Dissimilar Materials Weldability Concepts

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Introduction

- **Dissimilar materials welding refers to the joining of:**
  - Two different alloy systems (e.g., steel, stainless steel)
  - Materials of different fundamental types
    - Metals, ceramics, polymers, composite
    - Ferrous to non-ferrous
  - Materials with different compositions within a particular type (e.g., austenitic stainless steel, ferritic stainless steel, duplex stainless steel, etc.).
- **Importance to industry:**
  - Dissimilar lightweight material welding is used to connect different metals together for automotive industries
  - Used where an object is subjected to multiple environments in one application such as in chemical and petrochemical industries, power generation, and oil and gas industries
  - Minimize costs of fabrication.

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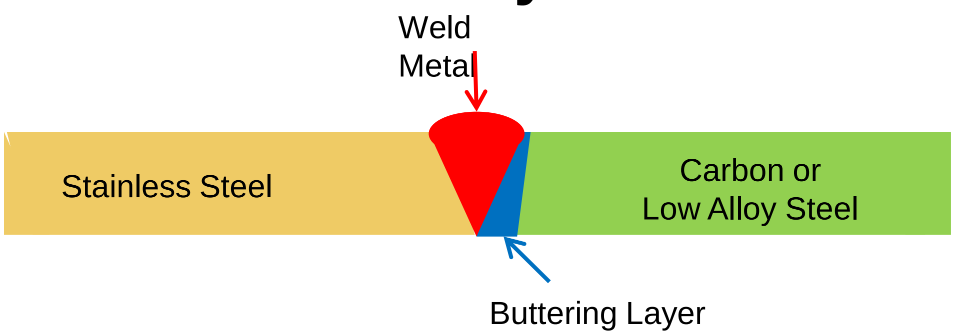
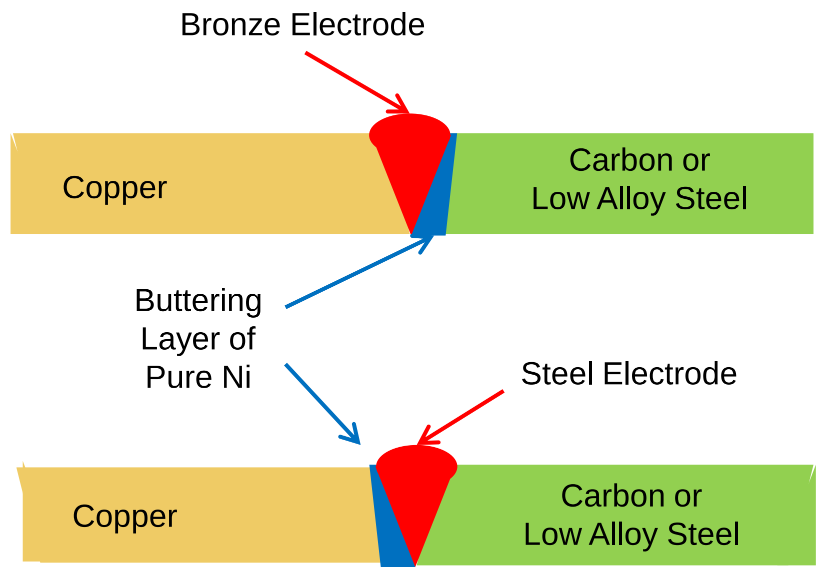
Advantages

- Each section of the welded component can be optimized for its specific application.
- Provide damage tolerance to the overall structure.
- Optimize design by matching the correct material to the needed property or behavior.
- High performance materials only used where they are absolutely required and provide real benefit.

Disadvantages

- **Weld metal consists of a mixture of materials which have unknown material properties when combined with unevenly distributed heating or stresses.**





Joint Parts	Material	Thermal Exp./Cont Coeff. (1/K) x 10^{-6}	YS (ksi)	UTS (ksi)
Stainless Steel	316 L	19	42	84
Weld Metal	308 L	19	29	84
Buttering	309 L	19	40	95
Alloy Steel	A 516 G60	12	29	60 - 80

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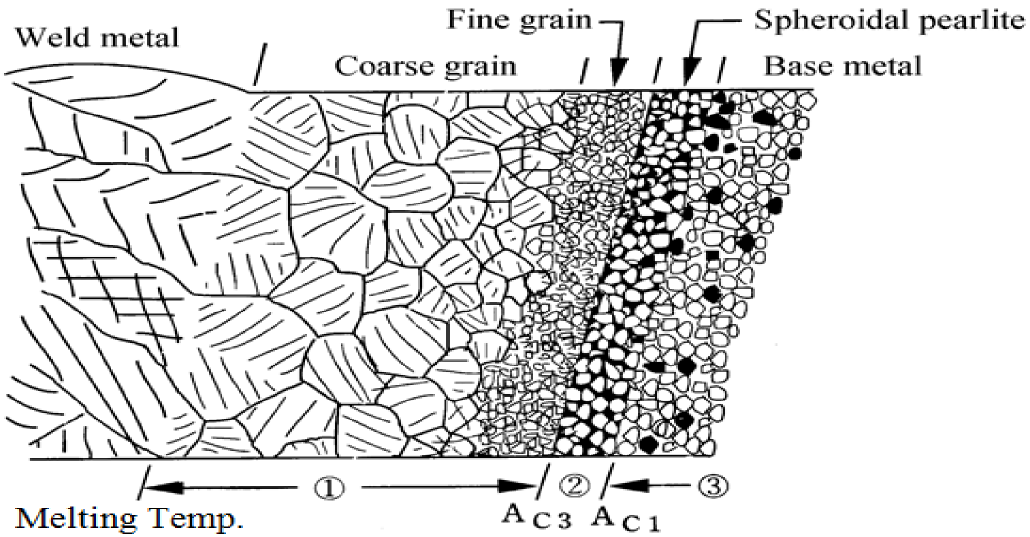
Metallurgical Processes

- **Metallurgically, all fusion welds are dissimilar metal welds because:**
  - Weld zone has a cast solidified structure, while the base metal has a wrought structure
  - The chemical composition of deposited weld metal is over-mismatch or under-mismatch to that of the base metal based on the required joint strength.



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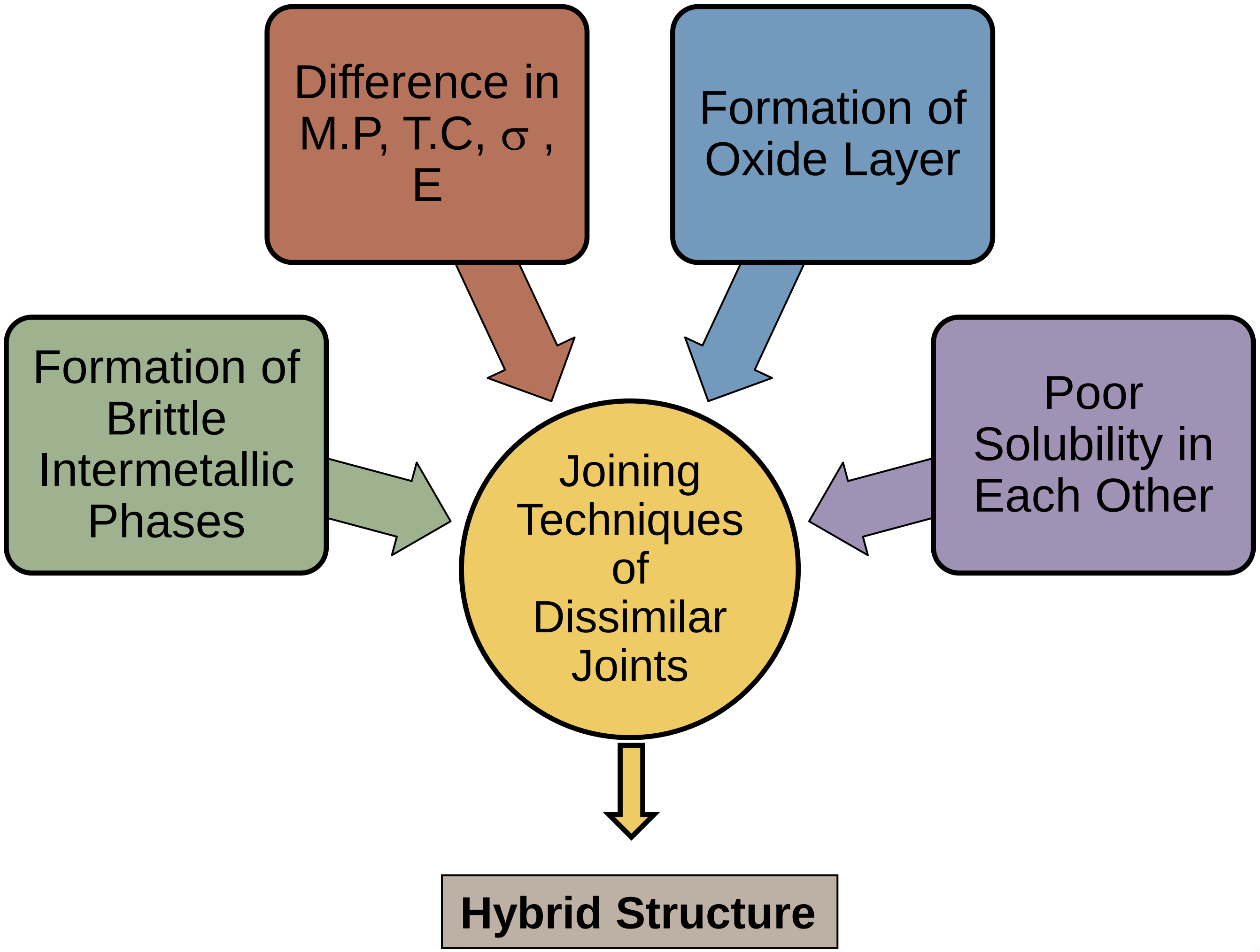
Challenges of Welding Dissimilar Metals

- **The existence of a transition zone between the metals and the intermetallic compounds formed in the heat affected zone:**
  - If there is mutual solubility of the two metals, the dissimilar joints can be made successfully
  - If there is little or no solubility between the two metals to be joined, the weld joint will not be successful.
- **The formation of intermetallic compounds and their effects on:**
  - Increasing the crack sensitivity
  - Reducing the ductility
  - Increasing the susceptibility to corrosion.

Challenges of Welding Dissimilar Metals

- **Differences in the coefficient of thermal expansion:**
  - The residual stresses in welds are generated by the thermal contraction of the weld metal and the adjacent base metal. As a result, the residual stress distribution and magnitude are not similar across the dissimilar weld joint
  - If these are widely different, there will be internal stresses set up in the inter-critical HAZ leading to service failure.
- **The difference in melting temperatures, since one metal will be molten and overheated before the other when subjected to the same heat source.**
- **The difference of the electrochemical potential could increase the susceptibility to corrosion at HAZ. If they are far apart on the scale, corrosion can be a serious problem.**

Difficulties

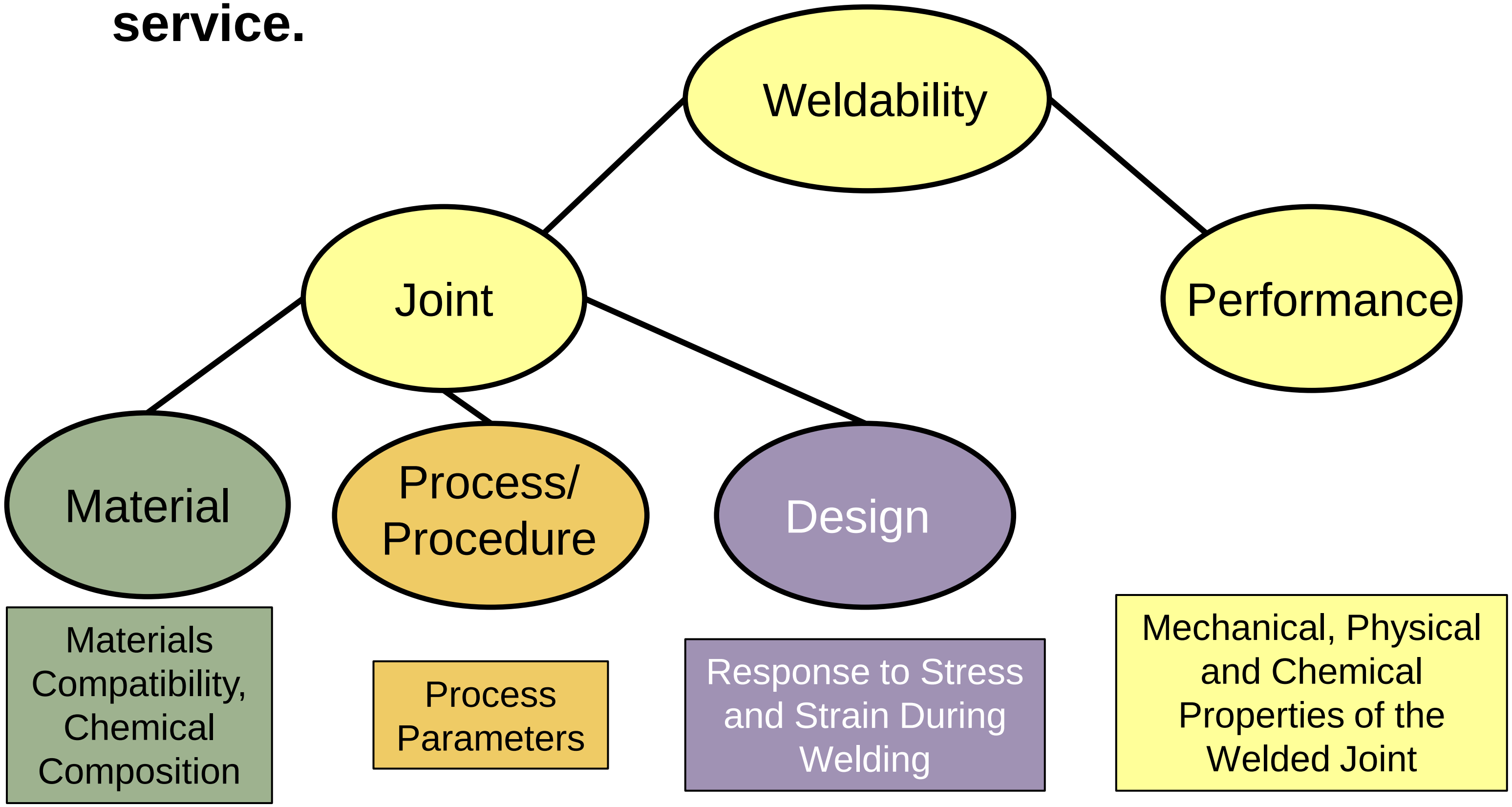


Relative Properties of Different Materials

Material	Melting Point (°F)	Density, (gm/cm^3)	Thermal Conductivity (BTU.In/ft^2.h.°F)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)
Mild Steel	2750	7.86	230-360	200	300	200
HSS		7.87		345	485	205
AHSS		7.78		800	1400	208
Stainless Steel (304)	2600	7.85	110	290	620	203
Aluminum Alloys	1220	2.71	1644	275	300	70
Magnesium Alloys	900-1150	1.77	360-504	120-160	220-230	45
Nickel Base Alloys	2300 - 2440	8.19	104-135	150	185	203

Weldability

- Weldability is the capacity of a material to be welded under the fabrication conditions imposed, into a specific, suitably designed structure, and to perform satisfactorily in the intended service.



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Classification of Weld Joint Discontinuities

- It is unusual for the weldments to be completely sound.
- They normally contain small defects.

Welding Process or Procedure -Related Discontinuities

- Porosity, slag, oxide inclusions, lack of fusion, undercut, crack, distortion, etc.

Metallurgical Discontinuities

- Cracks or fissures (hot, cold, reheat, lamellar)
- Microstructural alterations at HAZ
- Weld metal & HAZ segregation
- Base plate laminations

Design Related Discontinuities

- Changes in section & other stress Concentrators
- Weld joint type

Understand the Cause

↓

Solve/Prevent the Problem

- Furthermore, different metals have different weldability, so we need to understand the nature of the metal to be welded.

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Weldability of Metals and Alloys

- **Weldability of carbon steel alloys is inversely proportional to its hardenability due to martensite formation.**
- **Austenitic stainless steels tend to be the most weldable, but suffer from distortion due to high thermal expansion leading to cracking and reduced corrosion resistance.**
- **Ferritic and martensitic stainless steels are not easily welded, often to be preheated and use special electrodes.**
- **Aluminum alloys are susceptible to hot cracking, oxide inclusions, dross, and porosity (hydrogen).**
- **Titanium alloys with low amounts of alloying elements are more readily welded, while highly stabilized β titanium alloys are difficult to weld due to segregation.**

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Case Studies

Dissimilar Joining of Carbon Steel to Stainless Steel

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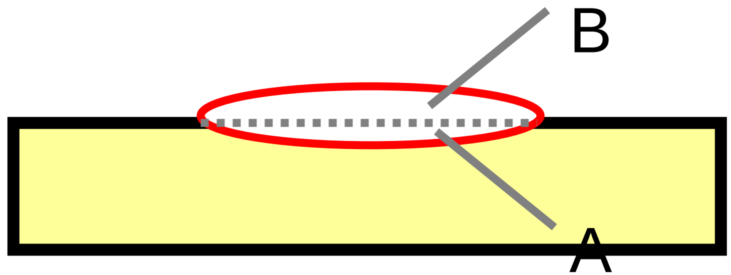
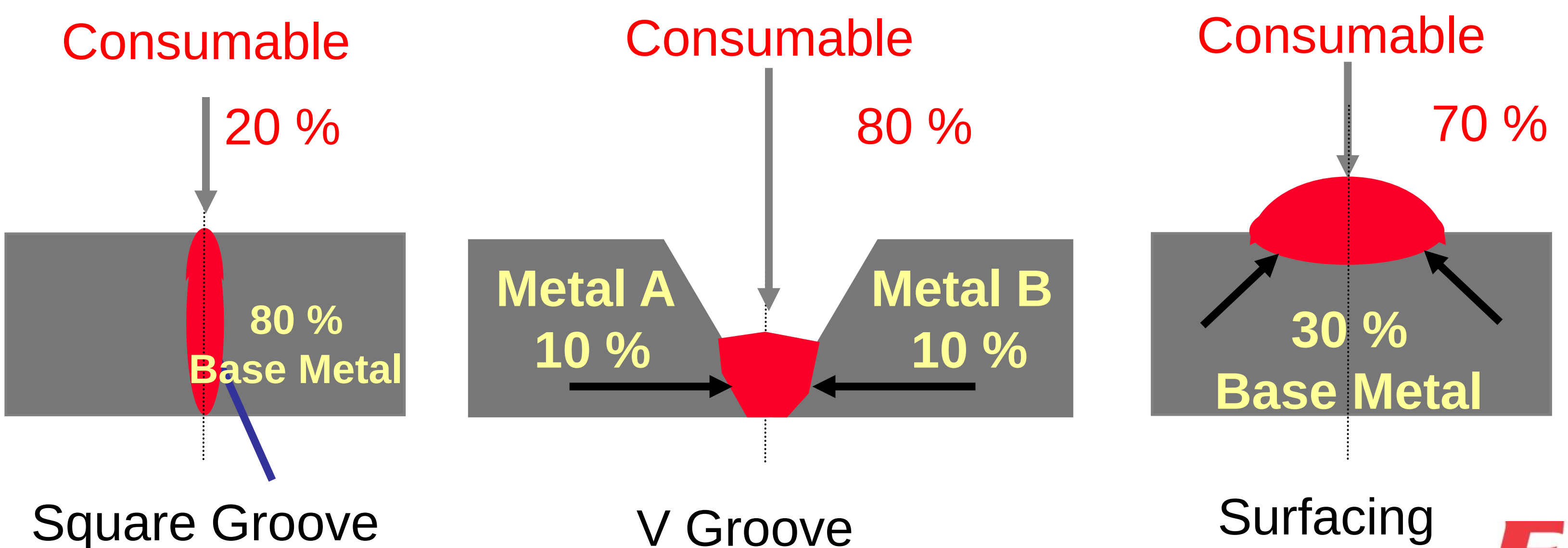
Difficulties

- A risk of martensite formation in the weld after dilution by the base metal and residual amounts of ferrite resulting in possible hot cracking.
- The deposition of carbon steel or low-alloy steel filler metal on austenitic stainless steel can result in hard, brittle weld deposits.
- Hot cracking may occur because of low melting point impurities such as phosphorous (P) and sulfur (S).

Dilution



Dilution = A / (A + B) × 100 %



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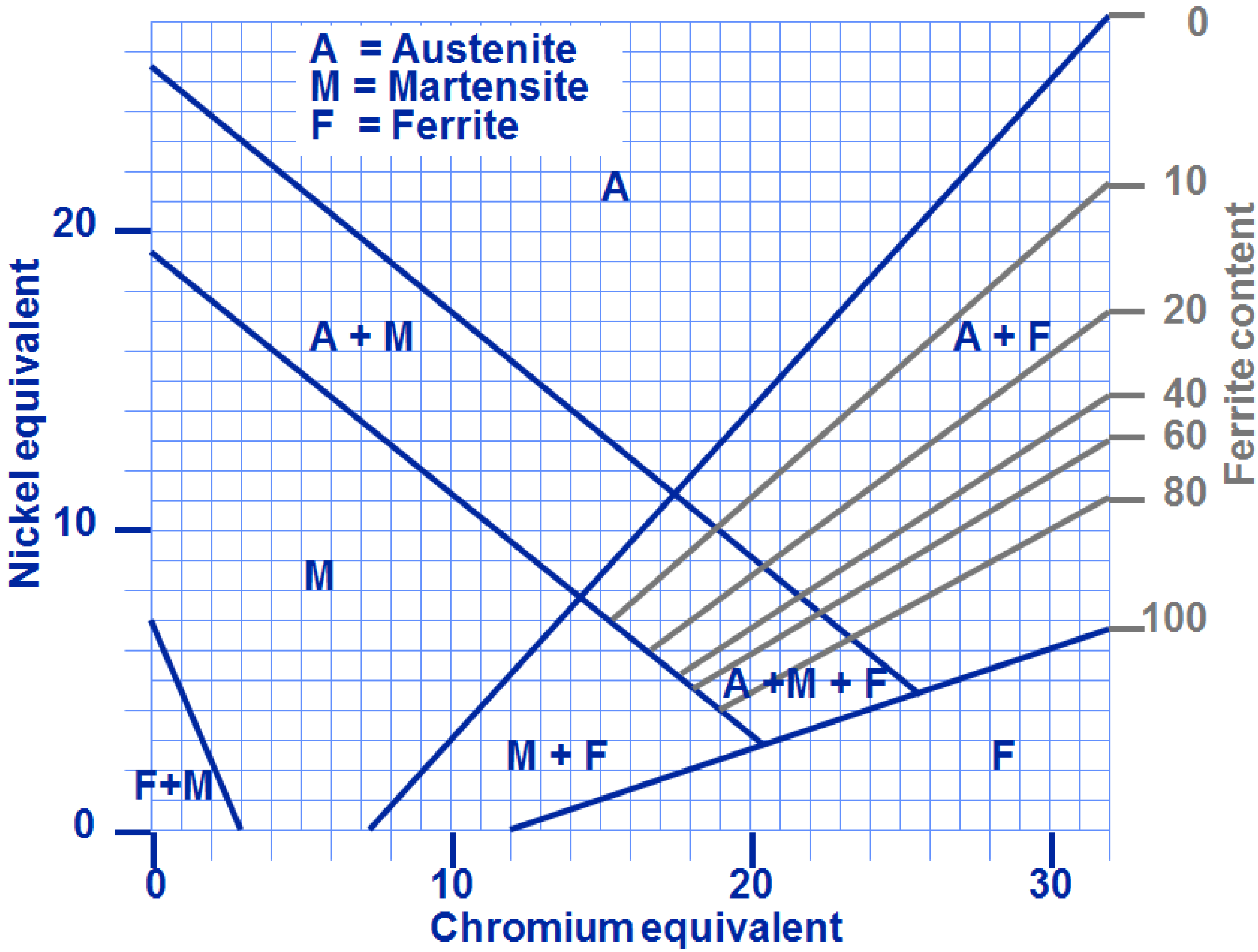
Schaeffler Diagram



Schaeffler diagram indicates the approximate microstructure for high-alloyed steel welds.

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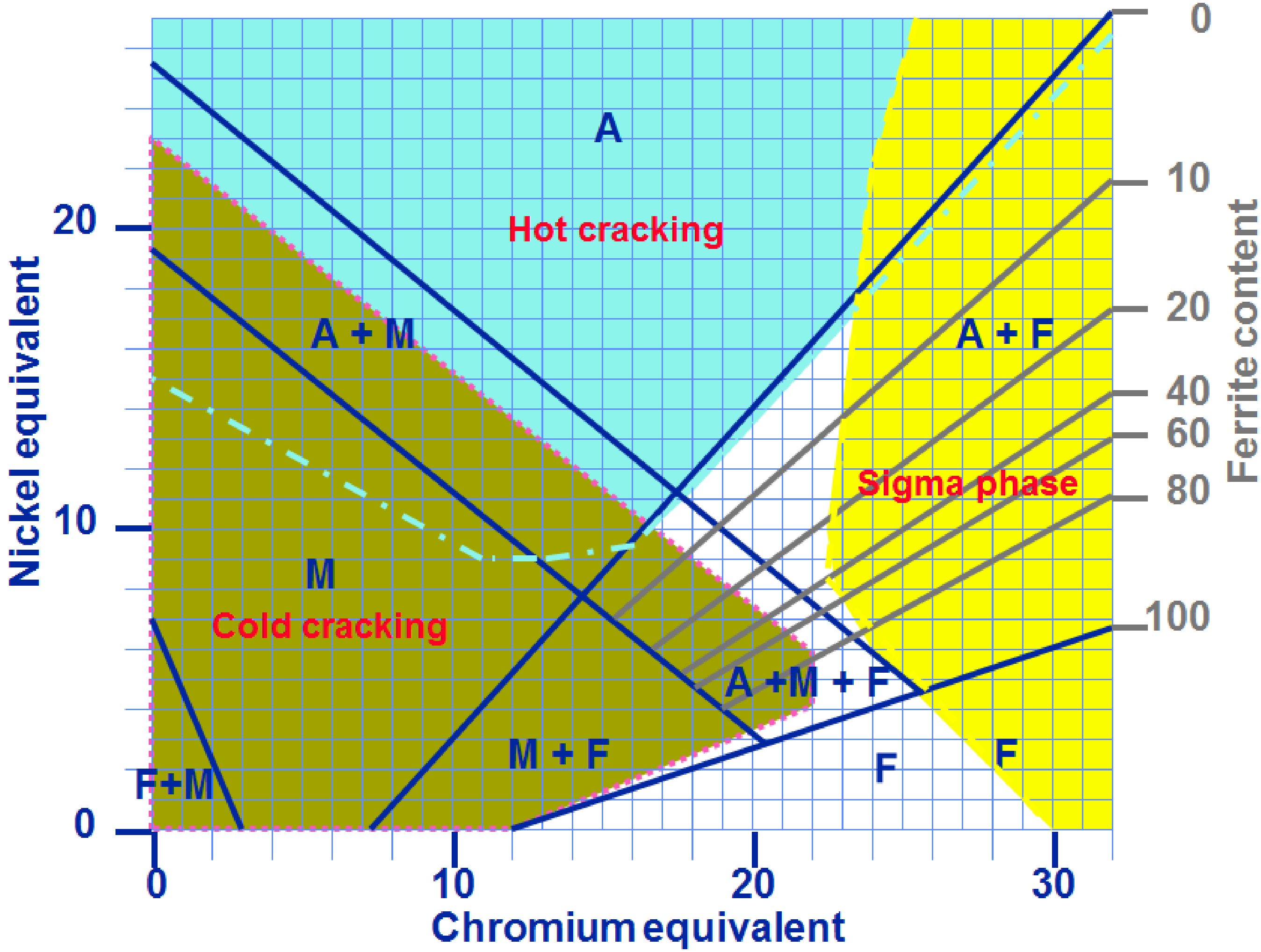
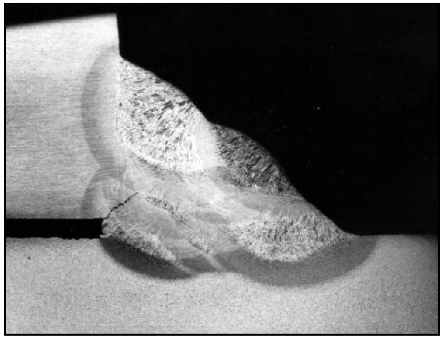
Area of Schaeffler Diagram

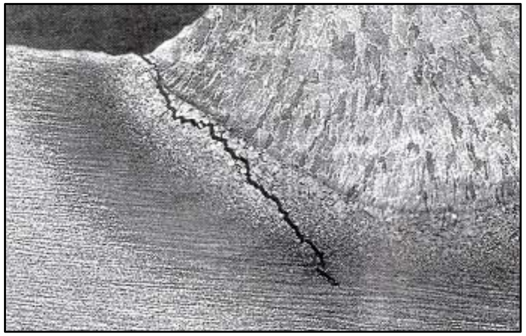


A = Austenite
M = Martensite
F = Ferrite

Cold Cracking

- **Cold cracking or hydrogen-induced cracking are terms for the same phenomena. Well-known types of cold cracks are:**
  - Under bead crack (base metal)
  - Root crack
  - Micro-crack or transverse crack in the weld metal.
- **Martensitic structures are the most susceptible structure with the presence of hydrogen and residual stresses.**
- **Cracks usually appear at weld temperatures below 200°C.**





Weld: To Avoid Martensitic Structures

- Selection of consumables with minimum martensite in the as-welded microstructure.

Base Metal: To Avoid Cold Cracking

- Preheating, if necessary.

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Solidification Cracking

- **Hot cracking refers to cracking that occurs during welding, casting, or hot working at temperature close to the melting point of the material.**
- **The cracking is known to occur both:**
  - above the liquation temperature known as super-solidus cracking and
  - in solid state, called sub-solidus cracking.
- **Super-solidus cracking may manifest as:**
  - Solidification cracking occurs in the presence of a liquid phase in the fusion zone, or as
  - Liquation cracking in the heat-affected zone where it is accompanied by grain boundary melting.

To Avoid Low Melting Constituents:

- Selection of consumables with at least 5 vol.-% ferrite in the as-welded microstructure.

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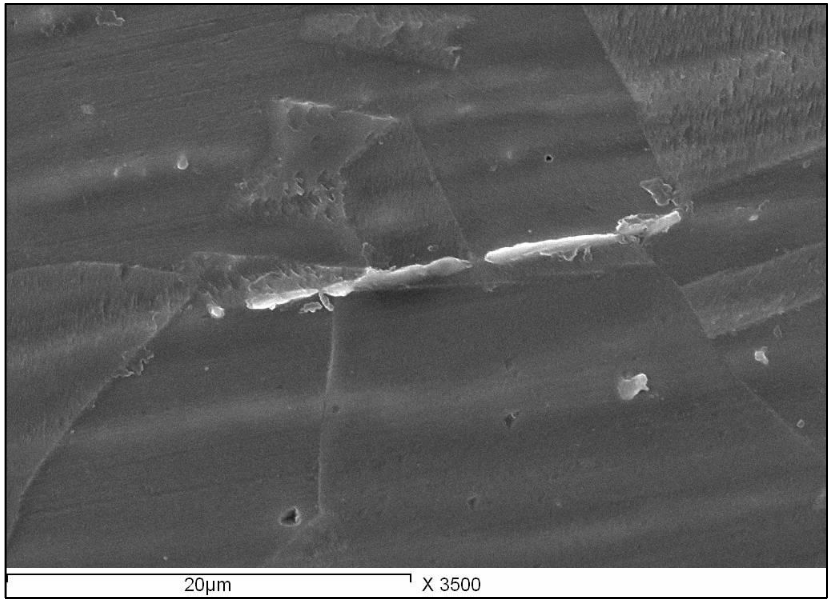
Sigma Phase

- **Sigma phase is intermetallic phase and it forms at temperatures between 500 and 900°C in ferritic stainless steels containing more than 14% Cr.**
- **The formation of sigma phase results in:**
  - Increased hardness (sometimes useful)
  - Decreased ductility
  - Decreased corrosion resistance.



- **Sigma phase embrittlement is a problem where long exposure at elevated temperature (welding of thick sections, heat treatments at temperatures between 500 and 900°C) are involved.**

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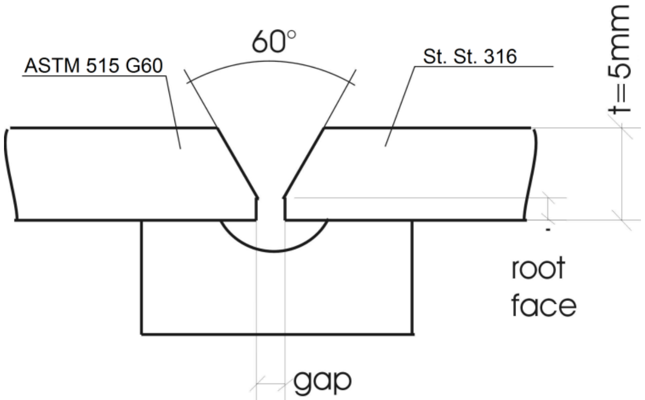
Materials

ASTM A 515 G60

C	Si	Mn	P	S
0,2	0,4	0,6	0,01	0,01

Austenitic stainless steel 316

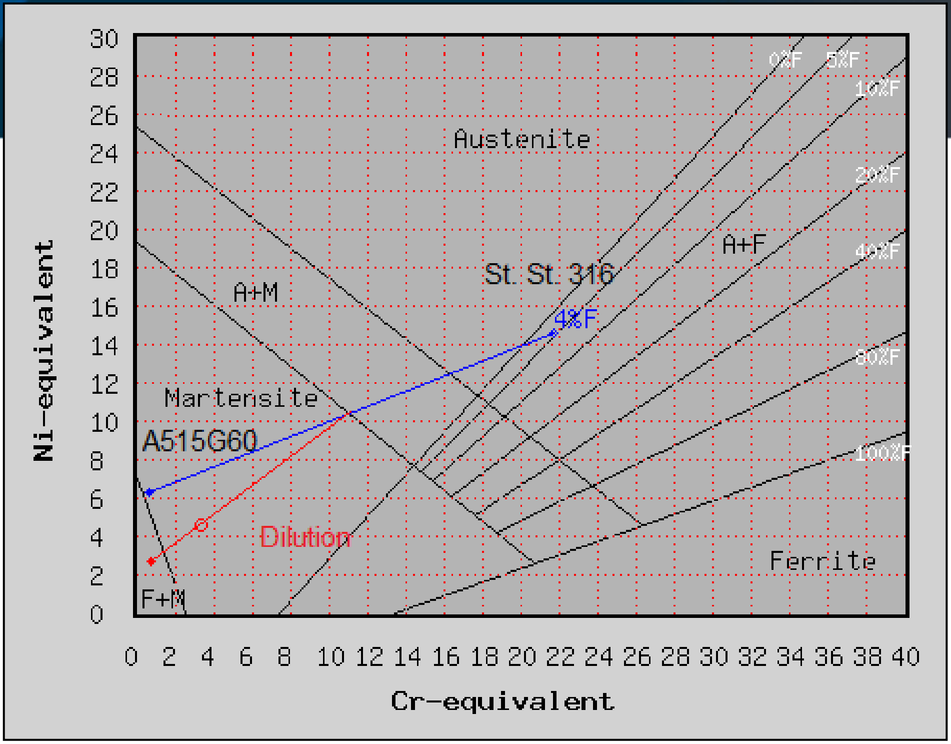
Chemical Composition (%)								
C	Si	Mn	Cr	Mo	Ni	Nb	P	S
0,05	0,6	1,2	18	2,5	12,5	0,6	0,01	0,01

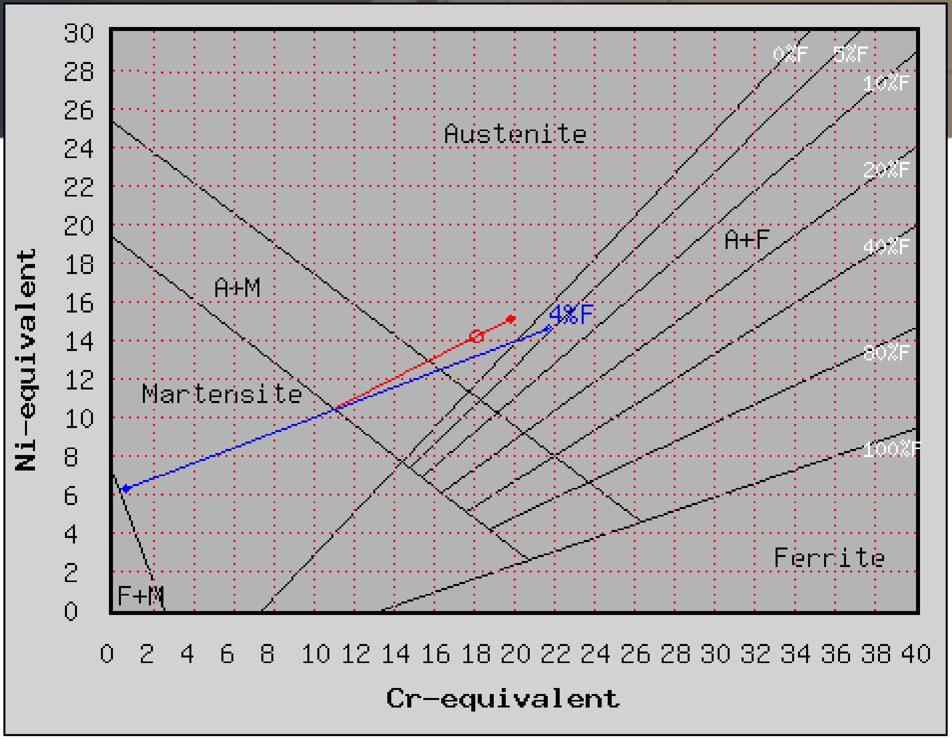


Consumables

Standard Electrode	Chemical Composition (%)						
	C	Si	Mn	Cr	Ni	Mo	Nb
AWS A5.1-91: E 7018-1 H4R	0,07	0,5	1,1				
AWS A5.4-92: E 318-17	≤0,03	0,8	0,8	19,0	11,5	2,7	0,35
AWS A5.4-92: E 316L-17	≤0,03	0,8	0,8	18,8	11,7	2,7	
AWS A5.4-92: E 307-15	0,1	0,7	6,5	18,8	8,8		
AWS A5.4-92: E 309 L-17	0,02	0,7	0,7	23,0	12,5		
AWS A5.4-95: E 309 MoL-17	0,02	0,7	0,8	23,0	12,5	2,7	

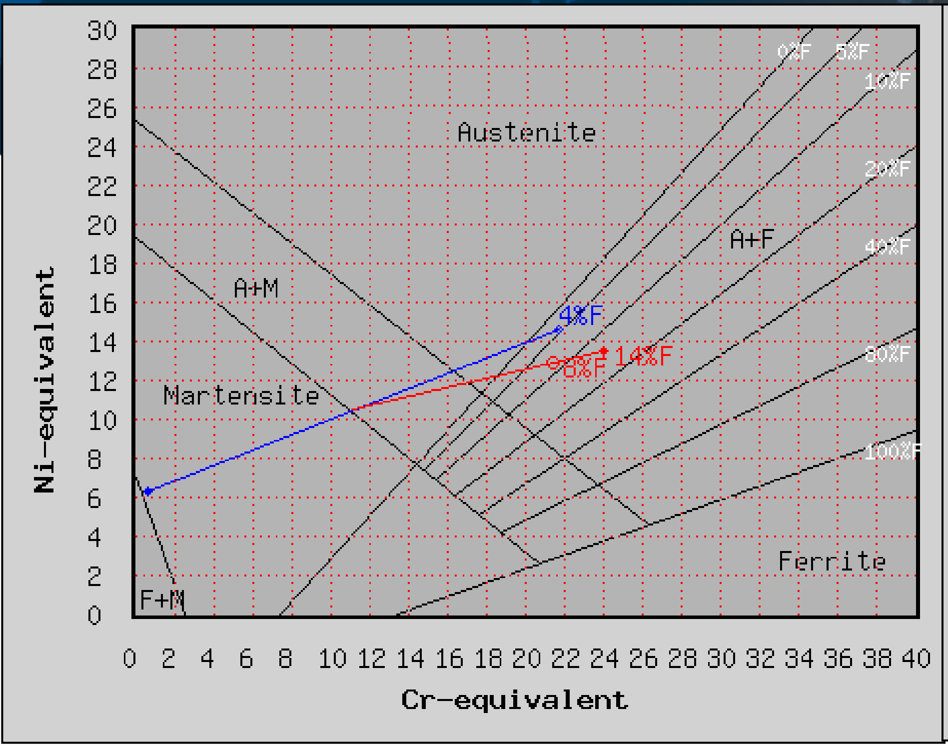
- The fusion ratio between base material and consumable is 20:80
- Which electrodes are useable to join the dissimilar materials?

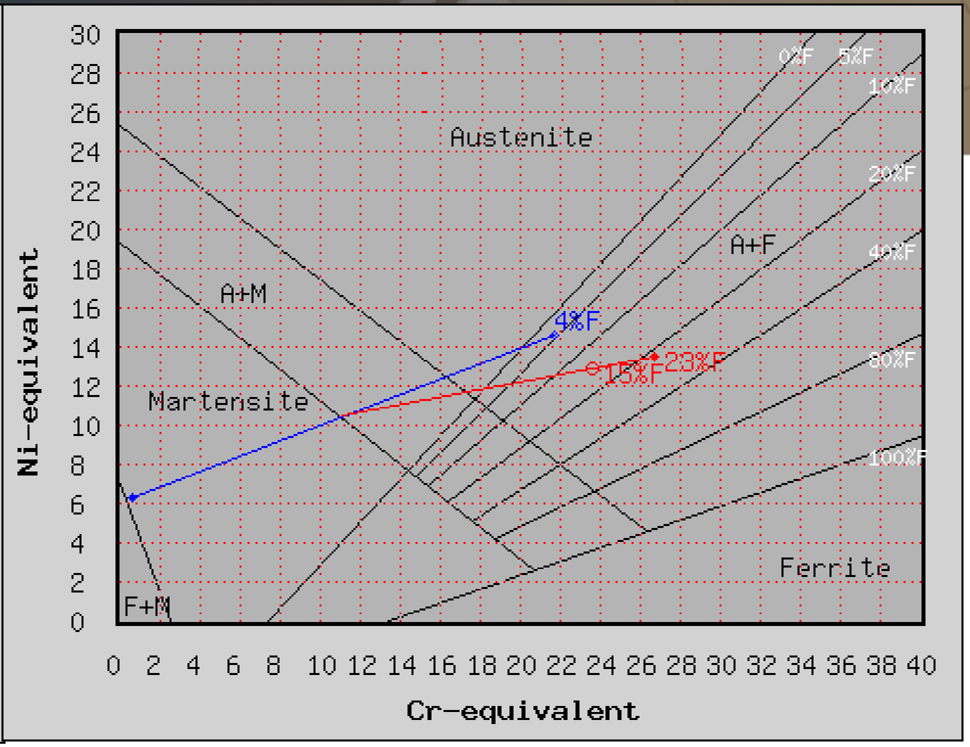




	A515G60	St.St.316	E 7018-1 H4R
Creq	0.60	21.70	0.75
Nieq	6.30	14.60	2.65
Dilution (20%)	Cr_{eq} = 2.83	Ni_{eq} = 4.21	

	A515G60	St.St.316	E 307-15
Creq	0.60	21.70	19,80
Nieq	6.30	14.60	15,05
Dilution (20%)	Cr_{eq} = 14.13	Ni_{eq} = 18.11	





	A515G60	St.St.316	E 309 L-17
Creq	0.60	21.70	24,05
Nieq	6.30	14.60	13,45
Dilution (20%)	Cr_{eq} = 12.85	Ni_{eq} = 21,47	

	A515G60	St.St.316	E 309 MoL-17
Creq	0.60	21.70	26,75
Nieq	6.30	14.60	15,0
Dilution (20%)	Cr_{eq} = 12.89	Ni_{eq} = 23,63	

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Electrode Selection

Standard Electrode	Weld Metal			Evaluation
	Cr_{eq}	Ni_{eq}	F%	
AWS A5.1-91: E 7018-1 H4R	2.83	4.21	0	Cold cracking
AWS A5.4-92: E 318-17	12.09	20.69	9	Good
AWS A5.4-92: E 316L-17	12.25	20.39	7	Good
AWS A5.4-92: E 307-15	14.13	18.11	0	Solidification cracking
AWS A5.4-92: E 309 L-17	12.85	21,47	8	Good
AWS A5.4-95: E 309 MoL-17	12.89	23,63	15	Sigma embrittlement

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Questions?

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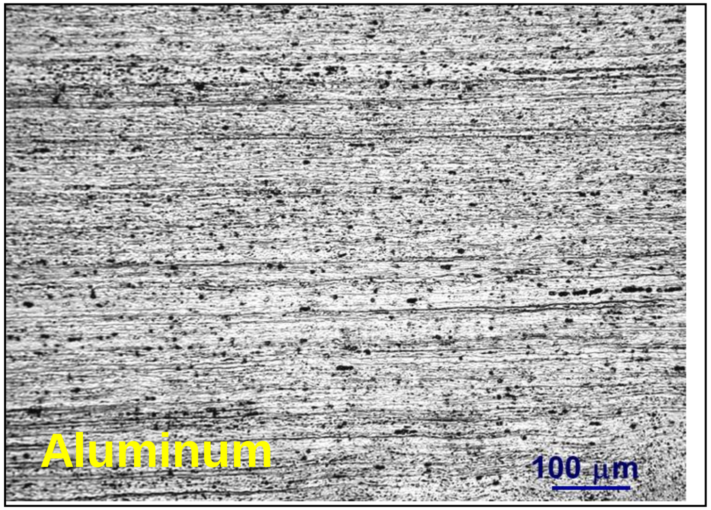
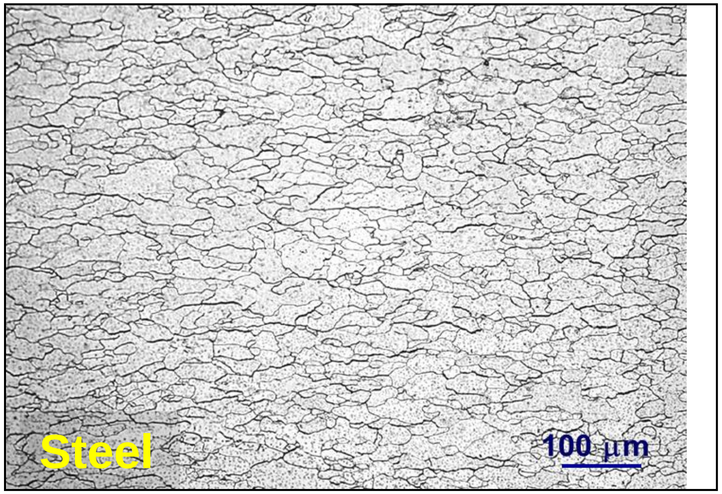
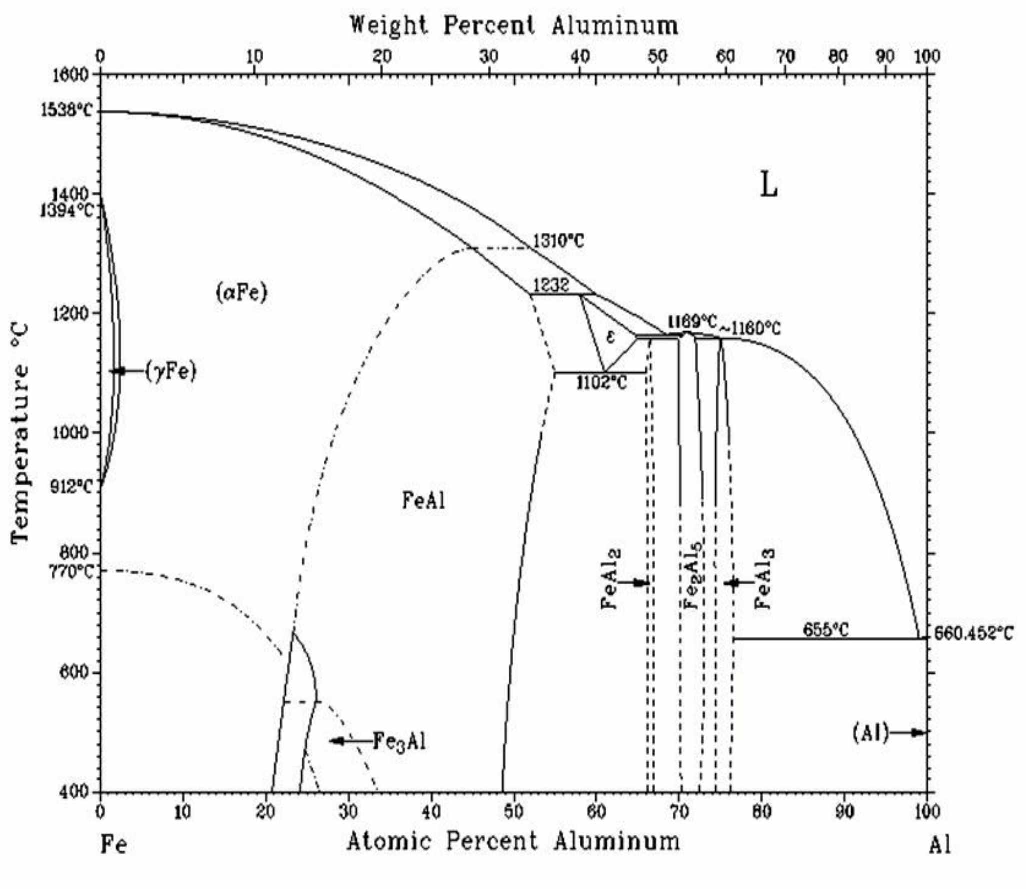
Case Studies

Dissimilar Joining of Steel to Aluminum

Material







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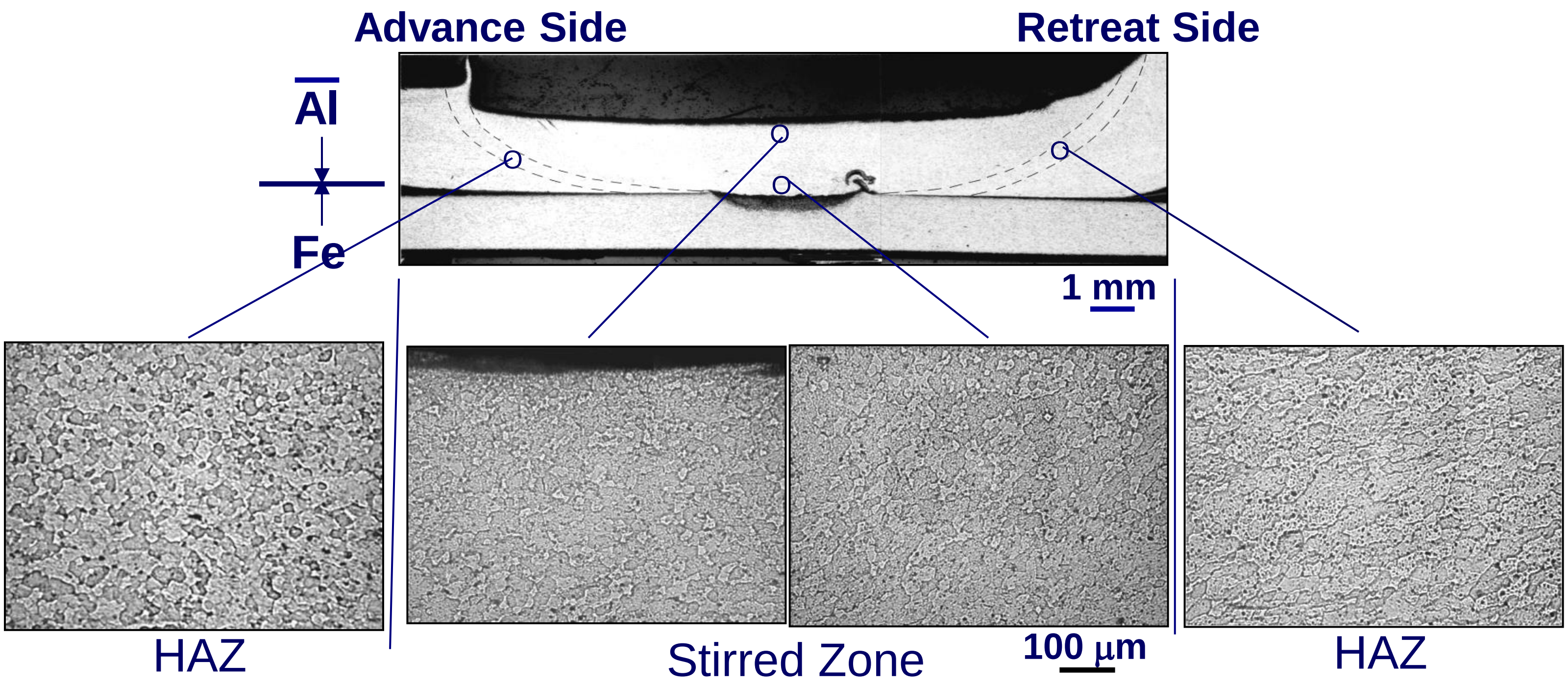
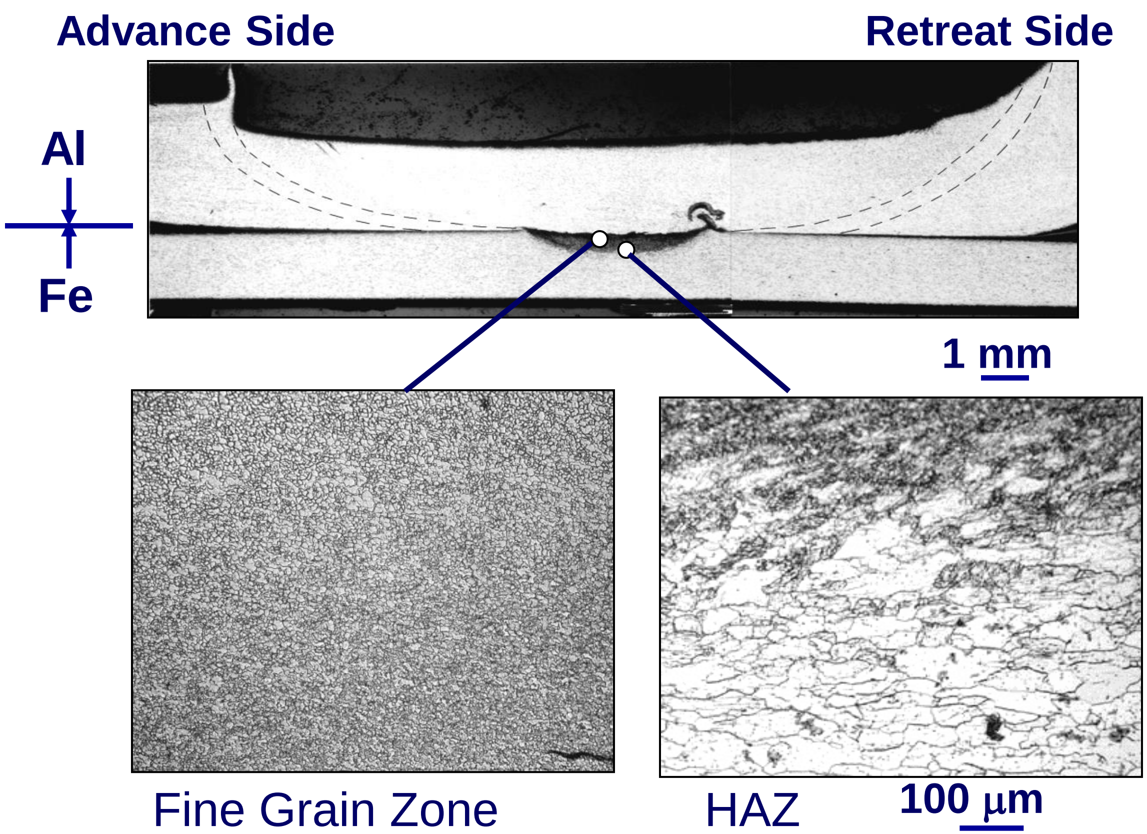
Characteristics Macrostructure and Microstructure (Al side)



- Characteristic microstructures observed in different areas on Al side of FSW joint (R_T= 41.7 s^{-1} V_r=3.3 mm/s).

Characteristics Macrostructure and Microstructure (steel side)

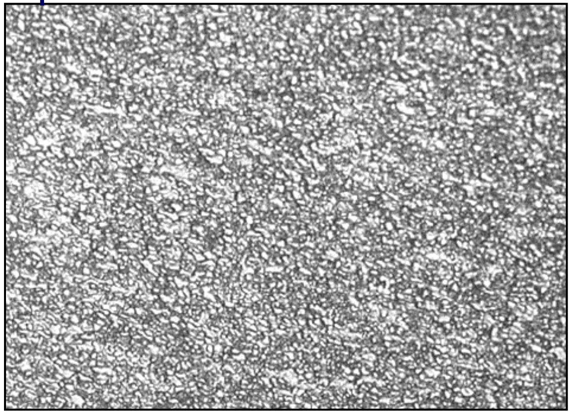


- Characteristic microstructures observed in different areas on steel side of FSW joint (R_T= 41.7 s^{-1} V_r=3.3 mm/s).

Effect of Rotation Speed on Fine Grain Size of Steel

Average Grain Size is 3 μm

R_T= 25.0 s-1
V_r= 3.3 mm/s

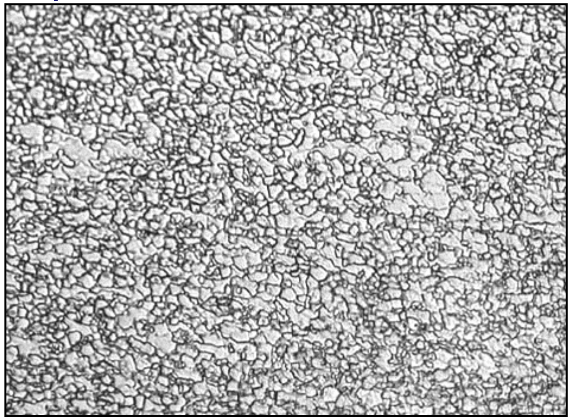


Average Grain Size is 4.7 μm

R_T= 33.3
V_r= 3.3

Average Grain Size is 6 μm

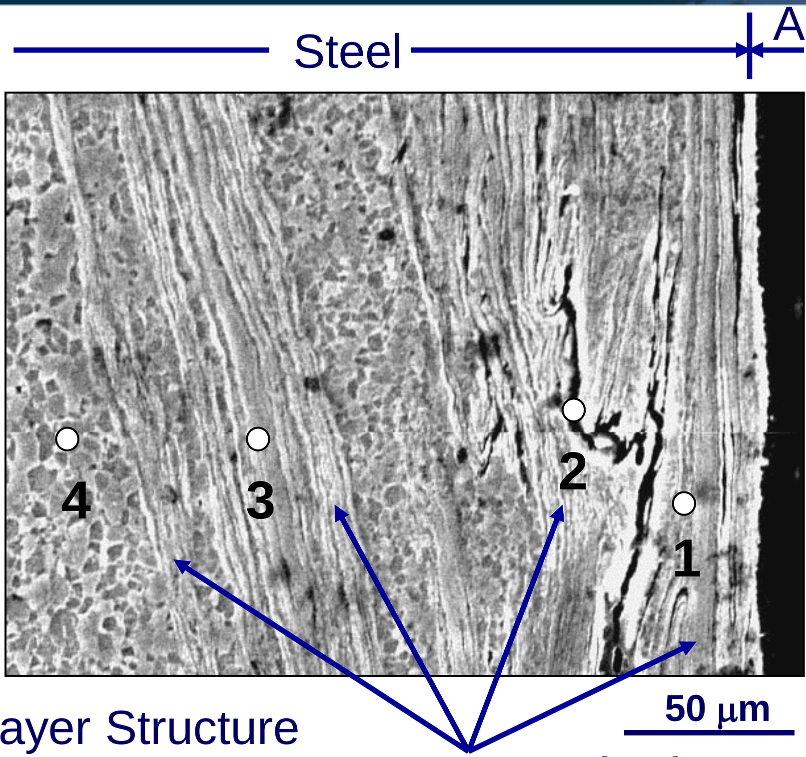
R_T= 41.7
V_r= 3.3



Increasing Rotation Speed

50 μm

Microstructure and Hardness of Interlayer



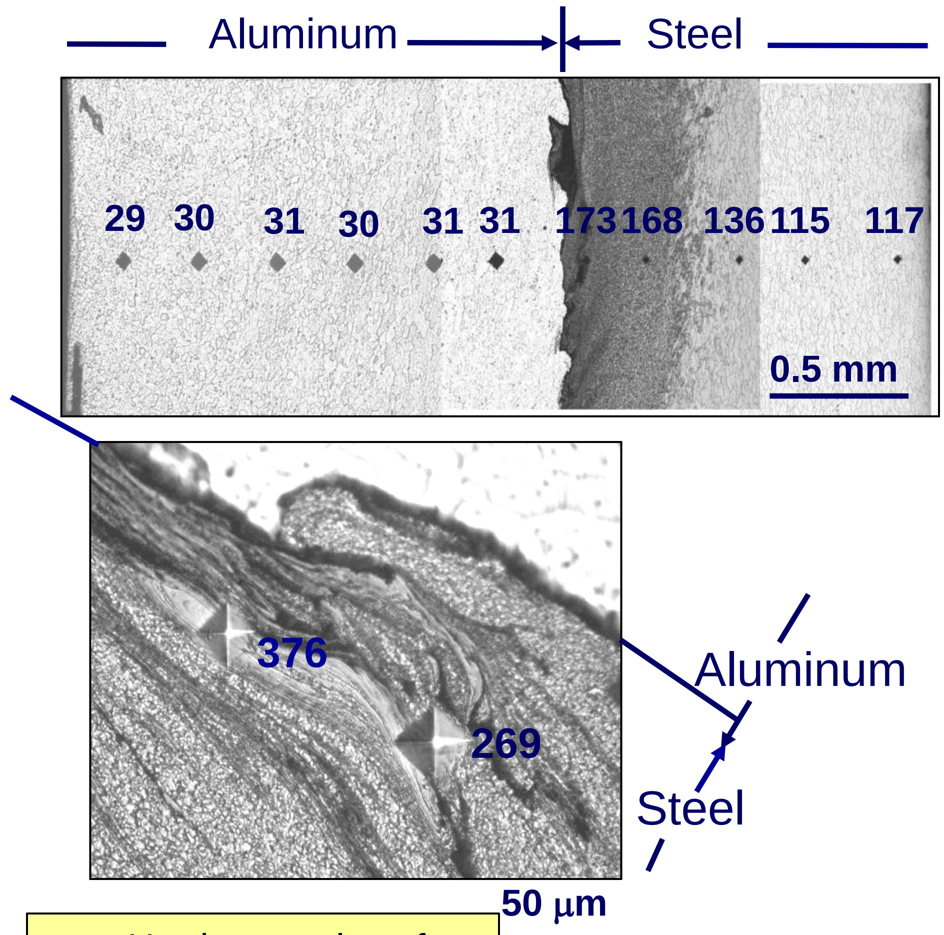
Layer Structure

R_T= 33.3 s^{-1}
V_r=3.3 mm/s

(at%)

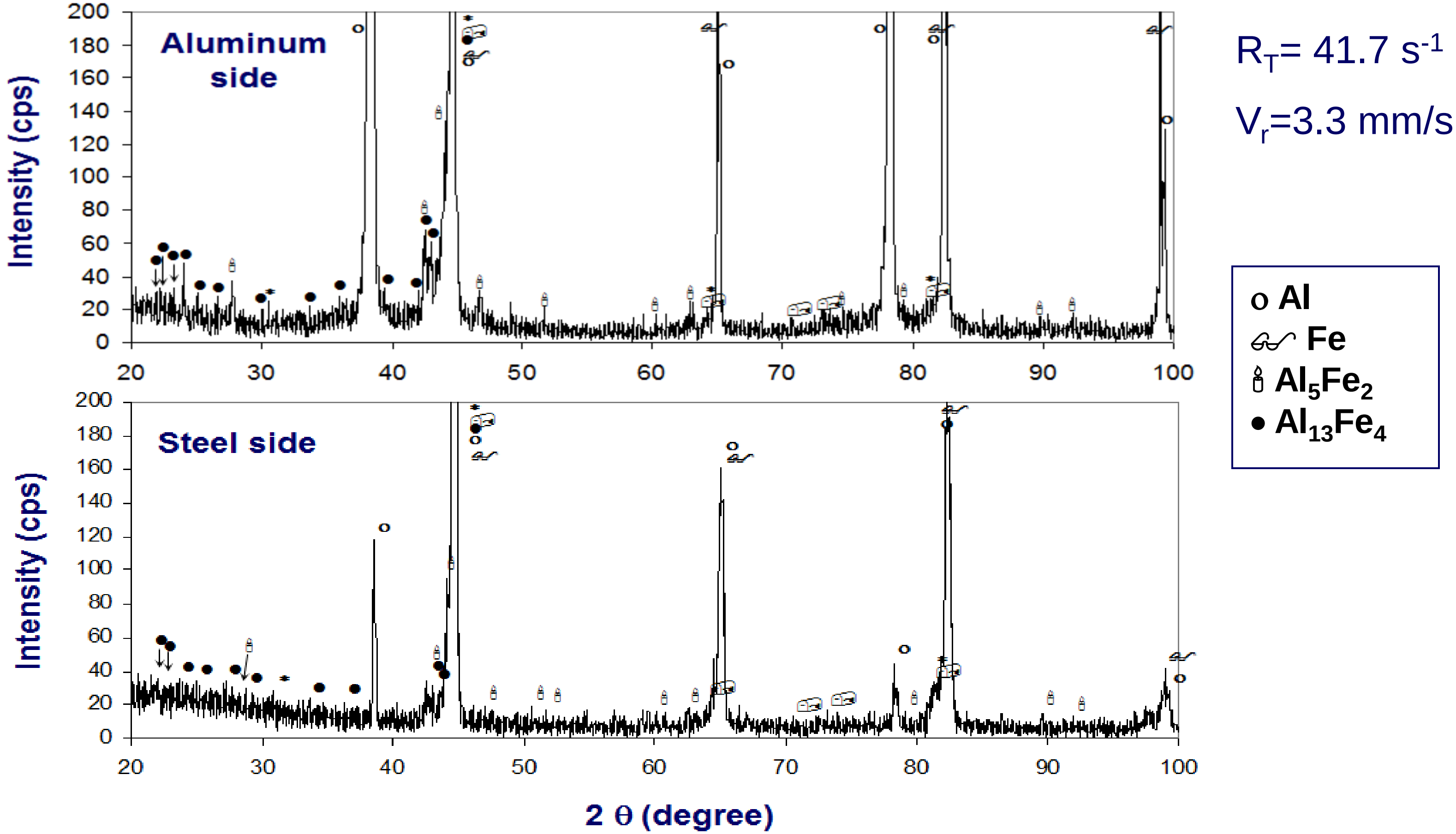
Elements	Points			
	1	2	3	4
Fe	80	57	78	98
Al	20	43	22	2

- Layer structure and EDX analyses at some points.



- Hardness values for the layered structure.

X-ray Diffraction Pattern



R_T= 41.7 s^{-1}

V_r=3.3 mm/s

- Careful adjustment of FSW parameters, avoids the formation of the layered structure and results in good joint quality.

Questions?

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Case Studies

Dissimilar Welding of Nodular Cast Iron to Steel

Problems

- **This type of dissimilar metal weldments are particularly characterized by:**
  - Compositional gradient and microstructural changes, which produce large variations in chemical, physical, and mechanical properties across the weldment
  - Further complexity arises with the addition of filler metal, which is a common practice in dissimilar metal welding
  - The formation of carbides during solidification and the formation of martensite during solid-state transformation.

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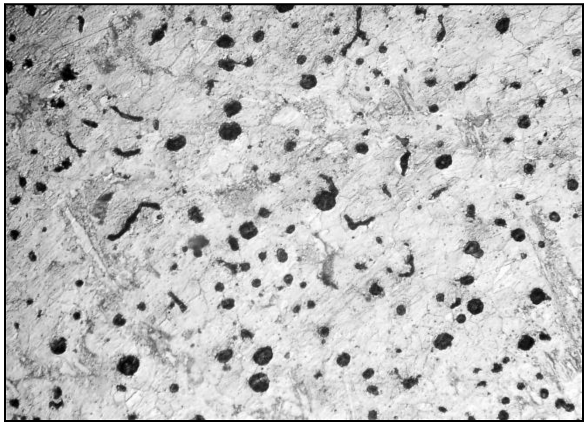
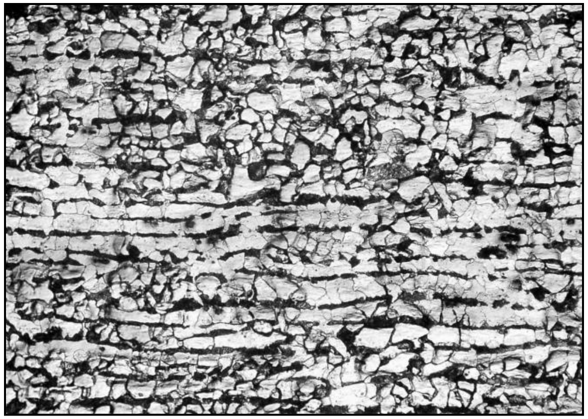
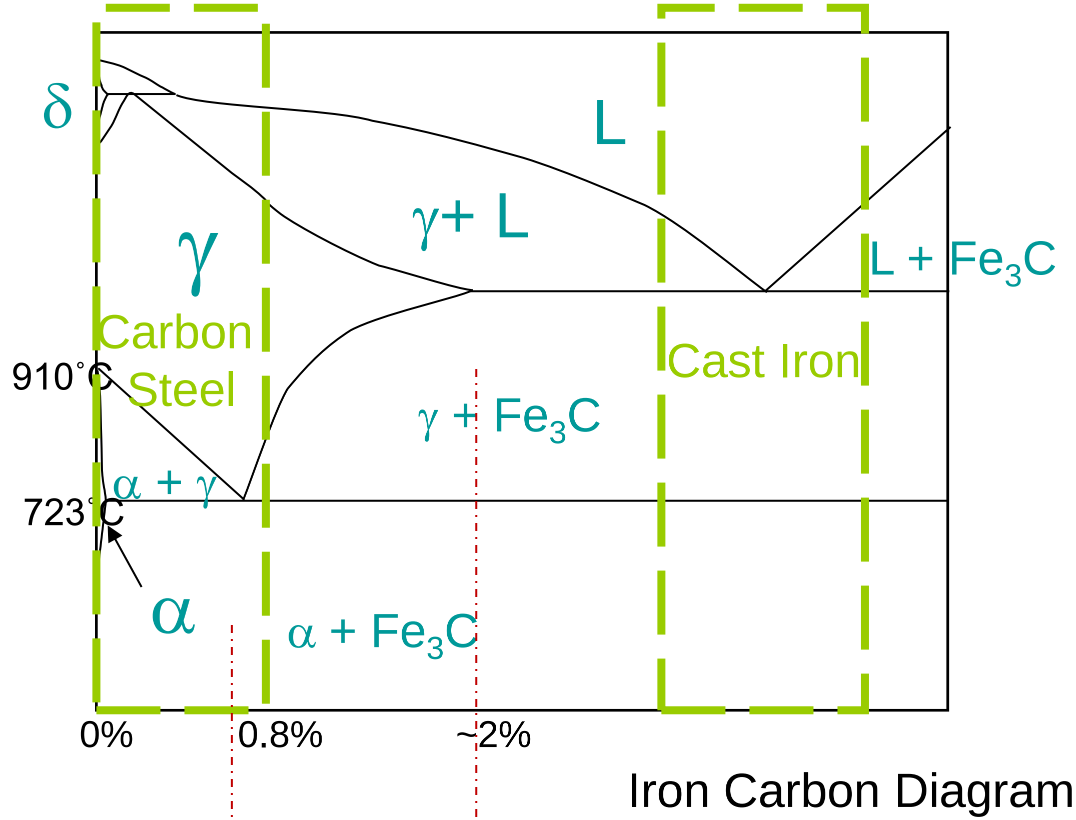
Materials



Cast Iron



Carbon Steel



Iron Carbon Diagram

Coefficient of Linear Expansion

- **Steel: 12.1 x 10^{-6} / ^{o}C**
- **Cast Iron: 10.8 x 10^{-6} / ^{o}C**
- **Nickel: 13.3 x 10^{-6} / ^{o}C**

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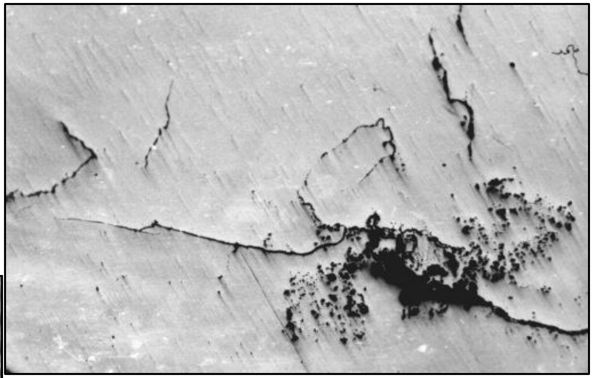
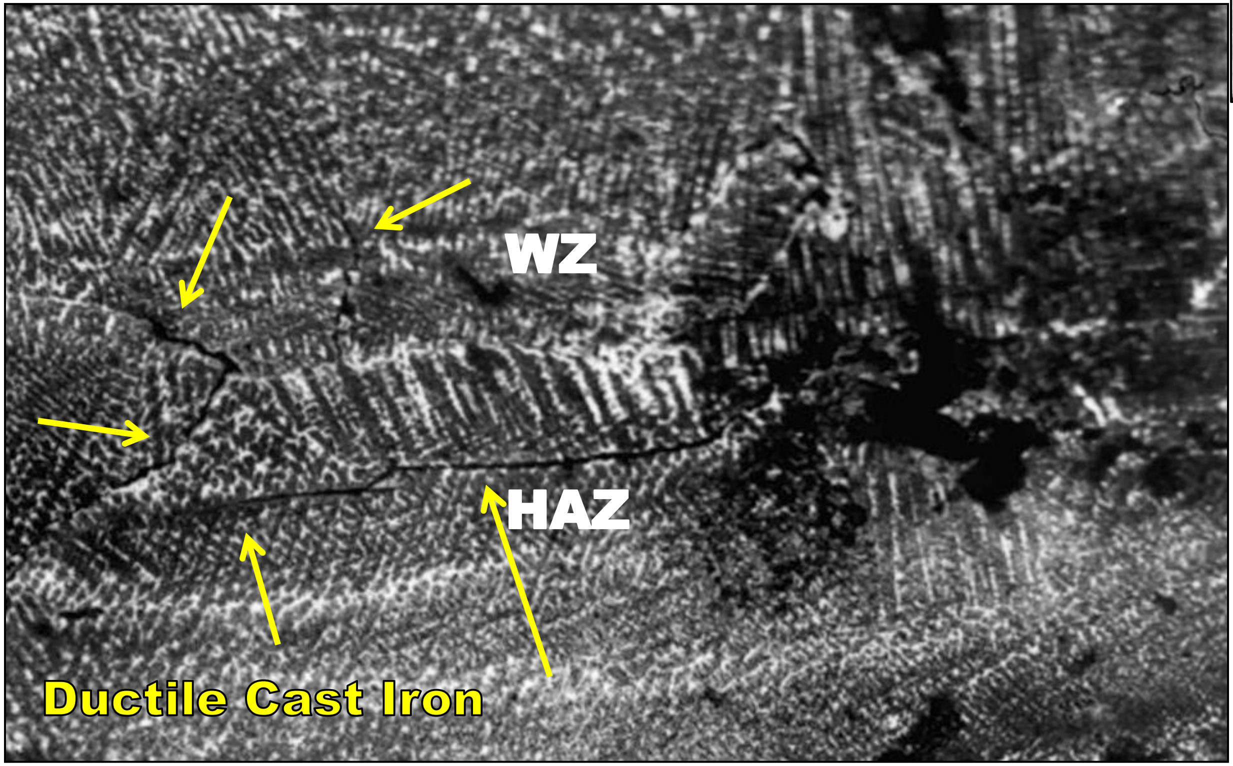
Cracking Tendency

- Cracking tendency at HAZ increases in case of welding without buttering layer.





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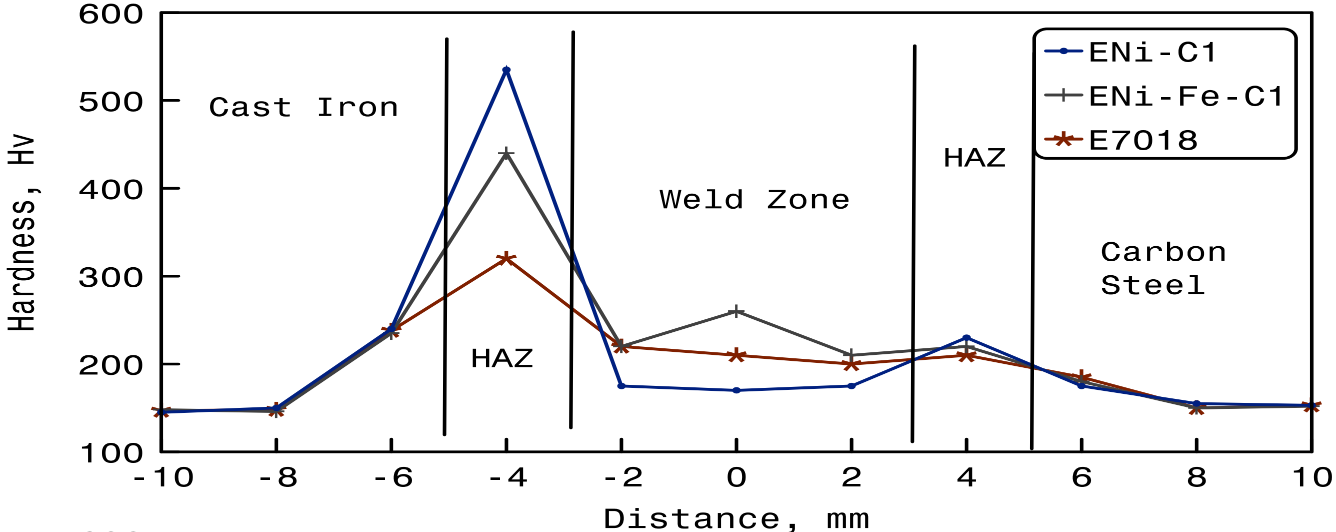
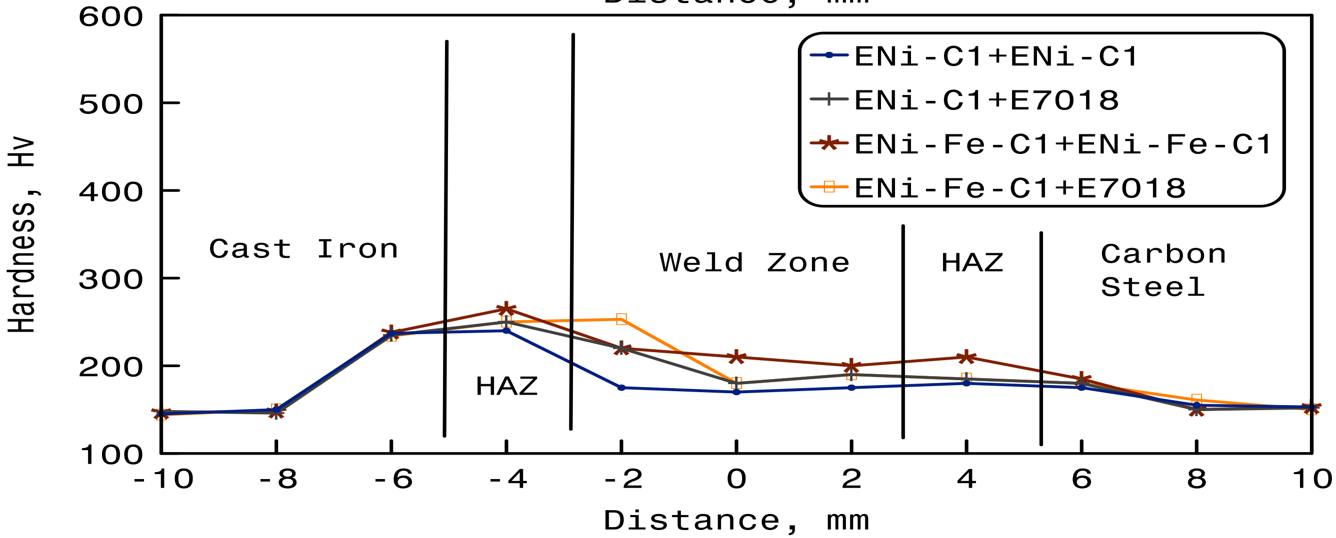
Hardness Measurement



Without Buttering Layer



With Buttering Layer

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Mechanical Properties

<table>
<tr><th rowspan="2">Type of Electrode</th><th rowspan="2">UTS (MPa)</th><th rowspan="2">Location of Failure</th><th rowspan="2">WM Hardness (Hv)</th><th colspan="2">Max. HAZ Hardness (Hv)</th></tr>
<tr><th>Cast Iron Side</th><th>Steel Side</th></tr>
<tr><td>ENi-C1</td><td>330 – 420</td><td rowspan="3">Cast Iron HAZ</td><td>175 – 210</td><td>535</td><td>203</td></tr>
<tr><td>ENi-Fe-C1</td><td>370 - 450</td><td>180 – 260</td><td>440</td><td>208</td></tr>
<tr><td>E7018</td><td>350 - 420</td><td>160 - 190</td><td>350</td><td>180</td></tr>
</table>

<table>
<tr><th colspan="2">Type of Joint</th><th rowspan="2">UTS (MPa)</th><th rowspan="2">Location of Failure</th><th rowspan="2">WM Hardness (Hv)</th><th colspan="2">Max. HAZ Hardness (Hv)</th></tr>
<tr><th>Buttering Electrode</th><th>Welding Electrode</th><th>Cast Iron Side</th><th>Steel Side</th></tr>
<tr><td rowspan="2">ENi-C1</td><td>ENi-C1</td><td>437 – 476</td><td rowspan="4">Cast Iron</td><td>200</td><td>237</td><td>176</td></tr>
<tr><td>E7018</td><td>379 – 386</td><td>180</td><td>240</td><td>161</td></tr>
<tr><td rowspan="2">ENi-Fe-C1</td><td>ENi-Fe-C1</td><td>436 – 468</td><td>230</td><td>260</td><td>180</td></tr>
<tr><td>E7018</td><td>380 - 396</td><td>180</td><td>252</td><td>172</td></tr>
</table>

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Summary

Metallurgically
Dissimilar metal welding requires consideration of all the basic factors found in conventional welding. On the other hand, the difference of the base metal and weld metal chemistry should be precisely analyzed.

Performance
The mechanical and physical properties, microstructural stability, and resistance to oxidation and corrosion of the weld metal as well as those of both heat-affected zones should be suited for the intended service.

Selection of Welding Consumables
The best selection results in a joint which has an acceptable range of dilution and metallurgical compatibility to achieve the required properties.

Welding Process
Selecting the welding process is a key factor when welding dissimilar metals, since the heat input affects dilution, alloy element migration, and residual stress caused by differences in the thermal coefficient.

Successful Dissimilar Metal Joint

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Questions?

Thank you!

If you would like to learn more or continue this discussion with Alber, members can reach out to Alber as part of their Member Services. If you are not a member of EWI, please visit our website at www.ewi.org to learn more about membership.

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