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Business from technology

Laser and hybrid laser welding of thick stainless steels

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Technological Exchange Event between Finland and Japan
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Content

- Background
- Thick section welding with laser
- Solidification and microsegregation
- Hot cracking
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- Conclusions

Background

- Stainless steels are a large variety of different grades
  - The most typical ones
    - “stainless steel” (18 Cr / 8 Ni, 304, 2343, 1.4301)
    - “acid-proof steel” (18 Cr / 10 Ni / 2-3 Mo, 316)
  - The most usual austenitic stainless steels are very well weldable with all welding methods; probably the easiest weldable of all metals
  - Reasons for large and variable use
    - Good weldability
    - Good formability
    - Good corrosion properties
    - Good manufacturability

Background

- The need for higher-alloyed stainless steels is increased because of demands of corrosion resistance in e.g. closed-circuits in chemical, oil or pulp and paper industry

  => contents of Cr, Ni and Mo is inceased

  - welding is more challenging: careful planning is needed, because of
    - risk for hot cracking of the welds
    - control of corrosion properties of the welds

- other grades of stainless steels are also more usual (e.g. price of Ni)
  - duplex stainless steels
  - ferritic stainless steels are more used today
  - high-Mn stainless steel grades (e.g. 201, 2101LN)
- weldability needs more attention than conventional grades
  - control of welding parameters
  - control of filler metal composition

Background

- The main advantages of laser or hybrid laser welding
  - high welding speed
  - low distortions
  - easiness to automation
  - freedom for joint design
- Laser and hybrid welding demands
  - strict control of joint preparation
  - long series to make it economical
- In weldability point of view
  - high cooling rate makes changes in solidification behaviour and therefore affects hot cracking susceptibility.

Thick section welding using laser

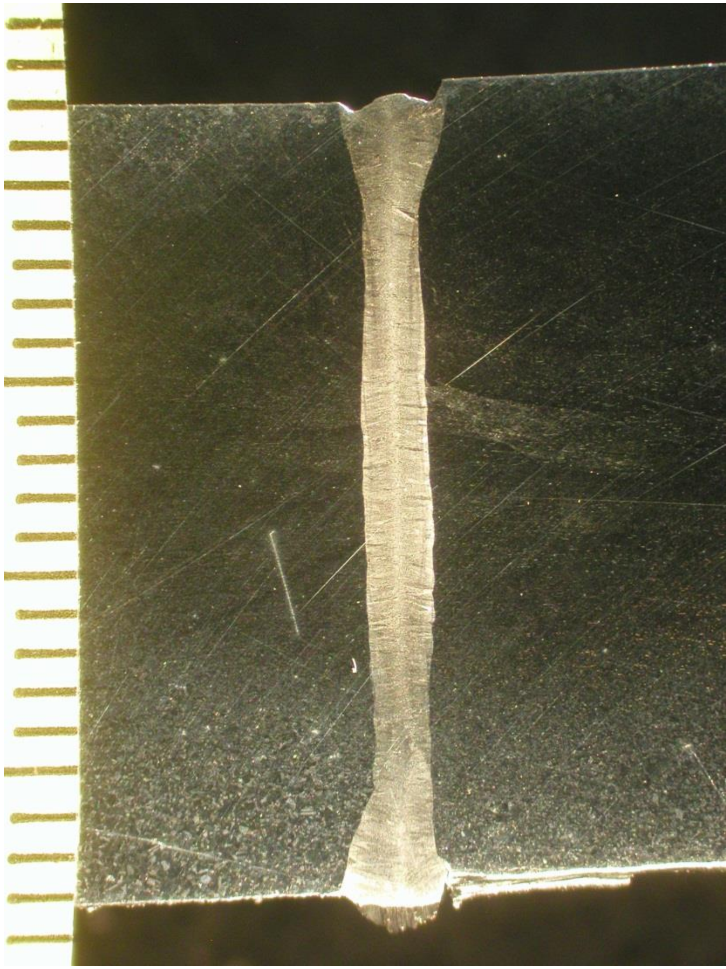
- Thick section laser welding can be made in many ways
  - Autogenous laser welding is possible to a certain thickness, depending on application, power and laser beam quality
- Typically one-pass welding can be used up to 10 mm in practice
  - New lasers with high laser beam quality (fiber and disc lasers) make higher thickness possible with one pass (up to 25-30 mm)
- In thicker sections filler metal needs to be used
  - Cold-wire laser welding
  - Hot-wire laser welding
  - Laser hybrid welding (e.g. MIG/GMA assisted laser welding)
  - In thick sections multi-pass welding must be used. Root pass can be autogenous

One-pass laser welding (autogenous)

Material Stainless steel AISI 316 L(N)

Penetration 20 mm
Fiber laser power19 kW
Welding speed 1.5 m/min
No air gap
Focus position -4 mm

Shielding gas: Ar2.5CO2 (~25 l/min),
root: Ar (47 l/min)



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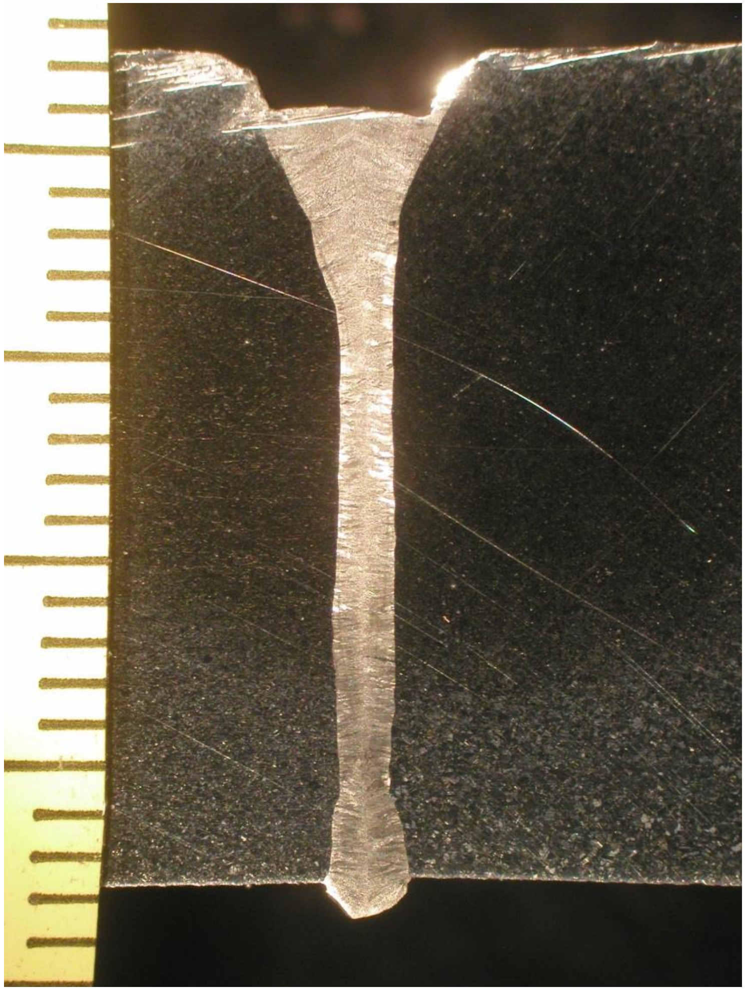
One-pass laser hybrid welding

Material Stainless steel AISI 316 L(N)
Filler wire 316LSi, Ø 1.0 mm
Penetration 18 mm
Fiber laser power19 kW
Welding speed 2.1 m/min
Wire speed 15m/min,
Air gap 0.2 mm
Focus position -4 mm
Arc leading

Pulsed GMAW, U=29.1V; I=288A
Shielding gas: Ar2.5CO2 (~25 l/min),
root: Ar (47 l/min)



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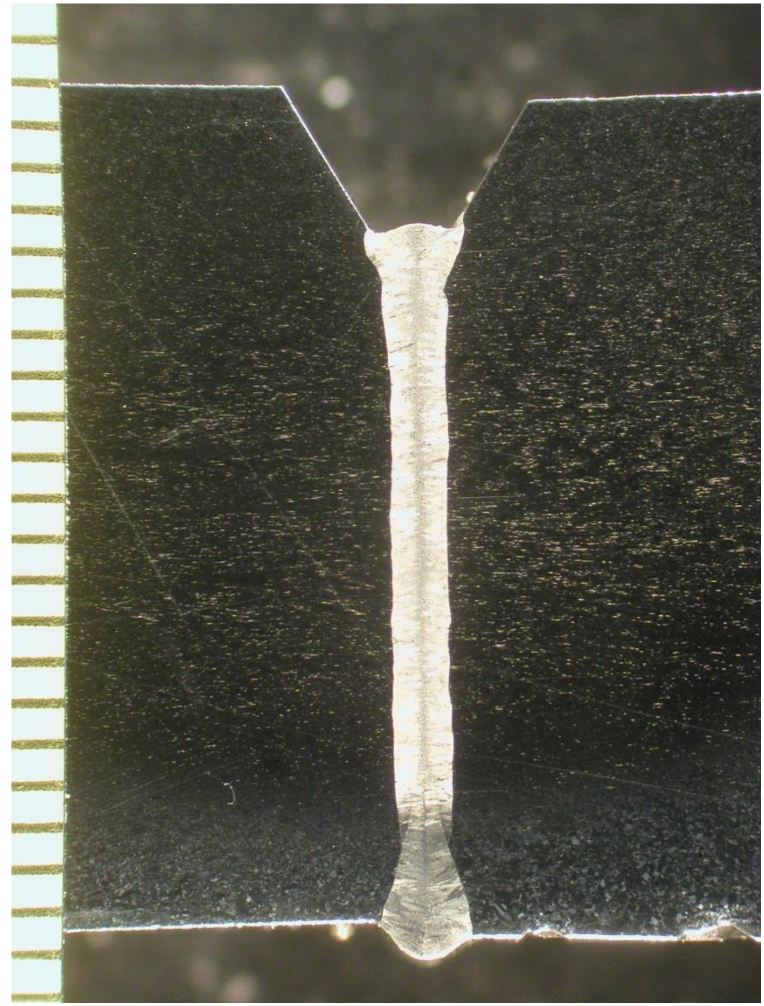
One-pass laser welding with cold-wire

Material Stainless steel AISI 316 L(N)
Filler wire 316LSi, Ø 1.0 mm
Penetration 17 mm
Fiber laser power19 kW
Welding speed 2.0 m/min
Wire speed 2.5 m/min,
No air gap
Focus position -4 mm
Laser leading

Shielding gas: Ar2.5CO2 (~25 l/min),
root: Ar (47 l/min)



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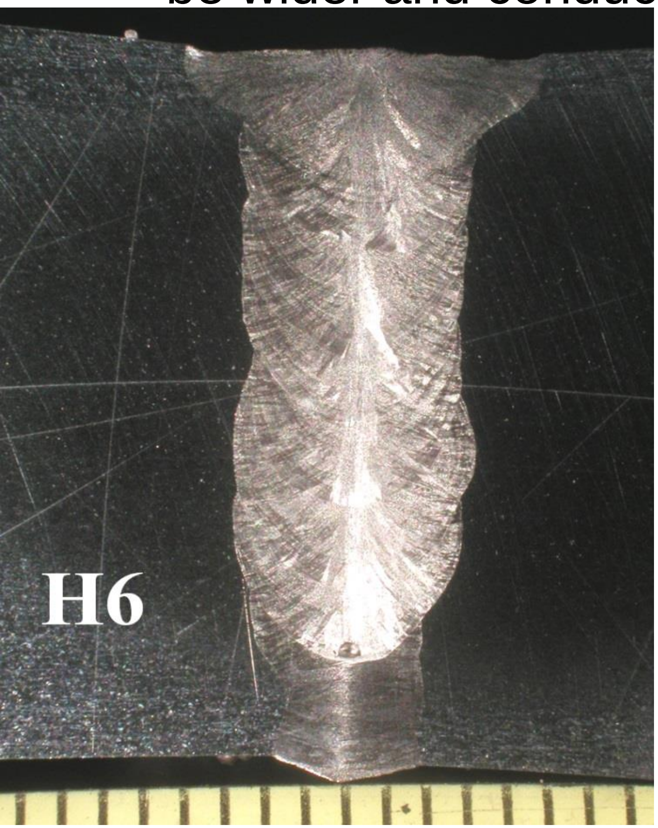
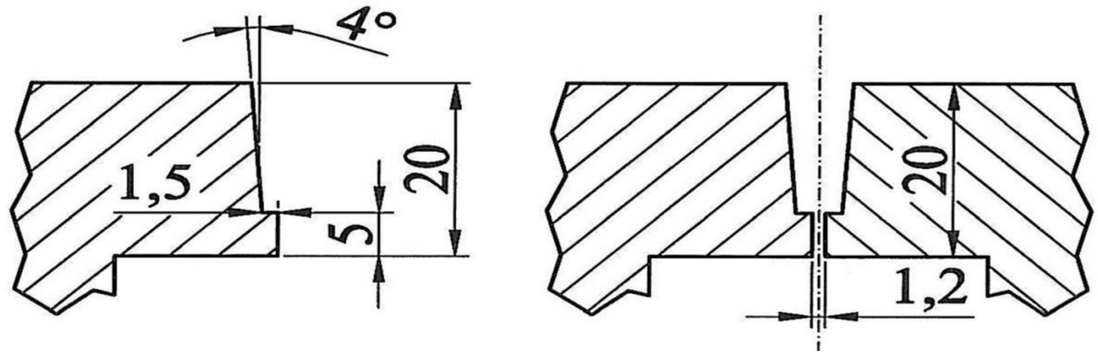
Multi-pass welding

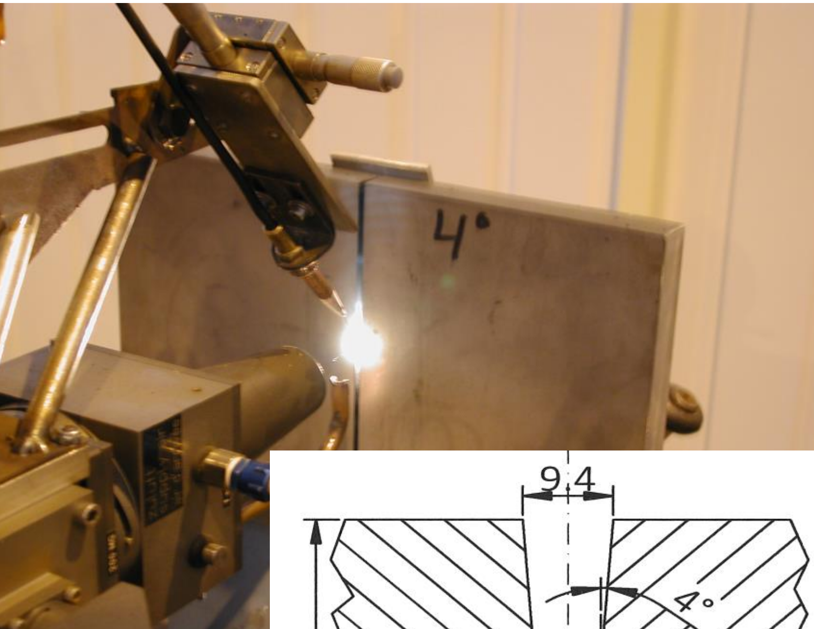
- Joint design is critical. It also affects welding method and choice of welding parameters
- In lower passes keyhole welding is suitable, but in higher passes weld must be wider and conduction-limited laser welding must be used

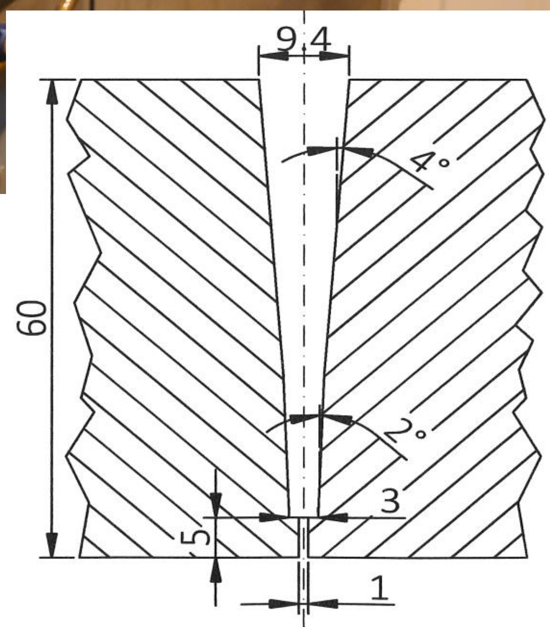


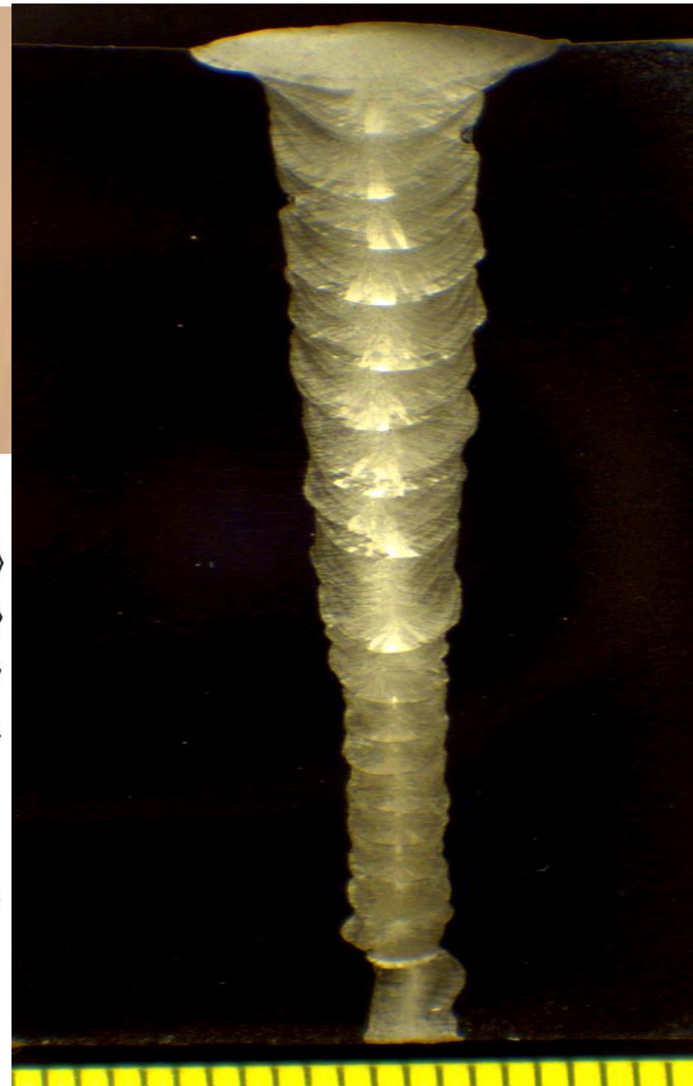


Multi-pass weld by 3 kW Nd:YAG
20 mm, laser-arc hybrid

Multi-pass welds





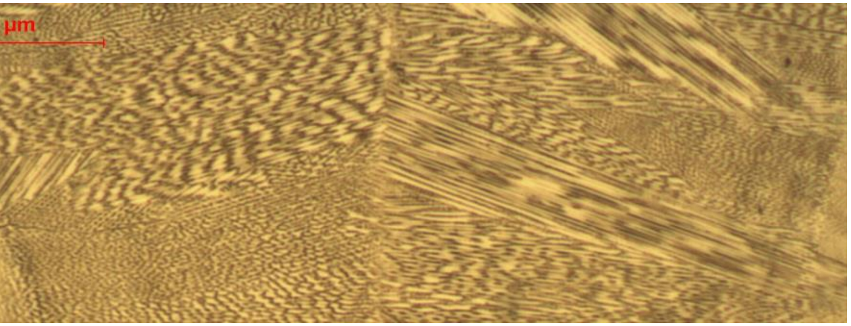


Solidification and micro-segregation

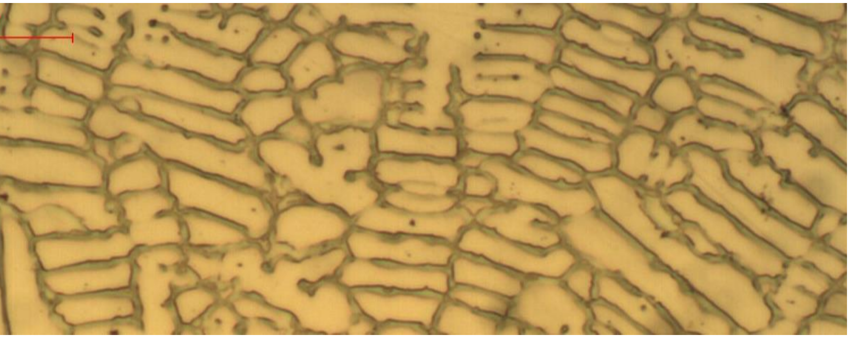
- In laser and hybrid laser welding cooling rate is 1000-10000 ^{o}C/sec.
- High temperature gradient
  - ⇒ narrow heat-affected zone
  - ⇒ no sensitization
  - ⇒ no brittle phase zones
  - (e.g. sigma phase)
- effect on homogeneity

Solidification and micro-segregation

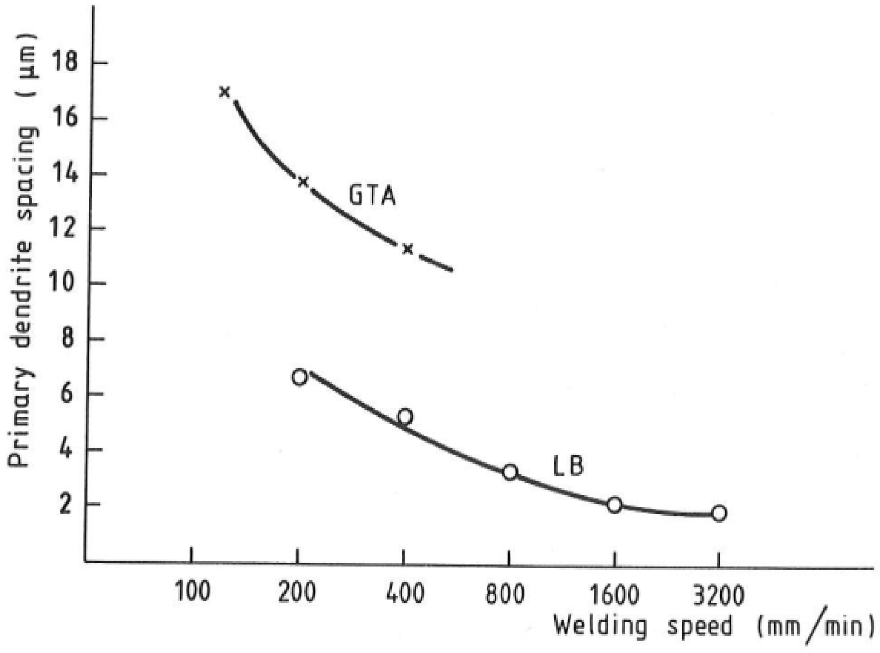
6 % Mo stainless steel



Laser weld 10 m/min



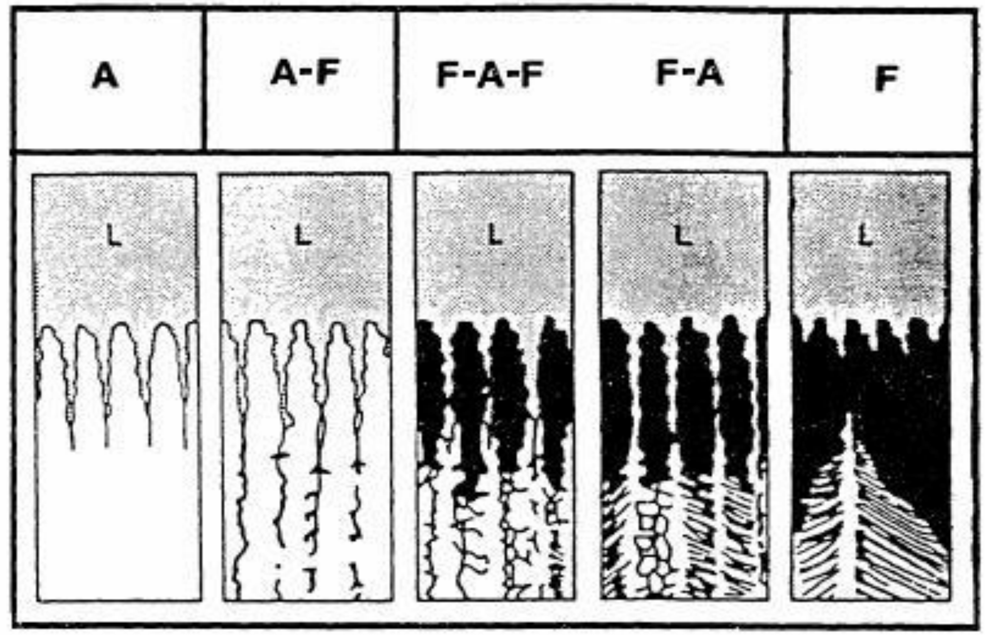
TIG (GTA) weld, 0,25 m/min



Kujanpää and David, ICALEO 1986

Solidification

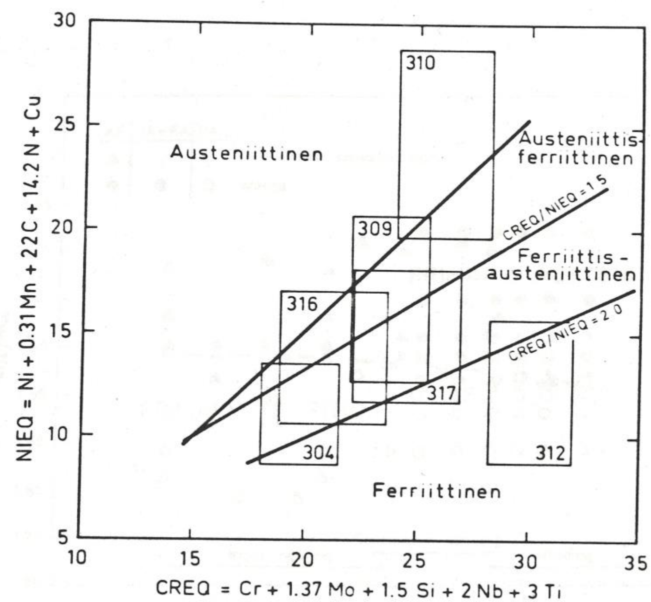
- Stainless steels can solidify in different modes depending on composition and welding parameters
  - Single-phase austenitic (A)
  - Austenitic-ferritic (AF)
  - Ferritic-austenitic-ferritic (FAF)
  - Ferritic-austenitic (FA)
  - Single-phase ferritic (F)



Suutala et al. Met Trans A, 1978

Solidification

- Solidification mode is dependent on (arc welding)
  - CREQ/NIEQ <1,5
    - => A or AF
  - CREQ/NIEQ 1,5-2,0
    - => FA or FAF
  - CREQ/NIEQ >2,0
    - => F



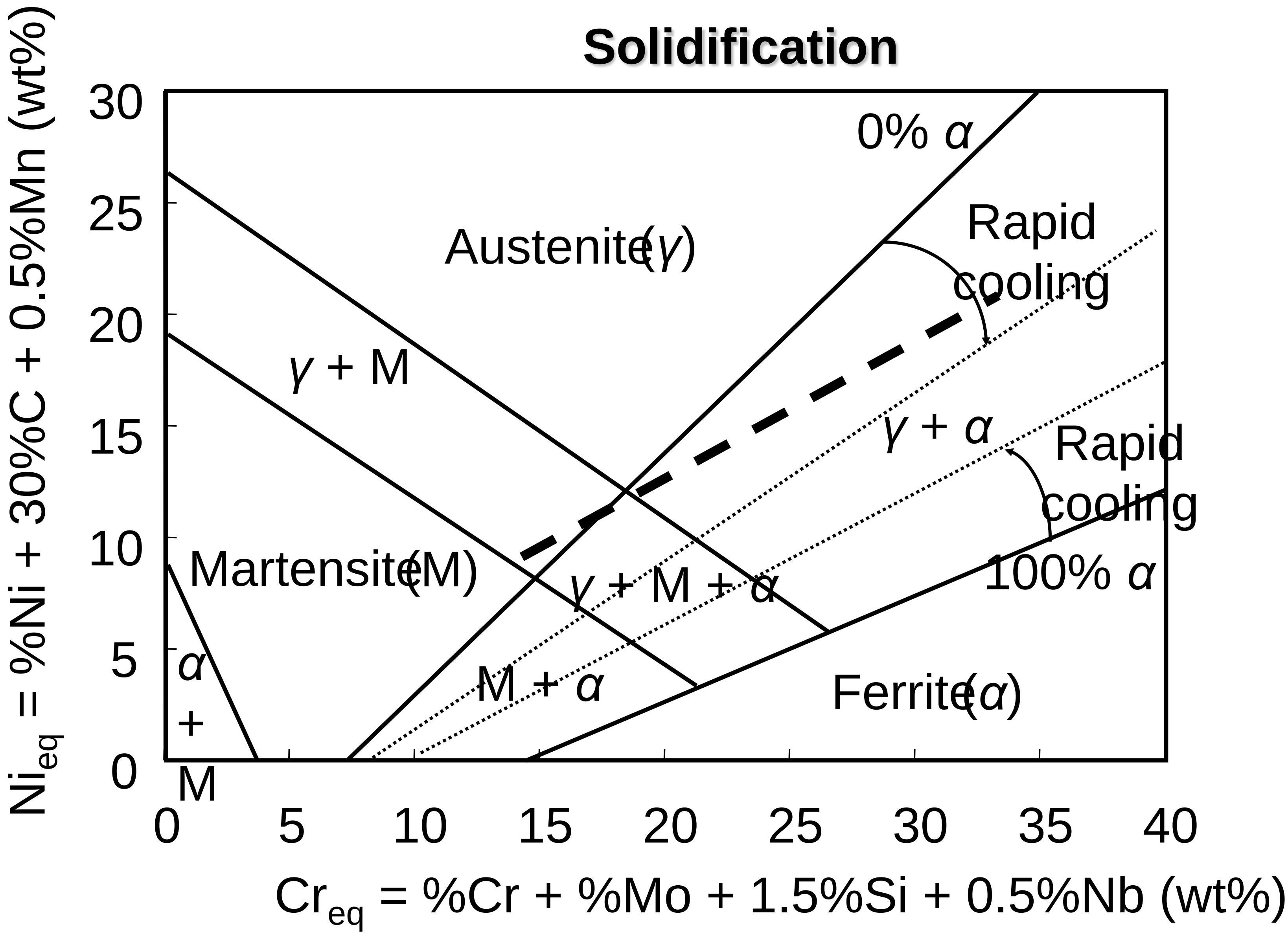
CREQ = Cr + 1, 37 Mo + 1, 5 Si + 2 Nb + 3 Ti

NIEQ = Ni + 0, 31 Mn + 22 C + 14, 2 N + Cu

Solidification

- Increase of solidification rate increases the trend to single-phase solification modes
  - CREQ/NIEQ close to value 1.5 => solidification mode changes
    - FAF or FA => A or AF
  - CREQ/NIEQ close to value 2, solidification mode changes
    - FAF or FA => F

Solidification



Solidification

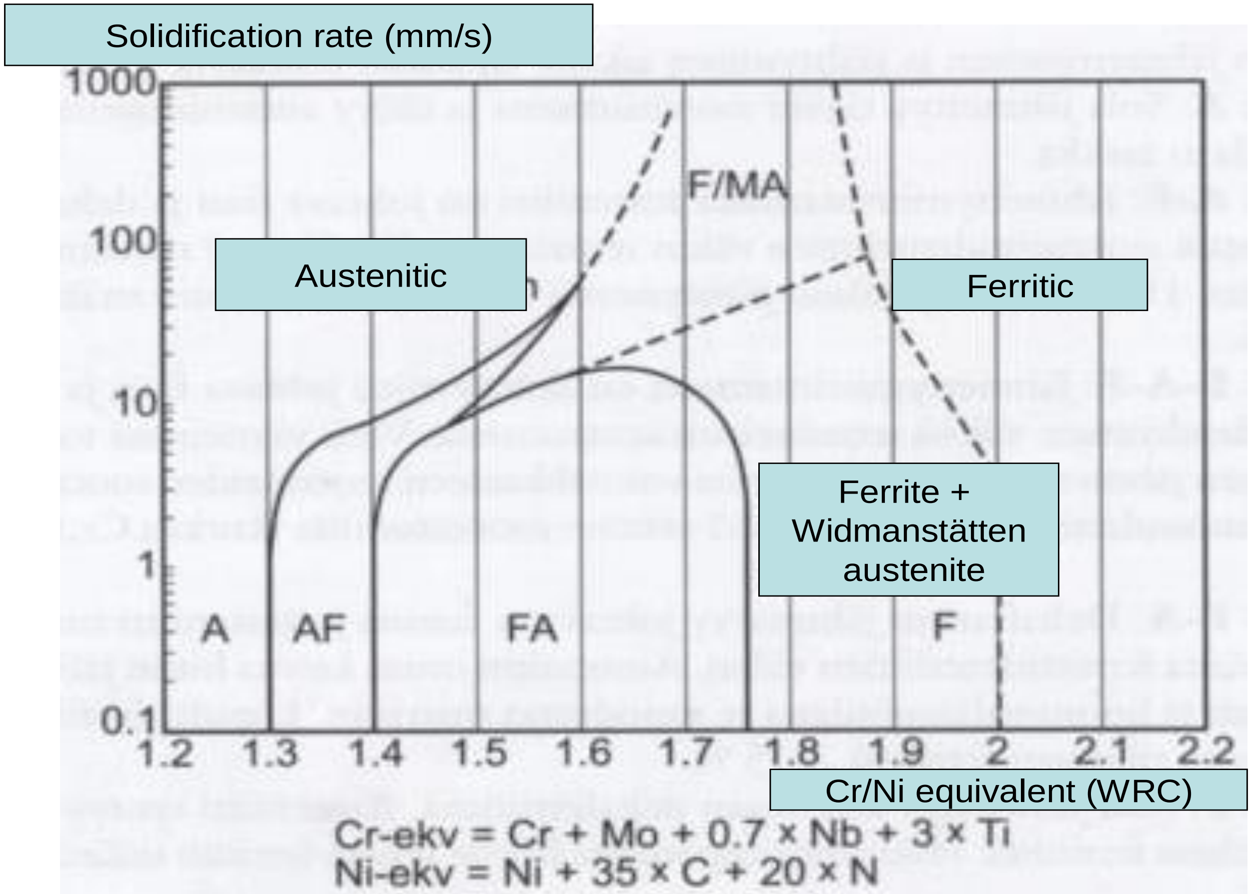
- This means that ordinary austenitic stainless steel grades (e.g. AISI 304 ja 316), which solidify as primary ferritic mode (FA), can solidify in laser or hybrid welding as primary austenitic mode (AF).

  => This can affect dramatically on hot cracking susceptibility or pitting corrosion

- On the other hand a duplex stainless steel can solidify in laser welding as single phase ferritic mode (F) without ferrite-austenite mode during cooling and leave microstructure almost 100 % ferrite

  => This can have a strong effect on e.g. stress corrosion properties

Solidification



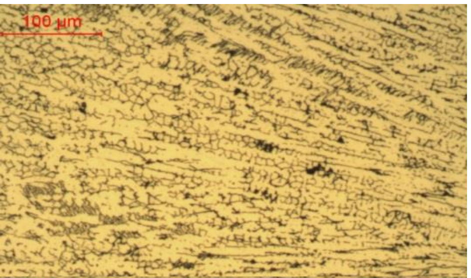
Lippold, Weld. J., 1994

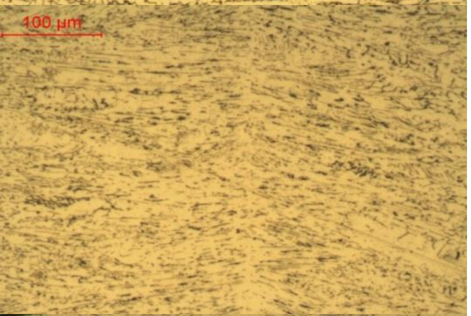
316L austenitic stainless steel (CREQ/NIEQ=1,82)

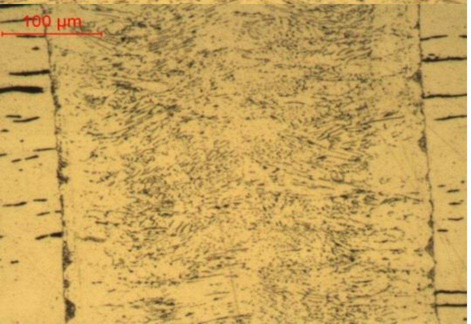
- At high welding speed solidification changes partly to primary austenitic mode

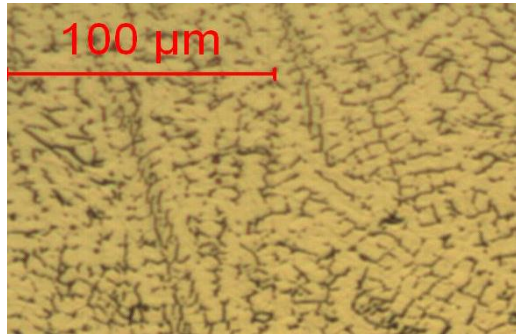
Pekkarinen, Kujanpää, ICALEO 2010

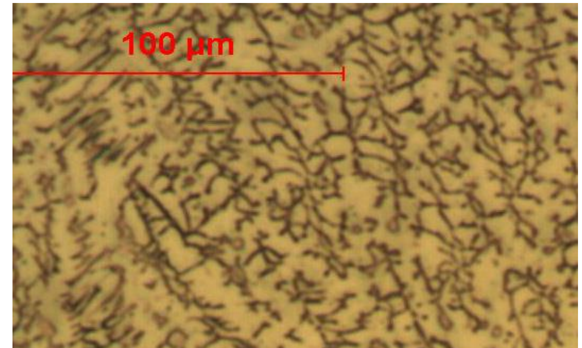
Welding method	Welding speed	Heat input (J/mm)	Solidifi-cation rate (m/min)	Solidifi-cation mode
Keyhole	1 m/min	248	5,38	FA
Keyhole	5 m/min	49,6	22,05	FA & AF
Keyhole	10 m/min	24,8	29,17	AF (FA)
Conduction LW	0,3 m/min	242	-	FA
GTAW	0,25 m/min	207	-	FA









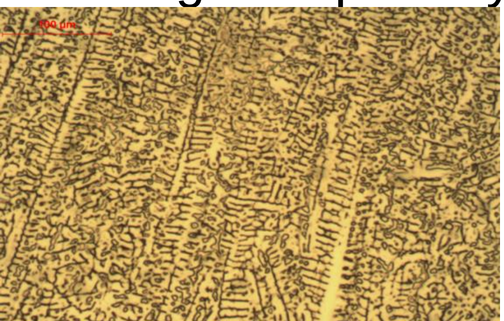


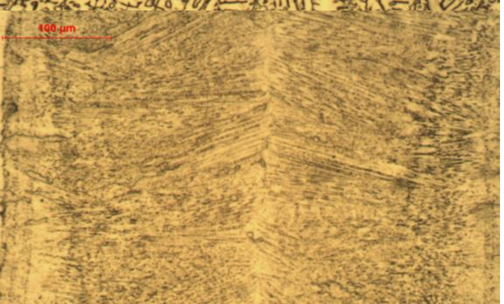
201 austenitic stainless steel

(17,4 Cr, 4,5 Ni, 6,6 Mn, CREQ/NIEQ=1,65)

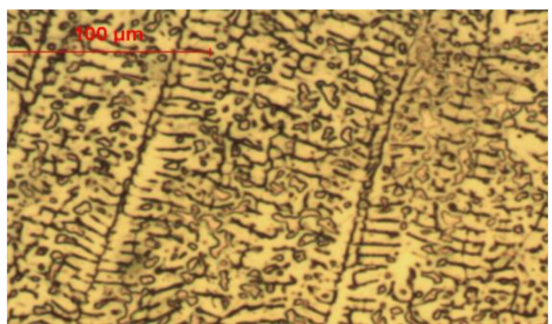
- At high welding speed the solidification changes to primary austenitic mode

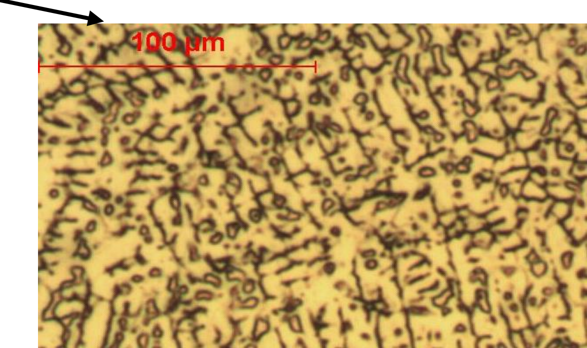
Pekkarinen, Kujanpää, ICALEO 2010





Welding method	Welding speed	Heat input (J/mm)	Solidifi-cation rate (m/min)	Solidifi-cation mode
Keyhole	1 m/min	248	5,15	FAF
Keyhole	5 m/min	49,6	17,17	FA & AF
Keyhole	10 m/min	24,8	30,33	AF
Conduction LW	0,3 m/min	185	-	FAF
GTAW	0,25 m/min	207	-	FAF



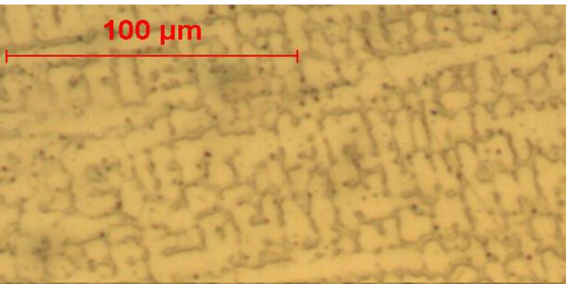


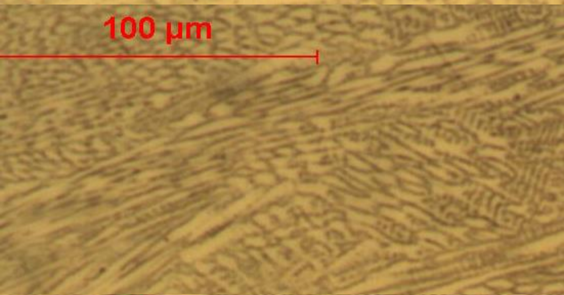
254 SMO austenitic stainless steel (6 % Mo) (CREQ/NIEQ=1,11)

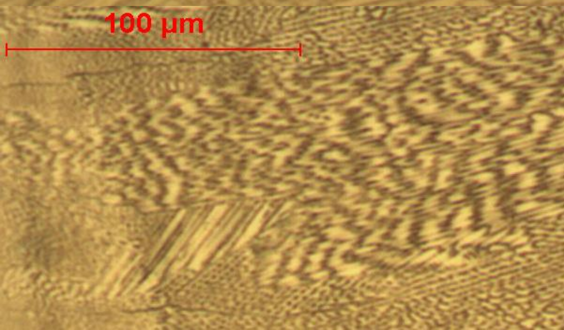
- Weld solidifies as primary austenitic independently of welding speed

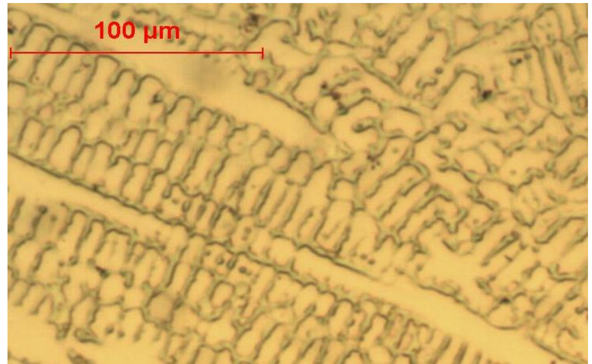
Pekkarinen, Kujanpää, ICALEO 2010

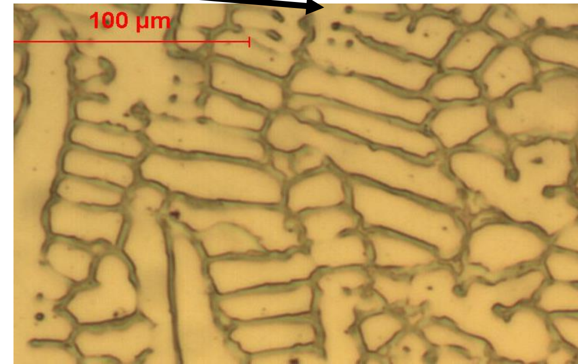
Welding method	Welding speed	Heat input (J/mm)	Solidifi-cation rate (m/min)	Solidifi-cation mode
Keyhole	1 m/min	248	3,28	AF
Keyhole	5 m/min	49,6	22,16	AF
Keyhole	10 m/min	24,8	27,67	AF
Conduction LW	0,3 m/min	185	-	AF
GTAW	0,25 m/min	189	-	AF











Microsegregation (254 SMO, 6 % Mo)

- Primary austenitic solidification causes strong microsegregation (Cr, Ni and especially Mo)
- Microsegregation is milder at high welding speed (high cooling rate)

  => milder differences in corrosion properties

	Nickel		Cromium		Molybdenum	
Weld	Highest (%)	Lowest (%)	Highest (%)	Lowest (%)	Highest (%)	Lowest (%)
KHLW 1 m/min	18,3	15,4	24,3	20,0	11,4	4,3
KHLW 5 m/min	19,2	15,5	23,5	20,0	8,7	4,5
KHLW 10 m/min	18,9	15,8	23,8	20,1	9	5,25
CLW	20	10,9	24,9	19,3	15,5	4,3
GTAW	19,4	11,4	26,1	19,9	13,8	3,9

Hot cracking

- Solidification cracking susceptibility is dependent on several aspects:
  - **Local strains and stresses** caused by rigidity of the joint and structure (S)
  - **Solidification cracking resistance** of the material (M)

If M < S ,

- where

M = material´s ability to resist cracking

S = structure´s tendency to affect cracking,

cracking occurs

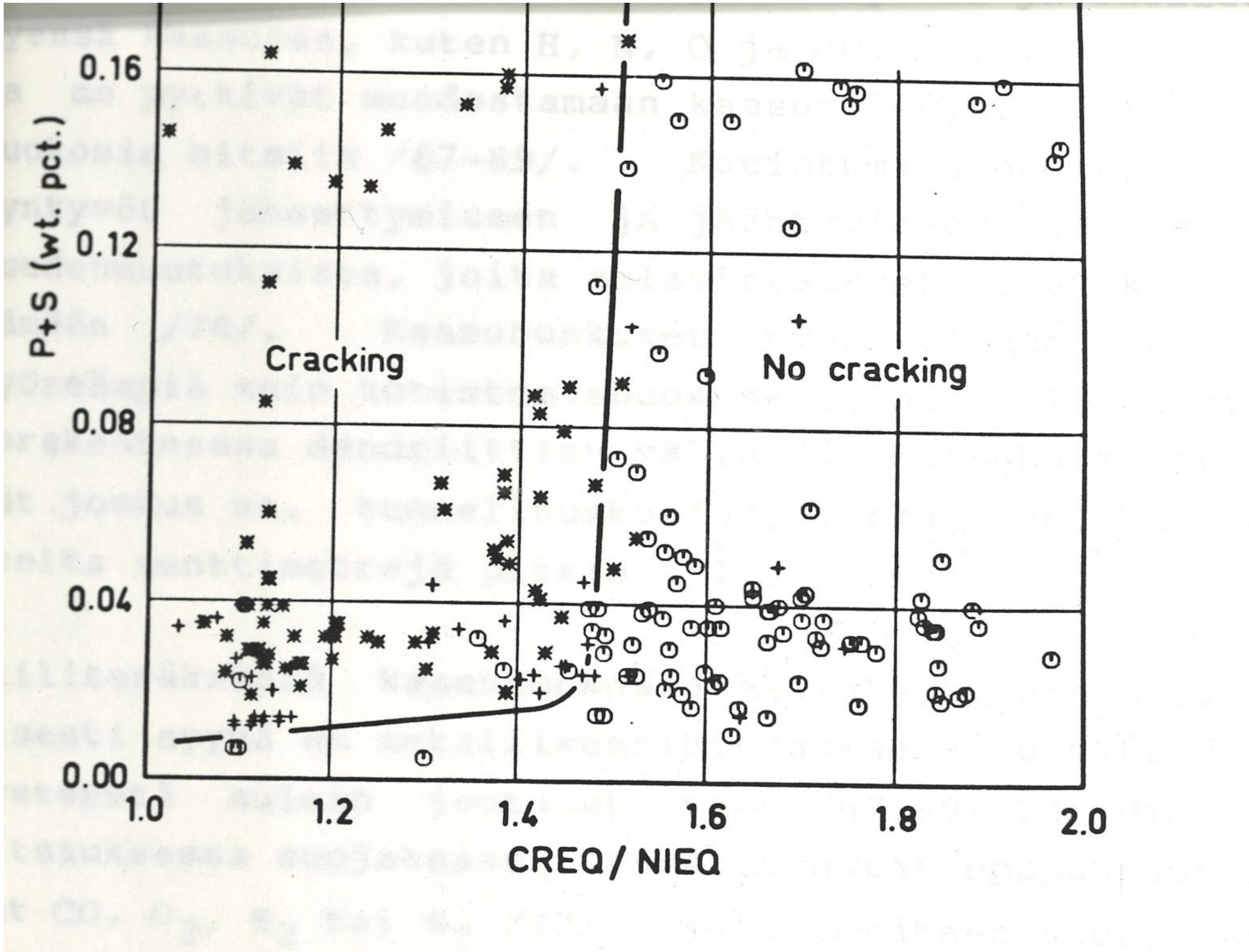
Hot cracking

- In laser and hybrid welding the strains caused are much lower than in conventional arc welding (S is low). Therefore one could suppose that hot cracking would not occur
- On the other hand the weld tends to solidify as primary austenitic solidification, which decreases material´s ability to resist cracking (M is also lower)

⇒The cracking susceptibility is very case-oriented

Hot cracking

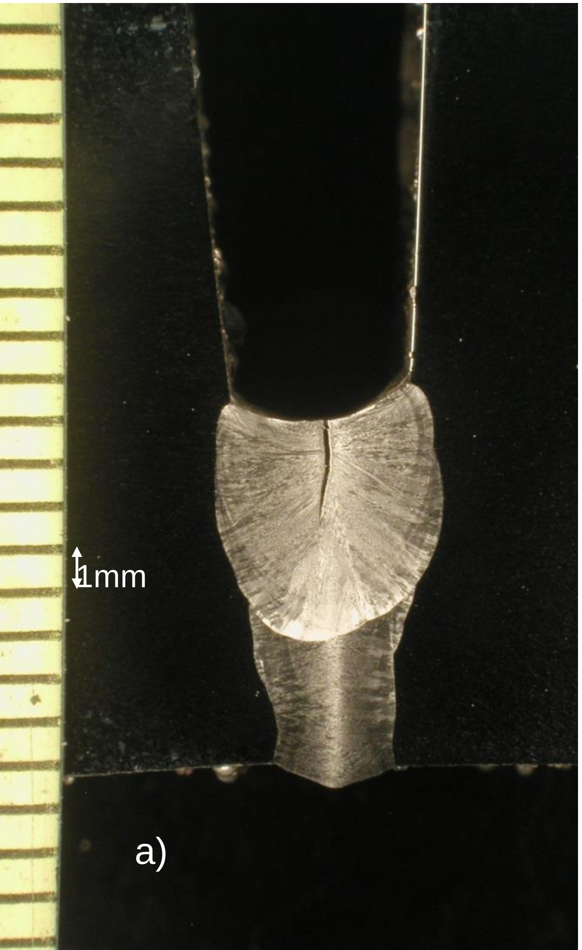
- Hot cracking is also affected by impurity content

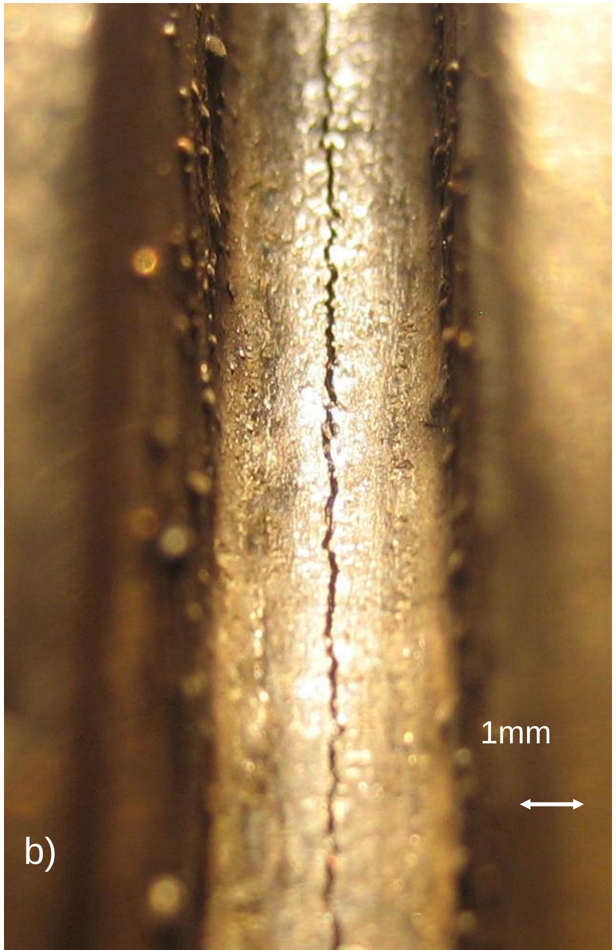


Kujanpää et al. WRI 1979

Hot cracking

- Practical welding tests have shown that hot cracking in stainless steels occurs easiest, if the structure is very rigid and solidification is primary austenitic





- E.g. in non-rigid sheet structures hot cracking is very rare
- In thick sections hot cracking must be taken into account

Karhu, Kujanpää, 3rd Hot Cracking Symp. 2010

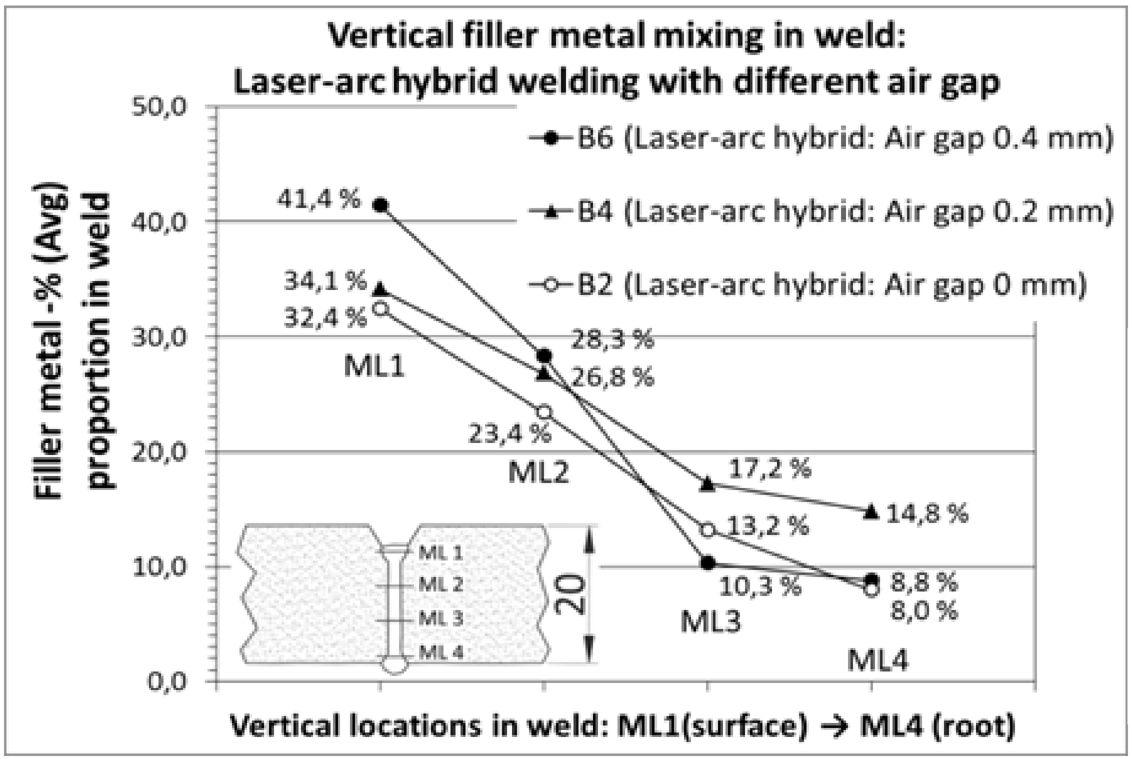
Mixing and homogeneity

- It is known in many studies that mixing is not complete in laser or hybrid laser welding
- It can be a problem
    - In dissimilar welding
    - If filler metal with non-matching composition with base metal is used

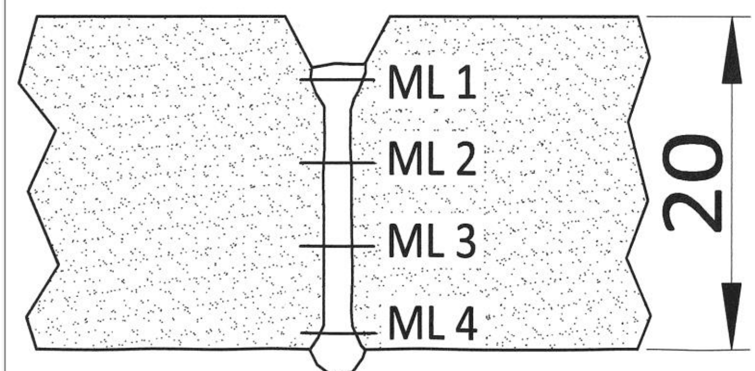
Mixing and homogeneity

- Laser – arc hybrid welds:
  - On the surface (ML1) mixing is close to 40 %
  - On the root (ML4) mixing is 10-15 %
  - Mixing depends also on air gap, but is essential

Karhu, Kujanpää, ICALEO 2013



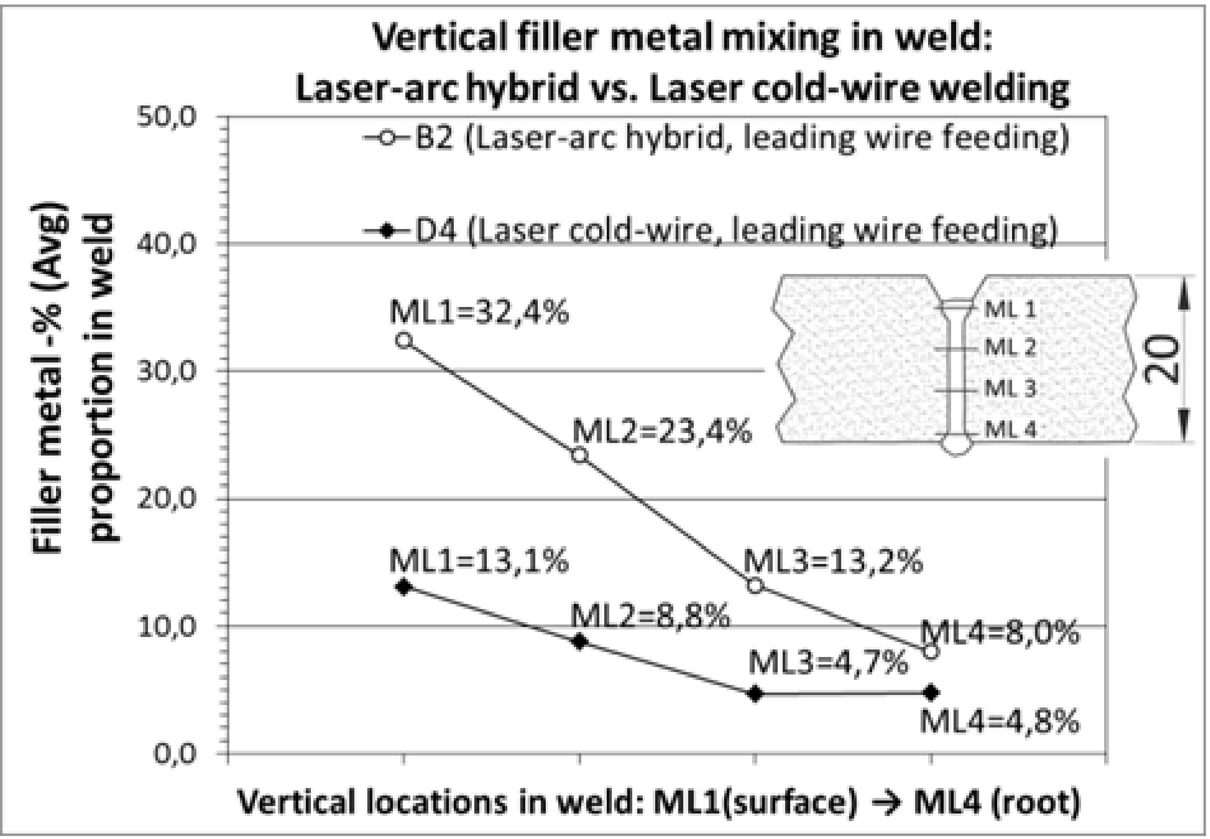
Laser-arc hybrid weld
Base metal AISI 316 (17.6 % Cr
Filler wire 2205 (22.9 % Cr)



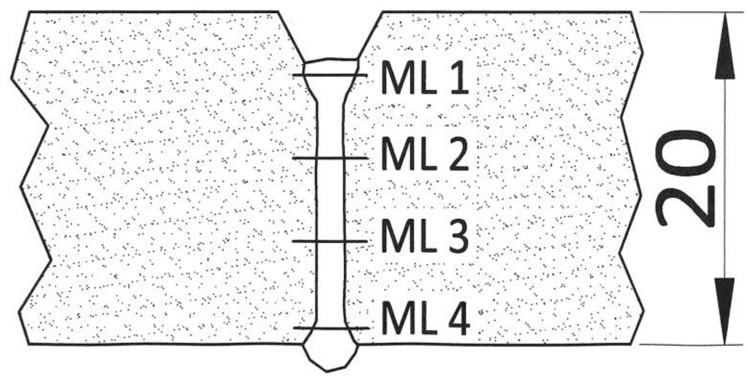
Mixing and homogeneity

- Laser-arc hybrid vs. Laser cold-wire welding
    - If cold-wire feeding is used, mixing is 13 % on the surface and 5 % on the root

Karhu, Kujanpää, ICALEO 2013



Laser-arc hybrid weld vs. laser cold-wire
Basemetal AISI 316 (17.6 % Cr
Filler wire 2205 (22.9 % Cr)

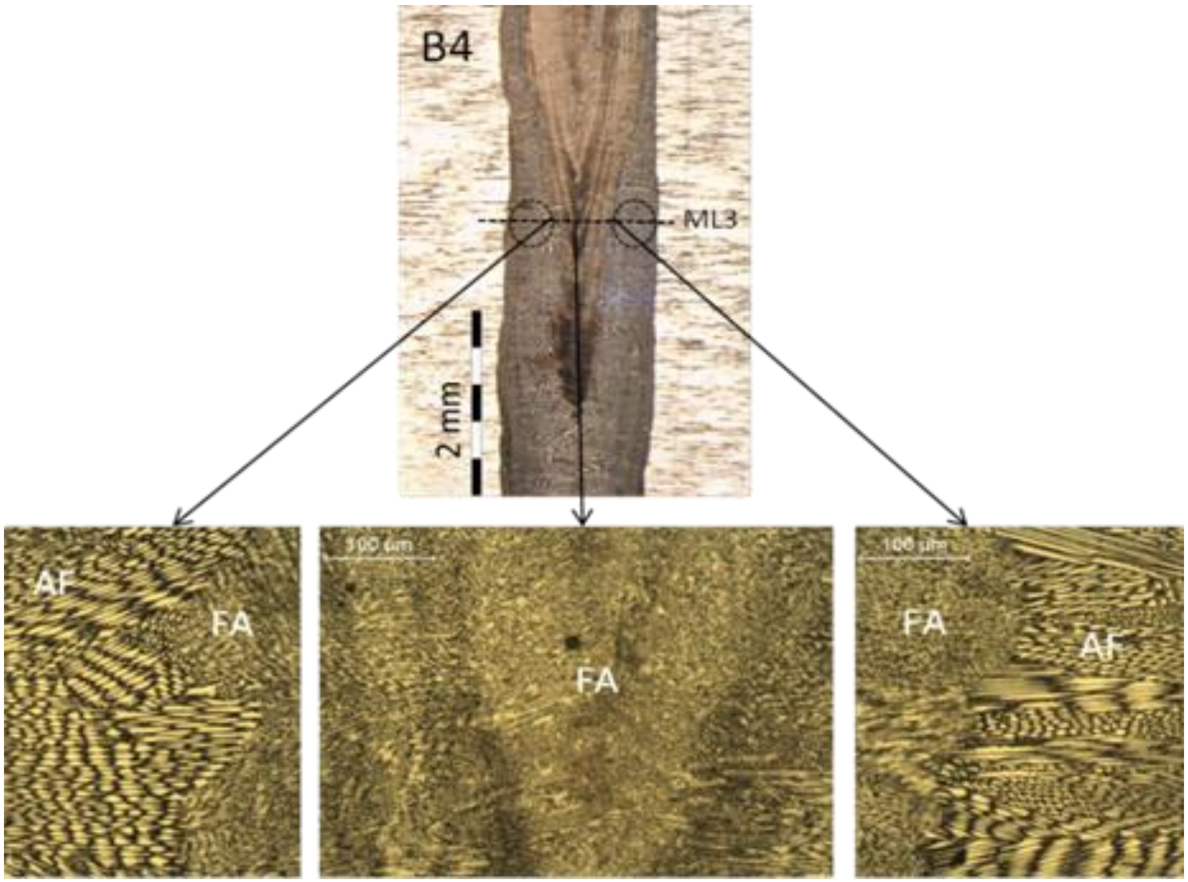


Mixing and homogeneity

- Incomplete mixing can affect unpredictable problems, if filler metal is used to optimize e.g. mechanical or corrosion properties
  - E.g. if high-nickel wire is used to increase ductility of structural steel. If the wire is fed on the surface, it is not clear that nickel is increased enough in the root
  - E.g. if composition is aimed to balanced by filler wire in stainless steels, it is not guaranteed that the aimed corrosion properties are reached, if mixing is not known

Mixing and homogeneity

- Incomplete mixing affects also solidification sequence and causes local variations in solidification modes. This can also cause practical problems, e.g. increased risk for hot cracking or differences in corrosion behaviour



Karhu, Kujanpää, ICALEO 2013

Conclusions

- Cooling rate of laser and laser hybrid welds is high. Therefore laser weld is very fine-grained and microsegregation is milder than in arc welding
- Laser weld of austenitic stainless steels tends to solidify as single mode, depending on composition and welding parameters. This can affect hot cracking susceptibility and corrosion properties
- In laser and laser-arc welding mixing is incomplete. This needs to be taken into account, if hot cracking, mechanical or corrosion properties can play a role
- In laser welding of thick sections filler metal is usually needed. It can be fed as cold- or hot-wire or arc-assisted hybrid laser welding as multi-pass
- Multi-pass weld is also very dependent on joint design, which affects the strategy of keyhole or conduction-limited laser welding

TECHNOLOGY FOR BUSINESS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