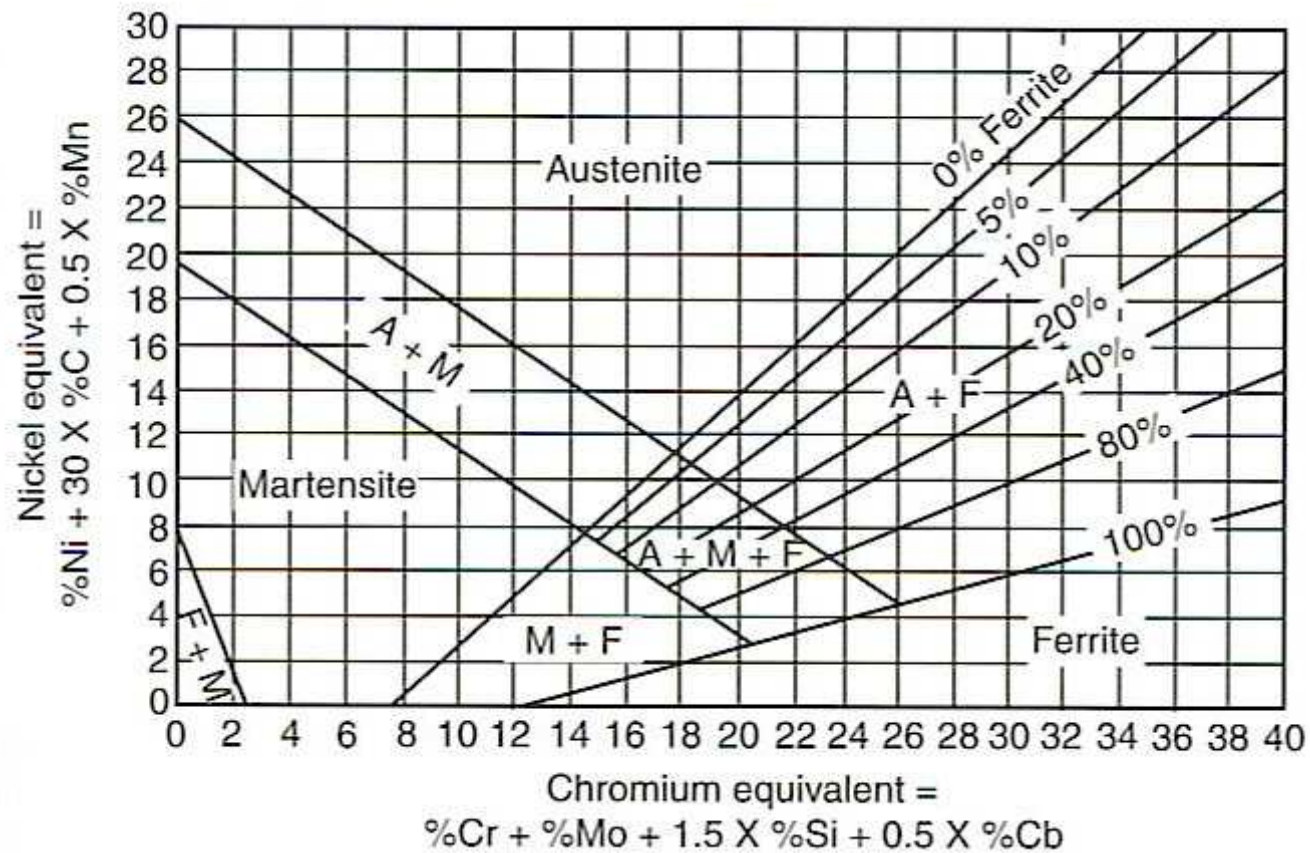


Mechanism for the formation of vermicular and lathy ferrite.



Prediction of ferrite contents

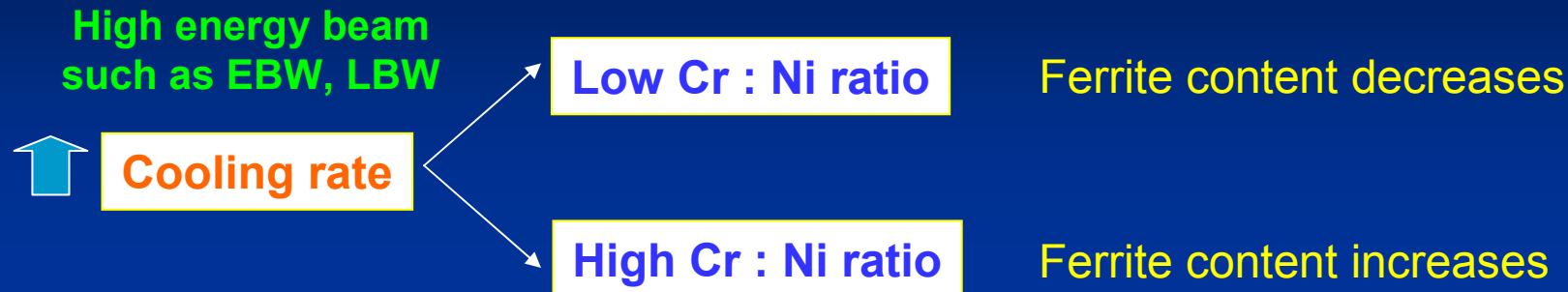
Schaeffler proposed **ferrite content prediction** from **Cr** and **Ni** equivalents (ferrite formers and austenite formers respectively).



Schaeffler diagram for predicting weld ferrite content and solidification mode.



Effect of cooling rate on solidification mode



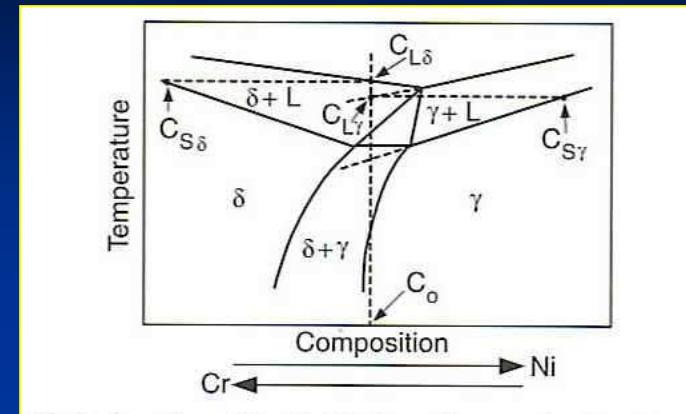
- Solid redistribution during solidification is reduced at high cooling rate for **low Cr: Ni ratio**.
- On the other hand, **high Cr : Ni ratio** alloys solidify as **δ ferrite** as the primary phase, and their ferrite content increase with increasing cooling rate because the **$\delta \rightarrow \gamma$ transformation** has less time to occur at high cooling rate.

Note: it was found that if **N_2** is introduced into the weld metal (by adding to **Ar** shielding gas), the **ferrite content** in the weld can be significantly reduced. (**Nitrogen** is a strong **austenite former**)



Ferrite to austenite transformation

- At composition C_o , the alloy solidifies in the **primary ferrite** mode at **low cooling rate** such as in GTAW.
- At **higher cooling rate**, i.e., EBW, LBW, the melt can undercool below the extended austenite liquidus ($C_{L\gamma}$) and it is thermodynamically possible for **primary austenite** to solidify.
- The closer the composition close to the **three-phase triangle**, the easier the solidification mode changes from **primary ferrite to primary austenite** under the condition of **undercooling**.



Section of F-Cr-Ni phase diagram showing change in solidification from ferrite to austenite due to dendrite tip undercooling



Cooling rate

Ferrite $\rightarrow$ austenite



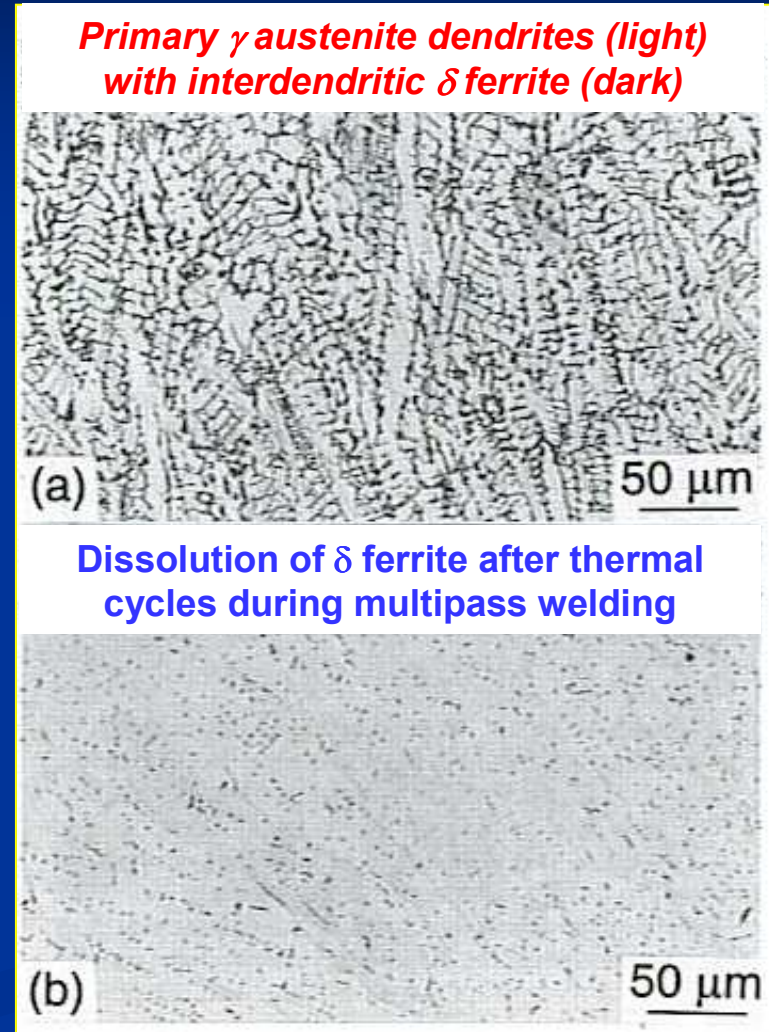
At compositions close to the three phase triangle.

Weld centreline austenite in an autogenous GTA weld of 309 stainless steel solidified as primary ferrite

Ferrite dissolution upon reheating

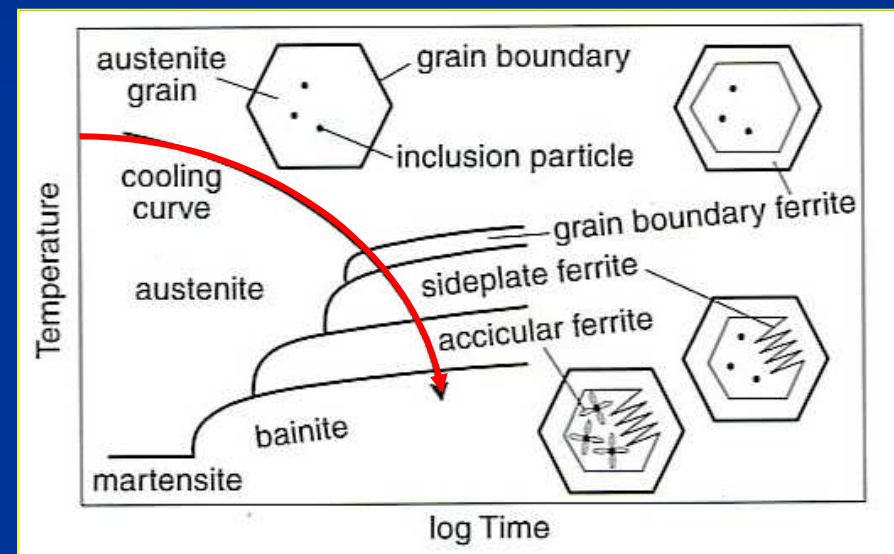
- **Multi pass welding** or repaired austenitic stainless steel weld consists of **as-deposited** of the previous weld beads and the **reheated region** of the previous weld beads.
- **Dissolution of δ ferrite** occurs because this region is reheated to below the **γ solvus temperature**.
- This makes it susceptible to fissuring under strain, due to **lower ferrite and reduced ductility**.

Effect of thermal cycles on ferrite content in 316 stainless steel weld (a) as weld (b) subjected to thermal cycle of 1250°C peak temperature three times after welding.



Solidification in low carbon steel welds

- The development of **weld microstructure** in **low carbon steels** is schematically shown in figure.
- As **austenite** γ is cooled down from high temperature, **ferrite** α nucleates at the grain boundary and grow inward as **Widmanstätten**.
- At lower temperature, it is too slow for **Widmanstätten ferrite** to grow to the grain interior, instead **acicular ferrite** nucleates from inclusions
- The **grain boundary ferrite** is also called **allotriomorphic**.



Continuous Cooling Transformation (CCT) diagram for weld metal of low carbon steel

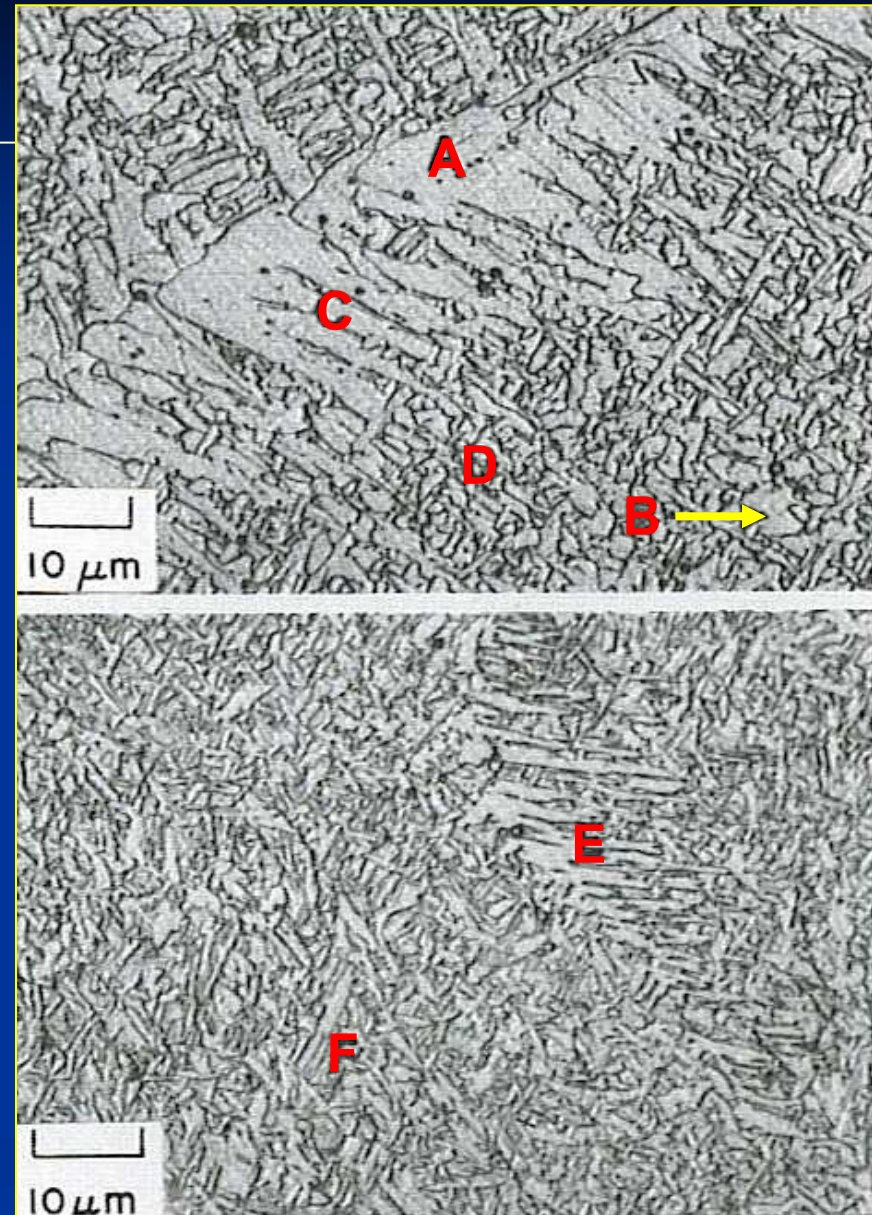


Weld microstructure in low-carbon steels

- A: Grain boundary ferrite
- B: polygonal ferrite
- C: Widmanstätten ferrite
- D: acicular ferrite
- E: Upper bainite
- F: Lower bainite

Note: Upper and lower bainites can be identified by using TEM.

**Which weld microstructure
is preferred?**



Weld microstructure of low carbon steels

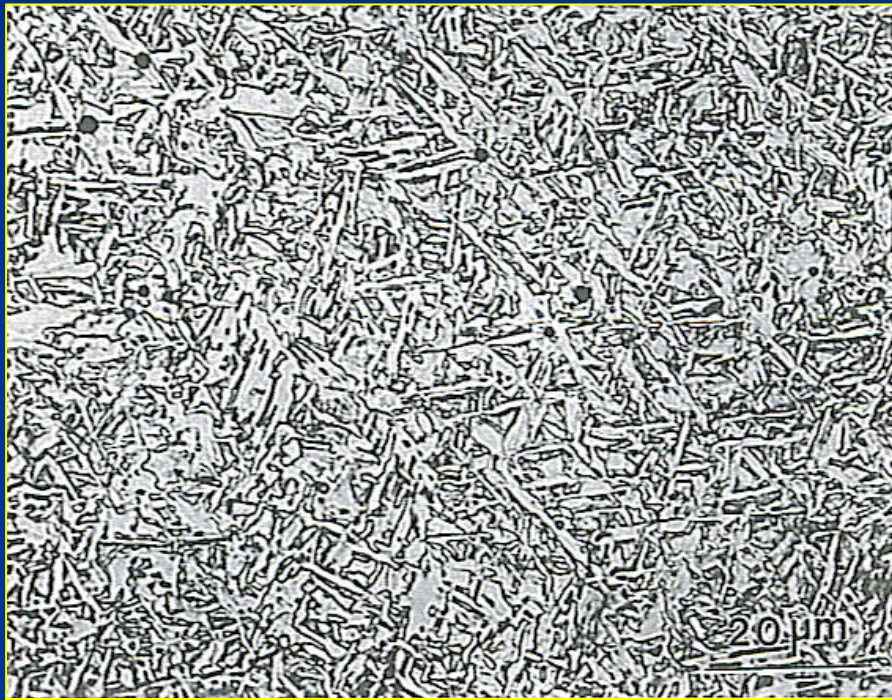
Tapany Udomphol

Sep-Dec 2007

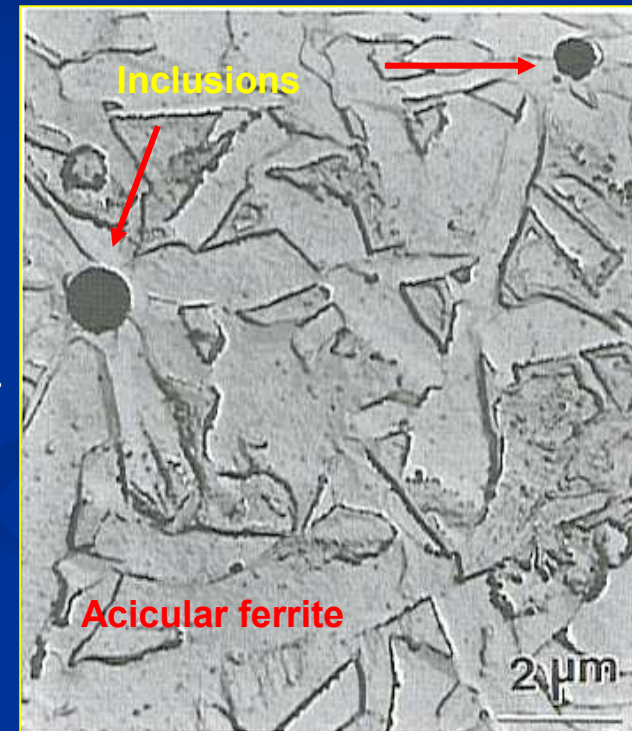
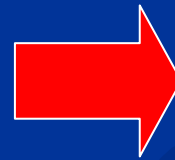


Suranaree University of Technology

Weld microstructure of acicular ferrite in low carbon steels



Weld microstructure of predominately acicular ferrite growing at inclusions.



Acicular ferrite and inclusion particles.

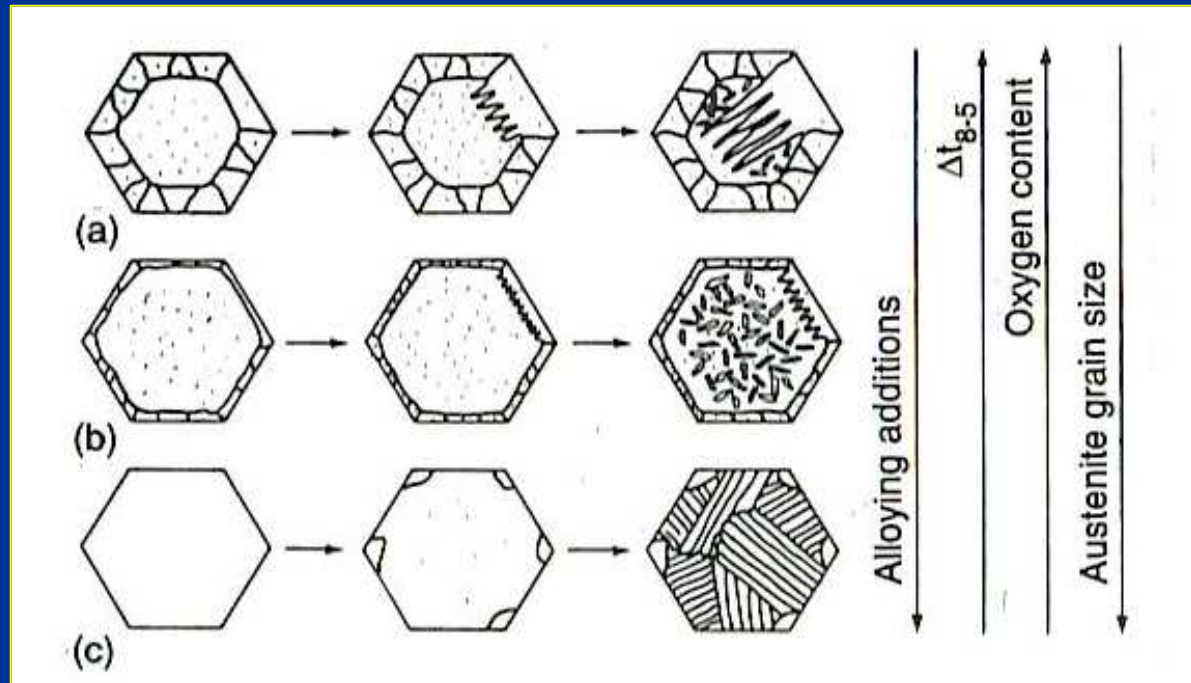


Factors affecting microstructure

- **Cooling time** ↓ GB and Widmanstätten ferrite → acicular ferrite → bainite
- **Alloying additions** ↑ GB and Widmanstätten ferrite → acicular ferrite → bainite
- **Grain size** ↑ GB and Widmanstätten ferrite → acicular ferrite → bainite
- **Weld metal oxygen content** ↑ inclusions ↑ prior austenite grain size ↓

Note: oxygen content is favourable for acicular ferrite → good toughness

Effect of alloying additions, cooling time from 800 to 500°C, weld oxygen content, and austenite grain size on weld microstructure of low carbon steels.



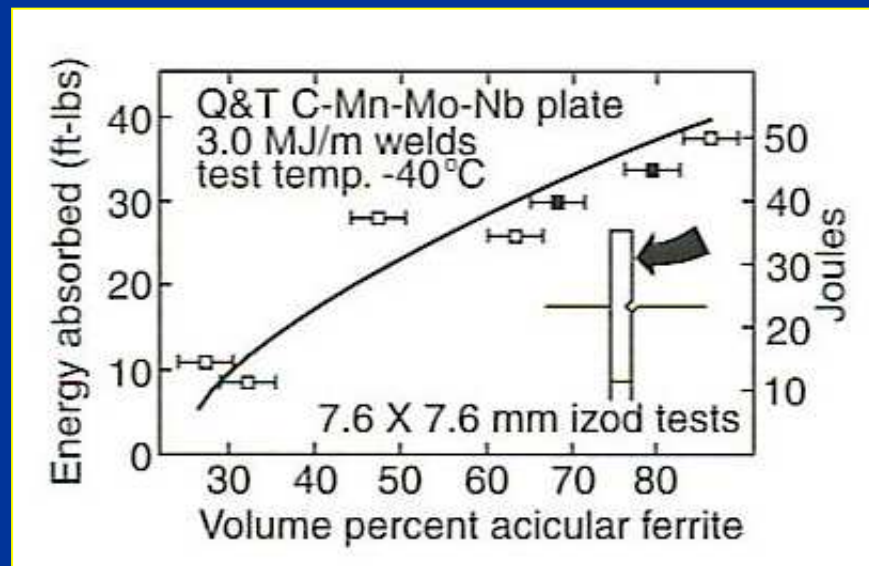
Weld metal toughness

- **Acicular ferrite is desirable** because it improves **toughness** of the weld metal in association with fine grain size. (provide the maximum resistance to cleavage crack propagation).

Acicular ferrite



Weld toughness



Subsize Charpy V-notch toughness values as a function of volume fraction of acicular ferrite in submerged arc welds.



Weld metal toughness

- **Acicular ferrite** as a function of **oxygen content**, showing the optimum content of oxygen (obtained from shielding gas, i.e., **Ar + CO₂**) at ~ 2% to give the maximum amount of **acicular ferrite** → highest toughness.

Acicular ferrite



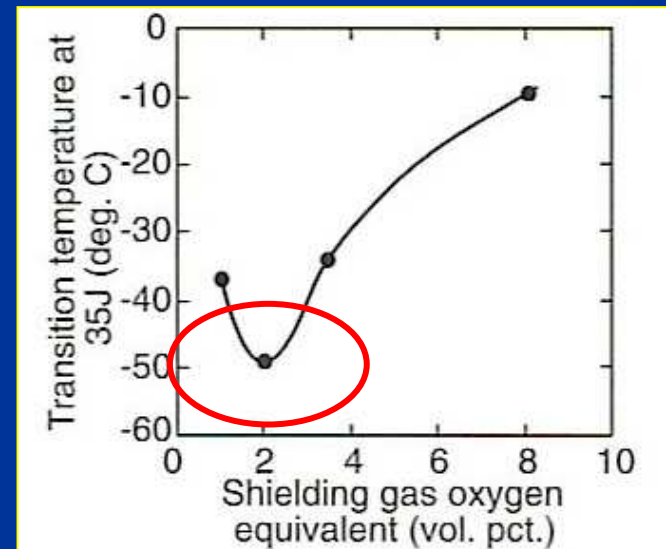
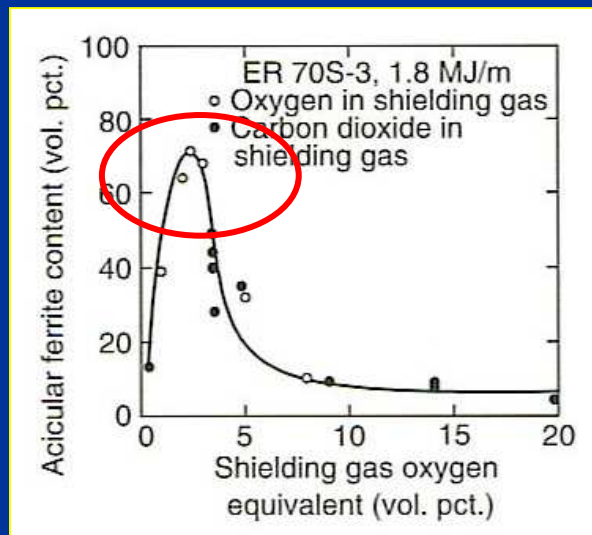
Weld toughness



Oxygen content



Transition temperature at 35 J



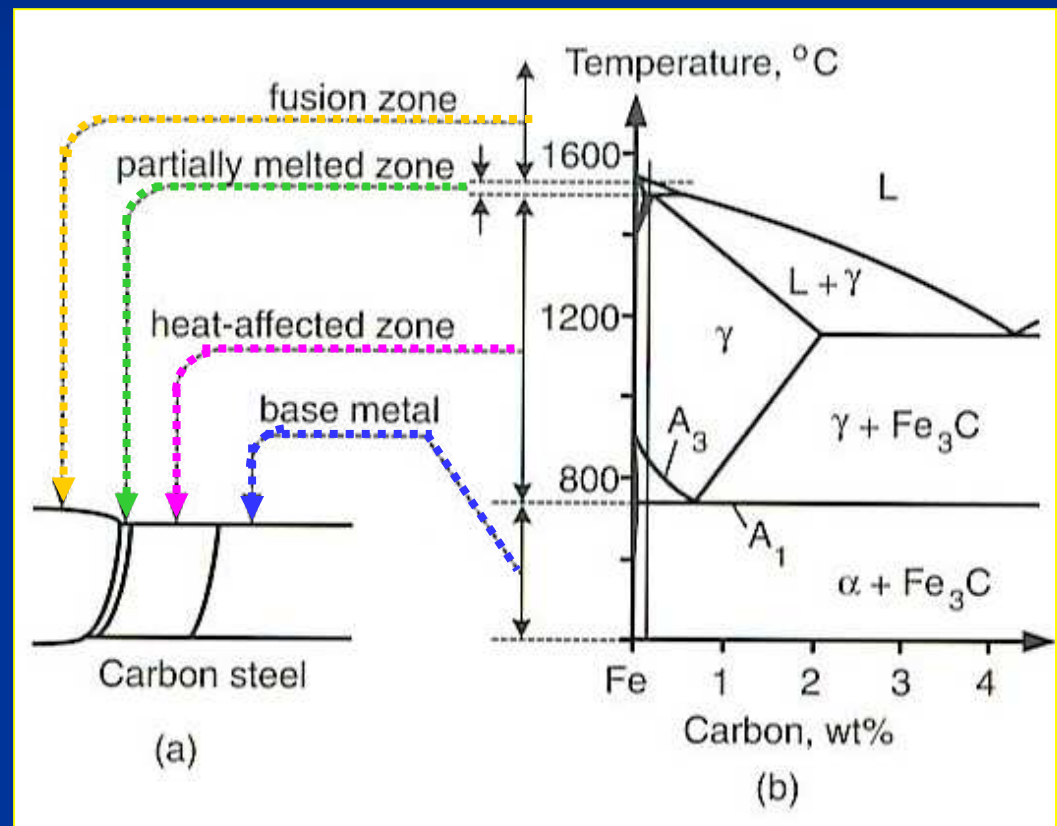
Note: the lowest transition temperature is at 2 vol% oxygen equivalent, corresponding to the maximum amount of acicular ferrite on the weld toughness.

Transformation hardening in carbon and alloy steels

If rapid heating during welding on phase transformation is neglected;

- **Fusion zone** is the area above the liquidus temperature.
- **PMZ** is the area between peritectic and liquidus temperatures.
- **HAZ** is the area between A_1 line and peritectic temperature.
- **Base metal** is the area below A_1 line.

Note: however the thermal cycle in welding are very short (**very high heating rate**) as compared to that of heat treatment. (with the exception of electroslag welding).



(a) Carbon steel weld (b) Fe-C phase diagram



Transformation hardening in welding of carbon steels

- *Low carbon steels (upto 0.15%C) and mild steels (0.15 - 0.30%)*
- *Medium carbon steels (0.30 - 0.50%C) and high carbon steels (0.50 - 1.00%C)*



Transformation hardening in low carbon steels and mild steels

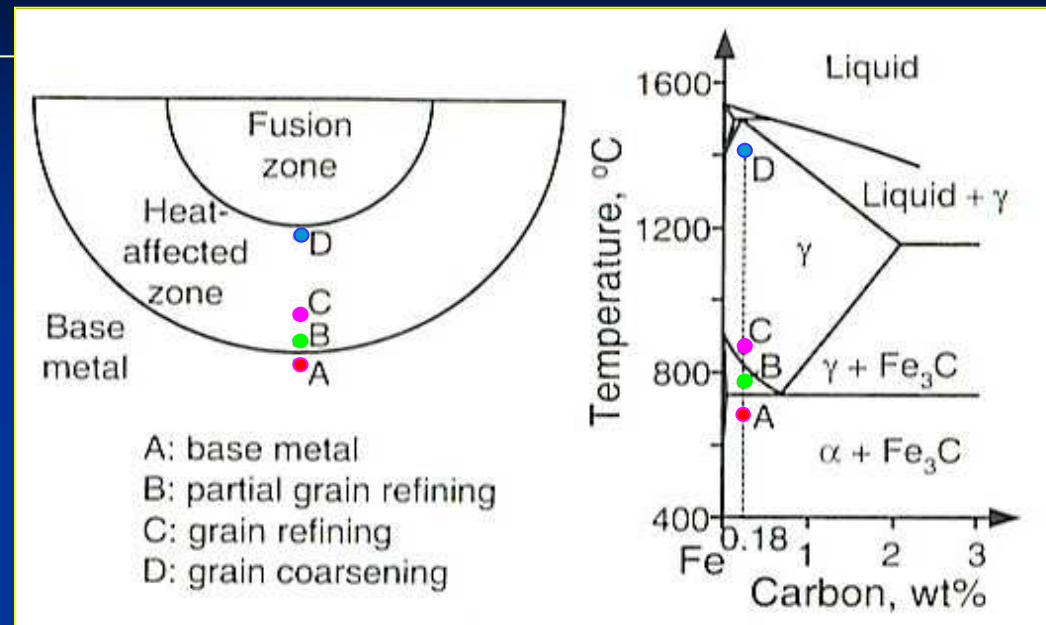
- **Base metal** ($T < A_{C1}$) consists of ferrite and pearlite (position **A**).
- **The HAZ** can be divided into three regions;

Position **B**: Partial grain-refining region

$T > A_{C1}$: prior pearlite colonies transform into **austenite** and expand slightly to **prior ferrite** upon heating, and then decompose to extremely fine grains of **pearlite and ferrite** during cooling.

Position **C**: Grain-refining region

$T > A_{C3}$: **Austenite** grains decompose into non-uniform distribution of small **ferrite and pearlite** grains during cooling due to limited diffusion time for **C**.



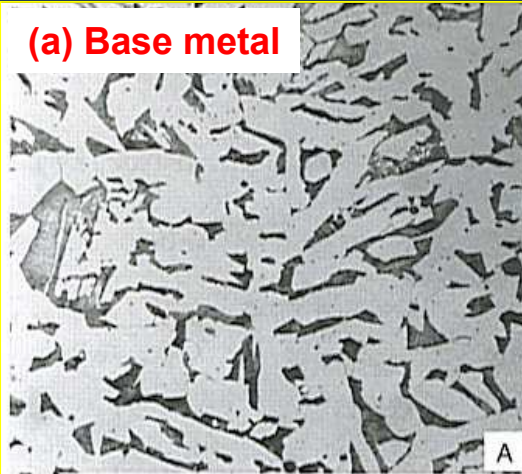
Carbon steel weld and possible microstructure in the weld.

Position **D**: Grain-coarsening region

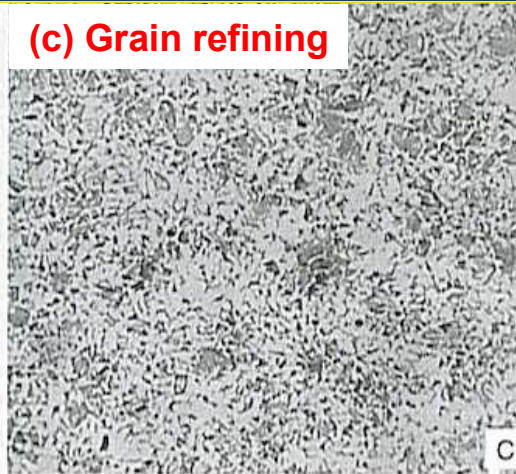
$T \gg A_{C3}$: allowing **austenite** grains to grow, during heating and then during cooling. This encourages ferrite to grow side plates from the grain boundaries called **Widmanstätten ferrite**.

Transformation hardening in low carbon steels and mild steels

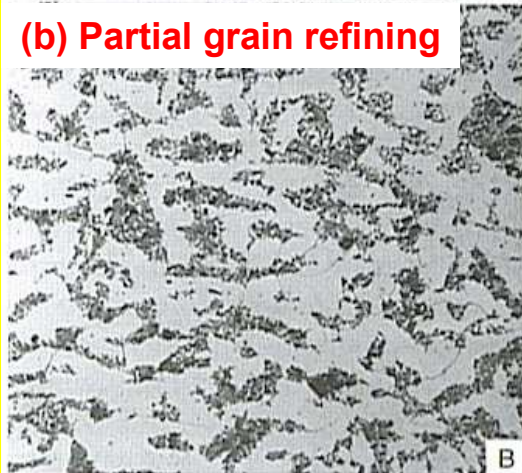
(a) Base metal



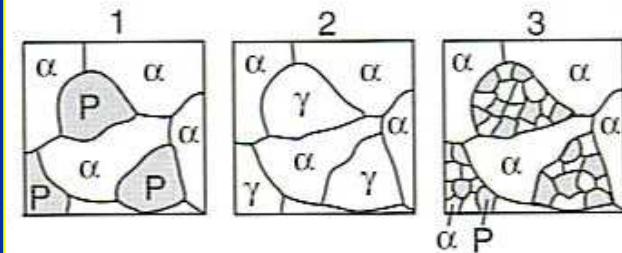
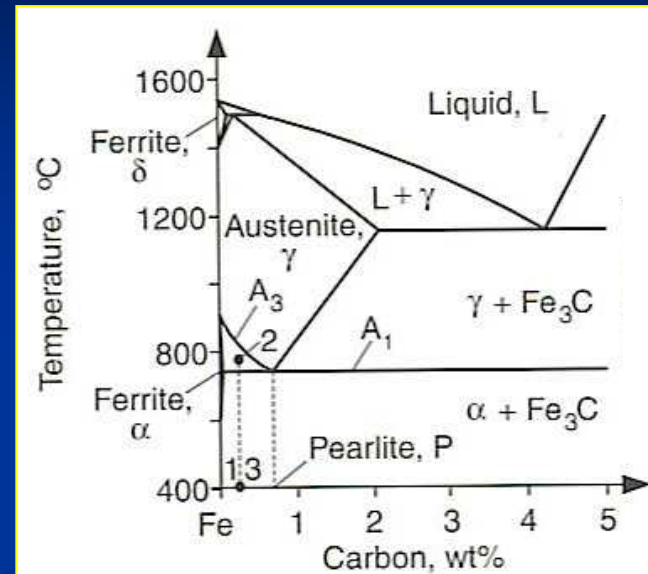
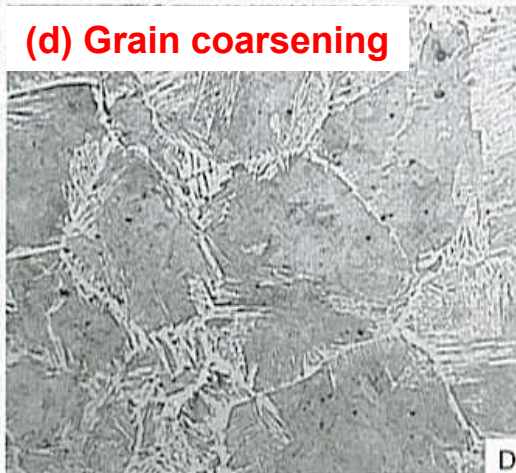
(c) Grain refining



(b) Partial grain refining



(d) Grain coarsening



HAZ microstructure of a gas-tungsten arc weld of 1018 steel.

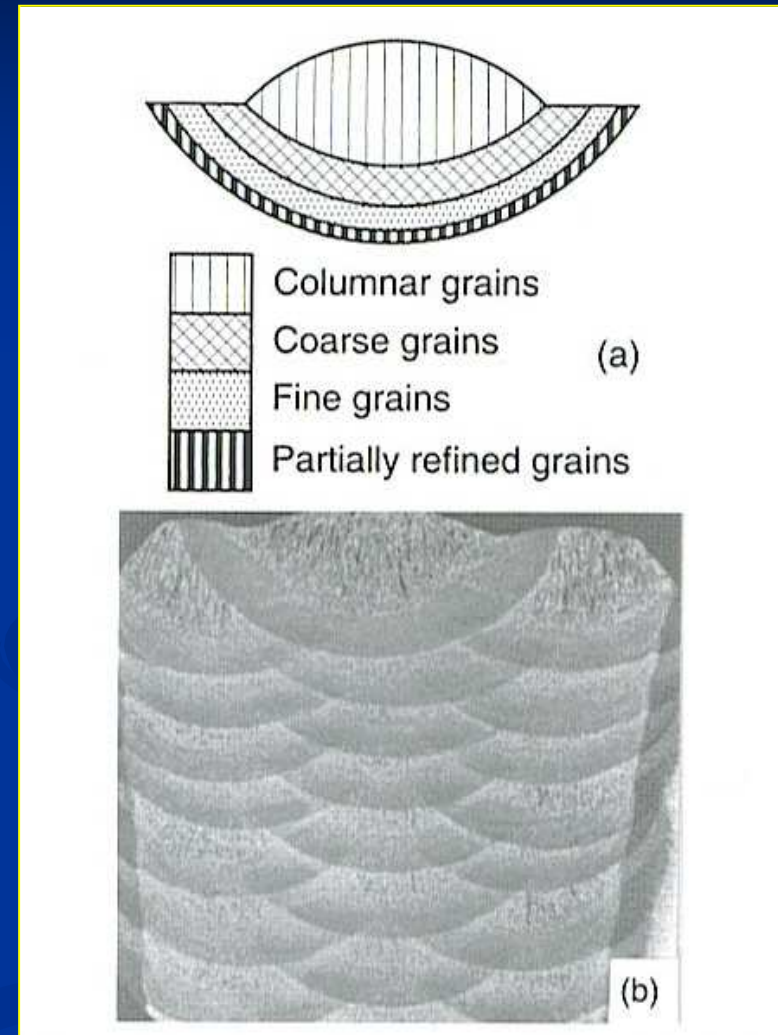
Mechanism of partial grain refining in a carbon steel.

Transformation hardening in low carbon steels and mild steels

Multipass welding of low carbon steels

- The **fusion zone** of a weld pass can be replaced by the **HAZs** of its subsequent passes.
- This **grain refining of the coarsening grains** near the fusion zone has been reported to improve the **weld metal toughness**.

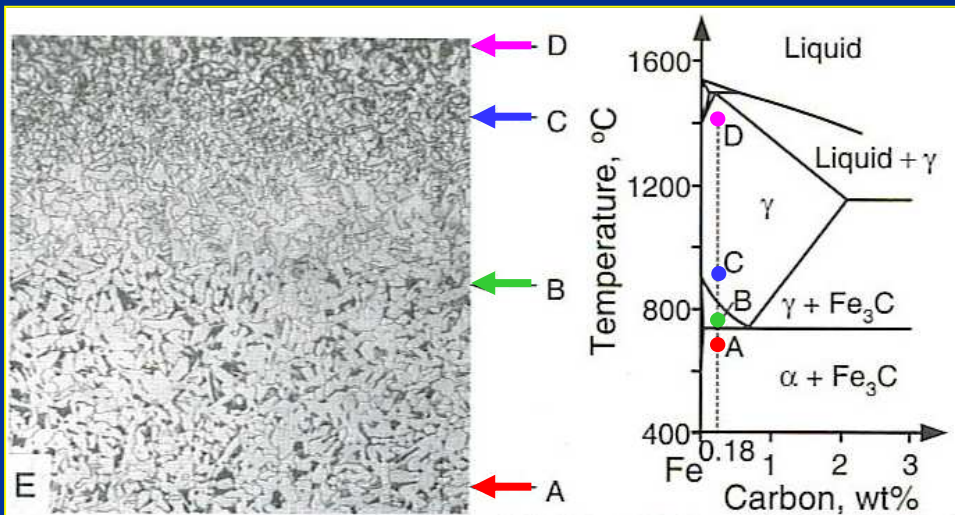
Note: in arc welding, martensite is not normally observed in the HAZ of a low carbon steel, however high-carbon martensite is observed when both heating rate and cooling rate are very high, i.e., laser and electron beam welding.



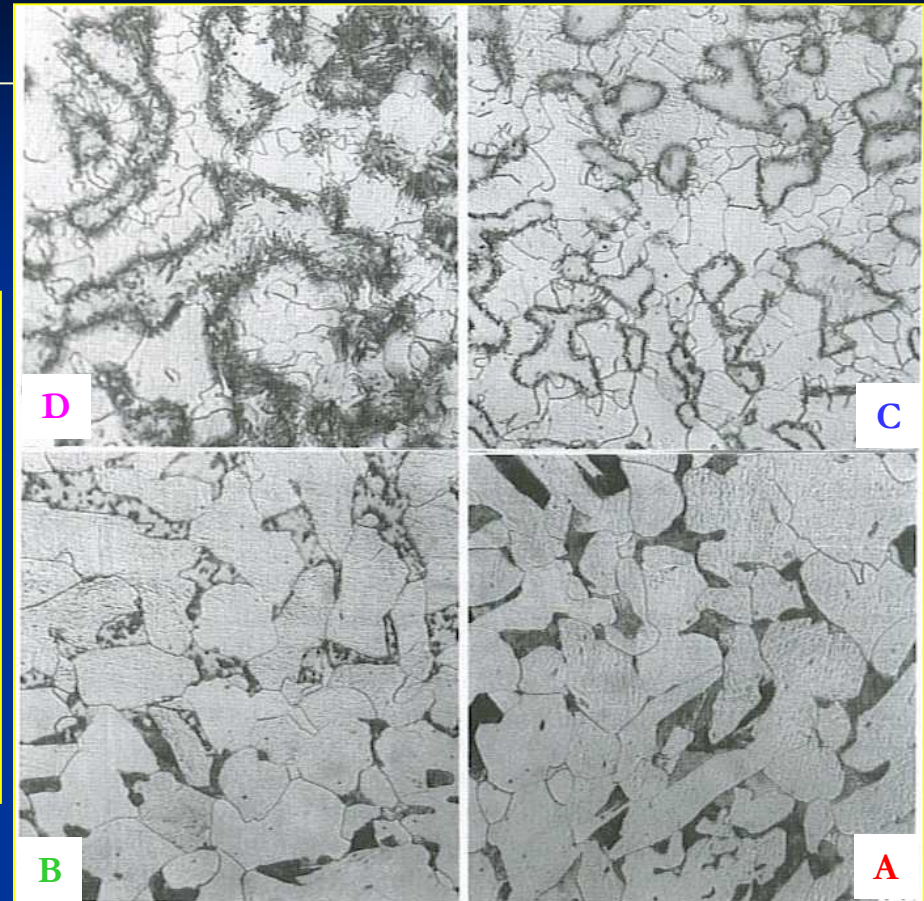
Grain refining in multipass welding (a) single pass weld, (b) microstructure of multipass weld

Transformation hardening in low carbon steels and mild steels

Phase transformation by high energy beam welding



HAZ microstructure of 1018 steel produced by a high-power CO_2 laser welding.

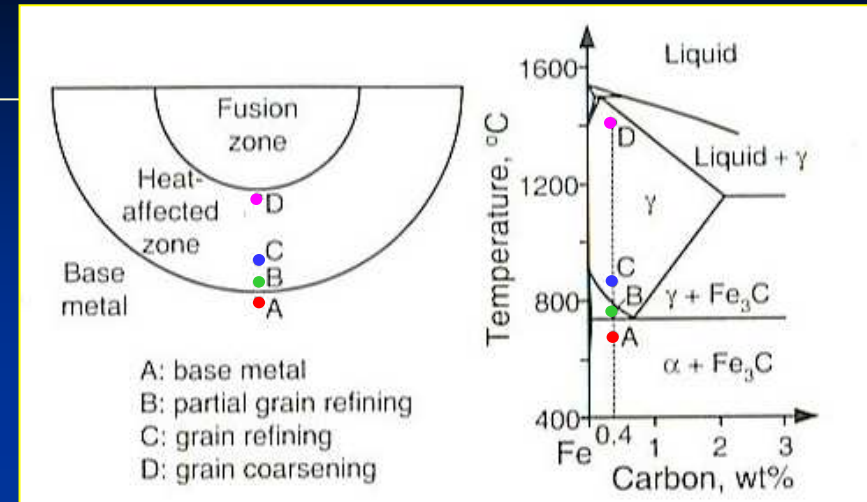
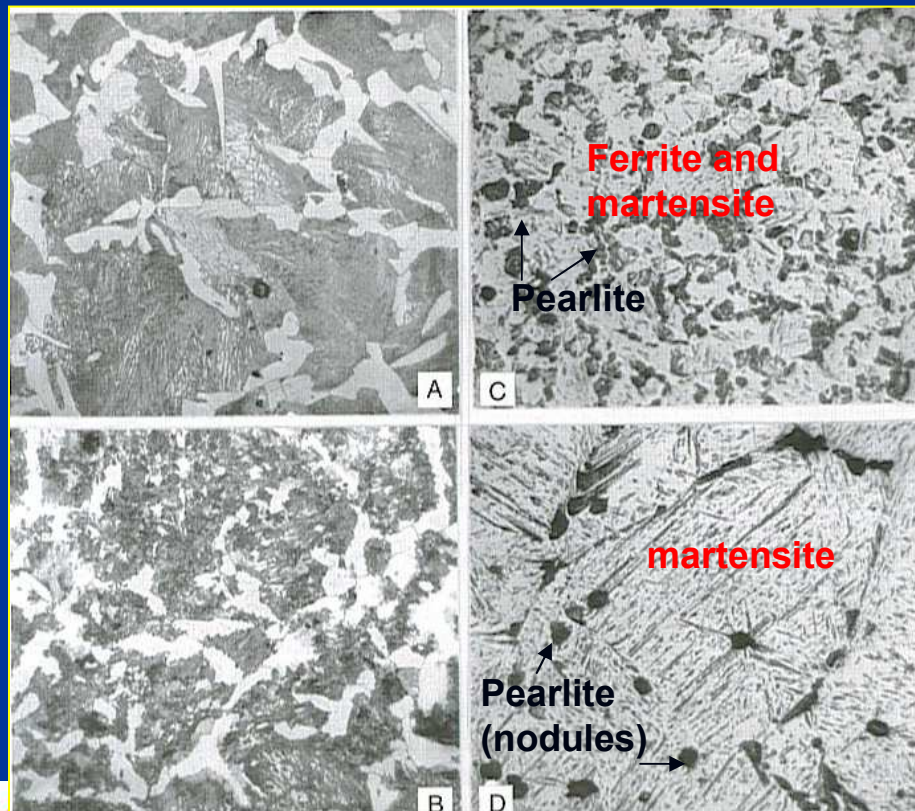


- **High carbon austenite** in position **B** transforms into **hard and brittle high carbon martensite** embedded in a **much softer matrix of ferrite** during rapid cooling.
- At $T > A_{C3}$, position **C** and **D**, austenite transformed into **martensite colonies of lower carbon content** during subsequent cooling.



Transformation hardening in medium and high carbon steels

- Welding of **higher carbon steels** is more difficult and have a greater tendency for **martensitic transformation** in the **HAZ** → **hydrogen cracking**.



- Base metal microstructure of **higher carbon steels** (A) of **more pearlite and less ferrite** than low carbon and mild steels.
- Grain refining region** (C) consists of mainly **martensite** and some areas of **pearlite and ferrite**.
- In **grain coarsening region** (D), high cooling rate and large grain size **promote martensite formation**.



HAZ microstructure of TIG weld of 1040 steel

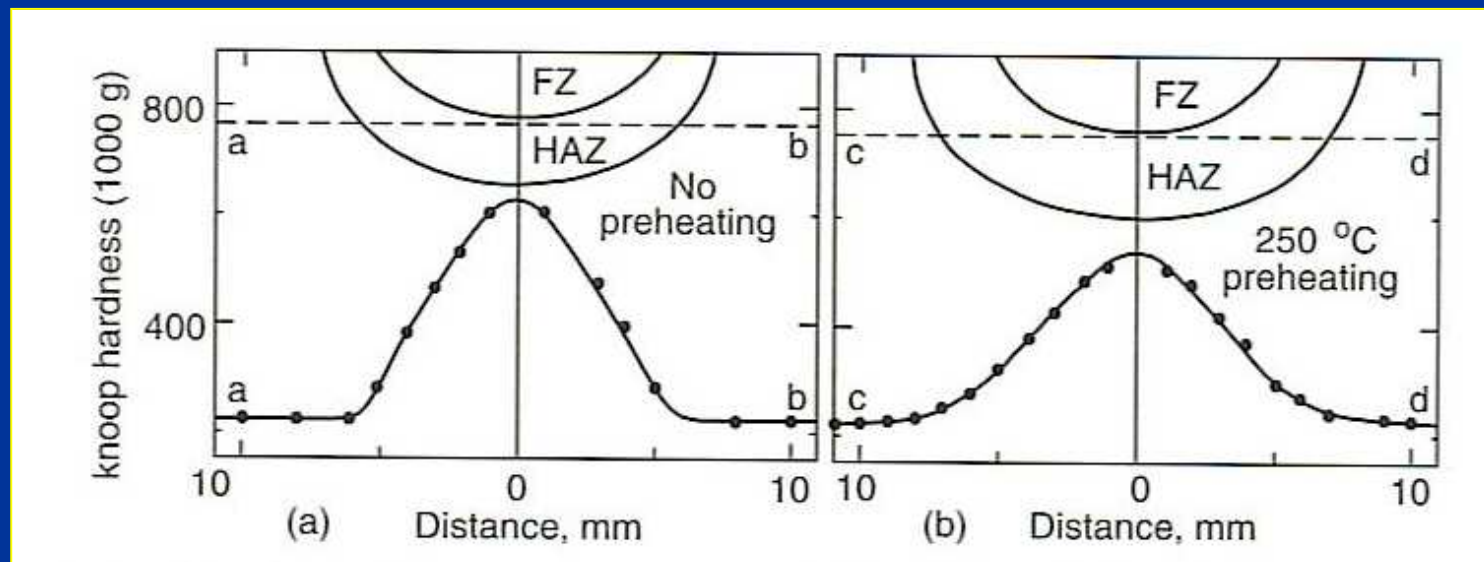
Transformation hardening in medium and high carbon steels

Solution

Hardening due to martensite formation in the **HAZ** in high carbon steels can be suppressed by preheating and controlling of interpass temperature.

Ex: for 1035 steel, preheating and interpass temperature are

- 40°C for 25 mm plates
- 90°C for 50 mm plates



Hardness profiles across HAZ of a 1040 steel
(a) without preheating (b) with 250°C preheating.



Part II: Overageing in aged hardenable Al welds (2xxx, 6xxx)

- Aluminium alloys are more frequently welded than any other types of nonferrous alloys due to their wide range of applications and fairly good weldability.
- However, higher strength aluminium alloys are more susceptible to
 - (i) Hot cracking in the fusion zone and the PMZ and
 - (ii) Loss of strength/ductility in the HAZ.



Aluminium welds



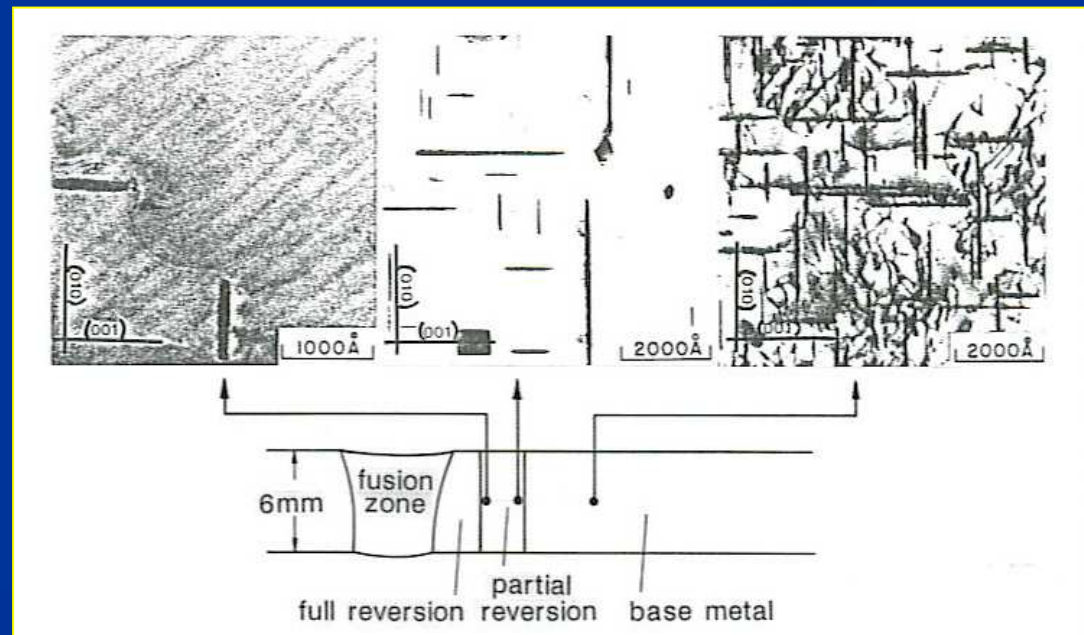
Friction stir weld



Overageing in aged hardenable Al welds (2xxx, 6xxx)

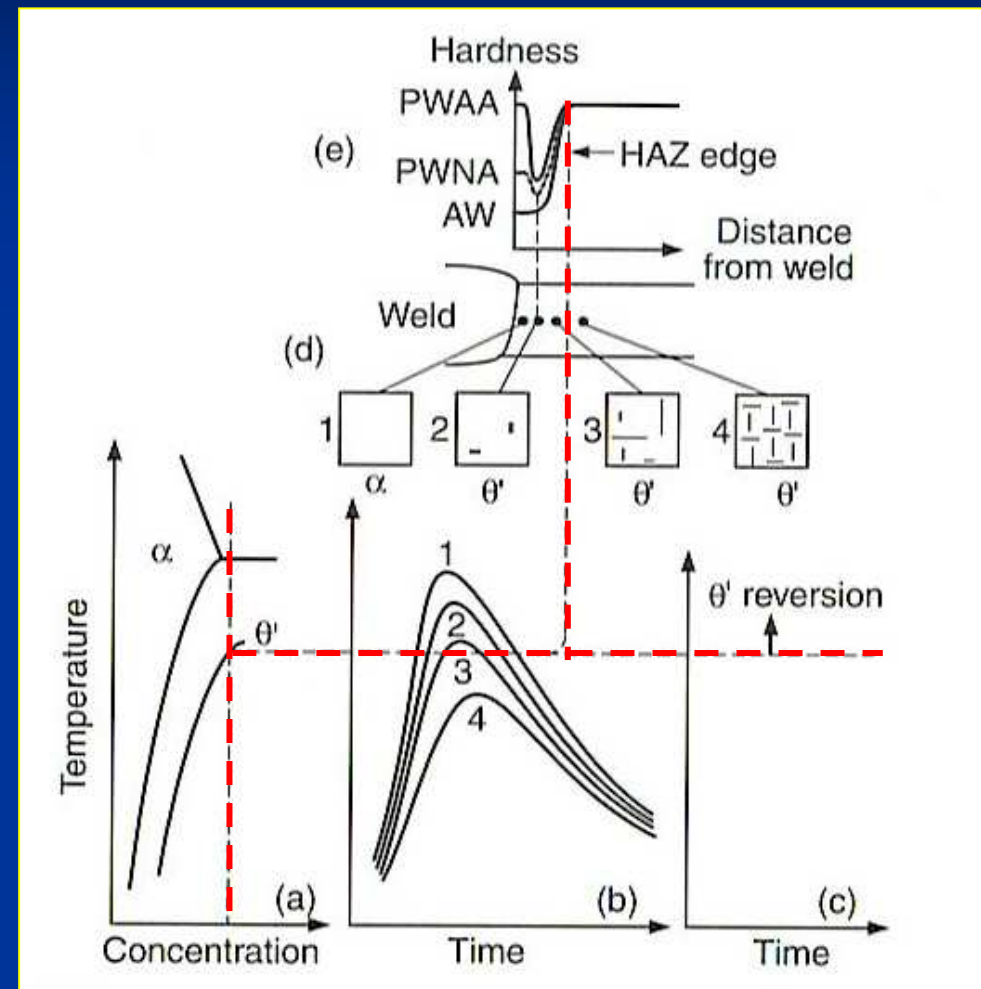
- **Precipitate hardening effect** which has been achieved in aluminium alloy base metal might be suppressed after welding due to the **coarsening of the precipitate phase** from fine θ' (high strength/hardness) to coarse θ (Over-ageing : non-coherent $\rightarrow$ low strength/hardness).
- **A high volume fraction of θ' decreases** from the base metal to the fusion boundary because of the **reversion of θ'** during welding.

TEMs of a 2219 Al artificially aged to contain θ' before welding.



Reversion of precipitate phase during welding

- **Al-Cu alloy** was precipitation hardened to contain θ' before welding.
- **Position 4** was heated to a peak temperature below θ' solvus and thus unaffected by welding.
- **Positions 2 and 3** were heated to above the θ' solvus and partial reversion occurs.
- **Position 1** was heated to an even higher temperature and θ' is fully reversed.
- The cooling rate is too high to cause reprecipitation of θ' and this θ' reversion causes a **decrease in hardness** in **HAZ**.

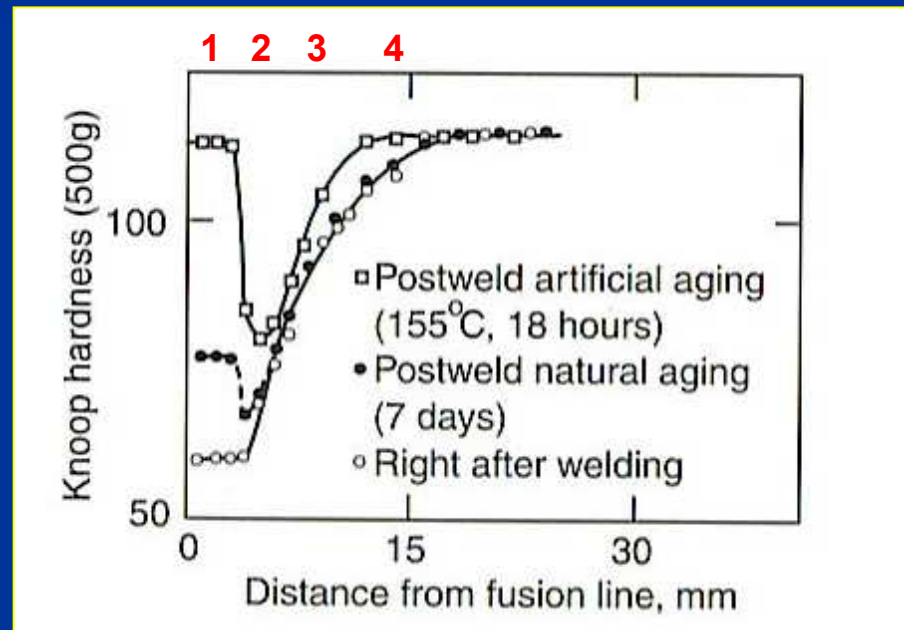


Reversion of precipitate phase θ during welding



Effect of postweld heat treatments

- **Artificial ageing** (**T6**) and **natural ageing** (**T4**) applied after welding have shown to **improve hardness profiles** of the weldment where **T6** has given the better effect.
- However, the hardness in the area which has been overaged did not significantly improved.



Hardness profiles in a 6061 aluminium welded in T6 condition. (10V, 110A, 4.2 mm/s)



Solutions

- Select the welding methods which have *low heat input per unit length*.

Heat input per unit length



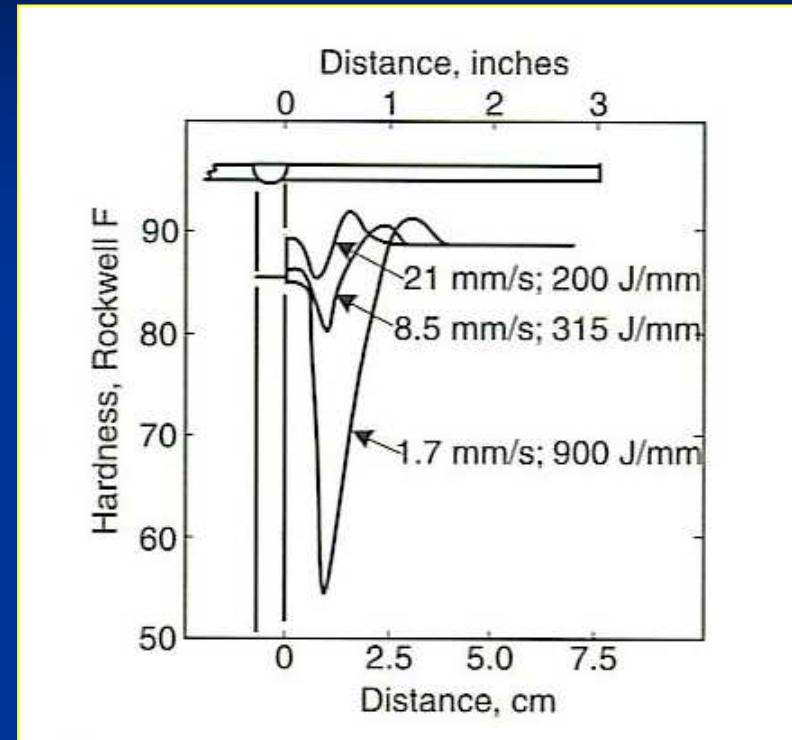
HAZ width



Severe loss of strength



- Solution treatment followed by quenching and artificial ageing of the entire workpiece can **recover the strength** to a **full strength**.

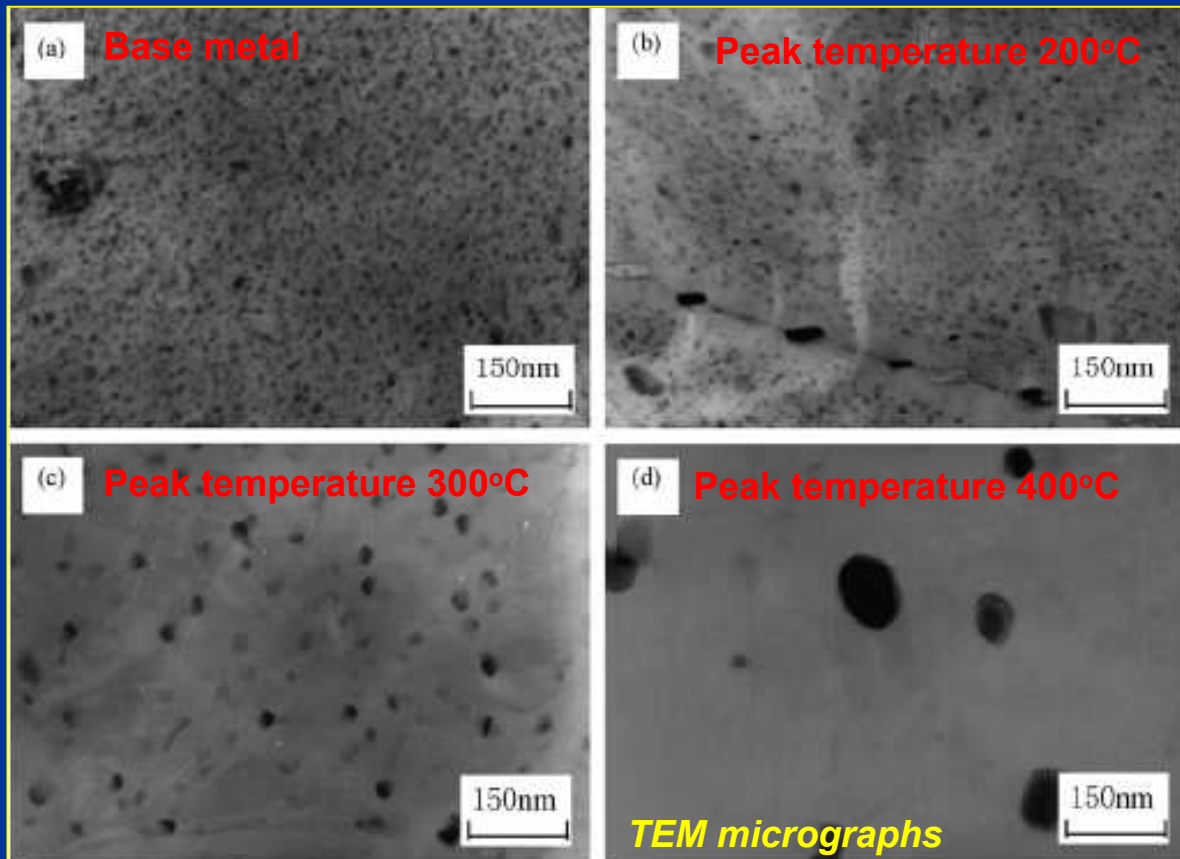
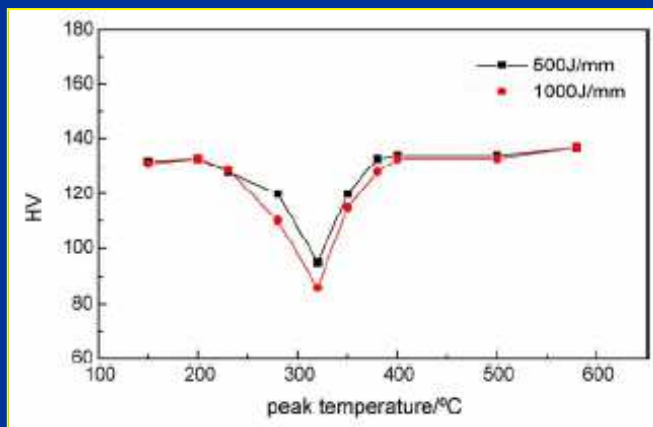
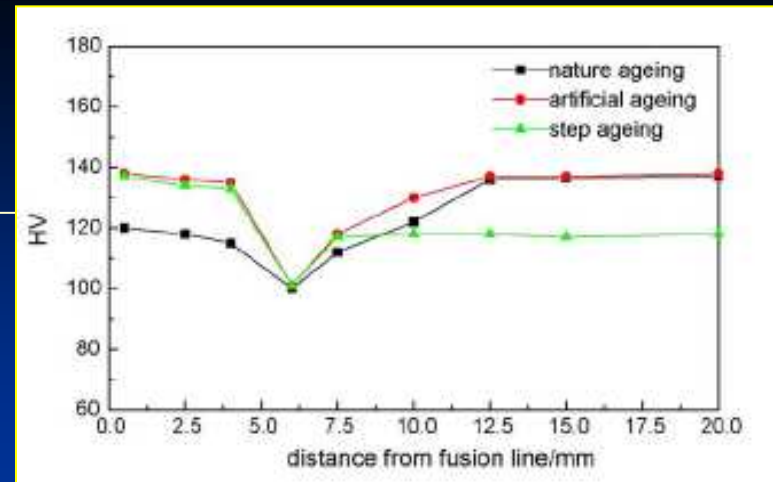


Hardness profiles in 6061-T4 aluminium after postweld artificial ageing.



Softening of HAZ in GMA welded Al-Zn-Mg alloy

- Small precipitates are visible in parent metal (fig a) and no significantly changed in fig b.
- **Dissolution and growth of precipitates** occur at peak temperature $\sim 300^\circ\text{C}$ resulting in lower hardness, fig c and d.



TEM micrographs



Part III: Phase transformation hardening in titanium welds

- Most titanium alloys are **readily weldable**, i.e., unalloyed titanium and alpha titanium alloys. Highly alloyed (β titanium) alloys nevertheless are less weldable and normally give embrittling effects.
- However, welding of $\alpha+\beta$ titanium alloys gives low weld ductility and toughness due to phase transformation (**martensitic transformation**) in the **fusion zone** or **HAZ** and the presence of **continuous grain boundary α phase** at the grain boundaries.
- The **welding environment** should be **kept clean**, i.e., using inert gas welding or vacuum welding to avoid reactions with oxygen.



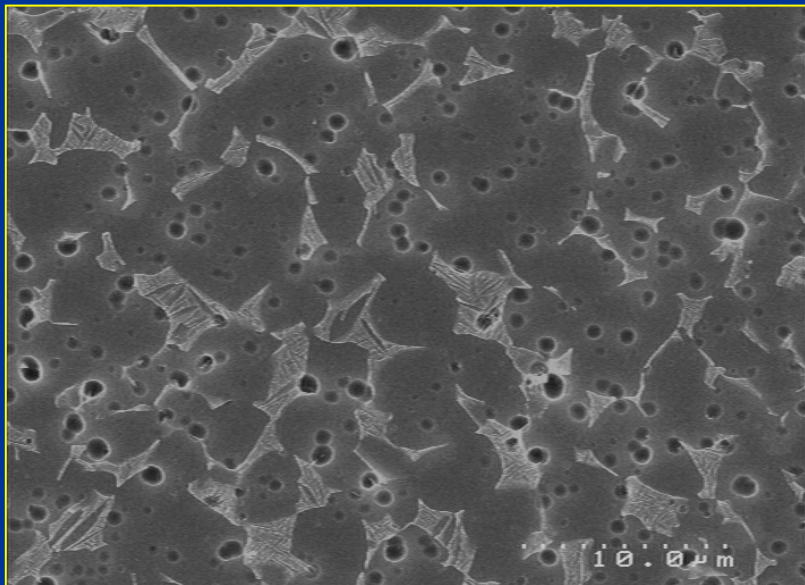
CO₂ laser weld of titanium alloy

Note: Oxygen is an α stabiliser, therefore has a significant effect on phase transformation.

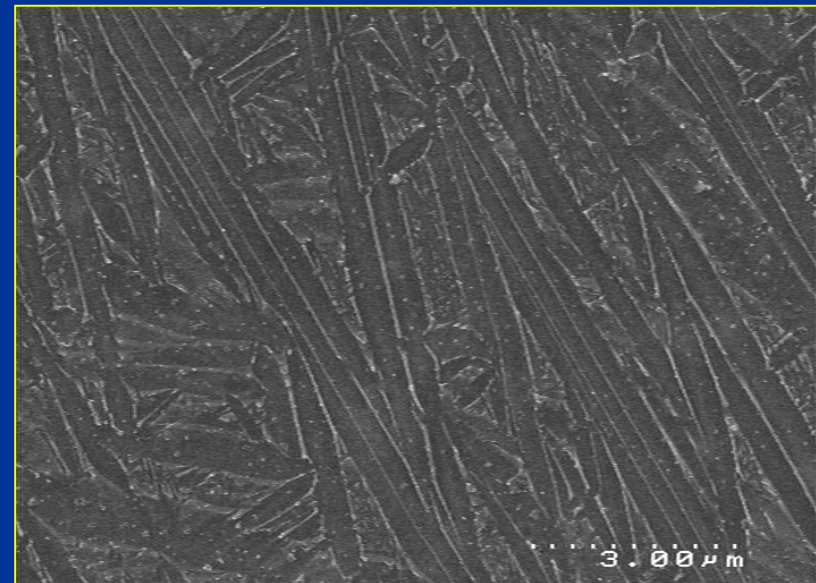
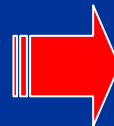


Phase transformation in $\alpha+\beta$ titanium welds

- **Ex:** Welding of annealed titanium consisting of **equilibrium equiaxed grains** will give metastable phases such as martensite, widmanstätten or acicular structures, depending on the **cooling rates**.



Ti679 base metal

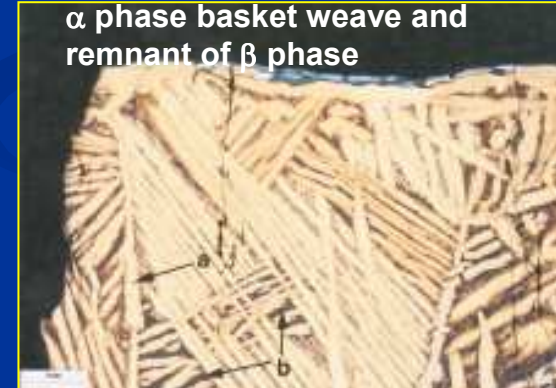
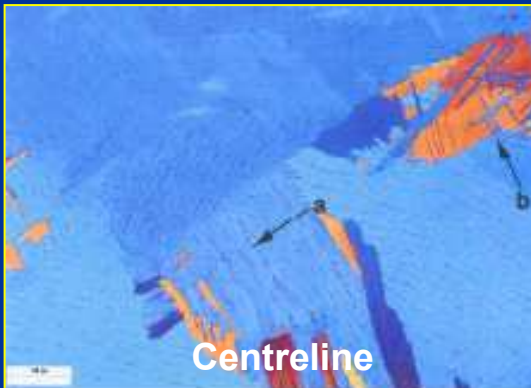
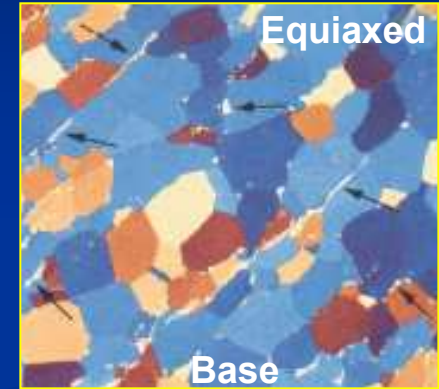
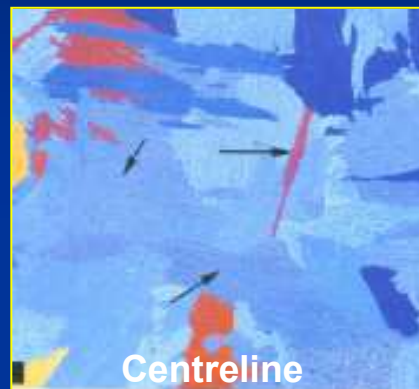


Ti679 Heat affected zone



Phase transformation in CP titanium welds

Ex: Weld microstructure of **GTA welding** of **CP Ti** alloy with **CP Ti** fillers has affected by the **oxygen contents** in the weld during welding.



Oxygen contamination causes acicular α microstructure with retained β between the α cells on the surface whereas low oxygen cause α microstructure of low temp α cell and large β grain boundaries.



References

- Kou, S., **Welding metallurgy**, 2nd edition, 2003, John Willey and Sons, Inc., USA, ISBN 0-471-43491-4.
- Fu, G., Tian, F., Wang, H., **Studies on softening of heat-affected zone of pulsed current GMA welded Al-Zn-Mg alloy**, Journal of Materials Processing Technology, 2006, Vol.180, p 216-110.
- www.key-to-metals.com, **Welding of titanium alloys**.
- Baeslack III, W.A., Becker D.W., Froes, F.H., **Advances in titanium welding metallurgy**, JOM, May 1984, Vol.36, No. 5. p 46-58.
- Danielson, P., Wilson, R., Alman, D., **Microstructure of titanium welds**, Struers e-Journal of Materialography, Vol. 3, 2004.

