Engineering Department

CAS course "Vacuum for Particle Accelerators", Lund, 6-16 June, 2017

Materials & Properties I: Introduction

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EN-MME-MM
CERN

07/06/2017

Outline

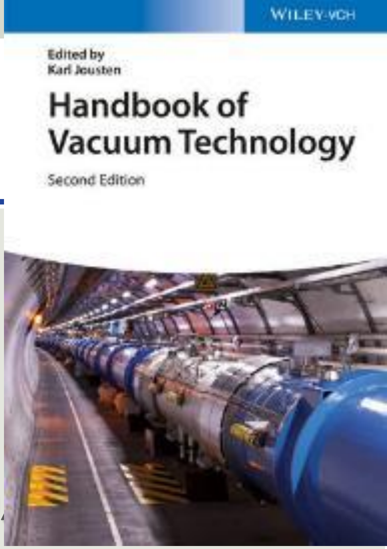
1. General rules for the selection and specification of quality materials for vacuum technology; an historical perspective
2. The main families of metals and alloys used in vacuum technology: from production processes to the final inspections
   a) Stainless steels
   b) Aluminium and alloys
   c) Copper and alloys
   d) Other innovative and/or less common materials/processes

   ⇒ Discussion of:
   - Examples of application
   - Aspects related to manufacturing and joining
   - Failure analyses, including corrosion issues
3. Advanced manufacturing and material examination technologies
4. Conclusions

1. General rules

1. Ease of degassing
2. Adequate strength at high as well as low T
3. Thermal expansion coefficients
4. The purity of the material
5. Exact knowledge of the material properties, critical selection, contr...
6. Very ...
7. Ease ...

(Espe...



1. Sufficient mechanical strength
2. Corrosion resistance
3. High gas tightness (leak rates < 10^{-9} mbar·l·s^{-1})
4. Low intrinsic vapor pressure
5. Low foreign gas content
6. Favorable degassing properties
7. High melting and boiling points
8. Clean surfaces
9. Adapted thermal expansion behaviour
10. High thermal fatigue resistance
11. Stainless steel is the dominant material

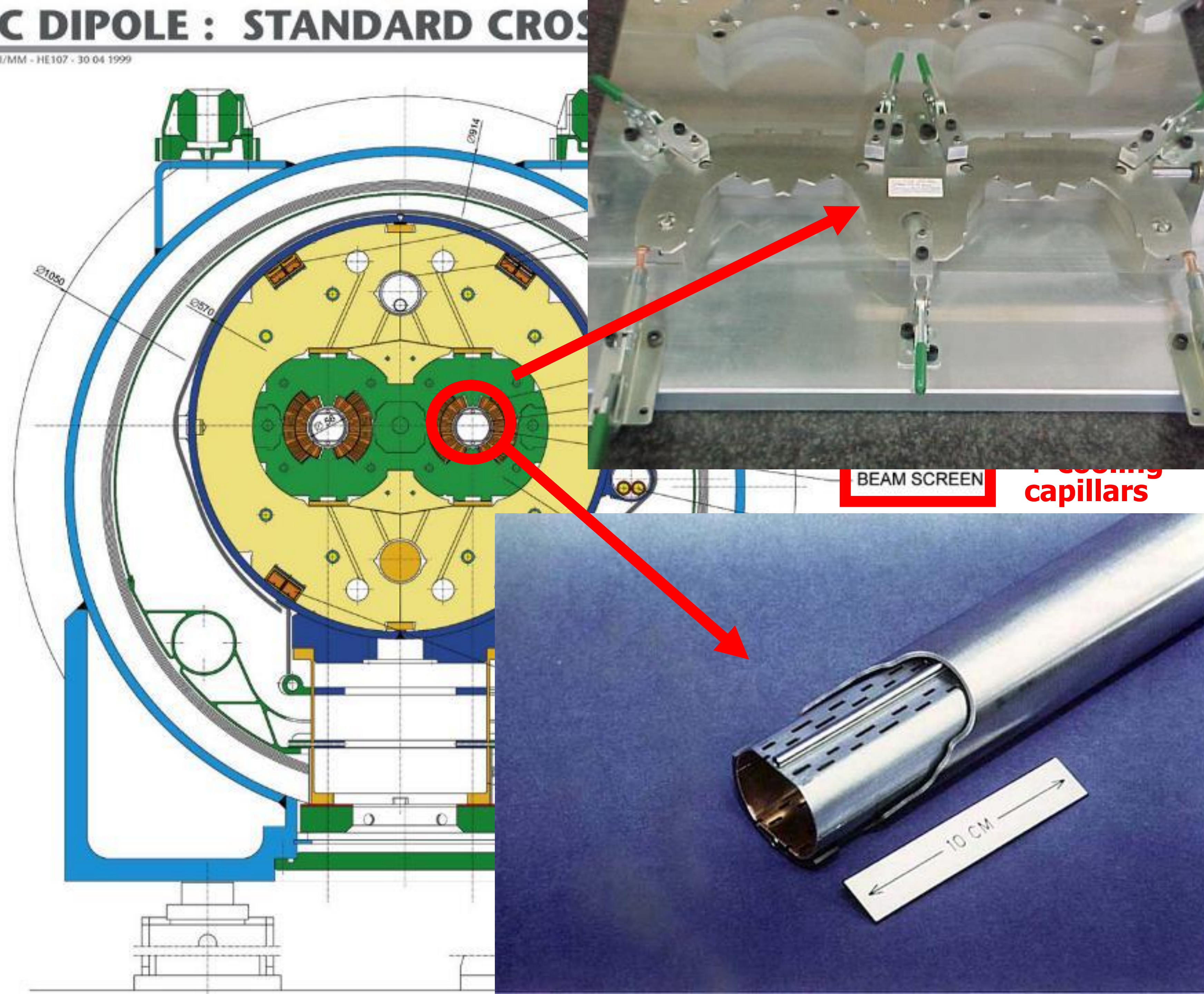
(K. Jousten ed., Handbook of Vacuum Technology, Wiley, 2008-16, see also O'Hanlon, A User's guide to Vacuum Technology, Wiley, 2003)

Ta...
M...
W an...
Precious ...
Nickel and Nickel...
Copper and copp...
Aluminum a...
Stai...
Iro...

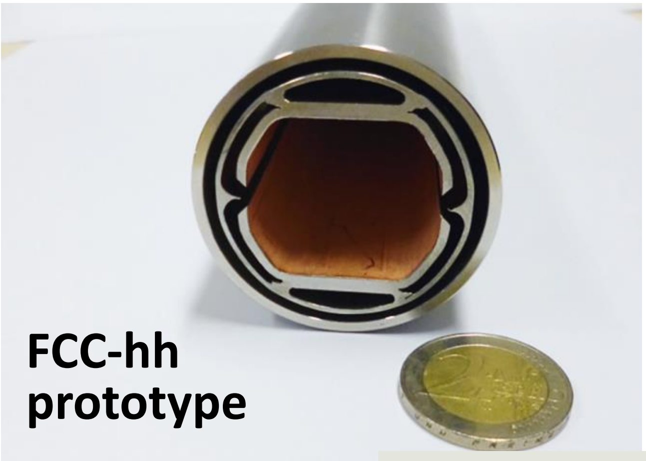

F
S
C
A

LHC DIPOLE : STANDARD CROS

CERN AC/DI/MM - HE107 - 30 04 1999



1. General rules



Beam screen

Being ordered:
- 3.1 km of finished strip;
- 4600 m of seamless cold-drawn cooling tubes in lengths of up to 14 m
- Same stainless steel as for the LHC

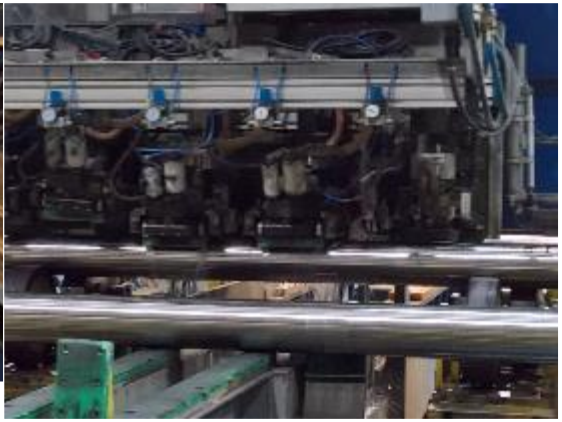
IT-4203/TE/**HL-LHC**

3.1.1 Special austenitic grade stainless steel strip (CERN supply)

The chemical composition of the CERN supplied stainless steel strip is given in table 2.

Table 2 - Typical chemical composition (weight-%) of the CERN supplied stainless steel strip.

%	C	Cr	Mo	Ni	Mn	Si	N	Cu	S	P	B	Co
Min		19.0	0.8	10.7	11.8		0.30					
Max	0.03	19.5	1.0	11.3	12.4	0.5	0.33	0.15	0.002	0.02	0.002	0.1



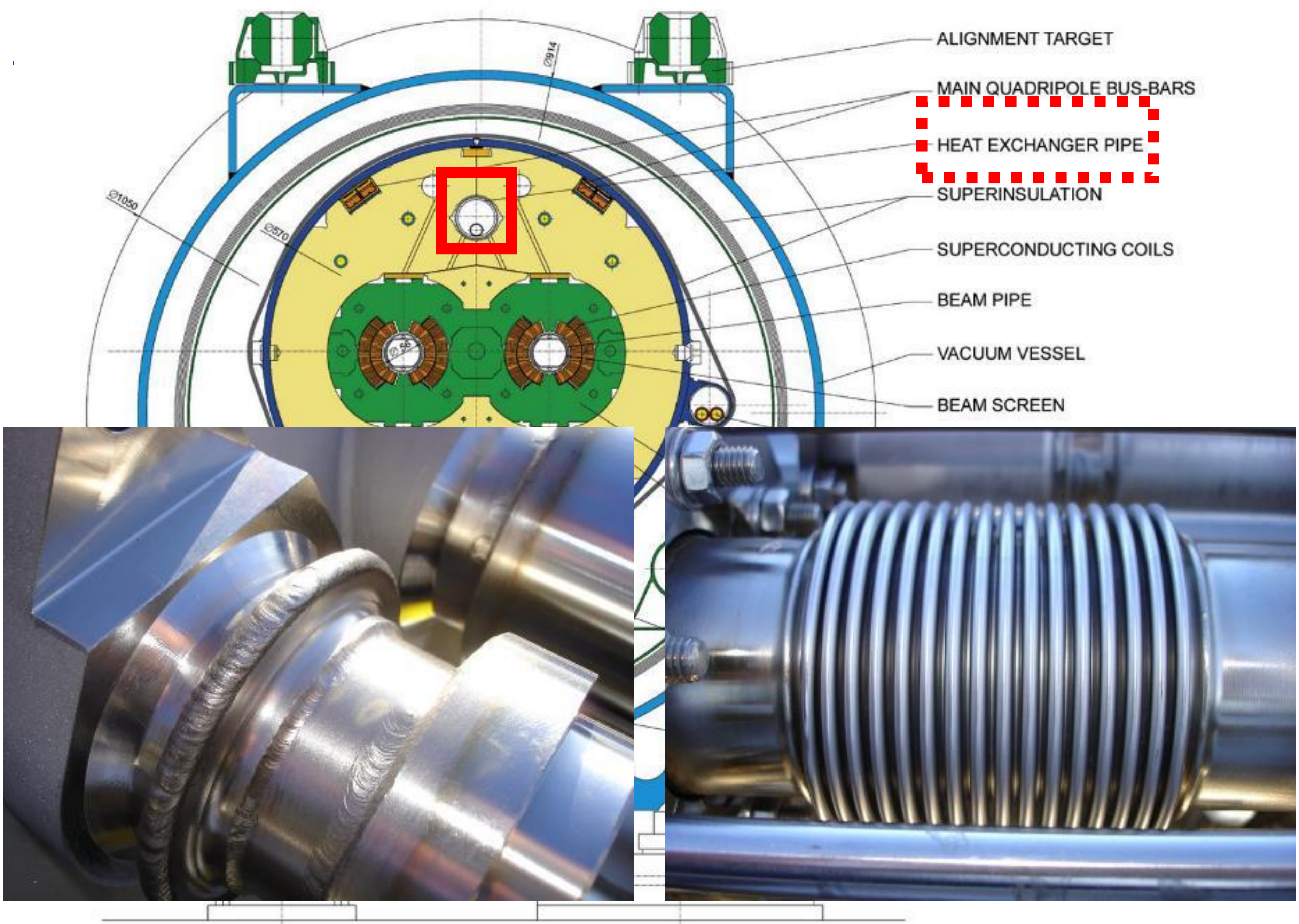
Fine-blanked collars

MS-4294

- More than 450 tonnes of austenitic stainless steel strips
- Same stainless steel specification as for the LHC

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



2.a Stainless steels

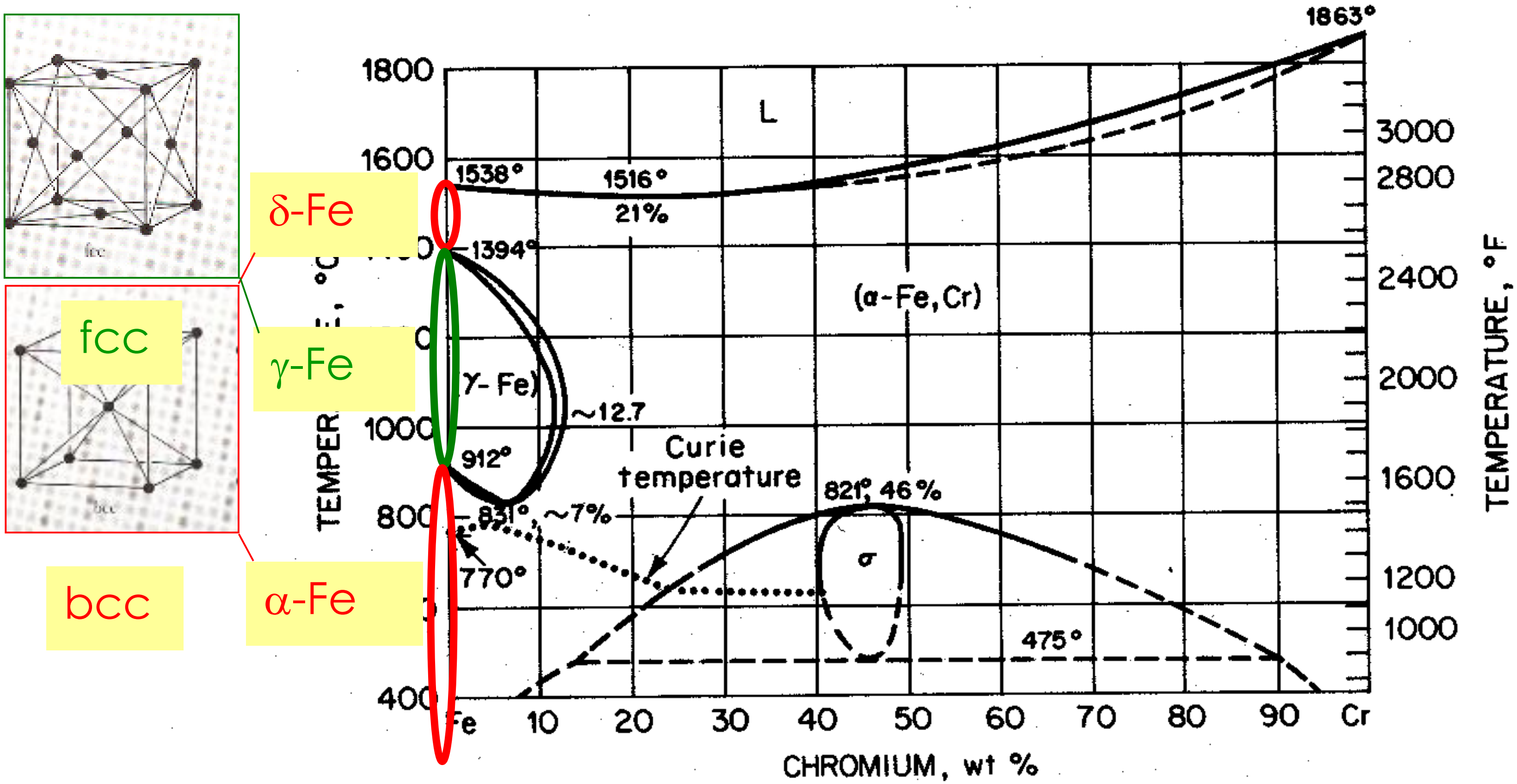


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

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

2.a Stainless steels, ferritic

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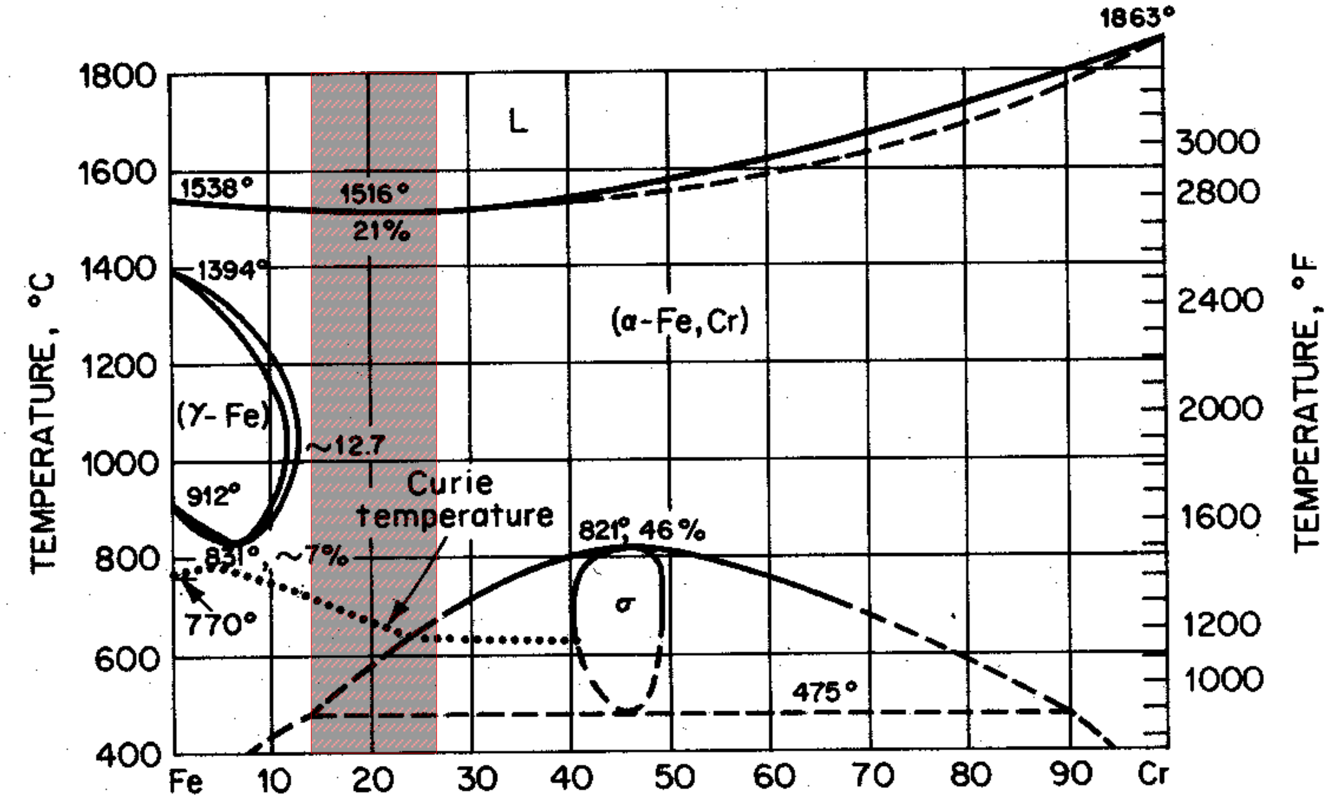


Fig. 2 The iron-chromiur ... , *8th ed.,*
American Society for Meta

- **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.a Stainless steels, martensitic

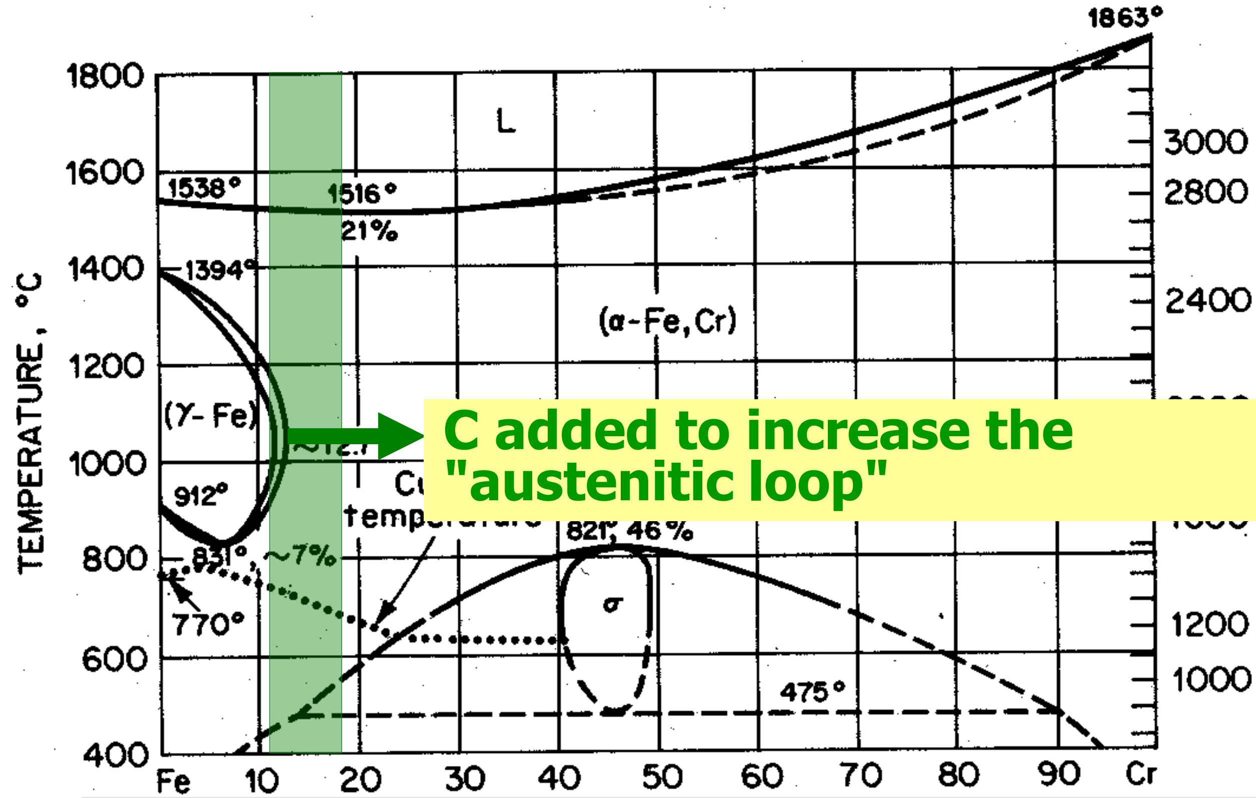


Fig. 2 The i... h ed., American Soc...

- 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

ng Department

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

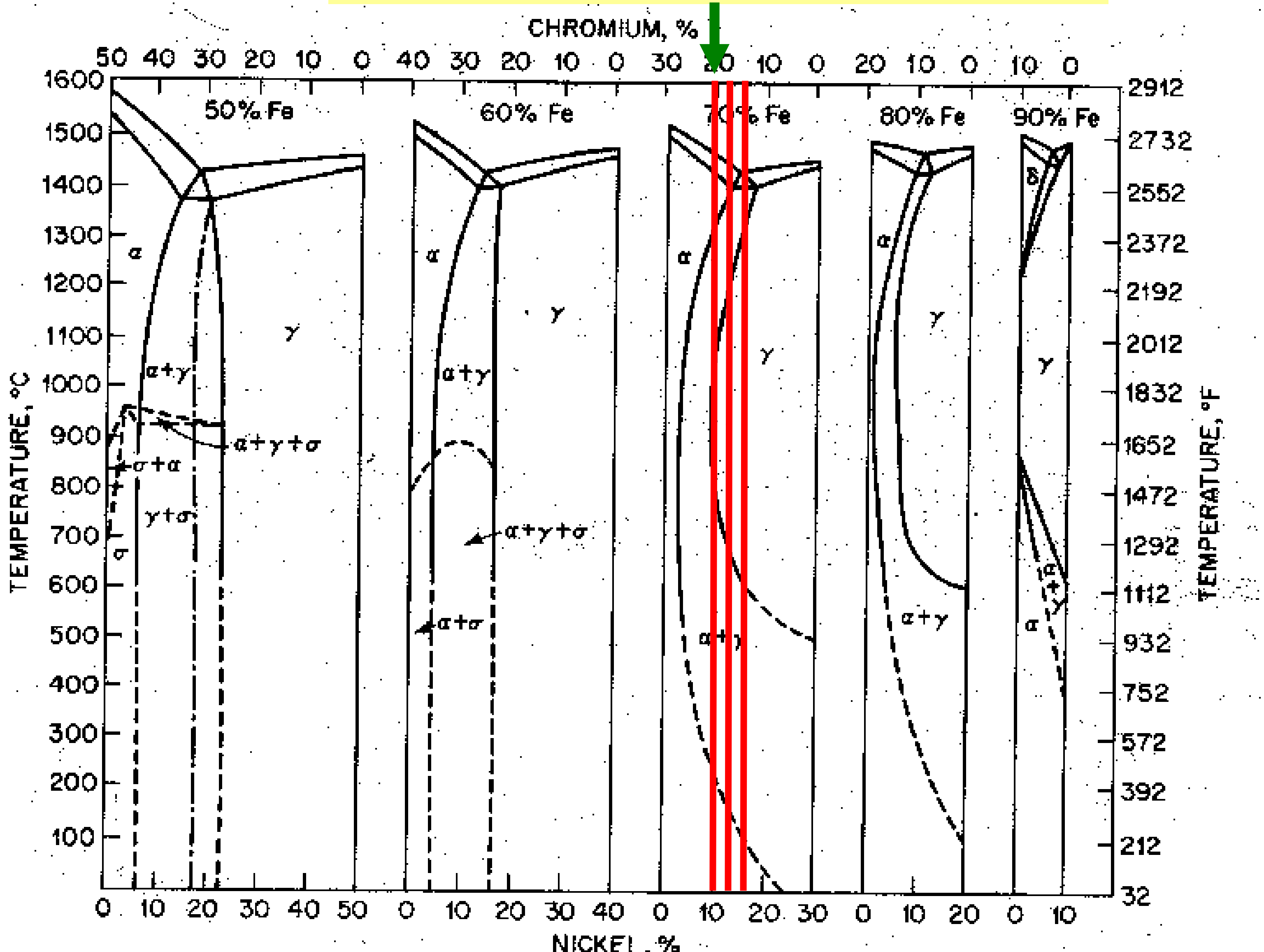


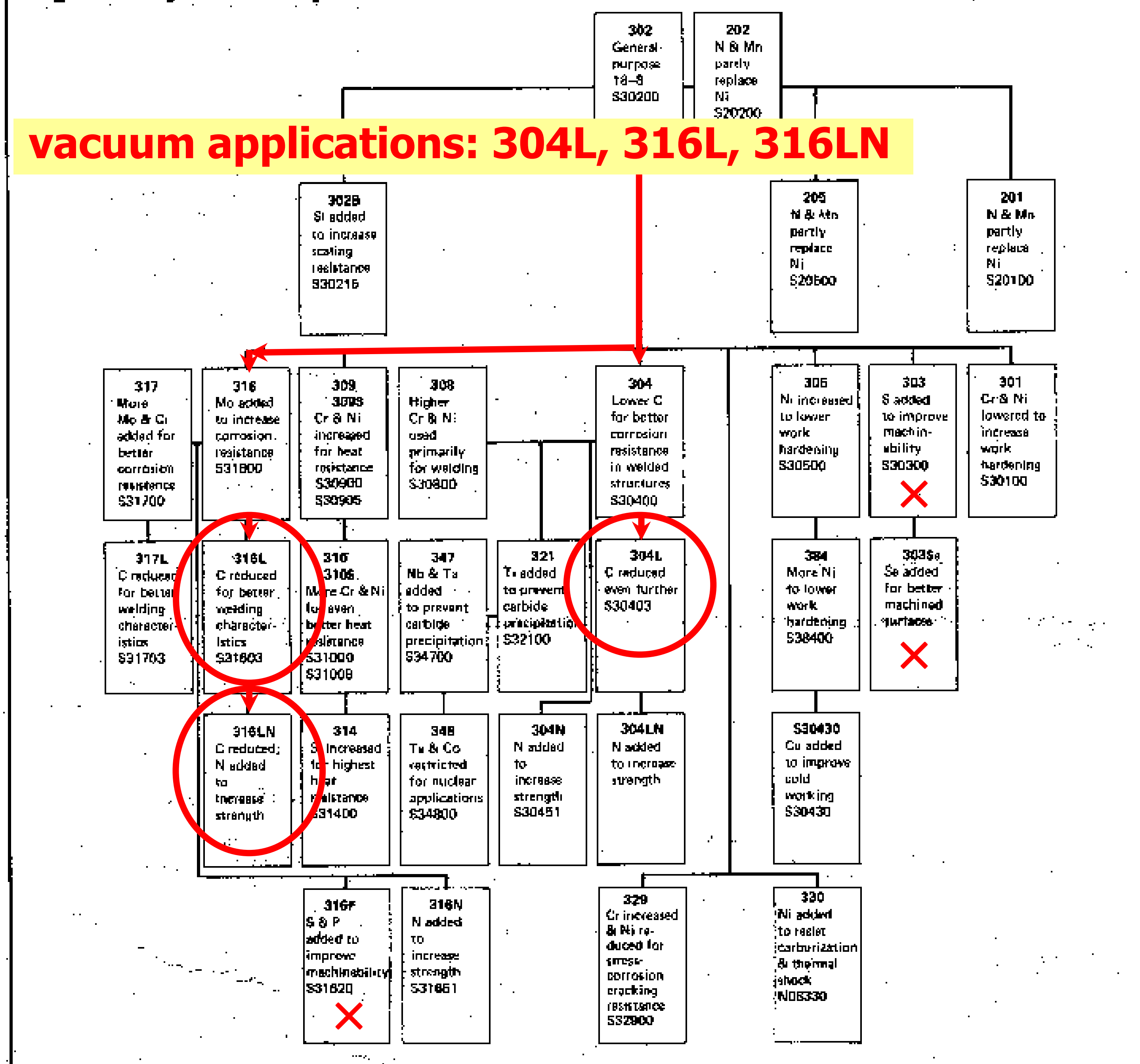
Fig. 14 Cross sections of Fe-Cr-Ni ternary.[26]

291, 8th ed.,

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

Fig. 2 Family relationships for standard austenitic stainless steels

vacuum applications: 304L, 316L, 316LN



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

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

"Sensitization" of base metal, HAZs and welds

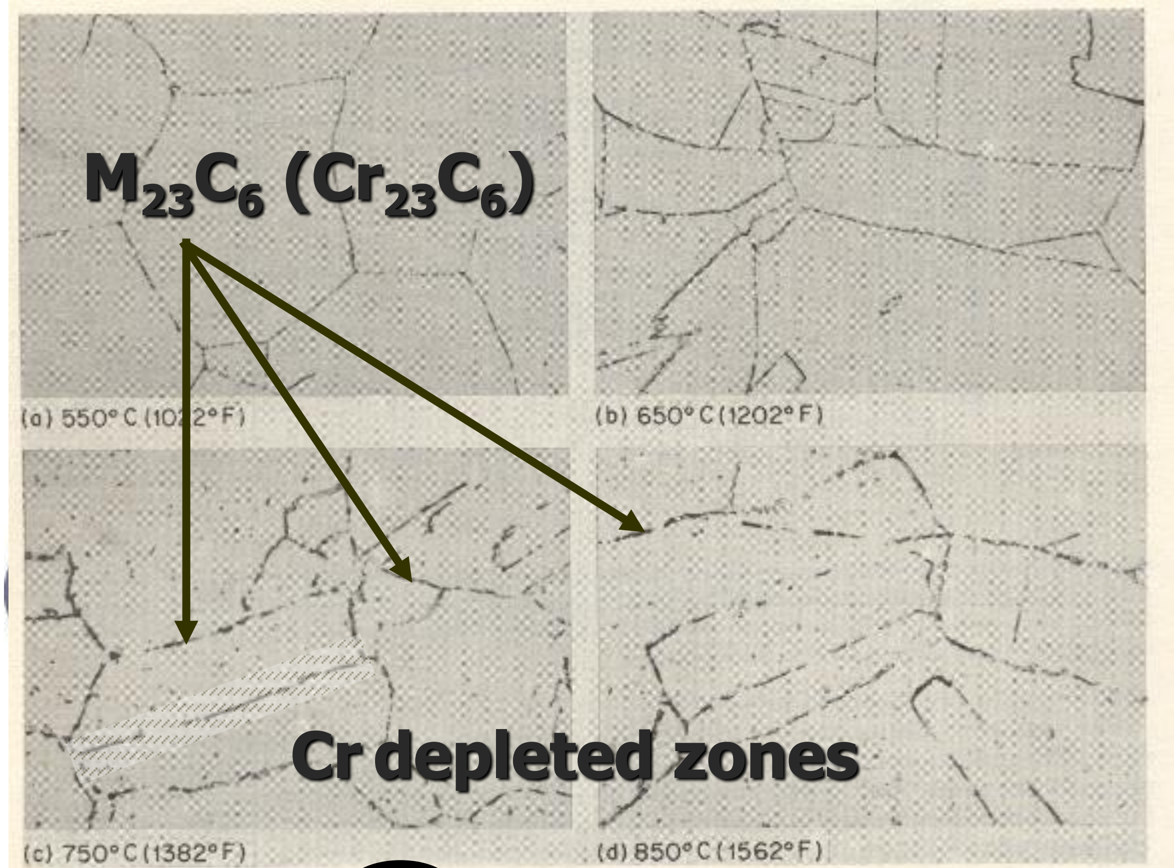
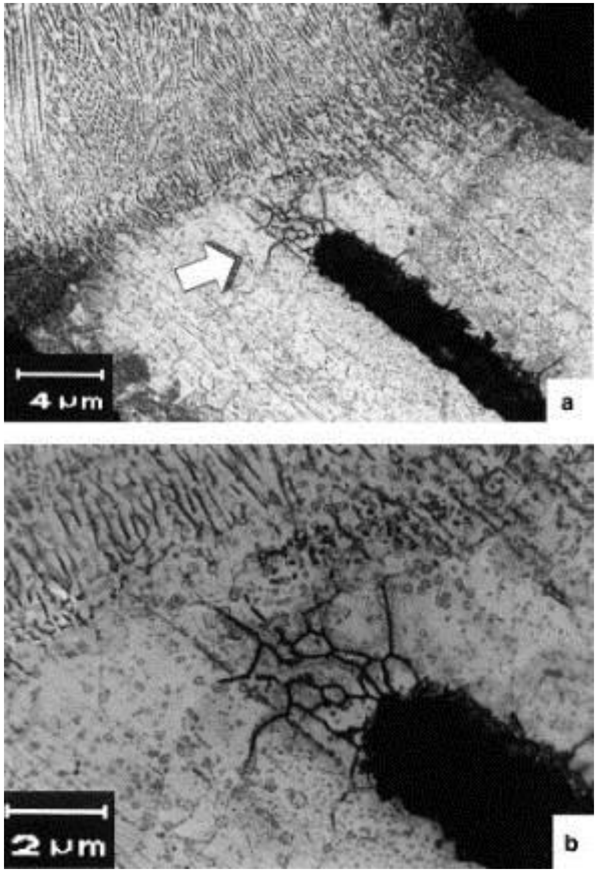


Fig. 55 Appearance of Type 304 stainless steel (0.065% carbon) sensitized for 6 days (144 h) at various temperatures. Specimens etched electrolytically in 10% oxalic acid.[128] (a) 550°C (1022°F). 750x. (b) 650°C (1202°F). 750x. (c) 750°C (1382°F). 750x (d) 850°C (1562°F). 750x.

D. Peckner, I.M. Bernstein, 1977



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

Engineering Department

CERN — European Organization for Nuclear Research

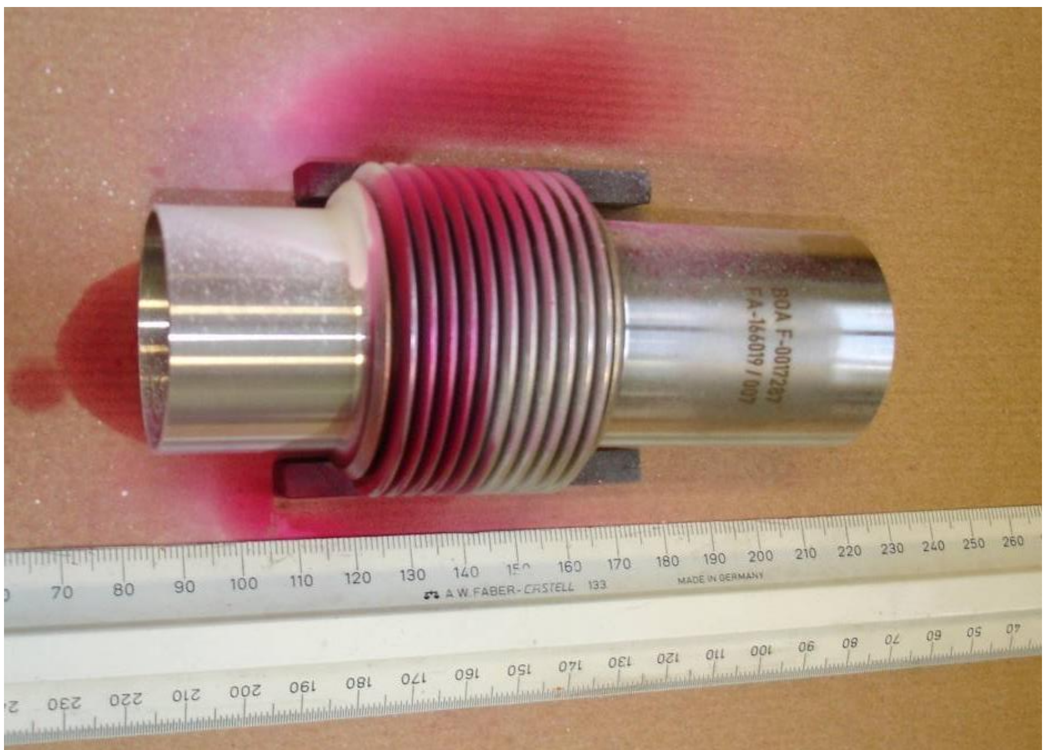
TS/MME-MM

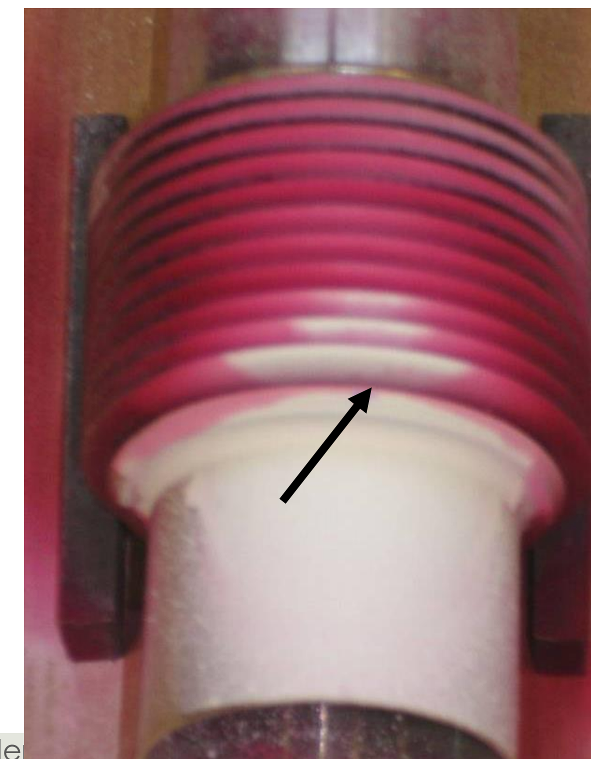
Section de Métallurgie et Métrologie/ *Metallurgy and Metrology section*

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*	

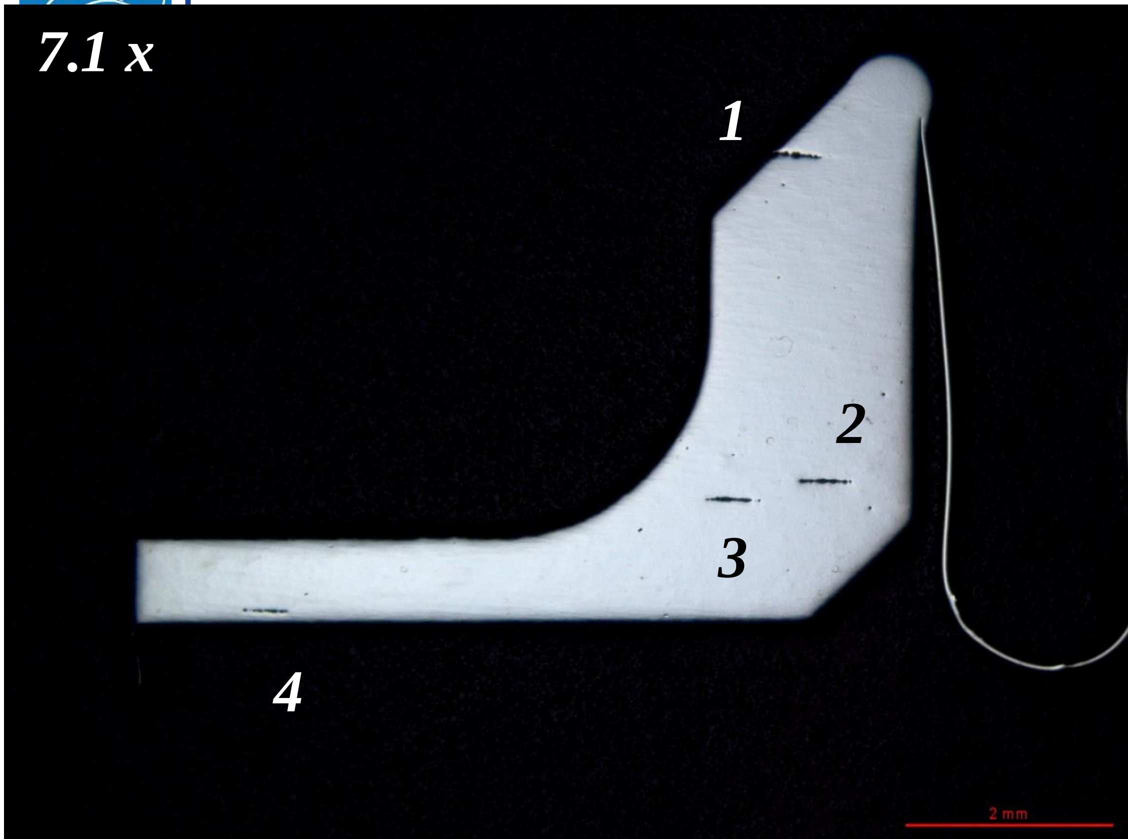
Metallographic observations of 316LN leaking bellow

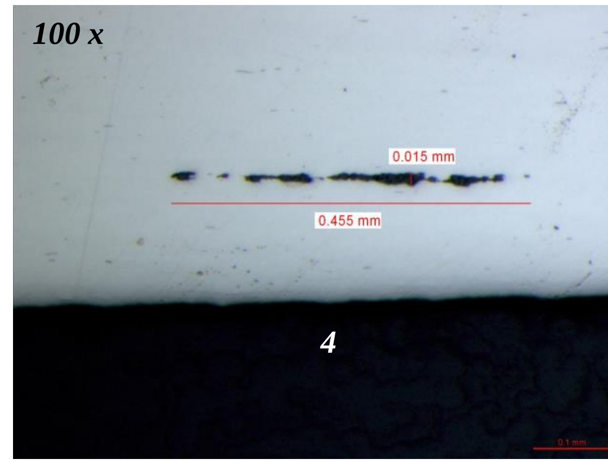


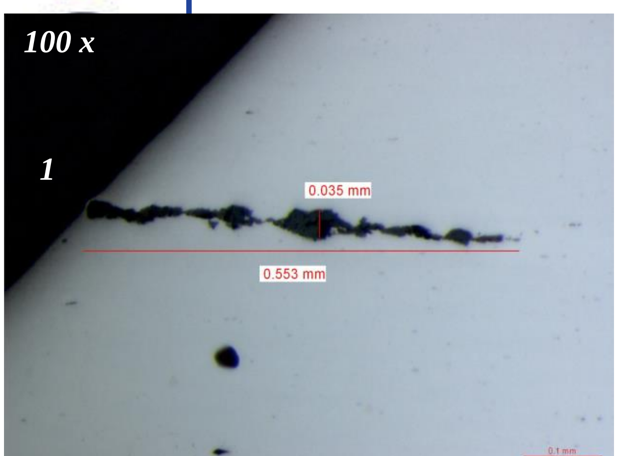


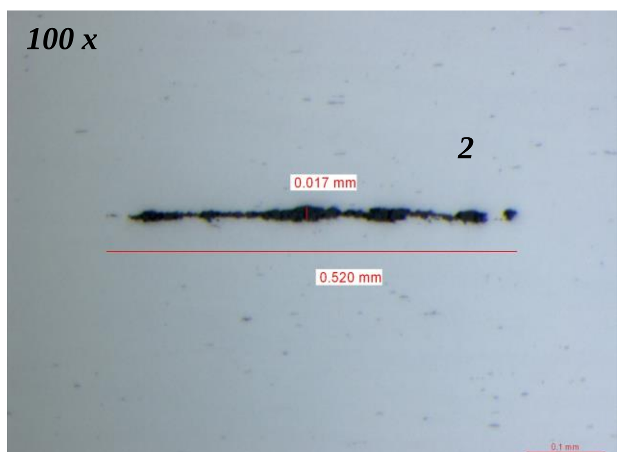
2.a Stainless steels, inclusions

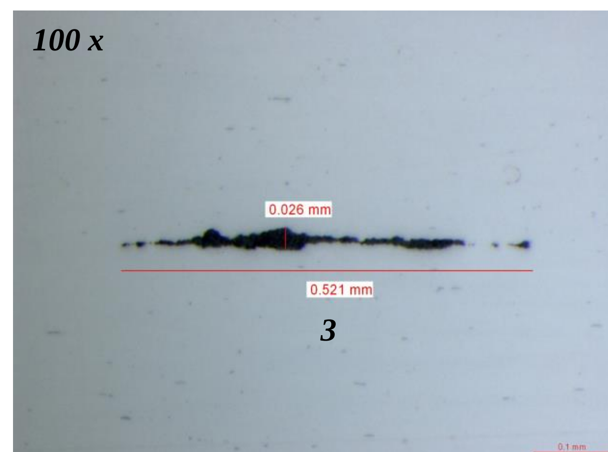
- **Oversized (1,2,3) and thick (4) B type inclusions up to class 2**



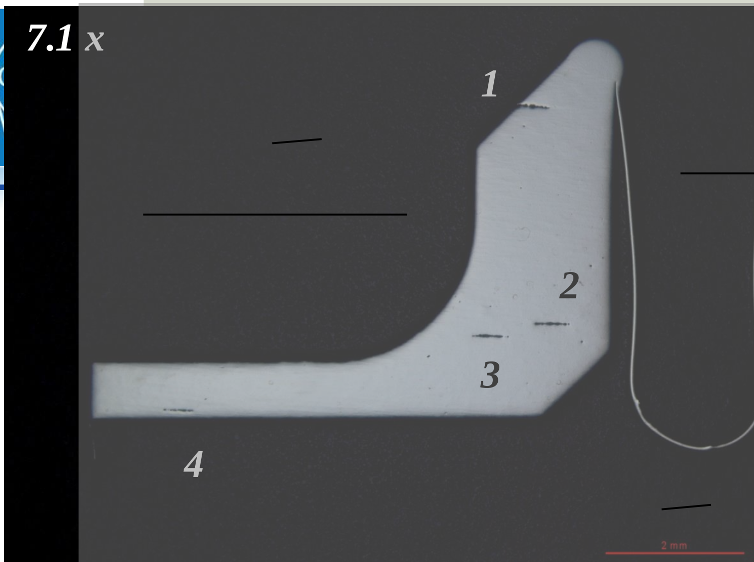


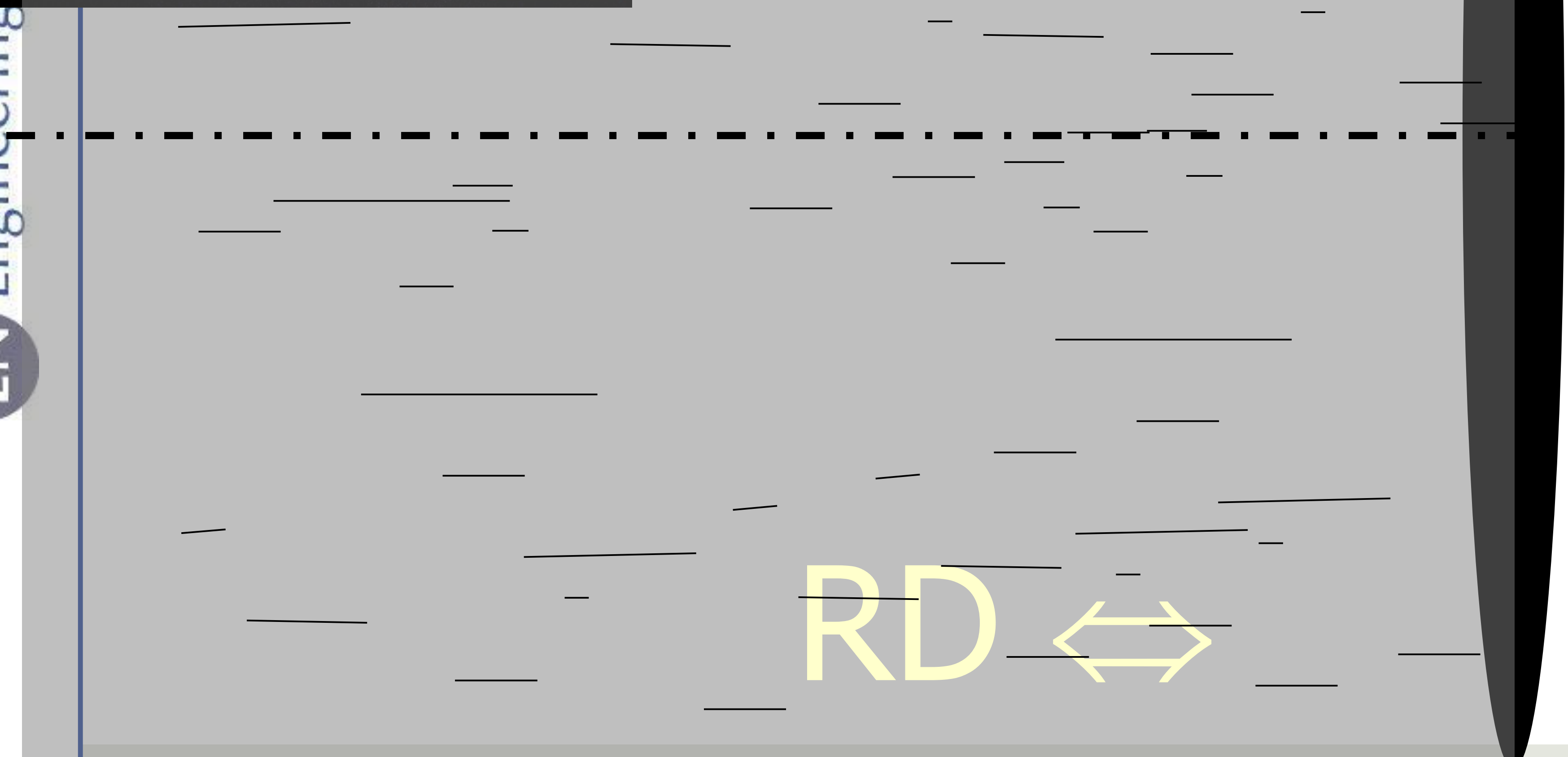




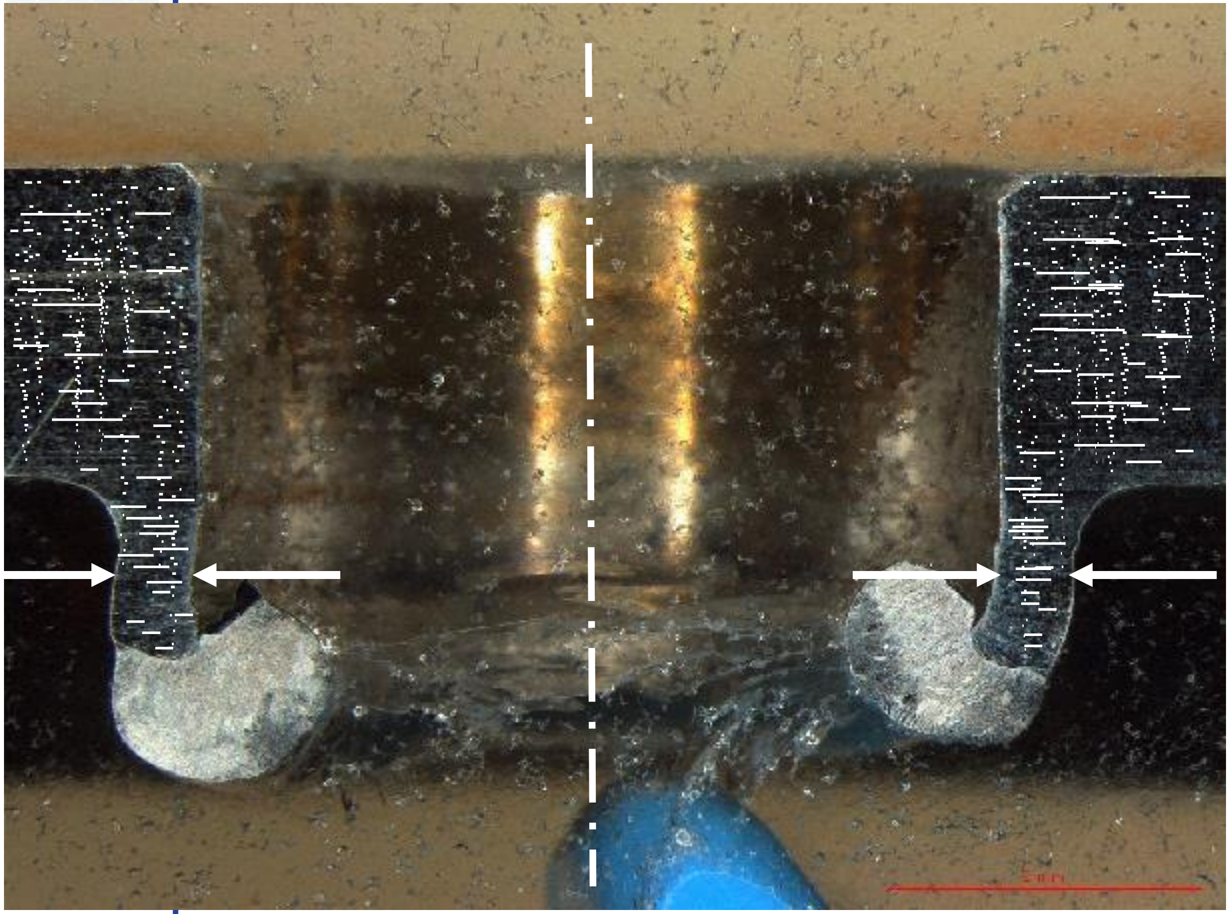


2.a Stainless steels, inclusions





2.a 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 – 11a

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

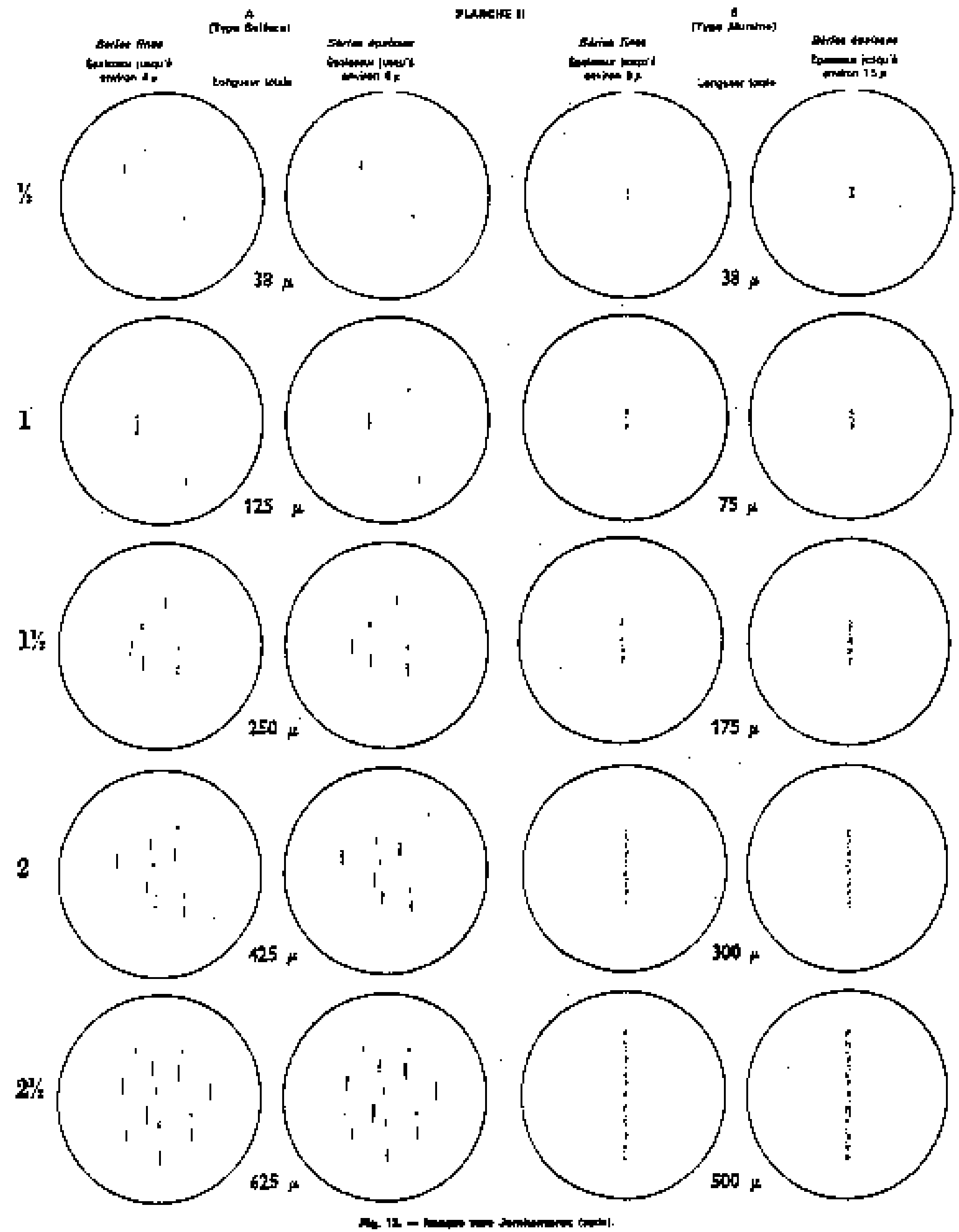
This standard is issued under the fixed designation E45; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates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

Severity	A	B	C	D[C]
(mm (in.) at 100×, or count)				
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

QUANTIMÉTRIE



M 220 – 16

Materials Technical Specification
GS-IS & EN-MME

11.12.2013

2.4. INCLUSIONS CONTENT

Amount and definition shall meet standard ASTM E45.

1. Micro-inclusions (indigenous inclusions detectable by microscopical test methods): method D is applicable. Severity level number shall be at most 1 for types A, B and C and at most 1.5 for type D. The tolerance for acceptance may be a half-class above the set limit to the extent of 2% of the fields counted. The table showing field counts shall be attached to the certificate.

2. Macro-inclusions (exogenous inclusions from entrapped slag or refractories): they are strictly forbidden and are cause for rejection.

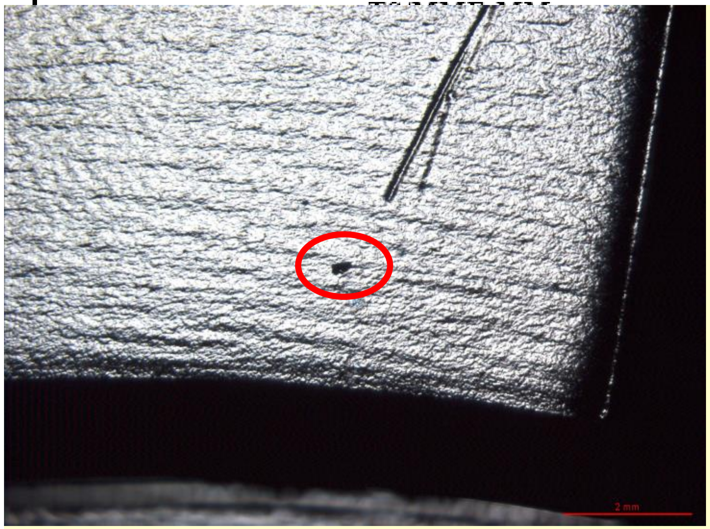
X2CrNiMoN17-13-3

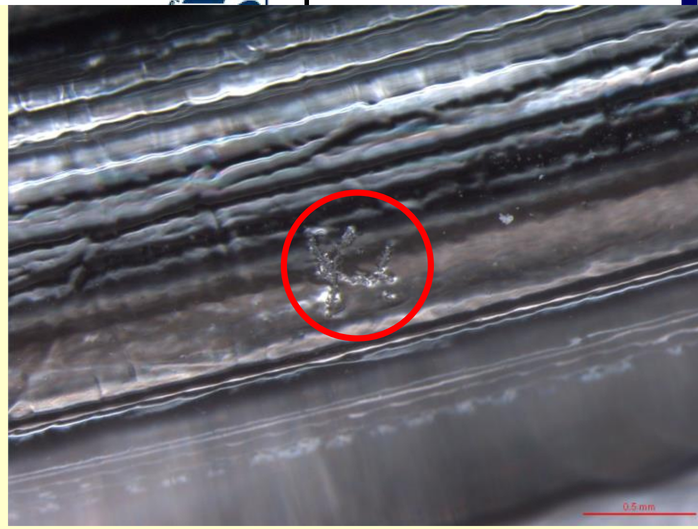
AISI 316LN

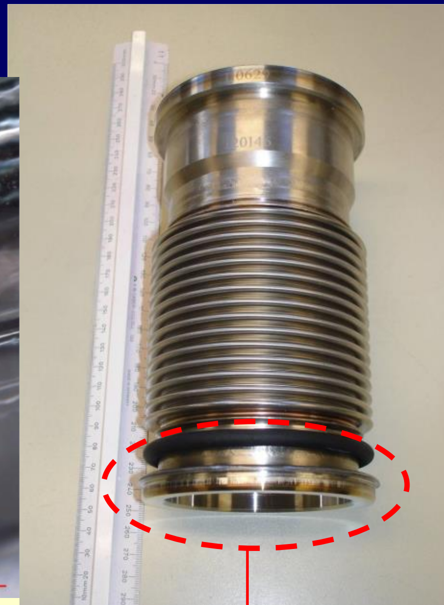
Spec. N°1001_1.4429_316LN_blanks

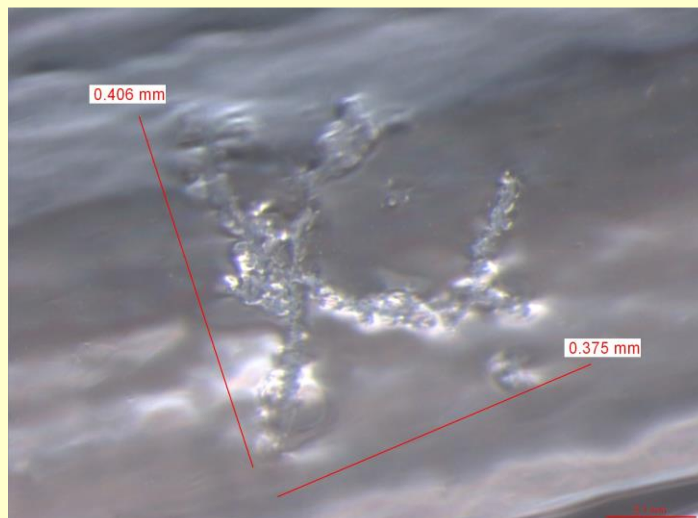
This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.

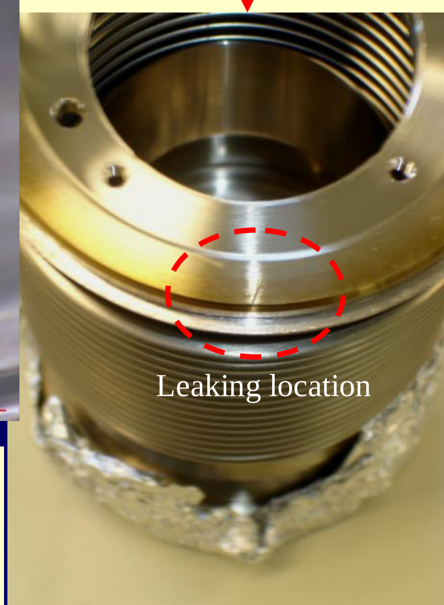
CERN — European Organization for Nuclear Research

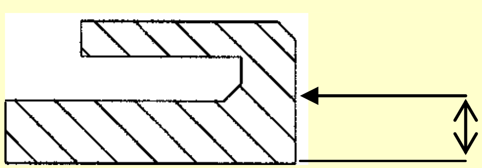


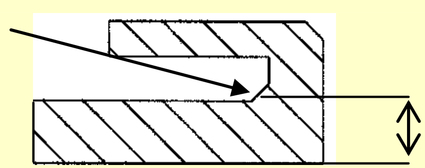




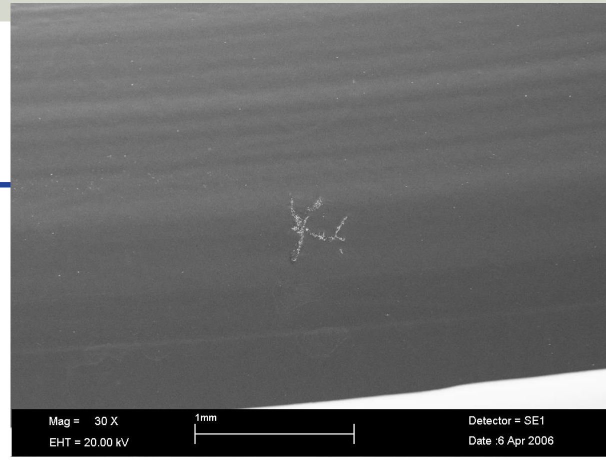


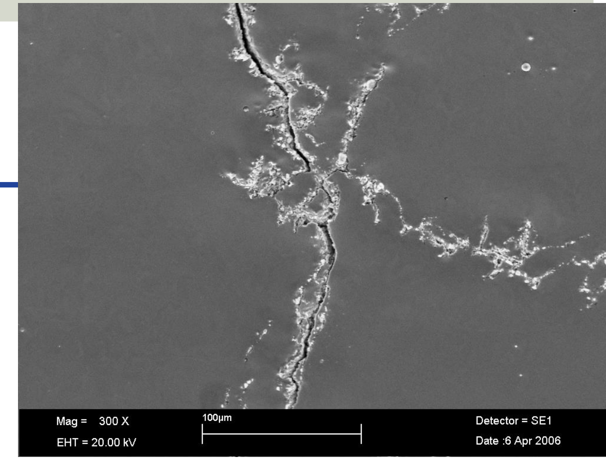


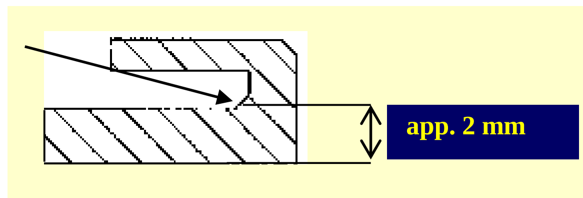


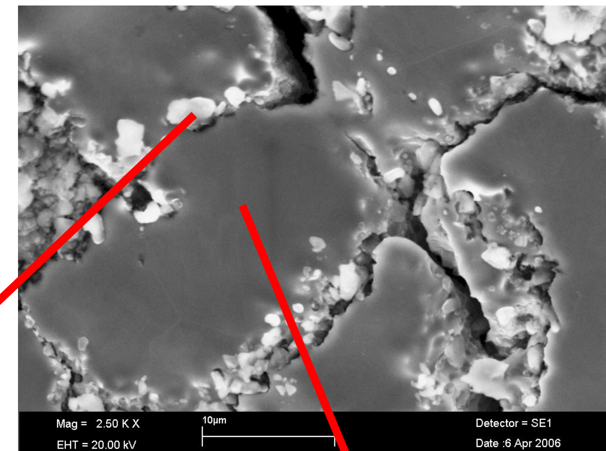


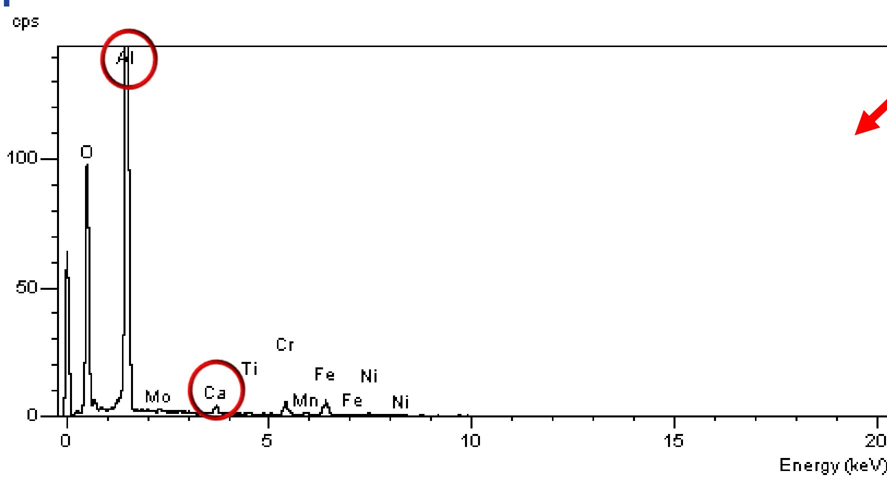
2.a Stainless steels, macro-inclusions

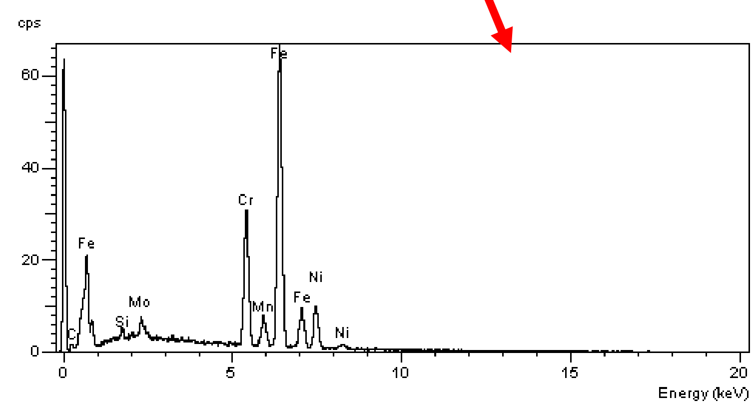


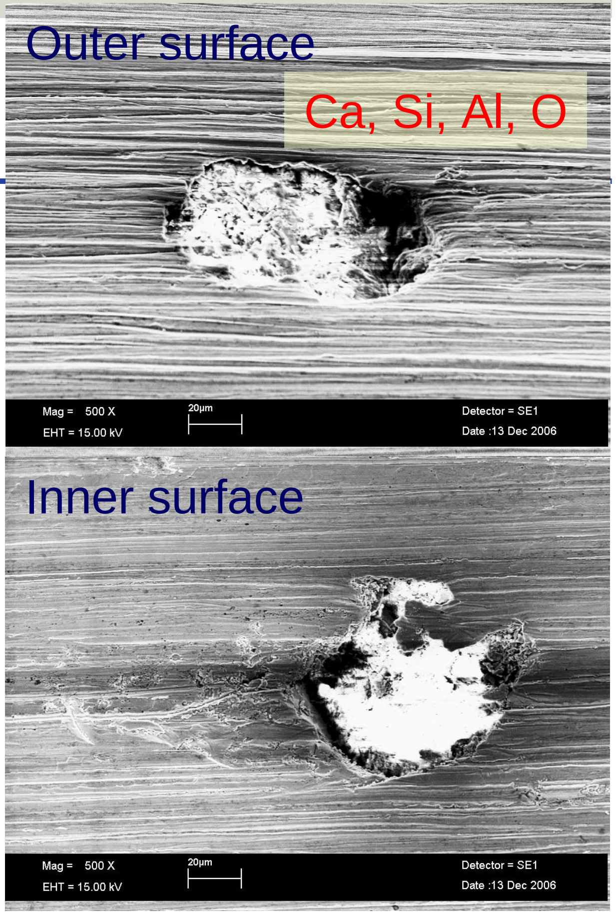




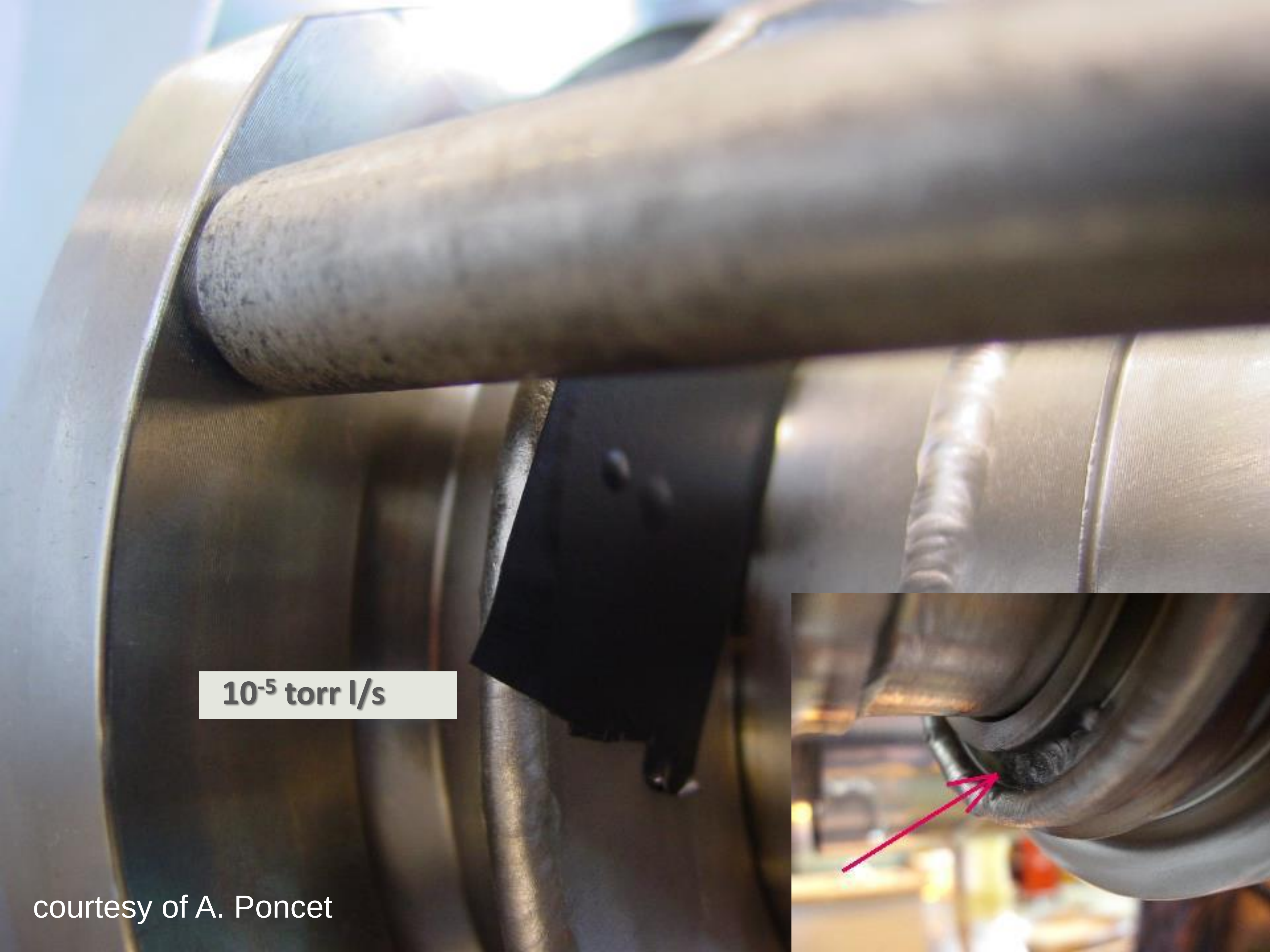








Multidirectional forging alone, even if including upsetting is not enough to avoid the risk of leaks due to macroinclusions



courtesy of A. Poncet

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

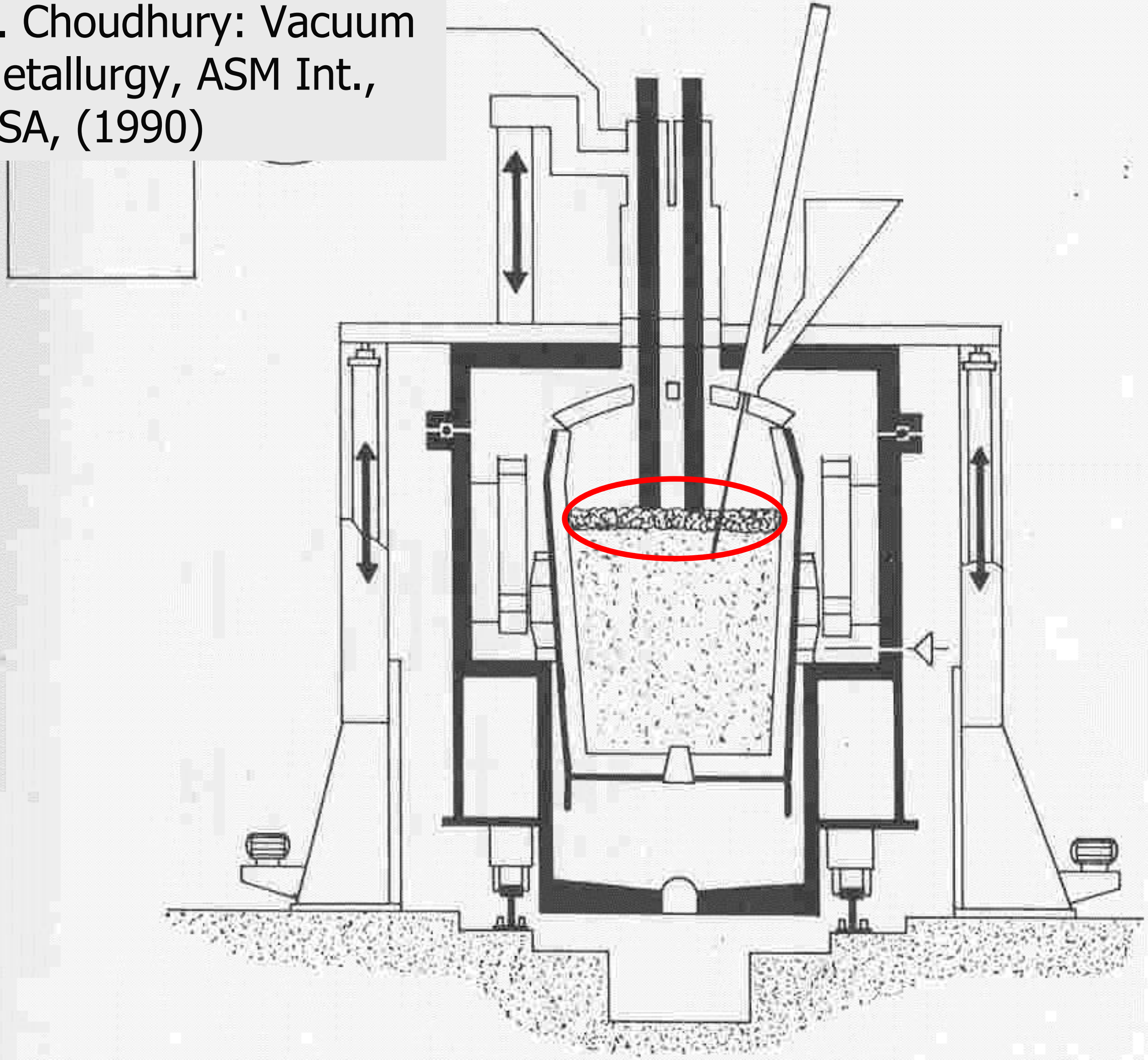
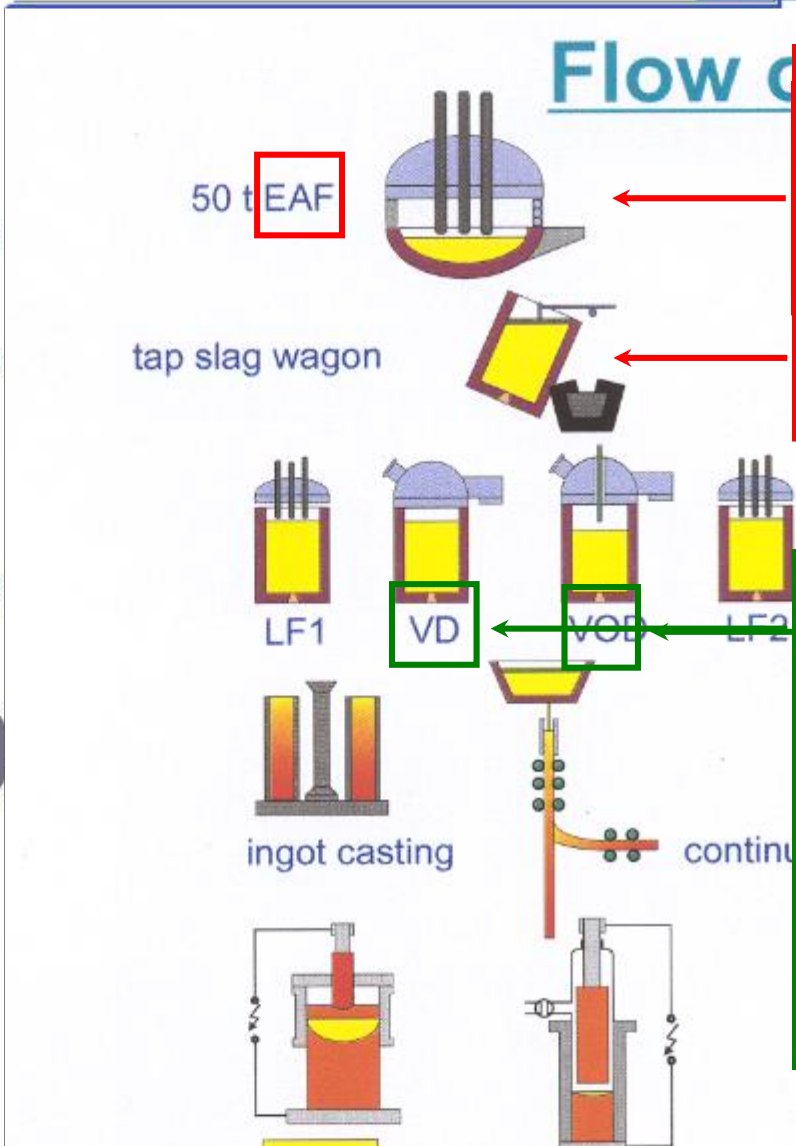


Fig. 23 Layout of a compact ladle furnace

BREITENFELD EDELSTAHL AG

2.a Stainless steels, steelmaking



C ↓
P ↓
(to a limited extent)

Tapped as free as possible of slag into the ladle

secondary-

De(
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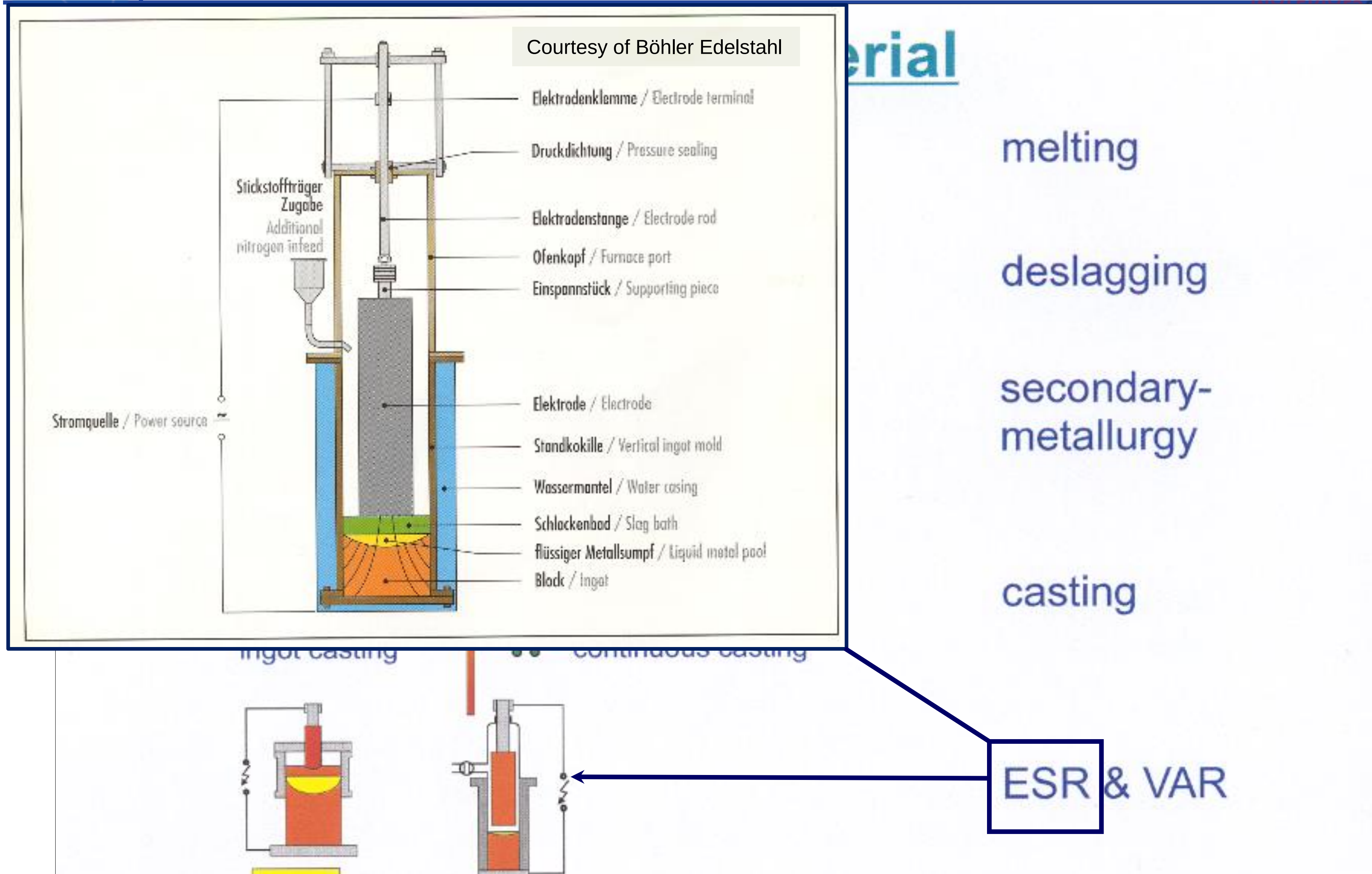
deh
to (
(fr
ppr
Metallic inclusions (NMI)

Pure gaseous oxigen blown onto the metal; for a pressure of 0.02 bar abs., C down to 0.015 % before Cr losses begin

2.a Stainless steels, steelmaking: ESR



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.

Stainless steels, vacuum firing, stress relieving, possible sensitization

Engineering Department

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.

Stainless steels, vacuum firing, stress relieving, possible sensitization

Engineering Department

EN

MATERIALS & METROLOGY

EN/MME

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

- Outgassing
- Restriction due to B content in 316LN
  ⇒ see P.Chiggiato, Materials & Properties IV, 8/06

Stainless steels, vacuum firing, stress relieving, possible sensitization

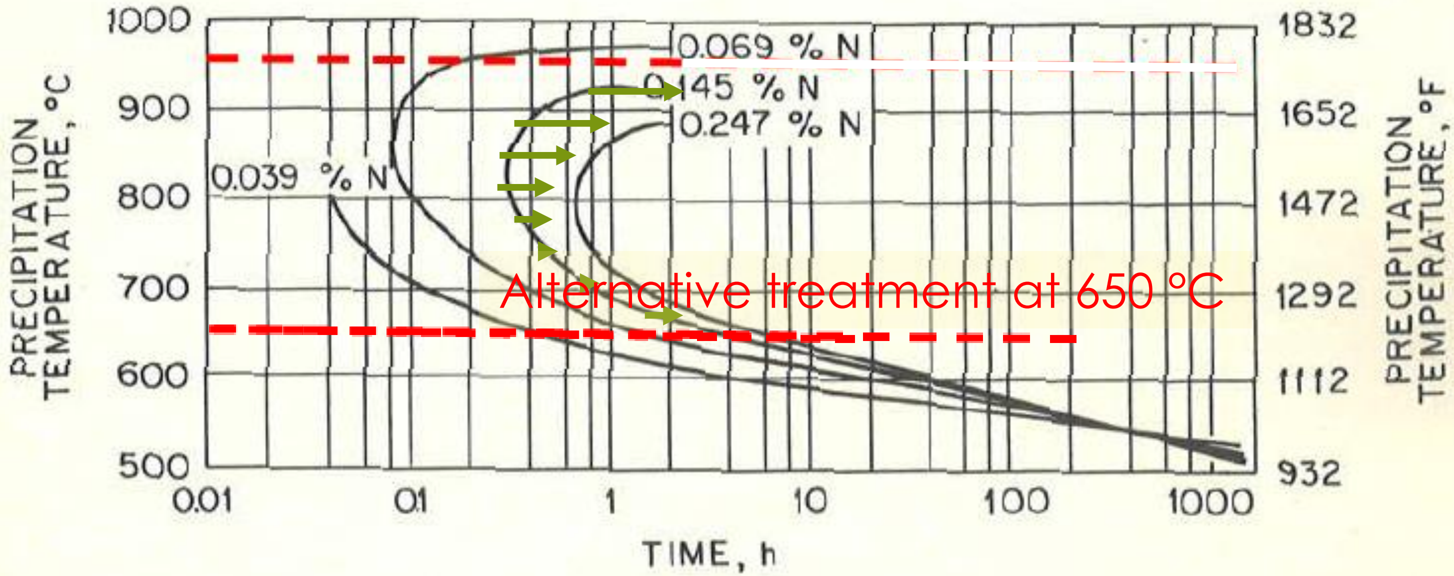


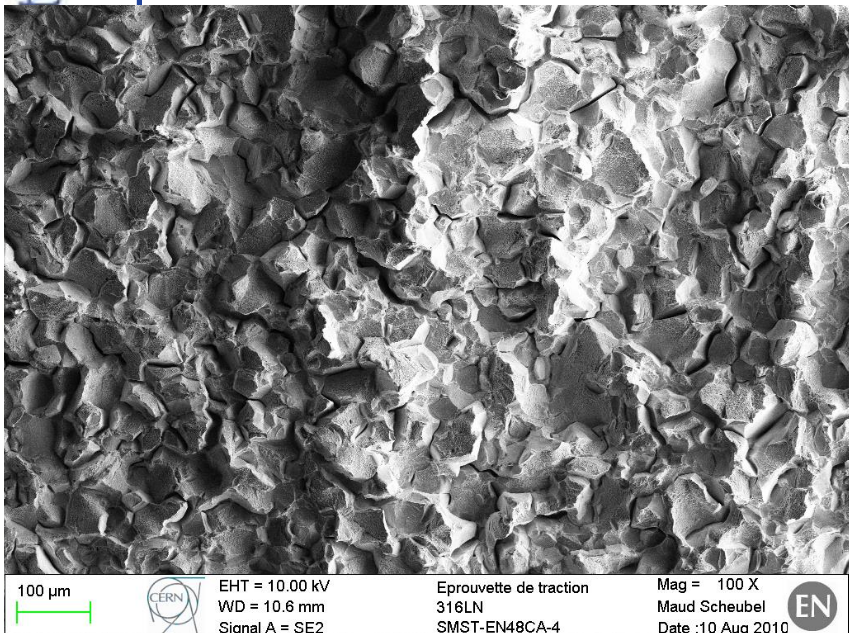
Fig. 62 Effect of nitrogen on precipitation of $M_{23}C_6$ in 0.05C-17Cr-13Ni-5Mo stainless steel.[172]

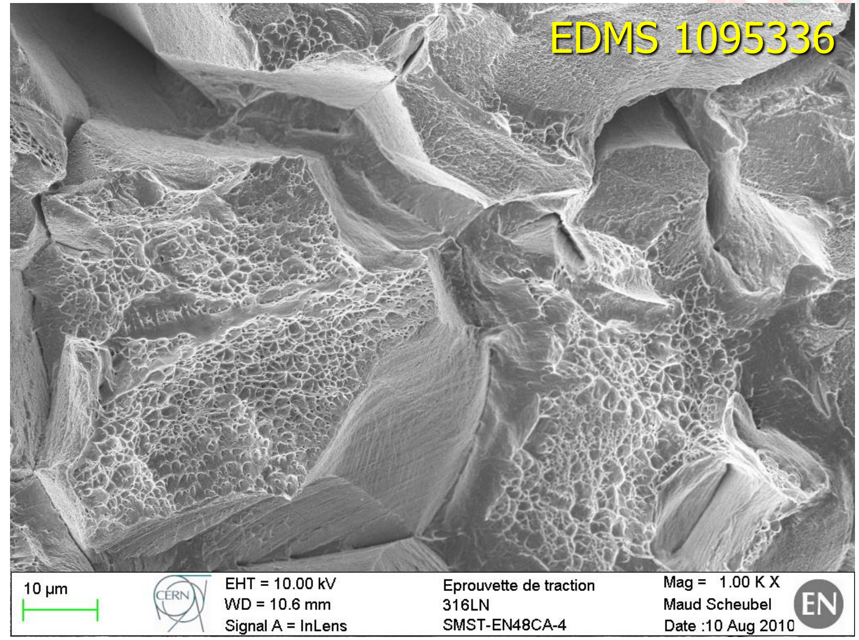
Handbook of stainless steels, D. Peckner, I.M. Bernstein. McGraw-Hill, 1977

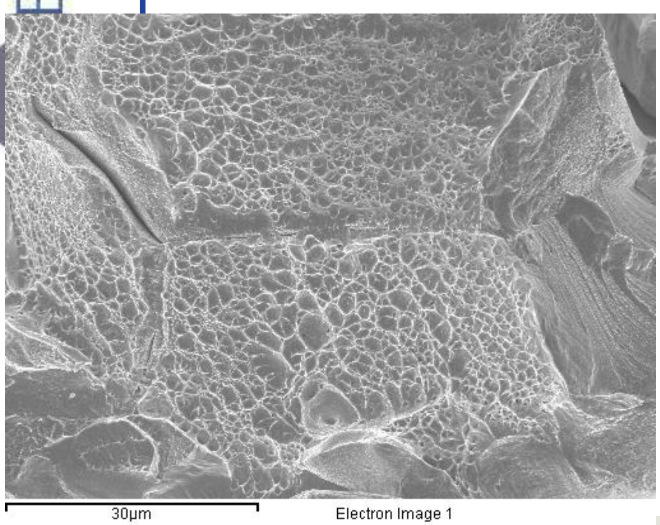
Stress relieving:

- **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**

Stainless steels, vacuum firing, stress relieving, possible sensitization







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

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

Stainless steels, vacuum firing, stress relieving, possible sensitization

S. Sgobba, et al., Fusion Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.05.002
S. Sgobba et al., IEEE Transactions on Applied Superconductivity, **22**, 2012, p. 7800104

Engineering Department

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

⇒ Assembly techniques, brazeability and weldability, see S. Mathot, 15/06

Designation: A262 – 02a (Reapproved 2008)

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

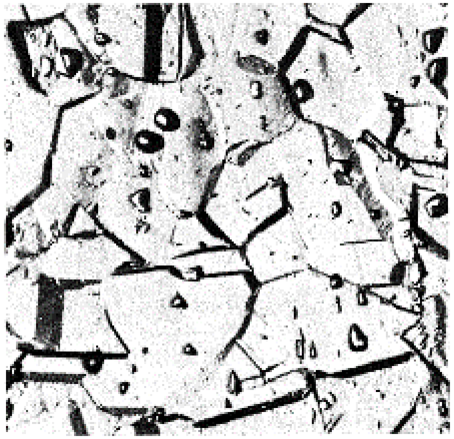


FIG. 1 Step Structure (500×) (Steps between grains, no ditches at grain boundaries)

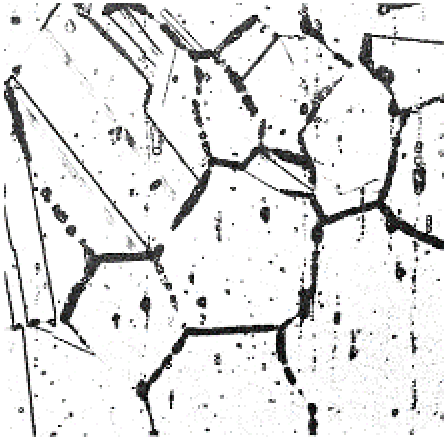


FIG. 2 Dual Structure (250×) (Some ditches at grain boundaries in addition to steps, but no one grain completely surrounded)

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

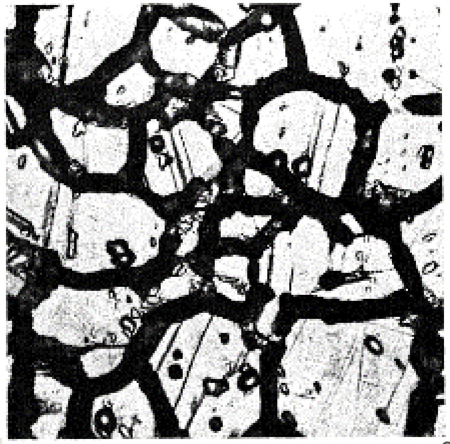
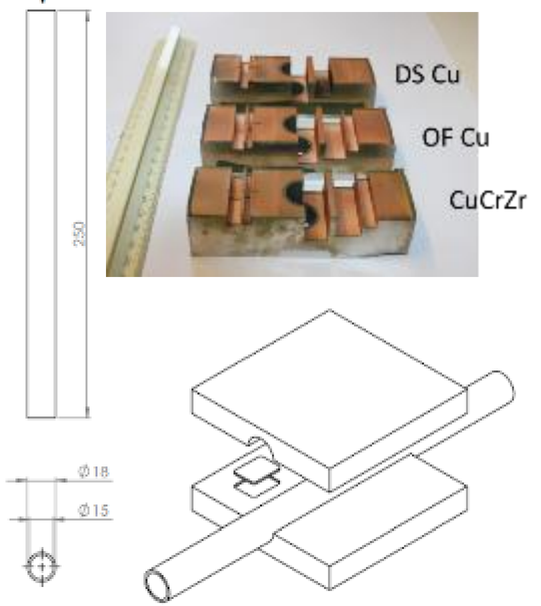


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

2.a Stainless steels, alternative joining techniques, **HIP diffusion bonding**

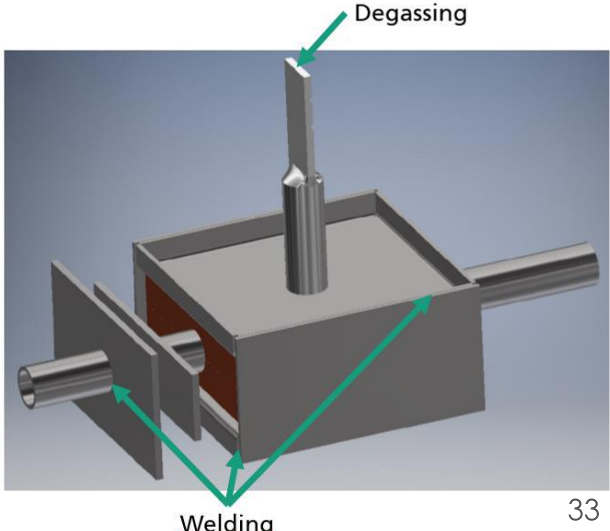
CuCr1Zr (CW106A, hard drawn) | Cu-OF (CW008A, R240 half hard) | DS-Cu (Discup C3/30)

Pipe

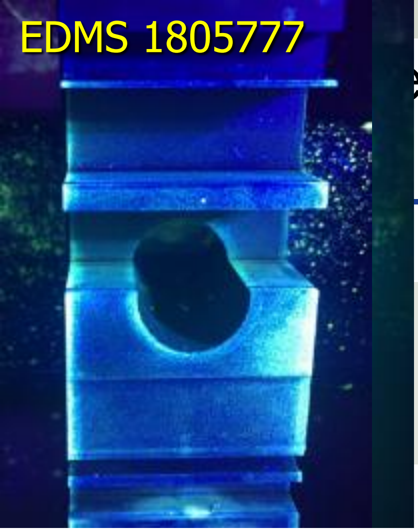


Courtesy of Fraunhofer IFAM Dresden /DE:

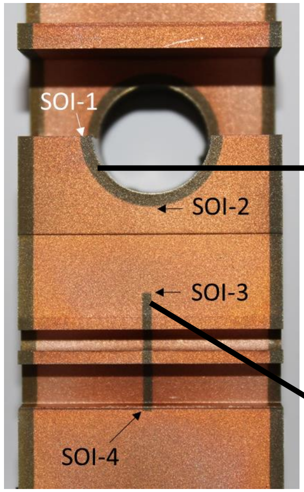
- **SS casing (1.4301)**
- **950°C - 3h – 100 MPa Hot Isostatic Pressing (HIP)ing cycle**

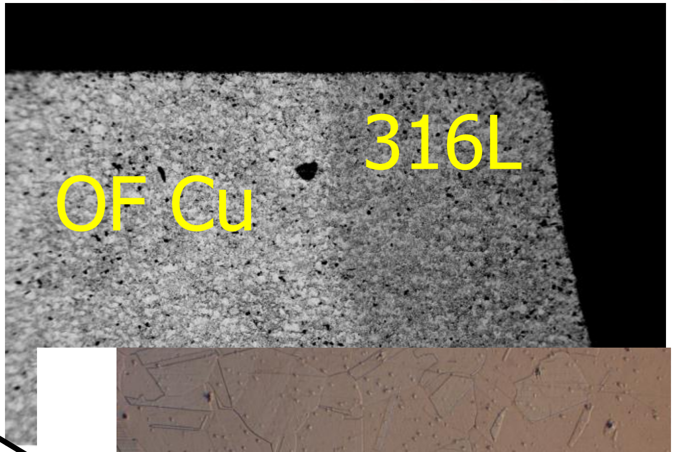


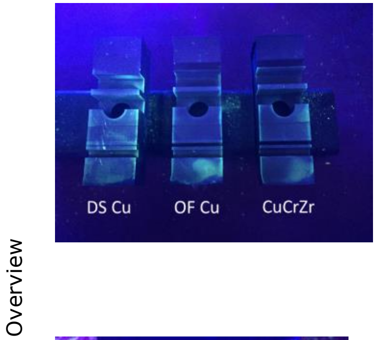
…ess steels, alternative joining …ques, **HIP diffusion bonding**

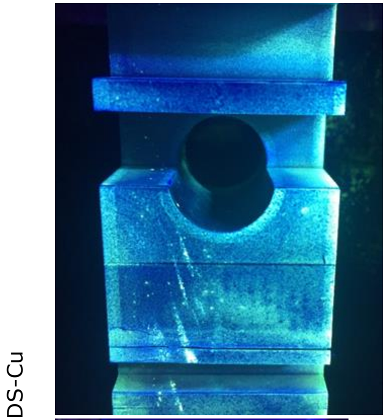


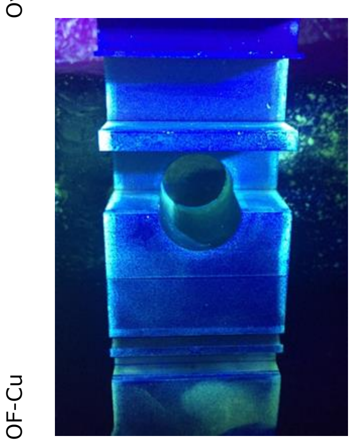
⇐ **Penetrant testing** ⇓

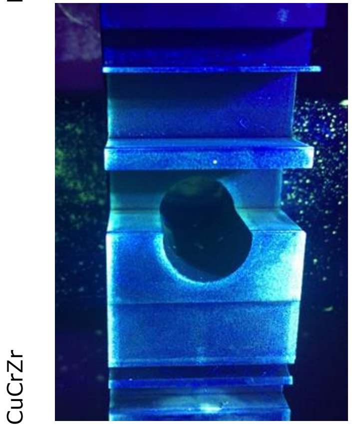












⇑ **Micro-structural obser-vations** ⇒

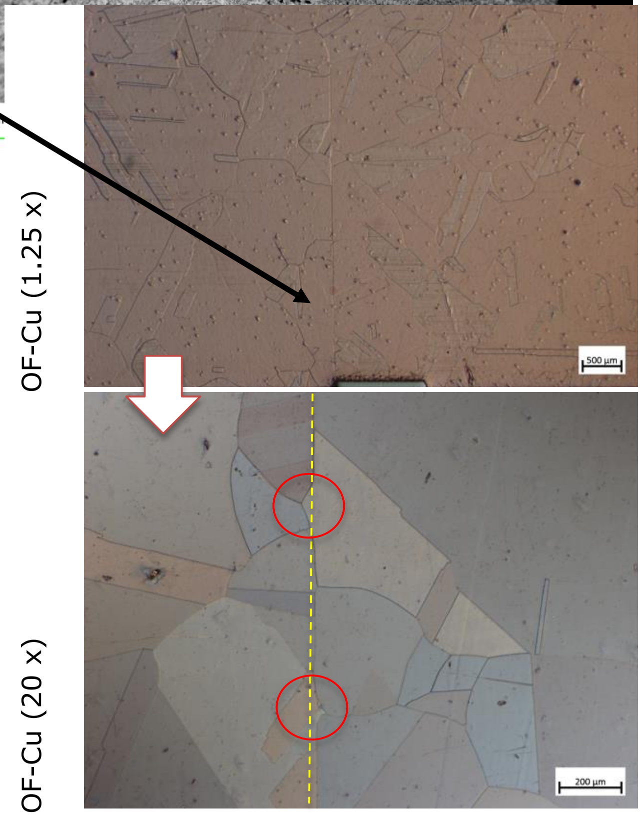
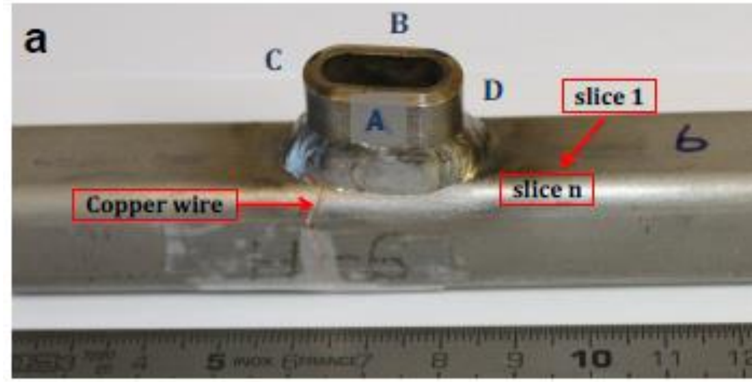


Figure 1 – UV light observation on the three samples after 30 minutes exposure to PT revelatory Androx developer 9D1B

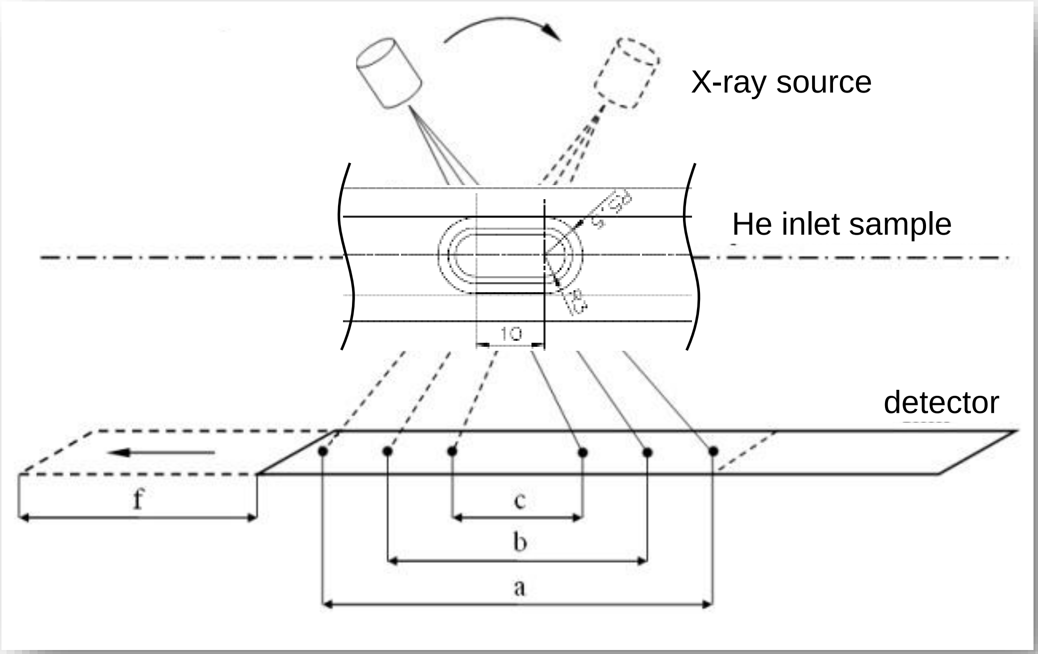
2.a/3 Advanced investigation techniques: X-ray microtomography



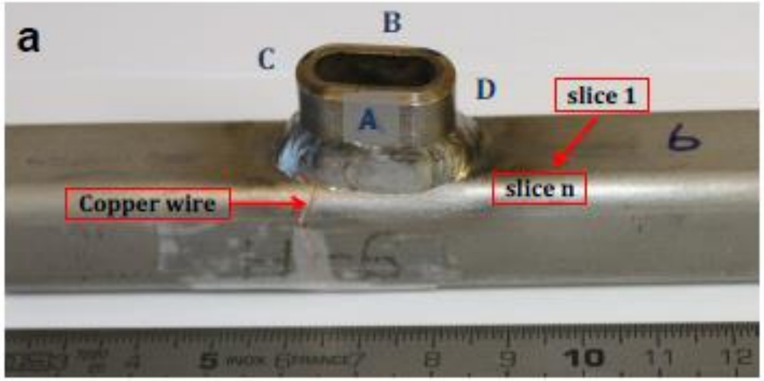
ITER magnet system, correction coils
He inlets and outlets of the NbTi cable-in-conduit conductor (CICC)

2.a/3 Advanced investigation techniques: X-ray microtomography

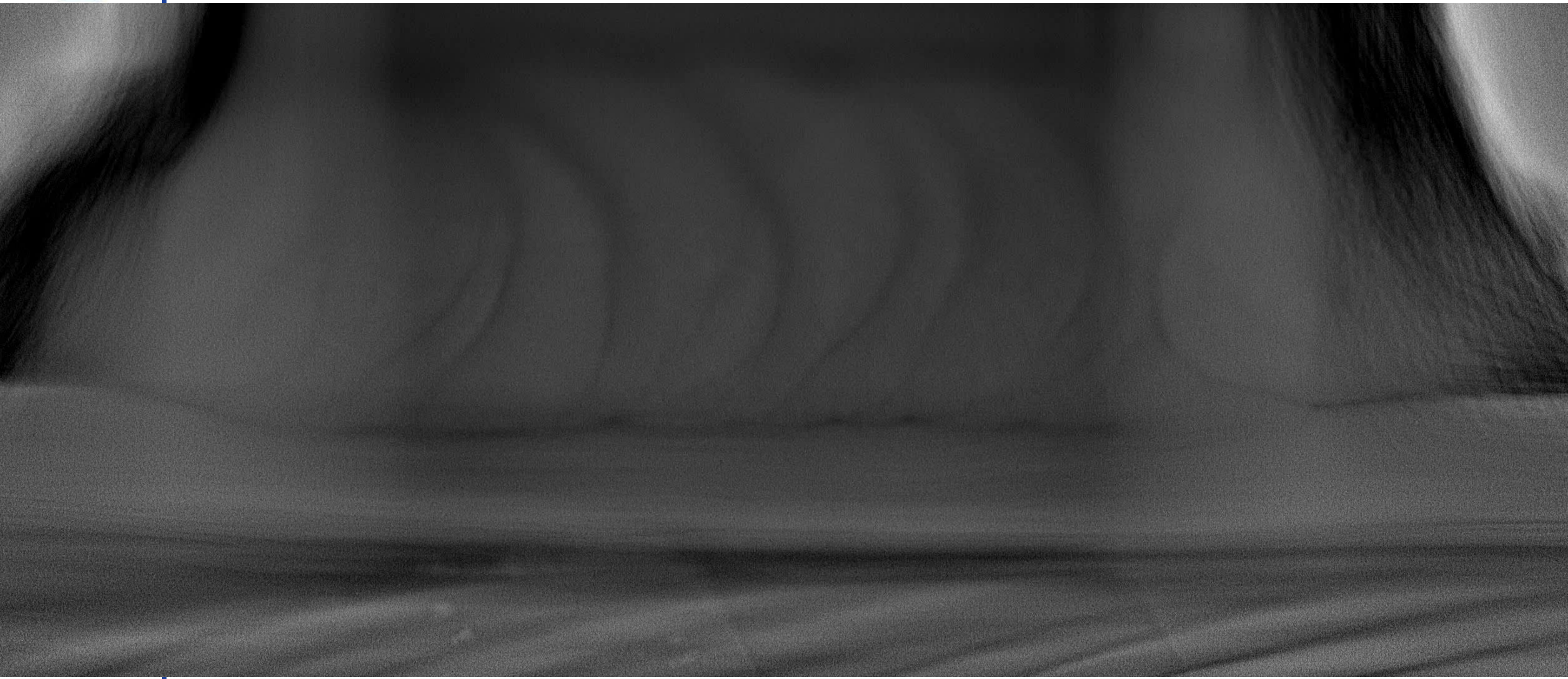
- **Most stringent quality of welds imposed (EN ISO 5817 - level B) or equivalent**
- **Volumetric NDT inspections indispensable**
- **Application of X-ray laminography (planar X-ray micro-tomography)**



2.a/3 Advanced investigation techniques: X-ray microtomography



- **Laminography**

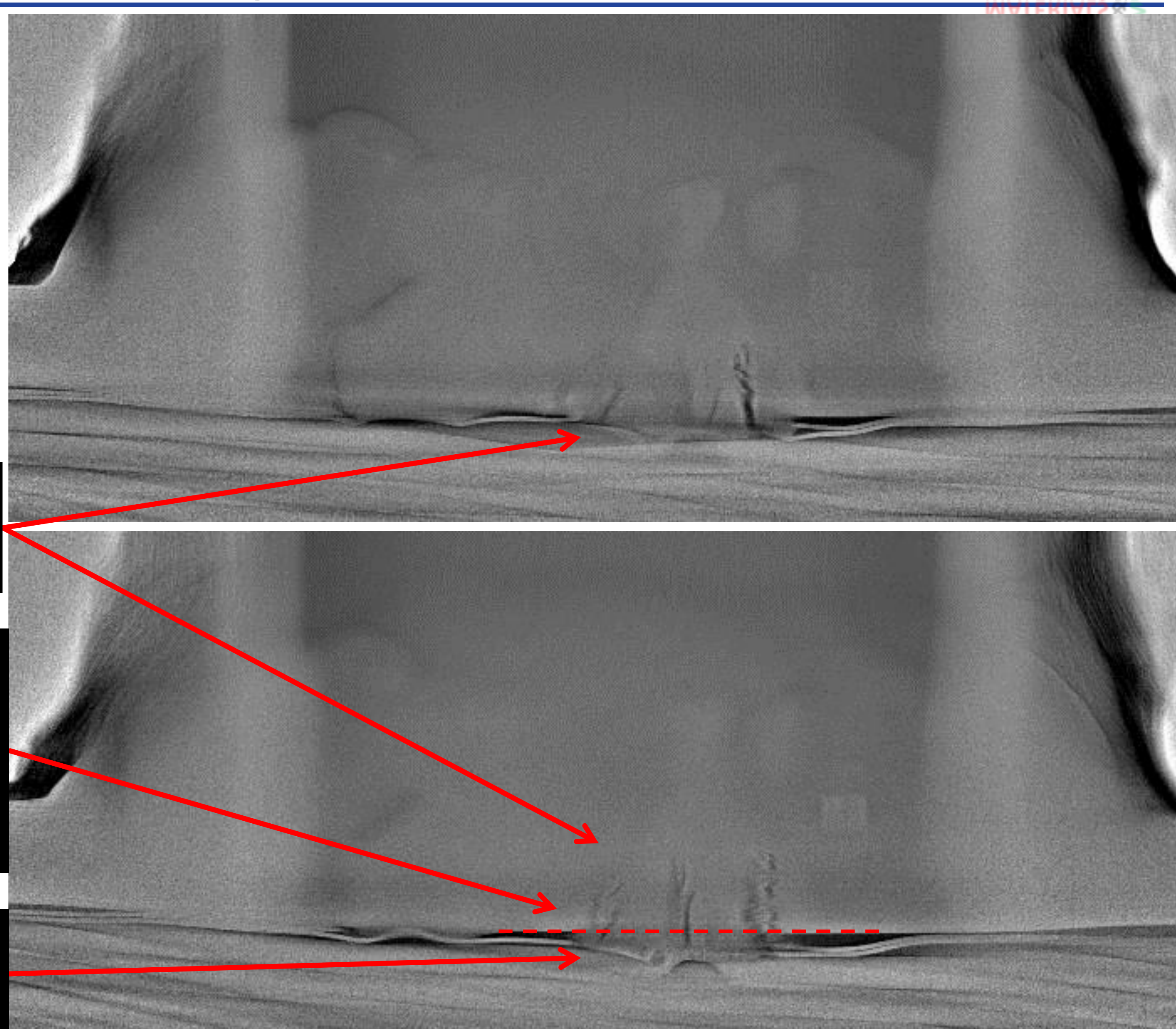


2.a/3 Advanced investigation techniques: X-ray microtomography

Cracks (ref: 401) unacceptable to ISO 5817 level B

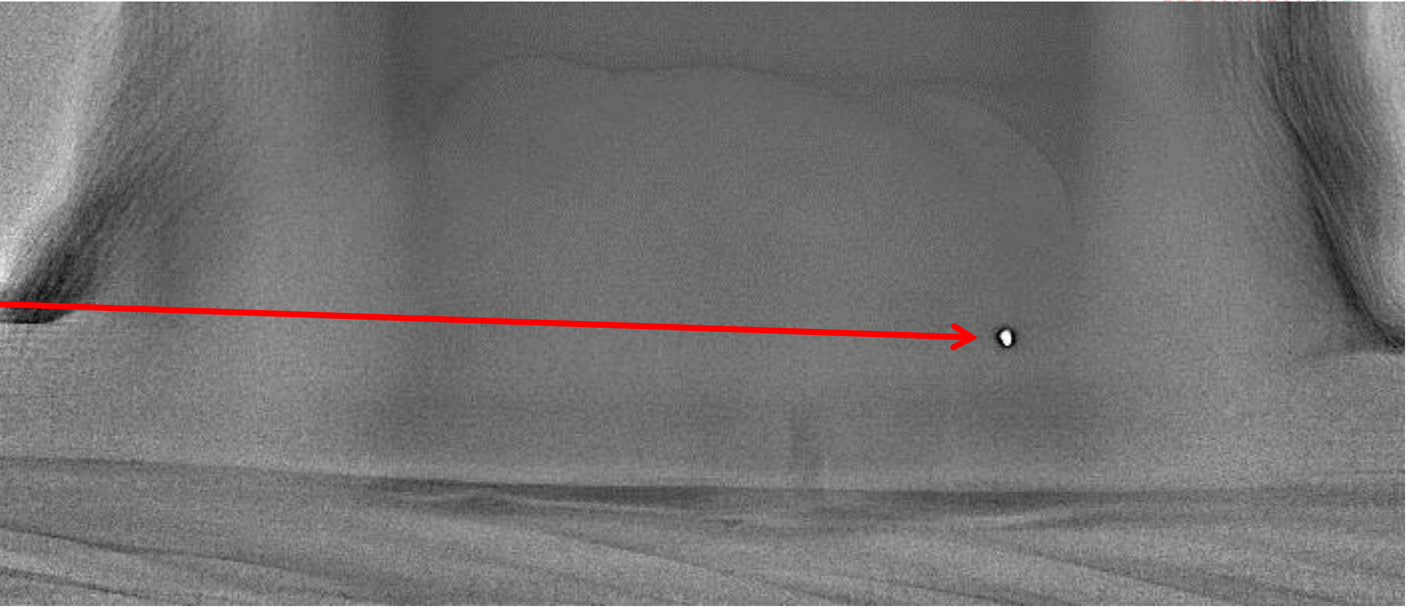
Excessive penetration and melt through (ref: 504) acceptable to ISO 5817 level B ($h \leq 1$ mm $+ 0.1\ b$, where b is a width of weld reinforcement)

Wrap welded with the jacket and possibly with the superconcuctor



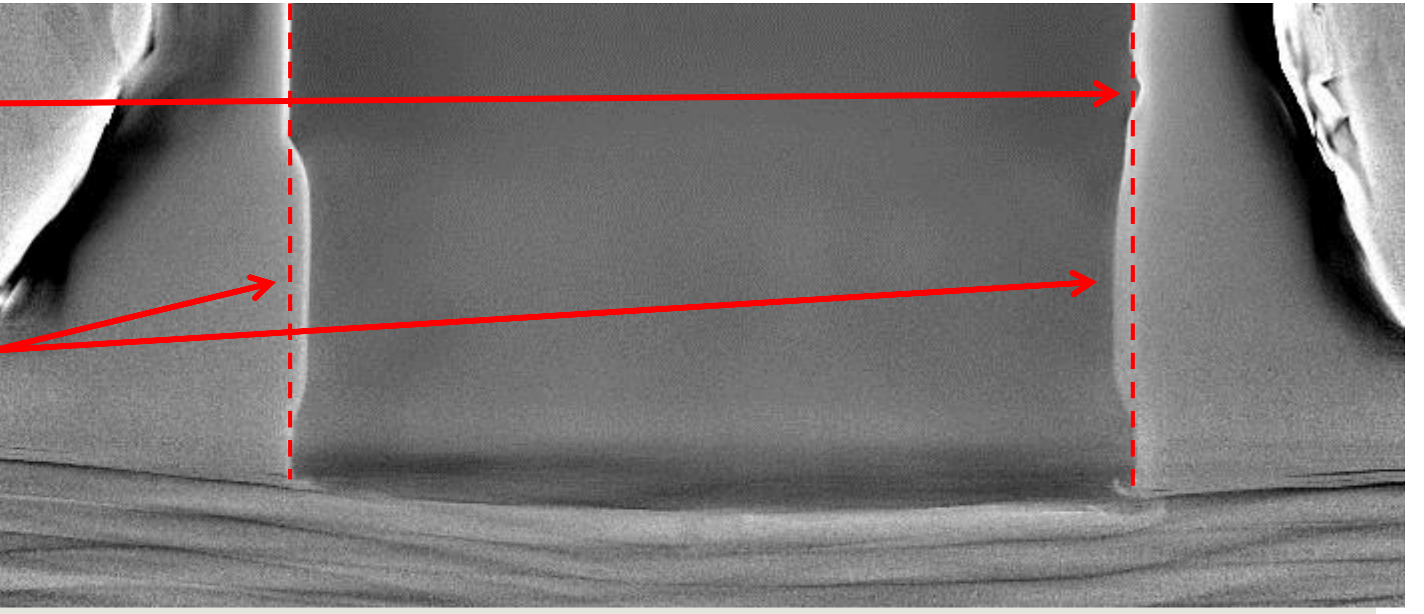
2.a/3 Advanced investigation techniques: X-ray microtomography

Tungsten inclusion (ref: 6021) according to ISO 5817 level B acceptance depends on application

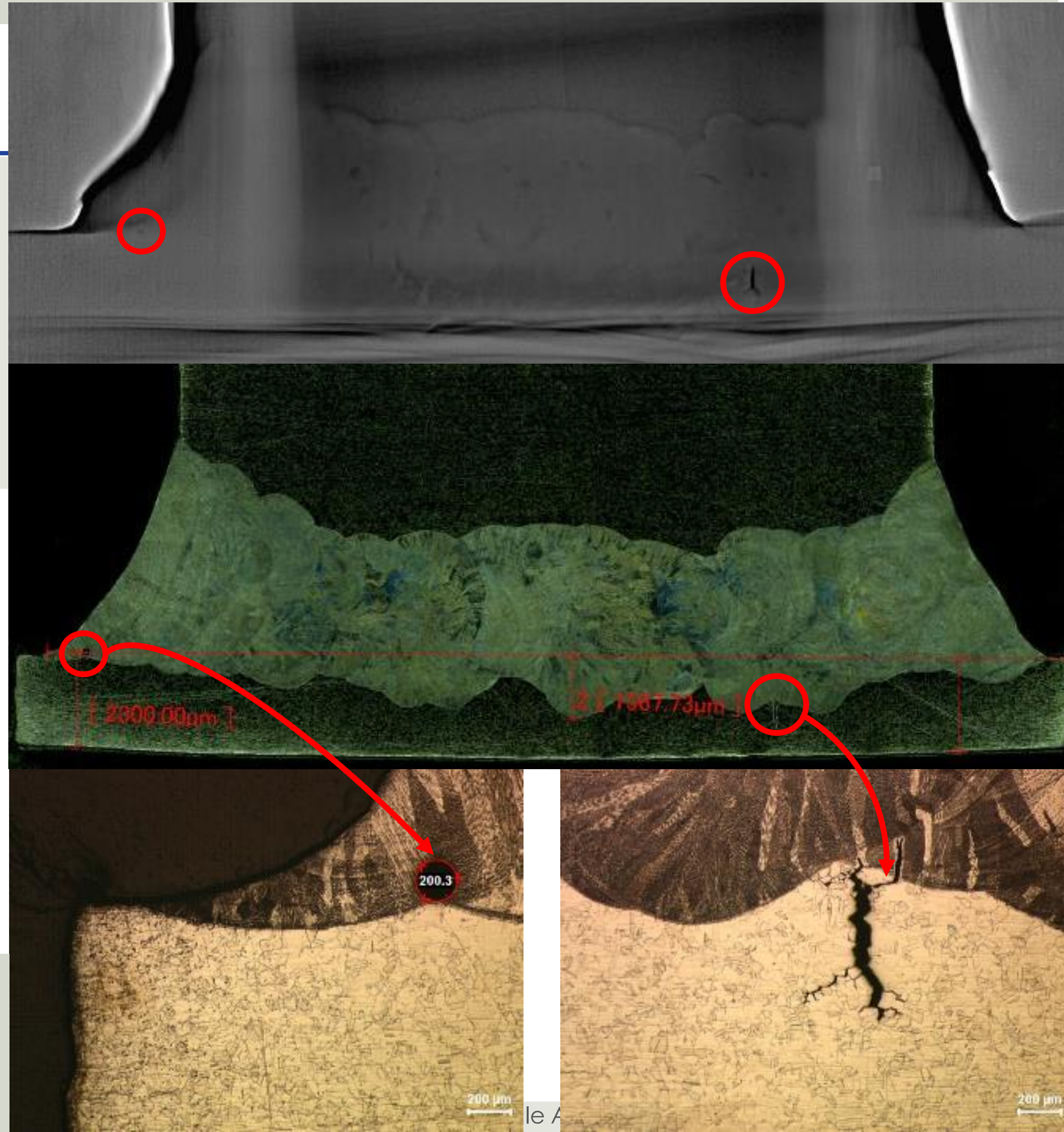


Shrinkage grooves (ref: 5013) not acceptable to ISO 5817 level B

Excessive penetration (ref: 504) acceptable to ISO 5817 level B (h ≤ 1 mm + 0.1 b, where b is the width of weld reinforcement)



X-ray laminography: impressive correspondence between XR tomography and microoptical observations



S. Sgobba, S.A.E. Langeslag, P. Libeyre, D. J. Marcinek, A. Piguiet, A. Cécillon, *Advanced Examination Techniques applied to the Qualification of Critical Welds for the ITER Correction Coils*, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.05.009

Wrough ... ations

Alloy Grou	...tion AA	Example
Pure alumi	es	
→ Al-Cu	es	EN AW-2219
→ Al-Mn	es	EN AW-3003
→ Al-Si	es	weld fillers
→ Al-Mg	es	EN AW-5083
→ Al-Mg-Si	es	EN AW-6082 (6061)
Al-Zn	es	
Al+other el	es	
→ Innovative		DS, rapid solidification

Table 2 Weldability of aluminum alloys by the gas metal-arc and gas tungsten-arc processes

Readily Weldable

Wrought alloys
- Unalloyed aluminum, 1060, 1100, 1350
- 2219
- 3003, 3004, 3105
- 5005, 5050, 5052, 5056, 5083, 5086, 5154, 5252, 5254, 5454, 5456, 5457, 5652, 5657
- 6061, 6063, 6070, 6101, 6201, 6262, 6463
- 7005

Casting alloys
- 328.0, 355.0, C355.0, 356.0, A356.0, 357.0, A357.0, 359.0
- 443.0, A443.0, B443.0

Weldable in Most Applications(a)

Wrought alloys: 2014, 4032, 6066

Casting alloys
- 208.0, 308.0, 319.0, 332.0
- 413.0, 712.0

Limited Weldability(b)

Wrought alloys: 2024, 2218, 2618

Casting alloys
- 213.0, 222.0, 295.0, 296.0
- 333.0, 336.0, 354.0
- 512.0, 513.0, 514.0
- Die casting alloys

Welding Not Recommended

Wrought alloys: 2011, 7075, 7178

Casting alloys
- 242.0, 520.0, 535.0
- 705.0, 707.0, 710.0, 711.0, 713.0, 771.0

(a) May require special techniques for some applications. (b) Require special techniques.

2.b Aluminium and alloys

Base Alloys / Filler Alloys		1060, EC (W S D C T M)	1100 (W S D C T M)	2014, 2036 (W S D C T M)	2219 (W S D C T M)	3003, ALCLAD 3003 (W S D C T M)
319.0, 333.0, 354.0, 355.0, C355.0, 380.0	2319 4043 4145	B A A A A A A A B A A A	B A A A A A A A B A A A	B A A A A A C C B C A A A B C B A A	B A A A A A C C B C A A A B C B A A	B B A A A A A A B A A A
413.0, 443.0, 444.0, 356.0, A356.0, A357.0, 359.0	4043 4145 5356	A A A A A A A A B B A	A A A A A A A A B B A	B B A A A A A A B A A	B B A A A A A A B A A	A A A A A A A A B B A
7005, 7021, 7039, 7046, 7146, A712.0, C712.0	4043 4145 5183 5356 5554 5556	A A C A A B A B A A B A A A A B A B A A	A A C A A B A B A A B A A A A B A B A A	B B A A A A B A A	B B A A A A A B A A	A B C A A B A B A A B A A A A B A B A A
6061	4043 5183 5356 5554 5556 5654	A C A A A D B A A B A B A A A B A B A	A A C A A A A D B A B A B A B A A A B A B A	B B A A A A A B A A	B B A A A A A B A A	A B C A A A A D B A B A B A B A A A B A B A
6005, 6063, 6101, 6151, 6201, 6351, 6951	4043 4145 5183 5356 5554 5556 5654	A A C A A A A D B A B A B A B A A A B A B A	A A C A A A A D B A B A B A B A A A B A B A	B B A A A A A B A A	B B A A A A A B A A	A B C A A A A D B A B A B A B A A A B A B A
					A A A A A	A B C C A

Legend

Filler alloys are rated on the following characteristics:

Symbol	Characteristic
W	Ease of welding (relative freedom from weld cracking.)
S	Strength of welded joint ("as welded" condition.) (Rating applies particularly to fillet welds. All rods and electrodes rated will develop the specified minimum strengths for butt welds.)
D	Ductility. (Rating is based upon free bend elongation of the weld.)
C	Corrosion resistance in continuous or alternate immersion in fresh or salt water.
T	Recommended for service at sustained temperatures above 65.5°C (150°F).
M	Colour match after anodizing.

- A,B,C and D are relative ratings in decreasing order of merit. The ratings have relative meaning only within a given block.
- Combinations having no rating are not usually recommended.
- Ratings do not cover these alloys when heat-treated after welding.

2.b Aluminium and alloys

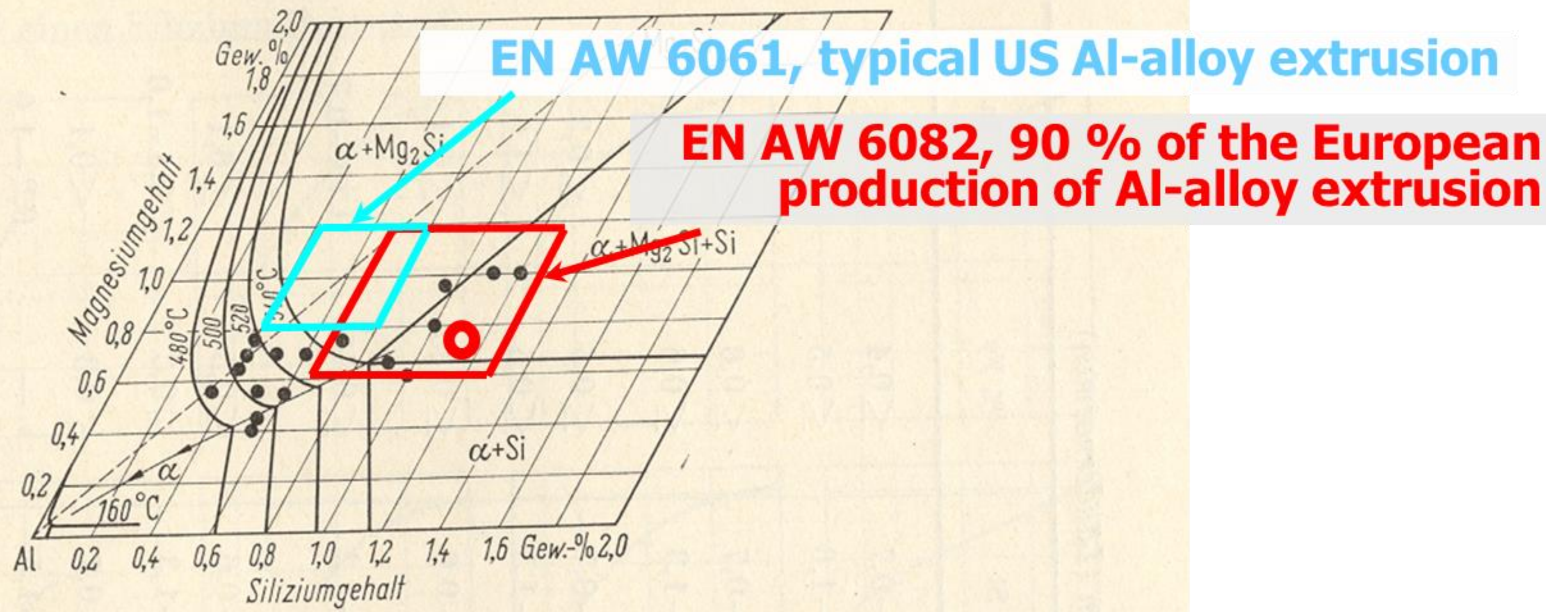
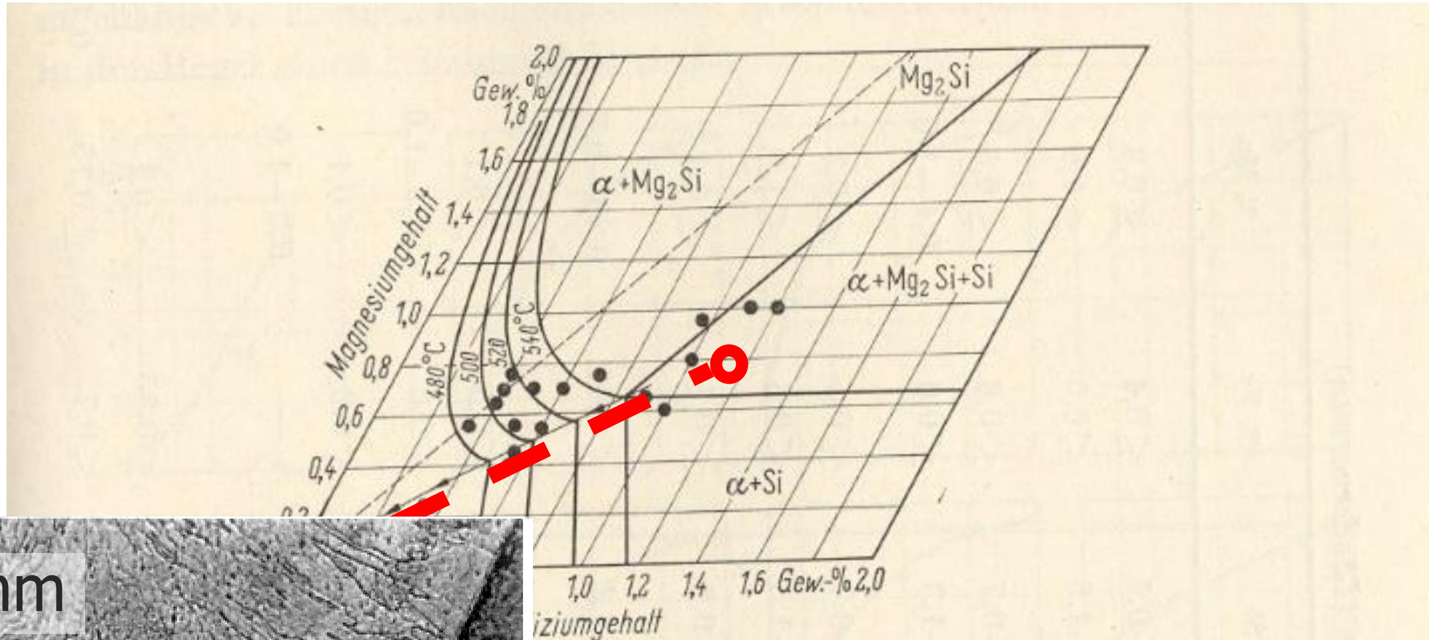


Abb. 597 a. Zustandsdiagramm der AlMgSi-Legierungen mit Isothermen für 540, 520, 500, 480 und 160 °C (nach D. W. Evans [25] und I. R. Harris u. P. C. Varley [26]).
• Lage von gebräuchlichen Handelslegierungen.

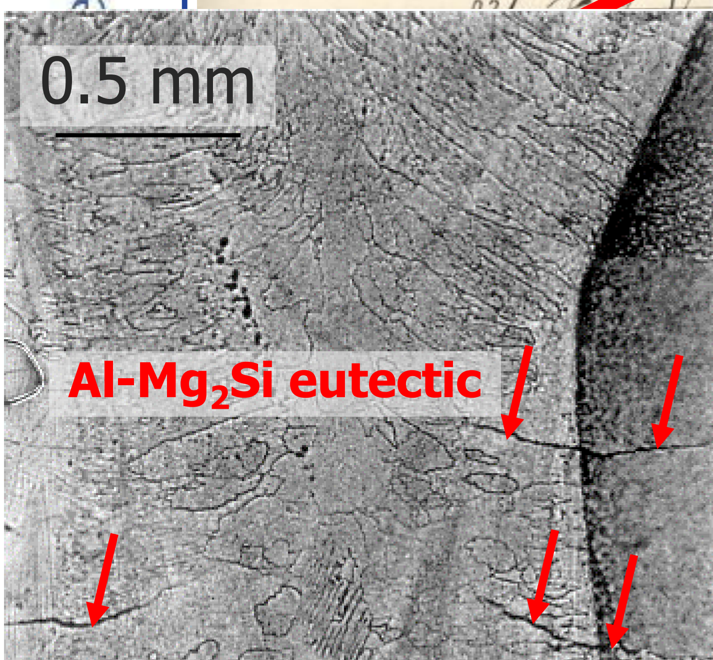
Table 1: Simplified summary of wrought aluminium alloys

	Legierungstyp	Werkstoff-Beispiel	Eignung für EB-Schweißen
nicht aushärtbar	Al	Al99,5	gut
	Al-Mn(-MG)	AlMn1	sehr gut
	Al-Mg(-Mn)	AlMg5	sehr gut; geringfügiges Ausdampfen von Mg; bei niedrigem Mg-Gehalt (unter etwa 3%); Neigung zu Heißrissigkeit
aushärtbar	Al-Mg-Si	AlMgSi1	sehr gut; bei einem kritischen Mg_2Si-Anteil (Mg unter etwa 1%, Si unter etwa 0,6%): Neigung zu Heißrissigkeit
	Al-Cu-Mg	AlCuMg2	gut; bei niedrigem Cu-Gehalt (unter etwa 4%); Neigung zu Heißrissigkeit
	Al-Zn-Mg(-Cu)	AlZnMgCu1,5	gut; geringfügiges Ausdampfen von Zn und Mg; Neigung zu Heißrissigkeit

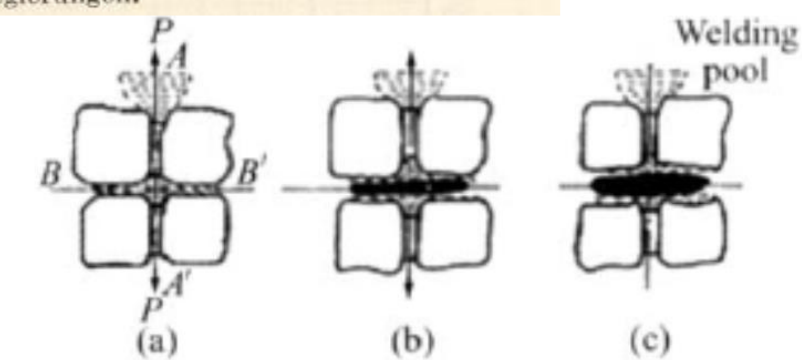
2.b Aluminium and alloys



AlMgSi-Legierungen mit Isothermen für 540, 520, 500, 480 und
ANS [25] und I. R. HARRIS u. P. C. VARLEY [26]).
n gebräuchlichen Handelslegierungen.

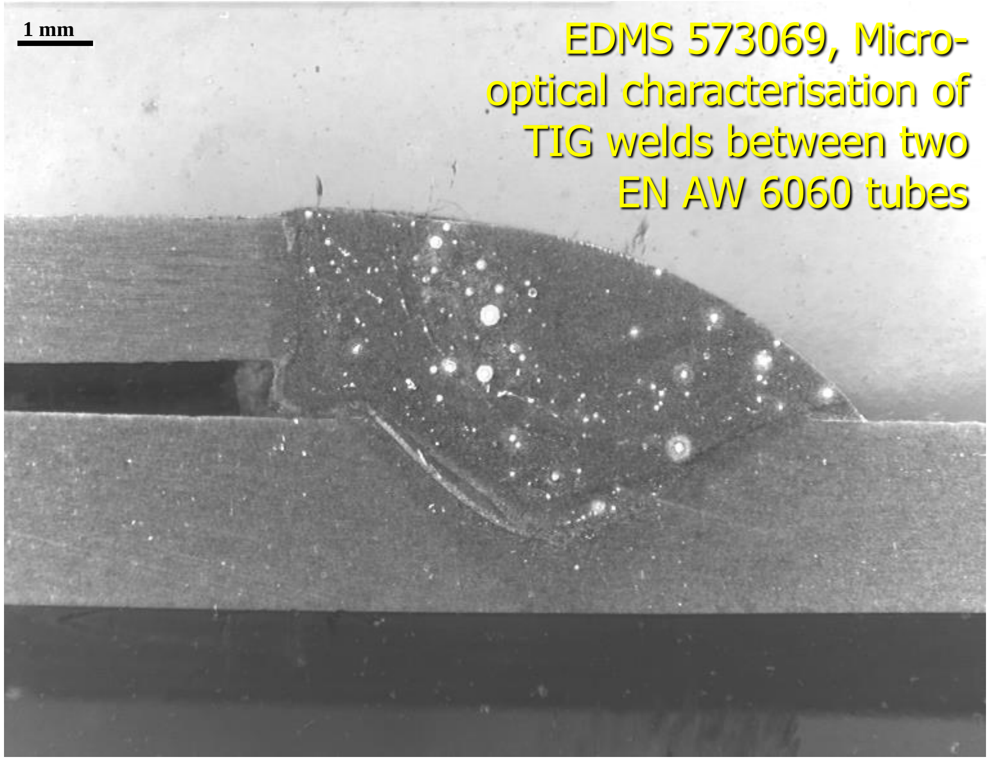


R. Liu, Z.J Dong and Y.M. Pan, *Solidification crack susceptibility of aluminum alloy weld metals*, Trans. Nonferrous Met. Soc. of China **16**, 2006, pages 110-116



Type B cracking model

2.b Aluminium and alloys



Porosity:
- Gas entrapment from poor shielding, shielding gas, air
- Hydrogen from moisture, unclean wire surface, base metal
- Excessive cooling rate (outgassing)

2.b Aluminium and alloys

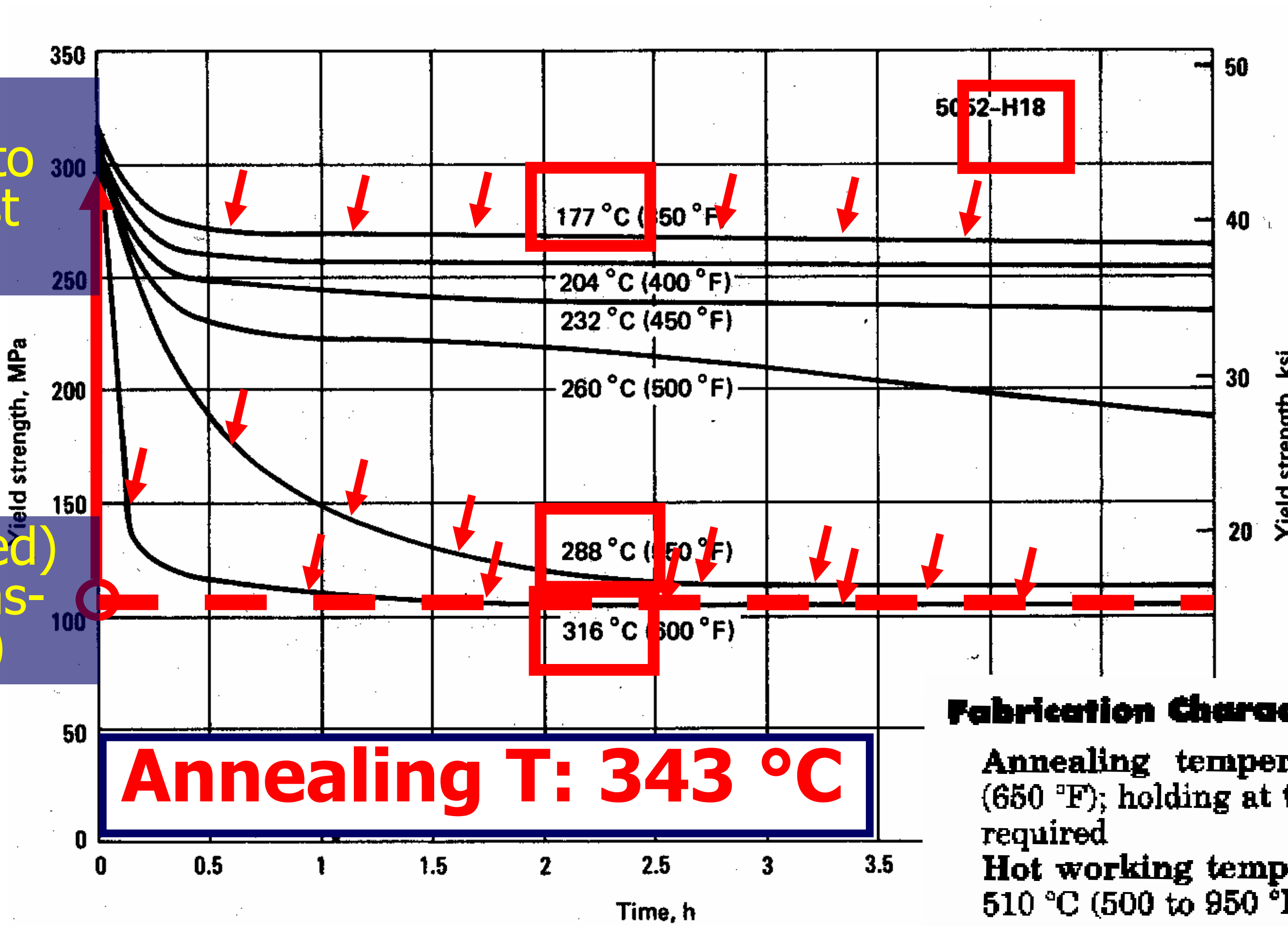
Heat treatable **Non heat treatable**

	Alloy Group	Designation AA
→ (non heat treatable)	Pure aluminium	1xxx series
→ (heat treatable)	Al-Cu	2xxx series
→ (non heat treatable)	Al-Mn	3xxx series
→ (non heat treatable)	Al-Si	4xxx series
→ (non heat treatable)	Al-Mg	5xxx series
→ (heat treatable)	Al-Mg-Si	6xxx series
→ (heat treatable)	Al-Zn	7xxx series
(⇒)	Al+other element (Li)	8xxx series

Non heat treatable

H18 (work hardened to the hardest state)

O (annealed) or H111 (as-fabricated)



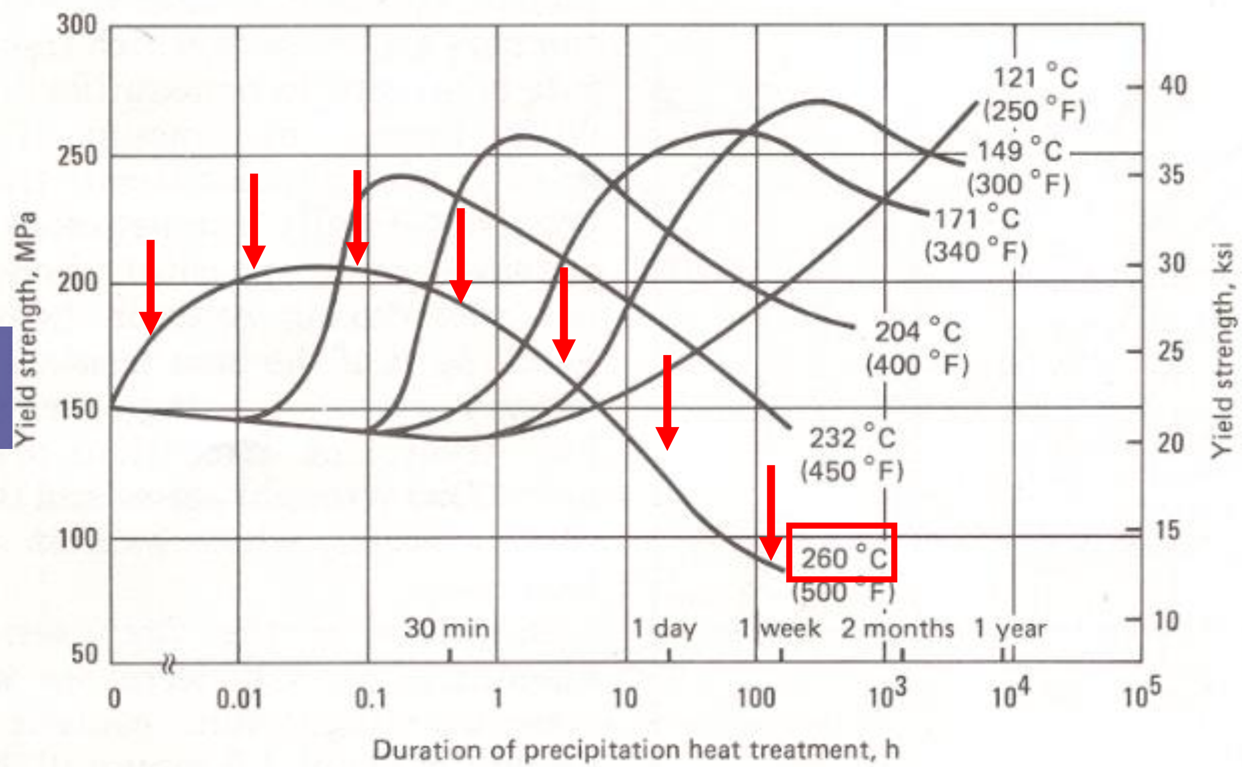
Fabrication Characteristics

Annealing temperature. 343 °C (650 °F); holding at temperature not required

Hot working temperature. 260 to 510 °C (500 to 950 °F)

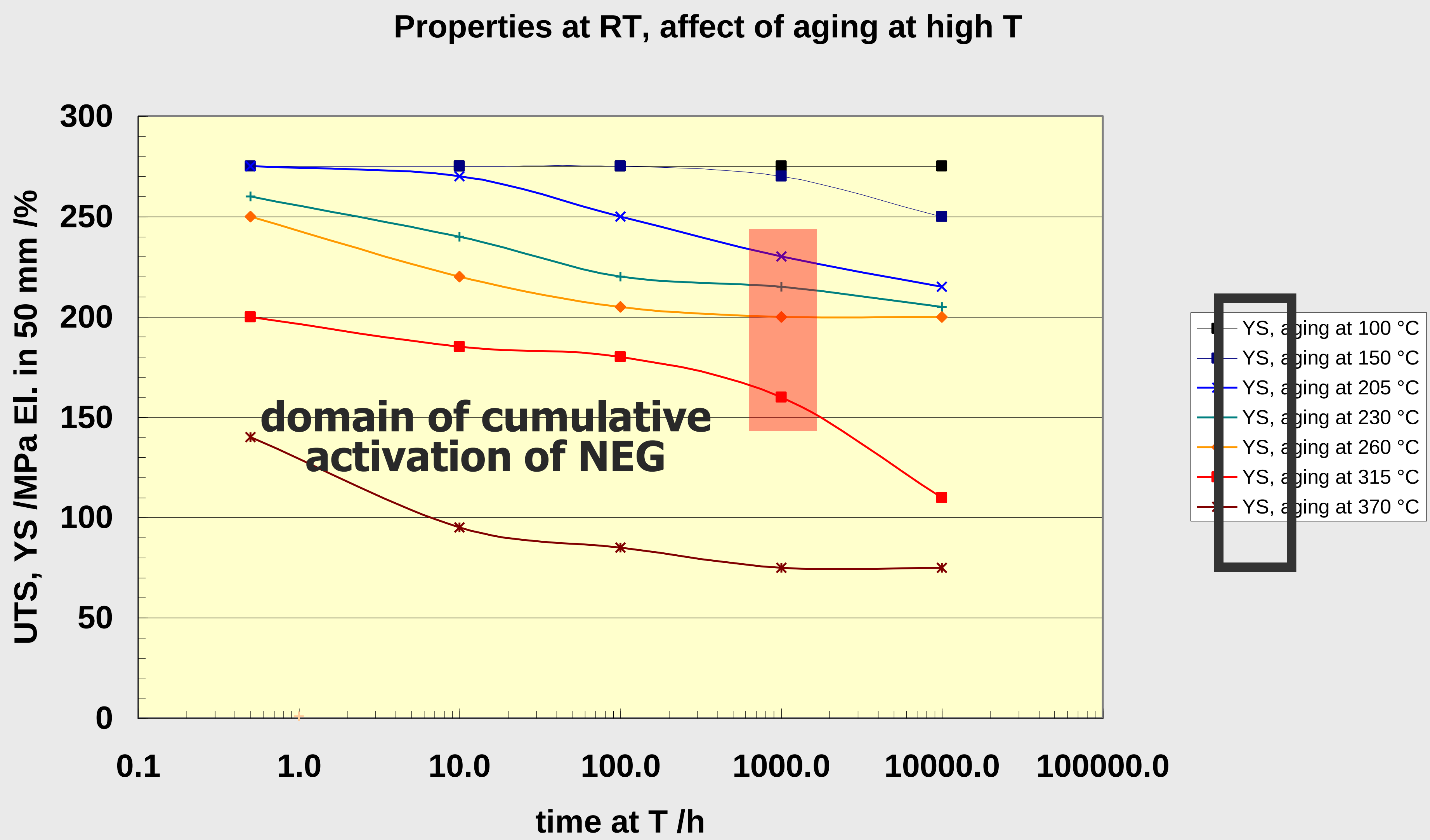
EN-AW 6061

O (solution annealed)



Toward artificially aged states (T6x tempers) ⇒

2.b Aluminium and alloys, EN AW 2219

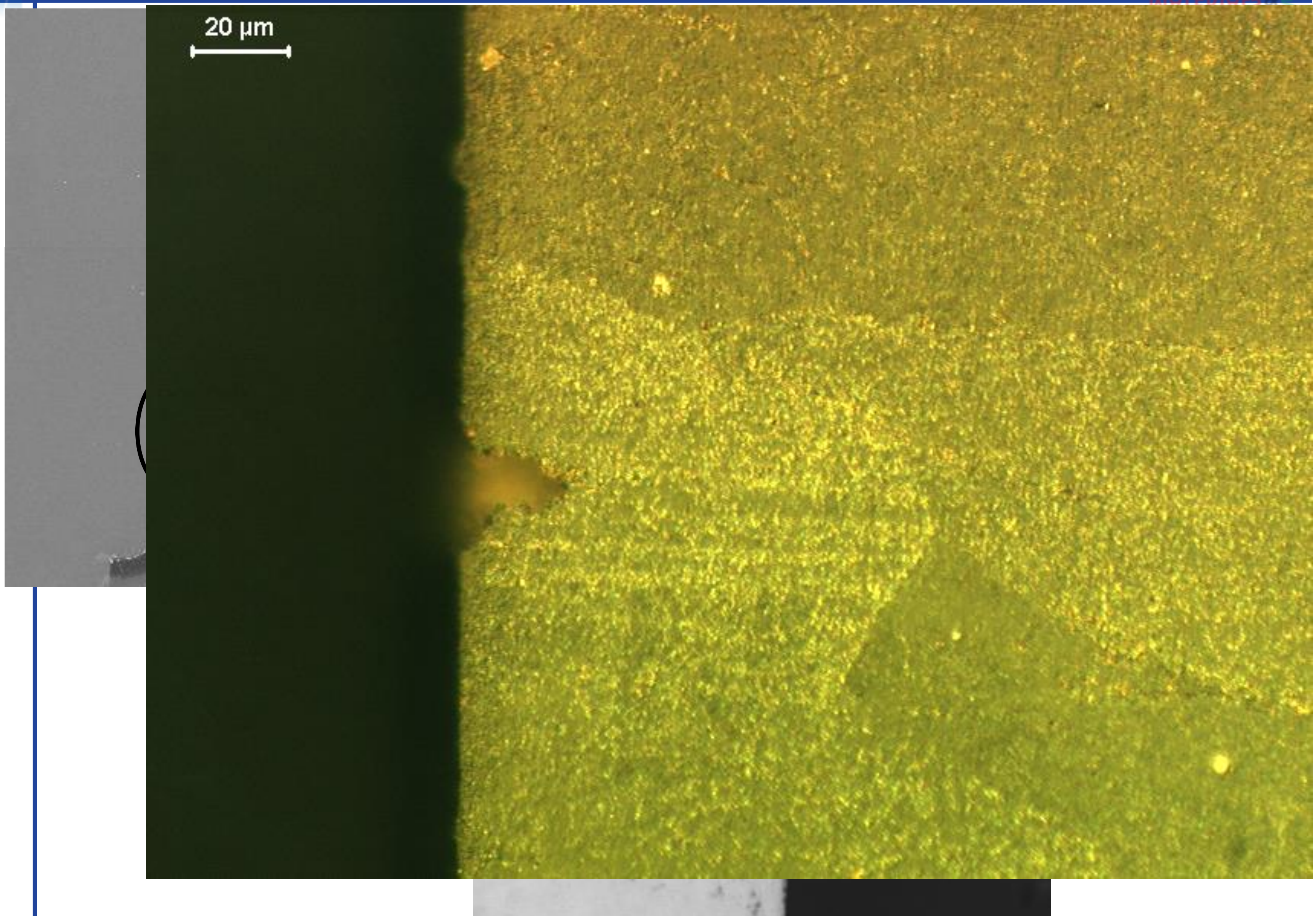


2.b Aluminium and alloys: failure analysis of thin walled Al-alloy bellows for the LHCb experiment

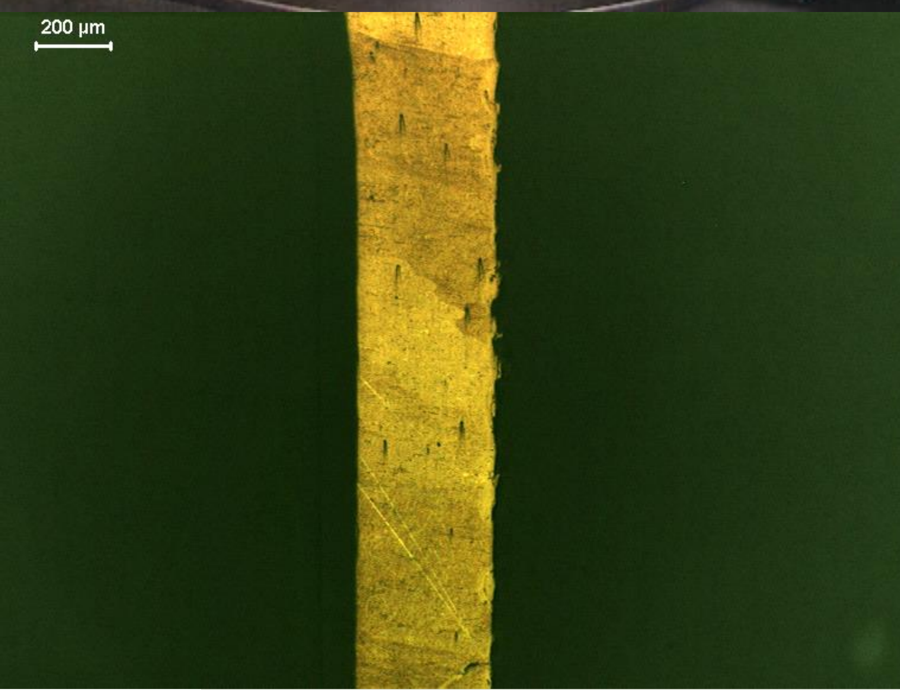
EN AW 2219 bellows

- **machined from forged round blocks**
- **welded assembly (2 flanges + 2 bellows + 1 tube) for the LHCb experiment**
- **leaks detected on a significant fraction of bellows**

2.b Aluminium and alloys: failure analysis of thin walled Al-alloy bellows for the LHCb experiment



2.b Aluminium and alloys: failure analysis of thin



METLAB OY
Metallurgical
Laboratory
Tampere
Finland

METALLOGRAAFINEN TARKASTELU -
METALLOGRAPHIC EXAMINATION

FORGED ALUMINIUM BLOCK no. 5

No. 2932 / 0.
Enclosure 1.

Sivu – Page 2 / 3

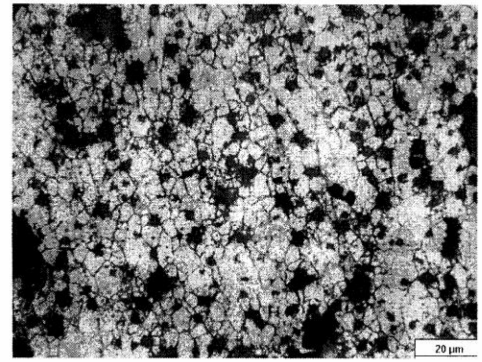


Figure 2932 / E1

The microstructure of the block 5 near outer surface no. 1.

Average ASTM E112 grain size 10,5 ± 0,5.

Magnification 700 X.

Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.

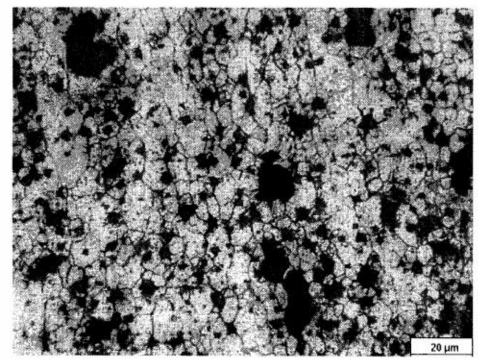


Figure 2932 / E2

The microstructure of the block 5 near outer surface no. 1.

Average ASTM E112 grain size 10,5 ± 0,5.

Magnification 700 X.

Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.

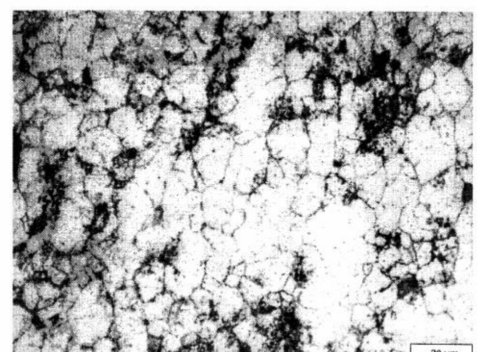


Figure 2932 / E3

The microstructure of the block 5 at centerline.

Average ASTM E112 grain size 9,5 ± 0,5.

Magnification 700 X.

Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.

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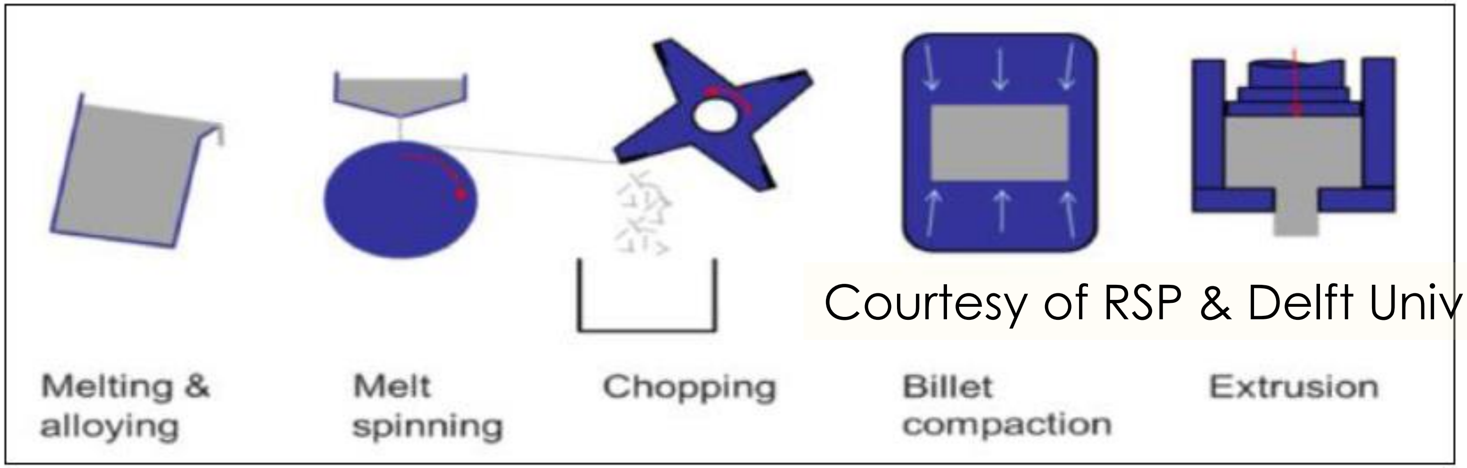
2.b Aluminium and alloys

EN AW-2219-T6 forged blanks for ultra-high-vacuum applications

2.b Aluminium and alloys



Courtesy of RSP & Delft University

Melt spinning is a rapid quenching process, cooling rates possible, up to 10^{+6} °C/s → Very fine microstructure, High mechanical properties

T. Mast, diploma work, 2014

Alloy	E-Modulus (GPa)	Hardness (HB)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
RSA 501	70	159	550	510	16
RSA 905	90	180	600	475	7
RSA 8009	9[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

RSA 501 composition
RSA 905 composition
RSA 8009 compositio

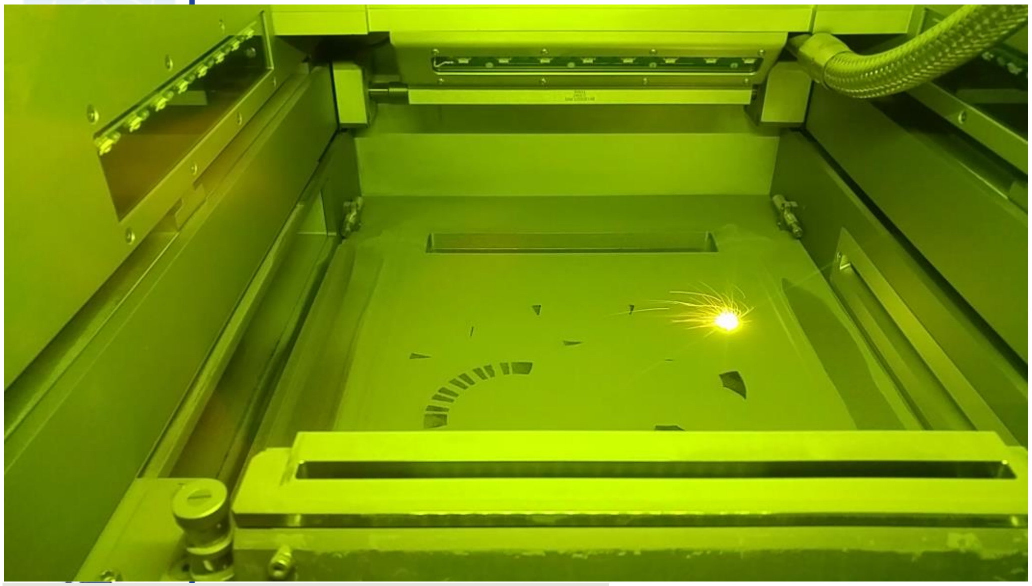
Espe, 1966

Recently, Al has been made by the SWISS ALUMINIUM-INDUSTRIE A.G. from pressed Al powder (so-called Al flake, about 1 $\mu \times 100 \mu$ with an O_2 content). The process is carried out at room temperature at pressures between 20 and 50 kg/mm²; then follows sintering in air at 550—600 °C; then hot pressing at 500—600 °C, with a pressure of 50 kg/mm², and finally hot extrusion at 500 to 600 °C through a die, to produce a material of density 2.75 g/ml; this can be rolled or drawn, hot or cold and is known in the trade as "SAP".

2.d Other grades, innovative materials and manufacturing techniques

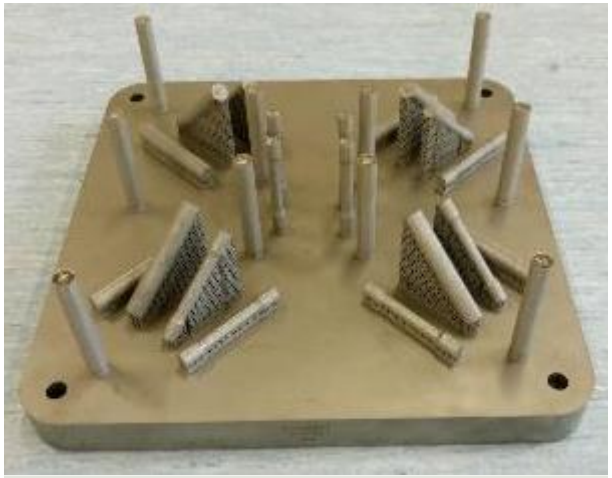
Additive manufacturing

⇒ Additional details about the process, see S. Mathot, 15/06

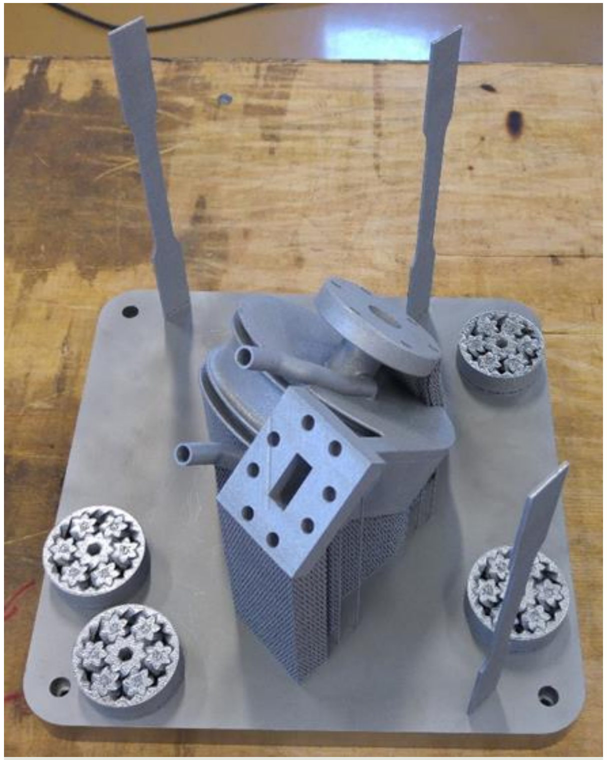


Selective Laser Melting Machine SLM 280 HL available at CERN

Diaphragm for UHV leak tightness tests, different models



Tensile test specimens for a study of the influence of orientation and location



Ti6Al4V additive manufactured “spiral load” prototypes (power attenuation at the output of RF cavities)

2.d Other grades, innovative materials and manufacturing techniques

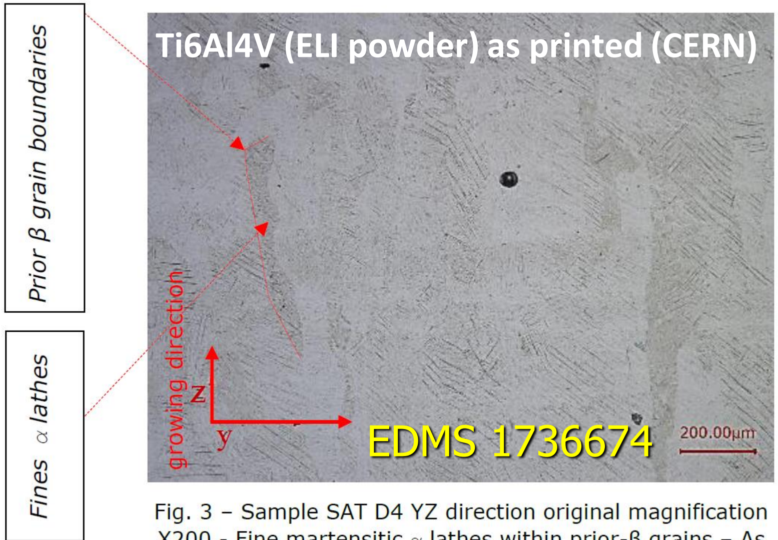
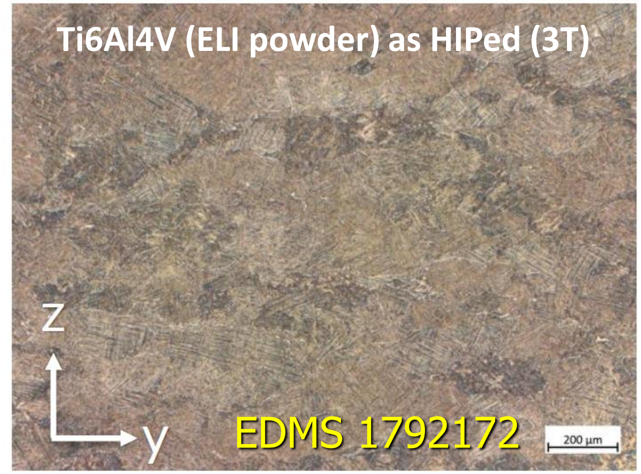
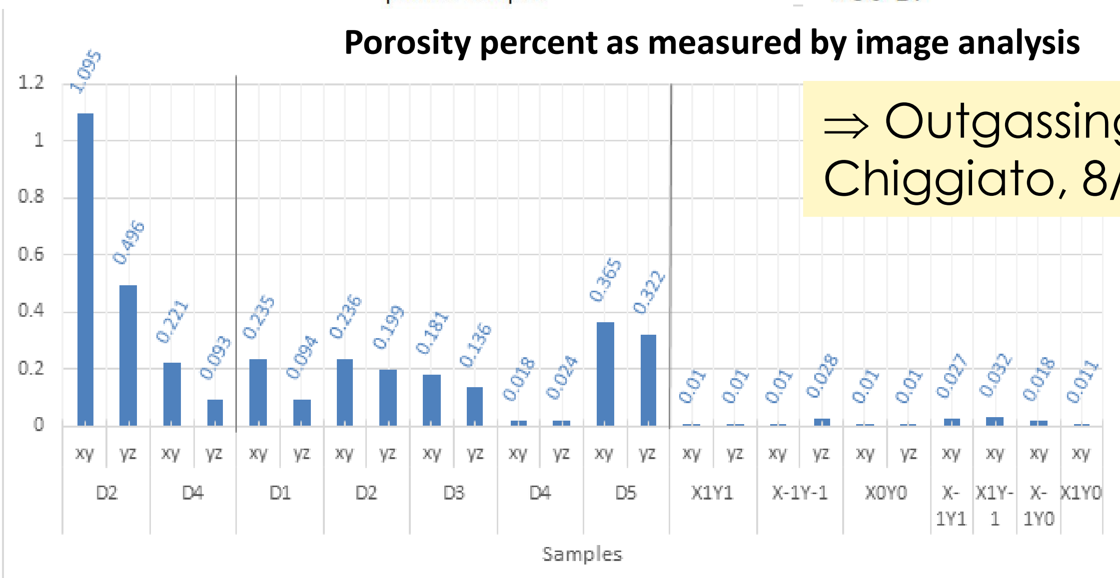


Fig. 3 – Sample SAT D4 YZ direction original magnification X200 - Fine martensitic α lathes within prior-β grains – As printed temper.

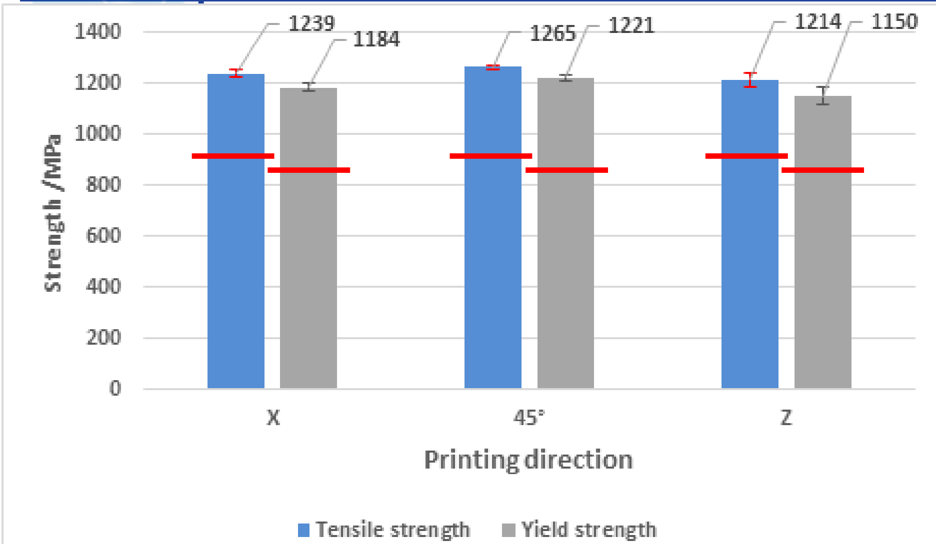


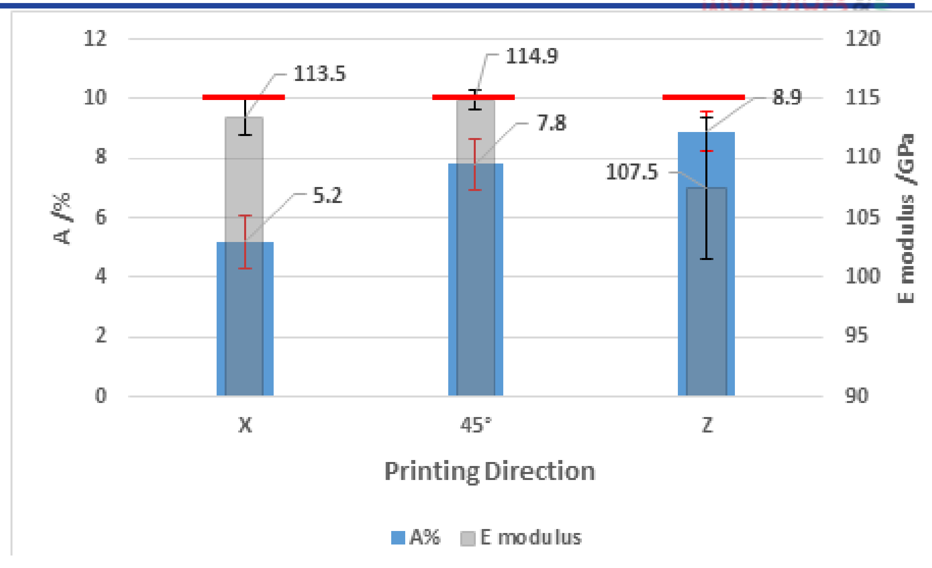
Pic11 – sample #6 – original magnification ×50 BF



⇒ Outgassing properties, see P. Chiggiato, 8/06

2.d Other grades, innovative materials and manufacturing techniques





B 381 – 09

TABLE 1 Tensile Requirements[A]

Grade	Tensile Strength, min		Yield Strength (0.2 % Offset), min or Range		Elongation in 4D, min, %	Reduction of Area, min, %
	ksi	(MPa)	ksi	(MPa)		
F-5	130	(895)	120	(828)	10	25

EDMS 1765091

		eference	Rm (MPa)	Rp0,2 (MPa)	A (%)
NO HIP	#1	B05412 M X	967,4 ± 3,1	870,7 ± 2,9	10,7 ± 0,1
	#2	B05412 M Z	960,3 ± 7,2	858,5 ± 7,3	14,0 ± 1,0
HIP treated	#3	B05414 M X	989,6 ± 4,5	886,3 ± 9,0	10,2 ± 0,7
	#4	B05414 M Z	959,9 ± 2,7	861,0 ± 1,9	13,3 ± 0,8
NO HIP	#5	B05648 M X	990,3 ± 0,3	908,1 ± 0,8	10,0 ± 0,9
	#6	B05713 M Z	985,7 ± 3,6	891,1 ± 2,7	11,7 ± 1,0
HIP treated	#7	B05713 M X	942,3 ± 12,3	876,7 ± 7,0	5,1 ± 1,3
	#8	B05648 M Z	895,4 ± 12,8	841,8 ± 15,0	5,5 ± 0,4

- **Good isotropy achieved**
- **High strength**
- **Limited ductility, toughness? (might prevent cryogenic applications)**
- **Annealing and/or HIPing treatments should be foreseen**

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)

Aluminium and alloys

- Al and alloys, general purpose ⇒ 5 EUR/kg
- EN AW 2219 forged blanks ⇒ 80 EUR/kg
- Special forgings, EN AW 6061, velo windows ⇒ 15 EUR/kg

Coppers

- OFE Cu ⇒ 25-40 EUR/kg (3D forged)
- OF Cu ⇒ 10 EUR/kg (basis)
- CuBe, high (low) Be ⇒ 40-90 EUR/kg (strips)
- Glidcop ⇒ 55 EUR/kg
- Additive manufactured 99.9 % Cu ⇒ 100 EUR/kg (powder)

Titanium

- Grade 2 ⇒ 50 EUR/kg (plates)
- Ti6Al4V (ELI) ⇒ (50-)140 EUR/kg (rods/plates)
- Additive manufactured Ti6Al4V ⇒ 320-360 EUR/kg (powder)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