“Mini-CAS” course on Mechanical and Materials Engineering for Accelerators, 6/11/20-22/01/21

Steels & Stainless Steels

Stefano Sgobba, EN-MME-MM, CERN - 20/11/2020

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ENGINEERING DEPARTMENT

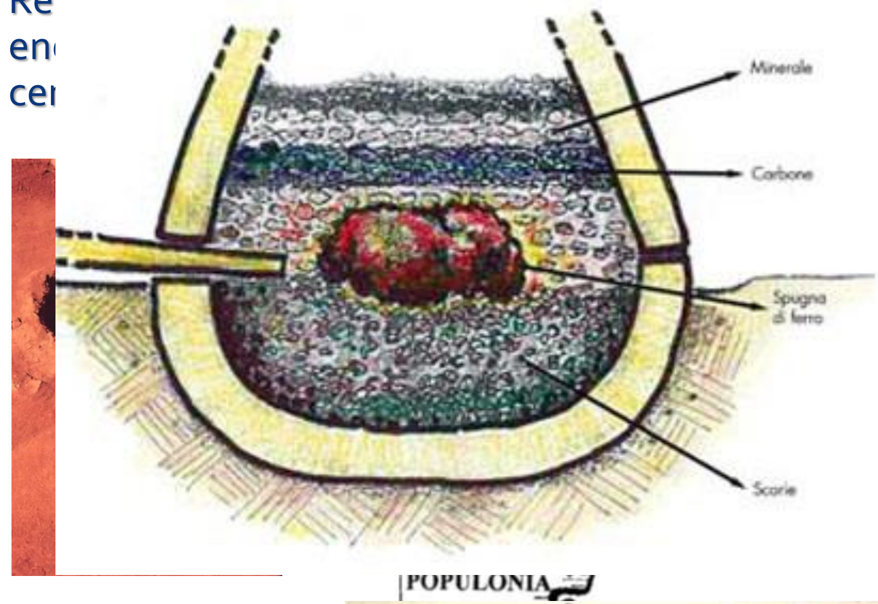
Outline

1. Introduction to steels and stainless steels:
   - Iron and steel, major players in the history of mankind
   - 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 specific applications
3. Steelmaking routes to secure the final quality of the product
4. Stability of the properties: precipitations and transformations
   - Considerations for welding
   - Case study: steel for the new CMS HG-CAL detector
5. Thermal treatments, sensitization, corrosion failures
6. Conclusions

A. Berveglieri, R. Valentini,
La Metallurgia Italiana,
June 2001, p. 49ff

1. Steels and stainless steel

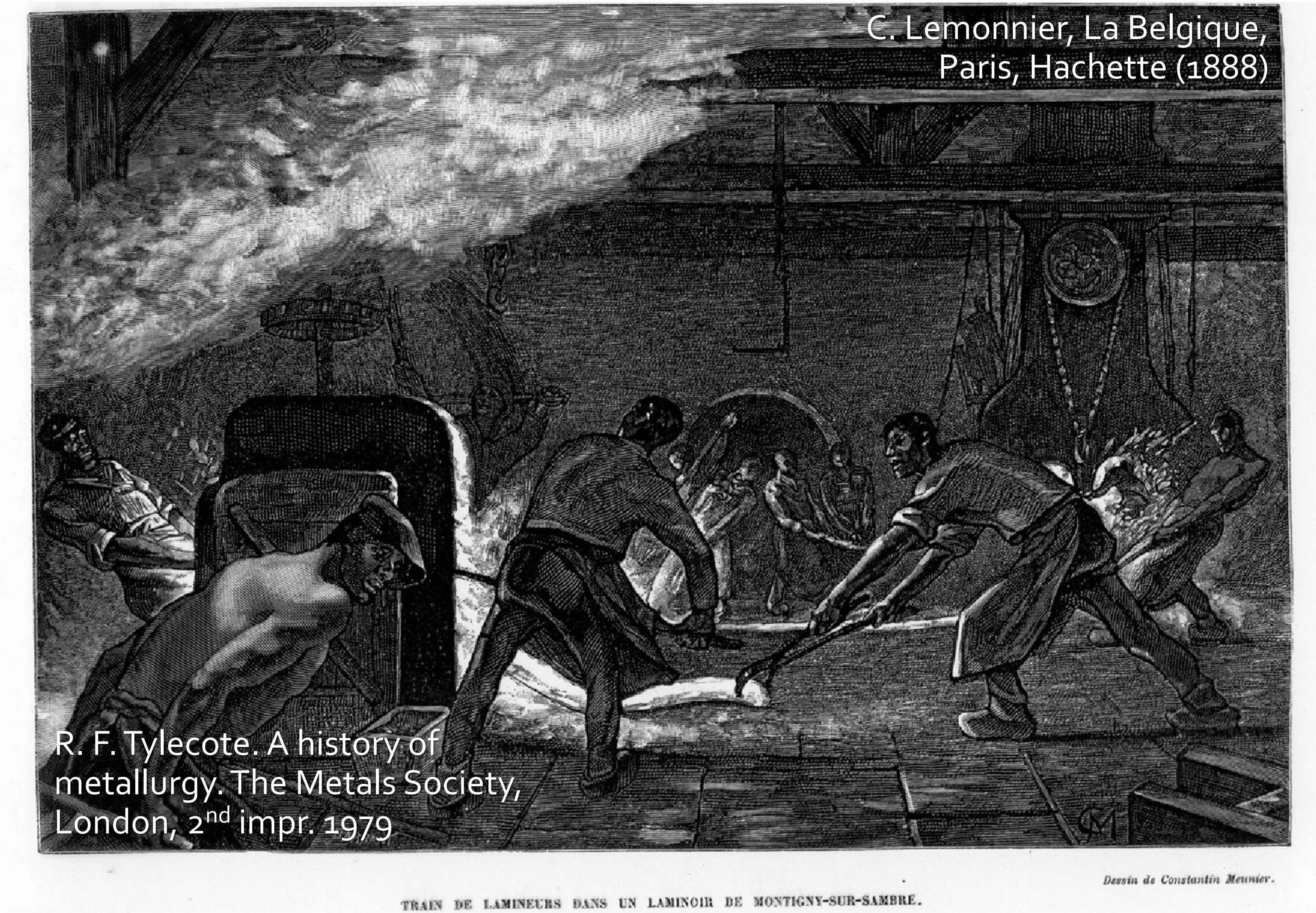
Remains of Etruscan furnaces, exploited from the
en
cer



Residues,
exploited
until 1969…

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$
$$FeO + CO \rightarrow Fe + CO_2$$
$$FeO + C \rightarrow Fe + CO$$

1. Steels and stainless steel



C. Lemonnier, La Belgique, Paris, Hachette (1888)

R. F. Tylecote. A history of metallurgy. The Metals Society, London, 2nd impr. 1979

1. Steels and stainless steel

Courtesy of TISCO /CN, hot rolling stainless steel plate mills, 2018

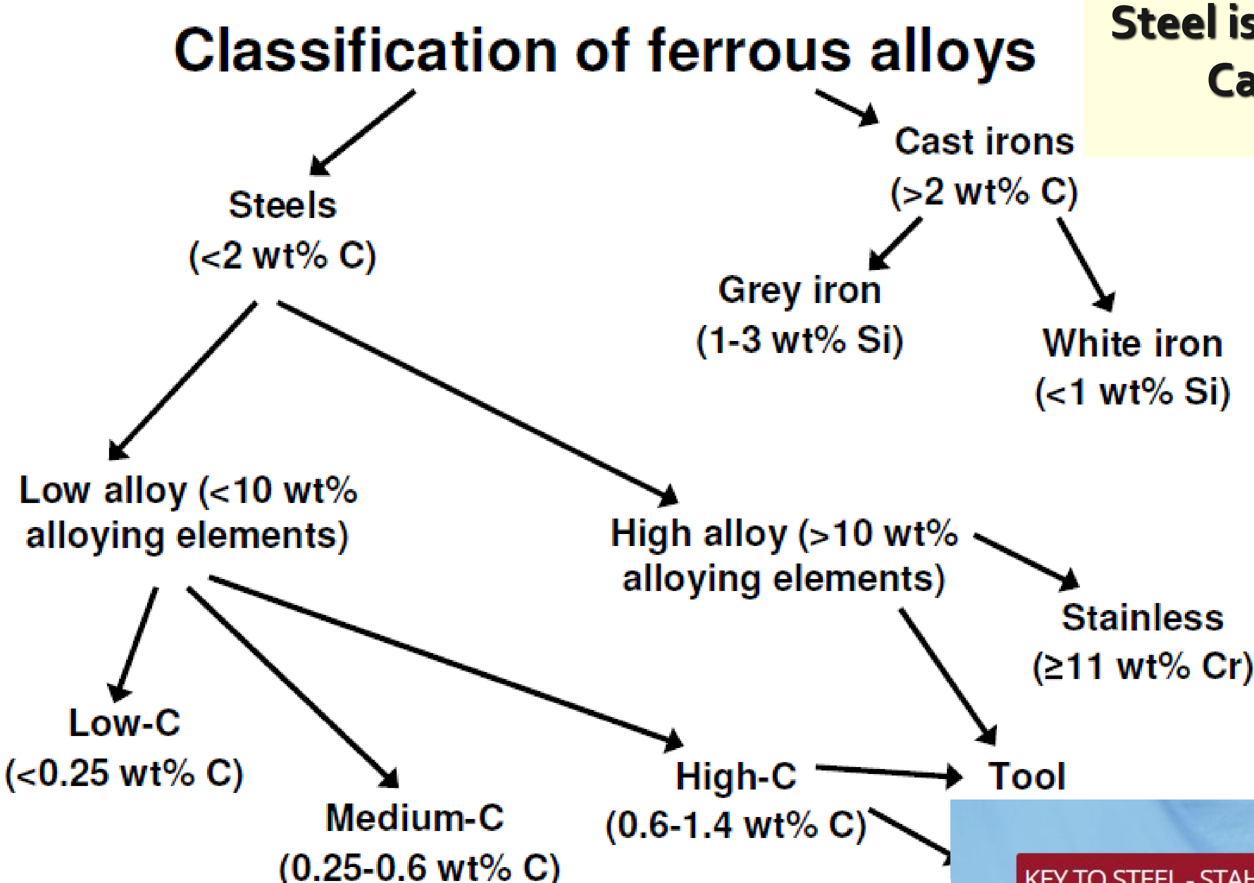
1. Steels and stainless steel

The Sandviken site in Sweden

- **SMT main site** with steel mill and manufacturing of bar, tube, strip and wire (~3500 employees)
- **Service HQ** located in the middle
- **R&D block** with labs and experts (~250 employees)
- **Additional manufacturing and R&D units** in US, Canada, Norway, Germany, France, Czech republic, India and China

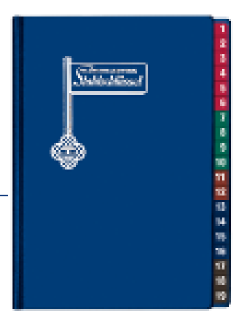
Courtesy of Sandvik Stainless Services

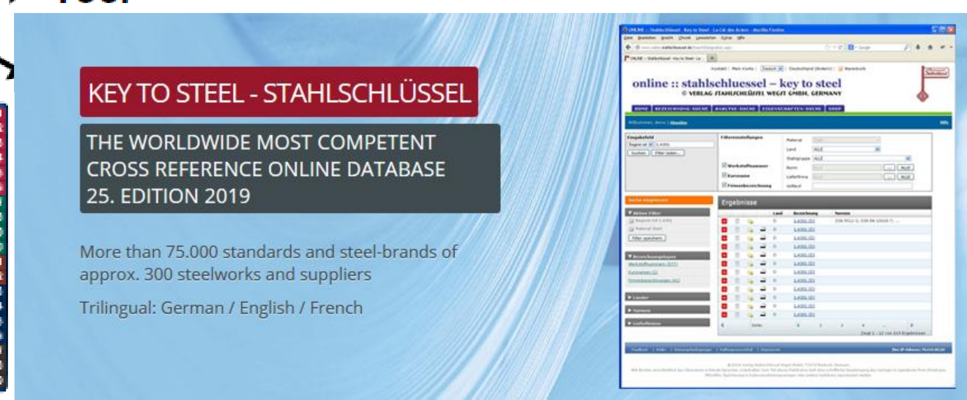
1. Steels and stainless steel



Steel is an iron based alloy containing Carbon, Silicon, Manganese etc.,
http://steel.nic.in/Glossary-I.pdf

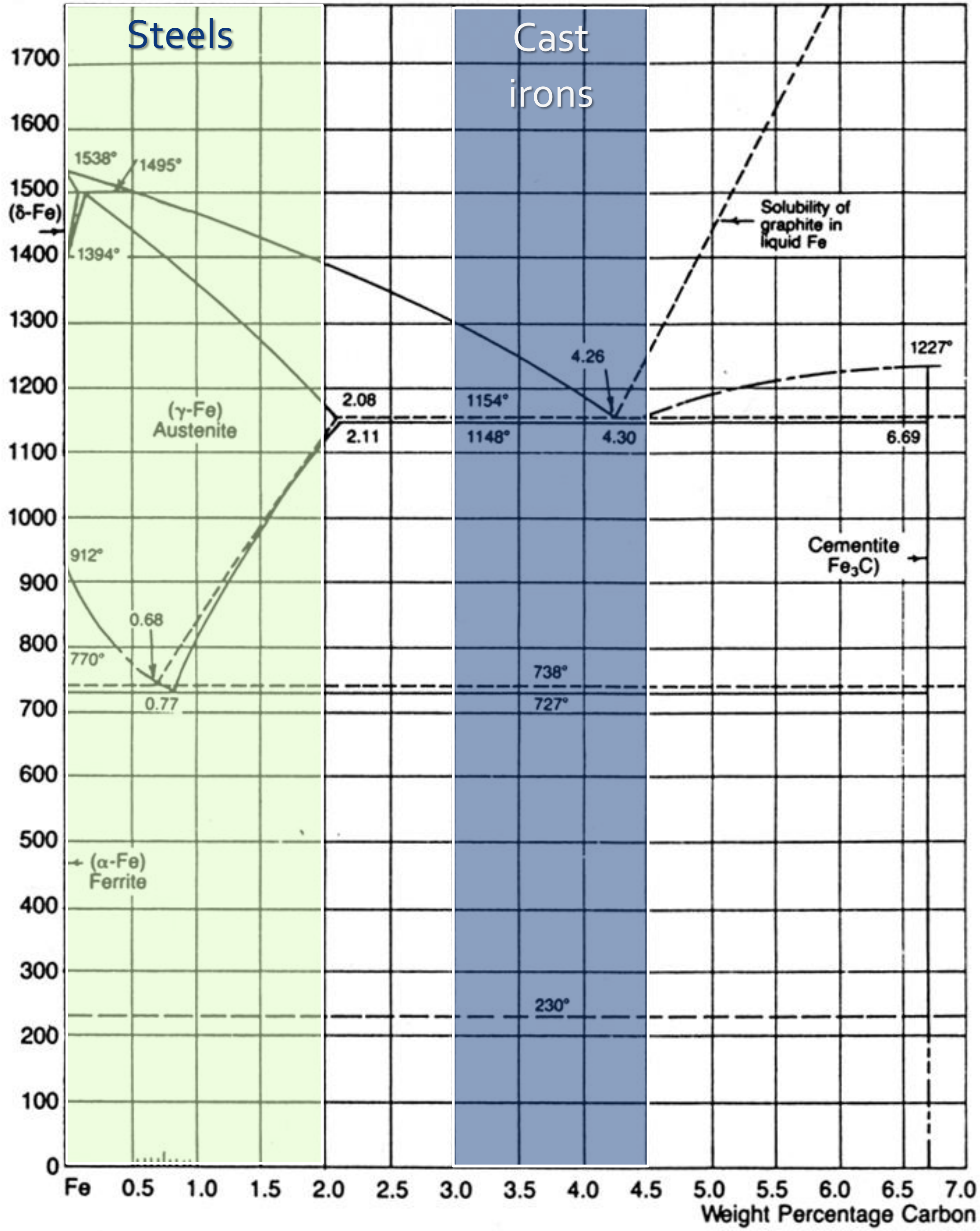
Steel is an alloy of iron and carbon. The amount of carbon dictates whether a steel is hard or it is tough. C content in steel usually falls a range between 0.3 ~ 1.5 % by volume,
http://www.ksky.ne.jp/~sumie99/ironandsteel.html





1. Steels and stainless steel

The Fe-C (Fe-Fe_3C) diagram



Fe_3C (metastable cementite) → **3 Fe + C** (graphite)

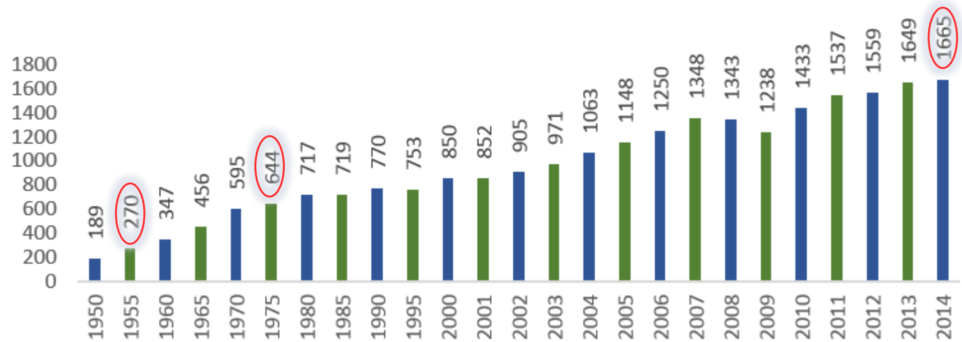
Fe - Fe3C

Fe - graphite

1. Steels and stainless steel

Autostrada del Sole, first open section 1958

WORLD STEEL PRODUCTION, 1950-2014 (IN MILLION TONNES)



SOURCE: WORLD STEEL

A2 (CH), Chiasso boundary, 2014

Hot galvanizing + powder coating

A22, Autobrennero, 1974

Weathering steel COR-TEN trademark of United States Steel Corporation (USS): by amount of Cu, P Si and Cr, can develop under favourable climatic conditions a patina of hydrated Fe oxide retarding further attack. Long dry summer periods required.

1. Steels and stainless steel

Cast irons:

- Class of ferrous alloys with C ≥ 2.14 %
- Most contain 3.0 % ≤ C ≤ 4.5 %
- Lower T_m (1150 °C - 1300 °C) than steel
- Easily melted and amenable to casting
- Based on the reaction $Fe_3C \rightarrow 3\ Fe + C$
- Tendency to form graphite regulated by composition and rate of cooling

Spheroid-graphite cast iron shielding blocks, LHC-R2E project. 436 t procured from NV Ferromatrix /BE.

More on steels, see ⇒ CAS course on "Mechanical & Materials Engineering", S. Sgobba, Steels & stainless steels I & II

2. Stainless steels, metallurgy and families

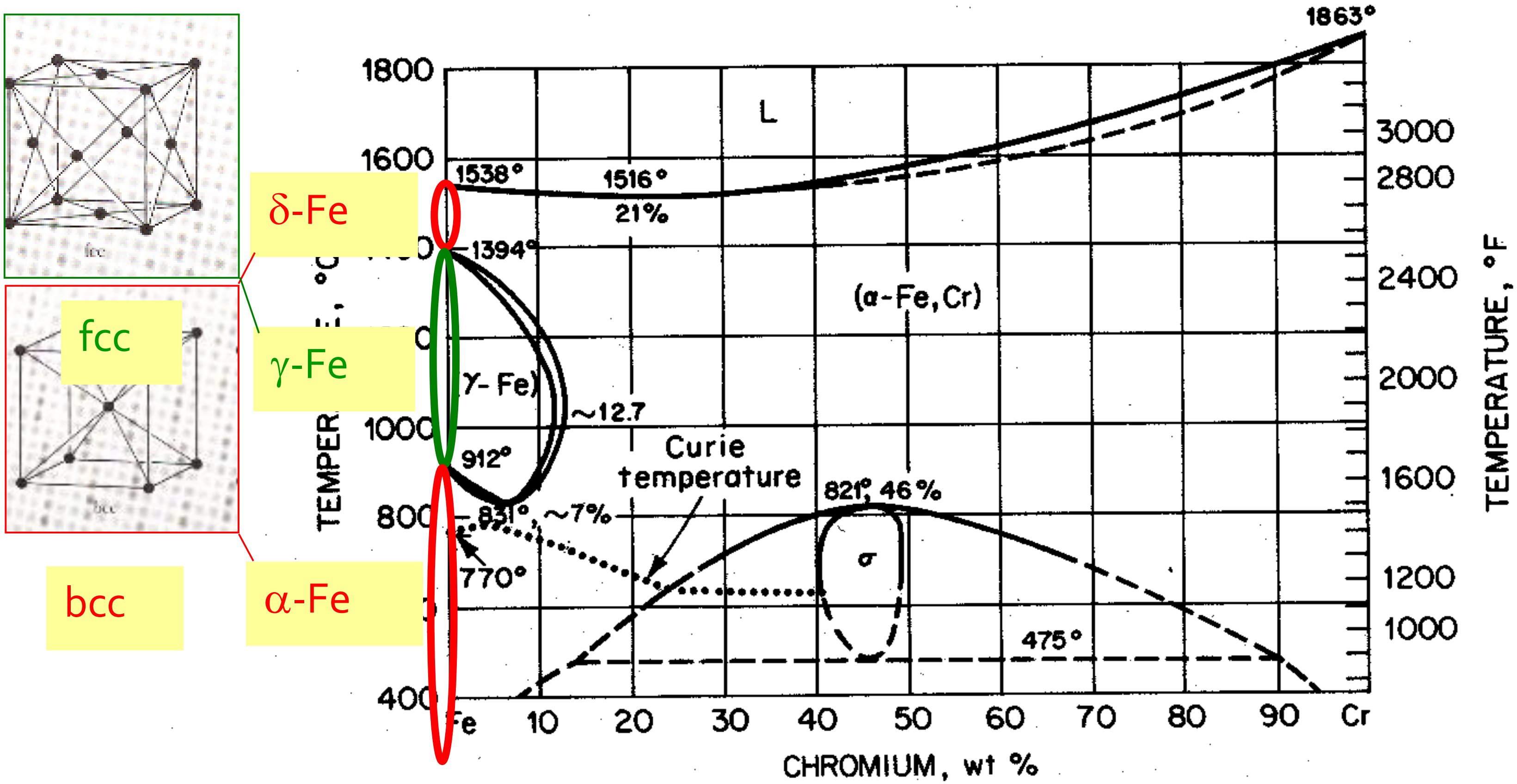


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

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

2 Stainless steels, ferritic

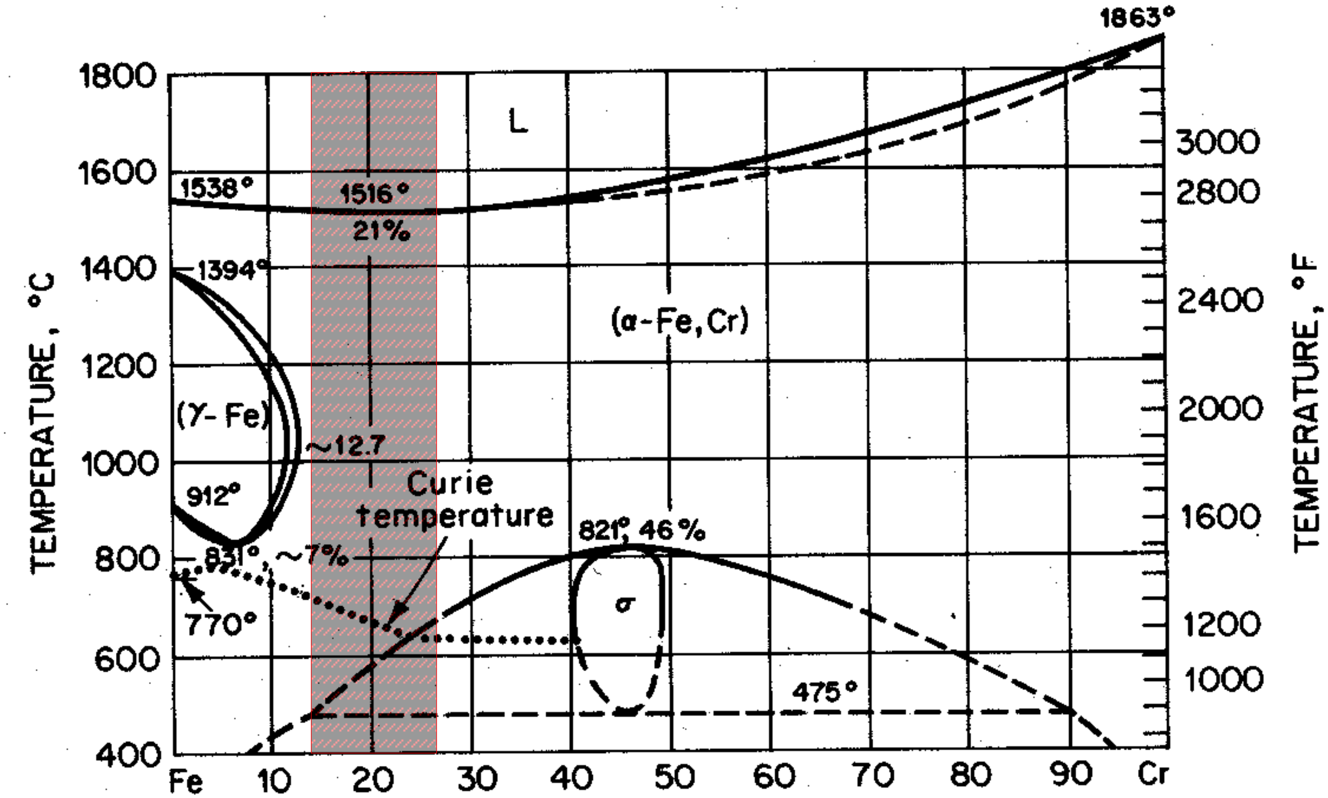
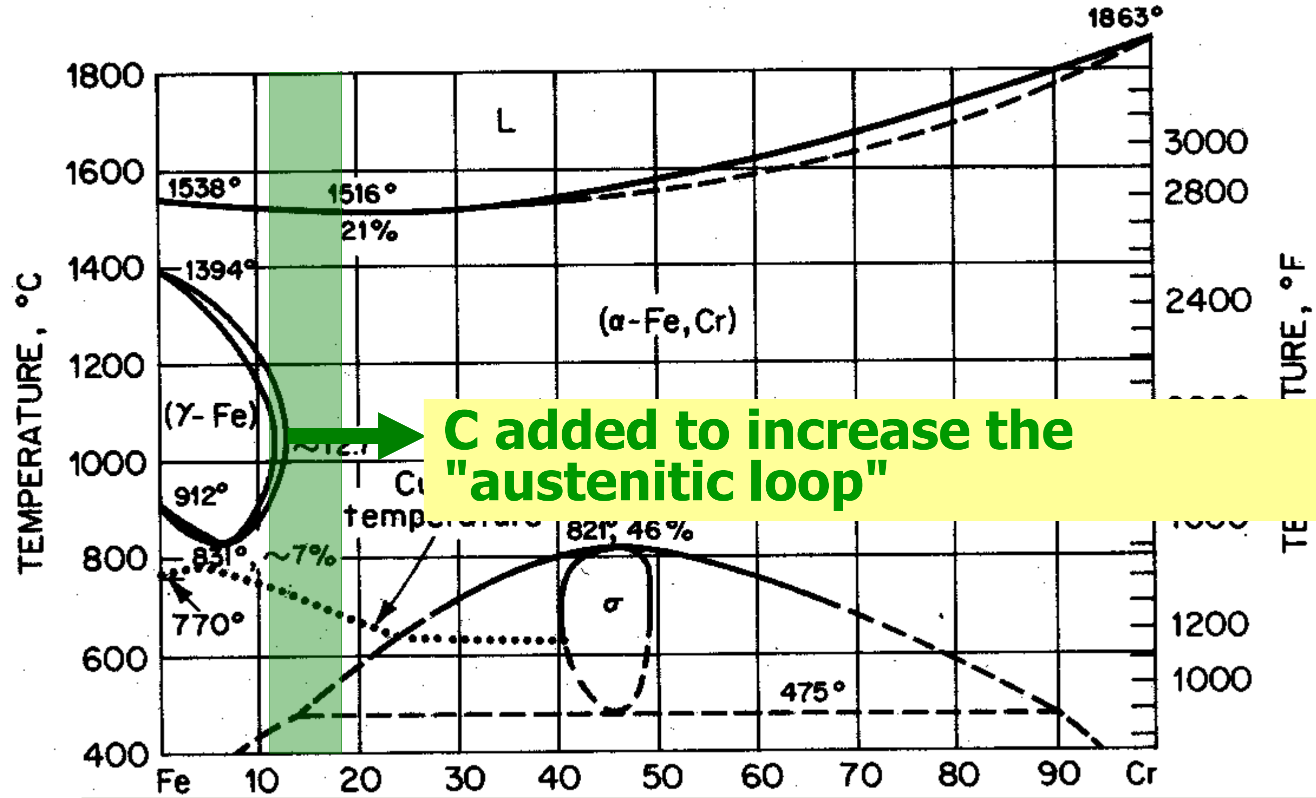


Fig. 2 The iron-chromiu ... , *8th ed.,*
American Society for Meta

- 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

2 Stainless steels, martensitic



C added to increase the "austenitic loop"

Fig. 2 The i ... h ed.,
American Soc

- 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

CERN | EN ENGINEERING DEPARTMENT

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

2

- forr fcc (FeC
- γ-lo
- γ-pl enla
- forr sup forr
- trar can sup allo

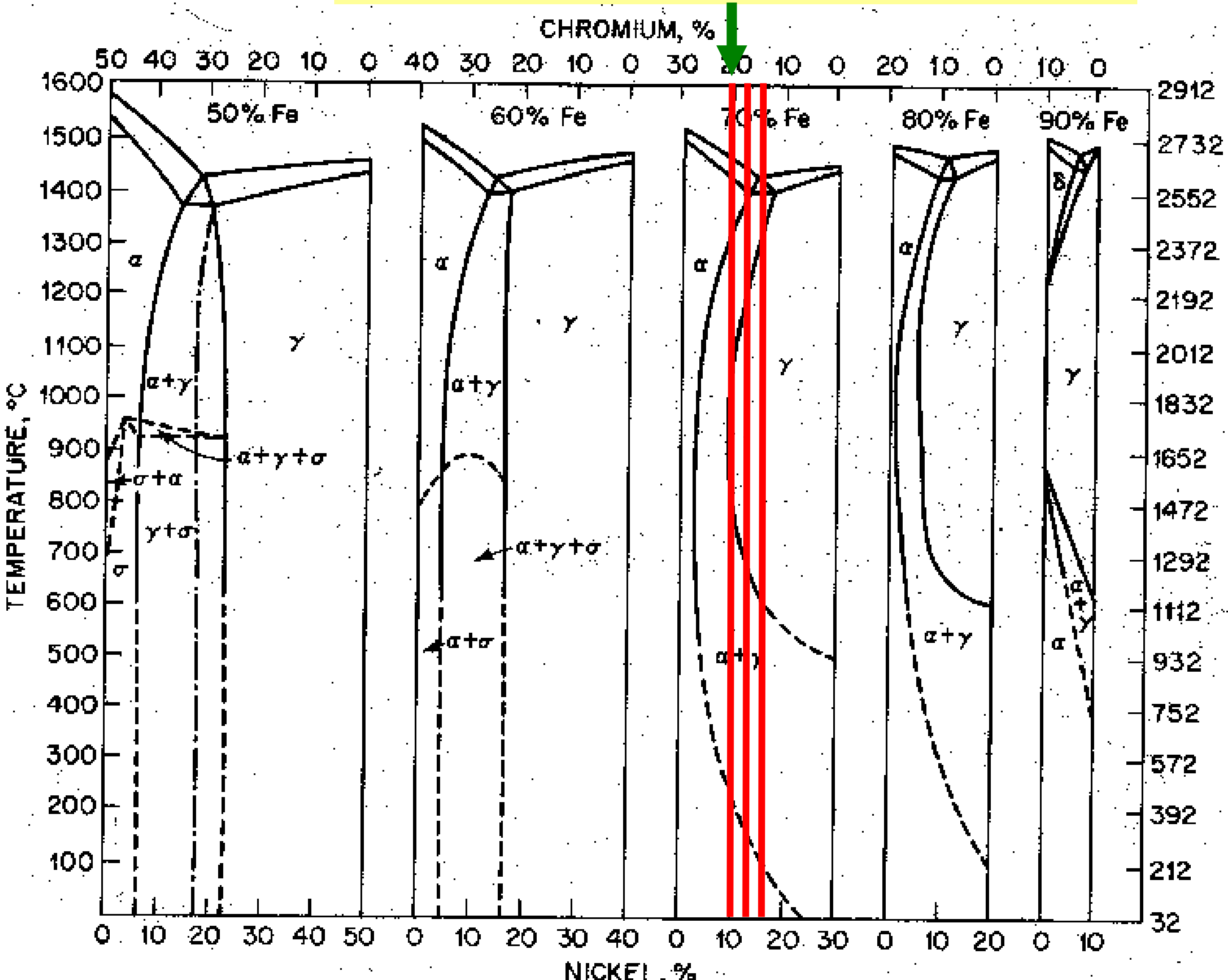
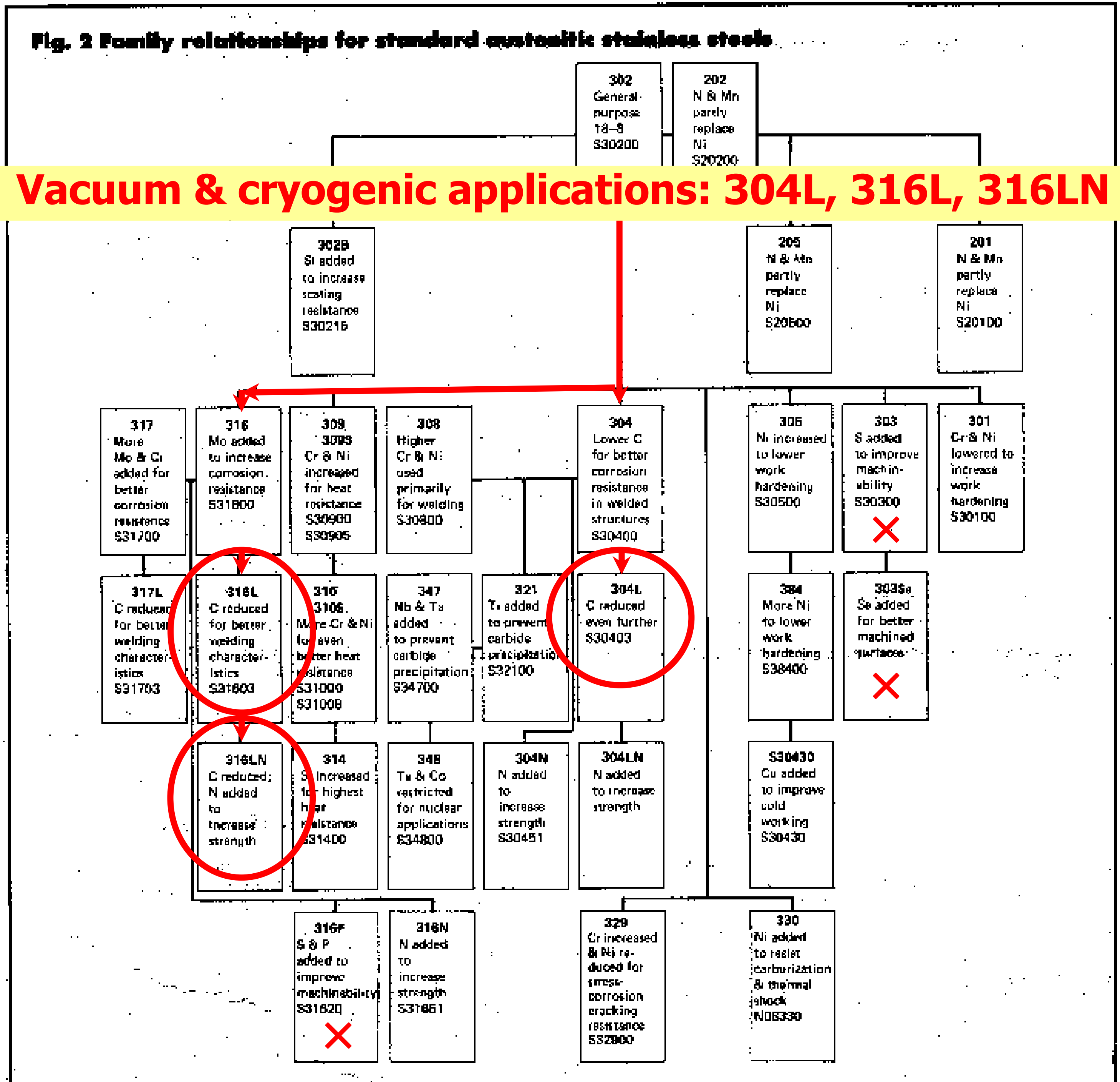


Fig. 14 Cross sections of Fe-Cr-Ni ternary.[26]

TEMPERATURE, °F

291, 8th ed.,



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

2. Stainless steels, austenitic

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

"Sensitization" of base metal, HAZs and welds

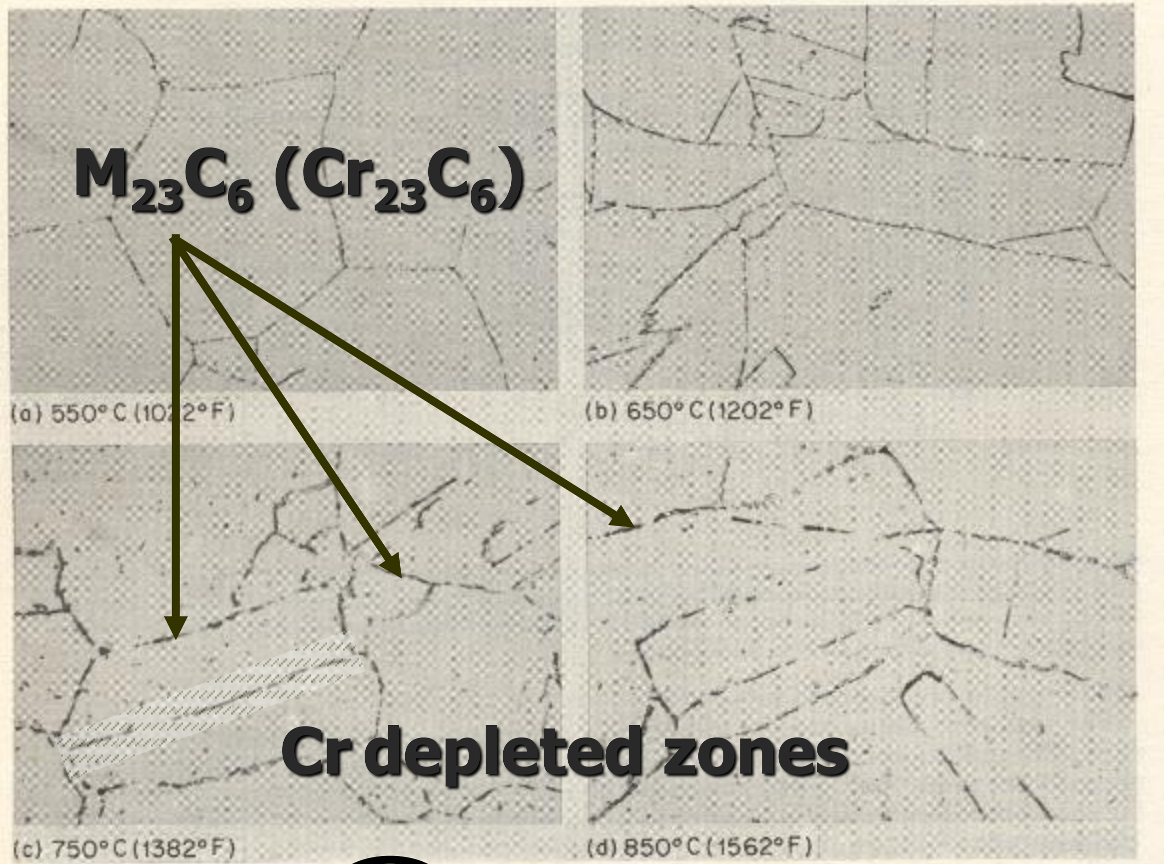
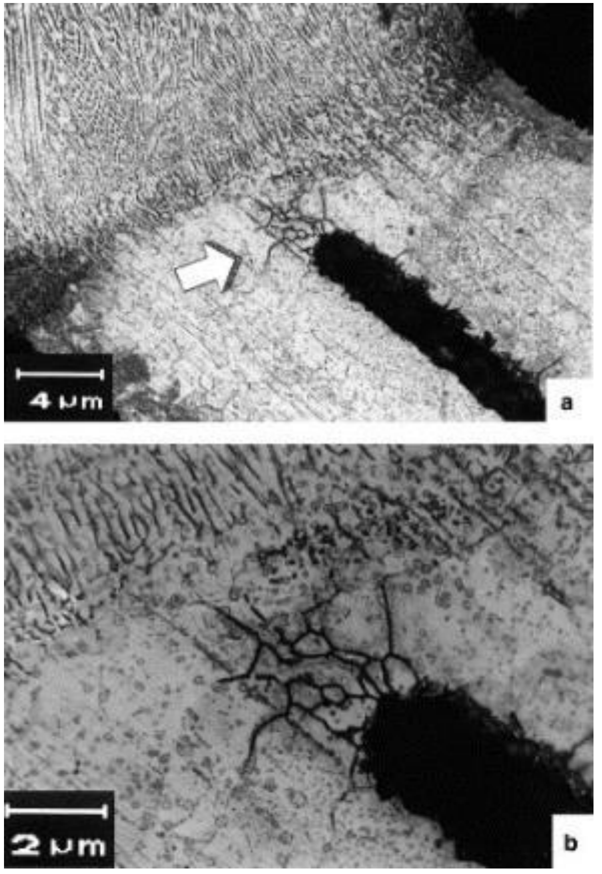


Fig. 55 Appearance of Type 304 stainless steel (0.065% carbon) sensitized for 6 days (144 h) at various temperatures. Specimens etched electrolytically in 10% oxalic acid.[128] (a) 550°C (1022°F). 750x. (b) 650°C (1202°F). 750x. (c) 750°C (1382°F). 750x (d) 850°C (1562°F). 750x.

D. Peckner, I.M. Bernstein, 1977



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

2. Stainl

CERN — European Organization for Nuclear Research

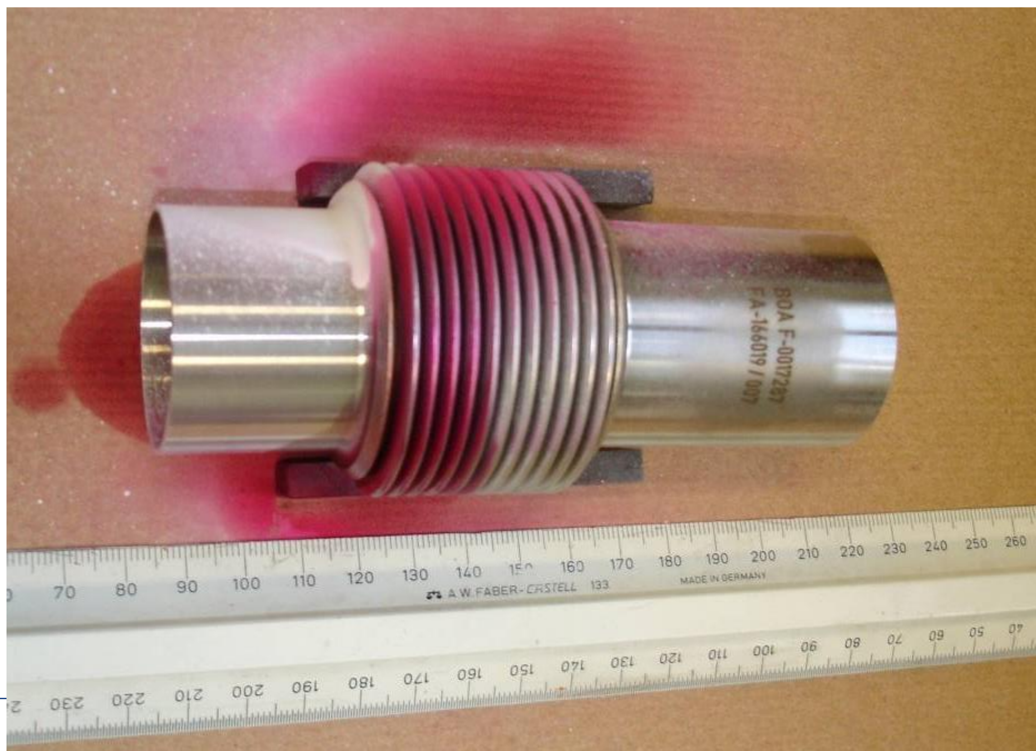
TS/MME-MM
Section de Métallurgie et Métrologie/ *Metallurgy and Metrology section*
Rapport expérimental / Investigation report

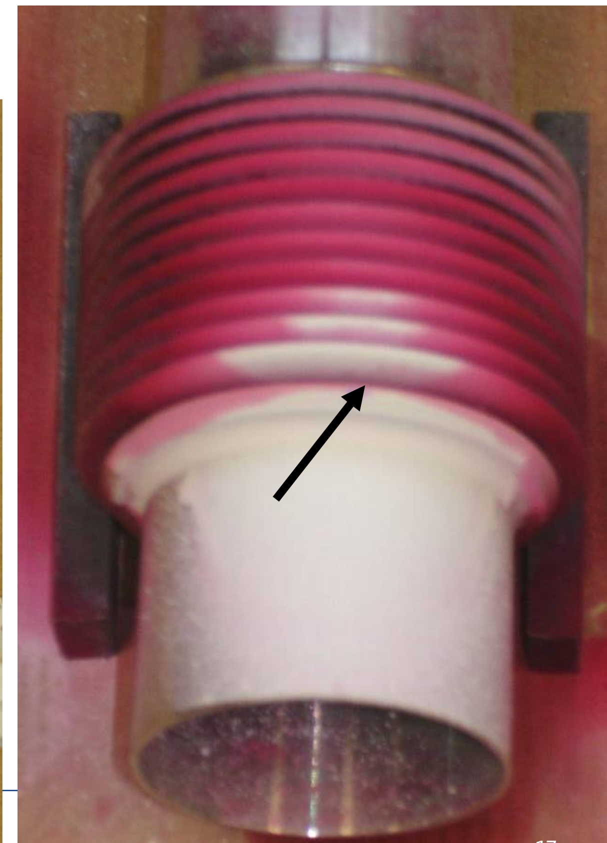
TECHNICAL SUPPORT DEPARTMENT

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*

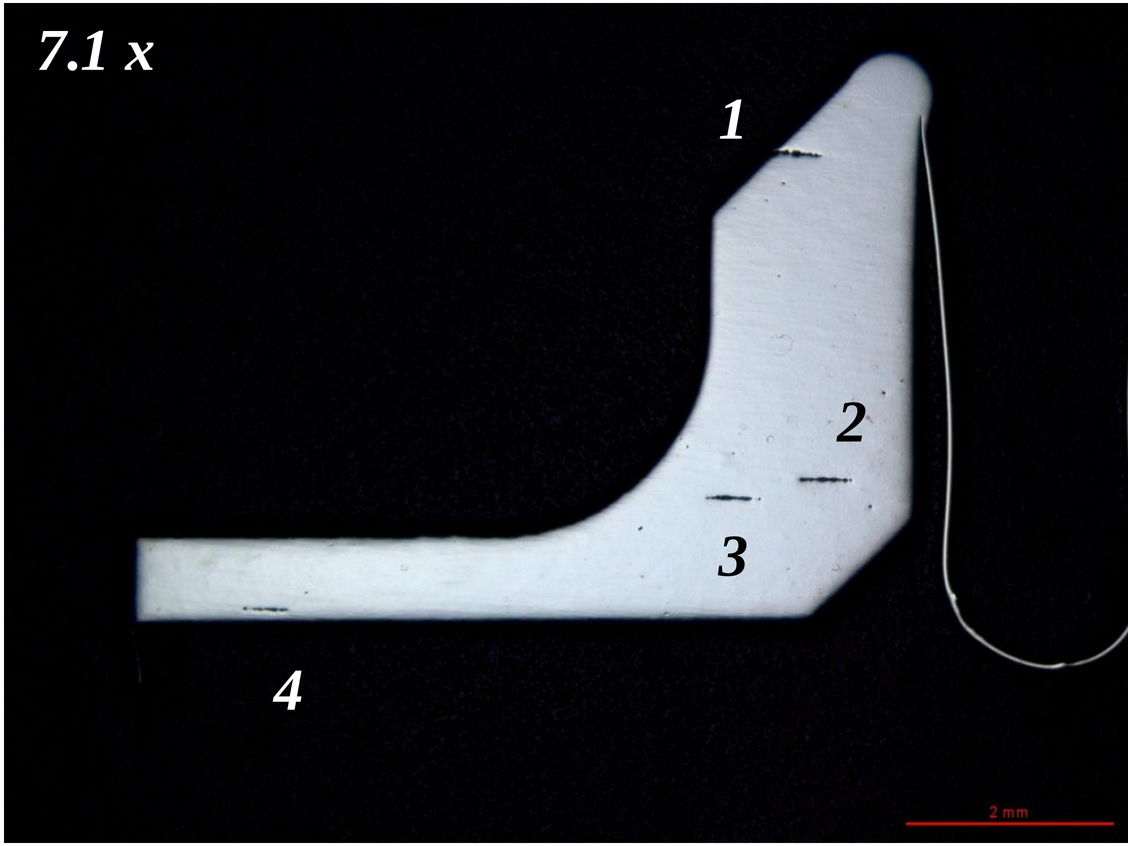
Metallographic observations of 316LN leaking bellow

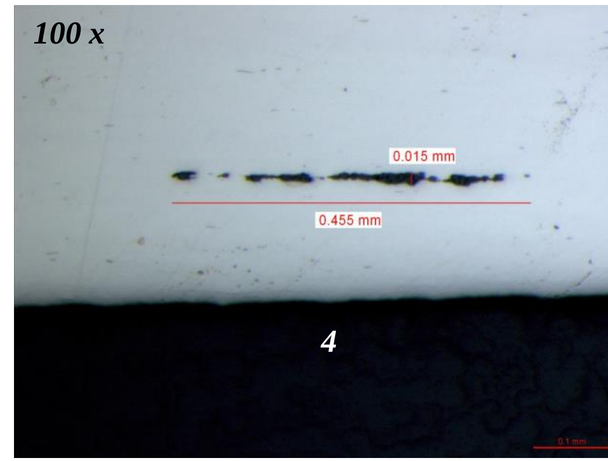


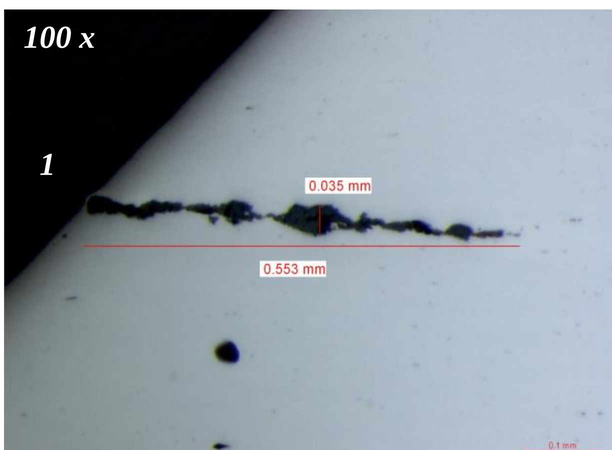


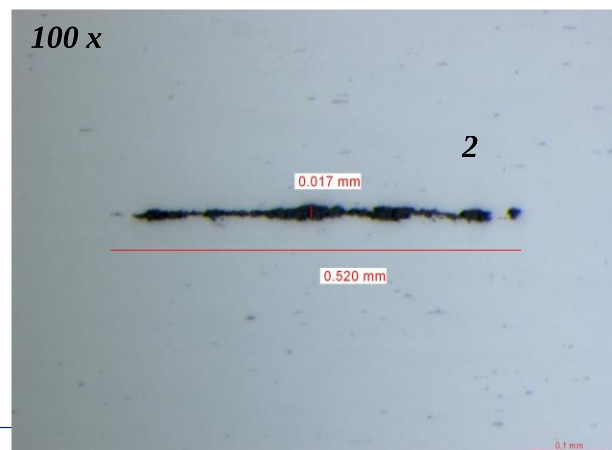
2. Stainless steels, inclusions

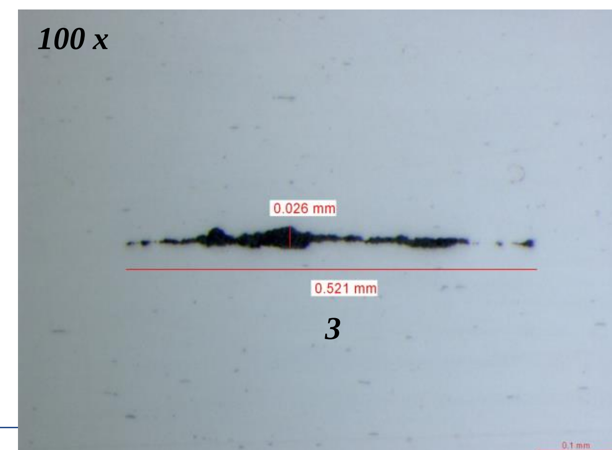
- Oversized (1,2,3) and thick (4) B type inclusions up to class 2.



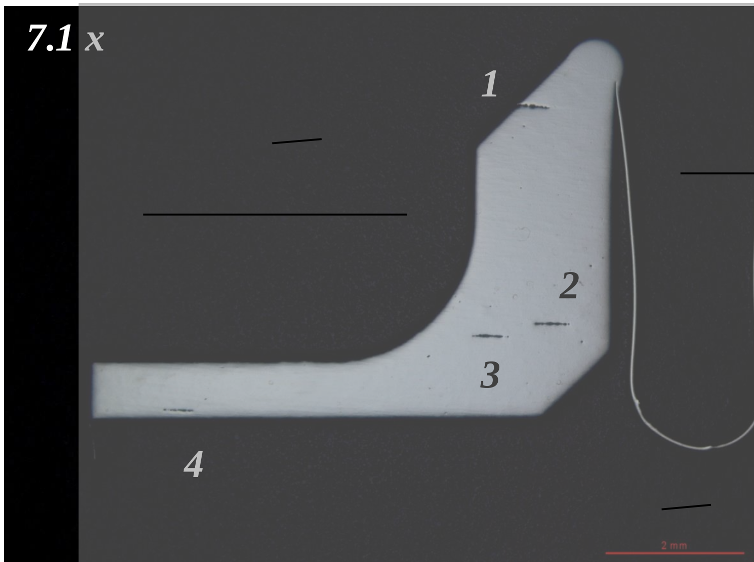








2. Stainless steels, inclusions



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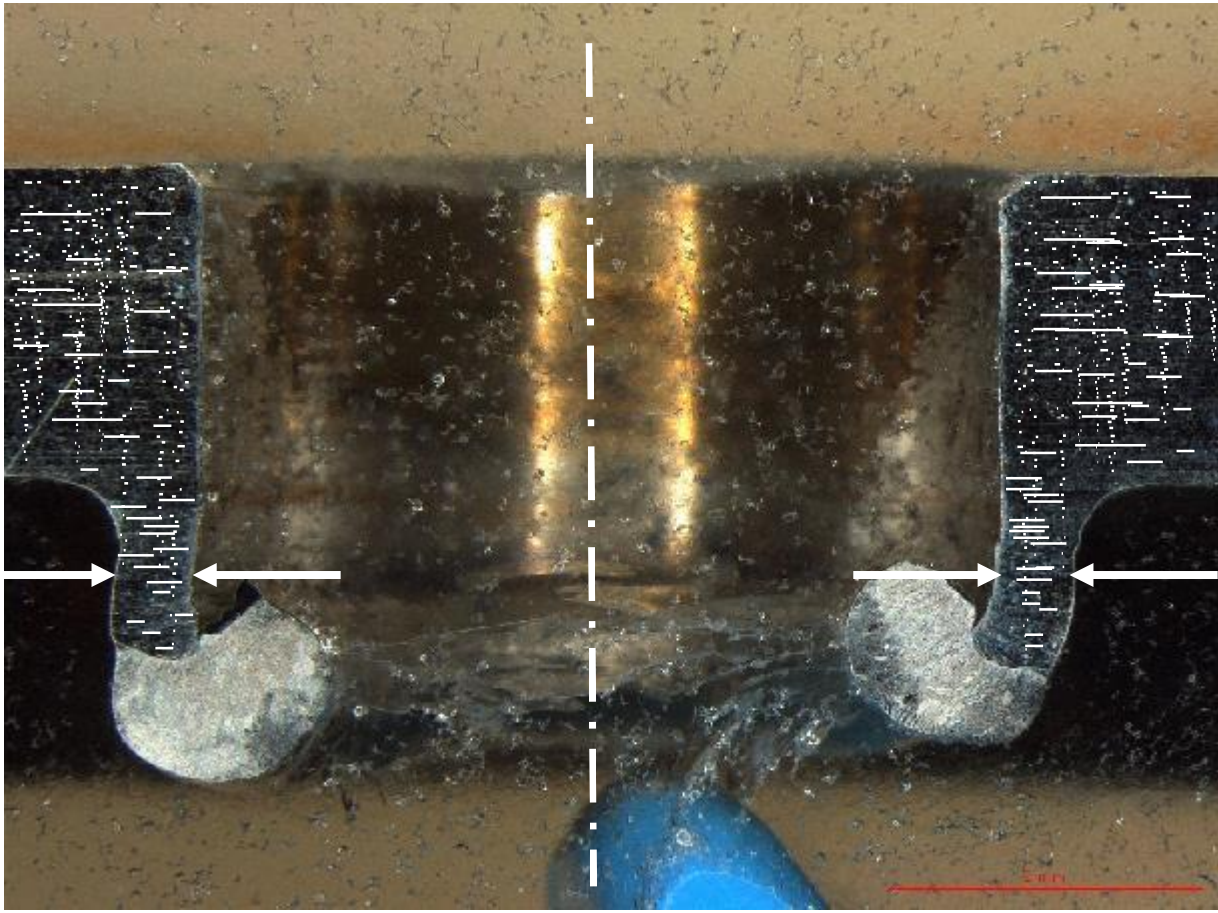
2. Stainless steels, inclusions



- **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.

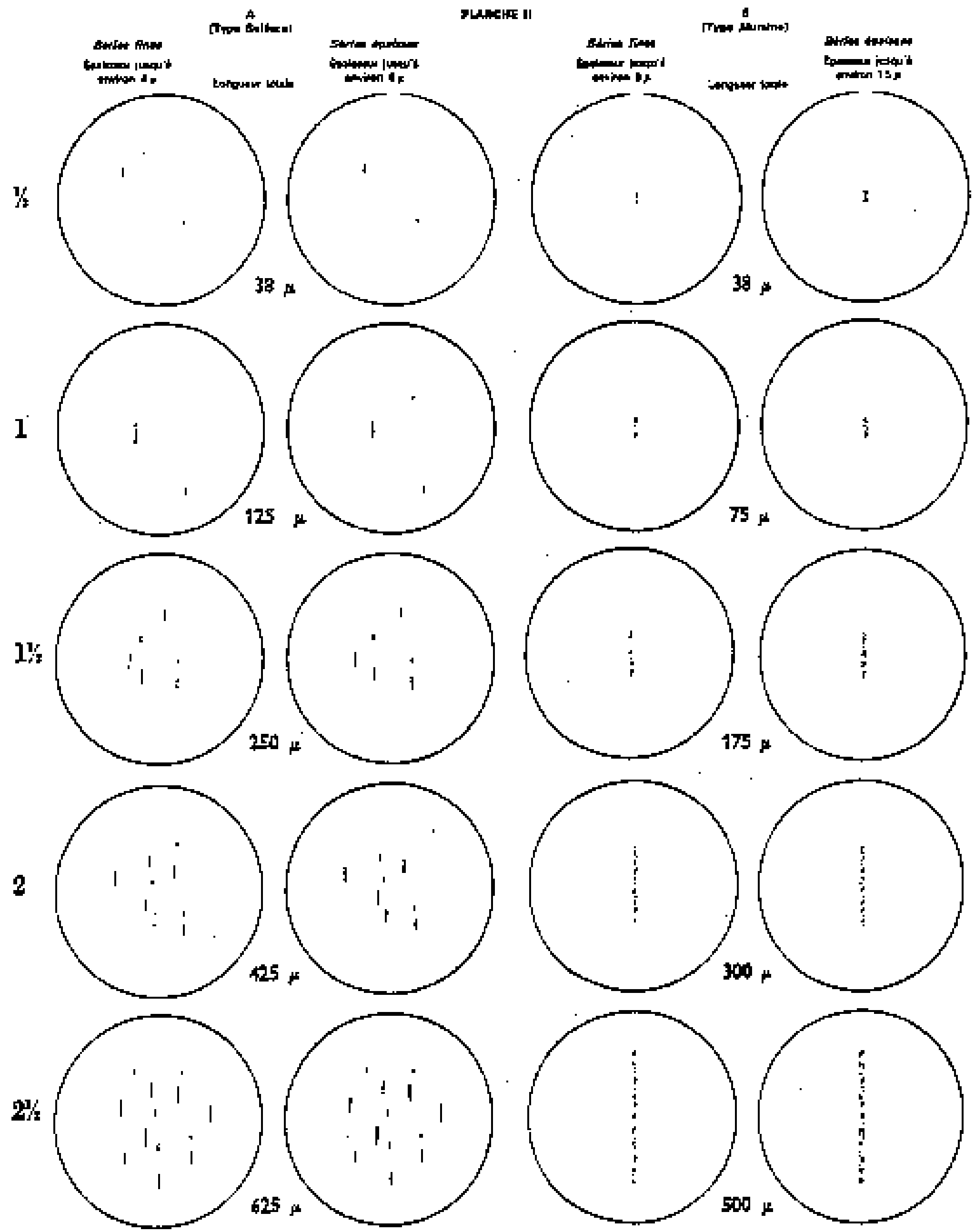
This standard has been approved for use by agencies of the Department of Defense.

TABLE 1 Minimum Values for Severity Level Numbers (Methods A, D, and E)[A,B]

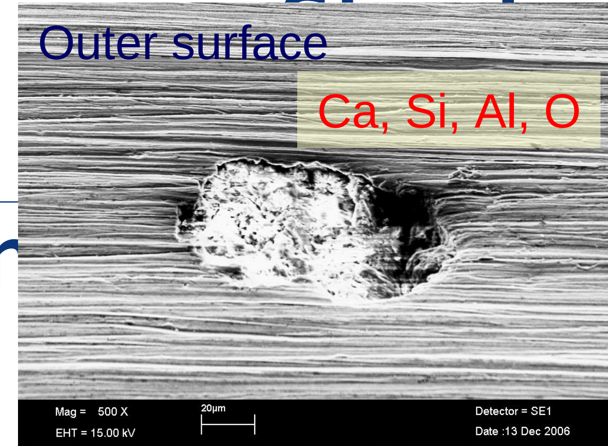
(mm (in.) at 100×, or count)				
Severity	A	B	C	D[C]
0.5	3.7(0.15)	1.7(0.07)	1.8(0.07)	1
1.0	12.7(0.50)	7.7(0.30)	7.6(0.30)	4
1.5	26.1(1.03)	18.4(0.72)	17.6(0.69)	9
2.0	43.6(1.72)	34.3(1.35)	32.0(1.26)	16
2.5	64.9(2.56)	55.5(2.19)	51.0(2.01)	25
3.0	89.8(3.54)	82.2(3.24)	74.6(2.94)	36
3.5	118.1(4.65)	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

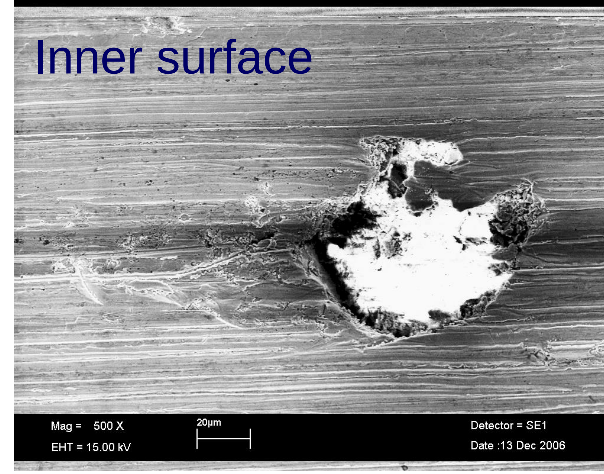
Spec. N°1001_1.4429_316LN_blanks

QUANTIMÉTRIE

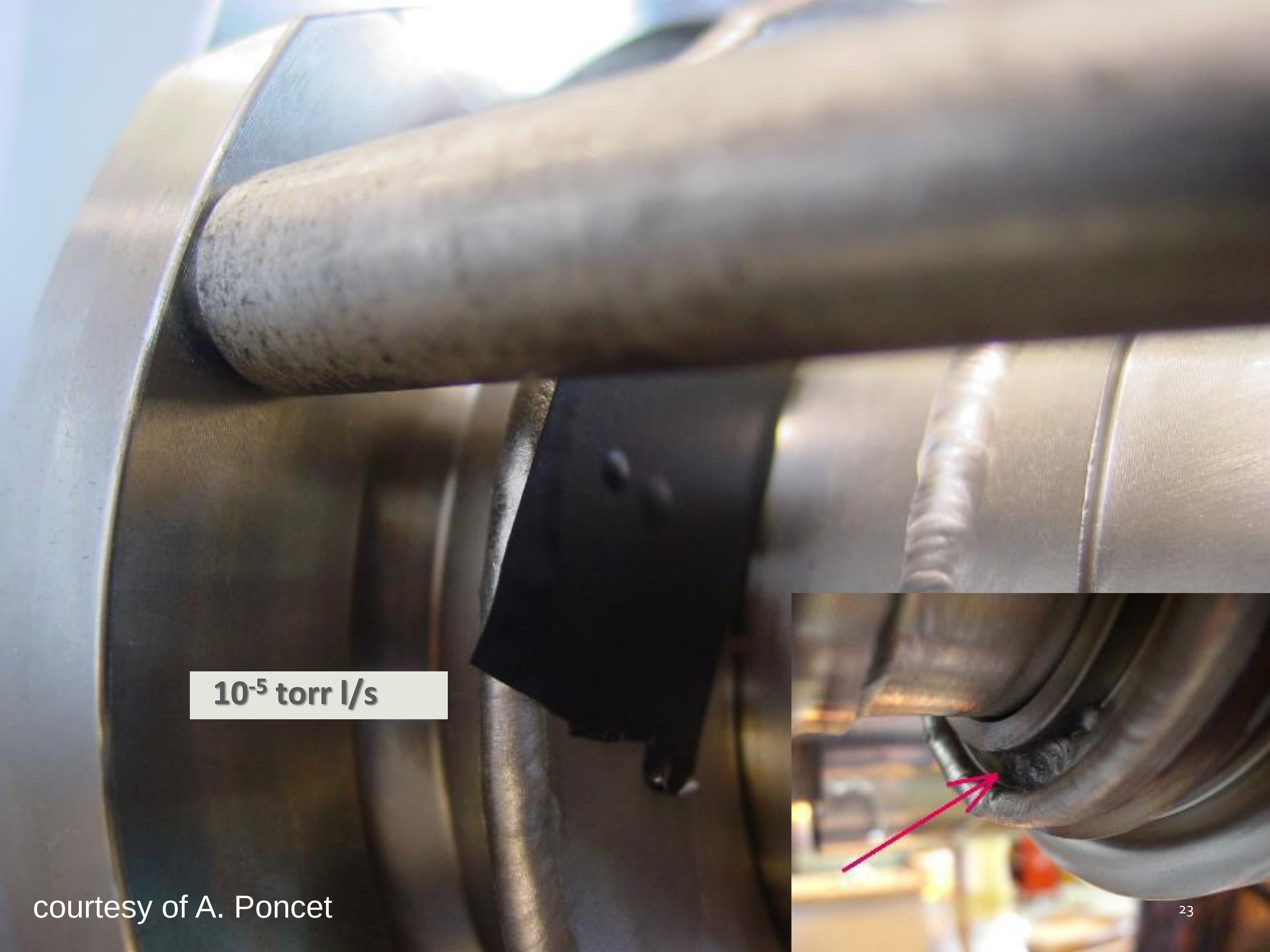


M 220 – 16





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



courtesy of A. Poncet

2. Stainless steels, macroinclusions

CERN - CH1211 Geneva 23 -
Switzerland

EDMS No.: 790775

2. REQUIREMENTS

2.1. MANUFACTURING PROCESS

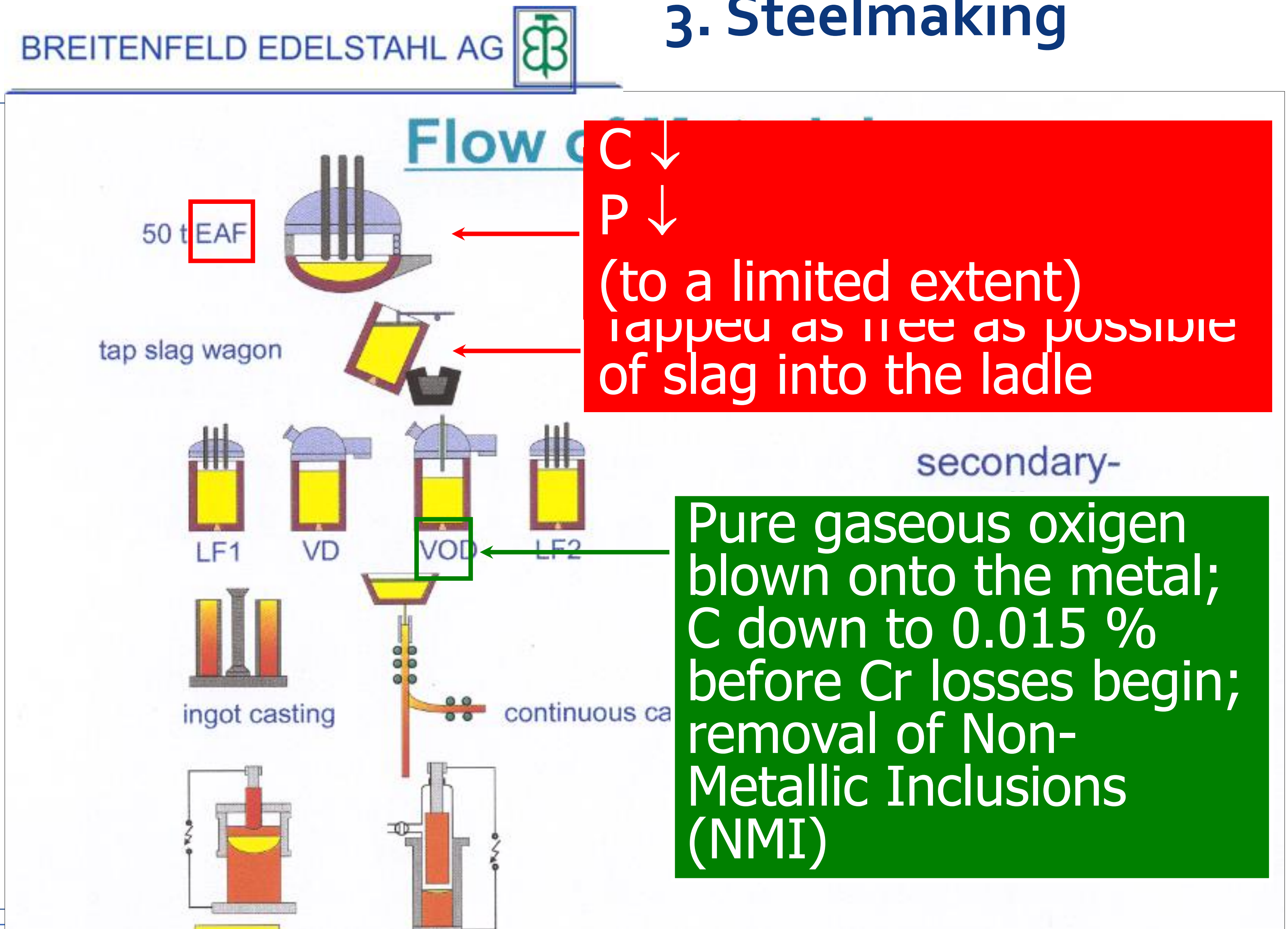
The stringent requirements of this material specification for products intended for UHV purposes, impose to apply an adapted metallurgy and manufacturing process, aimed at meeting the structure and inclusion limits specified in this document. The process shall include a mandatory ElectroSlag Remelting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

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

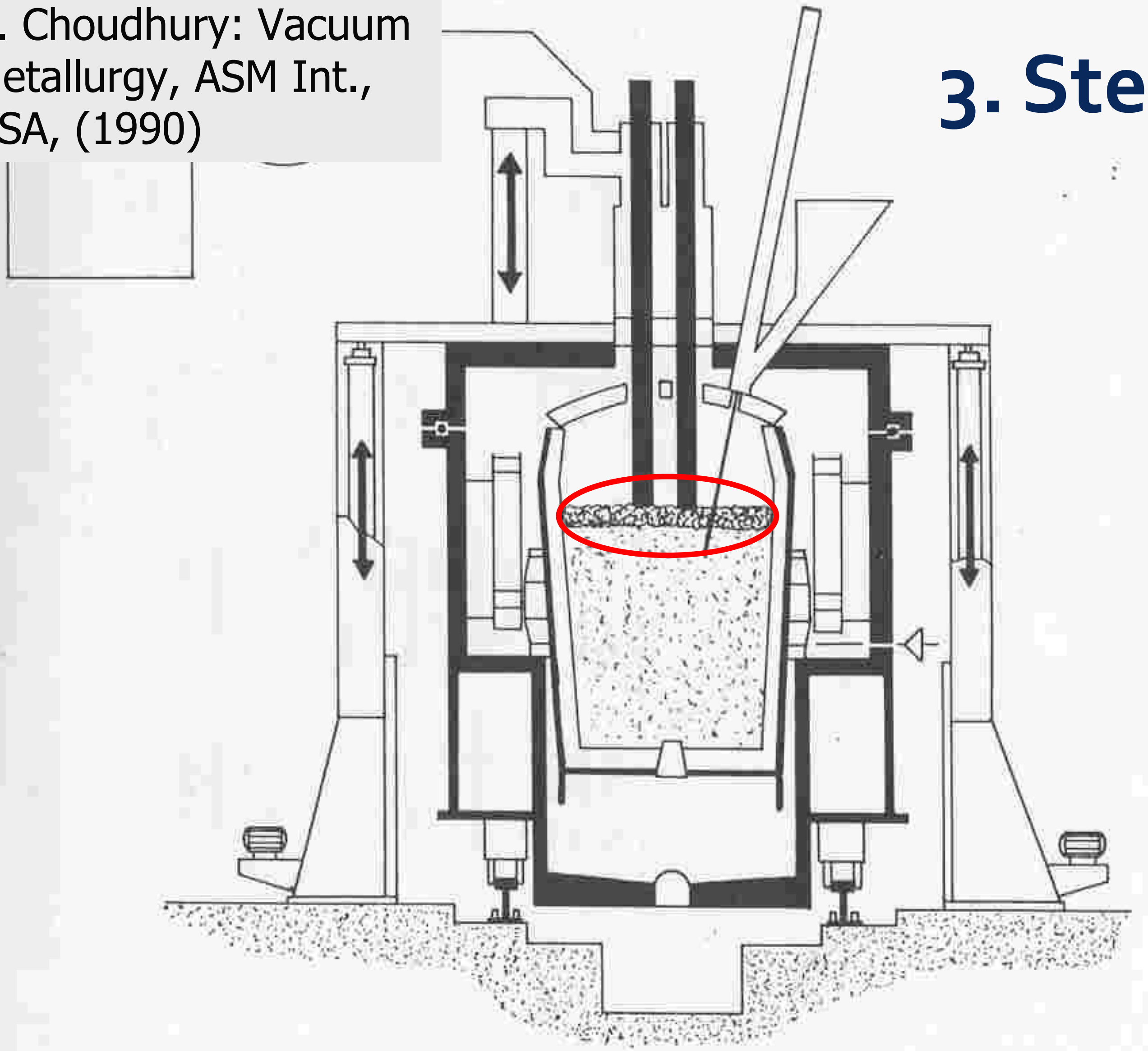
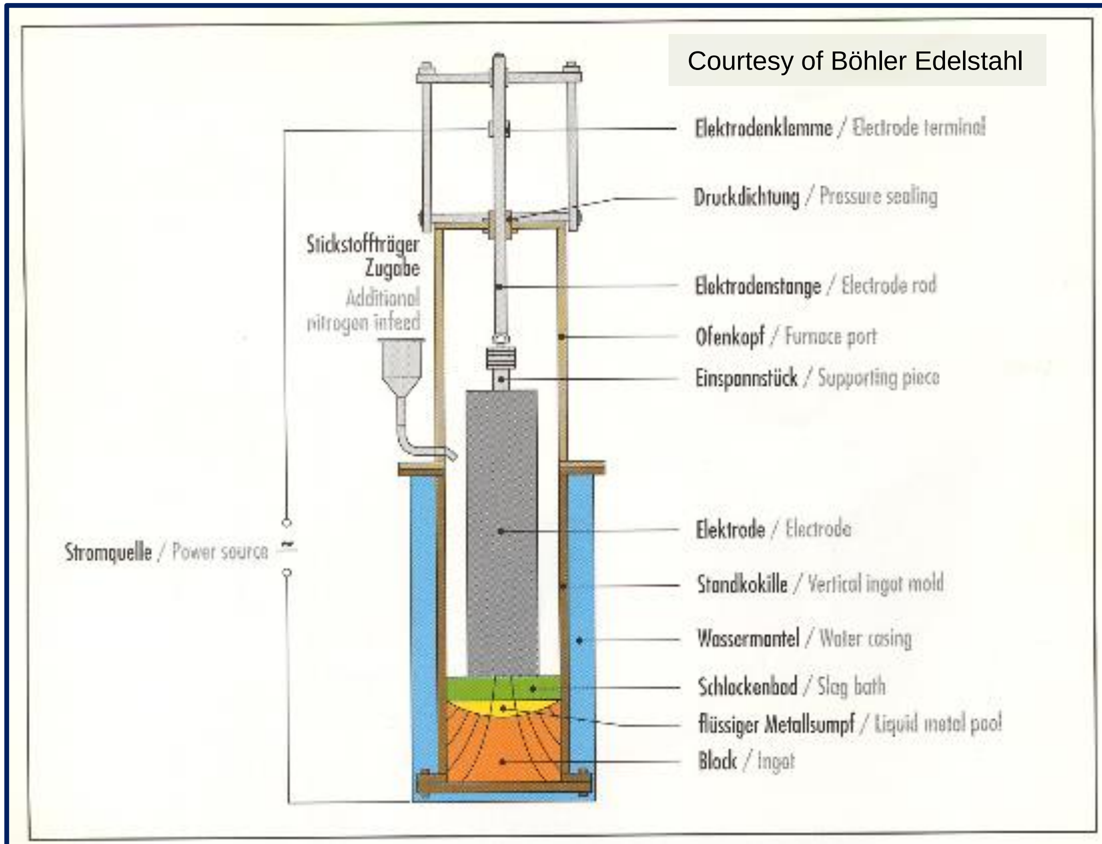
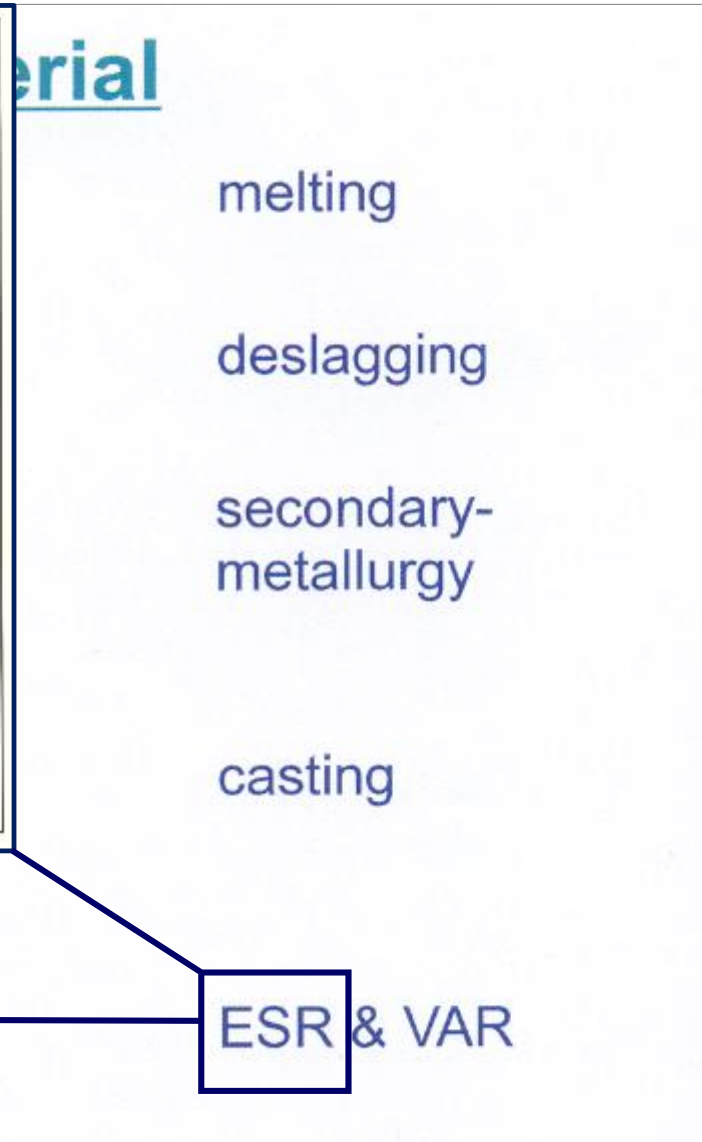
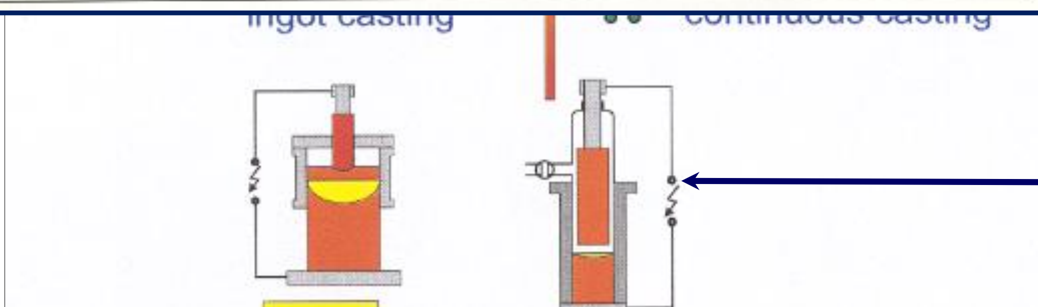


Fig. 23 Layout of a compact ladle furnace

3. Steelmaking, stainless steel





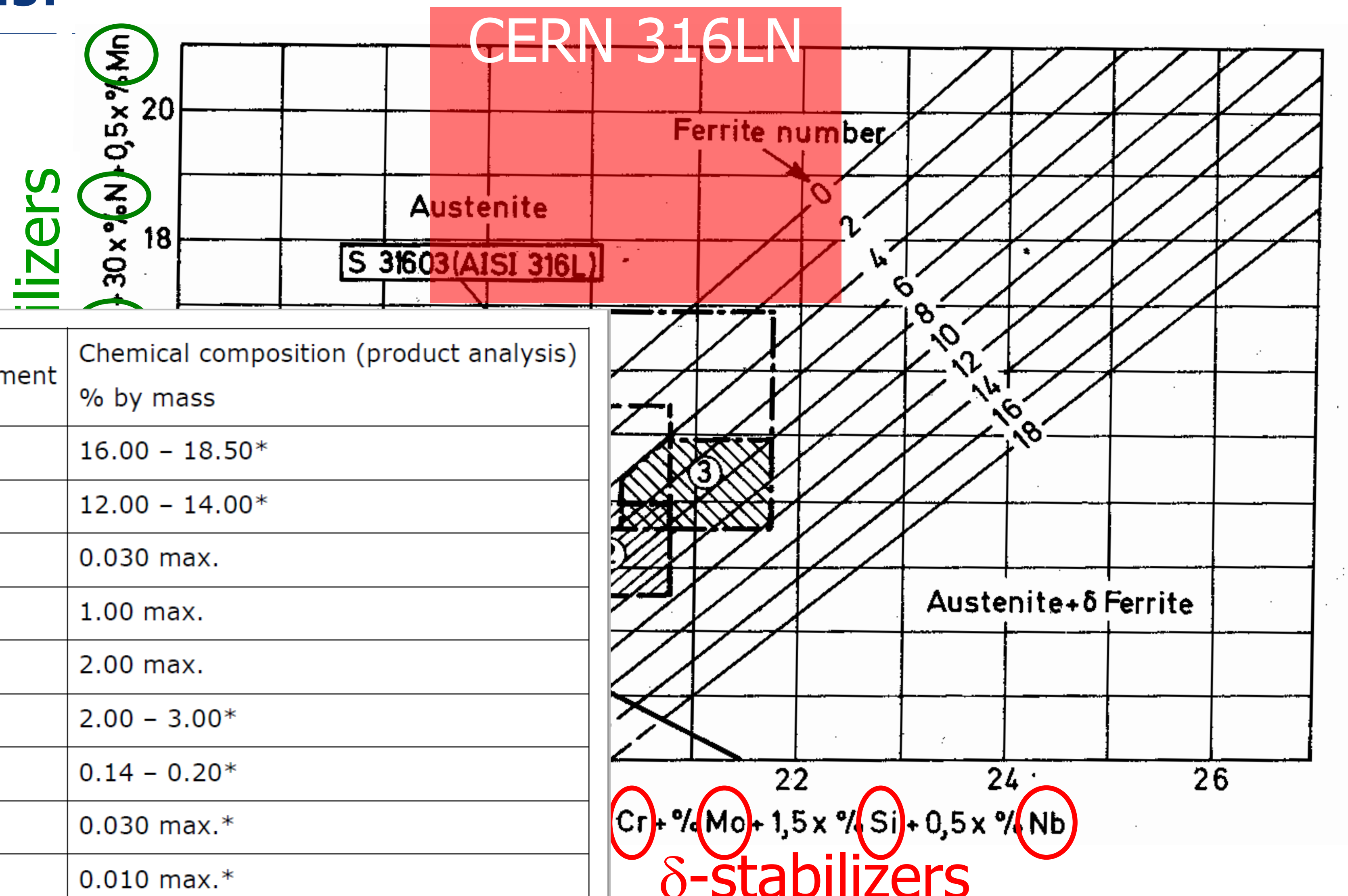


Courtesy of Forgiatura Vienna /IT
Max. ingot weight/capacity: 250 t
Two furnace heads, electrode exchange, protective gas hood, fully coaxial design; **biggest ESR plant worldwide in operation**

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. Stainless steels, precipitation and transformations, effect on properties

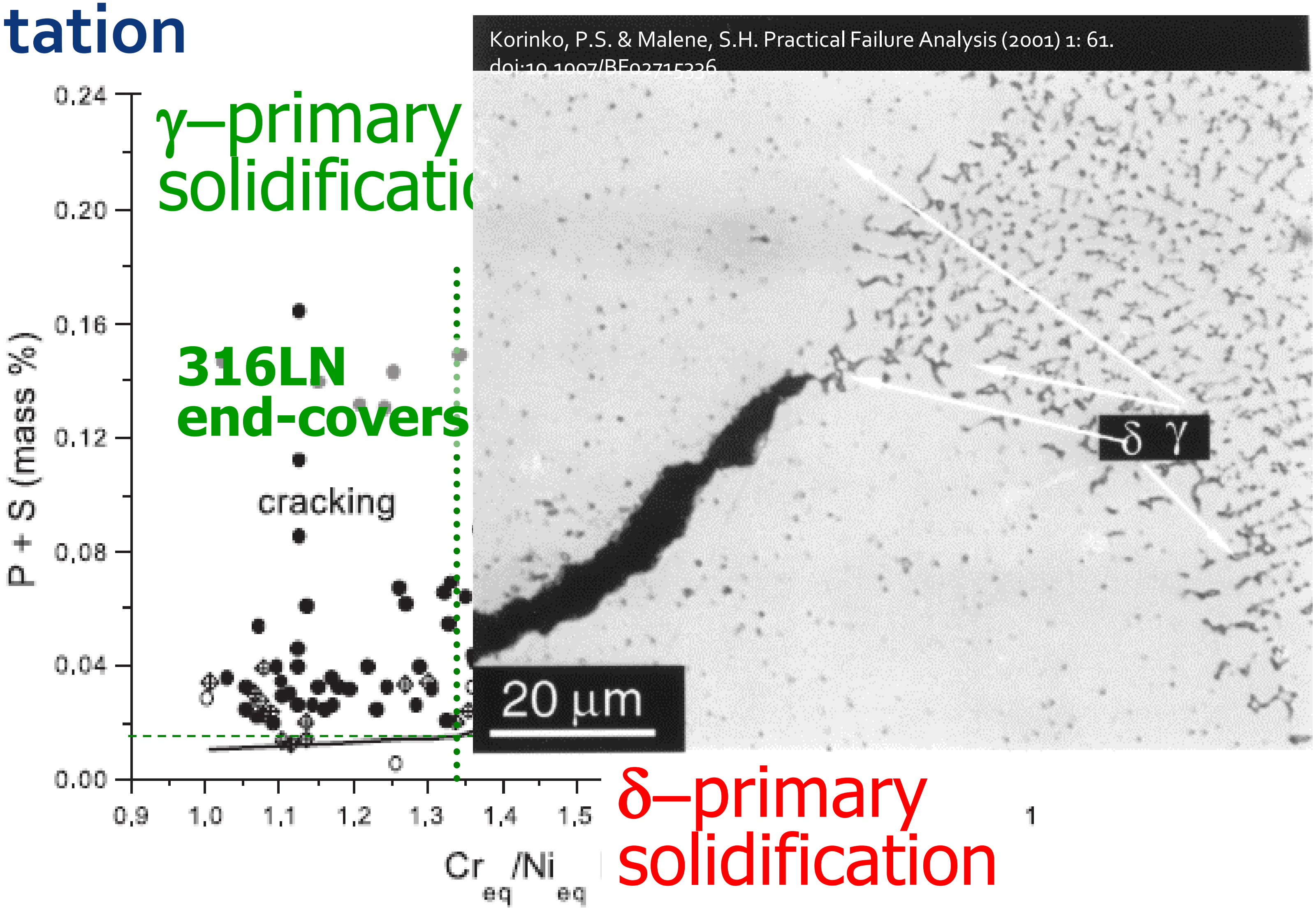


CERN 316LN

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

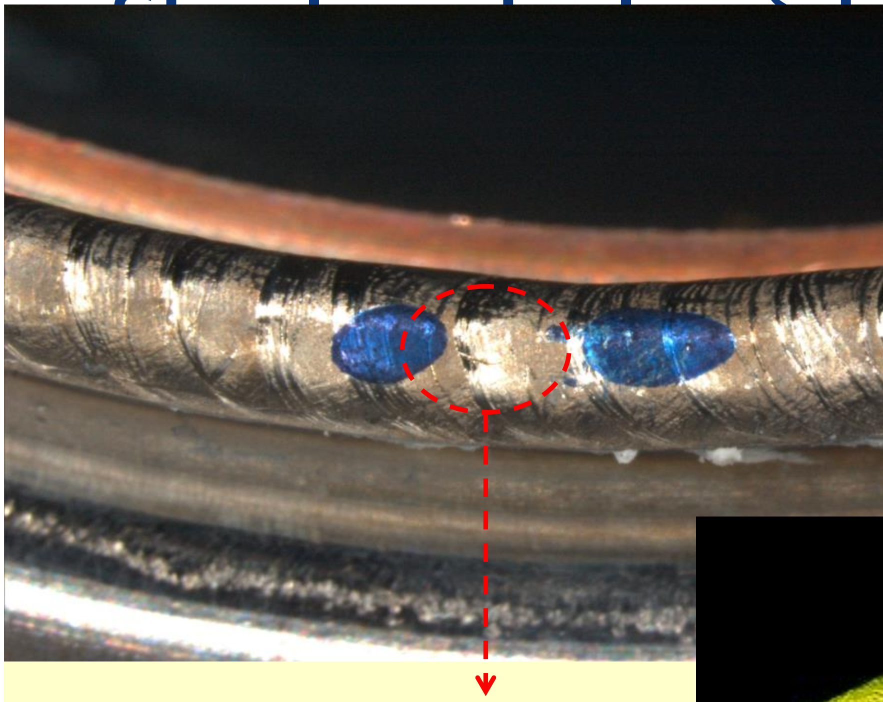
4. Stainless steels, precipitation

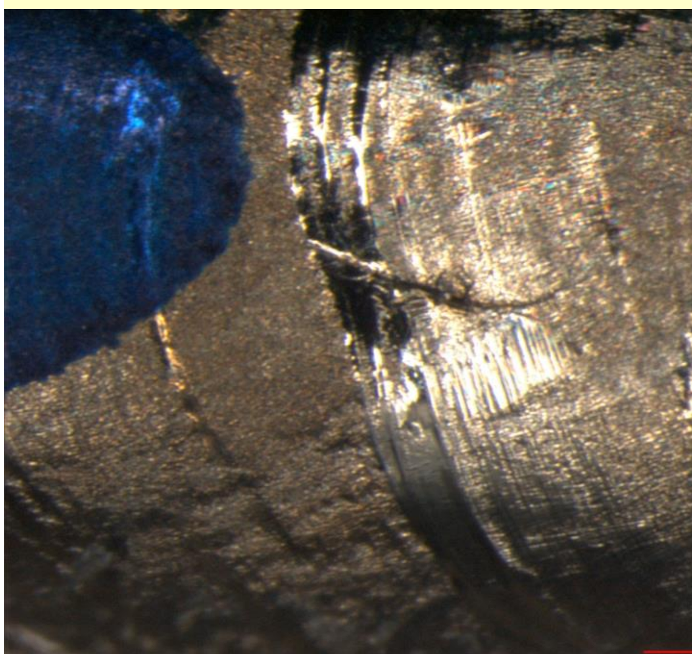


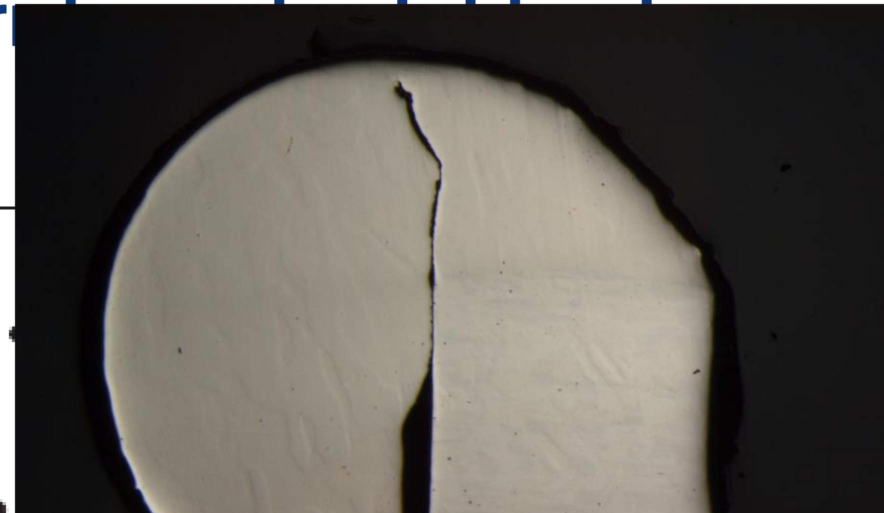
Schaeffler equivalent formulae for Cr_{eq} and Ni_{eq}

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

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



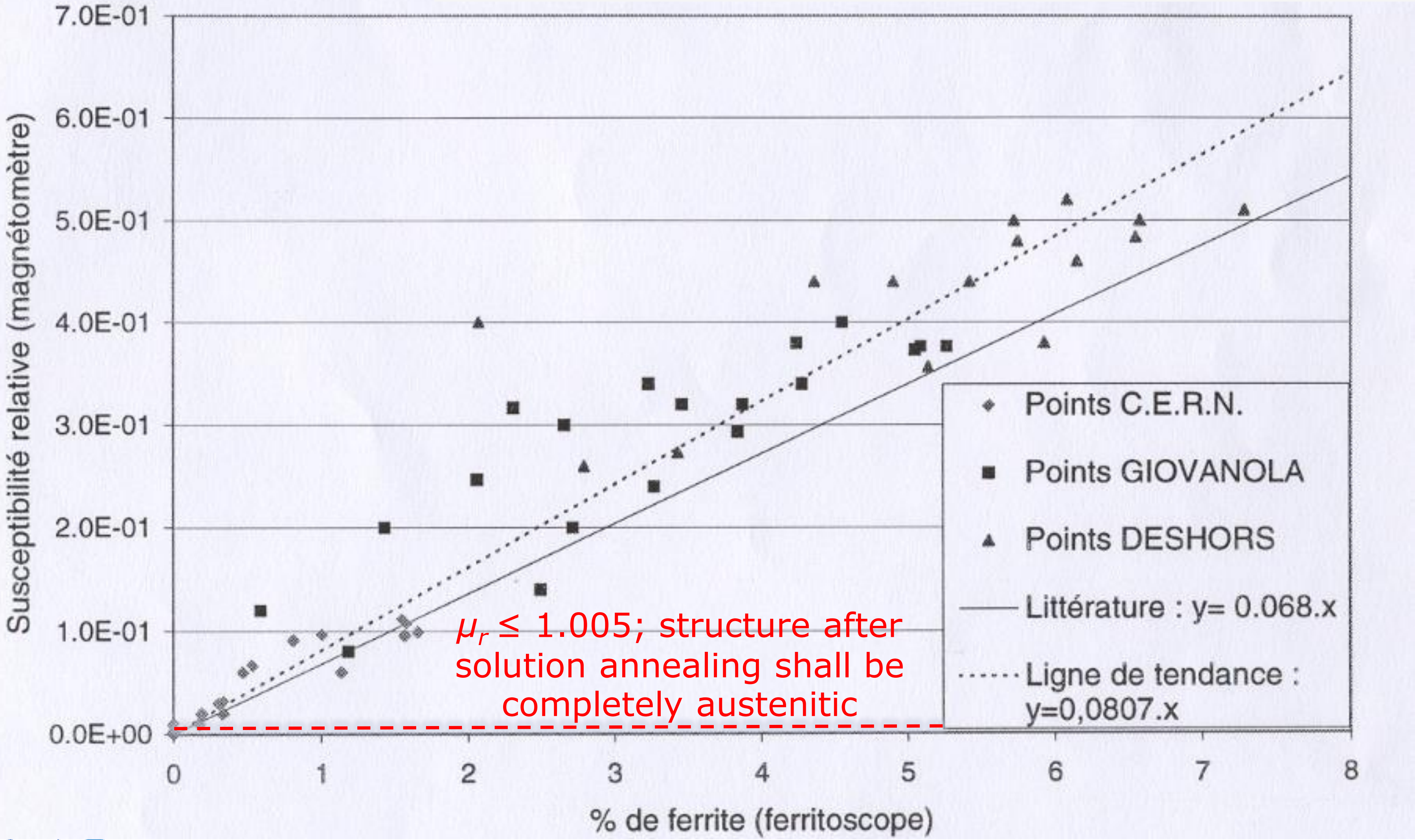




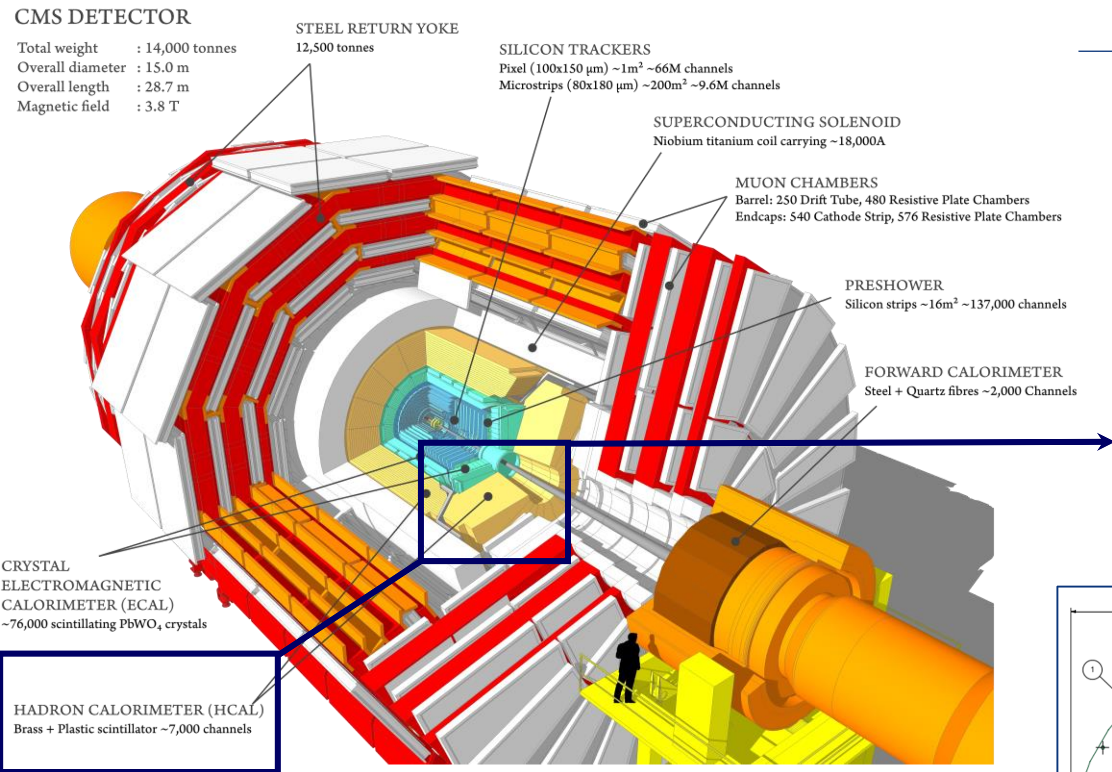

100 µm

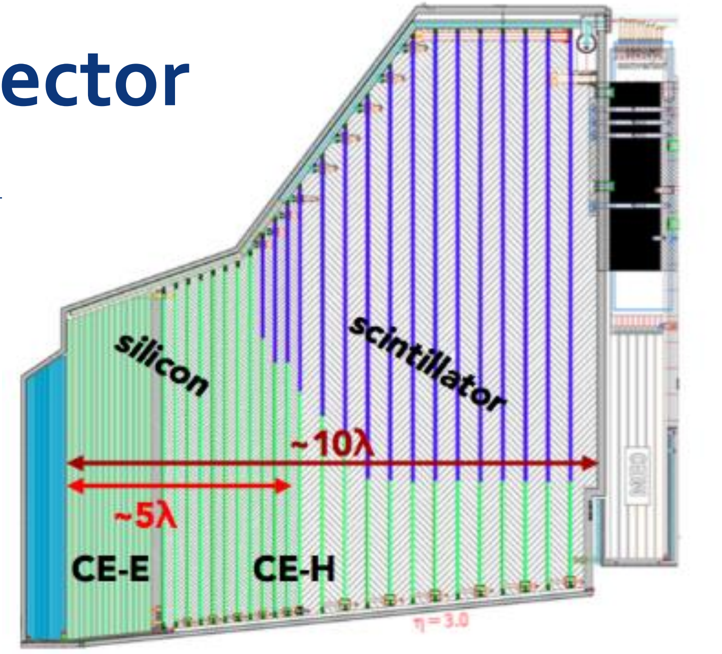
4. Stainless steels, δ-ferrite

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

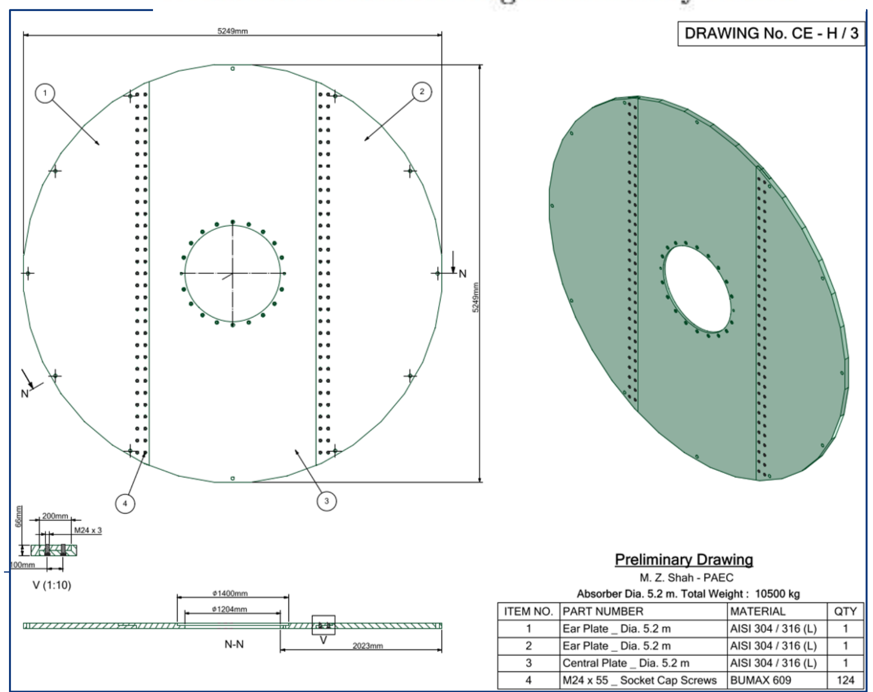


4. Case study, CMS HG-CAL detector





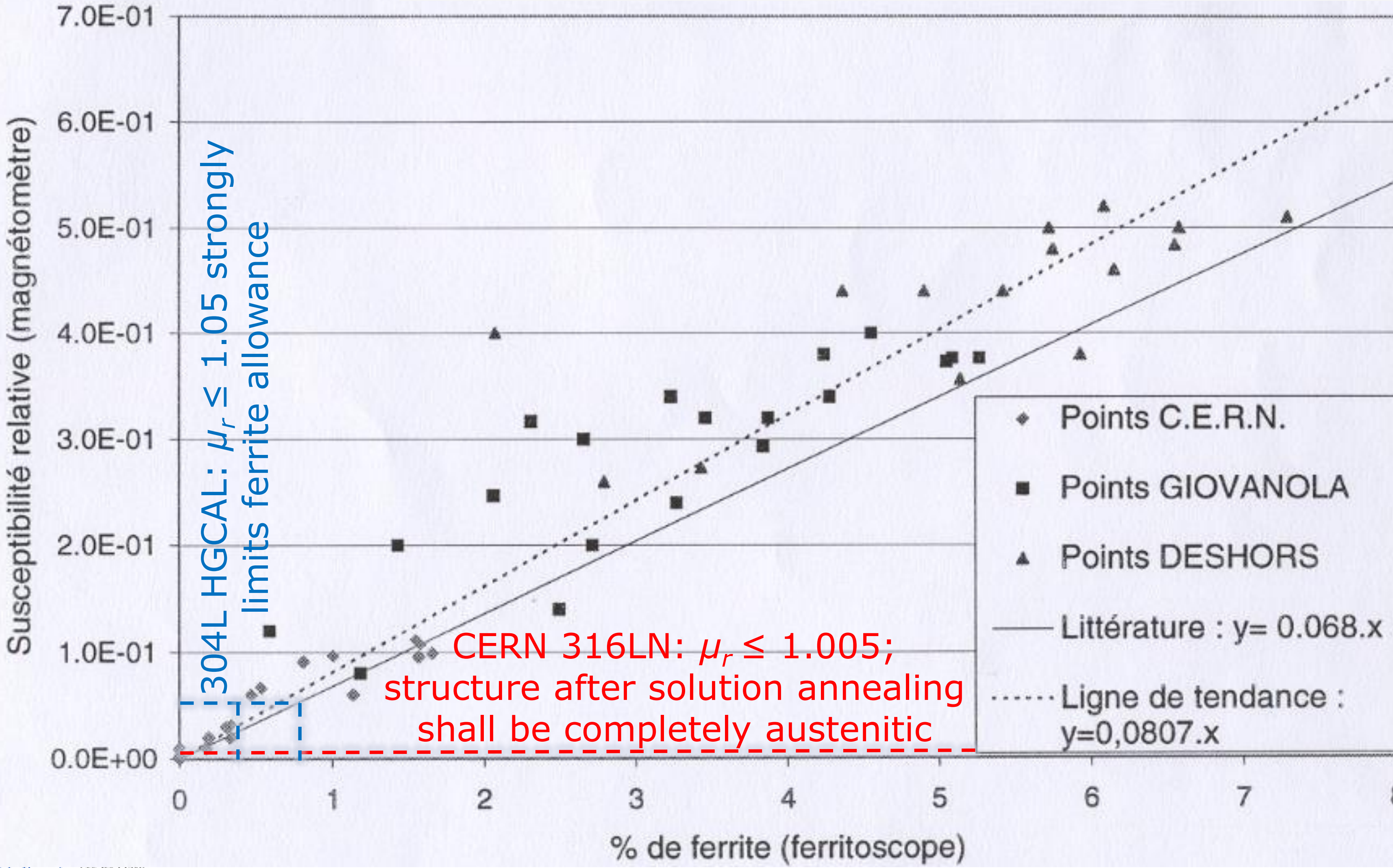
Schematic view of the High Granularity Calorimeter



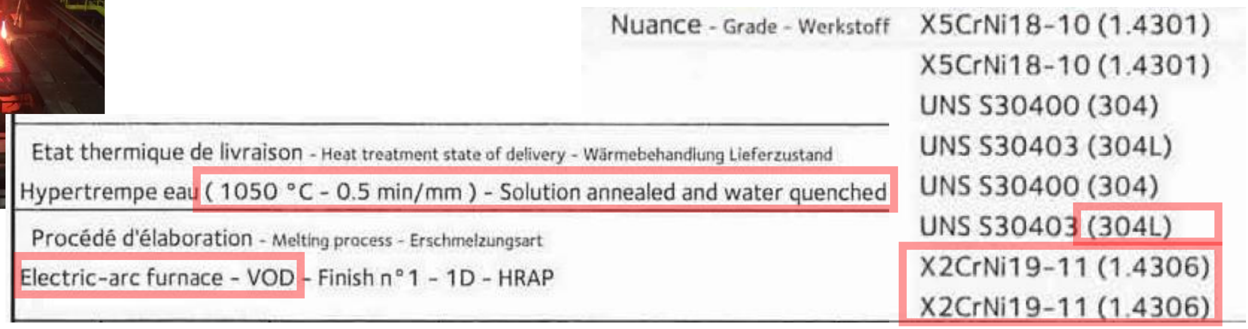
- 564 t of stainless steel required for the CE-H cassettes, thickness 45 ~110 mm
- The relative magnetic permeability in the bulk plate material shall not exceed **1.05** →
  - Stringent control of ferrite content
  - Stability against martensitic transformations

4. Case study, CMS HG-CAL detector

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



From Arcelor Mittal – Industeel /FR-BE, ref. [1] & [2]

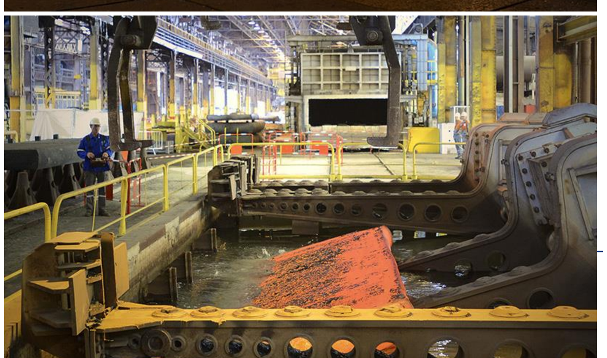


Nuance - Grade - Werkstoff	
Etat thermique de livraison - Heat treatment state of delivery - Wärmebehandlung Lieferzustand	X5CrNi18-10 (1.4301)
Hypertrempe eau (1050 °C - 0.5 min/mm) - Solution annealed and water quenched	X5CrNi18-10 (1.4301)
Procédé d'élaboration - Melting process - Erschmelzungsart	UNS S30400 (304)
Electric-arc furnace - VOD - Finish n°1 - 1D - HRAP	UNS S30403 (304L)
	UNS S30400 (304)
	UNS S30403 (304L)
	X2CrNi19-11 (1.4306)
	X2CrNi19-11 (1.4306)

Ingot or slab casting

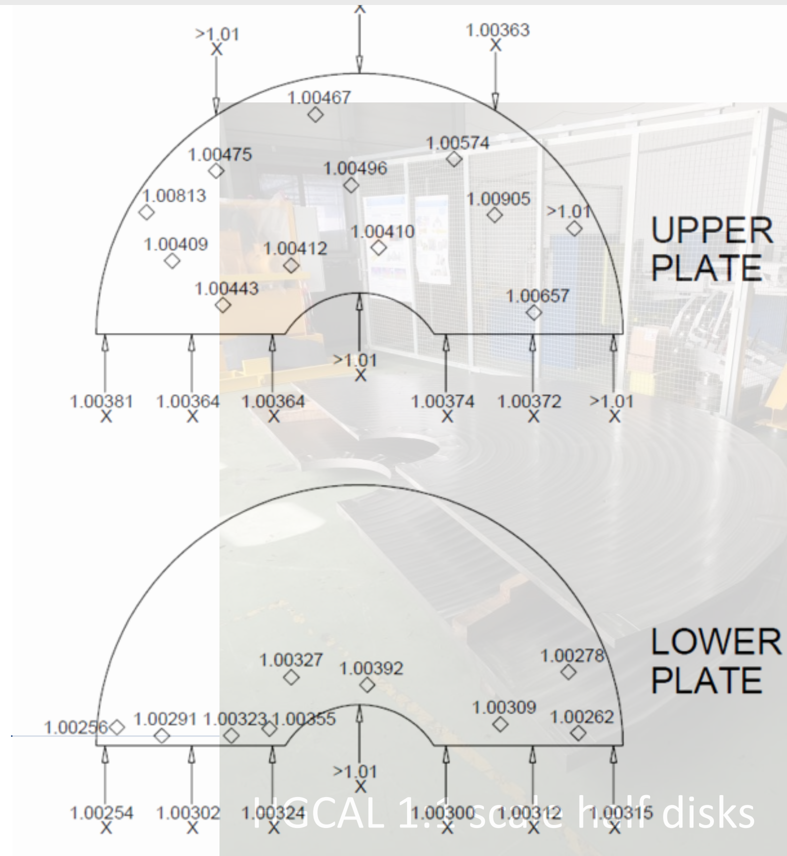
Rolled slab

Rolling of quarto plates



Solution annealing and finishing (descaling, grinding, skin pass rolling where applicable)

Courtesy of S. Moccia & M. Pentella



NUMERICAL DESIGNATION 1.4307	NUMERICAL DESIGNATION 1.4306

Basic Information

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

1.4307: "Low alloy" 304L

1.4306: "High alloy" 304L

Chemical Composition (%)

1.4307:

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	

1.4306:

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	

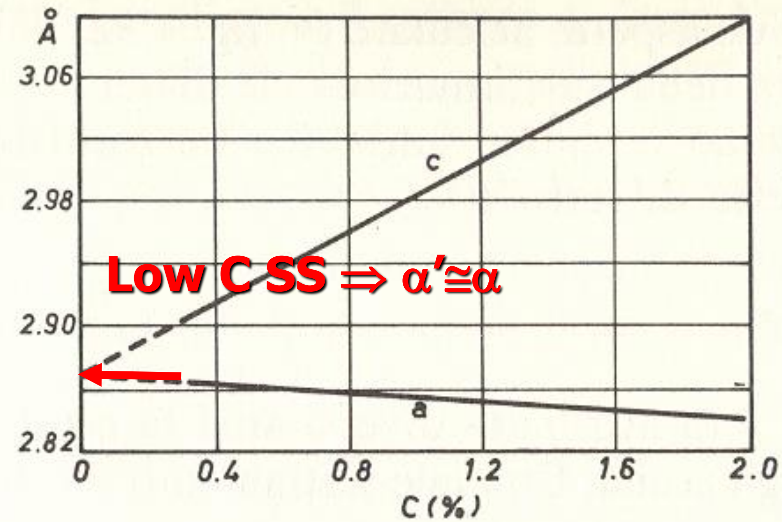
- Low magnetic permeability, ceteris paribus:
  - Stringent control of ferrite content (composition / steelmaking route)
  - Stability against martensitic transformations (grade selection)

4. Martensitic transformations

Martensitic transformation ($\gamma \Rightarrow \alpha'$),

a cause of loss of non-magnetism

in austenitic stainless steels



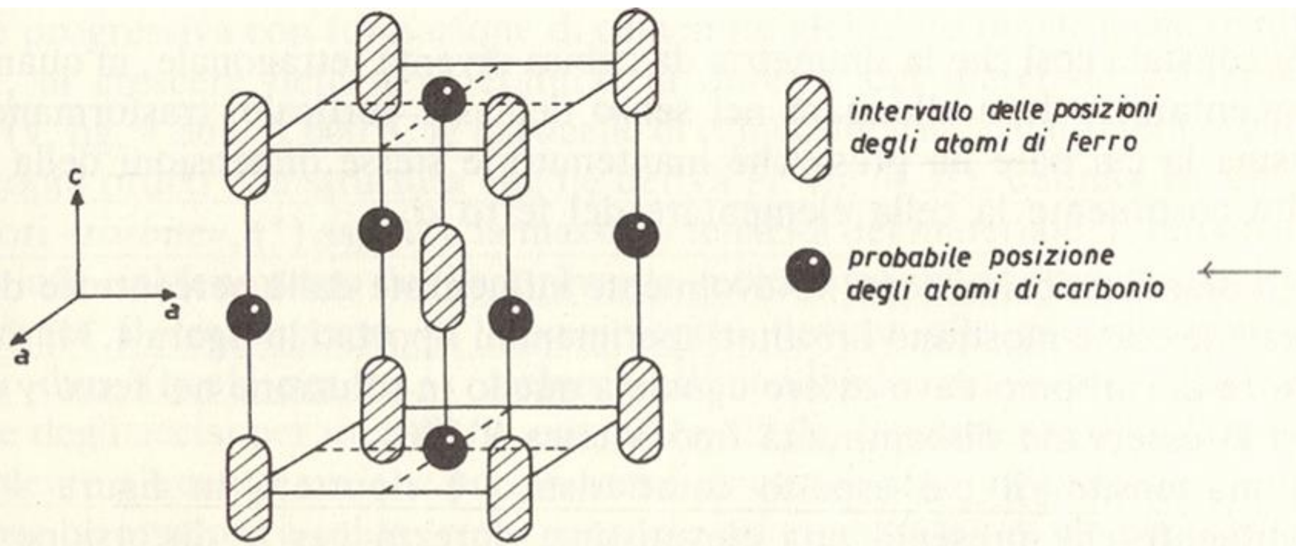


Fig. 4.33 *Schematizzazione del reticolo tetragonale della martensite: la forma allungata della posizione degli atomi di ferro sta ad indicare che la distanza reticolare degli stessi, relativamente all'asse c, può variare* (da H. Lipson).

4. Martensitic transformations

Martensitic transformation have two forms:

- $\gamma \Rightarrow \alpha'$, b.c.c., relevant for magnetic purposes
- $\gamma \Rightarrow \varepsilon$, h.c.p., not treated here

occur spontaneously on cooling and/or are strain induced under a given temperature

R.P. Reed, A.F. Clark (1983)

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

Investigator (Year)	Temperature Equivalent: Base	Cr	Ni	Mn	Si	C	N	Mo	Other	Comments, Composition Range (wt.%)
f.c.c.→b.c.c. (T_{ms}) cooling; Eichelman, Hull (1953)										21 alloys: 10–18Cr, 6–12 Ni, 0.6–5Mn, 0.3–26Si, 0.004–0.12C, 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)										30% tension, 50% α′
Hull (1973)									Co)	50% compression, 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. Martensitic transformations

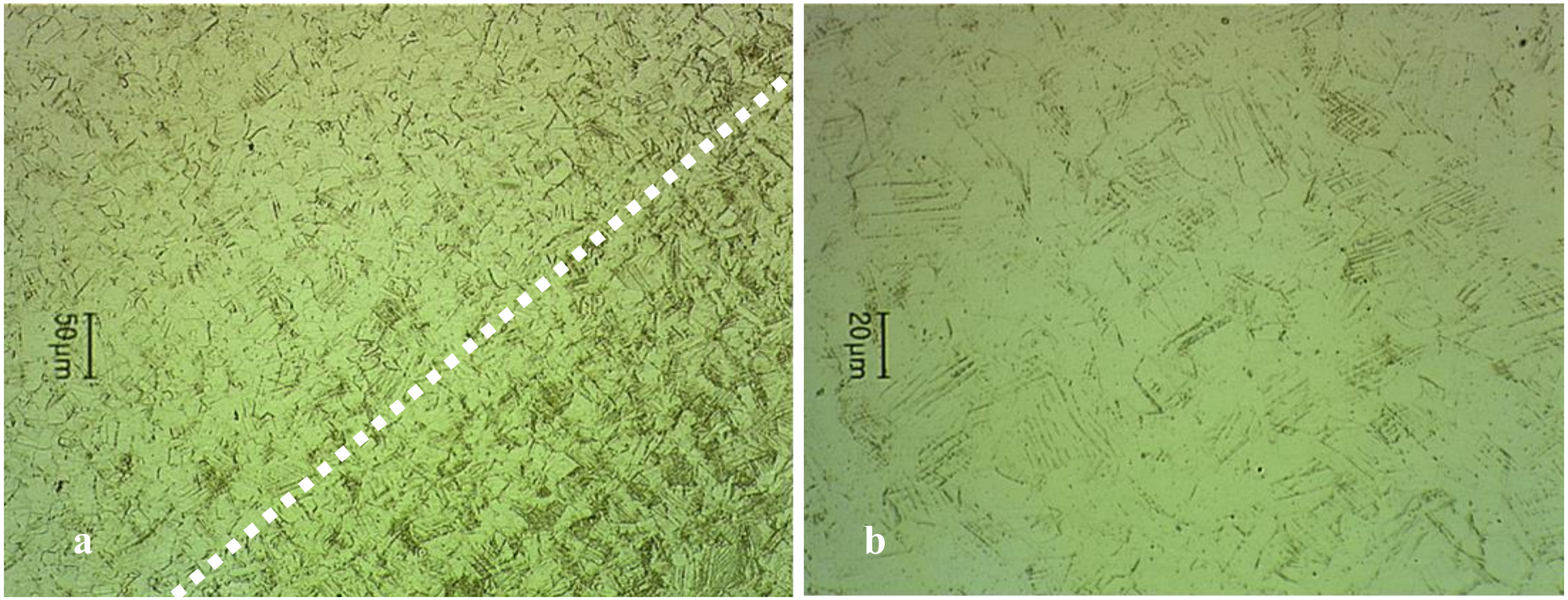
All coefficient are negative:

- 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 ($\mathbf{T_{ms}}$, 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. 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. Martensitic transformations

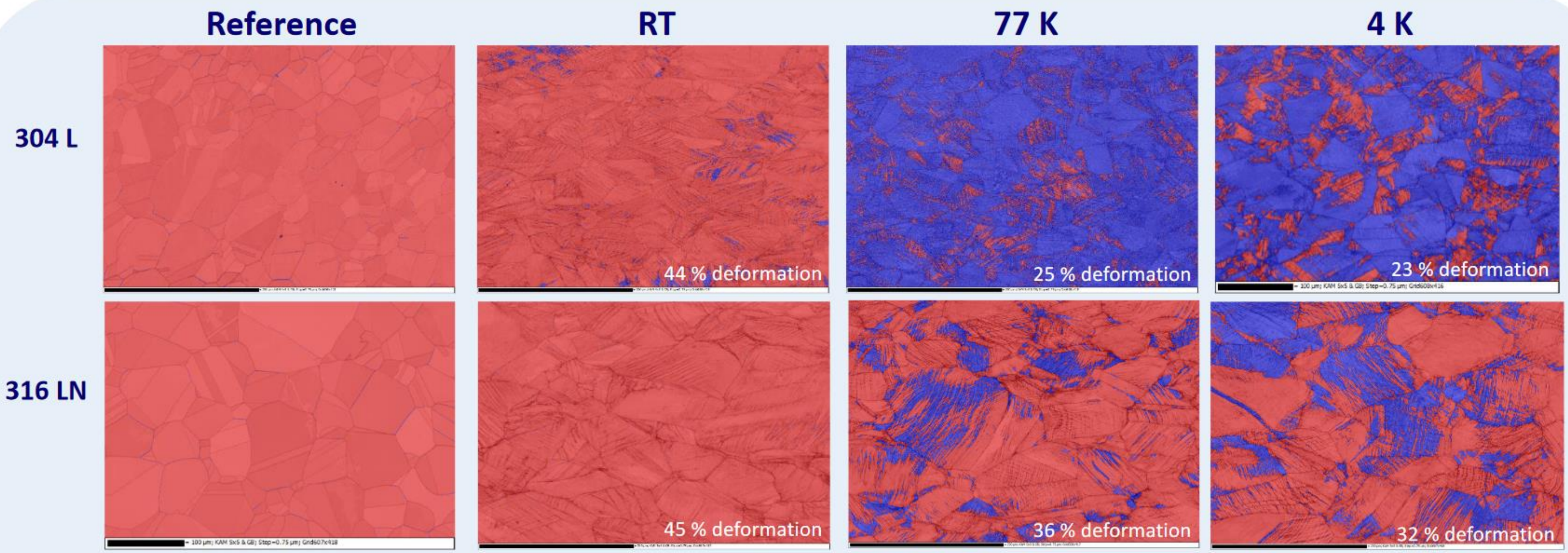


Figure 2 - EBSD phase map and band contrast map on 304 L and 316 LN samples at different temperatures. Colour code: martensite (Fe BCC) appears in blue, while the austenite (Fe FCC) is shown in red

Quantitative assessment through EBSD techniques associated to SEM

Courtesy of E. García-Tabarés Valdivieso, P. Fernandez Pison, A. T. Pérez Fontenla, to be published

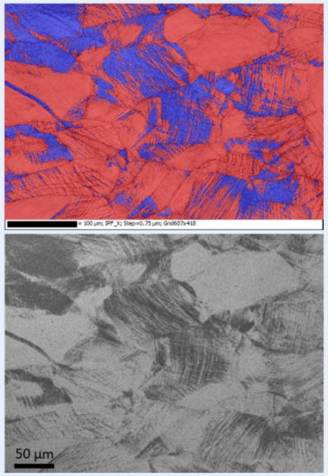
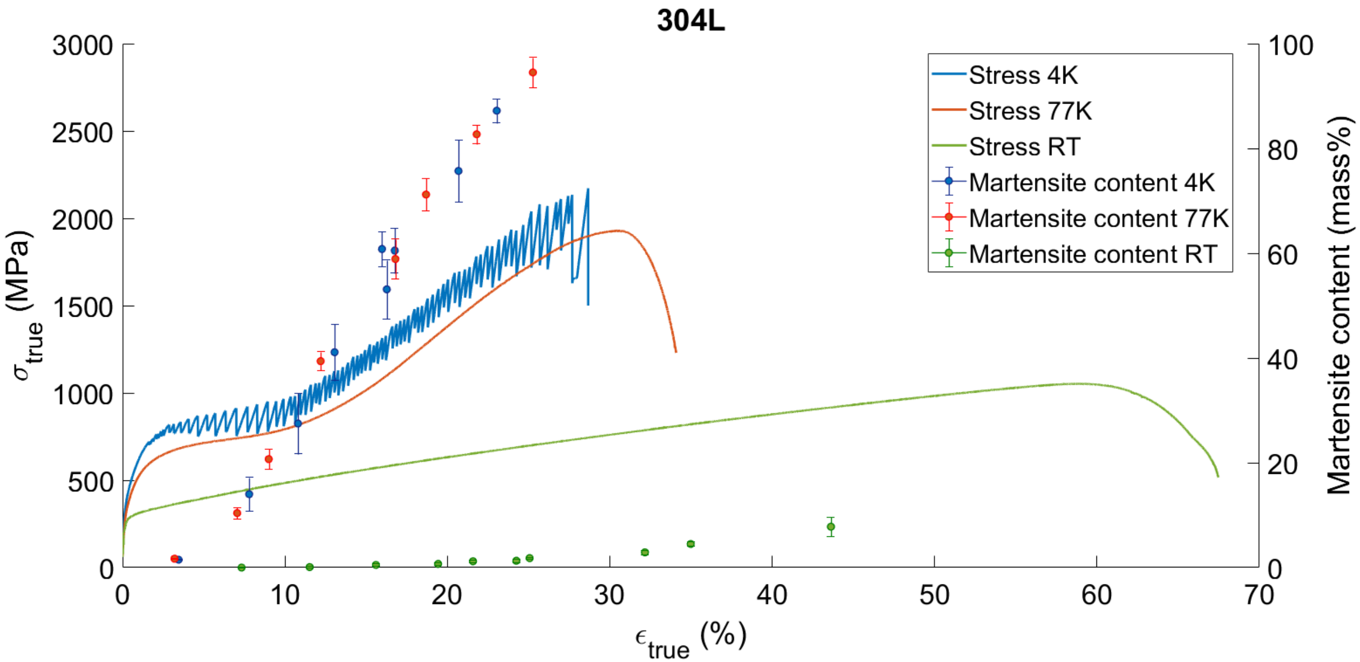
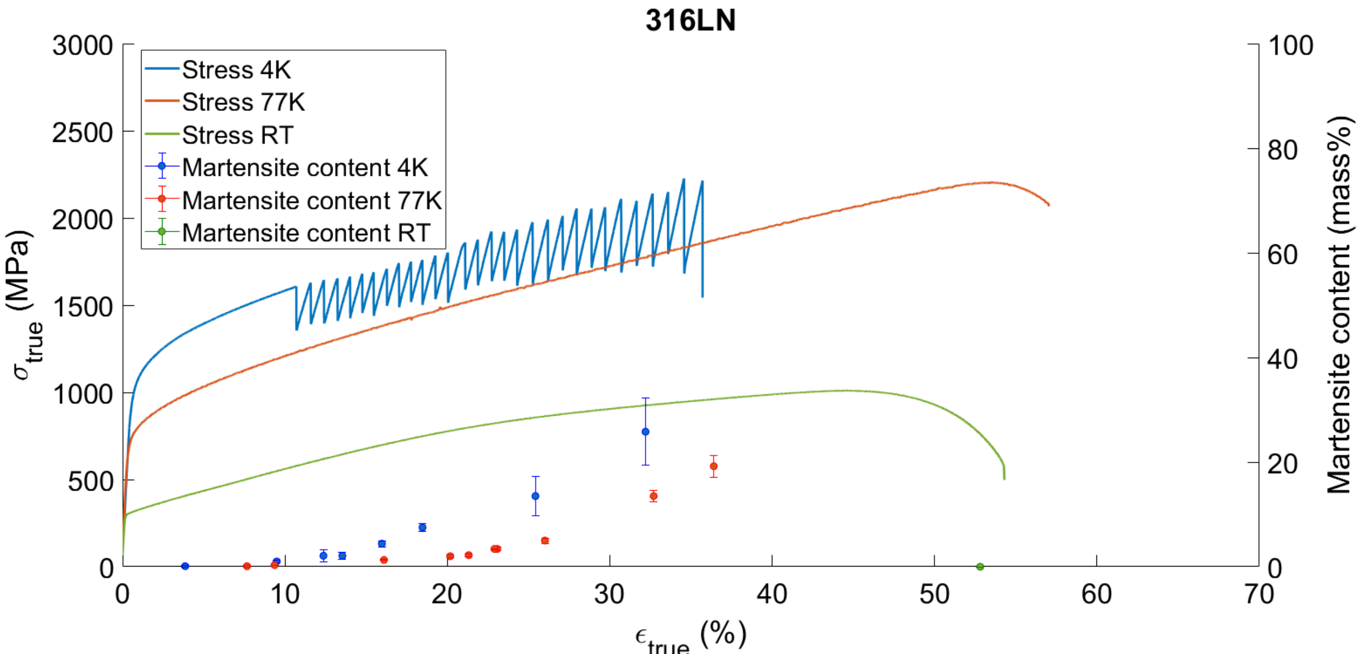


Figure 3 - Correlation between EBSD map and optical microscope image for SS 316 LN @ 4K, 32% deformation

4. Martensitic transformations

Courtesy P. Fernandez Pison, to be published





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

CERN specification, 316LN

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

See also ⇒ CAS course on "Mechanical & Materials Engineering", P. Chiggiato, Vacuum

5. Thermal treatments, sensitization, corrosion failures

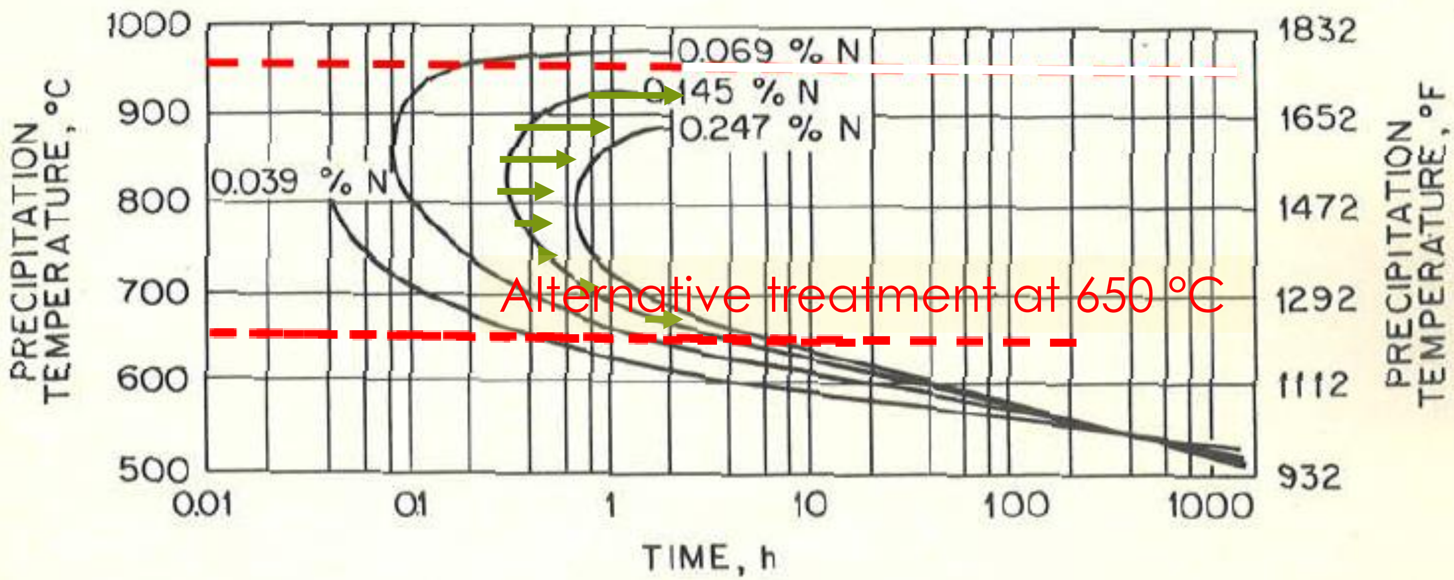


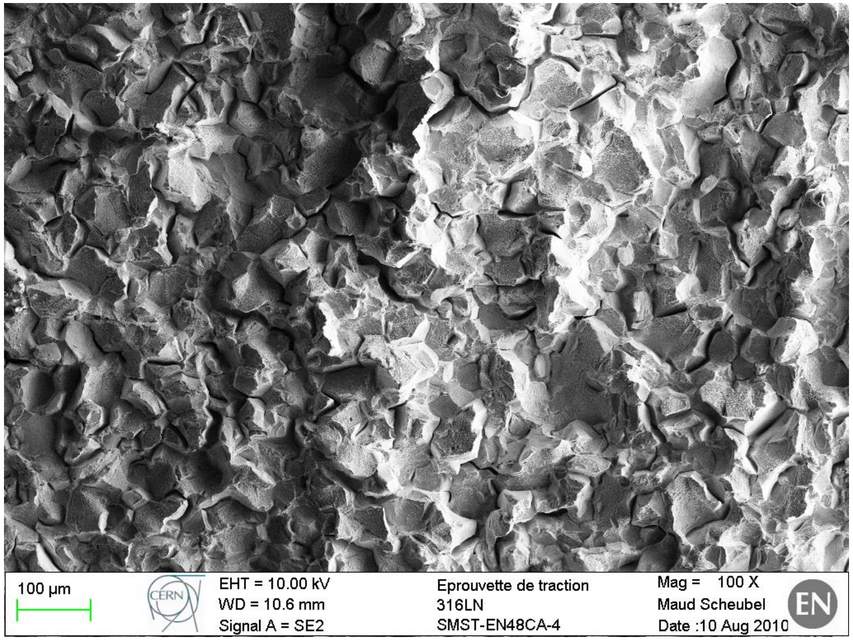
Fig. 62 Effect of nitrogen on precipitation of $M_{23}C_6$ in 0.05C-17Cr-13Ni-5Mo stainless steel.[172]

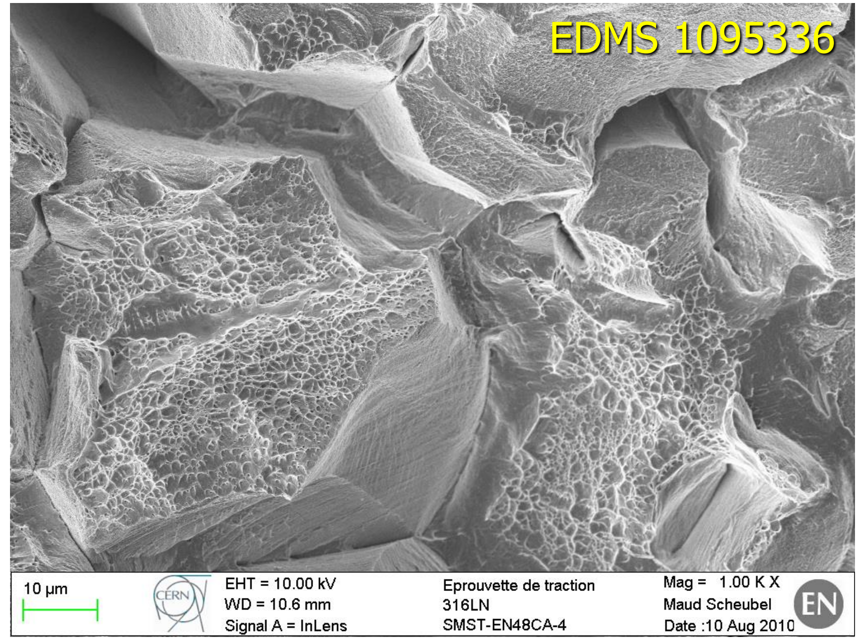
Handbook of stainless steels, D. Peckner, I.M. Bernstein. McGraw-Hill, 1977

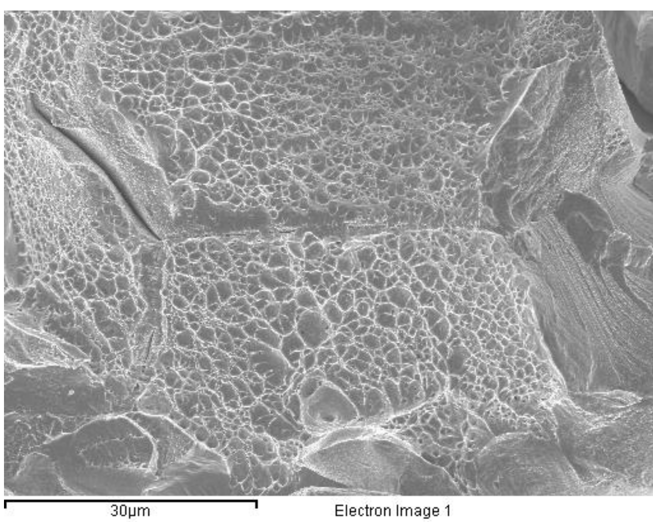
Stress relieving:

- **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







Sample	Young's modulus	Yield Strength	Ultimate Tensile Strength	Uniform Elongation	Total Elongation
	GPa	MPa	MPa	%	%
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 ⇒ CAS course on "Mechanical & Materials Engineering", 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)

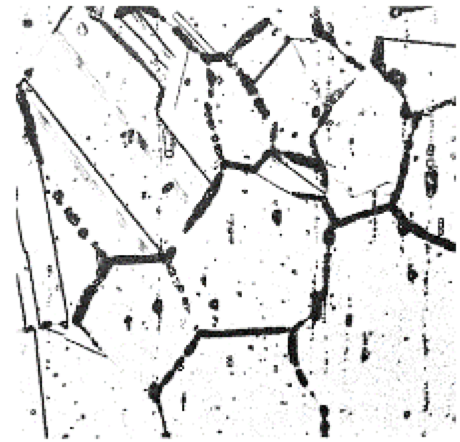


FIG. 2 Dual Structure (250×) (Some ditches at grain boundaries in addition to steps, but no one grain completely surrounded)

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

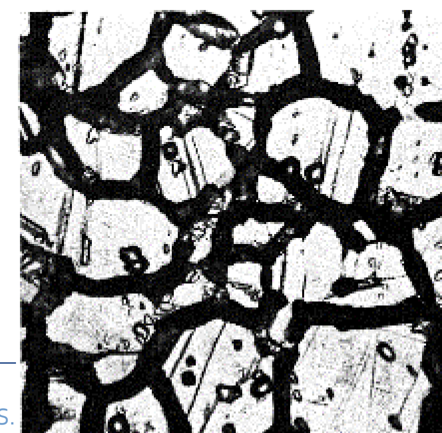


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

7. Conclusions

A stainless steel for an accelerator part is not a mere "chemical composition" or a designation

- specification
- steelmaking
- definition and extent of the controls
- certification
- price

Stainless steels

- **304L, general purpose** ⇒ **3-3.5 EUR/kg**
- **304L, vacuum/cryogenic application** ⇒ **6 EUR/kg**
- **316LN, as above** ⇒ **11 EUR/kg (bars) to 32 EUR/kg (plates)**
- **316LN, blanks** ⇒ **50 (and up to above 100) EUR/kg**
- **P506, 316L convolutions for bellows** ⇒ **50-80 EUR/kg**
- **Additive manufactured 316L** ⇒ **65 EUR/kg (powder)**

Corrosion environment during the whole life cycle of the parts

Advanced grades imply extensive prior R&D