Steels & Stainless Steels II

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CERN, Geneva, Switzerland

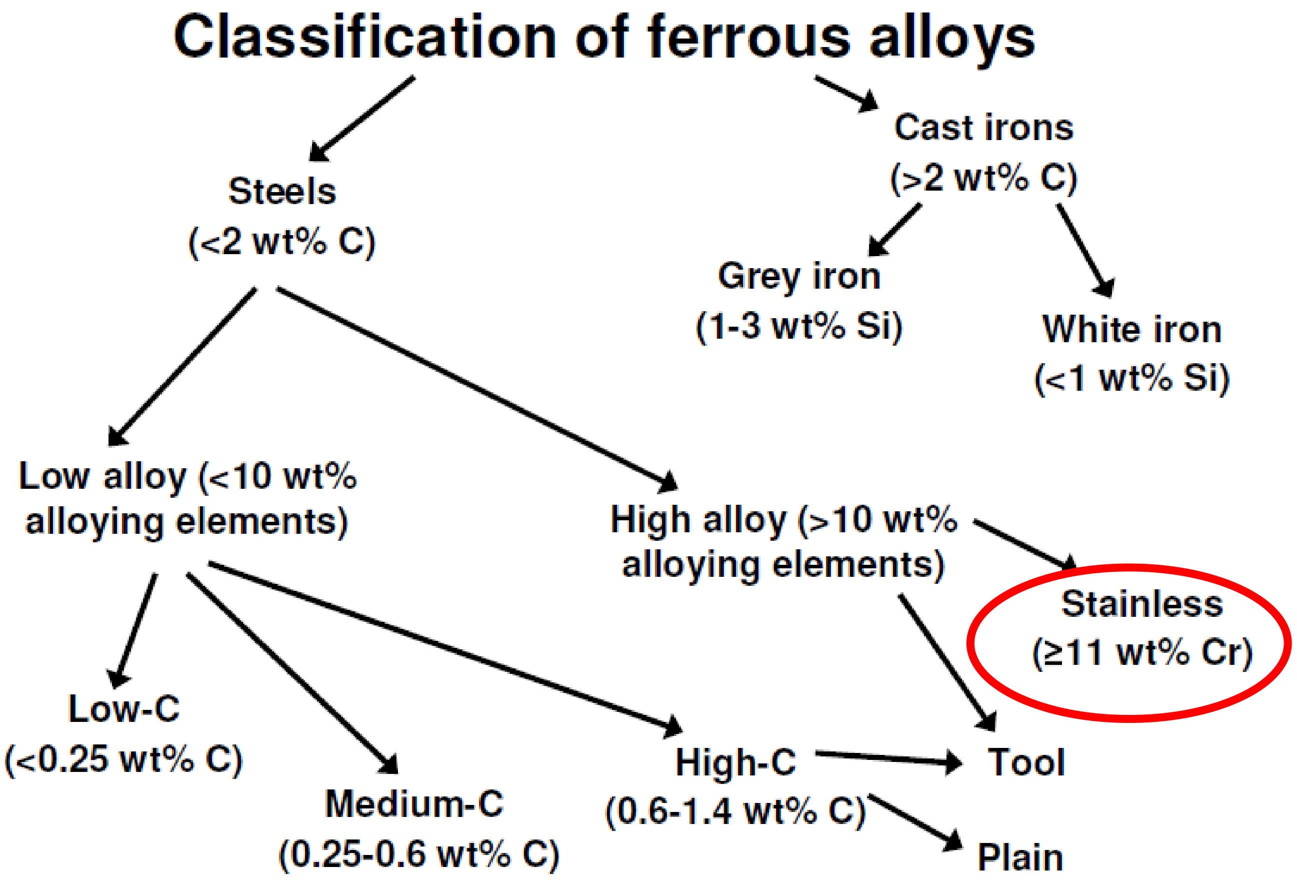
Mechanical & Materials Engineering for
Particle Accelerators and Detectors

2-15 June, 2024
Sint-Michielsgestel, NL

Outline

1. Stainless steels:
    - Stainless steels, a 100 years of know-how
2. Rules for the selection and specification of stainless steels
    - Metallurgy of general purpose and advanced stainless steels grades/processes for application to particle accelerators
3. Steelmaking routes to secure the final quality of the product
4. Stability of the properties: precipitations and transformations
    a. Considerations for welding
    b. Case study: steel for the new CMS HG-CAL detector
    c. Martensitic transformations
5. Thermal treatments, sensitization, corrosion failures
6. Conclusions

Take home from yesterday lecture



Classification of ferrous alloys

Steels
(<2 wt% C)

Cast irons
(>2 wt% C)

Grey iron
(1-3 wt% Si)

White iron
(<1 wt% Si)

Low alloy (<10 wt% alloying elements)

High alloy (>10 wt% alloying elements)

Stainless
(≥11 wt% Cr)

Low-C
(<0.25 wt% C)

Medium-C
(0.25-0.6 wt% C)

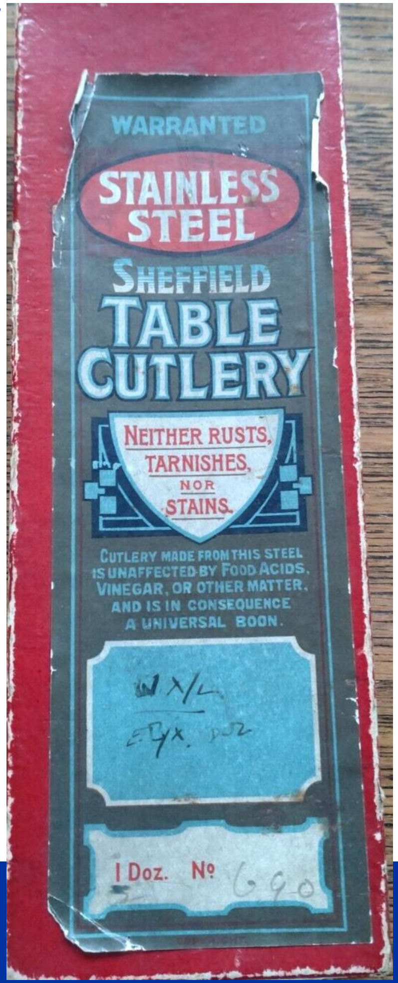
High-C
(0.6-1.4 wt% C)

Tool

Plain

Stainless steel: iron alloys containing a minimum of approx. 11 % Cr

On the 13th August 1913 Brearley created in Sheffield, UK, a steel with 12.8% chromium and 0.24% carbon, the first ever stainless steel.



1. Stainless steels, metallurgy and families

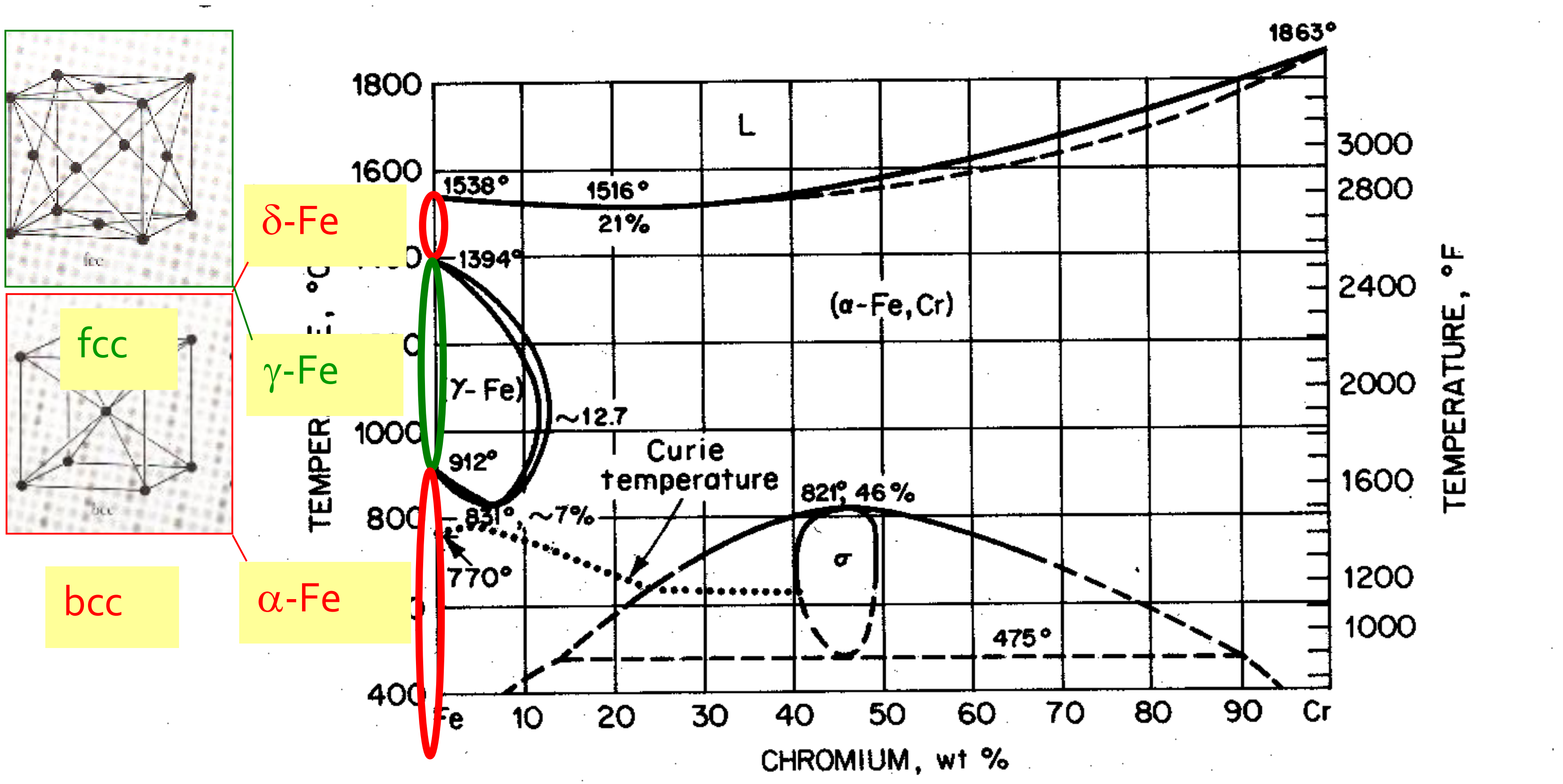


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

1. Stainless steels, ferritic

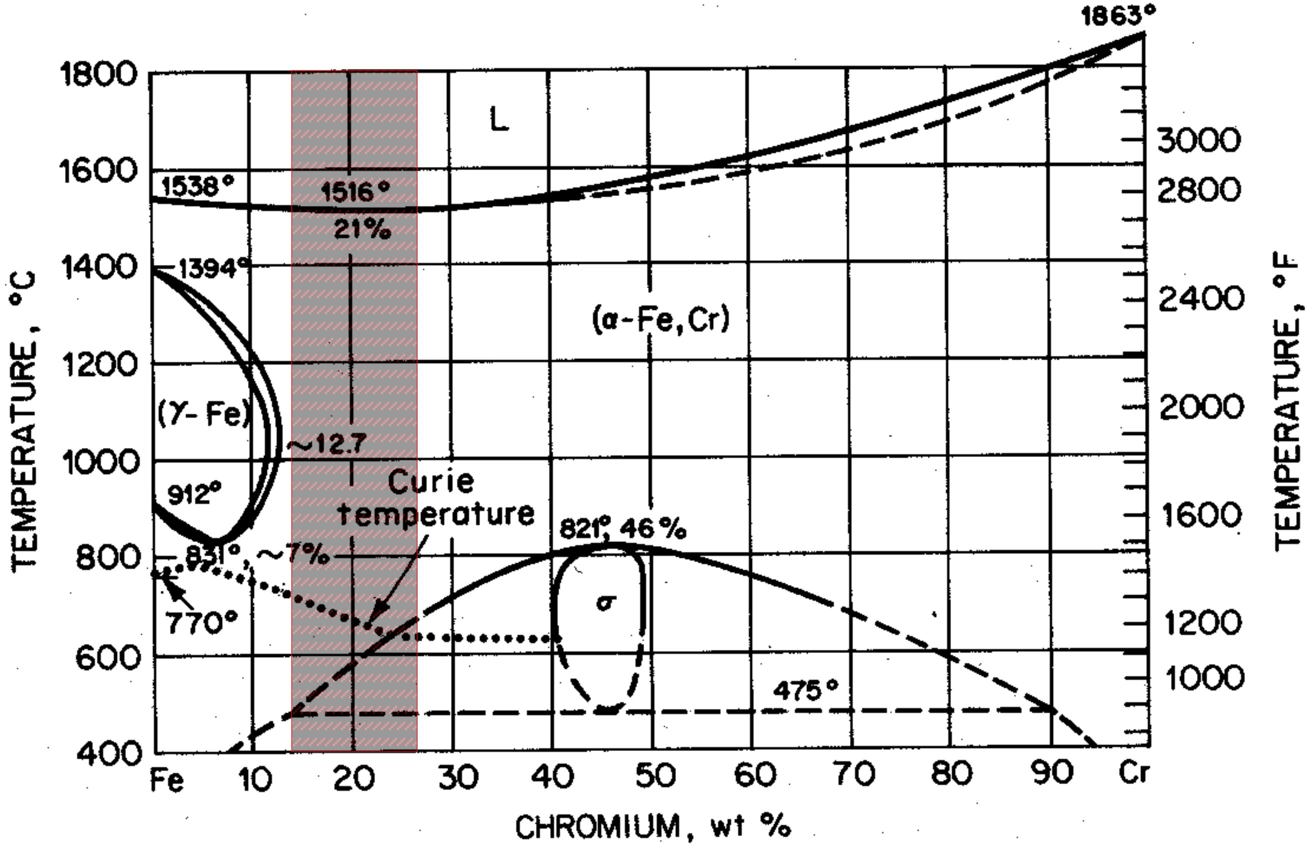
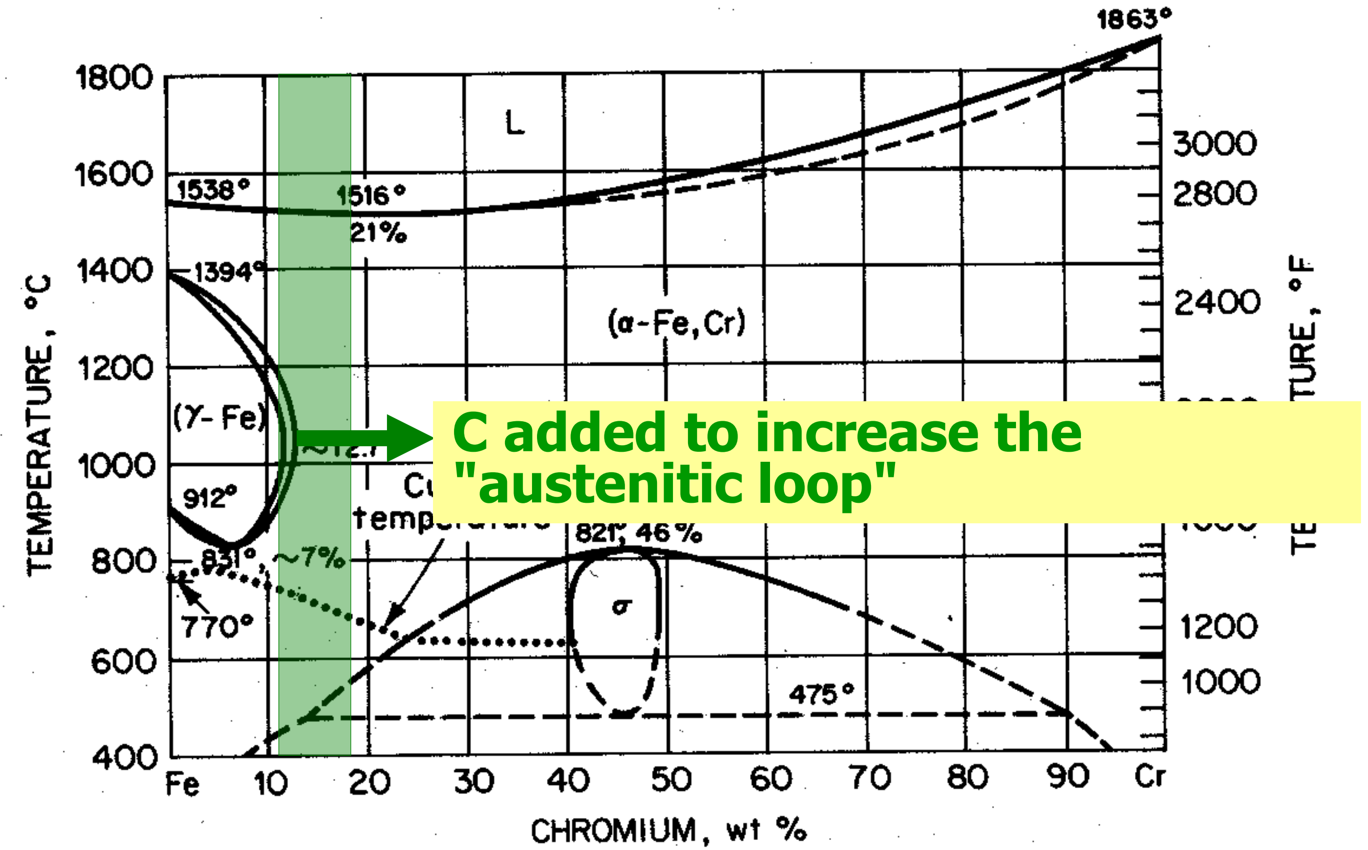


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

- ferritic grades, 14.5 % to 27 % Cr
- resistant to corrosion
- subject to grain growth during firing
- ferromagnetic at RT and below
- brittle at low T

1. Stainless steels, martensitic

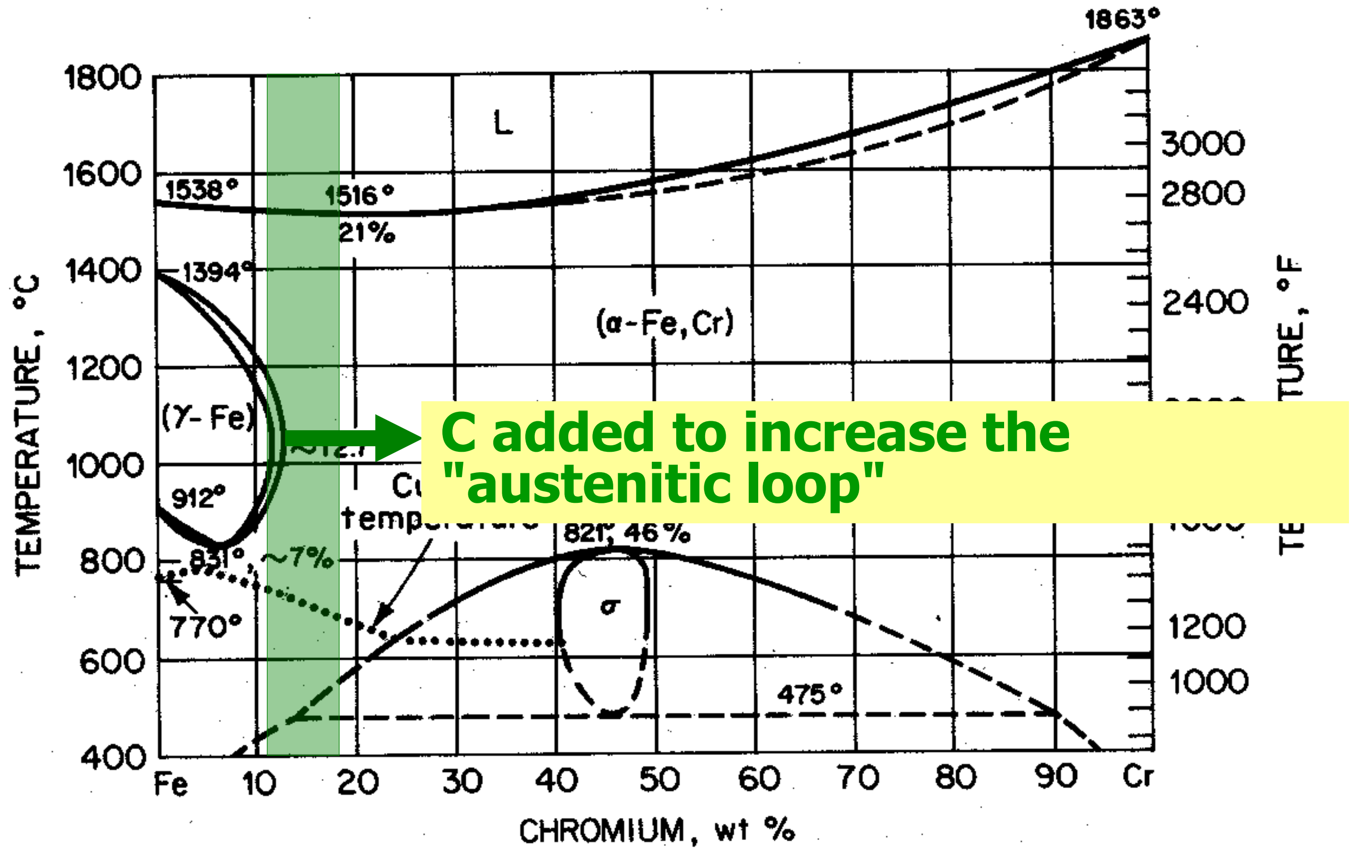


C added to increase the "austenitic loop"

Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

- martensitic grades, Cr between 11.5 % and 18 %, C up to 1.2 %
- hardenable by HT
- high strength
- ferromagnetic at RT and below
- brittle at low T

1. Stainless steels, martensitic



C added to increase the "austenitic loop"

Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

- martensitic grades, Cr between 11.5 % and 18 %, C up to 1.2 %
- hardenable by HT
- high strength
- ferromagnetic at RT and below
- brittle at low T

AISI 304, the "18-8" or "18-10" stainless (18%Cr, 8-10%Ni)

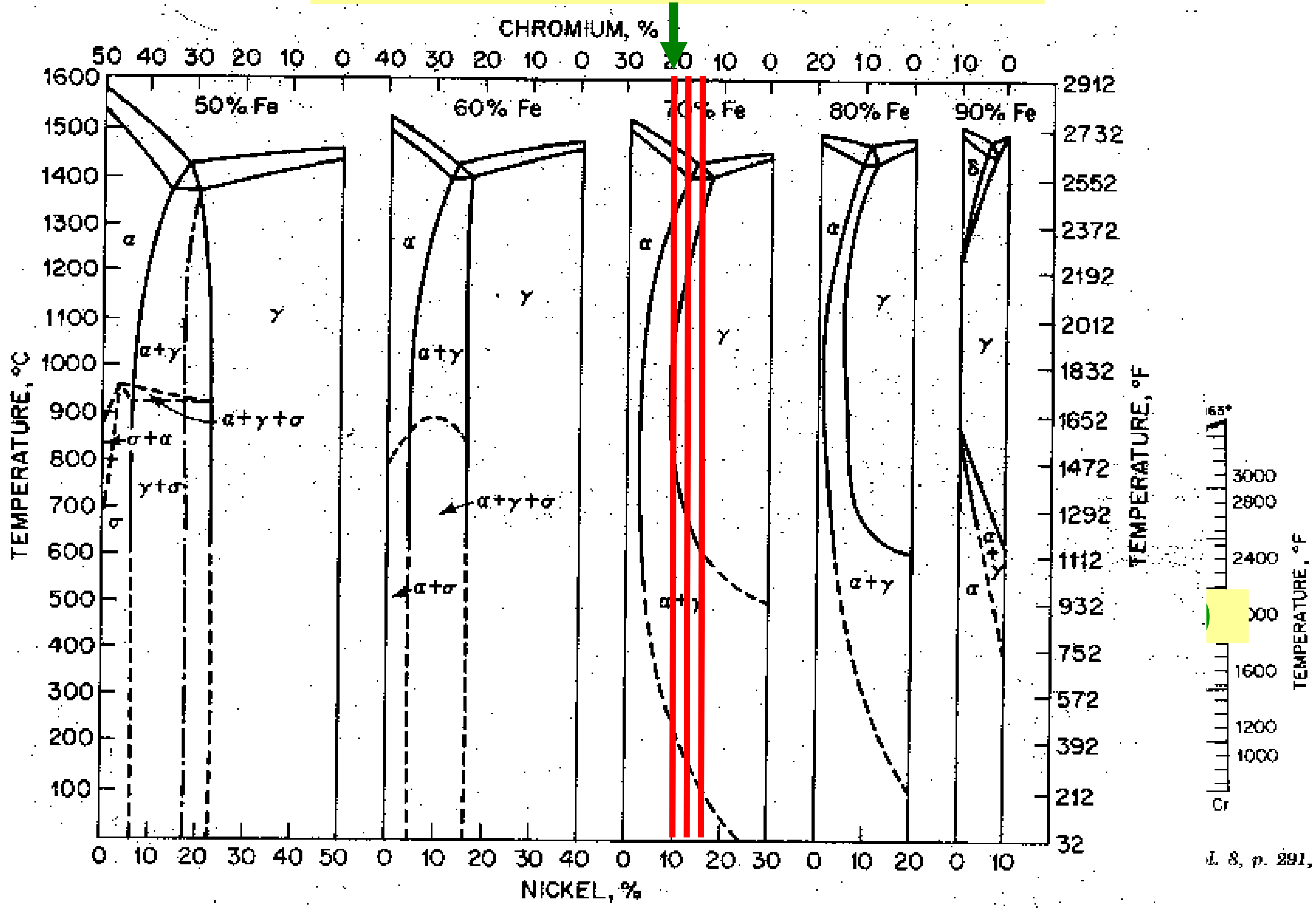
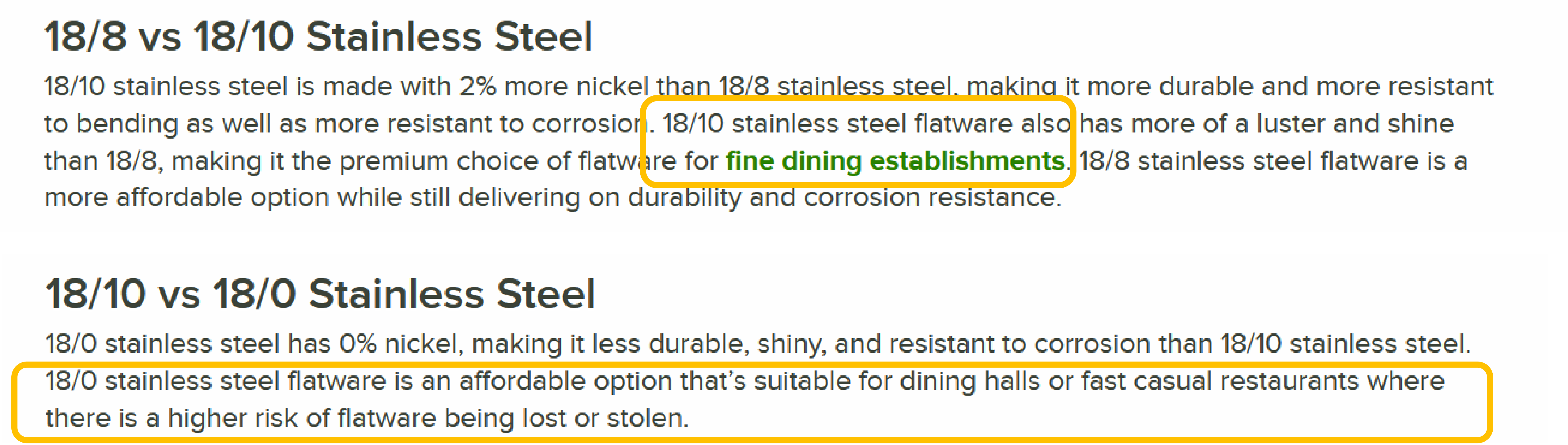


Fig. 14 Cross sections of Fe-Cr-Ni ternary.[26]

l. 8, p. 291, 8th ed.,

- formed by an addition of a fcc element (Ni, Mn) to the FeCr system
- γ-loop expanded
- γ-phase enhanced and enlarged
- formation of ferrite can be suppressed (austenite former elements)
- transformation to martensite can be reduced or suppressed (increasing alloying elements)



18/8 vs 18/10 Stainless Steel

18/10 stainless steel is made with 2% more nickel than 18/8 stainless steel, making it more durable and more resistant to bending as well as more resistant to corrosion. 18/10 stainless steel flatware also has more of a luster and shine than 18/8, making it the premium choice of flatware for **fine dining establishments**. 18/8 stainless steel flatware is a more affordable option while still delivering on durability and corrosion resistance.

18/10 vs 18/0 Stainless Steel

18/0 stainless steel has 0% nickel, making it less durable, shiny, and resistant to corrosion than 18/10 stainless steel. 18/0 stainless steel flatware is an affordable option that's suitable for dining halls or fast casual restaurants where there is a higher risk of flatware being lost or stolen.

What Is the Best Quality Stainless Flatware?

Vacuum & cryogenic applications: 304L, 316L, 316LN

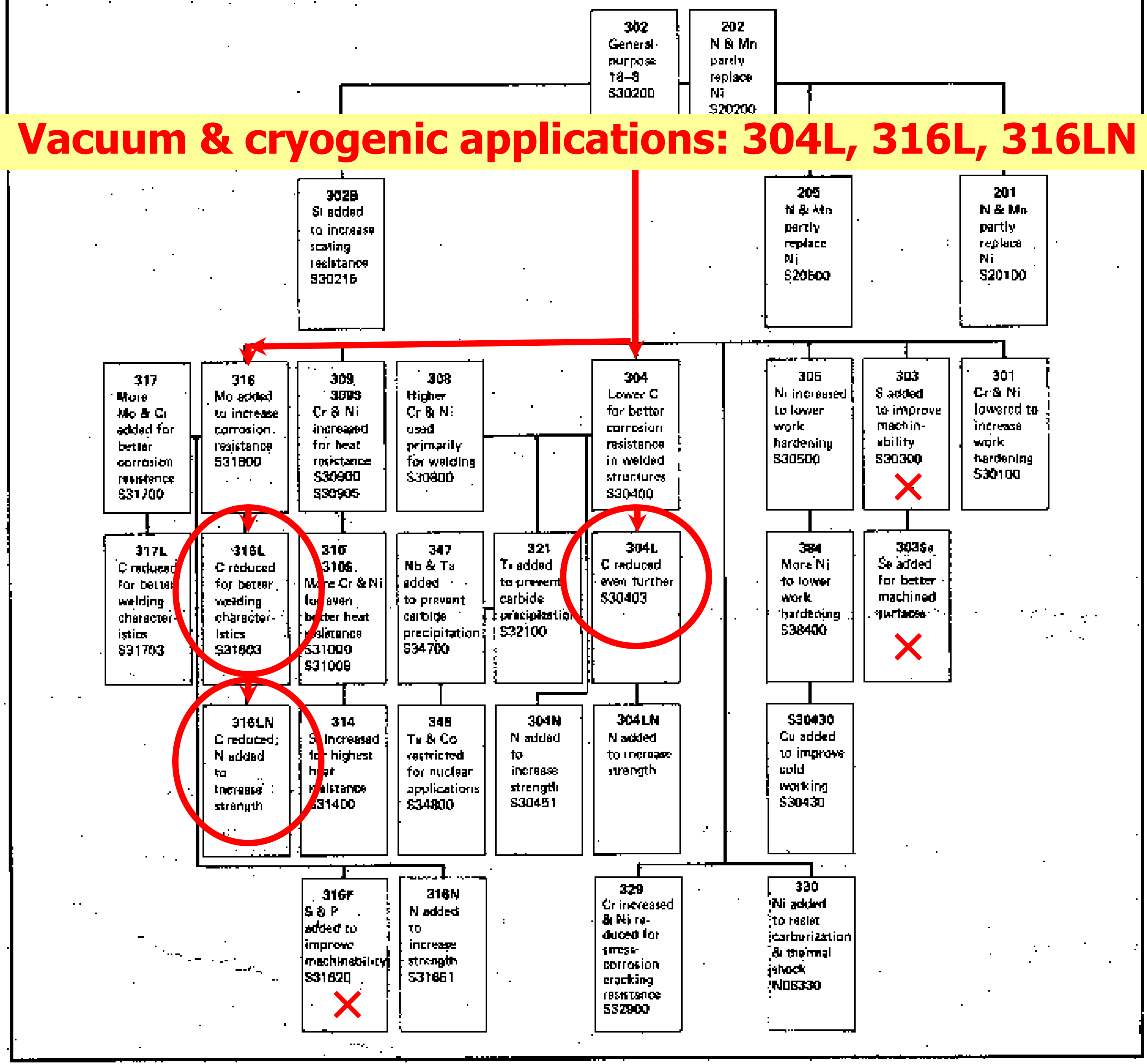


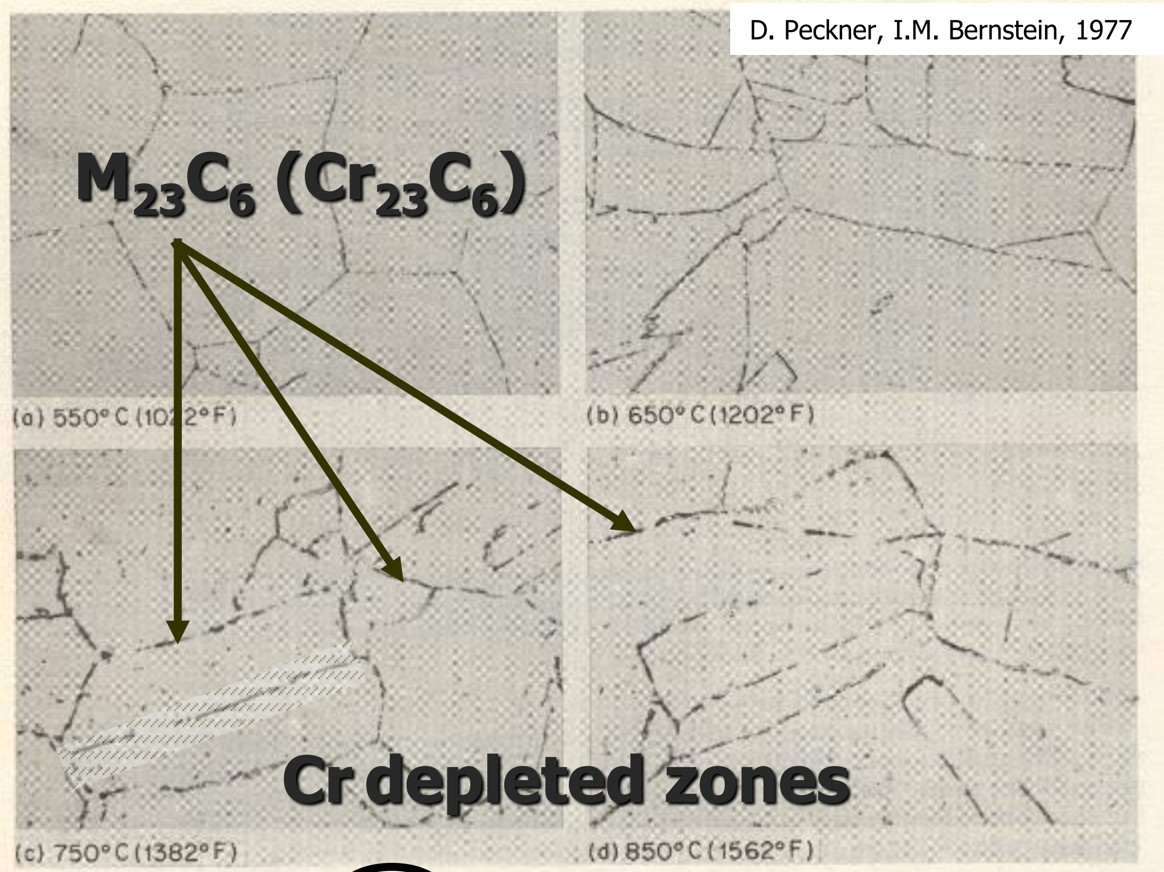
Fig. 2 Family relationships for standard austenitic stainless steels

Source: ASM Metals Handbook, vol. 3, 9th ed. (1980)

2. Rules for the selection and specification

Why low C (304L, 316L, 316LN)?

"Sensitization" of base metal, HAZs and welds

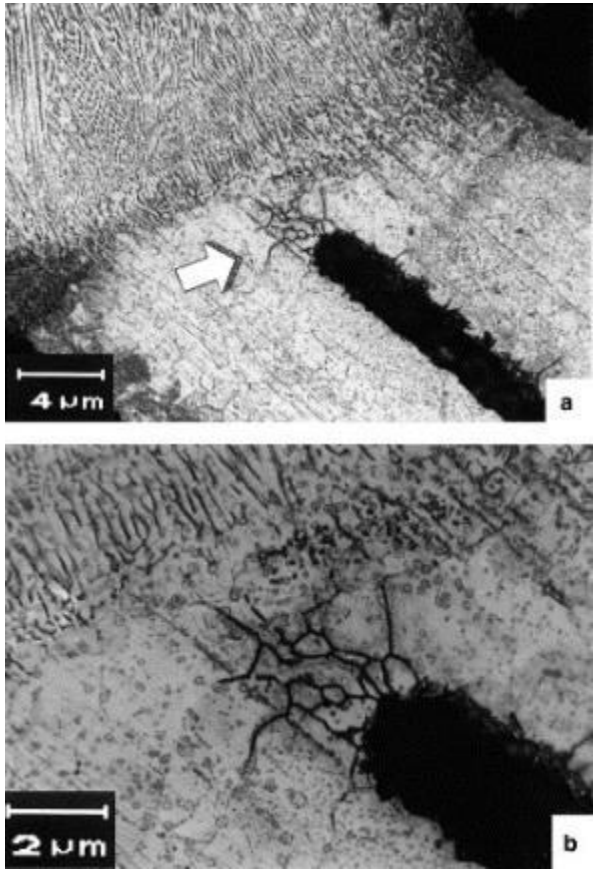


D. Peckner, I.M. Bernstein, 1977

$M_{23}C_6$ ($Cr_{23}C_6$)

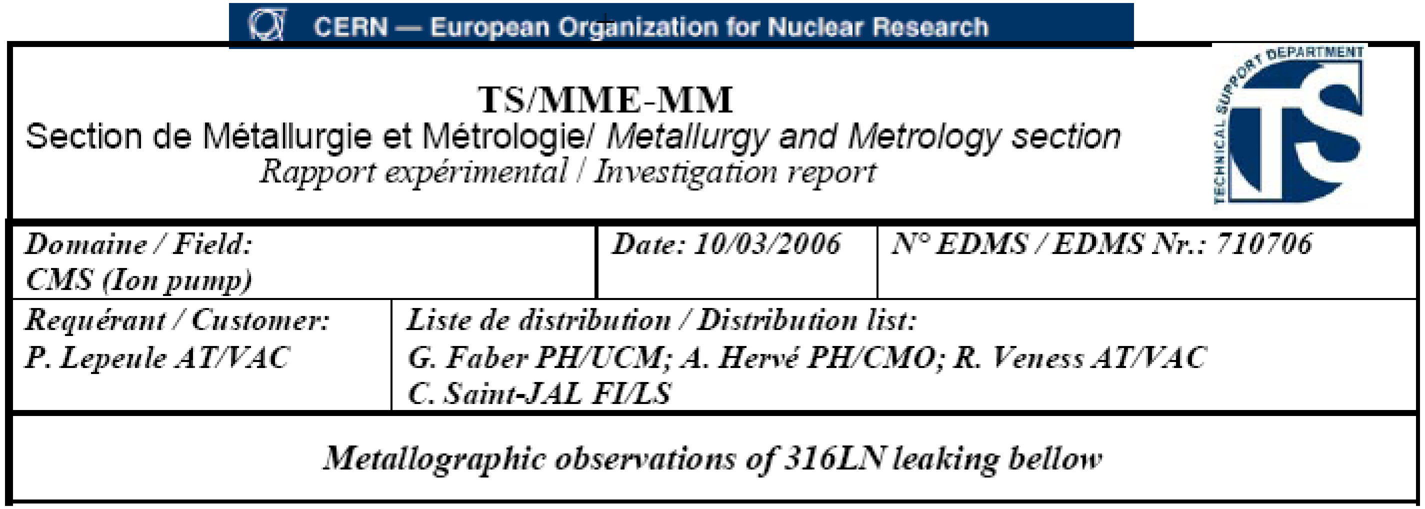
Cr depleted zones

Fig. 55 Appearance of Type 304 stainless steel (0.065% carbon) sensitized for 6 days (144 h) at various temperatures. Specimens etched electrolytically in 10% oxalic acid.[128] (*a*) 550°C (1022°F). 750x. (*b*) 650°C (1202°F). 750x. (*c*) 750°C (1382°F). 750x (*d*) 850°C (1562°F). 750x.



A.K. Jha et al., Engineering Failure Analysis

2. Rules for the selection and specification: inclusion content

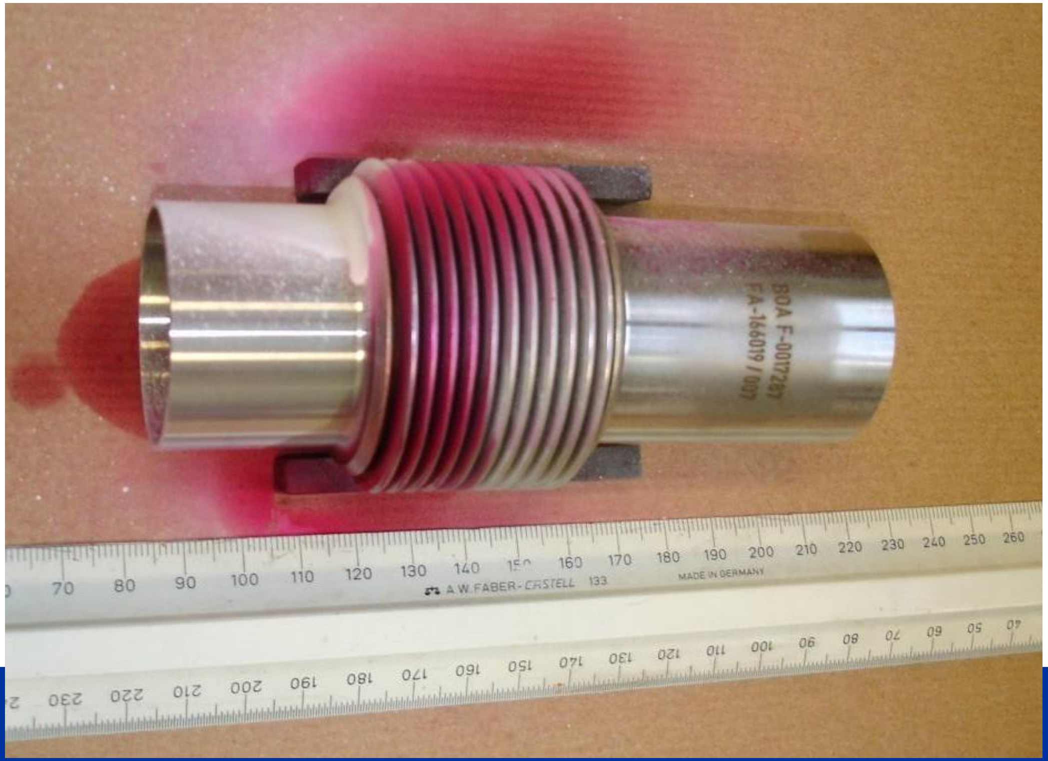


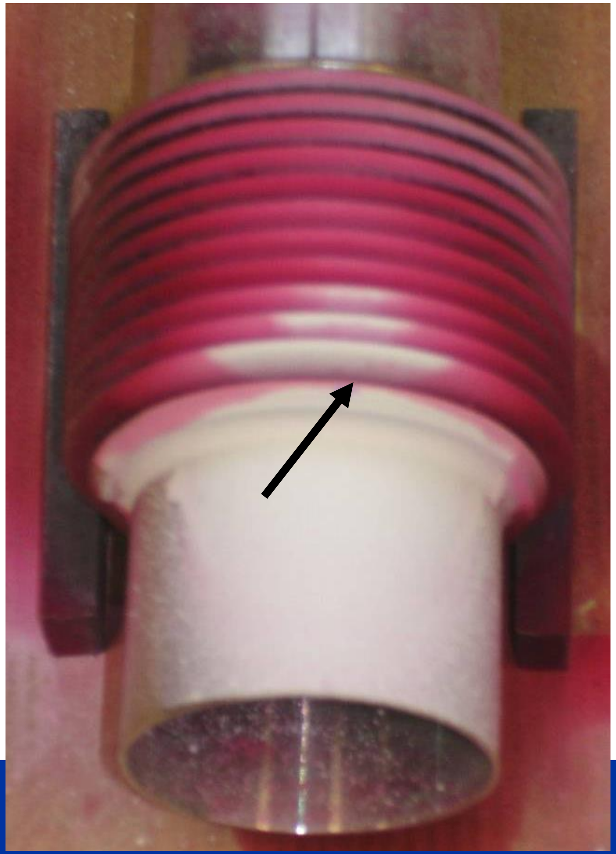
CERN — European Organization for Nuclear Research

TS/MME-MM
Section de Métallurgie et Métrologie/ *Metallurgy and Metrology section*
Rapport expérimental / Investigation report

Domaine / Field: *CMS (Ion pump)*	*Date: 10/03/2006*	*N° EDMS / EDMS Nr.: 710706*
Requérant / Customer: *P. Lepeule AT/VAC*	*Liste de distribution / Distribution list:* *G. Faber PH/UCM; A. Hervé PH/CMO; R. Veness AT/VAC* *C. Saint-JAL FI/LS*	

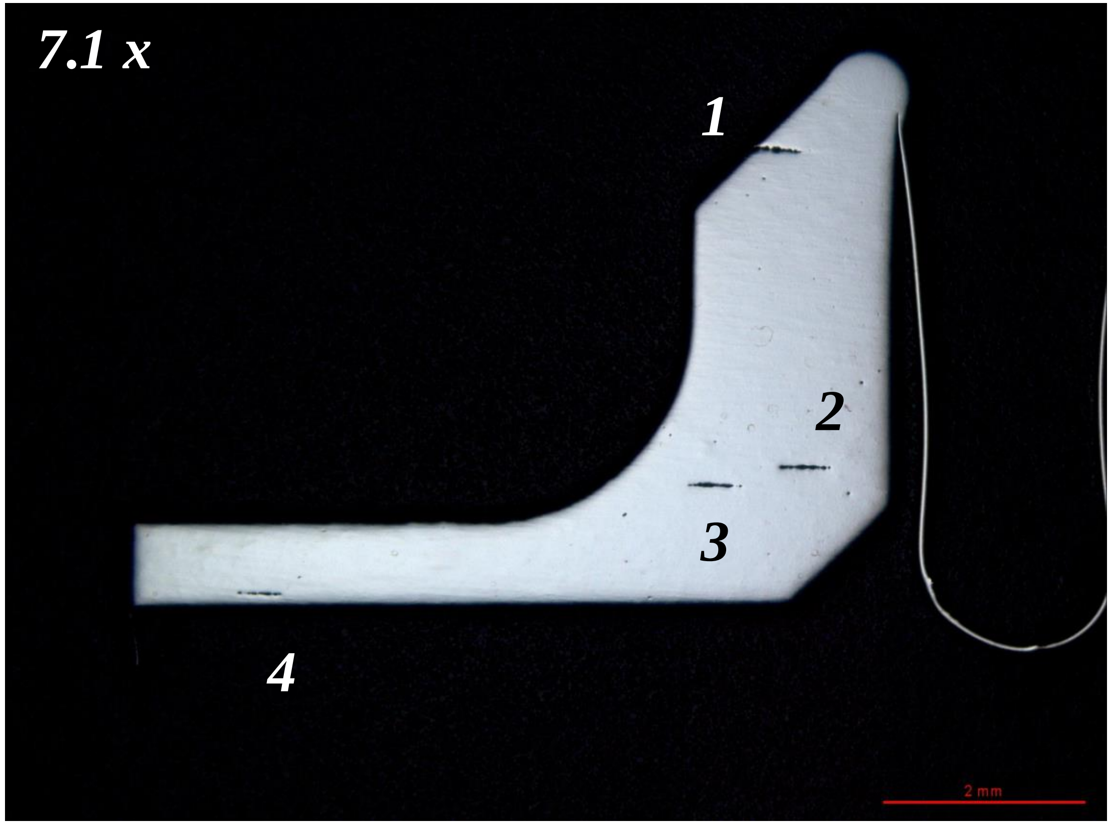
Metallographic observations of 316LN leaking bellow

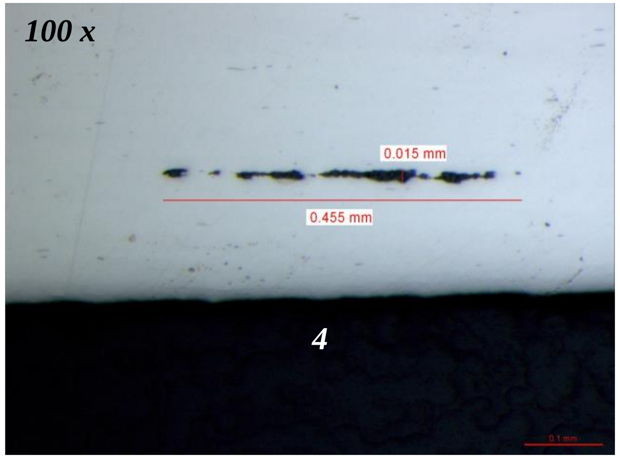


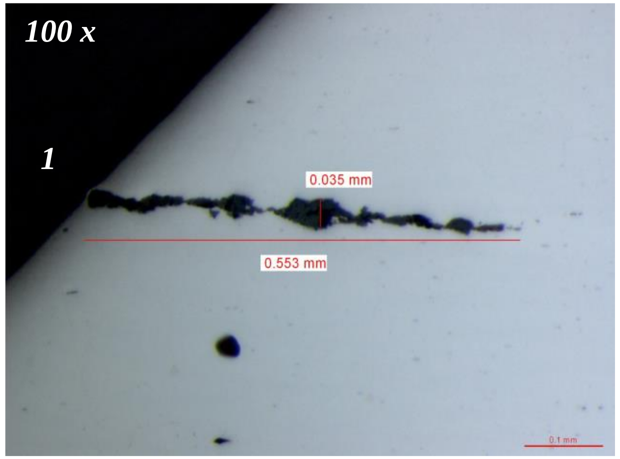


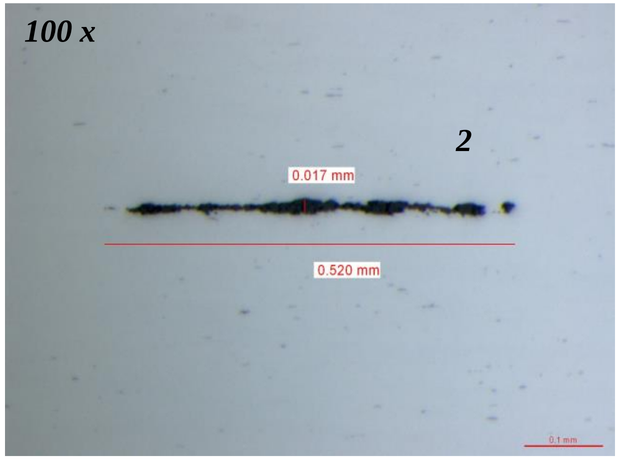
2. (…), inclusions

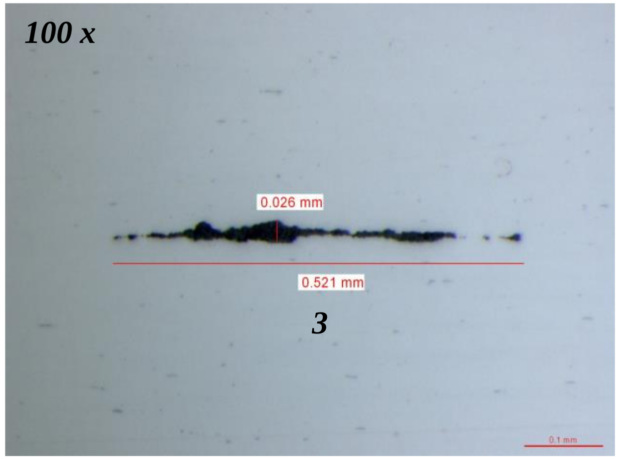
- **Oversized (1,2,3) and thick (4) B type inclusions up to class 2.**



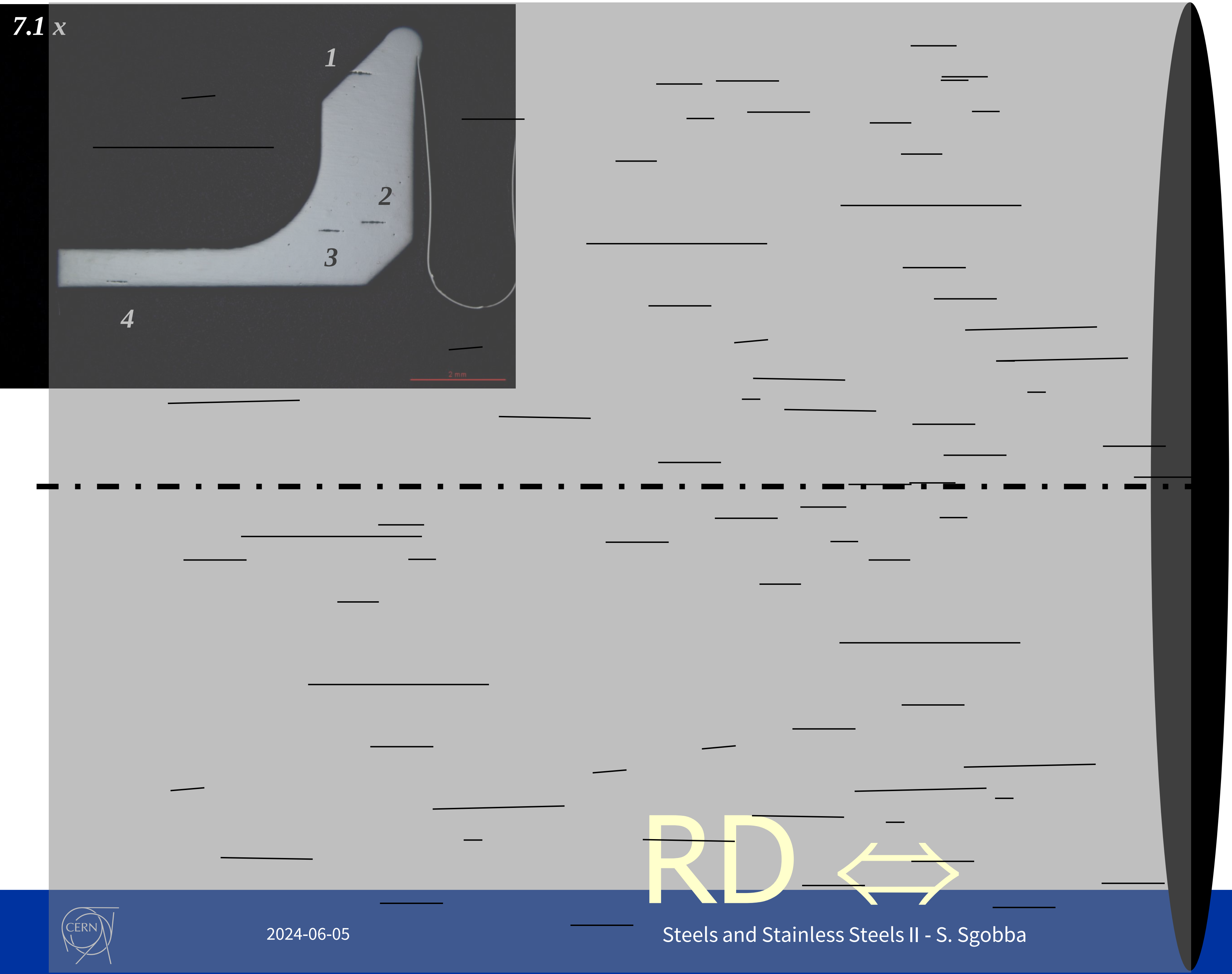




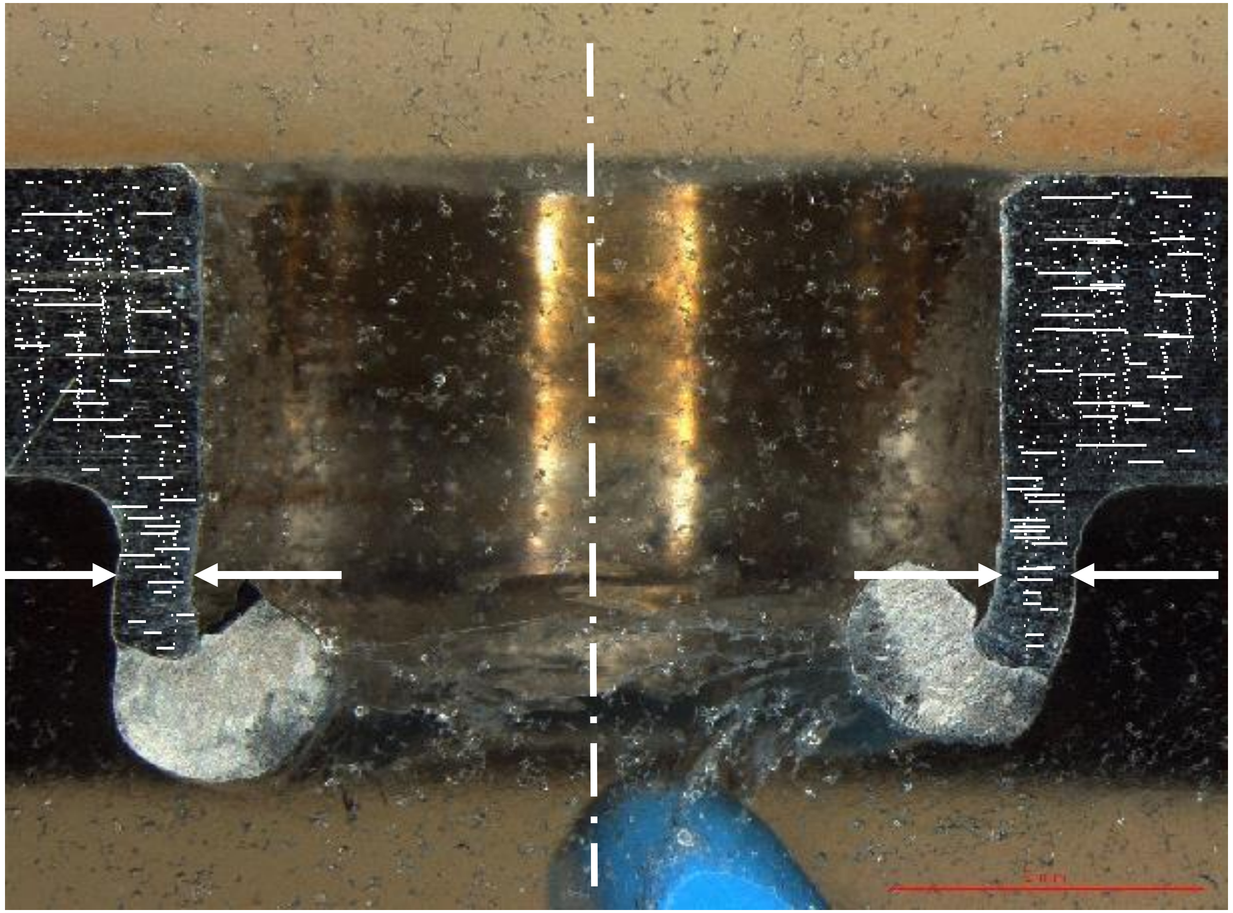




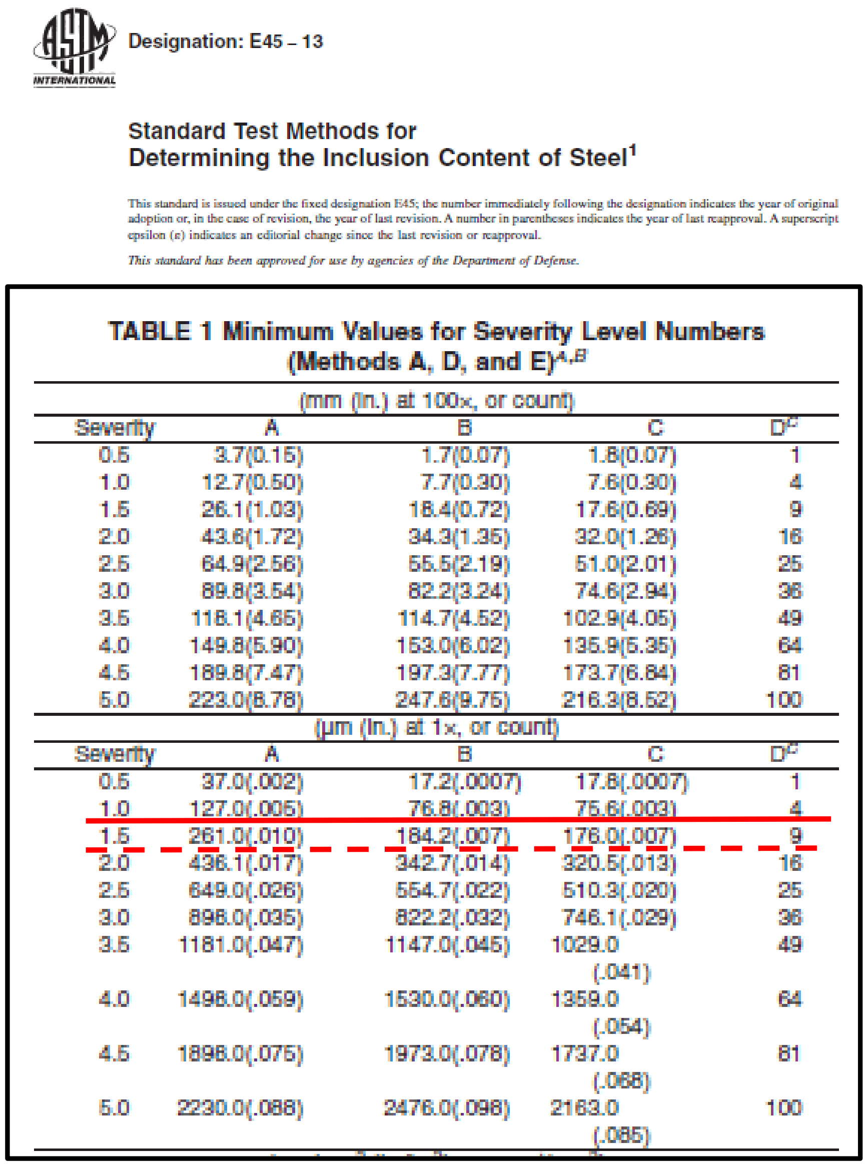
2. (…), inclusions



2. (…), inclusions



- **For any wrought product (plate, tube, bar), an unfavourable inclusions alignment will be anyway present in the rolling or drawing direction**



Designation: E45 – 13

Standard Test Methods for Determining the Inclusion Content of Steel[1]

This standard is issued under the fixed designation E45; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

TABLE 1 Minimum Values for Severity Level Numbers (Methods A, D, and E)^{A,B}

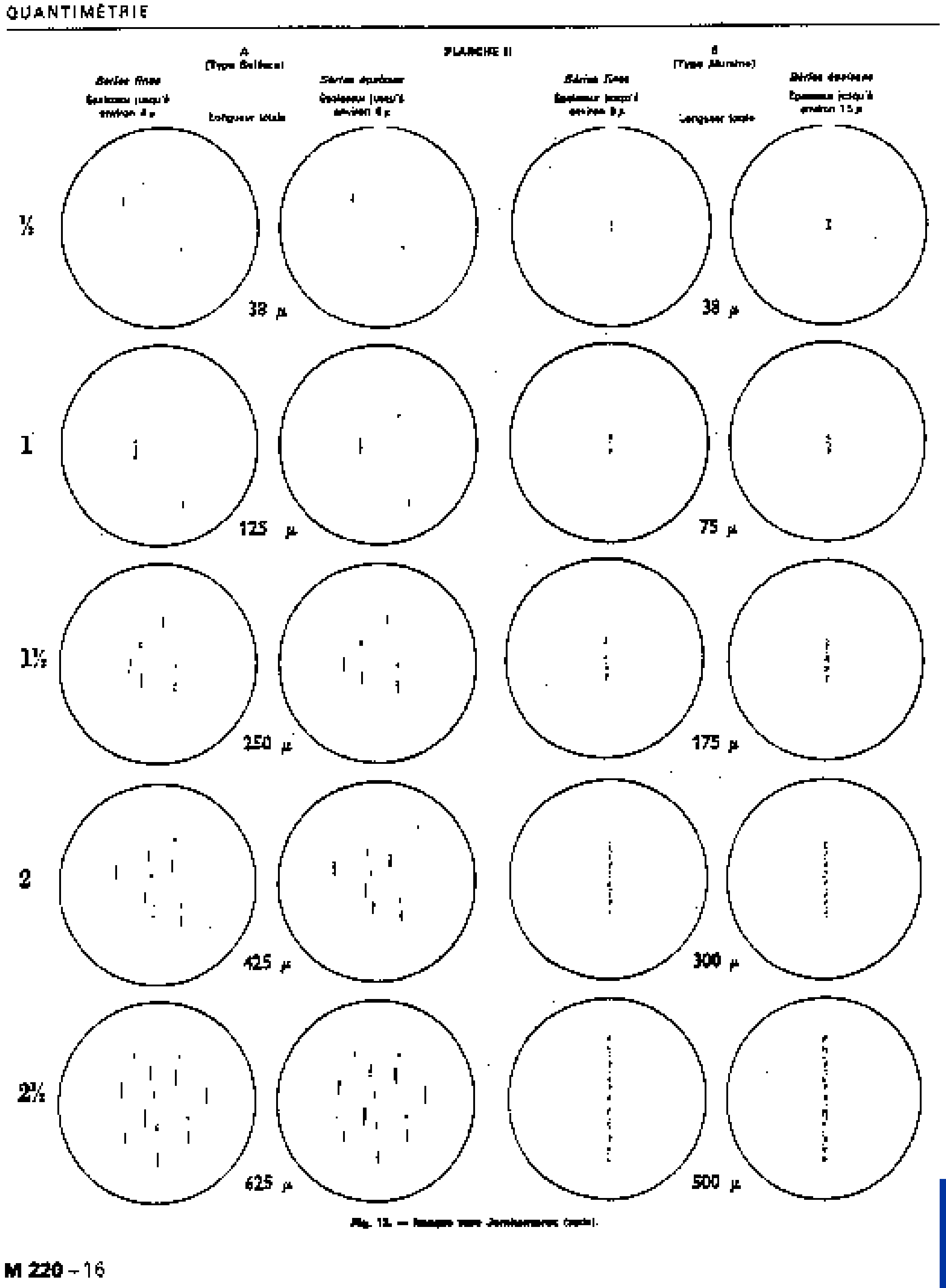
(mm (in.) at 100×, or count)

Severity	A	B	C	D^C
0.5	3.7(0.15)	1.7(0.07)	1.8(0.07)	1
1.0	12.7(0.50)	7.7(0.30)	7.6(0.30)	4
1.5	26.1(1.03)	18.4(0.72)	17.6(0.69)	9
2.0	43.6(1.72)	34.3(1.35)	32.0(1.26)	16
2.5	64.9(2.56)	55.5(2.19)	51.0(2.01)	25
3.0	89.8(3.54)	82.2(3.24)	74.6(2.94)	36
3.5	118.1(4.65)	114.7(4.52)	102.9(4.05)	49
4.0	149.8(5.90)	153.0(6.02)	135.9(5.35)	64
4.5	189.8(7.47)	197.3(7.77)	173.7(6.84)	81
5.0	223.0(8.78)	247.6(9.75)	216.3(8.52)	100

(µm (in.) at 1×, or count)

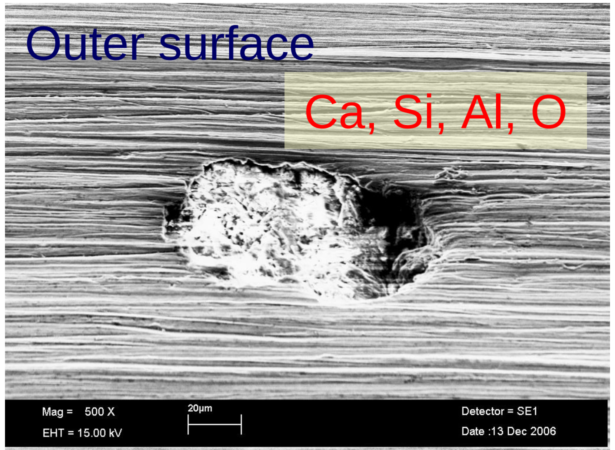
Severity	A	B	C	D^C
0.5	37.0(.002)	17.2(.0007)	17.8(.0007)	1
1.0	127.0(.005)	76.8(.003)	75.6(.003)	4
1.5	261.0(.010)	184.2(.007)	176.0(.007)	9
2.0	436.1(.017)	342.7(.014)	320.5(.013)	16
2.5	649.0(.026)	554.7(.022)	510.3(.020)	25
3.0	898.0(.035)	822.2(.032)	746.1(.029)	36
3.5	1181.0(.047)	1147.0(.045)	1029.0 (.041)	49
4.0	1498.0(.059)	1530.0(.060)	1359.0 (.054)	64
4.5	1898.0(.075)	1973.0(.078)	1737.0 (.068)	81
5.0	2230.0(.088)	2476.0(.098)	2163.0 (.085)	100

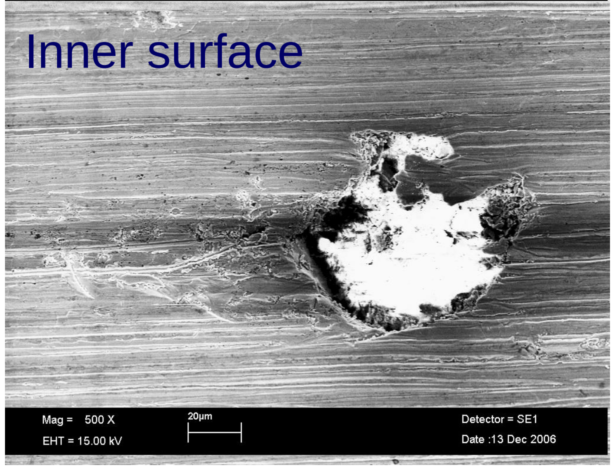
Spec. N°1001_1.4429_316LN_blanks



2. Rules for the selection: avoiding macroinclusions

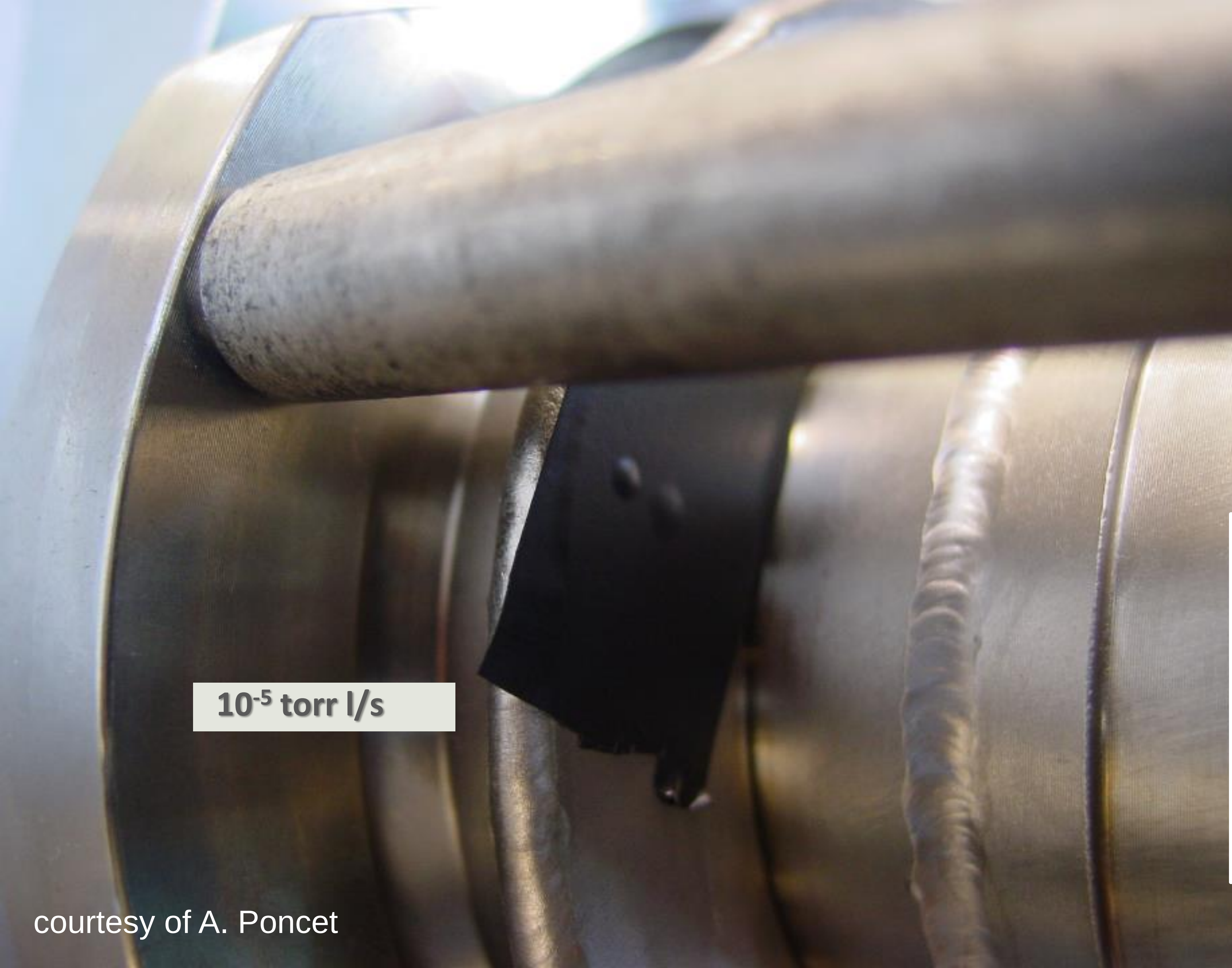

Courtesy of Interforge /FR

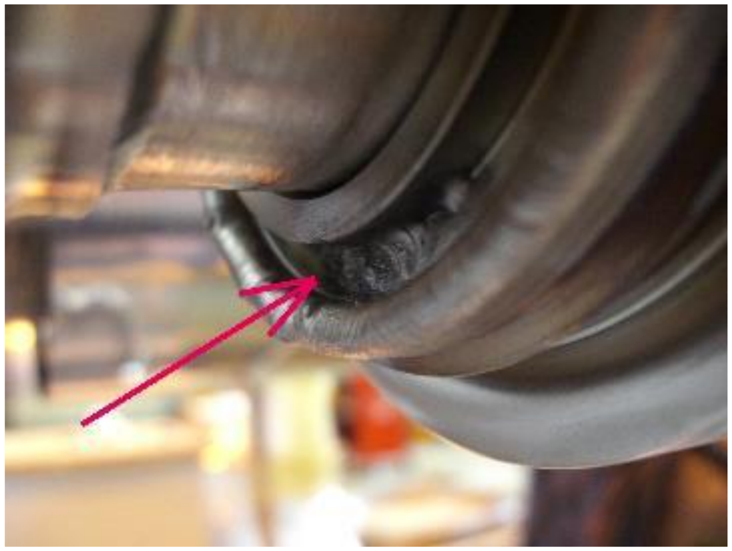

Outer surface


Inner surface

Multidirectional forging alone, even if including upsetting is not enough to avoid the risk of leaks due to macroinclusions

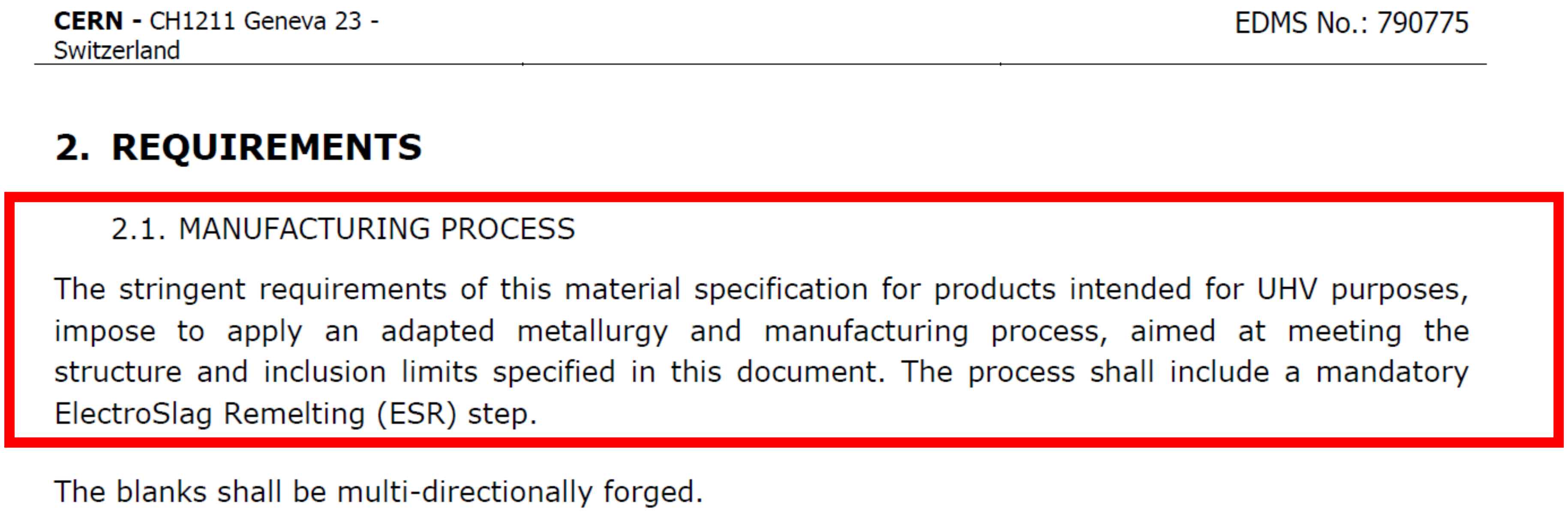
2. Rules for the selection: avoiding macroinclusions





courtesy of A. Poncet

2. Rules for the selection: avoiding macroinclusions



CERN - CH1211 Geneva 23 -
Switzerland

EDMS No.: 790775

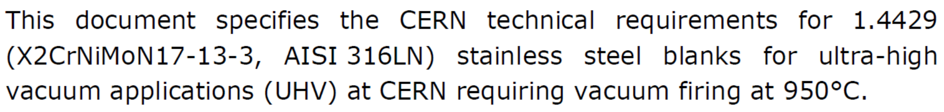
2. REQUIREMENTS

2.1. MANUFACTURING PROCESS

The stringent requirements of this material specification for products intended for UHV purposes, impose to apply an adapted metallurgy and manufacturing process, aimed at meeting the structure and inclusion limits specified in this document. The process shall include a mandatory ElectroSlag Remelting (ESR) step.

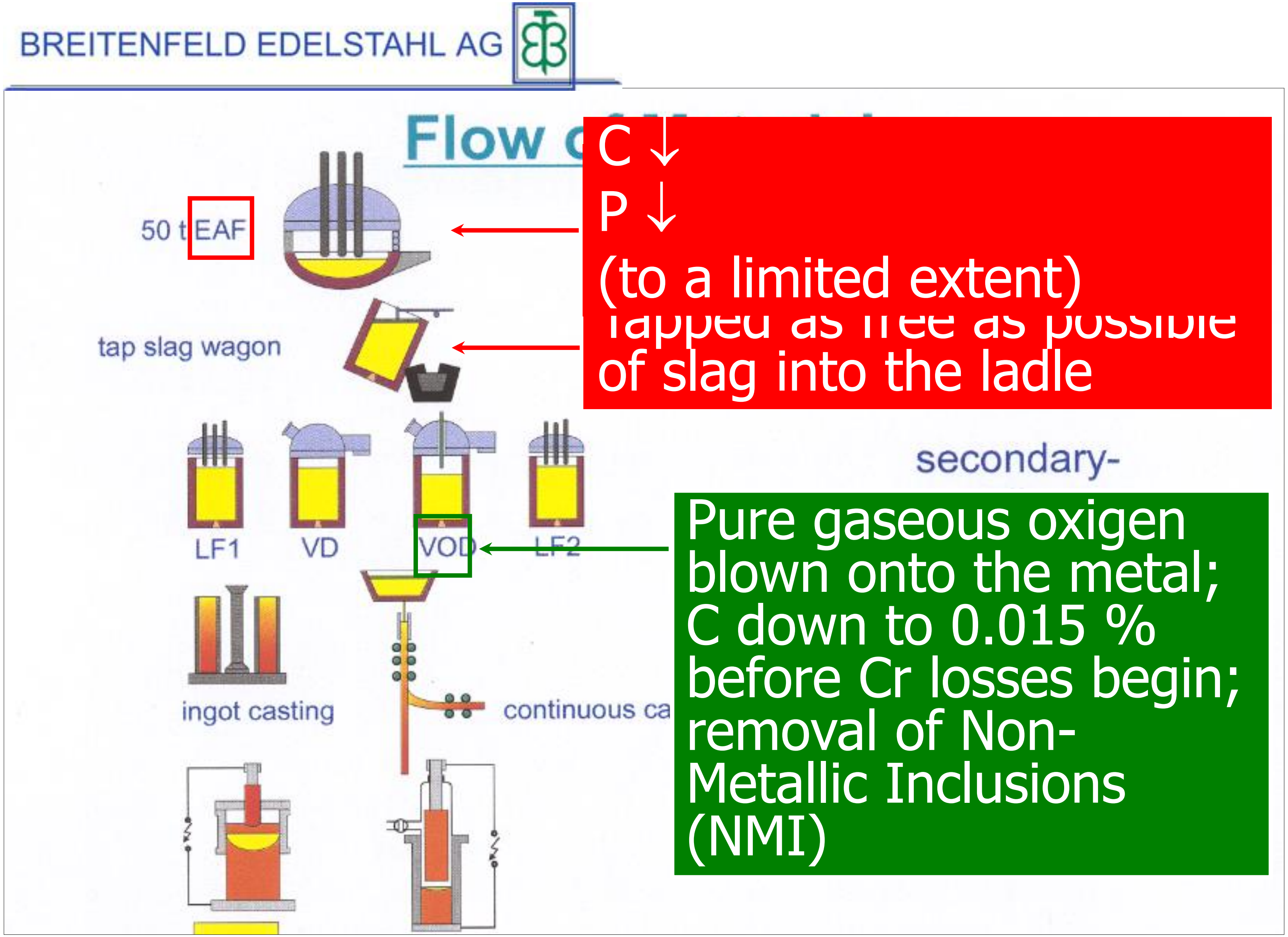
The blanks shall be multi-directionally forged.

Spec. N°1001_1.4429_316LN_blanks



This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.

3. Steelmaking



C ↓

P ↓

(to a limited extent)

Tapped as free as possible of slag into the ladle

Pure gaseous oxigen blown onto the metal; C down to 0.015 % before Cr losses begin; removal of Non-Metallic Inclusions (NMI)

3. Steelmaking

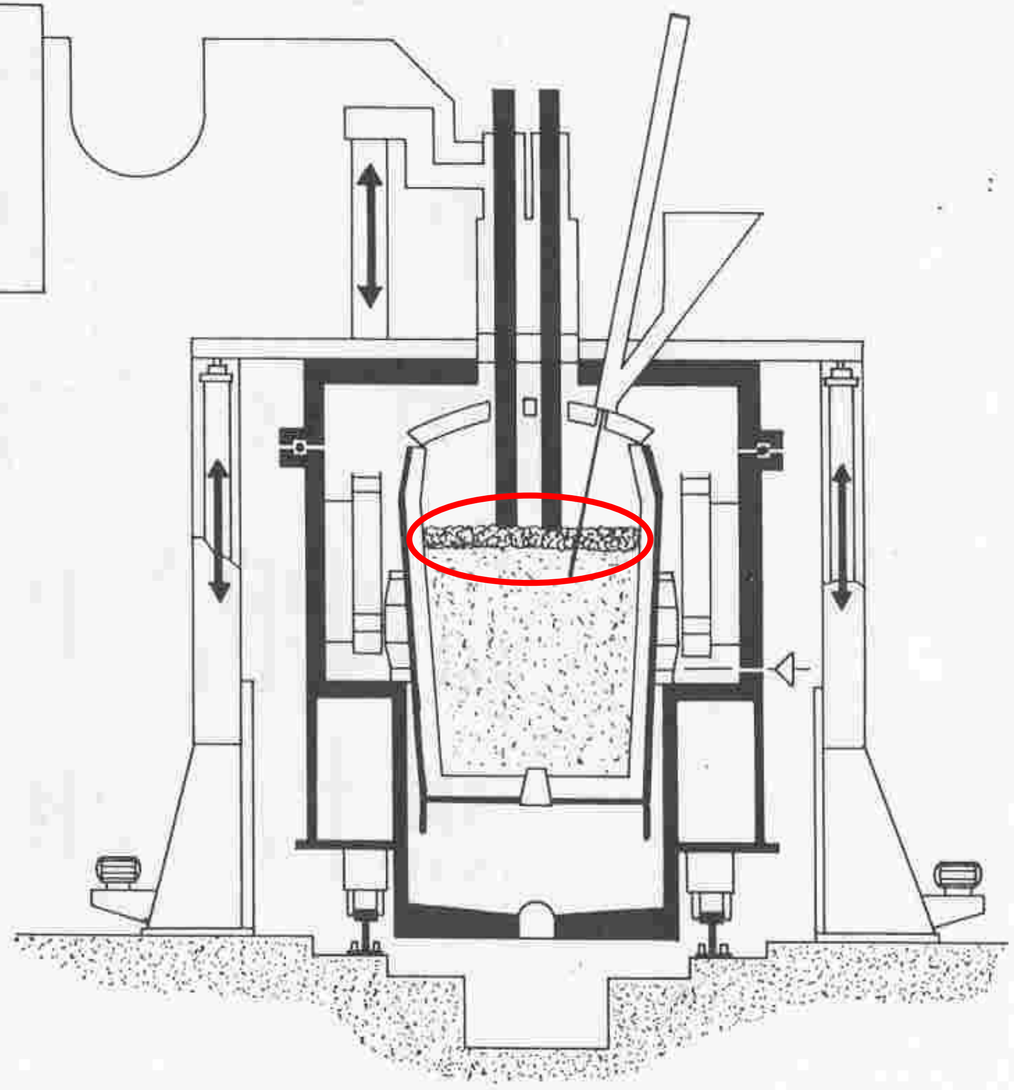
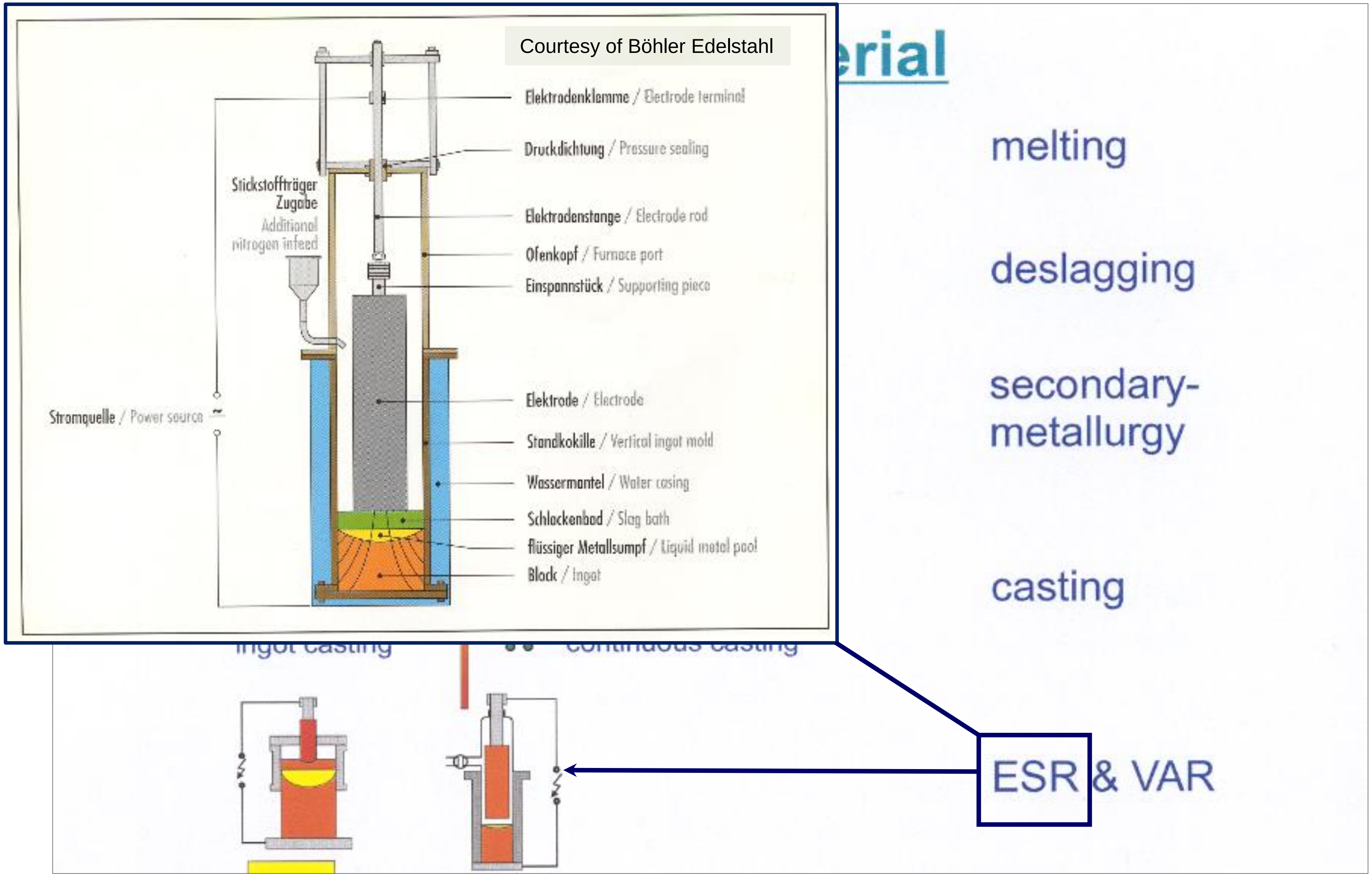


Fig. 23 Layout of a compact ladle furnace

A. Choudhury: Vacuum Metallurgy, ASM Int., USA, (1990)

3. Steelmaking


Courtesy of Böhler Edelstahl

melting

deslagging

secondary-metallurgy

casting

ESR & VAR

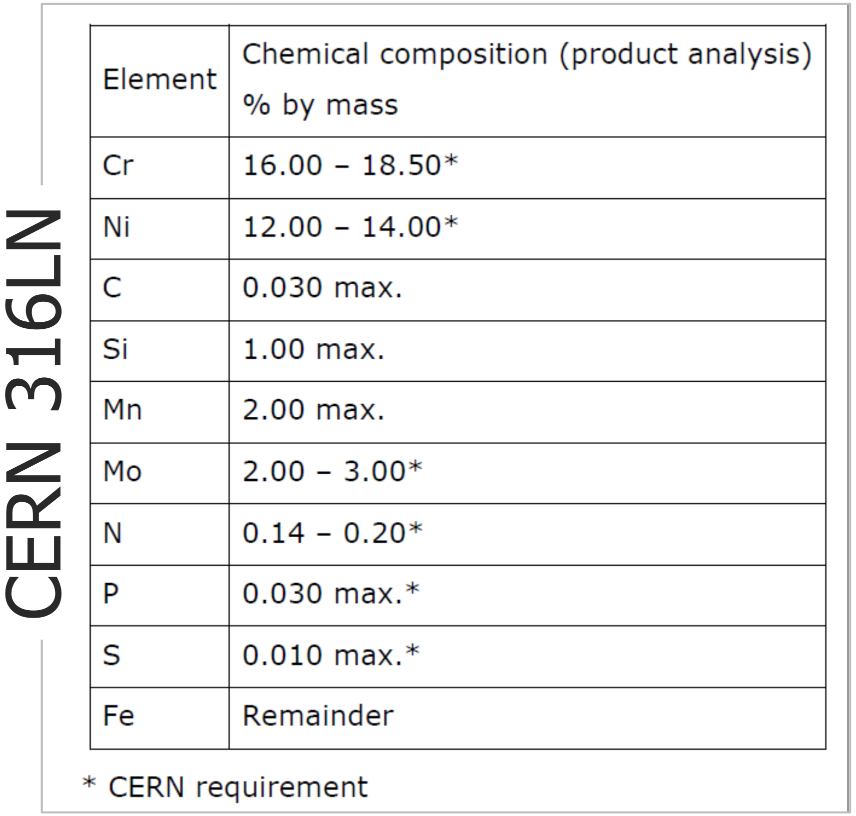
Courtesy of Forgiatura Vienna /IT
Max. ingot weight/capacity: 250 t
Two furnace heads, electrode exchange, protective gas hood, fully coaxial design;
largest ESR plant worldwide in operation

The additional cost of ESR ingots is in the order of 1 EUR/kg (Minutes of the visit to Company A on 27 January 2015, ITER CS Lower Keyblock Material Progress Meeting)

Courtesy of Breitenfeld Edelstahl /AT.
Electrodes of diam. 500 mm, 750 mm, 1000 mm, 1200 mm, respectively, up to a length of 4 m and a weight of 35 t.
Annual capacity is 250 000 t.

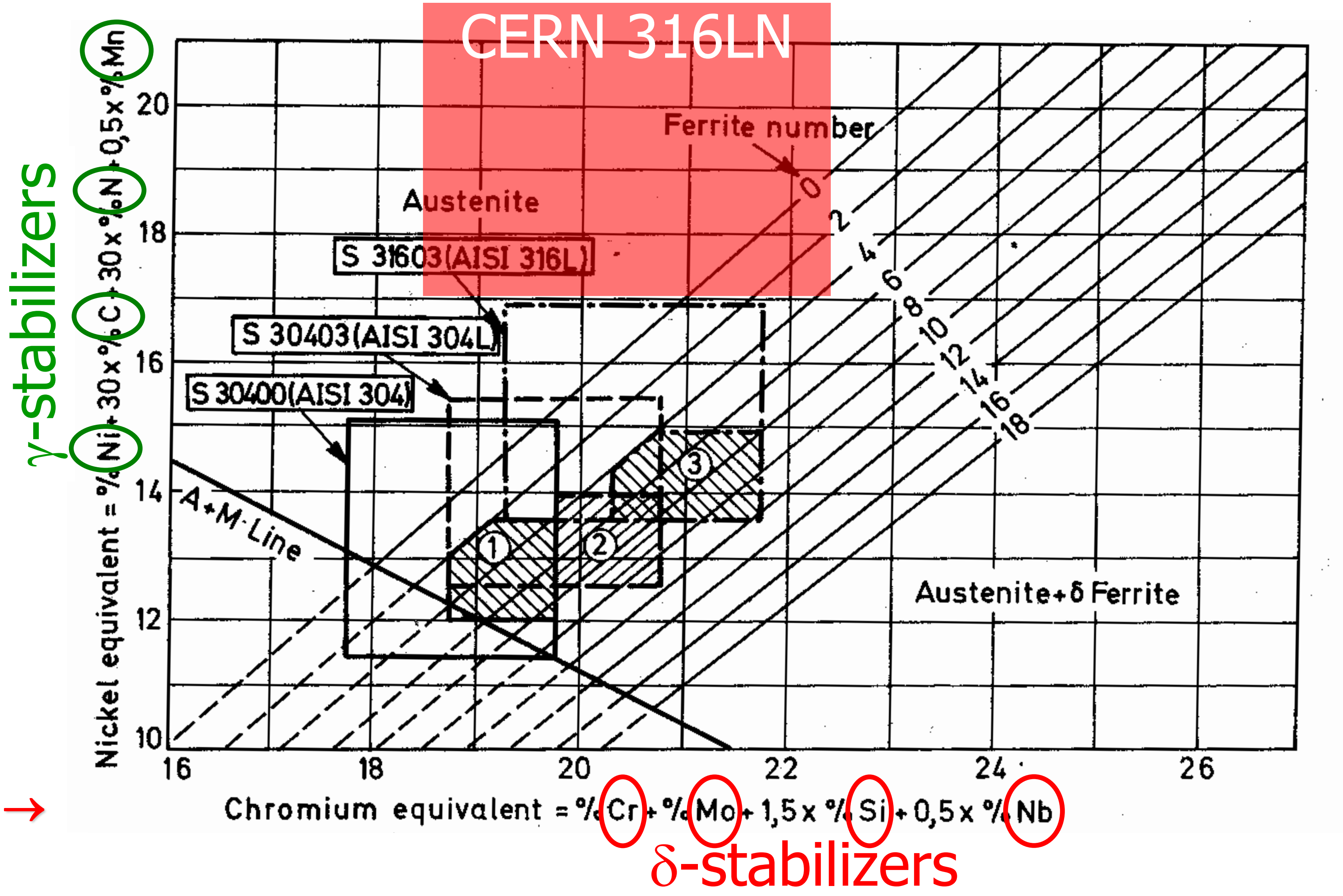
4.a Precipitations and transformations - welding

CERN 316LN



Element	Chemical composition (product analysis) % by mass
Cr	16.00 – 18.50*
Ni	12.00 – 14.00*
C	0.030 max.
Si	1.00 max.
Mn	2.00 max.
Mo	2.00 – 3.00*
N	0.14 – 0.20*
P	0.030 max.*
S	0.010 max.*
Fe	Remainder

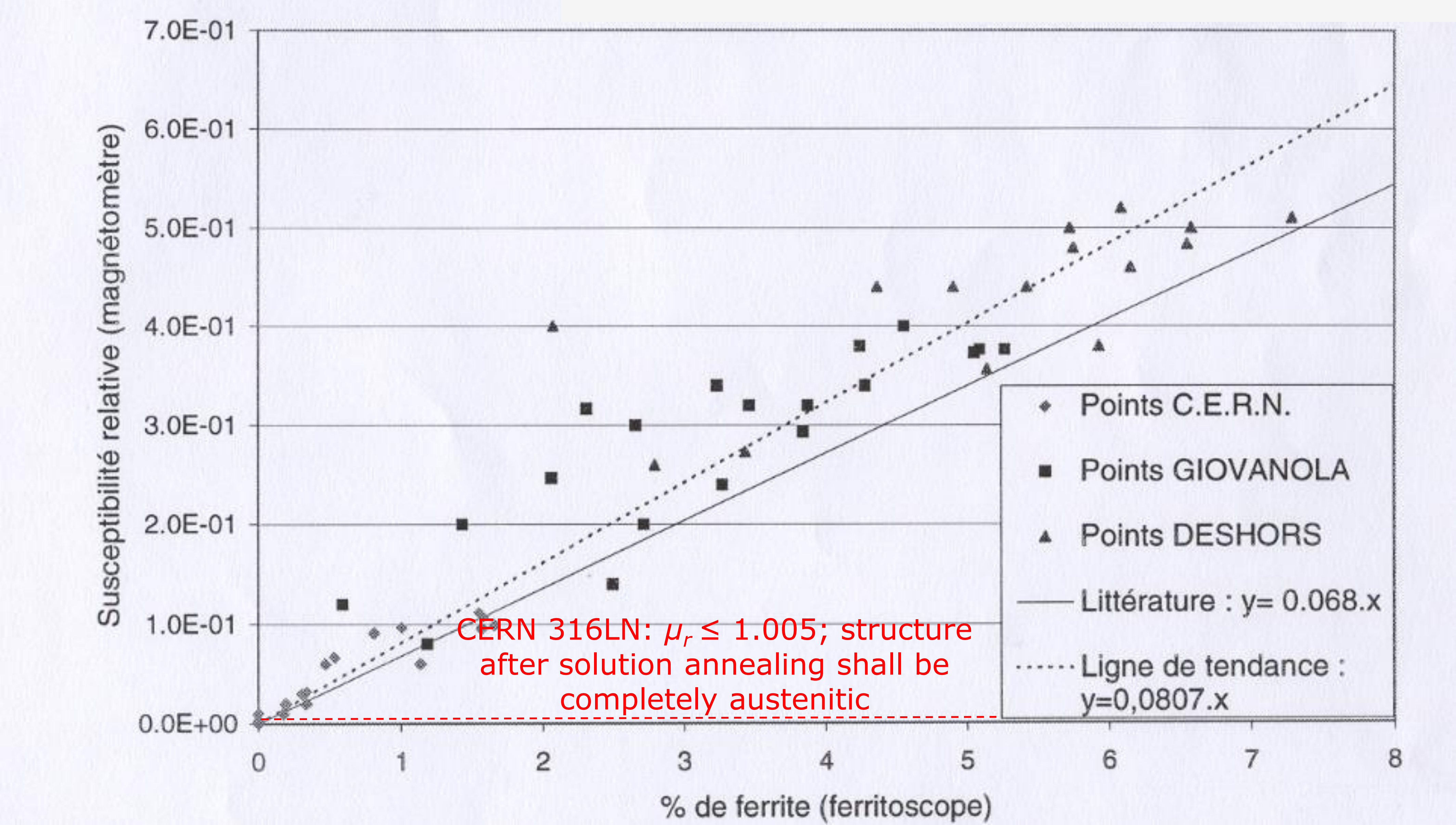
* CERN requirement



Maximum allowed magnetic permeability μ_r = 1.005 at RT → allowed content of δ-ferrite is nil

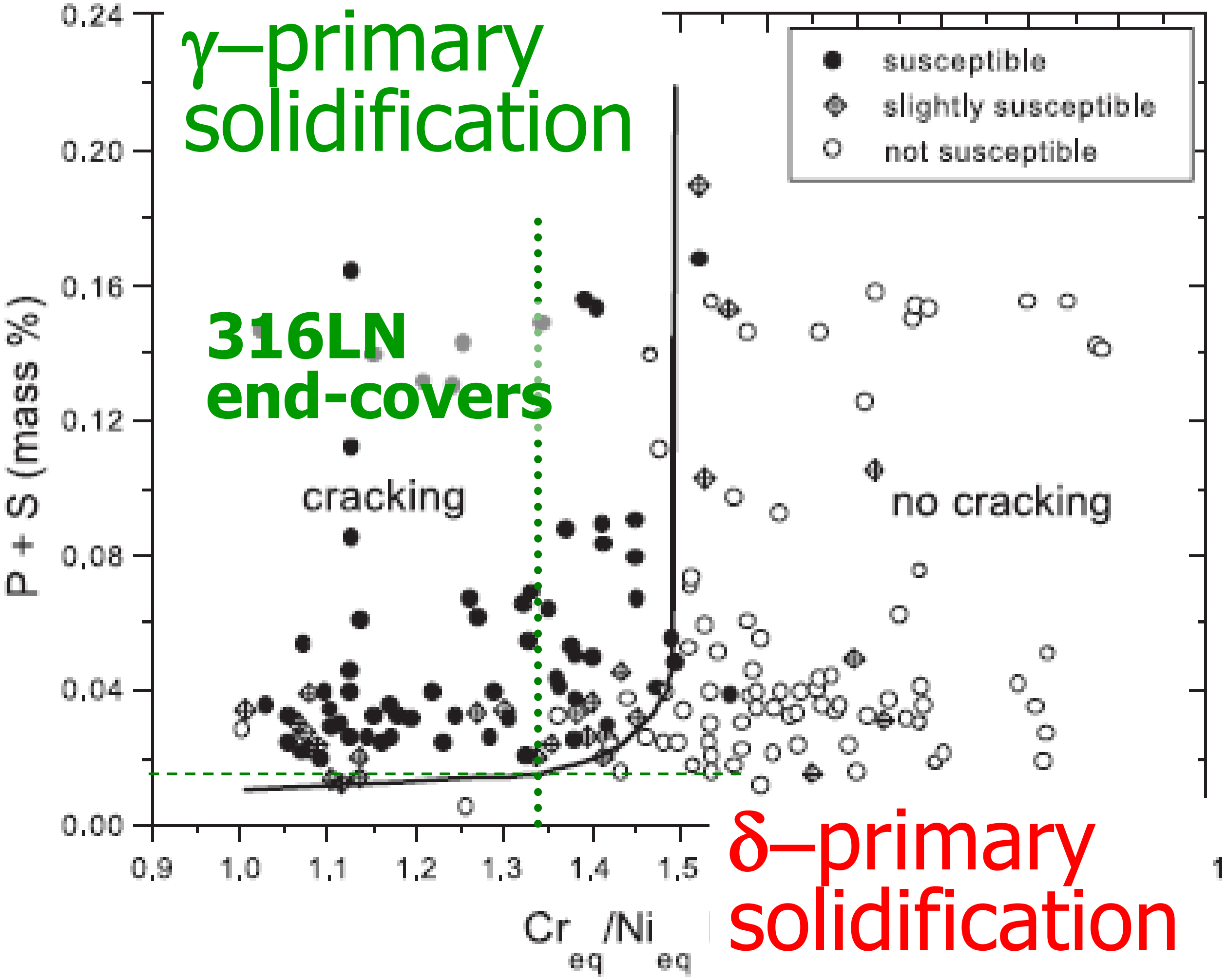
4.a Precipitations and transformations - welding

S. Sgobba and C. Boudot, Matériaux et Techniques 95, vol. 11-12, p. 23 (1997)



CERN 316LN: $\mu_r \leq 1.005$; structure after solution annealing shall be completely austenitic

4.a Precipitations and transformations - welding

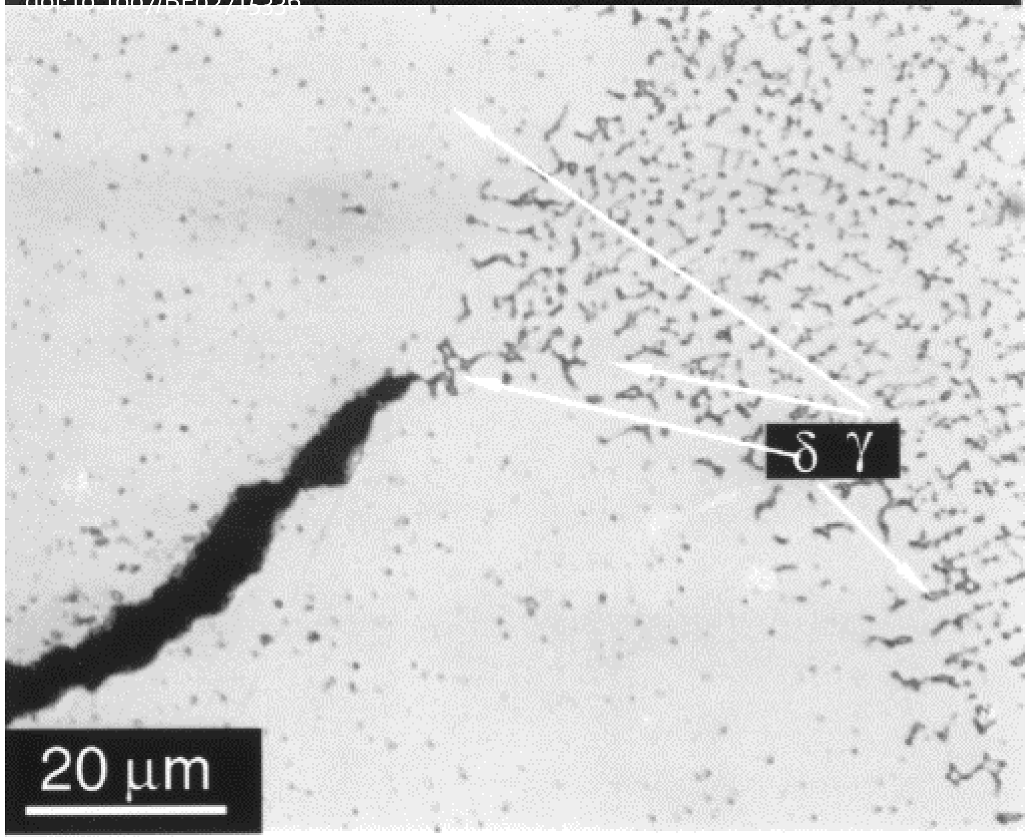


γ–primary solidification

316LN end-covers

δ–primary solidification

Korinko, P.S. & Malene, S.H. Practical Failure Analysis (2001) 1: 61. doi:10.1007/BF02715336

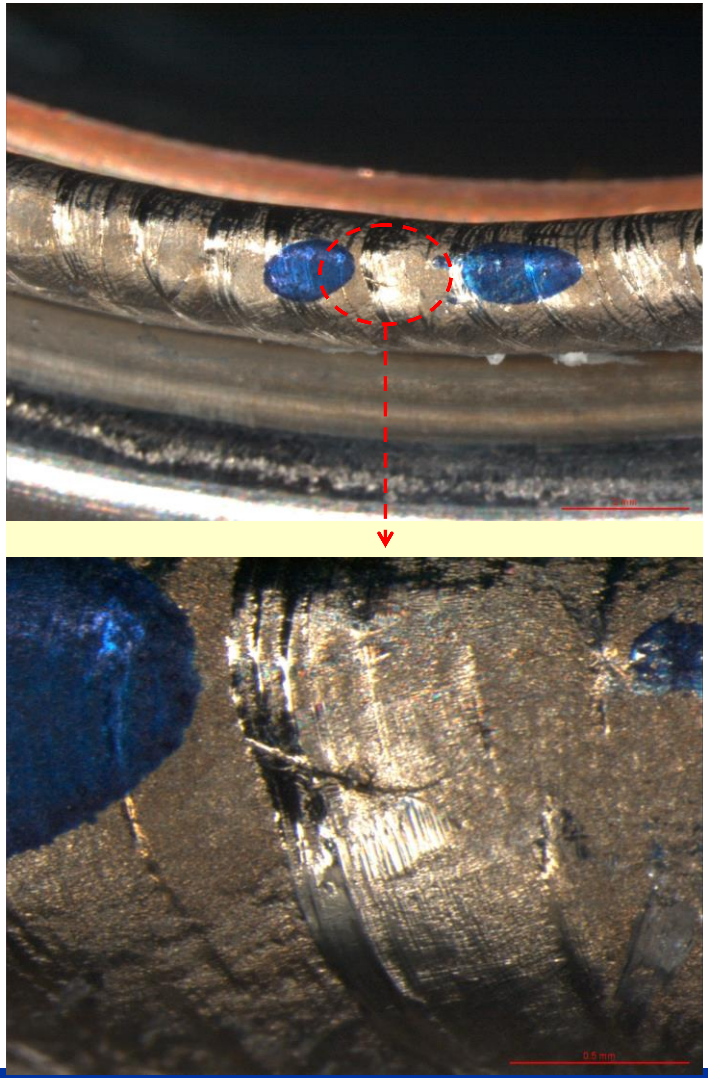


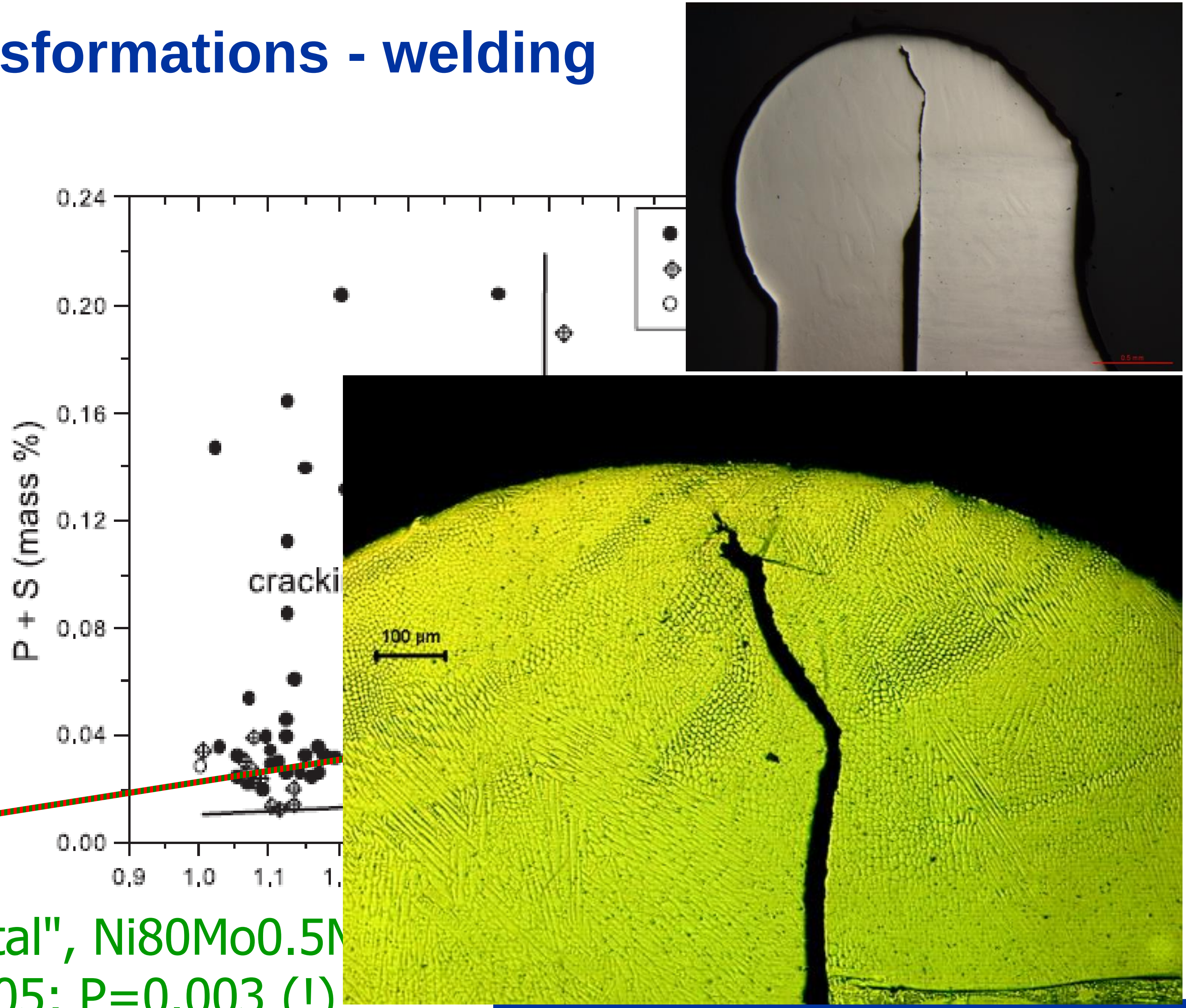
Schaeffler equivalent formulae for Cr_{eq} and Ni_{eq}

$Cr_{eq} = Cr + 1.5Si + 1.37Mo$

$Ni_{eq} = Ni + 0.31Mn + 22C + 14.2N$

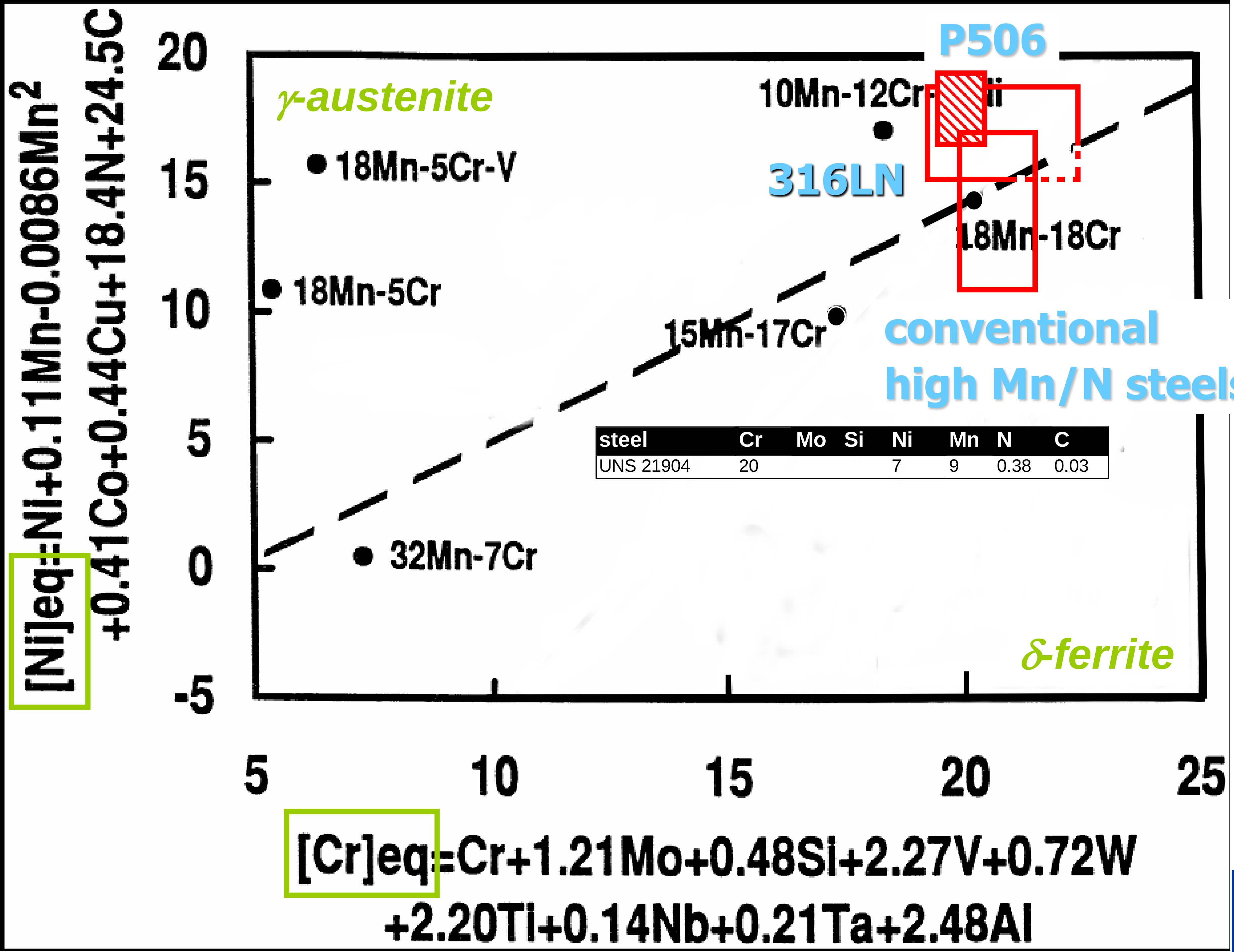
4.a Precipitations and transformations - welding





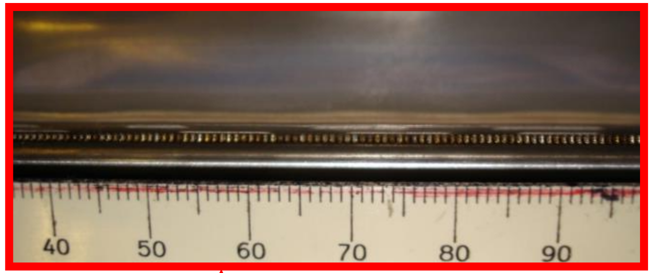
"mumetal", Ni80Mo0.5N
S<0.0005; P=0.003 (!)

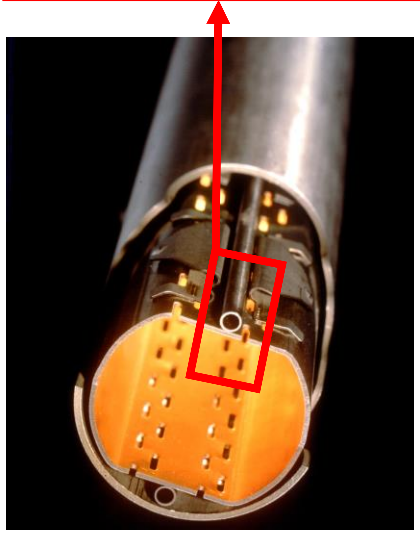
4.a Precipitations and transformations - welding



steel	Cr	Mo	Si	Ni	Mn	N	C
UNS 21904	20			7	9	0.38	0.03

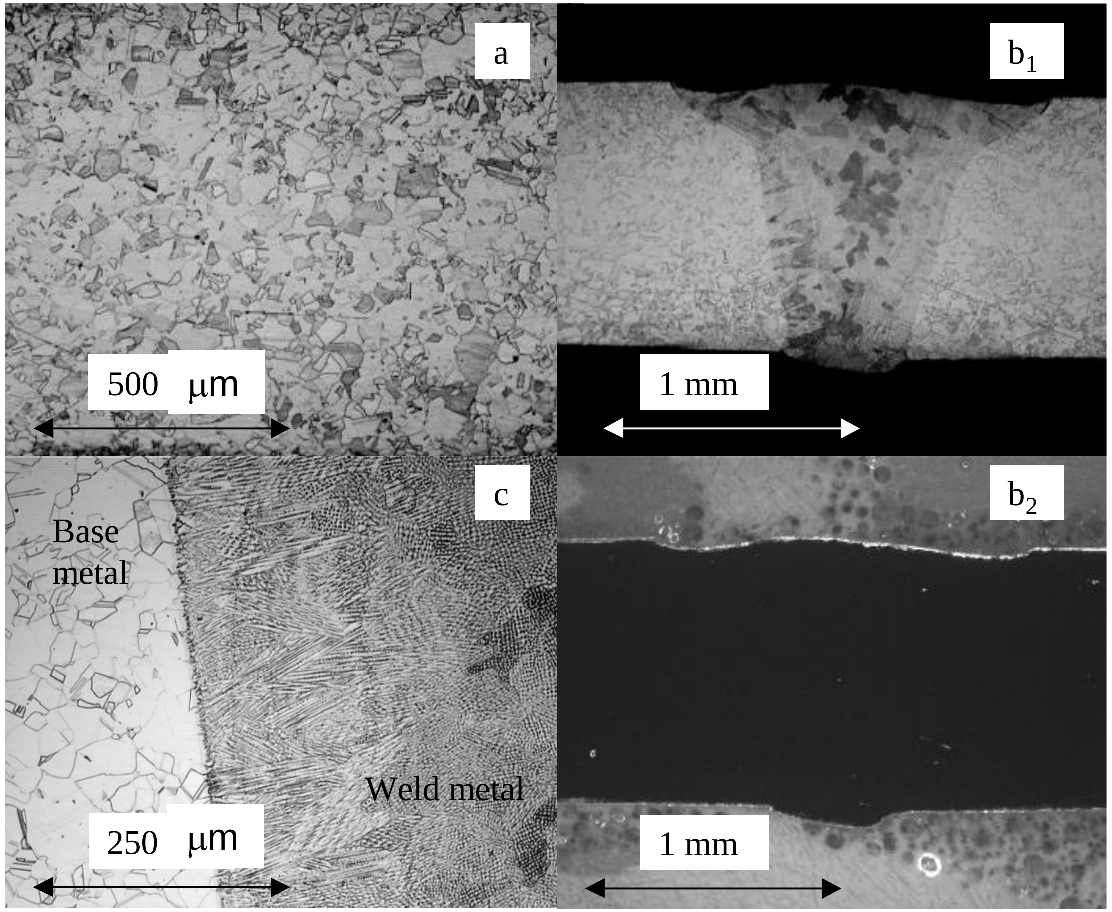
4.b Precipitations and transformations - welding





LHC, then HL-LHC beam screen + cooling pipes

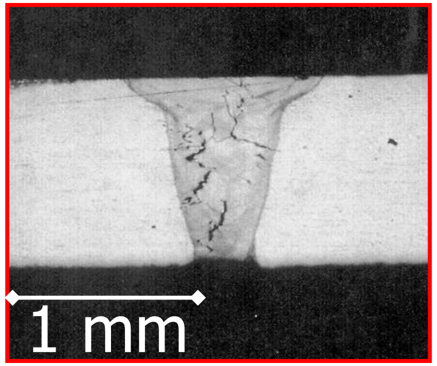
Steels	C	Mn	Ni	Cr	Mo	Si	N	P	S	B
P506	0.012	**12.05**	10.90	19.18	0.86	0.23	**0.33**	0.005	0.001	<0.001



S. Sgobba, C. Boudot, Soudabilité laser d'aciers inoxydables austénitiques, Matériaux et Techniques 95, n°11-12, p. 23 (1997).

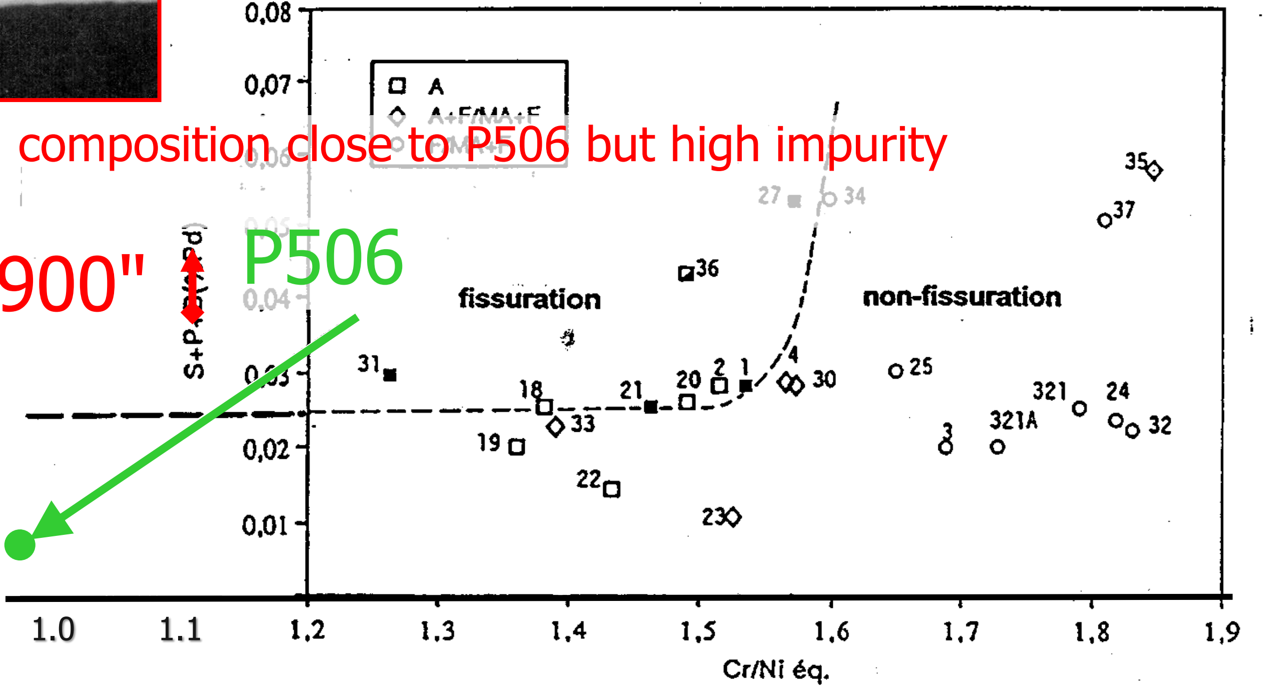
J.P. Bacher and S. Sgobba, TIG Weldability of Special Stainless Steels for the Beam Screen of the Large Hadron Collider, Bulletin du Cercle d'Etude des Métaux, XVI, p. 13.1 (1995)

4.b Precipitations and transformations - welding

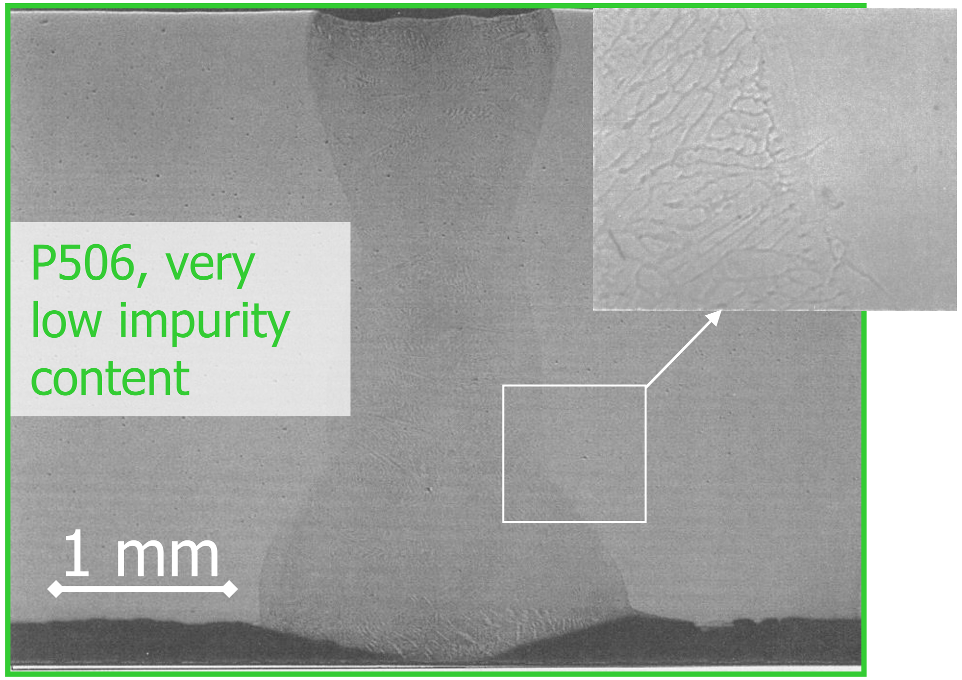


"900" steel: composition close to P506 but high impurity content

DIAGRAMME MODIFIÉ DE SUUTALA
- LASER CO_2 CONTINU -



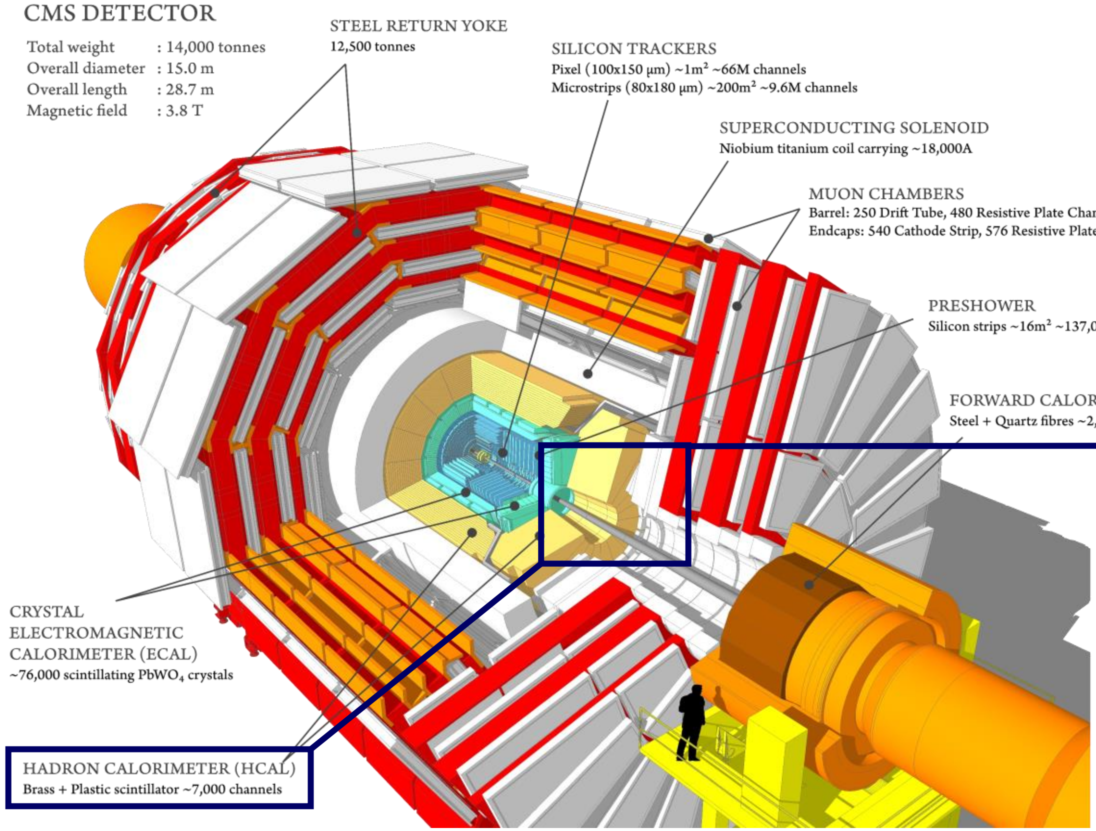
$$\frac{\text{Créq.}}{\text{Niéq.}} = \frac{Cr + 1{,}37Mo + 1{,}5Si + 2Nb + 3Ti}{Ni + 0{,}31Mn + 22C + 14{,}2N + Cu}$$

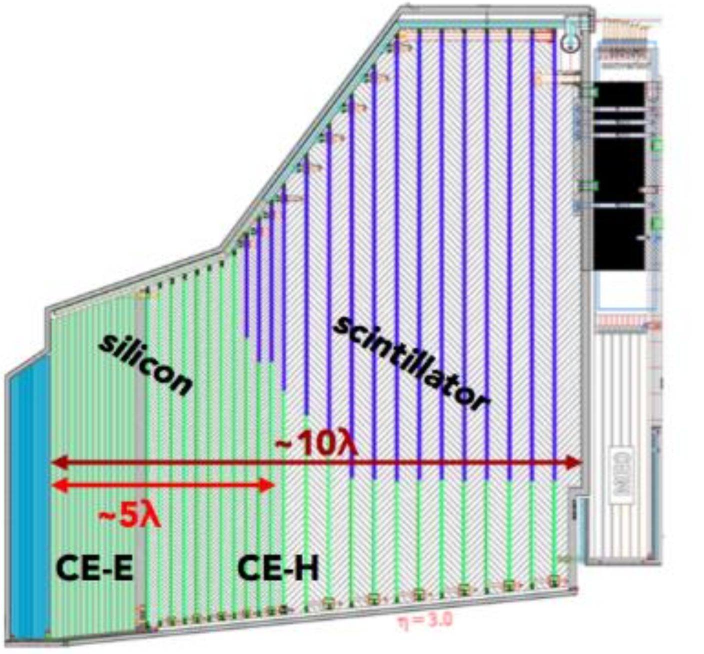


P506, very low impurity content

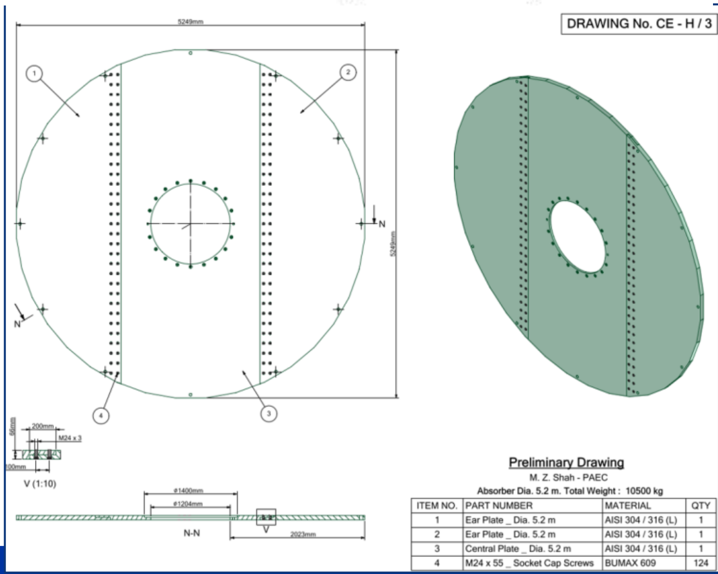
S. Sgobba: proc. Cycle Métaux et Procédés, CIP - Tramelan /CH, 1996, p. 8/1-10

4.b A low permeability steel for CMS HG-CAL





Schematic view of the High Granularity Calorimeter



Preliminary Drawing

M. Z. Shah - PAEC

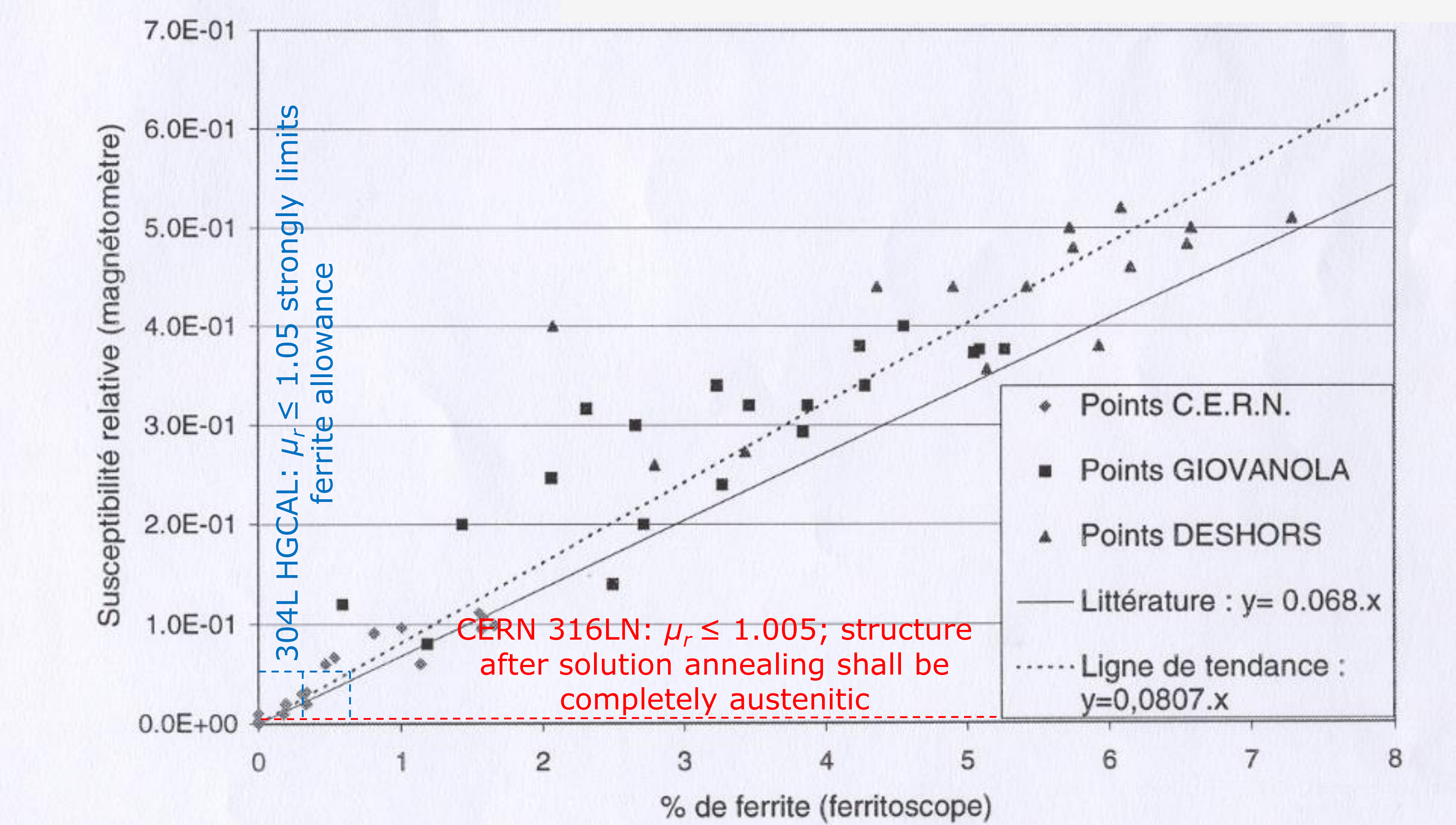
Absorber Dia. 5.2 m. Total Weight : 10500 kg

ITEM NO.	PART NUMBER	MATERIAL	QTY
1	Ear Plate _ Dia. 5.2 m	AISI 304 / 316 (L)	1
2	Ear Plate _ Dia. 5.2 m	AISI 304 / 316 (L)	1
3	Central Plate _ Dia. 5.2 m	AISI 304 / 316 (L)	1
4	M24 x 55 _ Socket Cap Screws	BUMAX 609	124

- 564 t of stainless steel required for the CE-H cassettes, thickness 45 ~110 mm
- The relative magnetic permeability in the bulk plate material shall not exceed **1.05**
  - Stringent control of ferrite content
  - Stability against martensitic transformations

4.b A low permeability steel for CMS HG-CAL

S. Sgobba and C. Boudot, Matériaux et Techniques 95, vol. 11-12, p. 23 (1997)



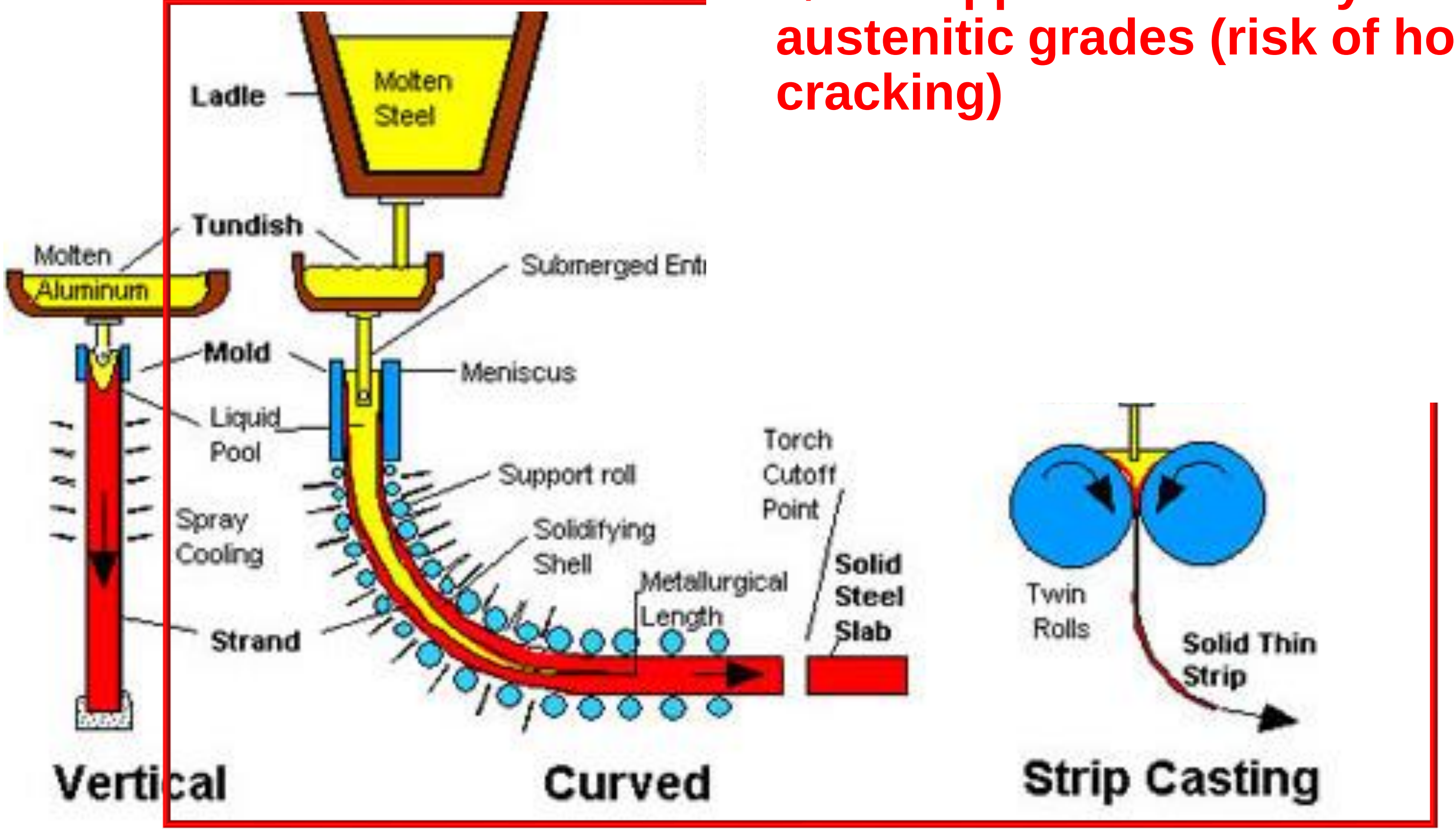
304L HGCAL: $\mu_r \leq 1.05$ strongly limits ferrite allowance

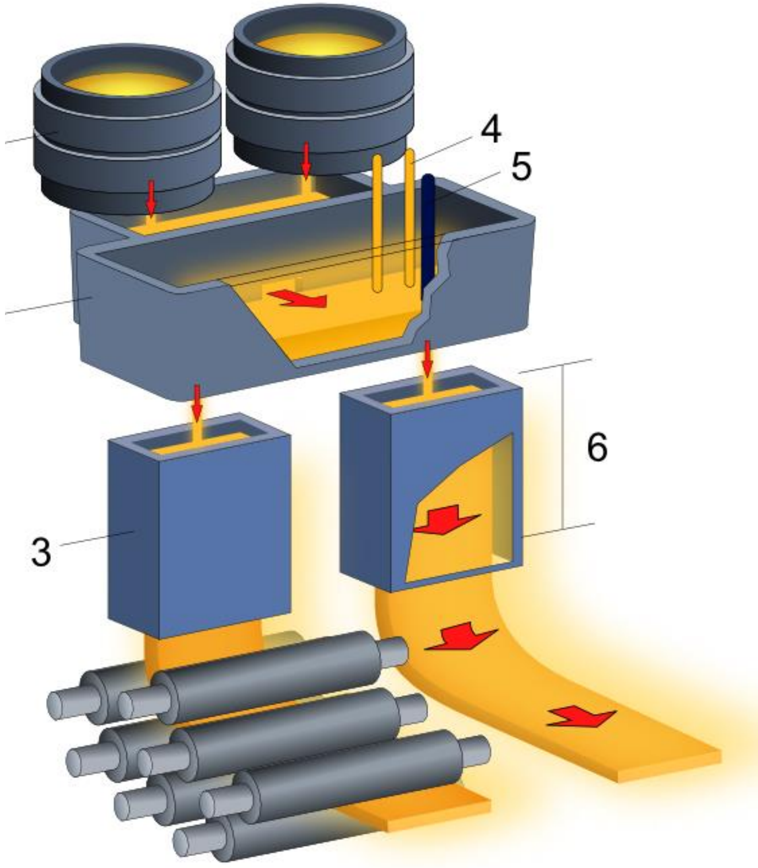
CERN 316LN: $\mu_r \leq 1.005$; structure after solution annealing shall be completely austenitic

4.b A low permeability steel for CMS HG-CAL

Two metallurgical routes:

- **Ingot casting**
- ~~**Continuous casting (95% of the world's steel production)**~~
  ⇒ not applicable to fully austenitic grades (risk of hot cracking)



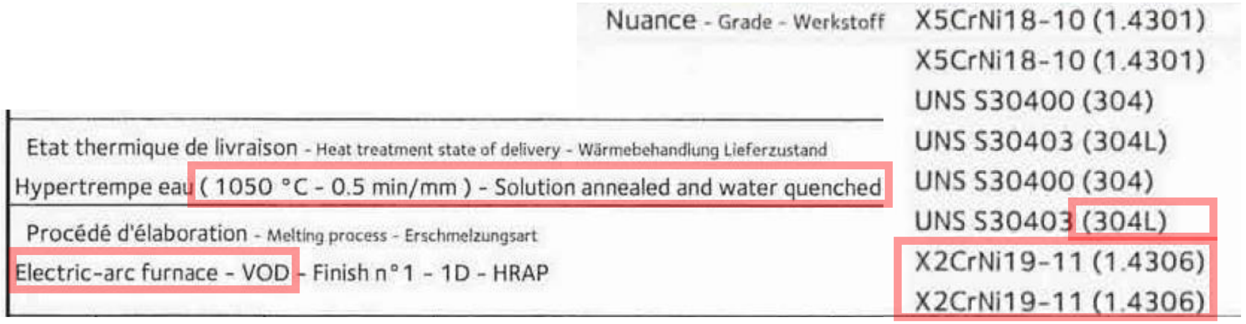


Our process

Courtesy Dr. N. Pauze,
ArcelorMittal Industeel

Industeel ArcelorMittal
Industeel is an ArcelorMittal company

Courtesy of S. Moccia & M. Pentella



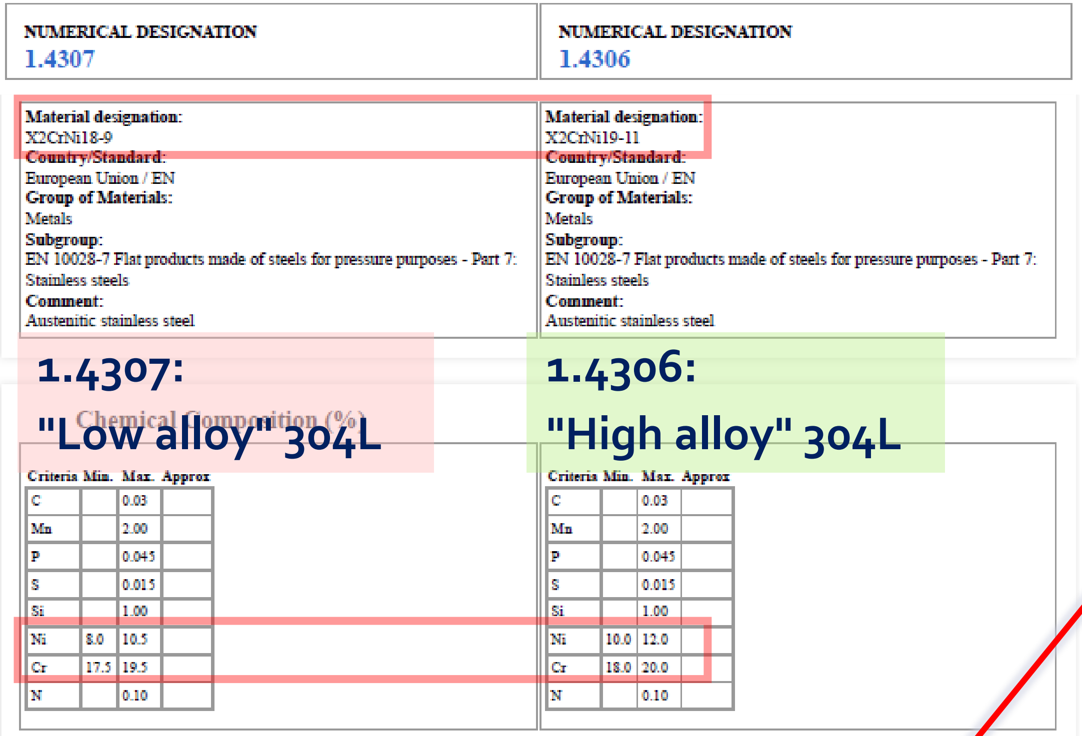
Nuance - Grade - Werkstoff	X5CrNi18-10 (1.4301)
	X5CrNi18-10 (1.4301)
	UNS S30400 (304)
	UNS S30403 (304L)
	UNS S30400 (304)
	UNS S30403 (304L)
	X2CrNi19-11 (1.4306)
	X2CrNi19-11 (1.4306)

Etat thermique de livraison - Heat treatment state of delivery - Wärmebehandlung Lieferzustand

Hypertrempe eau (1050 °C - 0.5 min/mm) - Solution annealed and water quenched

Procédé d'élaboration - Melting process - Erschmelzungsart

Electric-arc furnace - VOD - Finish n°1 - 1D - HRAP



NUMERICAL DESIGNATION 1.4307	NUMERICAL DESIGNATION 1.4306
Material designation: X2CrNi18-9 **Country/Standard:** European Union / EN **Group of Materials:** Metals **Subgroup:** EN 10028-7 Flat products made of steels for pressure purposes - Part 7: Stainless steels **Comment:** Austenitic stainless steel	**Material designation:** X2CrNi19-11 **Country/Standard:** European Union / EN **Group of Materials:** Metals **Subgroup:** EN 10028-7 Flat products made of steels for pressure purposes - Part 7: Stainless steels **Comment:** Austenitic stainless steel

1.4307:
"Low alloy" 304L

1.4306:
"High alloy" 304L

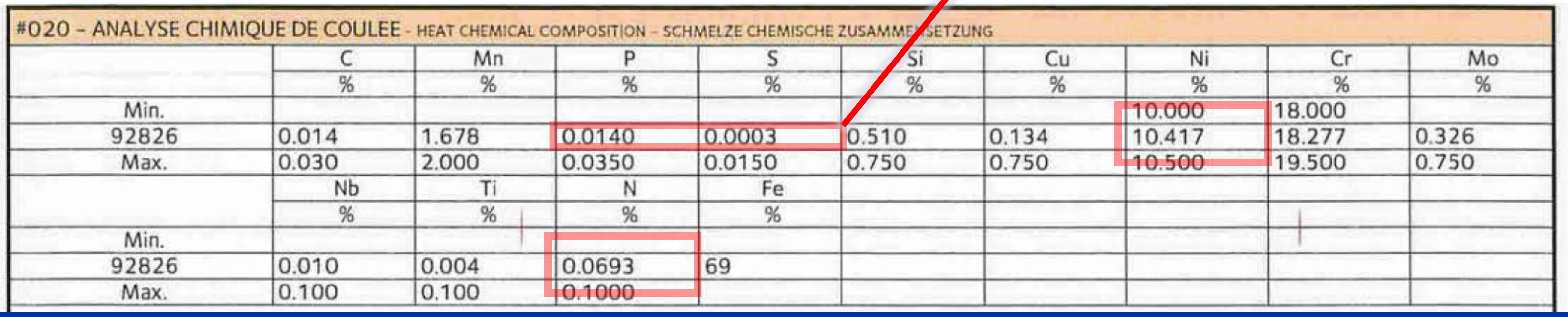
Chemical Composition (%)

Criteria	Min.	Max.	Approx.
C		0.03	
Mn		2.00	
P		0.045	
S		0.015	
Si		1.00	
Ni	8.0	10.5	
Cr	17.5	19.5	
N		0.10	

Criteria	Min.	Max.	Approx.
C		0.03	
Mn		2.00	
P		0.045	
S		0.015	
Si		1.00	
Ni	10.0	12.0	
Cr	18.0	20.0	
N		0.10	

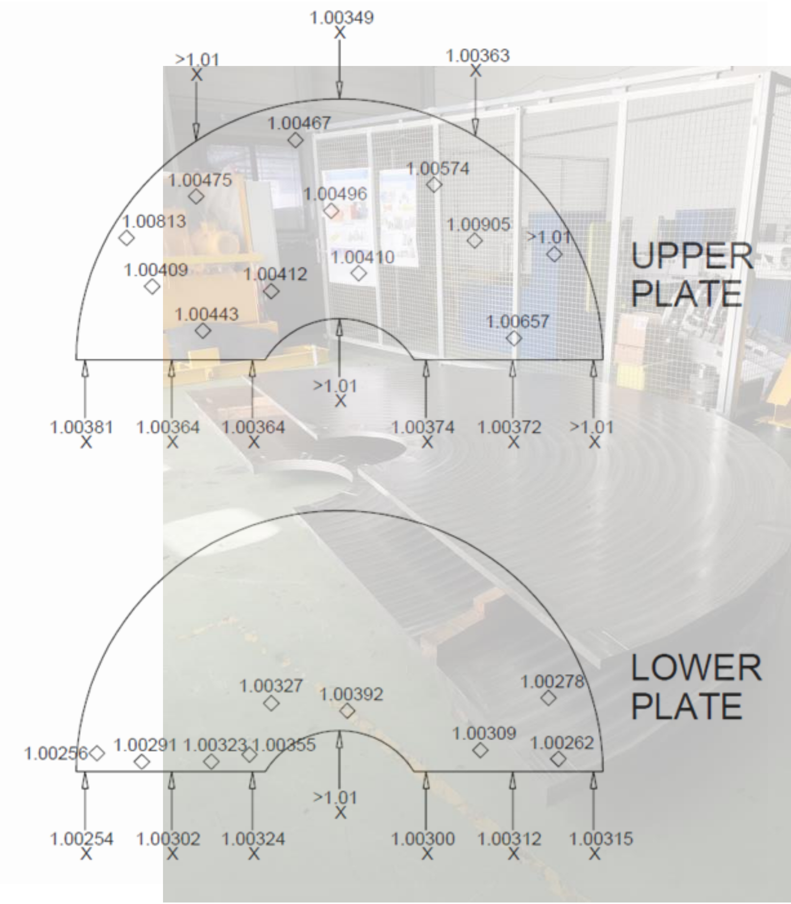
Very clean heat, 143 ppm S+P

"High alloy" 1.4306



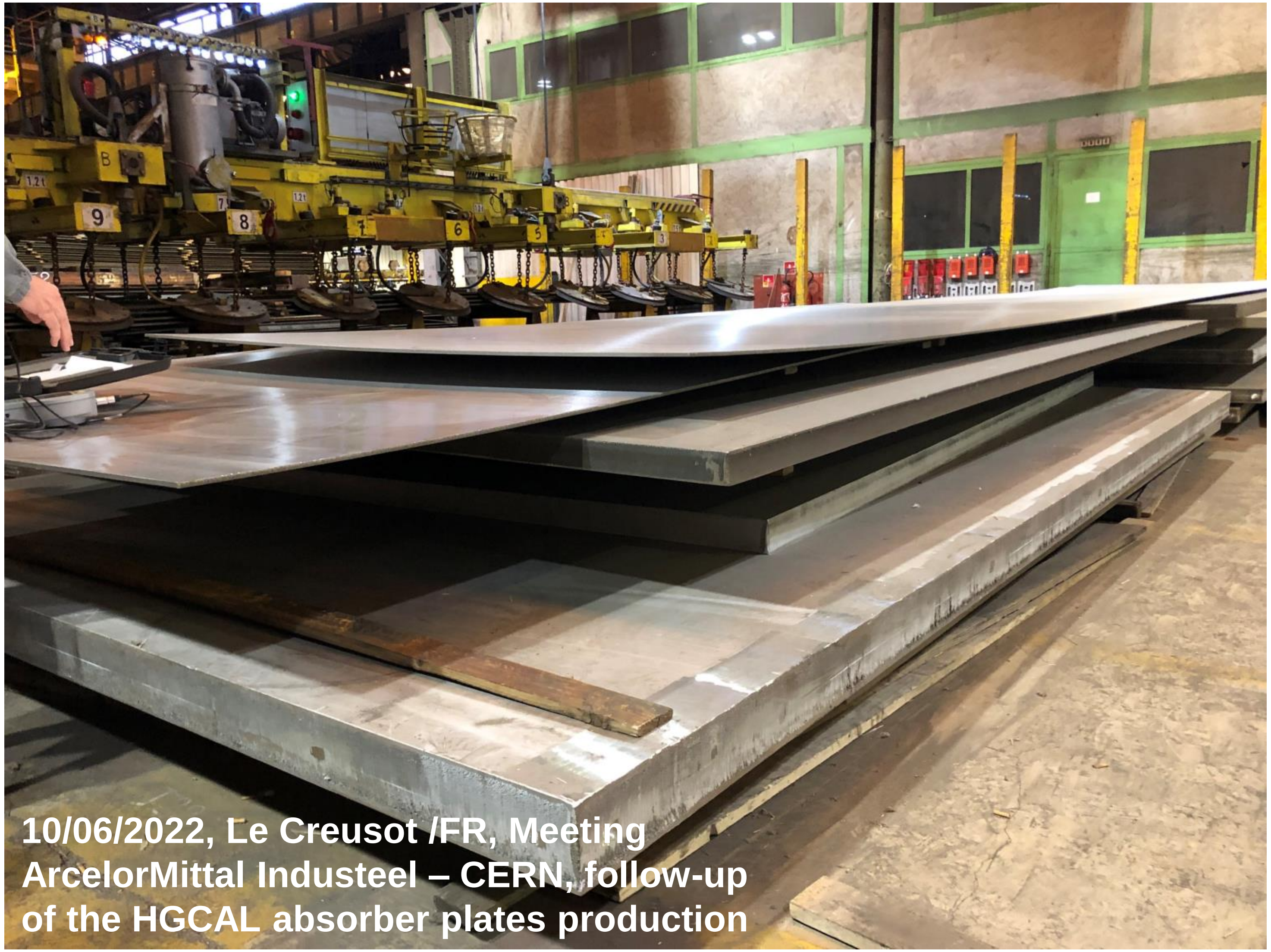
#020 - ANALYSE CHIMIQUE DE COULEE - HEAT CHEMICAL COMPOSITION - SCHMELZE CHEMISCHE ZUSAMMENSETZUNG

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
	%	%	%	%	%	%	%	%	%
Min.							10.000	18.000	
92826	0.014	1.678	0.0140	0.0003	0.510	0.134	10.417	18.277	0.326
Max.	0.030	2.000	0.0350	0.0150	0.750	0.750	10.500	19.500	0.750
	Nb	Ti	N	Fe					
	%	%	%	%					
Min.									
92826	0.010	0.004	0.0693	69					
Max.	0.100	0.100	0.1000						

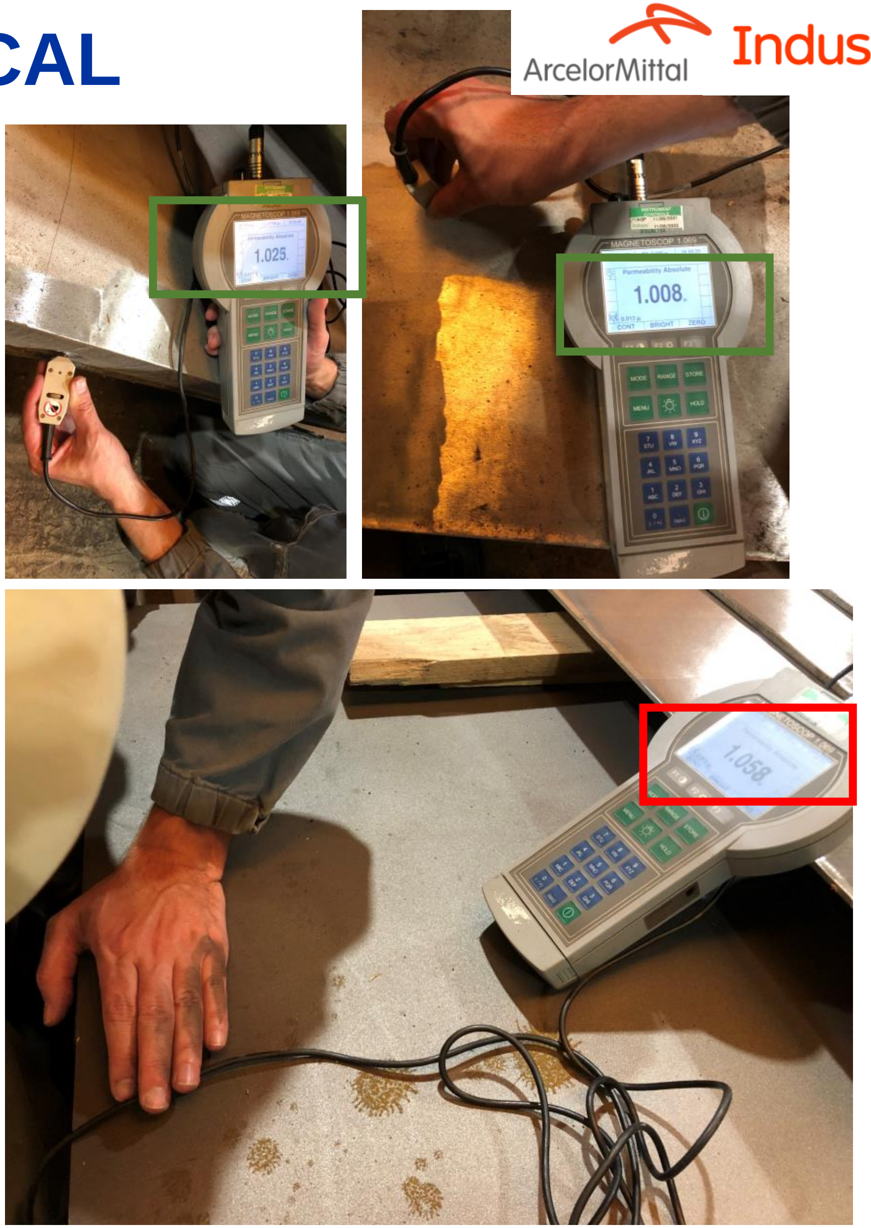


- Low magnetic permeability, ceteris paribus:
  - Stringent control of ferrite content (composition / steelmaking route)
  - Stability against martensitic transformations (grade selection)

4.b A low permeability steel for CMS HG-CAL



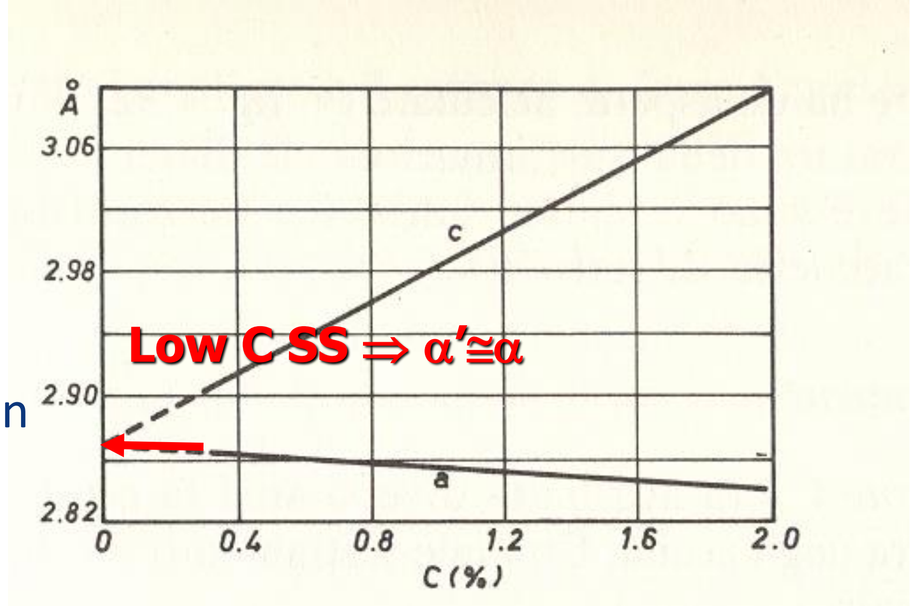
10/06/2022, Le Creusot /FR, Meeting ArcelorMittal Industeel – CERN, follow-up of the HGCAL absorber plates production



4.c Martensitic transformations

Martensitic transformation have two forms:

  - $\gamma \Rightarrow \alpha'$, b.c.c., relevant for magnetic purposes
- occurs spontaneously on cooling and/or is strain induced under a given temperature
- cause of loss of non-magnetism in austenitic stainless steels



Low C SS ⇒ α'≅α

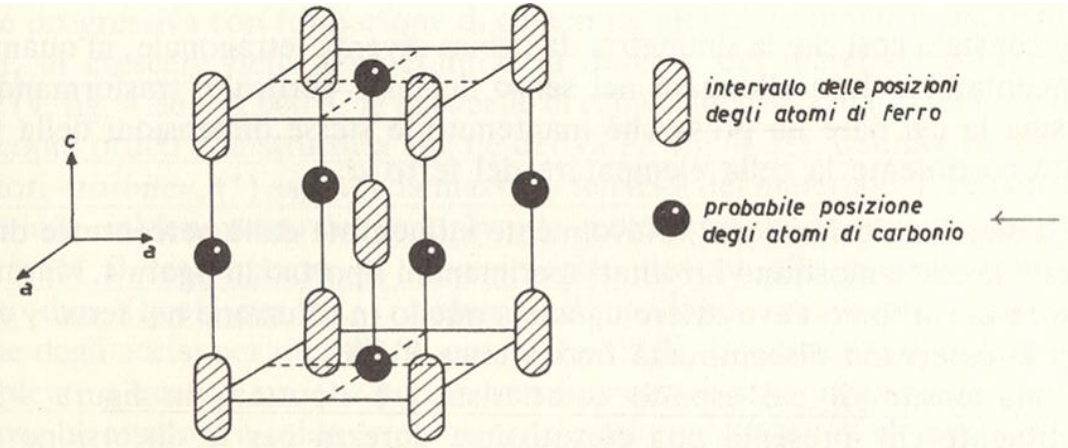


Fig. 4.33 *Schematizzazione del reticolo tetragonale della martensite: la forma allungata della posizione degli atomi di ferro sta ad indicare che la distanza reticolare degli stessi, relativamente all'asse c, può variare* (da H. Lipson).

4.c Martensitic transformations

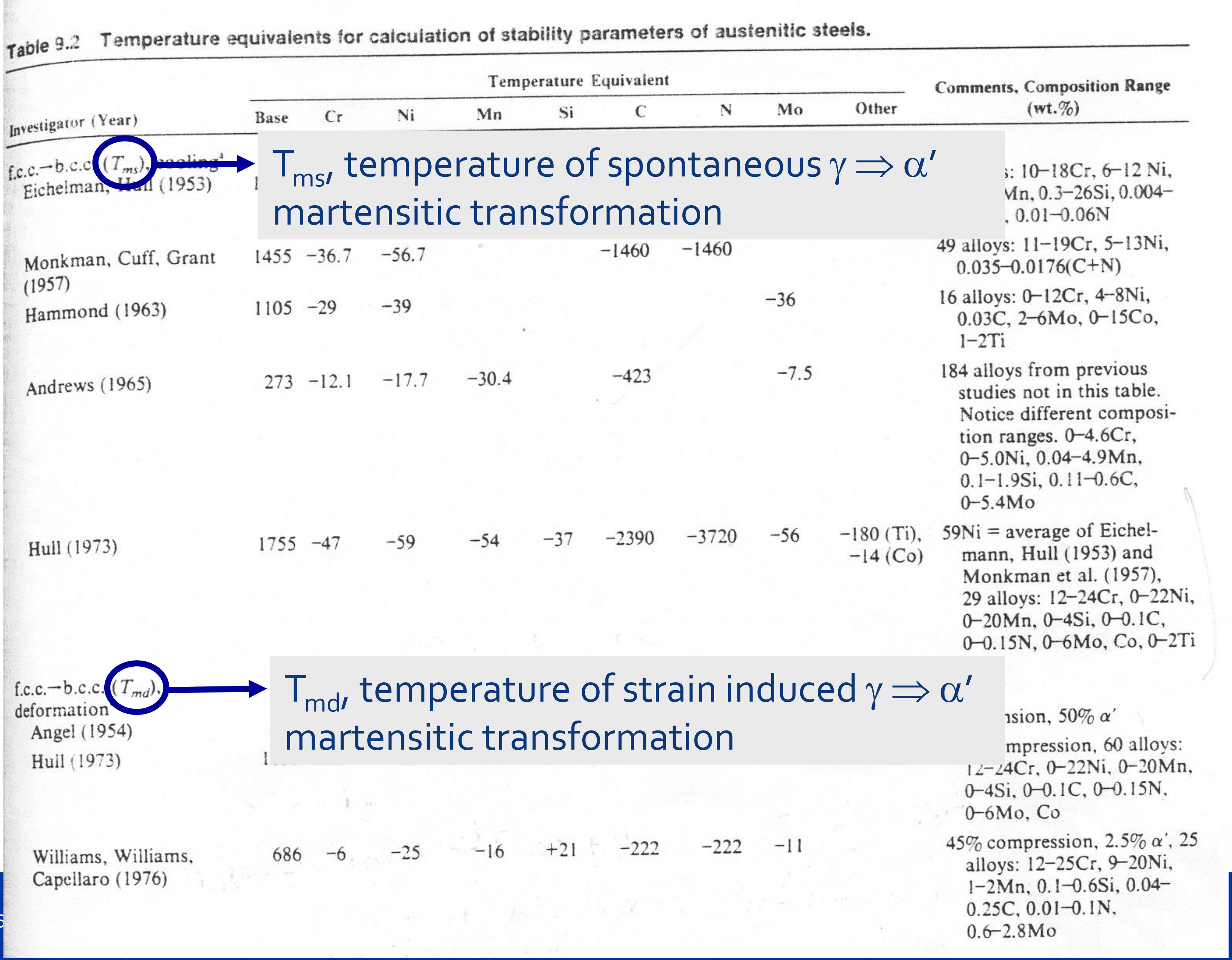


Table 9.2 Temperature equivalents for calculation of stability parameters of austenitic steels.

Investigator (Year)	Base	Cr	Ni	Mn	Si	C	N	Mo	Other	Comments, Composition Range (wt.%)
f.c.c.→b.c.c. (T_{ms}), cooling[a]										
Eichelman, Hull (1953)	1									s: 10–18Cr, 6–12 Ni, Mn, 0.3–26Si, 0.004– , 0.01–0.06N
Monkman, Cuff, Grant (1957)	1455	−36.7	−56.7			−1460	−1460			49 alloys: 11–19Cr, 5–13Ni, 0.035–0.0176(C+N)
Hammond (1963)	1105	−29	−39					−36		16 alloys: 0–12Cr, 4–8Ni, 0.03C, 2–6Mo, 0–15Co, 1–2Ti
Andrews (1965)	273	−12.1	−17.7	−30.4		−423		−7.5		184 alloys from previous studies not in this table. Notice different composition ranges. 0–4.6Cr, 0–5.0Ni, 0.04–4.9Mn, 0.1–1.9Si, 0.11–0.6C, 0–5.4Mo
Hull (1973)	1755	−47	−59	−54	−37	−2390	−3720	−56	−180 (Ti), −14 (Co)	59Ni = average of Eichelmann, Hull (1953) and Monkman et al. (1957), 29 alloys: 12–24Cr, 0–22Ni, 0–20Mn, 0–4Si, 0–0.1C, 0–0.15N, 0–6Mo, Co, 0–2Ti
f.c.c.→b.c.c. (T_{md}), deformation										
Angel (1954)										nsion, 50% α′
Hull (1973)	1									mpression, 60 alloys: 12–24Cr, 0–22Ni, 0–20Mn, 0–4Si, 0–0.1C, 0–0.15N, 0–6Mo, Co
Williams, Williams, Capellaro (1976)	686	−6	−25	−16	+21	−222	−222	−11		45% compression, 2.5% α′, 25 alloys: 12–25Cr, 9–20Ni, 1–2Mn, 0.1–0.6Si, 0.04–0.25C, 0.01–0.1N, 0.6–2.8Mo

T_{ms}, temperature of spontaneous $\gamma \Rightarrow \alpha'$ martensitic transformation

T_{md}, temperature of strain induced $\gamma \Rightarrow \alpha'$ martensitic transformation

4.c Martensitic transformations

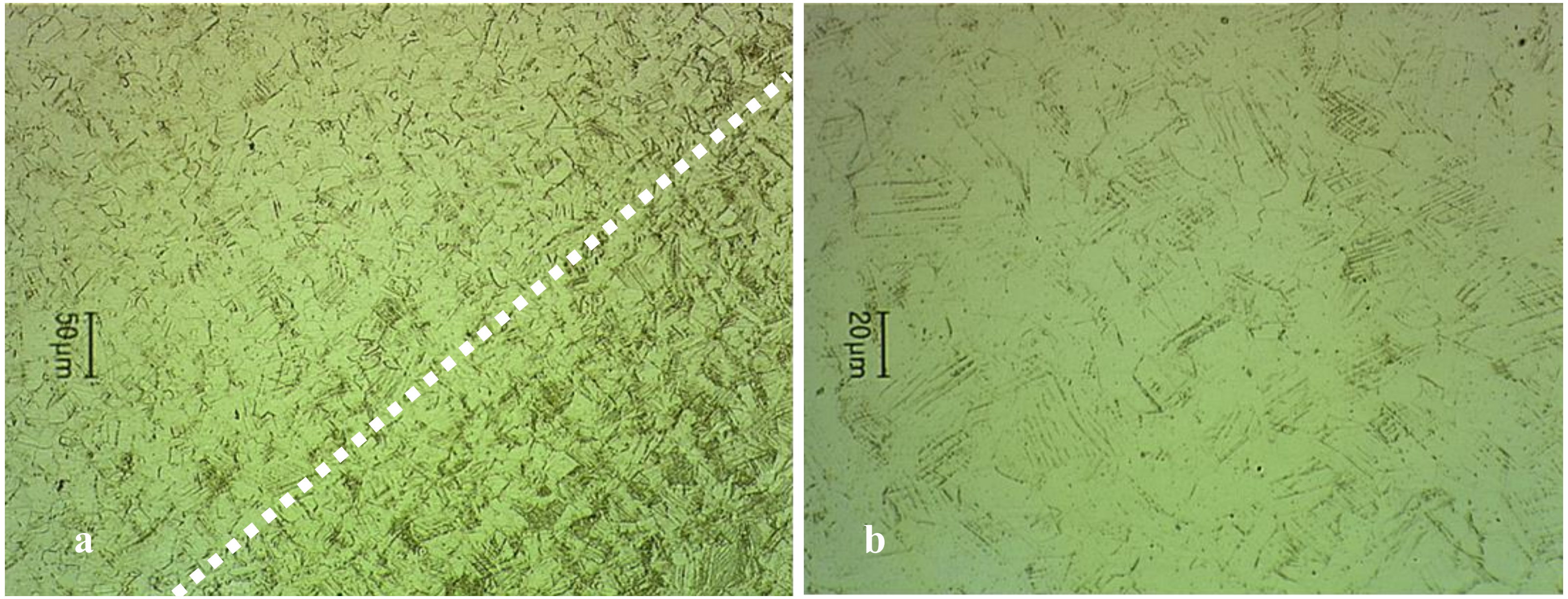
All coefficient are negative:

- good rule: "the more alloying elements one uses (and can afford!), the more stable the austenite will be"
- 304L is the least stable among the alloys used at CERN.
- **1.4306** generally specified by CERN and preferred to **1.4307** (general purpose)
- total stability requires a specific alloy selection or design, see the (HL-) LHC beam screen example

Transformation (**T_{ms}**, T_{md}, calculated):

- General purpose 304L (1.4307, X2CrNi18-9) ⇒ **T_{ms} = 280 K, T_{md} = 346 K**
- High alloy 304L (1.4306, X2CrNi19-11) ⇒ **T_{ms} = 140 K, T_{md} = 320 K**
- Prototype HG-CAL 304L (as above) ⇒ **T_{ms} = 76 K, T_{md} = 305 K**
- CERN store 316LN (1.4429, X2CrNiMoN17-13-3) ⇒ **T_{ms} = n.a, T_{md} = 240 K**
- Beam screen P506 grade ⇒ **T_{ms} = n.a, T_{md} = 36 K**

4.c Martensitic transformations



Partially transformed austenite of an AISI 316L austenitic stainless steel sample strained 6.5% at 4.2 K. Martensite is concentrated in bands (under the white boundary in Fig. a), developing during tensile deformation. A detail of the austenite-martensite microstructure is shown in Fig. b (see also C. GARION, S. SGOBBA, B. SKOCZEN, Constitutive modelling and identification of parameters of the plastic strain-induced martensitic transformation in 316L stainless steel at cryogenic temperatures, International Journal of Plasticity, 22 (2006) 1234-1264)

4.c Martensitic transformations

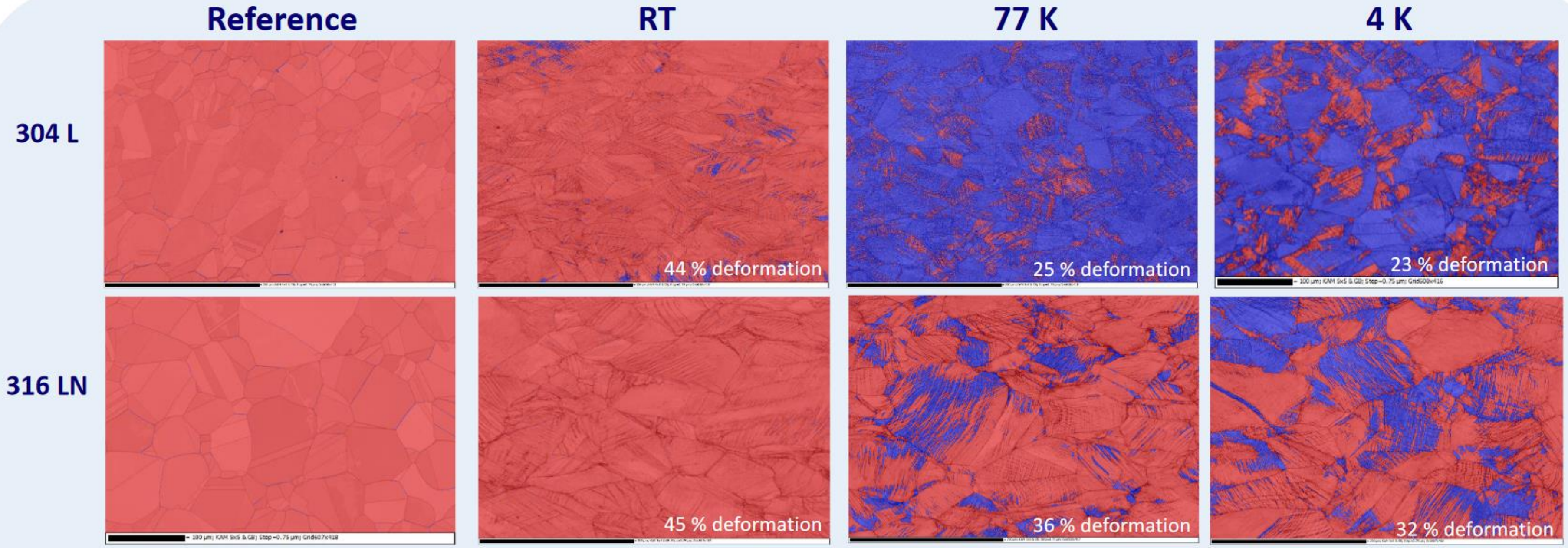


Figure 2 - EBSD phase map and band contrast map on 304 L and 316 LN samples at different temperatures. Colour code: martensite (Fe BCC) appears in blue, while the austenite (Fe FCC) is shown in red

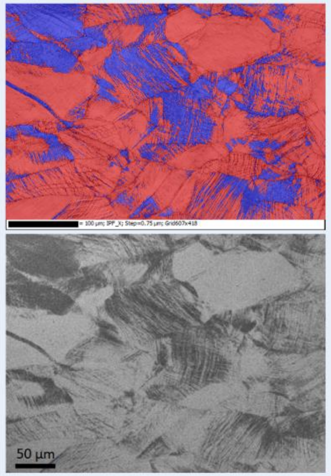
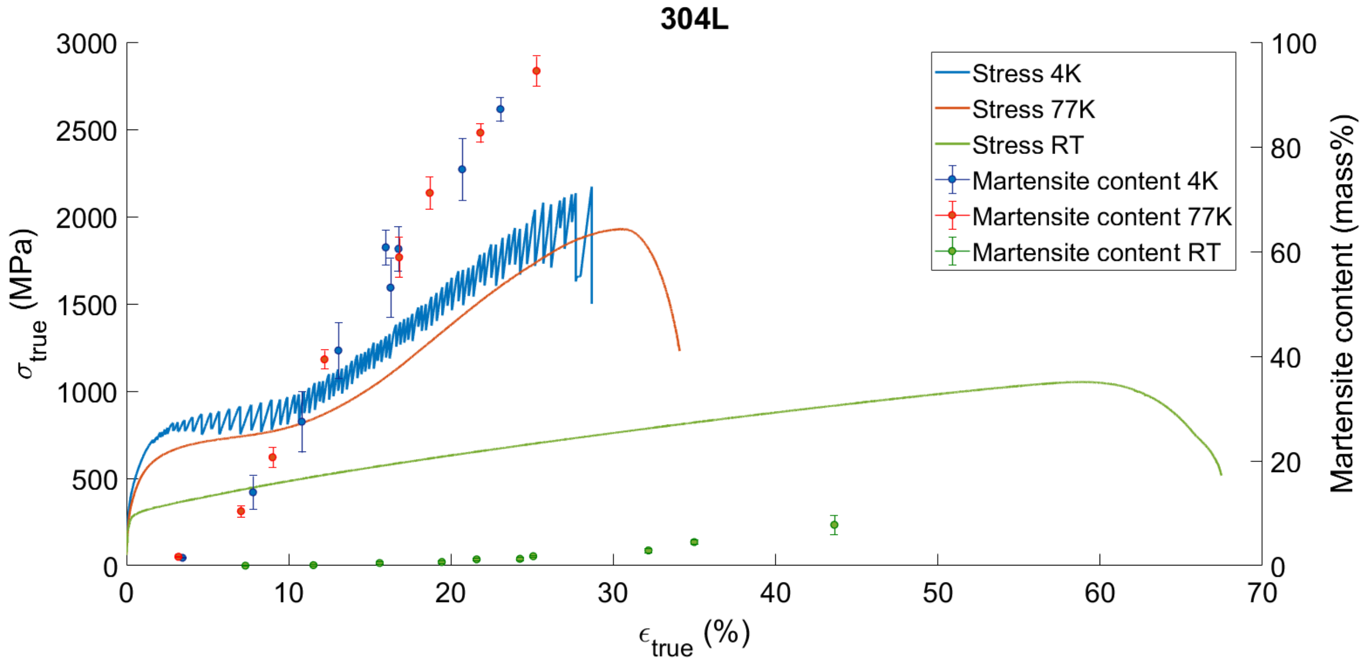


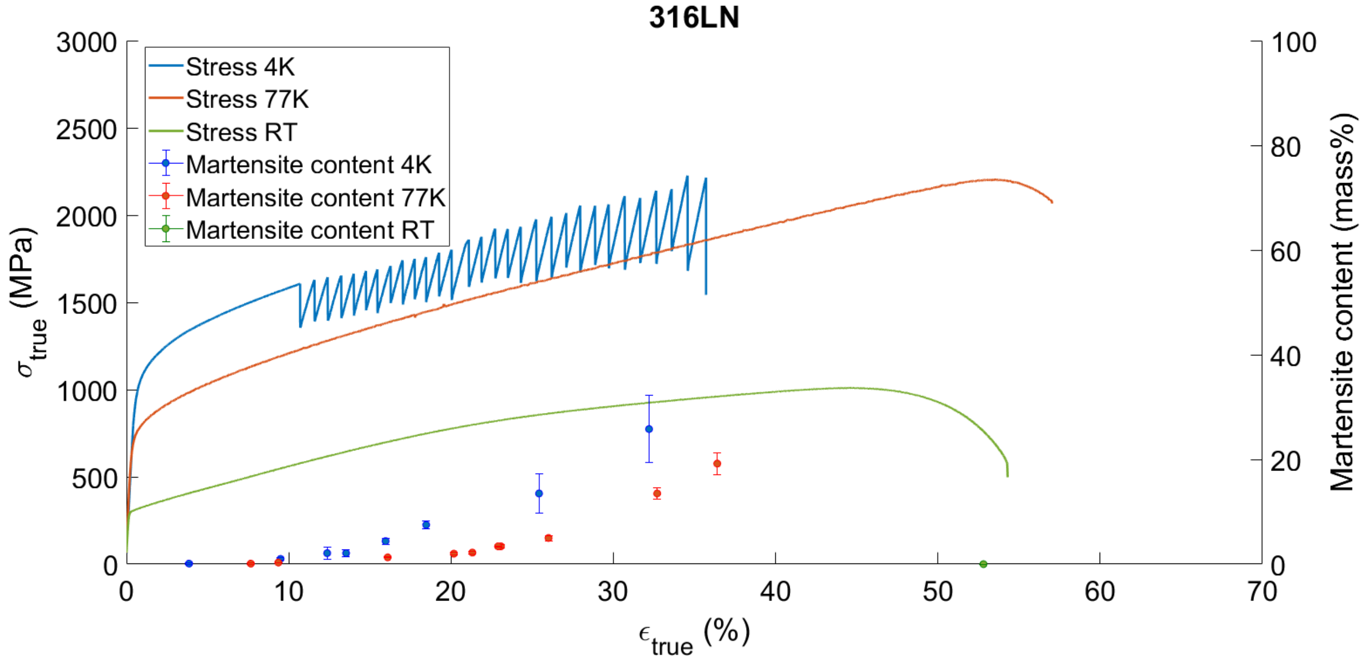
Figure 3 - Correlation between EBSD map and optical microscope image for SS 316 LN @ 4K, 32% deformation

Quantitative assessment through EBSD techniques associated to SEM

P. Fernández-Pisón, J.a Rodríguez-Martínez, E. García-Tabarés, I. Avilés-Santillana, S. Sgobba, Flow and fracture of austenitic stainless steels at cryogenic temperatures, Eng. Fracture Mechanics, Vol. 258, 2021, 108042, https://doi.org/10.1016/j.engfracmech.2021.108042

4.c Martensitic transformations





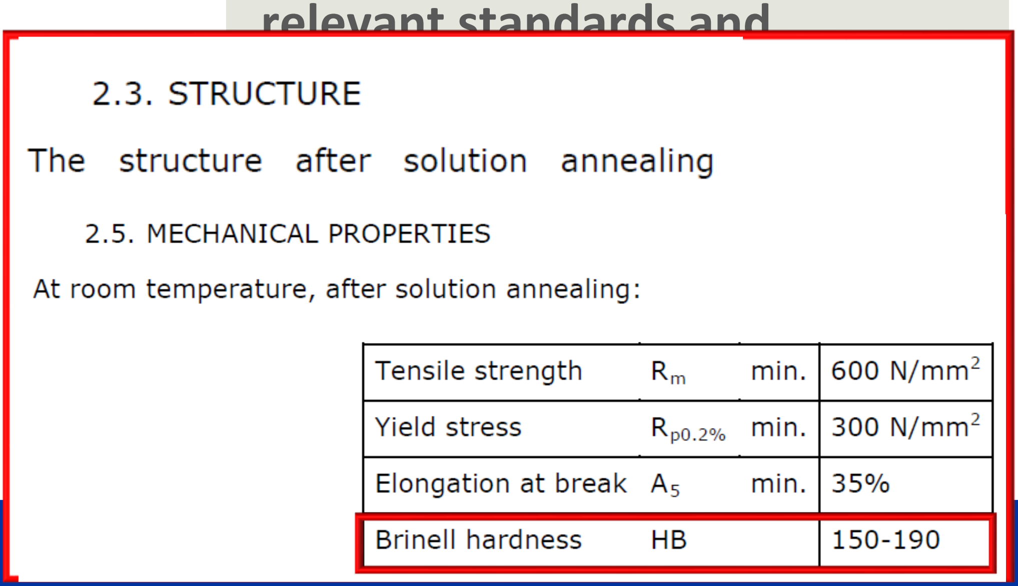
P. Fernandez Pison et al., ibid.

5. Thermal treatments, sensitization, corrosion failures

Austenitic stainless steels to be furnished and preferentially used in their solution annealed condition

All standards (except for specific applications) impose furnishing in the solution annealed condition

Max. hardness also limited by relevant standards and



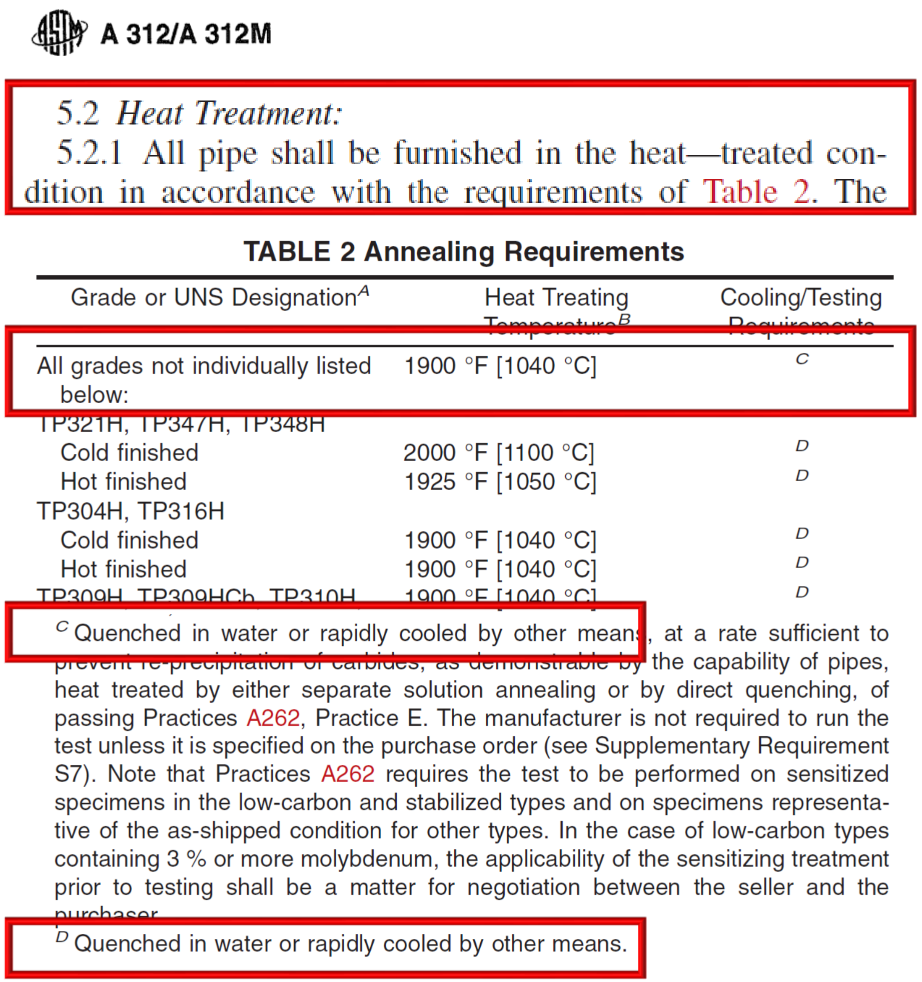
2.3. STRUCTURE

The structure after solution annealing

2.5. MECHANICAL PROPERTIES

At room temperature, after solution annealing:

Tensile strength	R_m	min.	600 N/mm^2
Yield stress	$R_{p0.2\%}$	min.	300 N/mm^2
Elongation at break	A_5	min.	35%
Brinell hardness	HB		150-190



A 312/A 312M

5.2 *Heat Treatment:*

5.2.1 All pipe shall be furnished in the heat—treated condition in accordance with the requirements of Table 2. The

TABLE 2 Annealing Requirements

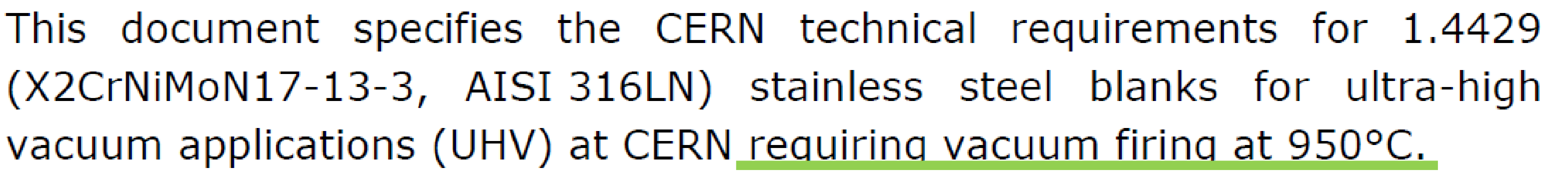
Grade or UNS Designation^A	Heat Treating Temperature^B	Cooling/Testing Requirements
All grades not individually listed below:	1900 °F [1040 °C]	^{C}
TP321H, TP347H, TP348H		
Cold finished	2000 °F [1100 °C]	^{D}
Hot finished	1925 °F [1050 °C]	^{D}
TP304H, TP316H		
Cold finished	1900 °F [1040 °C]	^{D}
Hot finished	1900 °F [1040 °C]	^{D}
TP309H, TP309HCb, TP310H	1900 °F [1040 °C]	^{D}

[C] Quenched in water or rapidly cooled by other means, at a rate sufficient to prevent re-precipitation of carbides, as demonstrable by the capability of pipes, heat treated by either separate solution annealing or by direct quenching, of passing Practices A262, Practice E. The manufacturer is not required to run the test unless it is specified on the purchase order (see Supplementary Requirement S7). Note that Practices A262 requires the test to be performed on sensitized specimens in the low-carbon and stabilized types and on specimens representative of the as-shipped condition for other types. In the case of low-carbon types containing 3 % or more molybdenum, the applicability of the sensitizing treatment prior to testing shall be a matter for negotiation between the seller and the purchaser.

[D] Quenched in water or rapidly cooled by other means.

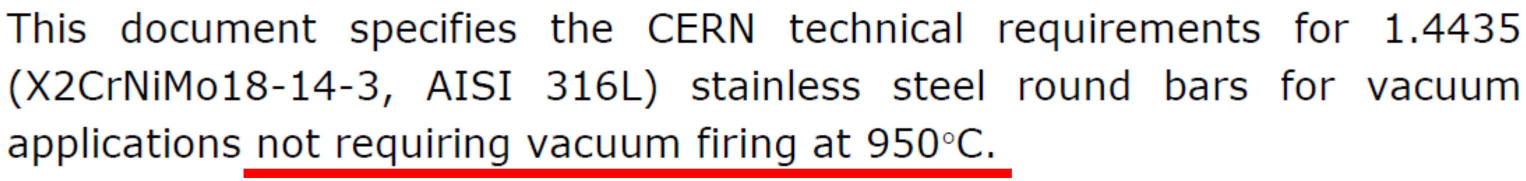
5. Thermal treatments, sensitization, corrosion failures

316LN



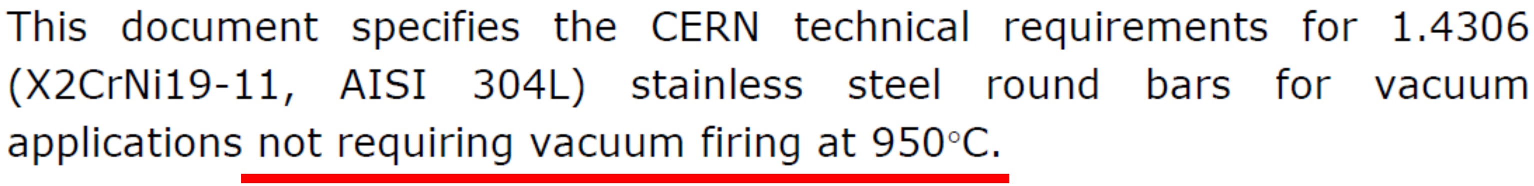
This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.

316L



This document specifies the CERN technical requirements for 1.4435 (X2CrNiMo18-14-3, AISI 316L) stainless steel round bars for vacuum applications not requiring vacuum firing at 950◦C.

304L



This document specifies the CERN technical requirements for 1.4306 (X2CrNi19-11, AISI 304L) stainless steel round bars for vacuum applications not requiring vacuum firing at 950◦C.

Vacuum firing of components and subassemblies to effectively remove the dissolved gas load in cleaned and degreased parts

5. Thermal treatments …

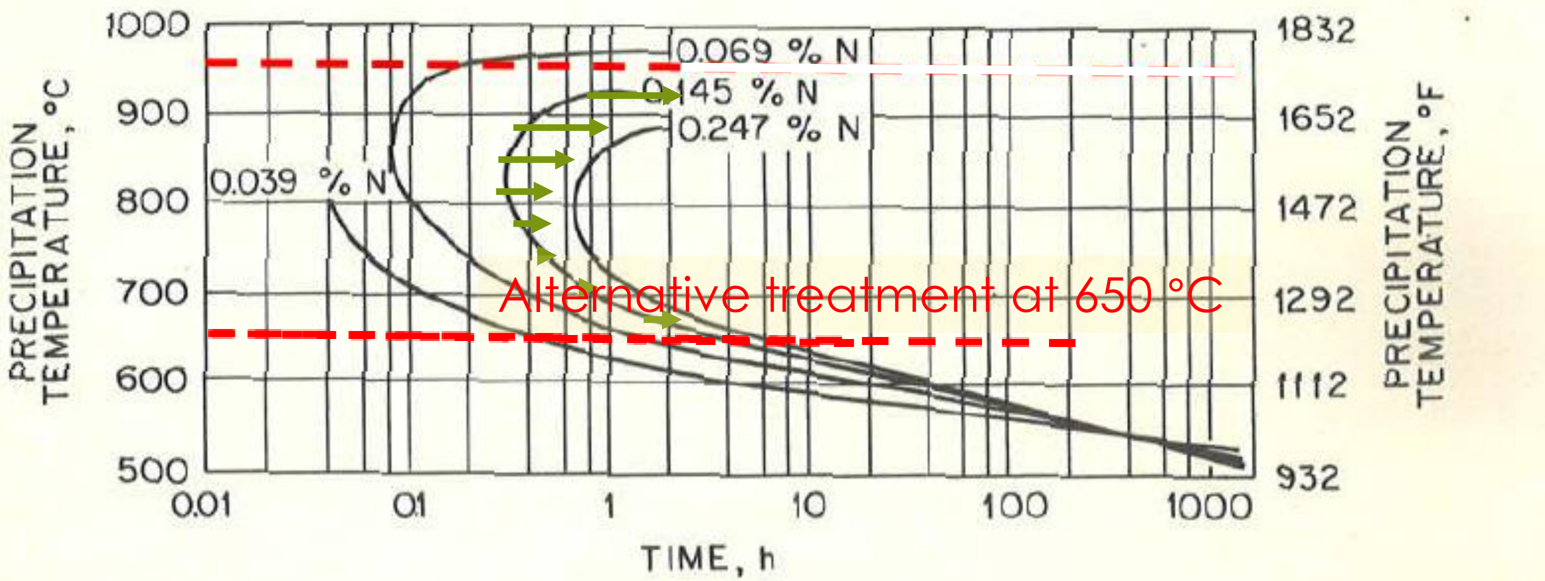


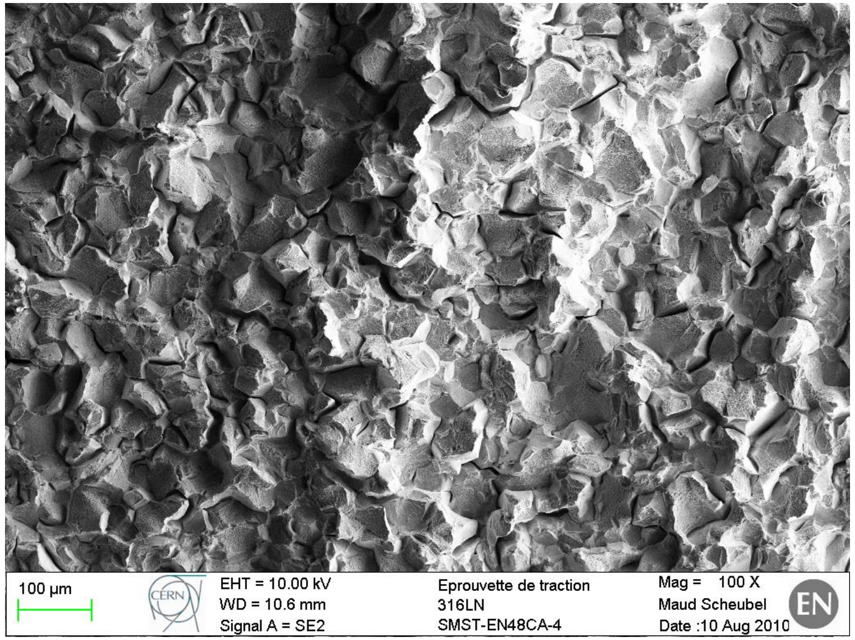
Fig. 62 Effect of nitrogen on precipitation of $M_{23}C_6$ in 0.05C-17Cr-13Ni-5Mo stainless steel.[172]

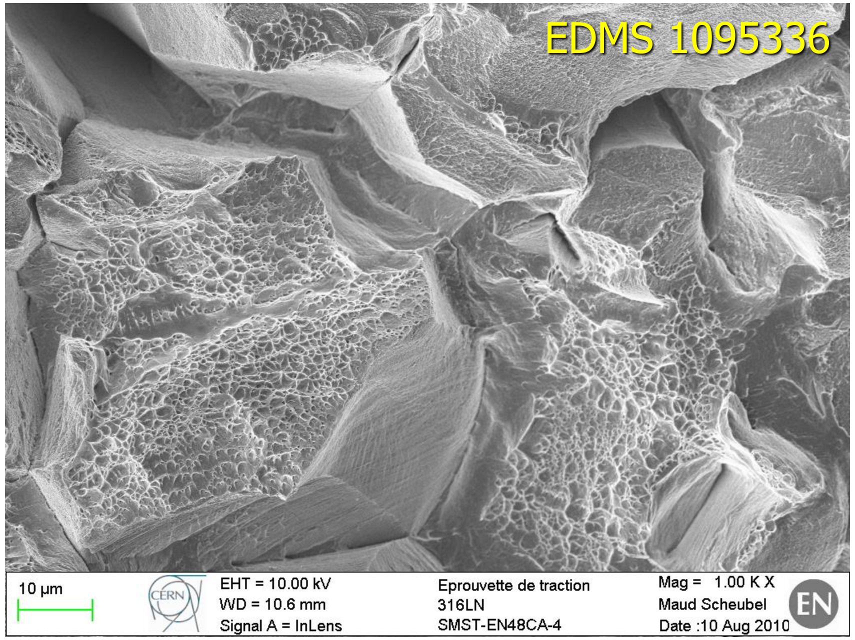
Handbook of stainless steels, D. Peckner, I.M. Bernstein. McGraw-Hill, 1977

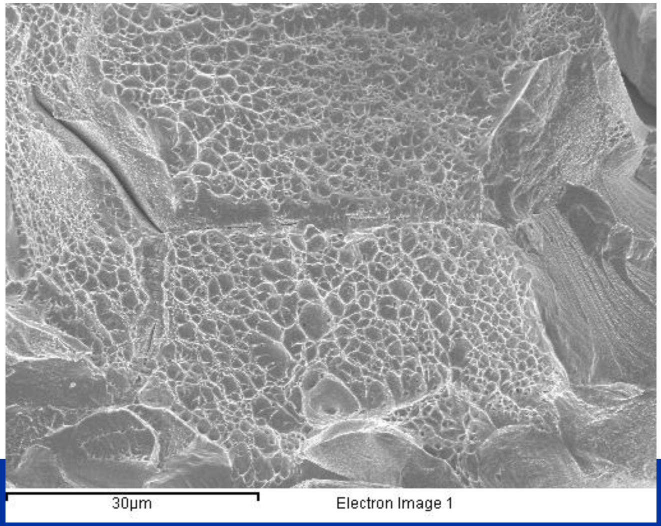
Stress relieving:

- **Select temperature-time combinations outside the sensitization range**
- **It can be made coincident with 950 °C vacuum firing treatment whenever possible**
- **Avoid ranges of σ-phase precipitation specially for welded structures**

5. Thermal treatments, sensitization, corrosion failures




EDMS 1095336



Sample	Young's modulus	Yield Strength	Ultimate Tensile Strength	Uniform Elongation	Total Elongation
	[illegible]	[illegible]	[illegible]	%	%
EN48CA-4	198.2	1209	1494	10.4	11.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

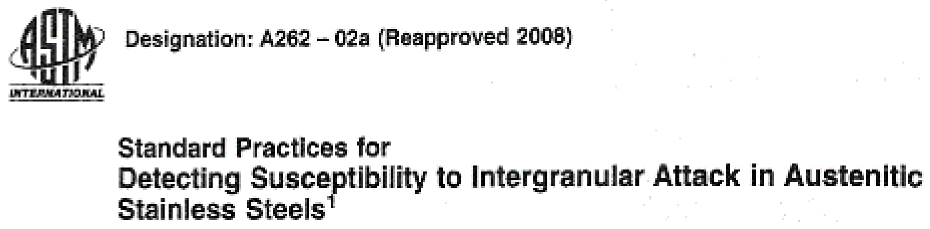
316LN ITER grade, TF jackets, extra low C (<0.015%) grade, aged 200 h at 650 °C, tensile tested at 7 K

See also ⇒
Klaus Peter Weiss,
Mechanical testing

5. Thermal treatments, sensitization, corrosion failures

Sensitization:

- ○ Loss of corrosion resistance (Cr depletion at GB)
- ○ Loss of ductility (specially at cryogenic temperatures), ductile-to-brittle transition onset
- ○ Check the effects of your treatment against ASTM A262



Designation: A262 – 02a (Reapproved 2008)

Standard Practices for
Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels[1]

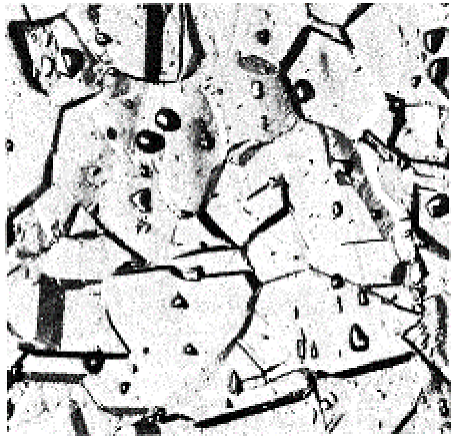


FIG. 1 Step Structure (500×) (Steps between grains, no ditches at grain boundaries)

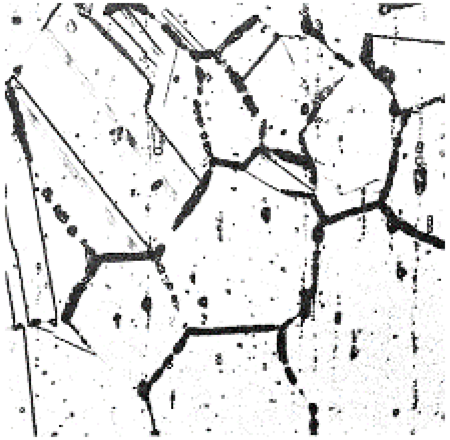


FIG. 2 Dual Structure (250×) (Some ditches at grain boundaries in addition to steps, but no one grain completely surrounded)

Sensitization:
oxalic acid etching,
ASTM A262,
practice A (⇒E)

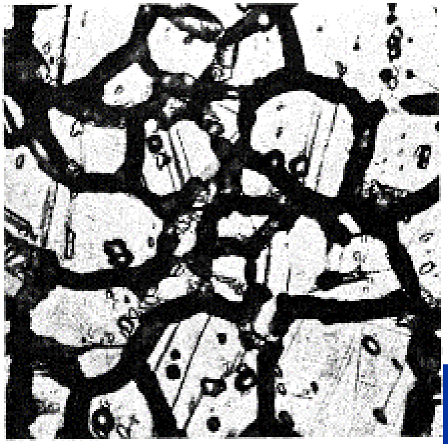
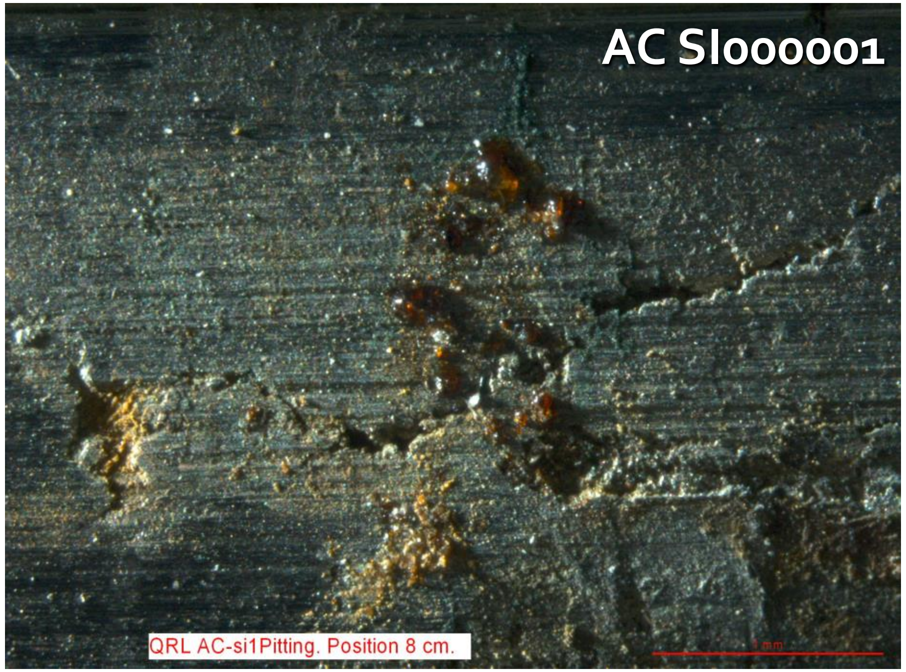


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

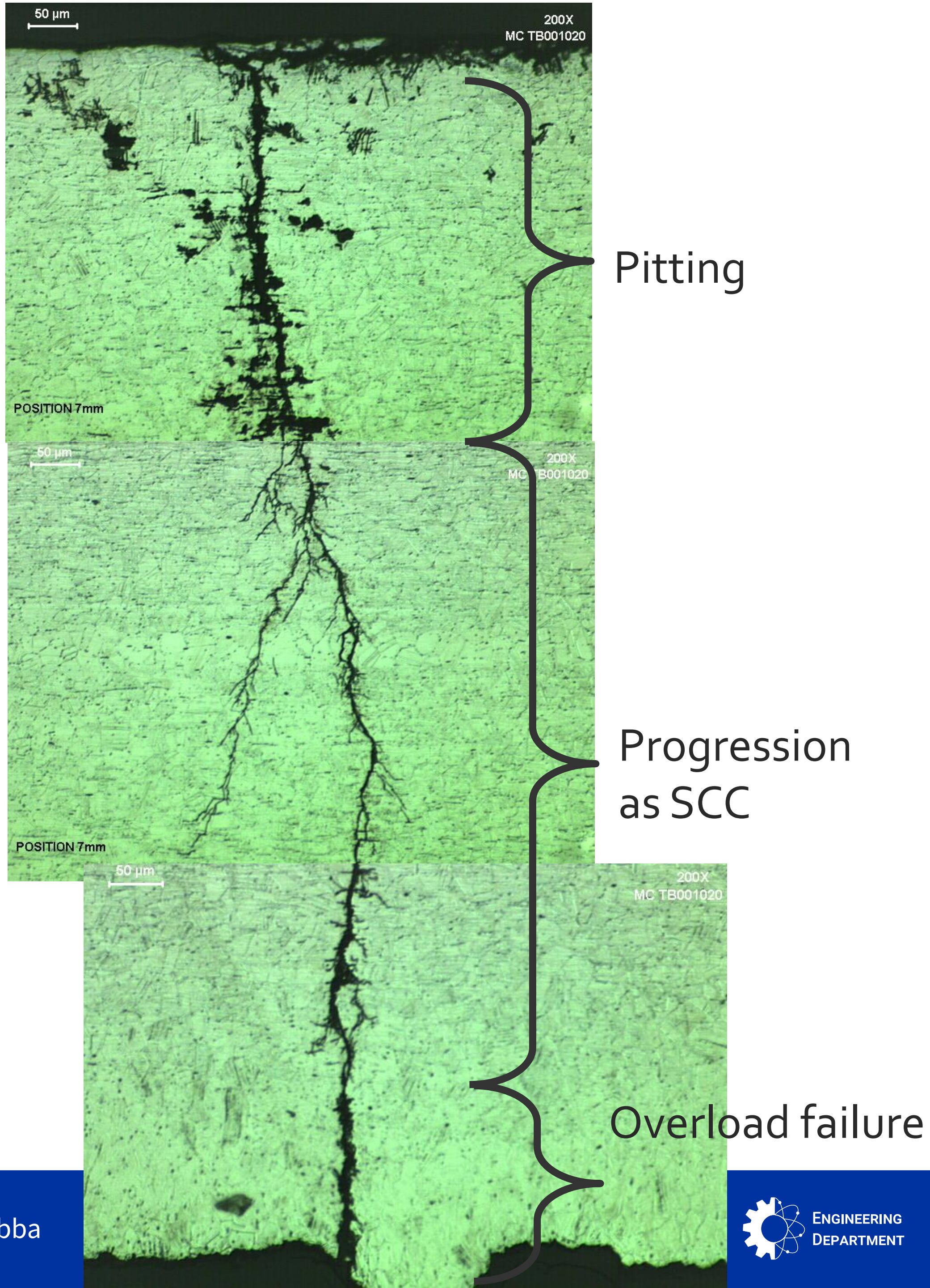
5. Thermal treatments, sensitization, corrosion failures



Appearance and start as pitting corrosion

Progression as Stress Corrosion Cracking (SCC)

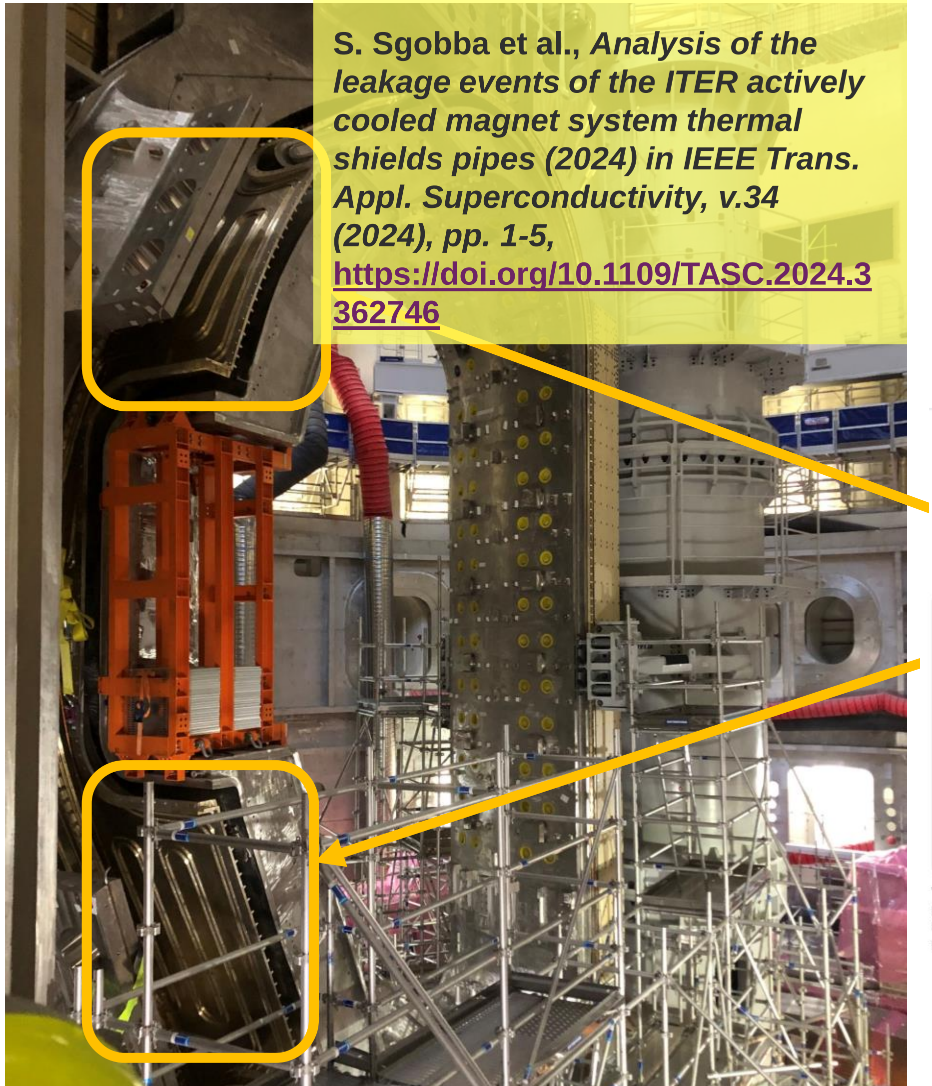
Final failure (leak) by overload

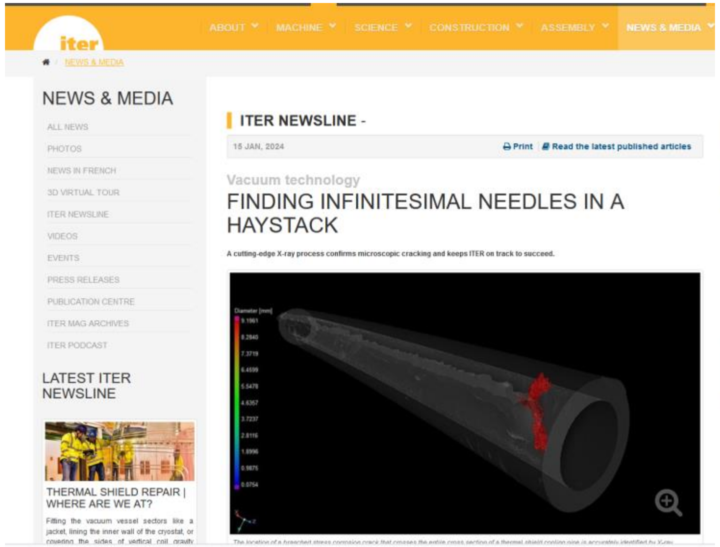


ITER VVTS

- **Root cause analysis associated to failure elimination**

S. Sgobba et al., *Analysis of the leakage events of the ITER actively cooled magnet system thermal shields pipes (2024) in IEEE Trans. Appl. Superconductivity, v.34 (2024), pp. 1-5,* https://doi.org/10.1109/TASC.2024.3362746





ITER NEWSLINE -

15 JAN, 2024

Vacuum technology

FINDING INFINITESIMAL NEEDLES IN A HAYSTACK

A cutting-edge X-ray process confirms microscopic cracking and keeps ITER on track to succeed.

THERMAL SHIELD REPAIR | WHERE ARE WE AT?

Fitting the vacuum vessel sectors like a jacket, lining the inner wall of the cryostat, or covering the sides of vertical coil gravity

ITER NEWSLINE -

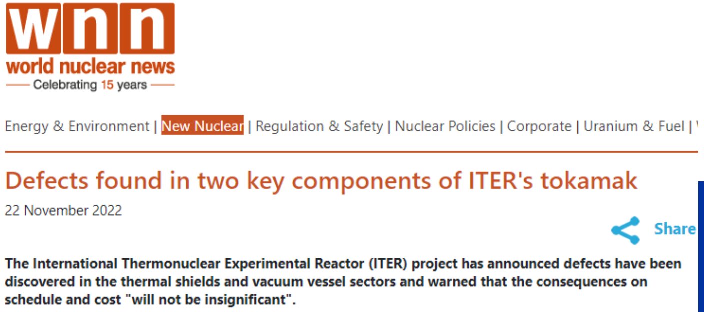
21 NOV, 2022

Machine assembly

KEY COMPONENTS TO BE REPAIRED

Investigative techniques (high-resolution CT scanning, scanning electron microscope, energy-dispersive X-ray spectrometer, and metallographic observation) revealed cracks in thermal shield cooling pipes such as the ones pictured here. At left, the crack is 1.5 mm deep. At right it is 2.2 mm deep and crosses the full width of the pipe.

"The risk is too high, and the consequences of a leaking thermal shield panel during operation are too dire. We must assume the problem is extensive," says ITER Director-General Pietro Barabaschi. "Dealing with it in the pit on the module that has already been assembled would be enormously difficult. This means we have to lift out the installed module and disassemble it in order to proceed with the repairs. We are exploring different possibilities, from on-site repair to re-manufacturing in an outside facility,



Defects found in two key components of ITER's tokamak

22 November 2022

The International Thermonuclear Experimental Reactor (ITER) project has announced defects have been discovered in the thermal shields and vacuum vessel sectors and warned that the consequences on schedule and cost "will not be insignificant".

Le projet de réacteur à fusion Iter doit réparer des composants clés du tokamak, au prix d'importants retards

Défauts et retards pour le projet international de fusion nucléaire Iter

Par Le Figaro avec AFP

Publié le 06/01/2023 à 17:50 , mis à jour le 06/01/2023 à 18:16

Pietro Barabaschi a été nommé à la tête du programme Iter en septembre 2022. *NICOLAS TUCAT / AFP*

Deuxième défaut relevé, des traces de corrosion sur les «*écrans thermiques*» qui doivent protéger de la très forte chaleur émise lors de la fusion. Ce qui pourrait aboutir à des fuites de l'hélium utilisé dans le circuit de refroidissement. Ces réparations vont retarder le projet. «*Ça n'est pas un processus qui prend des semaines, mais des mois, voire quelques années*», a expliqué Pietro Barabaschi, qui do [illegible] fin de l'année un nouveau calendrier des opérations.

See also ⇒ Neil Mitchell, Large structures for Fusion Technology

Conclusions

- A stainless steel for an accelerator or fusion magnet part is not a mere "chemical composition" or a designation
  - specification
  - steelmaking
  - definition and extent of the controls
  - certification
  - price
- Application of extensive “state of the art” NDT techniques
  - stainless steels for vacuum, cryogenic and/or structural applications 100 % examined during production and at reception
- Low T and/or non-magnetism of components require special care
- Irreprocheable production route, starting from steelmaking
- Stainless steel not always stainless: corrosion environment during the whole life cycle of the parts