CAS course "Vacuum in Accelerators", Platja d'Aro, 17-24 May 2006

Materials of high vacuum technology, an overview

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TS-MME-MM
CERN

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 and less common materials (and processes)

   $\Rightarrow$ Discussion of

   Examples of application
   Aspects related to manufacturing, joining, near net shaping techniques
   Failure analyses, including corrosion issues…

3. Conclusions

General rules

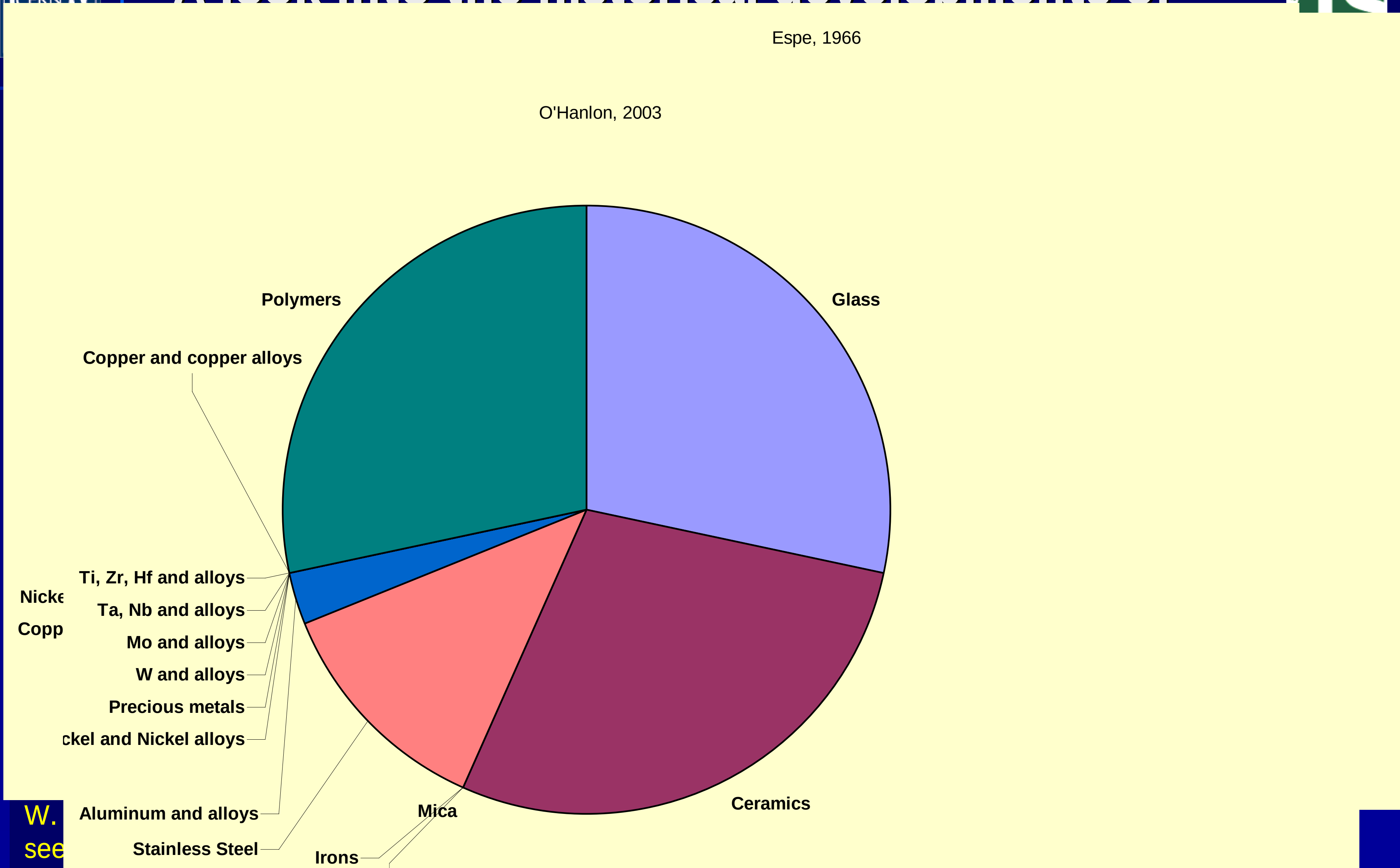
1. Ease of degassing
2. Adequate strength at high as well as low T
3. Thermal expansion coefficients

1. Ease of machinability and joining
2. Sealing glasses, ceramics and other insulators
3. Materials to yield low outgassing rates
4. Bakeability
5. Interdependence of cleaning, joining, construction and application
6. Stainless steel is the dominant material

(*O'Hanlon, A User's guide to Vacuum Technology, Wiley, 2003*)

Press, 1966)

A look into the historical developments of



W.

see

H.

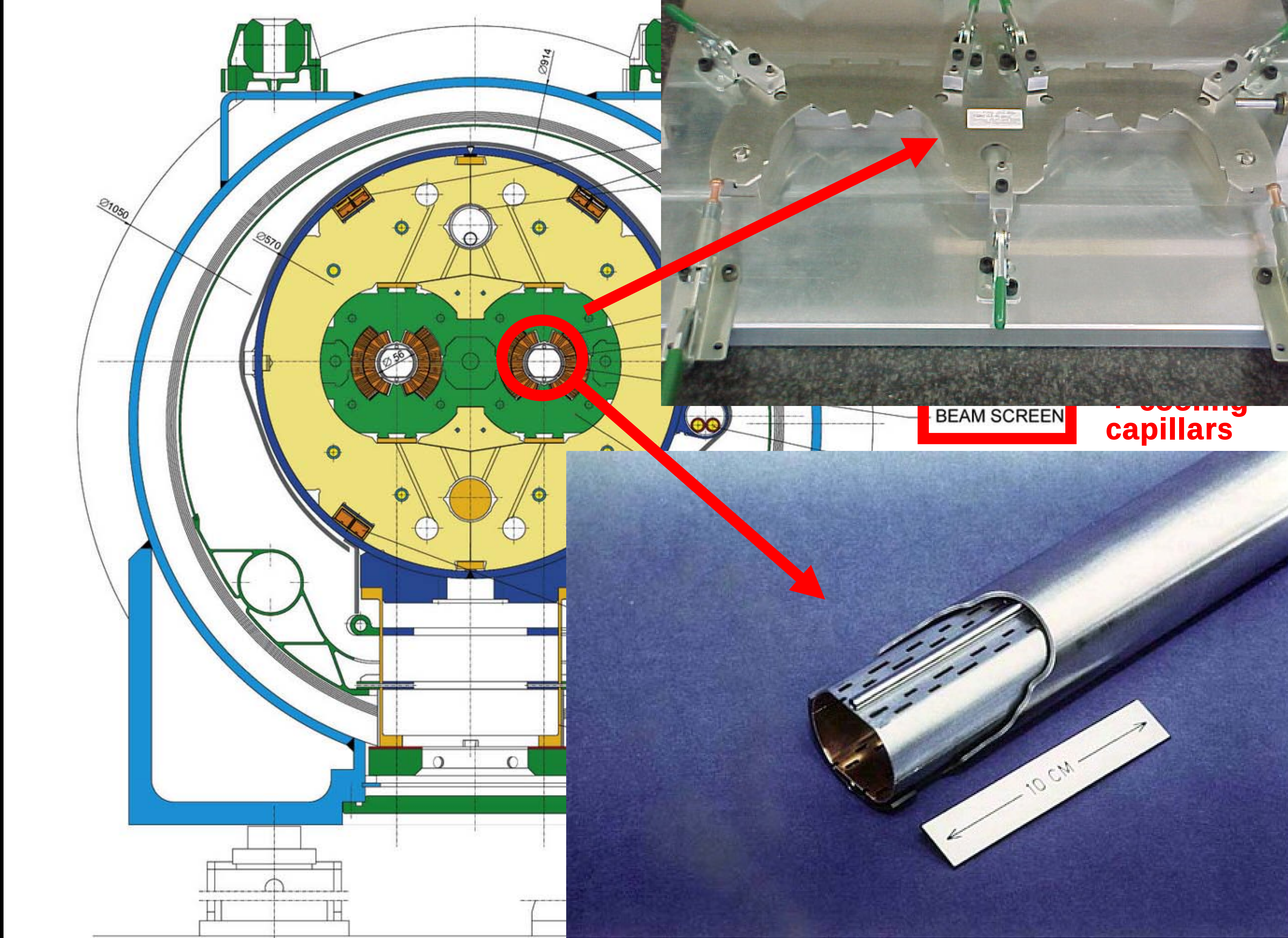
J.

J.F. O'Hanlon, A user's guide to vacuum technology, 3rd ed., Hoboken, Wiley, 2003

K. Diels, Werkstoffe und Werkstoffverbindungen in der Vakuum-Technik, Essen, Classen, 1968

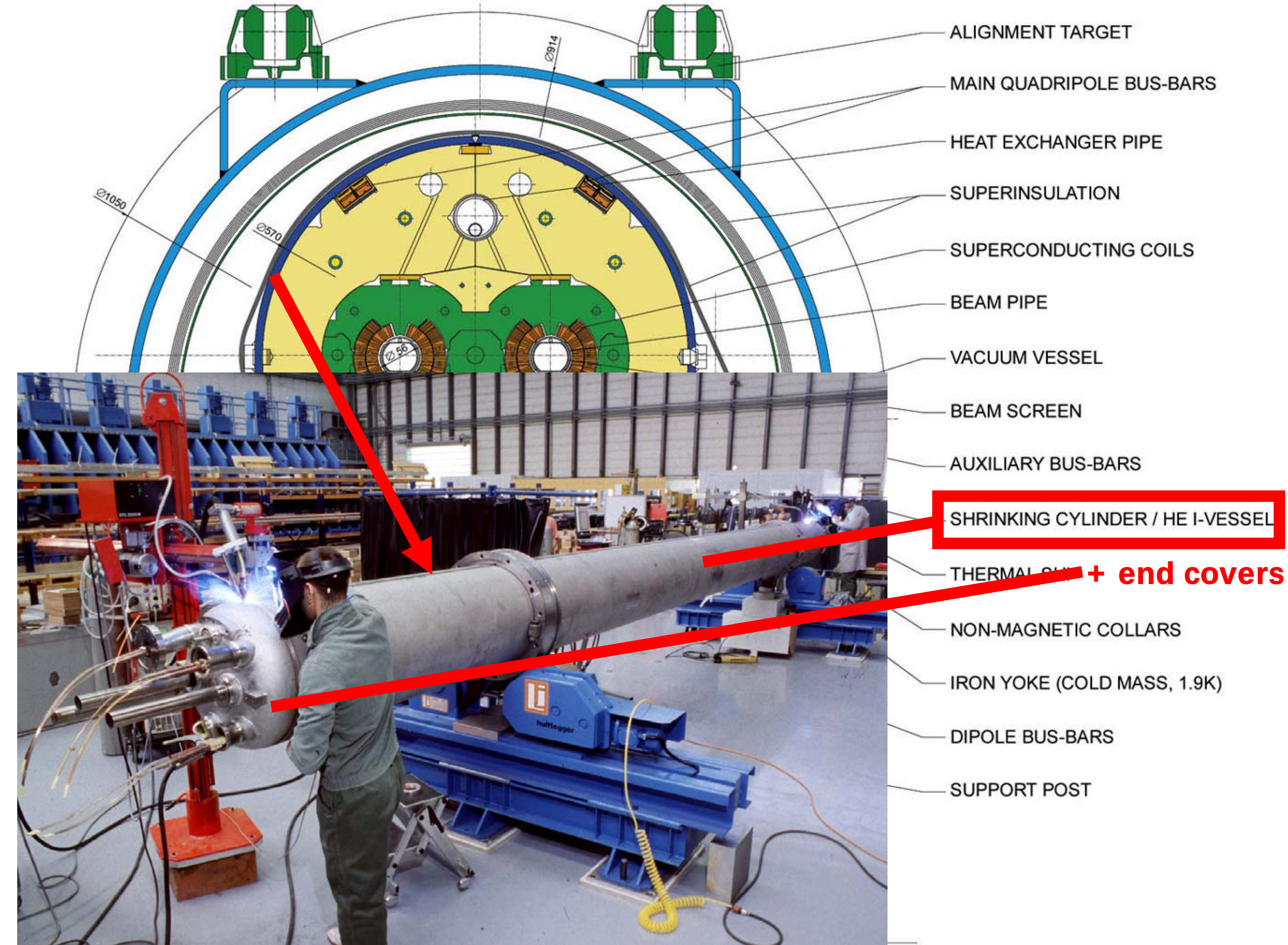
LHC DIPOLE : STANDARD CROS

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



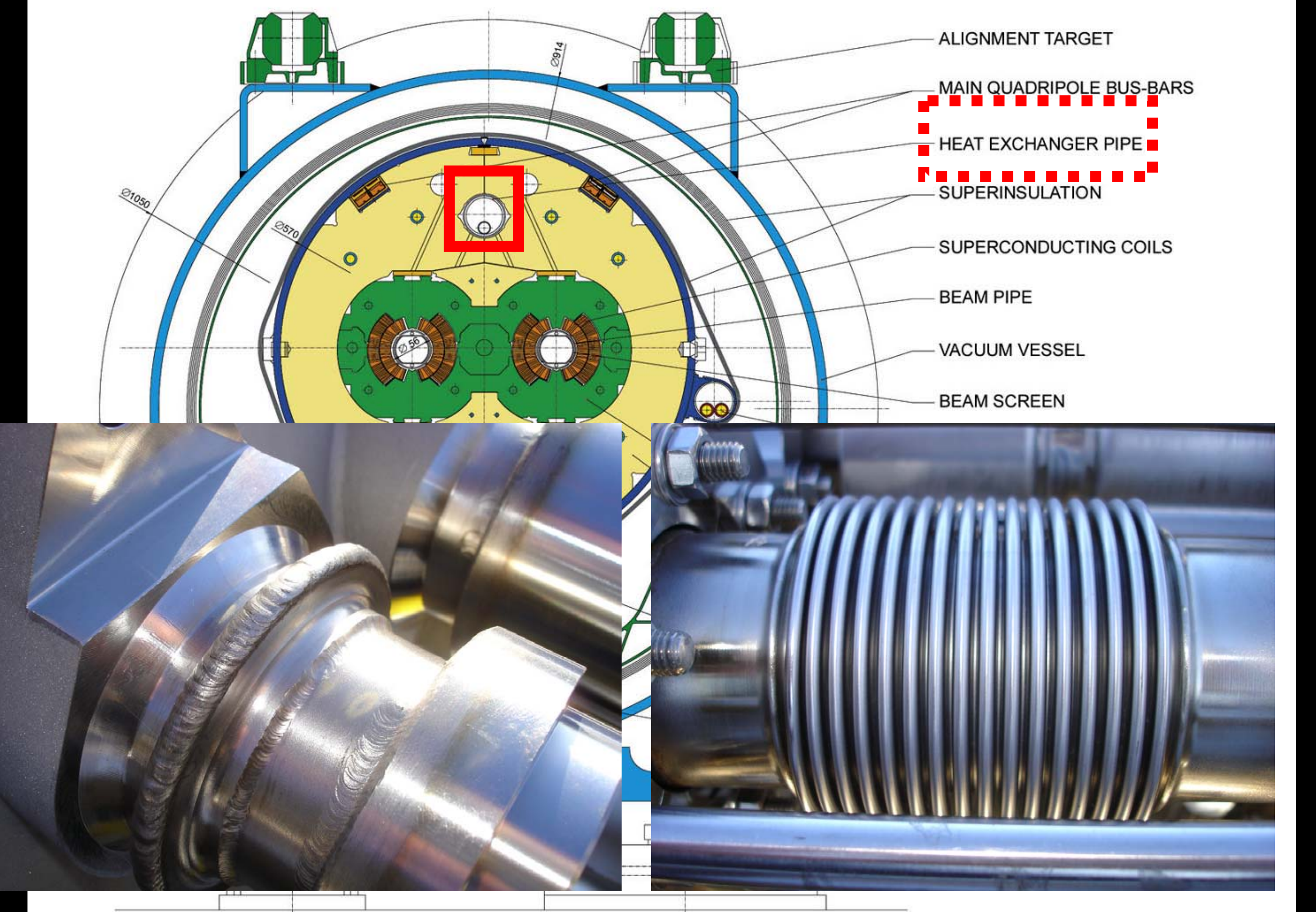
LHC DIPOLE : STANDARD CROSS-SECTION

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



LHC DIPOLE : STANDARD CROSS-SECTION

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



2.a Stainless steels

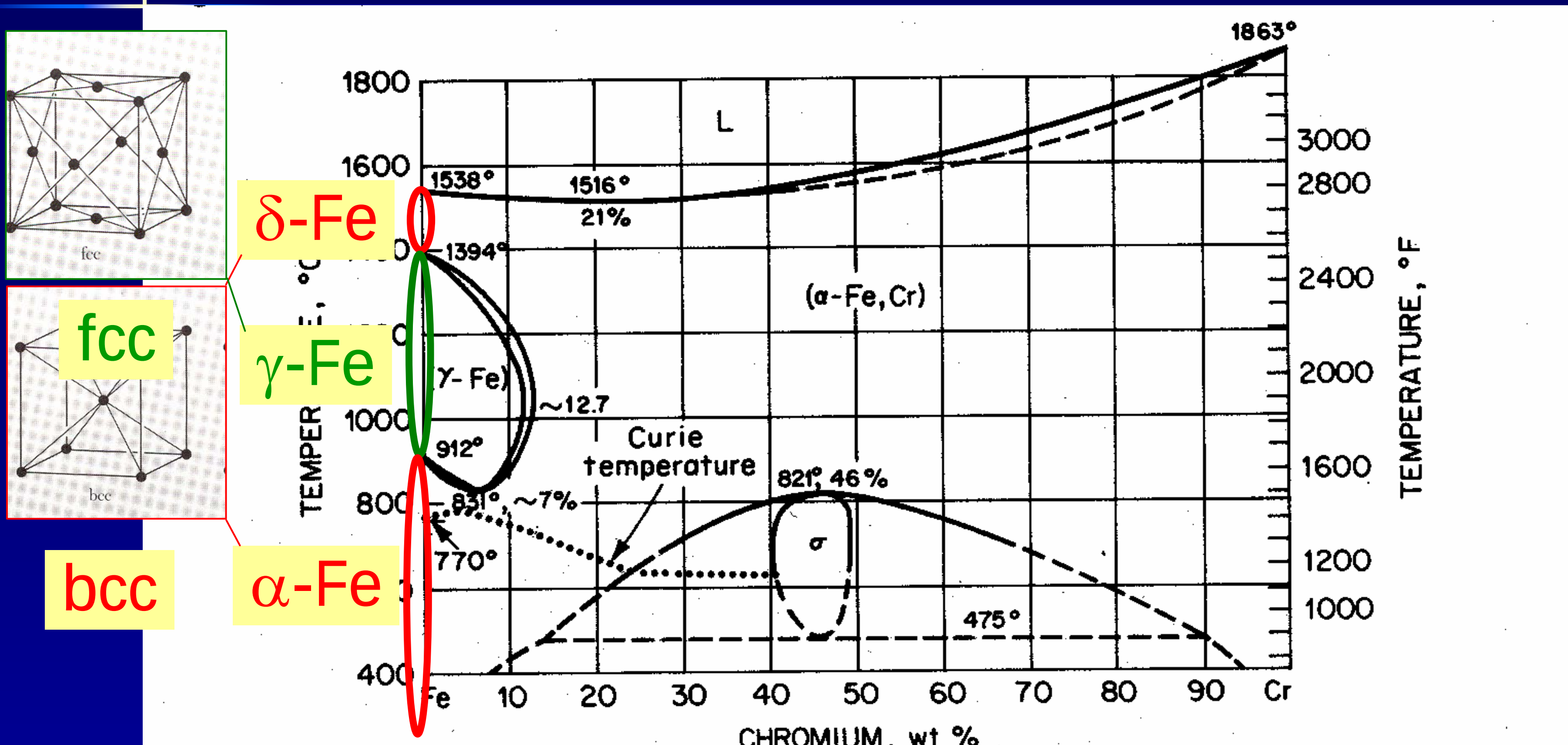


Fig. 2 The iron-chromium phase diagram. *(From "Metals Handbook," vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)*

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

2.a Stainless steels, introduction and ferritic grades

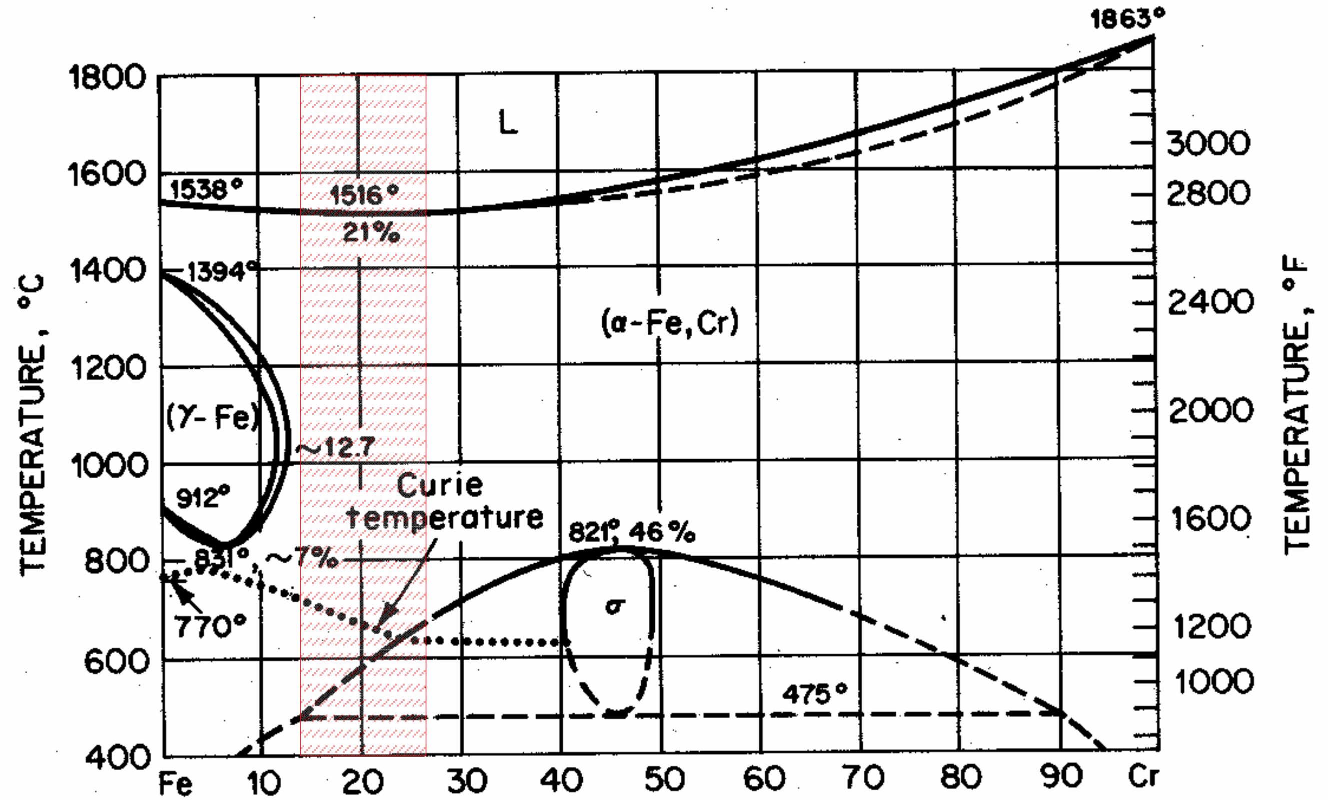
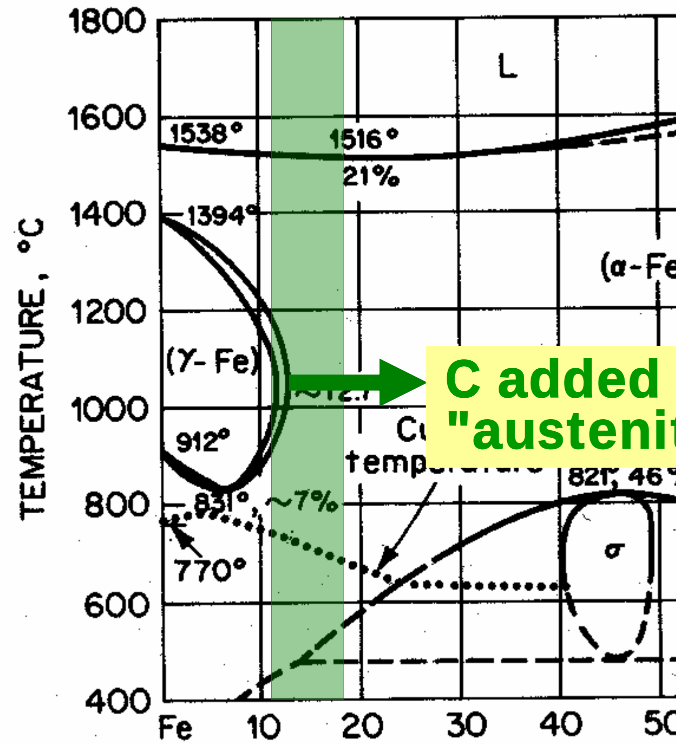


Fig. 2 The iron-chromiur ... h ed., *American Society for Meta*

- 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

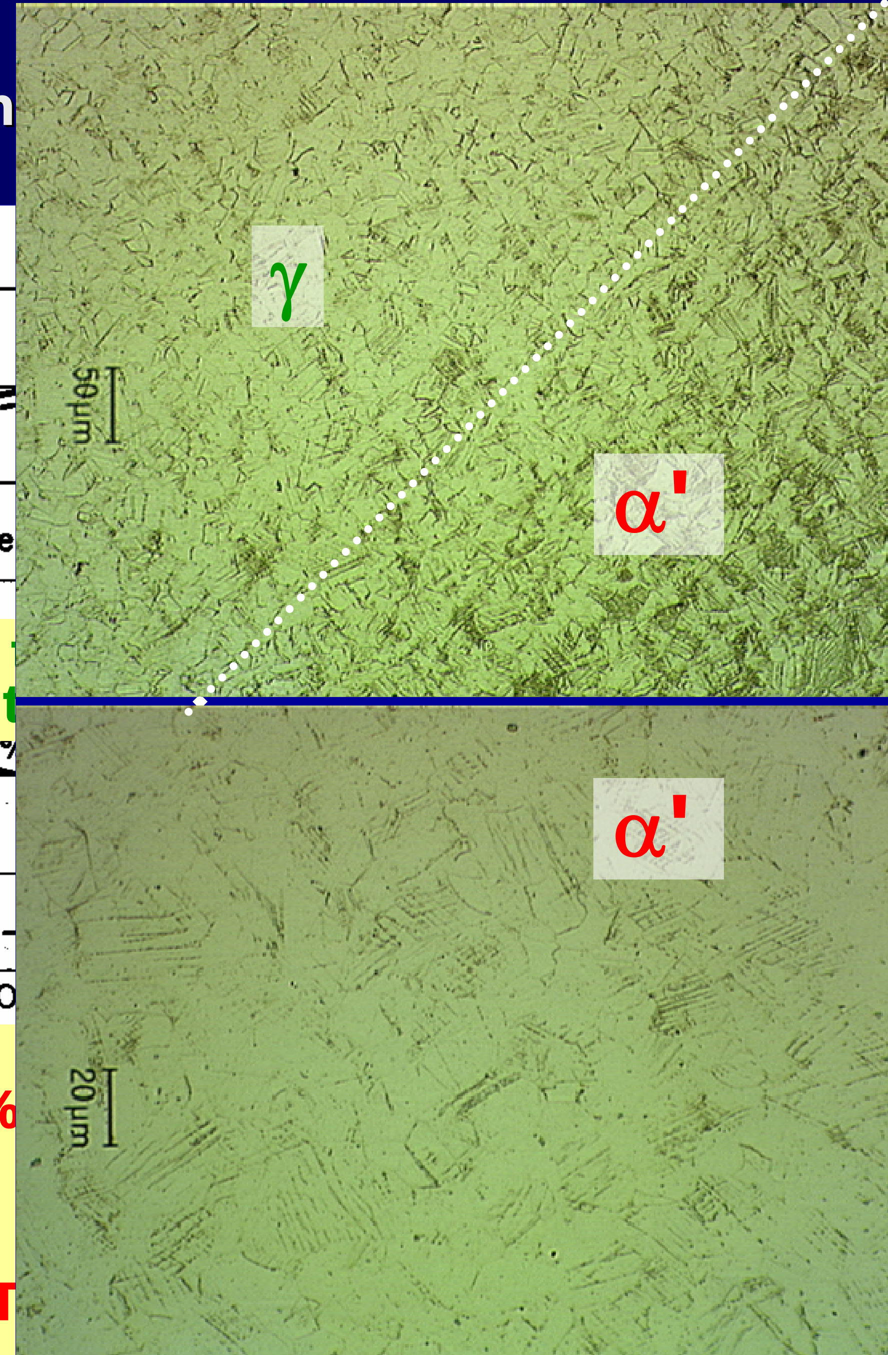
2.a Stainless steels, marten



C added t
"austenit

Fig. 2 The iro
American Socie

- martensitic grades,
  C up to 1.2 %
- hardenable by HT
- high strength
- ferromagnetic at RT
- brittle at low T



30/05/2006

C.Garion, B. Skoczen, S. Sgobba, International Journal of Plasticity, **22,** 2006, 1234-1264

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

form
fcc el
FeCr

γ-loo

γ-pha
enlar

form
supp
form

trans
mart
or su
alloyi

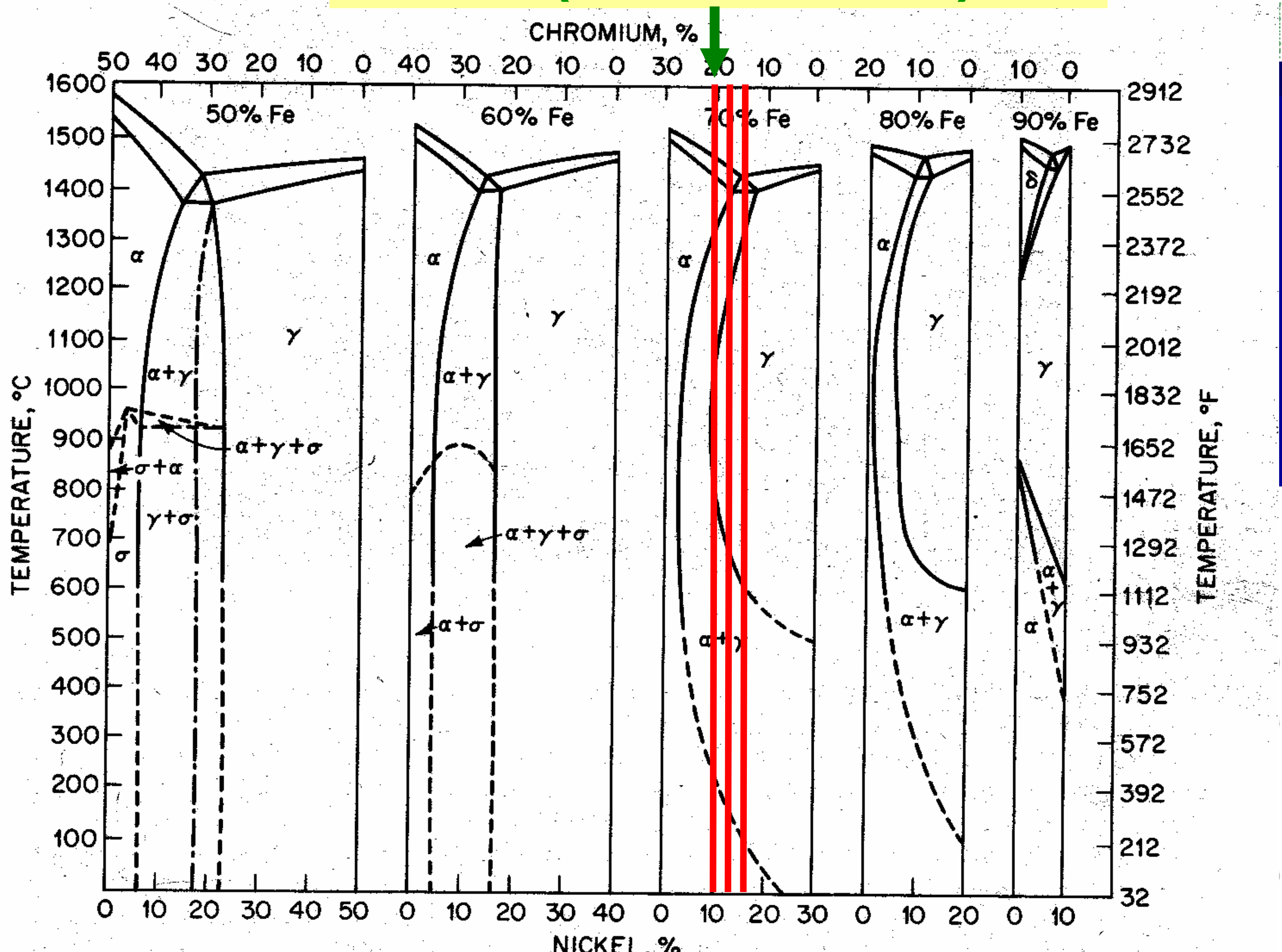


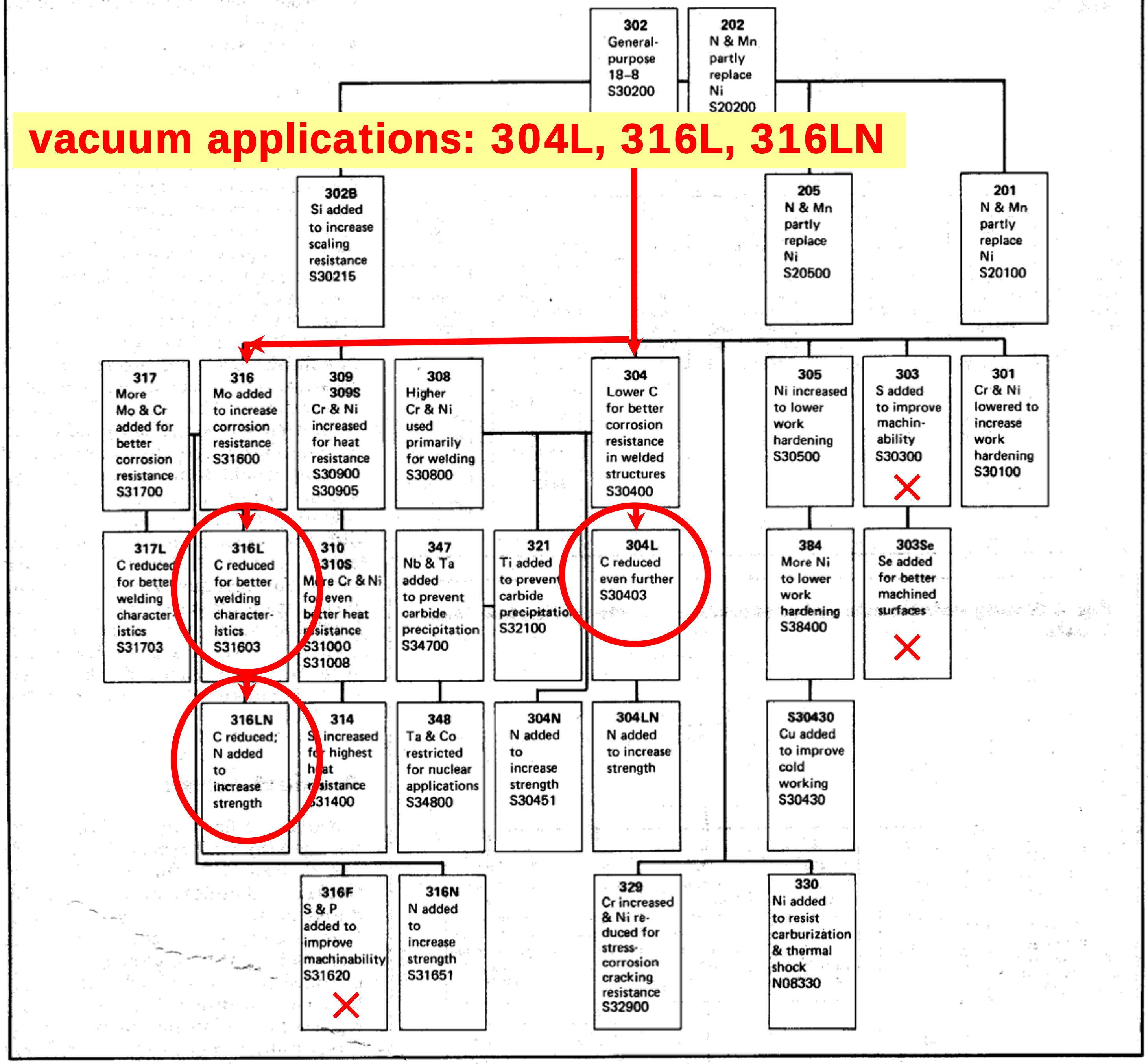
Fig. 14 Cross sections of Fe-Cr-Ni ternary.[26]

TEMPERATURE, °F

291, 8th ed.,

Fig. 2 Family relationships for standard austenitic stainless steels

vacuum applications: 304L, 316L, 316LN



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

2.a Stainless steels, austenitic grades, low C

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

"Sensitization" of base metal, HAZs and welds

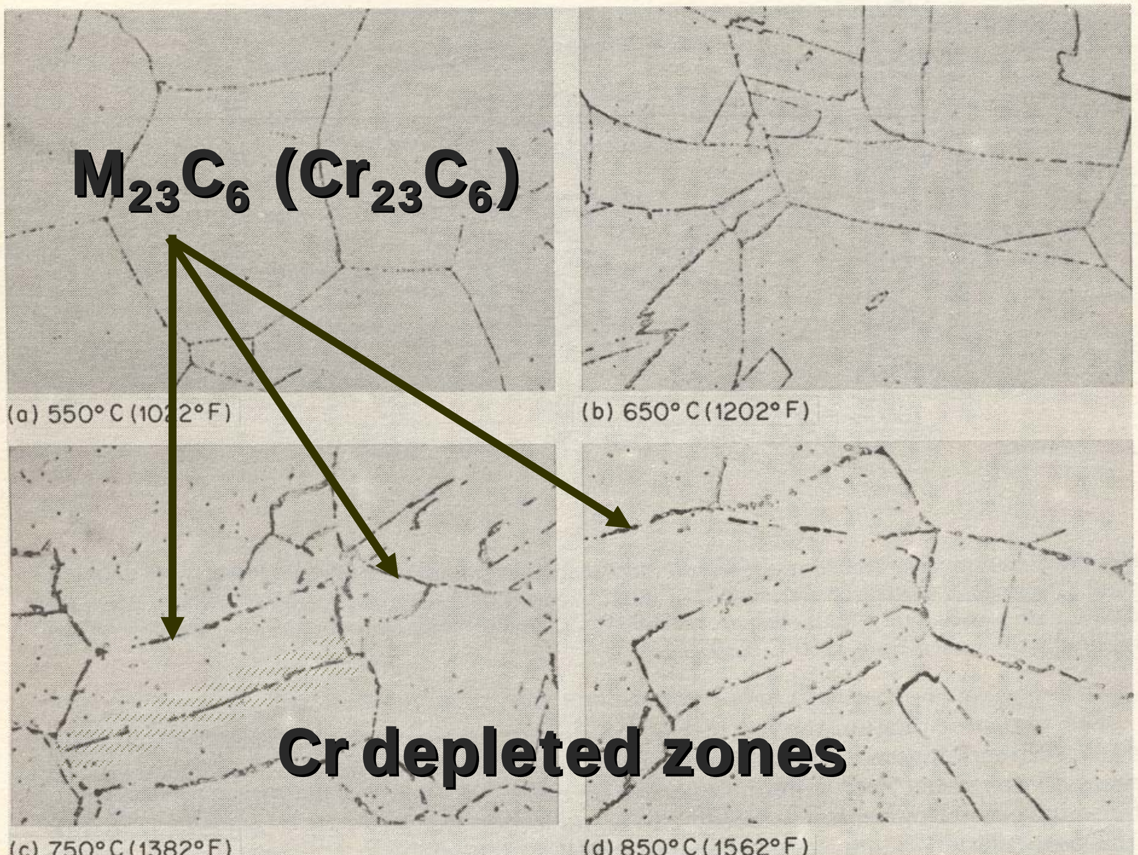
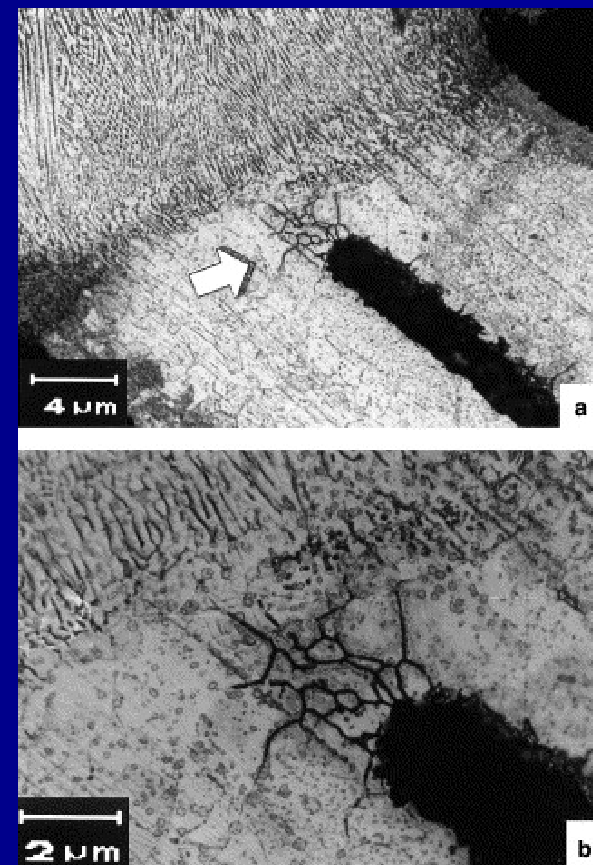


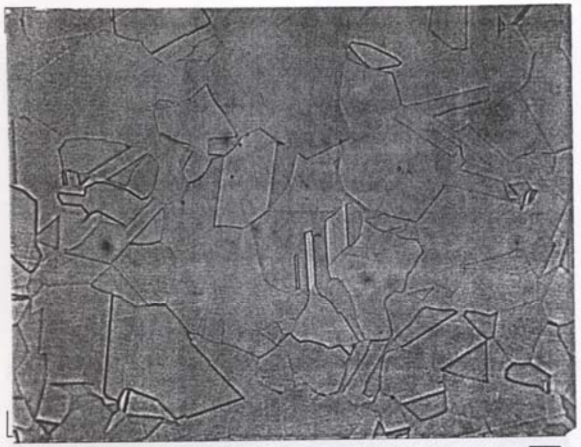
Fig. 55 Appearance of Type 304 stainless steel (0.065% carbon) sensitized for 6 days (144 h) at various temperatures. Specimens etched electrolytically in 10% oxalic acid.[128] (*a*) 550°C (1022°F). 750x. (*b*) 650°C (1202°F). 750x. (*c*) 750°C (1382°F). 750x (*d*) 850°C (1562°F). 750x.

D. Peckner, I.M. Bernstein, 1977



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

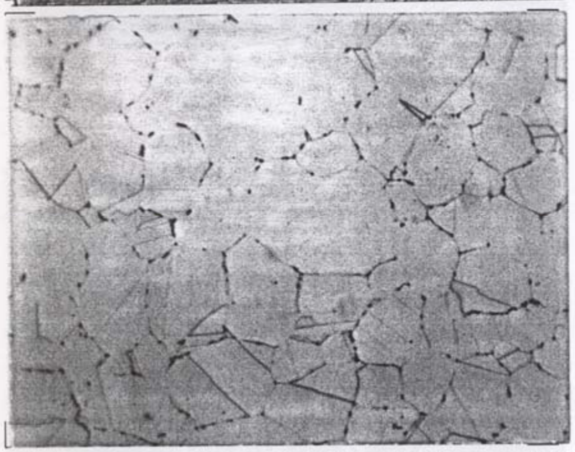
ANNEXE



N°1

RÉFÉRENCE

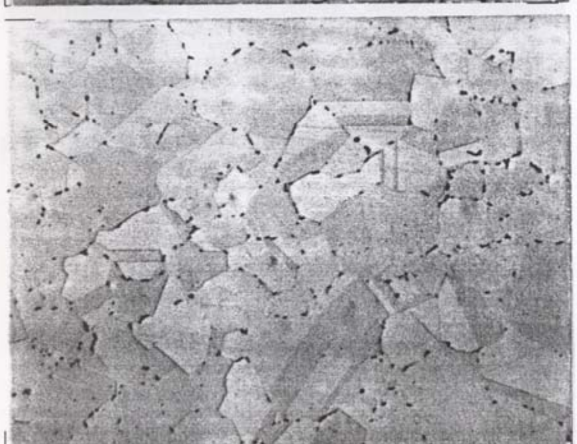
x 1000



N°2

x 1000

700°C - 10 ′ - 200°C/h



N°3

x 1000

770°C - 10 ′ - 300°C/h

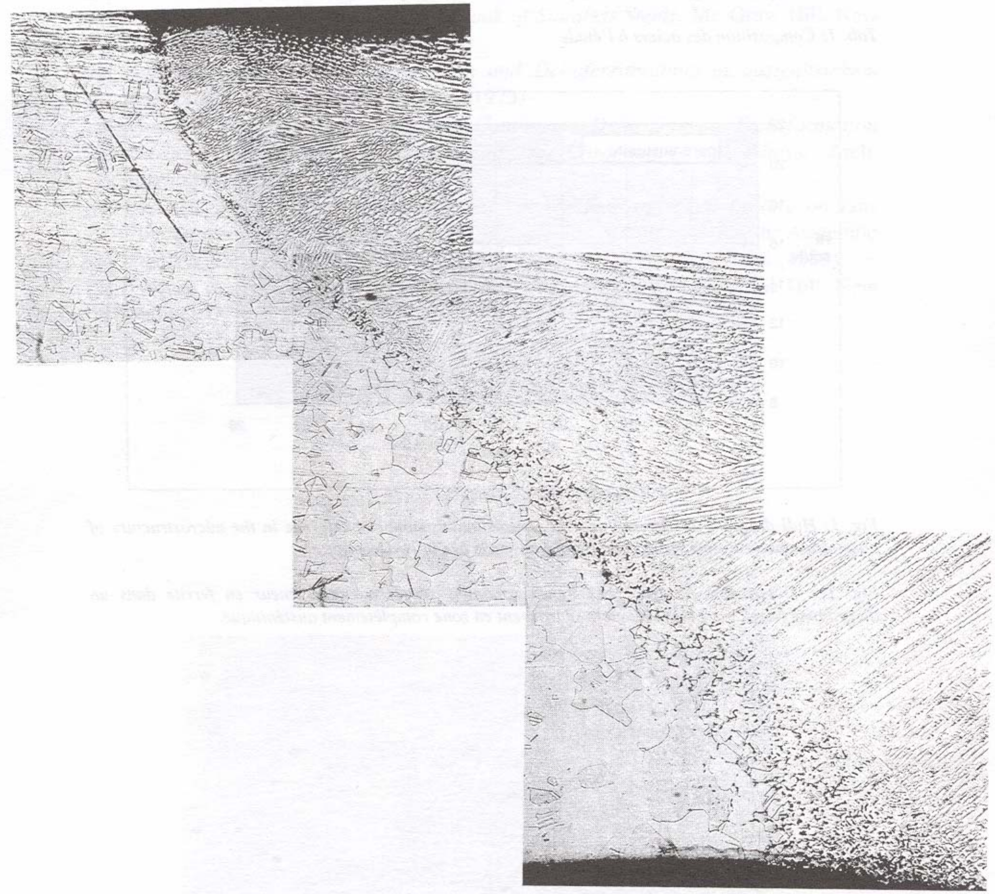


Fig. 3 : HAZ of the steel UNS 21904, welded under 15% N_2 (speed : 100 cm/min)

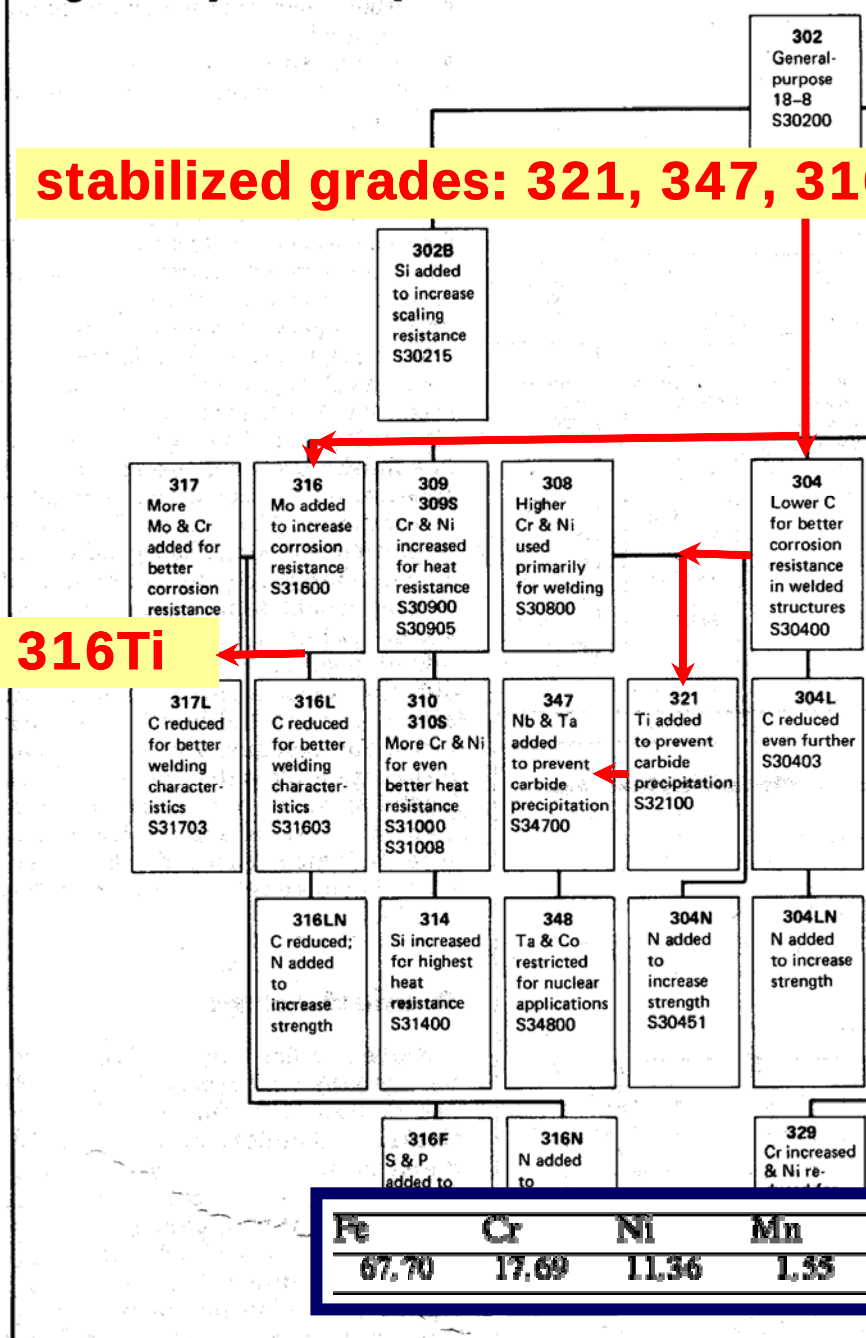
Fig. 3 : Microstructure (ZAT) relative à l'acier UNS 21904, soudé sous protection de 15% N_2, à la vitesse de 100 cm/min.

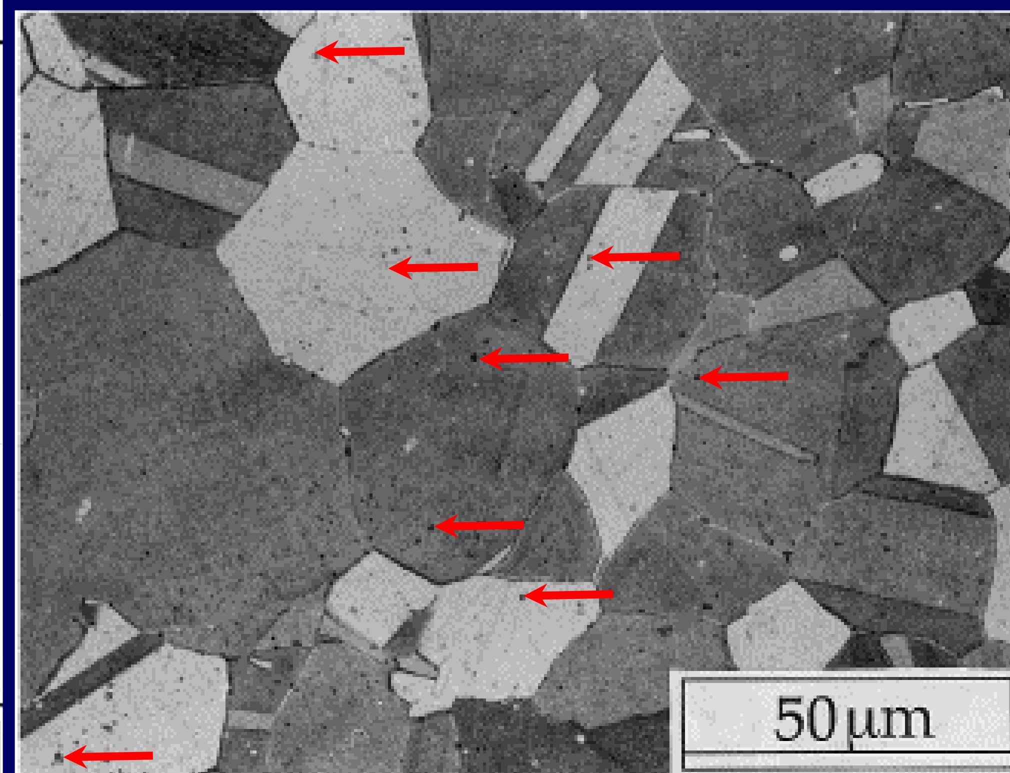
UNS 21904, Cr20Ni7Mn9N, C=0.03%

S. Sgobba et al., Bull. Cercle Et. Mét, 10, 1995, p. 13.1 ff.

stabilized grades: 321, 347, 316Ti

Fig. 2 Family relationships for standard austenitic stainless steels





Fe	Cr	Ni	Mn	Mo	Nb	Si	C	P	N	B
67.70	17.69	11.36	1.55	0.28	0.78	0.55	0.054	0.021	0.02	< 0.004

J. Källqvist and H.-O. Andrén, Mat. Sci. Eng. A, 270, 1999, p. 27-32

CERN — European Organization for Nuclear Research

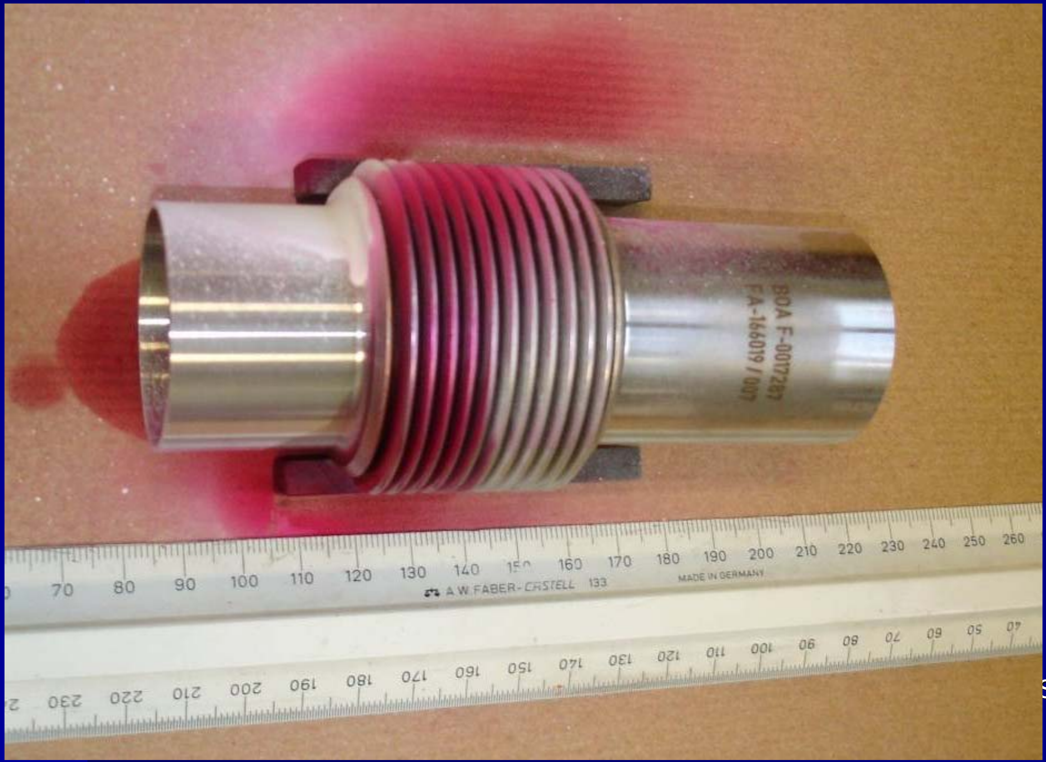
TS/MME-MM

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

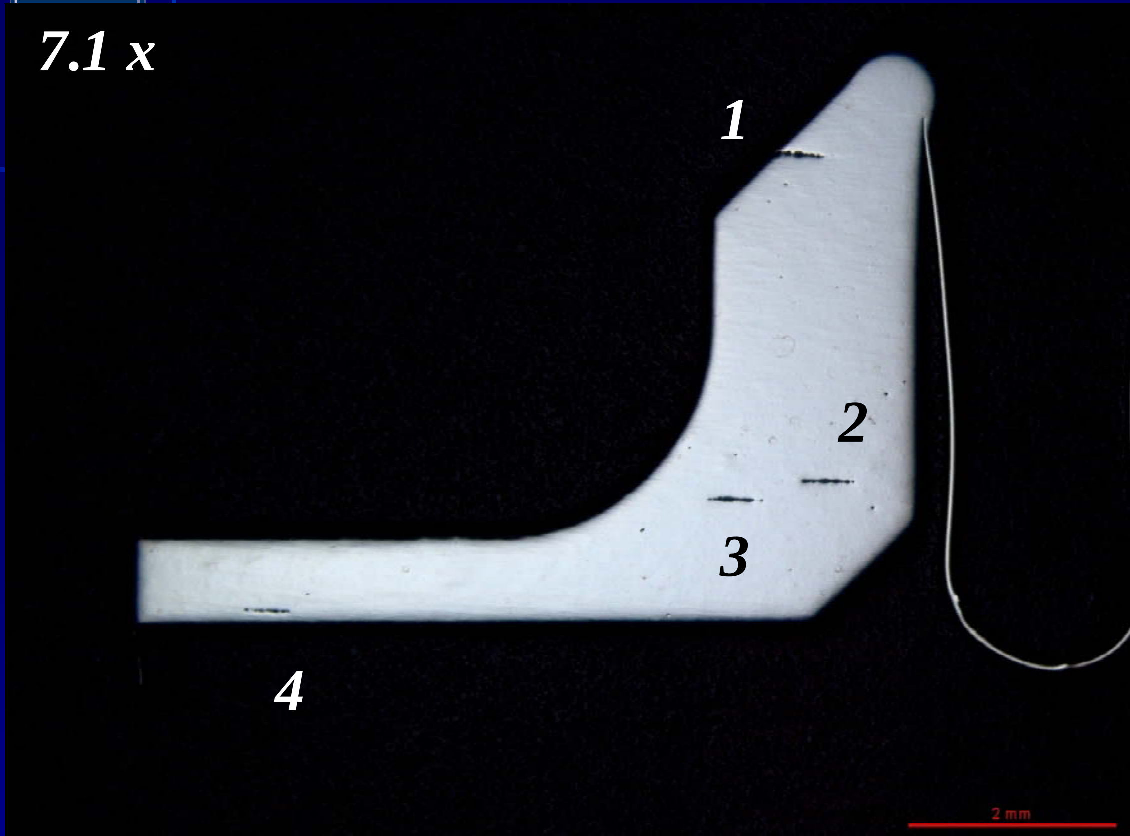
Rapport expérimental / Investigation report

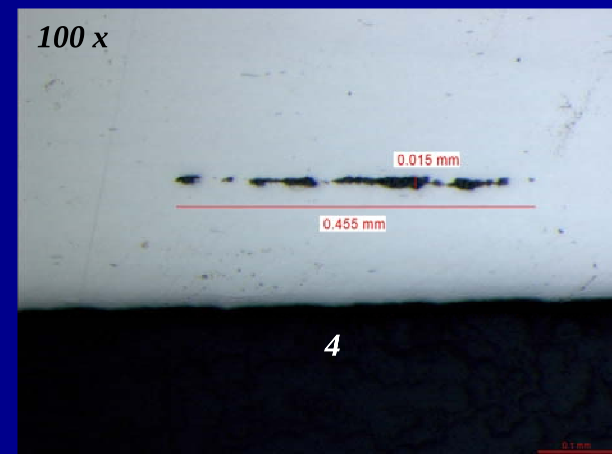
Domaine / Field: *CMS (Ion pump)*	*Date: 10/03/2006*	*N° EDMS / EDMS Nr.: 710706*
Requérant / Customer: *P. Lepeule AT/VAC*	*Liste de distribution / Distribution list:* *G. Faber PH/UCM; A. Hervé PH/CMO; R. Veness AT/VAC* *C. Saint-JAL FI/LS*	

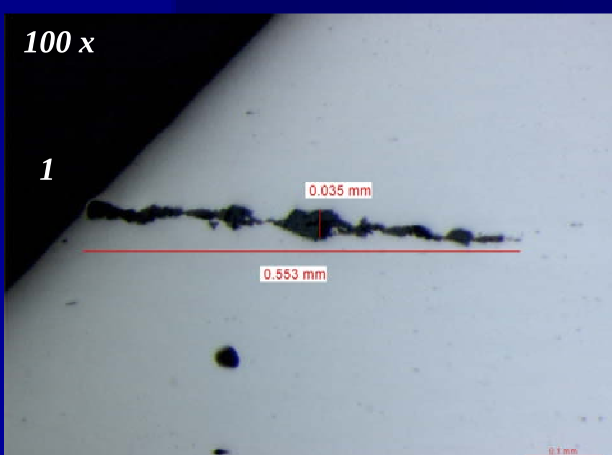
Metallographic observations of 316LN leaking bellow

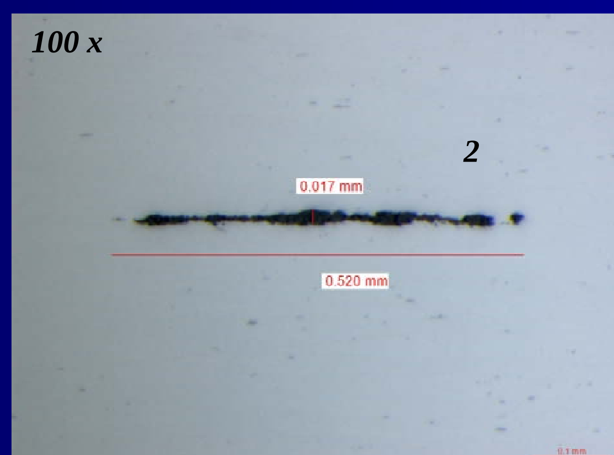


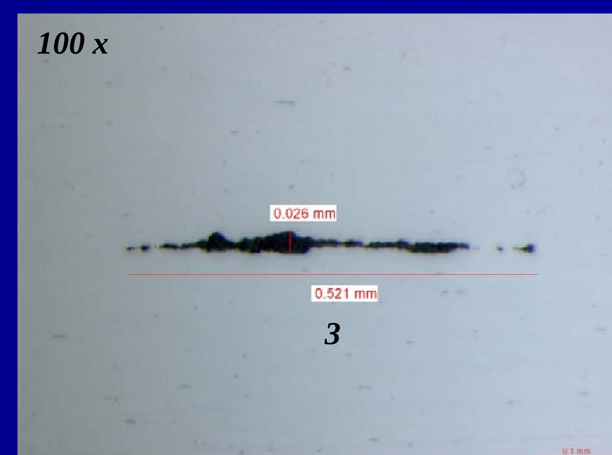
Oversized (1,2,3) and thick (4) B type inclusions up to class 2

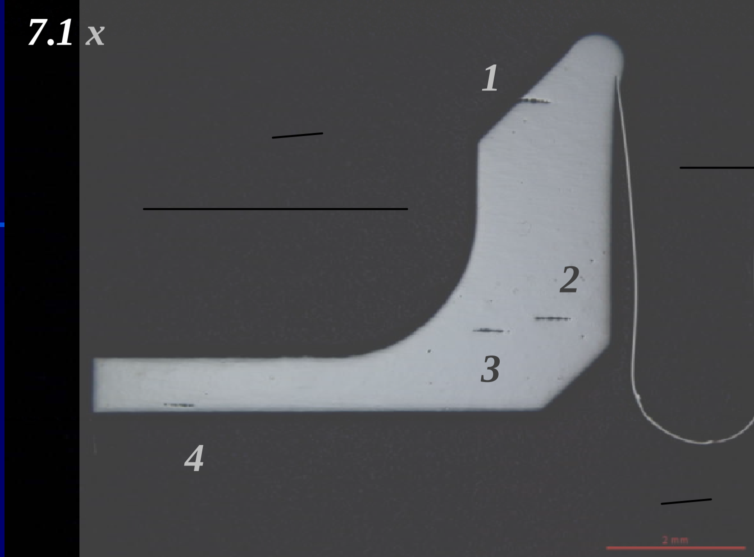








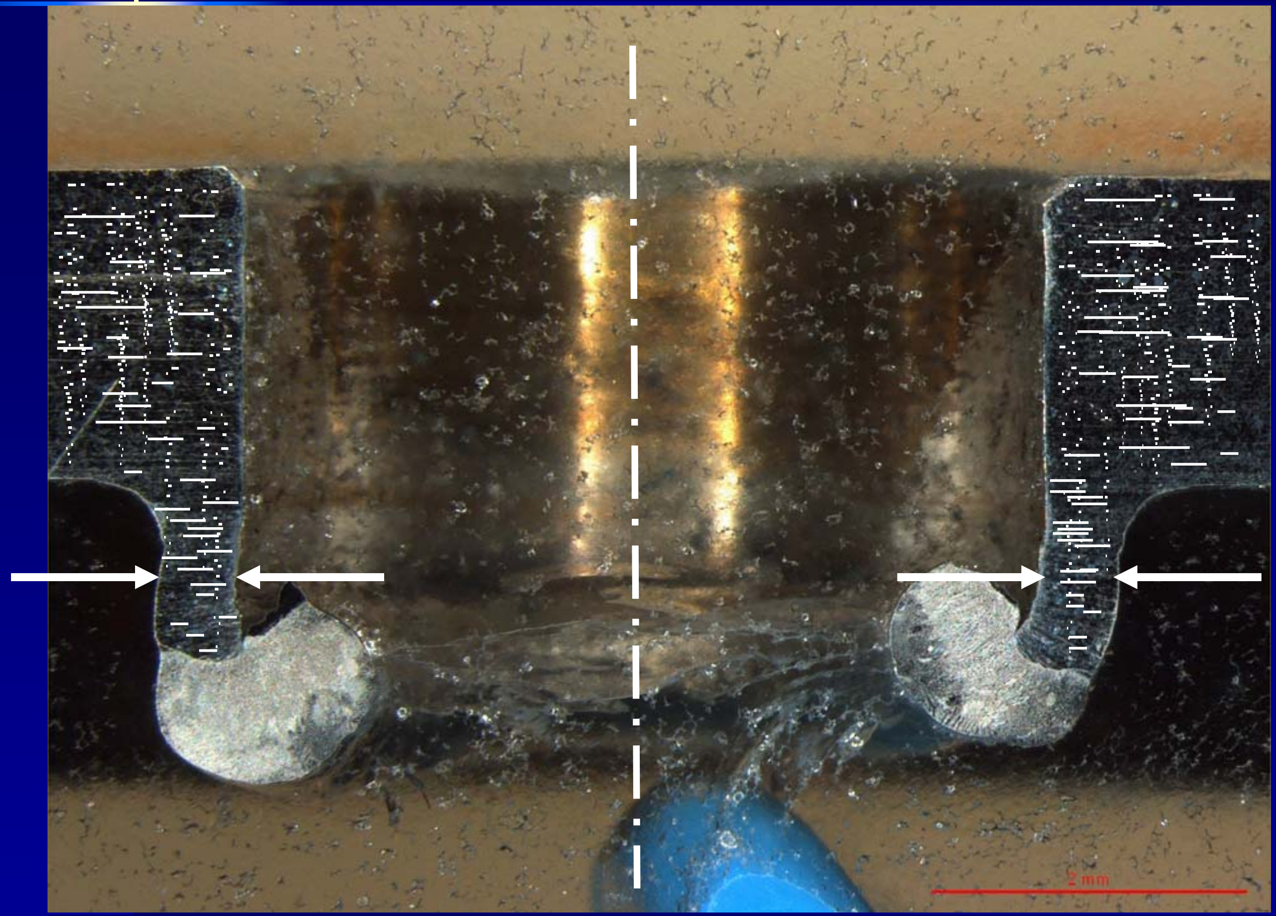




nclusions

RD ⇔

2.a Stainless steels, inclusion content



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

Multidirectional forging might not be applicable due to the diameter needed of the capable product

Designation: E 45 – 97ε2

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

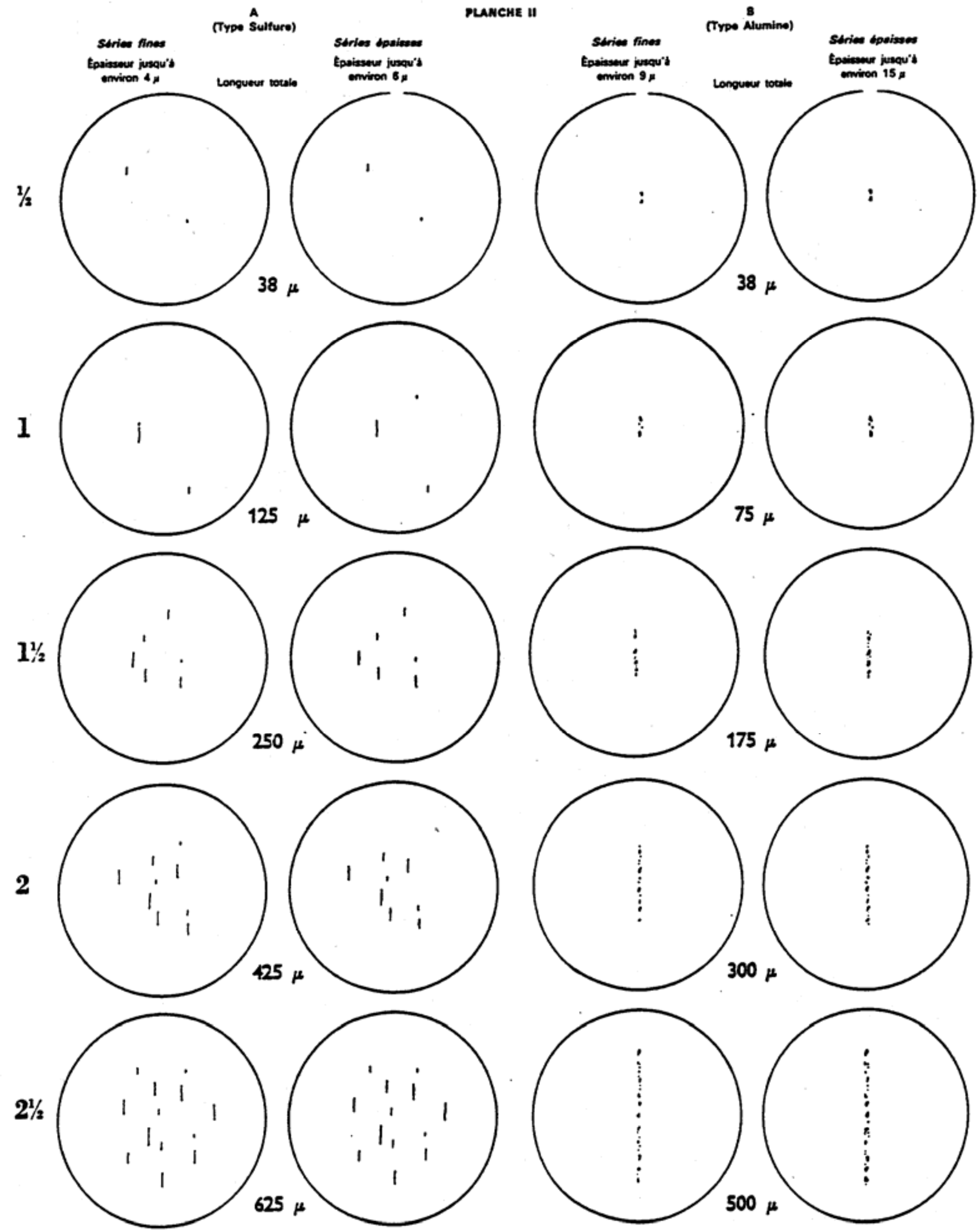
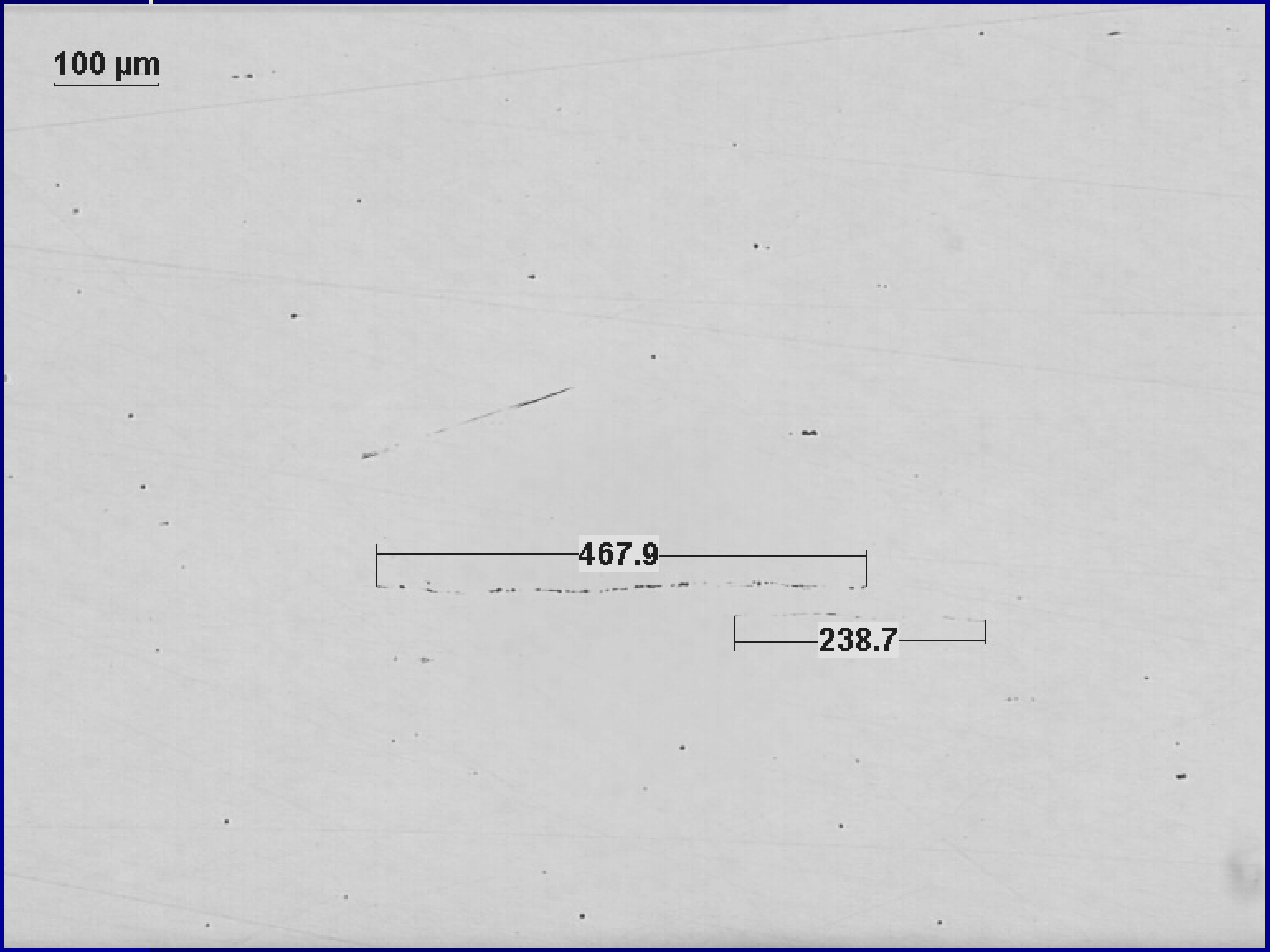


Fig. 13. — Images type Jernkontoret (suite).

Investigations of TS-MME-MM on the materials supplied to date



EDMS 673464:

27 mm outer Ø, 4 mm wall thickness

316L tubes

sample 1 delivered 14/10/05

Original magnification : 100 x
inclusion type B class 2 ½

Materials Technical Specification (SPL-LS)

3.2.2 Inclusions

Amount and definition shall meet standard ASTM E45-97e1, method D.

The class of inclusions shall be at most 1 for types A, B and C and at most 1.5 for type D.

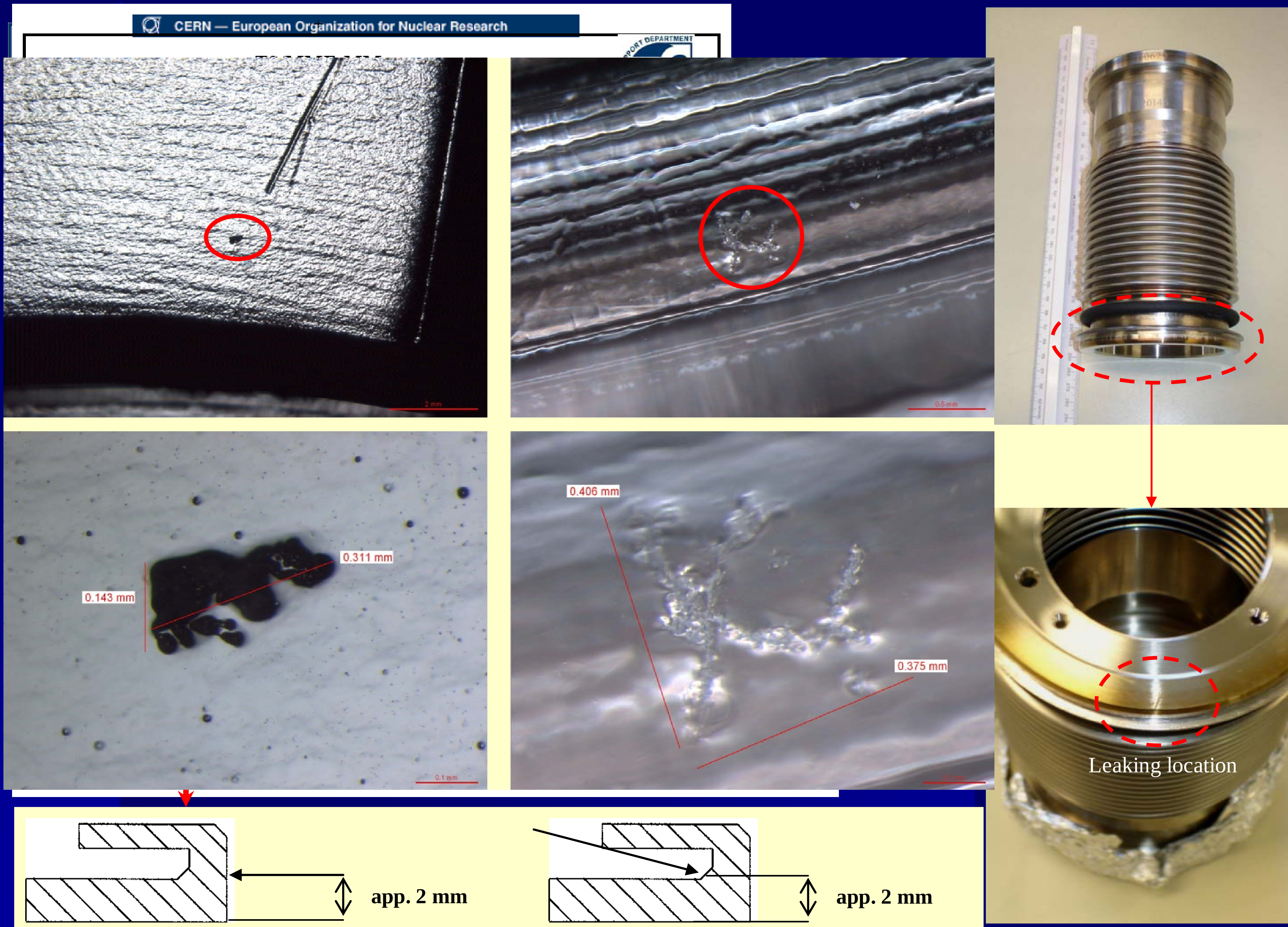
The tolerance for acceptance may be a half-class above the set limit to the extent of 2% of the fields counted.

FORGED ROUND BAR

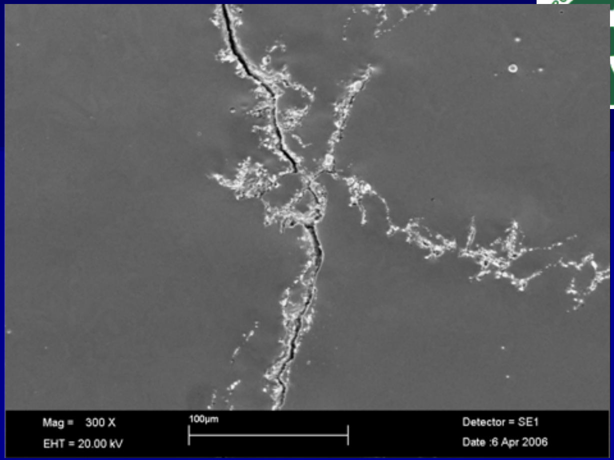
FOR VACUUM APPLICATIONS

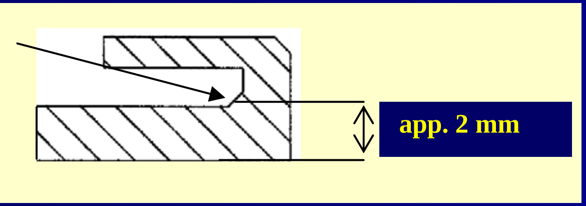
STAINLESS STEEL

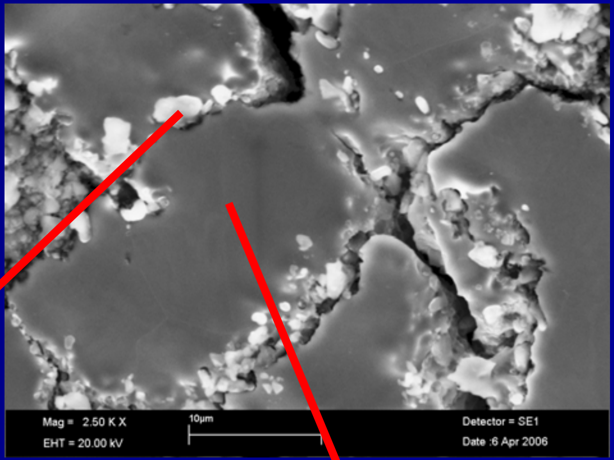
TYPE X2CrNiMoN17-13-3 (1.4429, AISI 316LN)

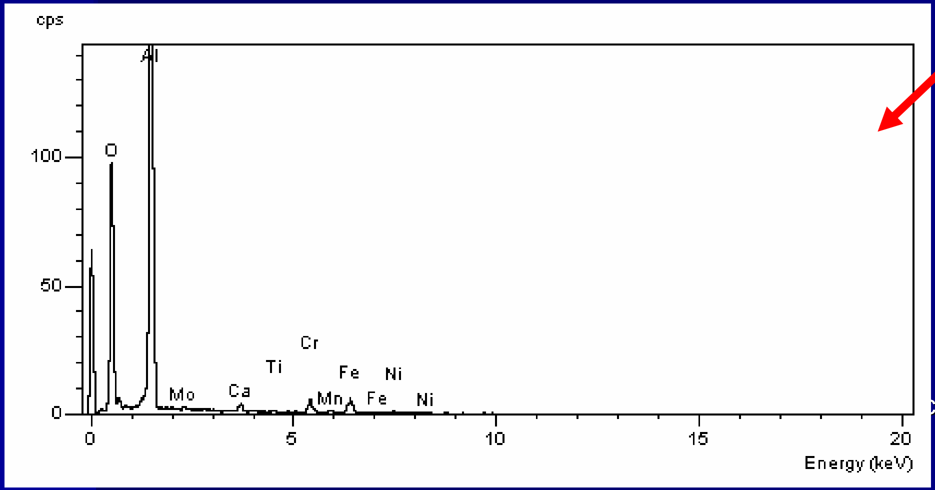

CERN — European Organization for Nuclear Research
0.143 mm
0.311 mm
0.406 mm
0.375 mm
Leaking location
app. 2 mm
app. 2 mm

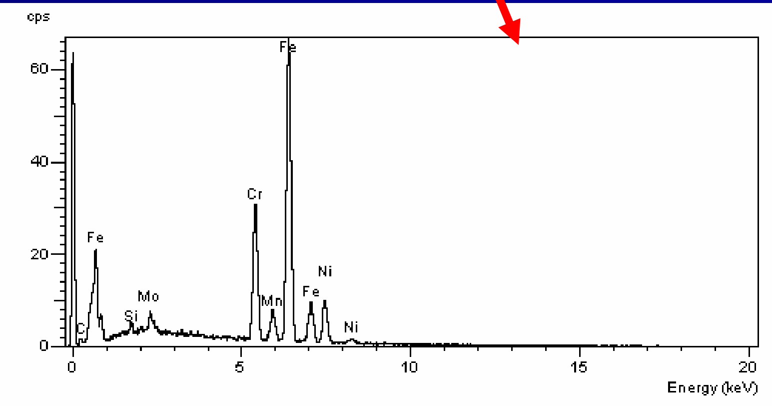

Mag = 30 X
EHT = 20.00 kV
1mm
Detector = SE1
Date :6 Apr 2006

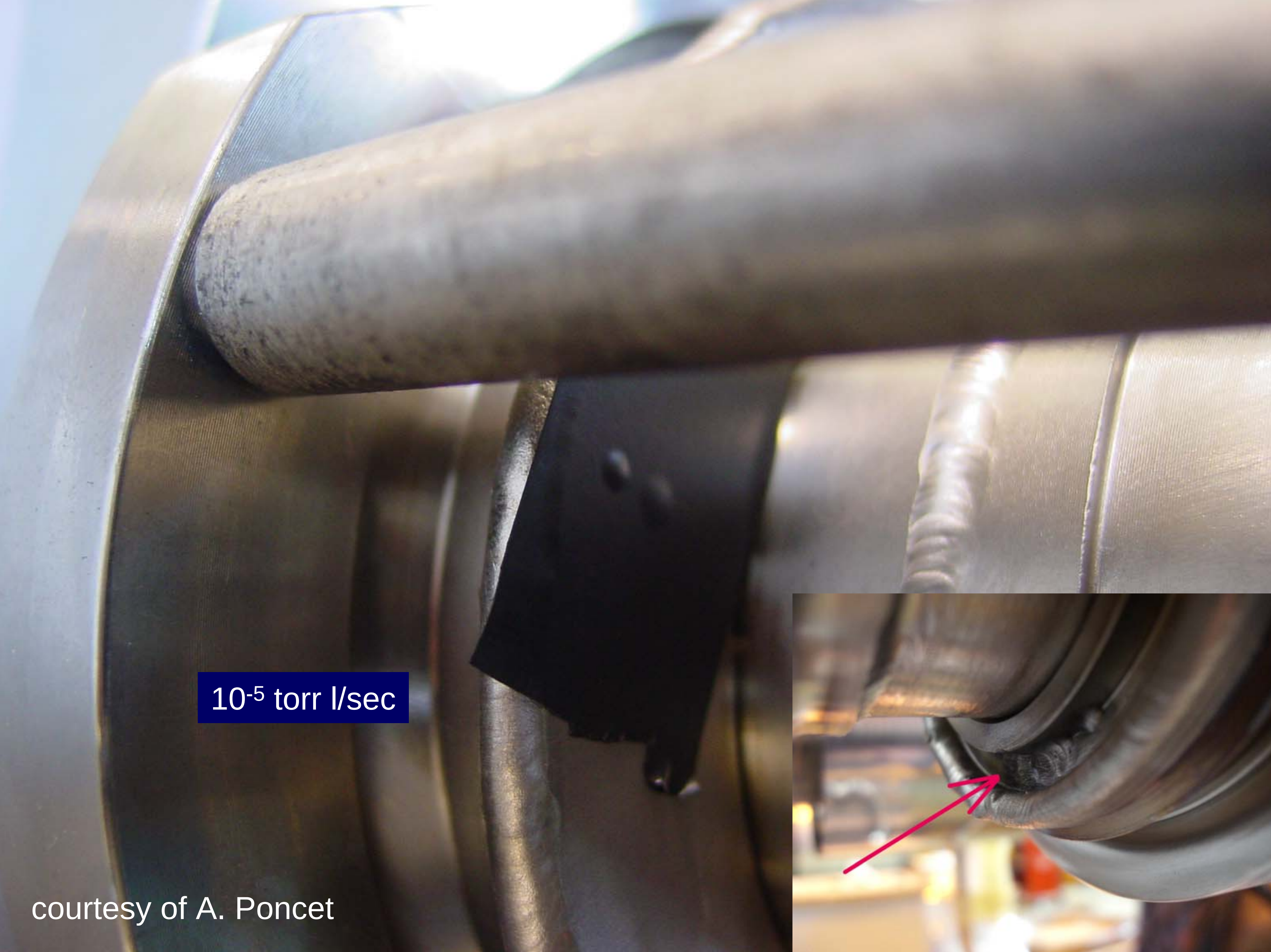

Mag = 300 X
EHT = 20.00 kV
100µm
Detector = SE1
Date :6 Apr 2006


app. 2 mm


Mag = 2.50 K X
EHT = 20.00 kV
10µm
Detector = SE1
Date :6 Apr 2006

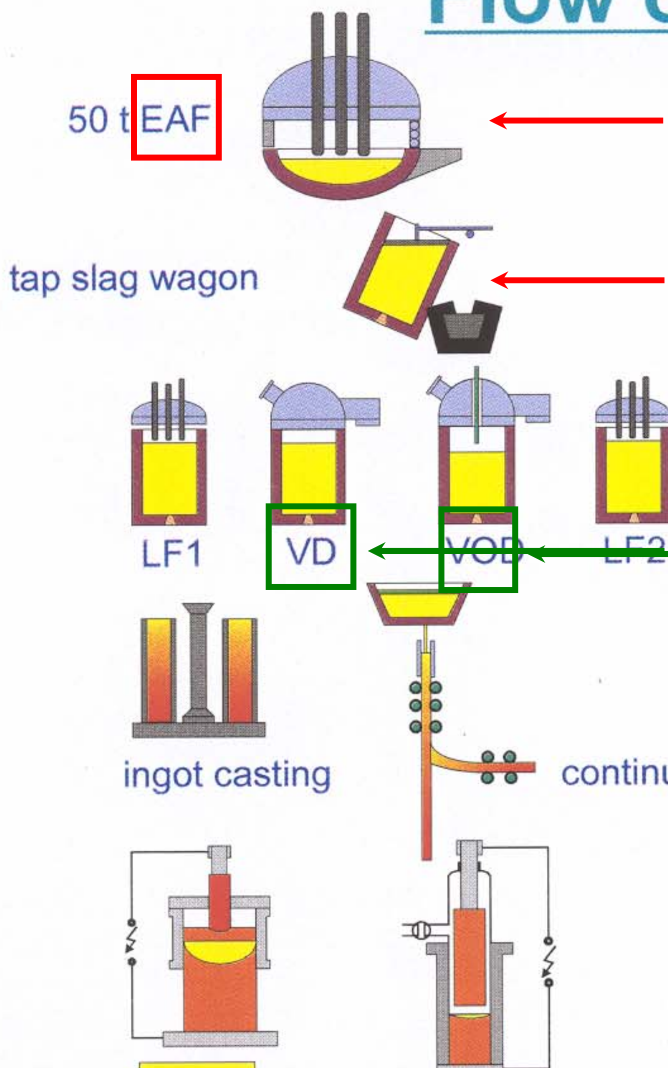

cps
Al
O
Mo
Ca
Ti
Cr
Mn
Fe
Ni
Fe
Ni
100
50
0
0
5
10
15
20
Energy (keV)


cps
Fe
Fe
Cr
Mo
Si
C
Mn
Fe
Ni
Ni
60
40
20
0
0
5
10
15
20
Energy (keV)


10^{-5} torr l/sec
courtesy of A. Poncet

BREITENFELD EDELSTAHL AG

Flow o



C ↓

P ↓

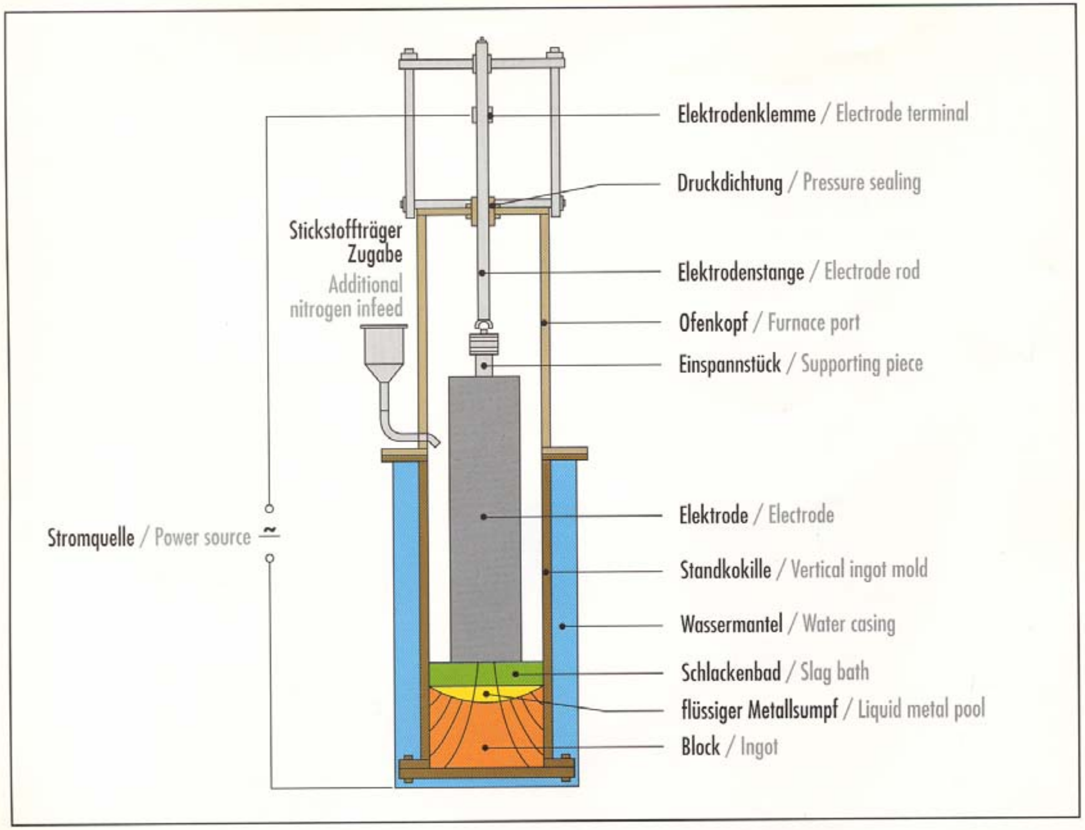
(to a limited extent)

Tapped as free as possible of slag into the ladle

secondary-

De
(do
deh
to (
(fro
ppm
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



Zusätzliche Vorteile gegenüber konventionellen ESU-Anlagen

Additional Advantages compared to Standard ESR-Furnaces

Keine H-Erhöhung während des Umschmelzens (Versprödung)	No H-increase during remelting (embrittlement)
N-Zulegieren bis ca. 0,80%	N-alloying up to approx. 0.80 %
Niedrige Si-, Al-Gehalte (Super clean Technology) für Turbinenbau	Low Si, Al contents (Super Clean Technology) for turbine application
Kein Abbrand von chemischen Elementen z.B. Ti / Al / Si, präzise Einstellung der Legierungsgehalte	No deflagrate of chem. elements e.g. Ti/Al/Si, precise adjustment of alloying element contents

Technische Daten

Technical Data

Elektrische Leistung:	2700 KVA	Electric Power:	2700 KVA
Schmelzrate:	300-1000 kg/h	Melt Rate:	300-1000 kg/h
Strom:	35 kA AC	Current:	35 kA AC
Druck:	bis 16 bar	Pressure:	up to 16 bar (232 psi)
Spannung:	82 V	Voltage:	82 V
Atmosphäre:	N und/oder Ar	Atmosphere:	N and/or Ar

rial

melting

Variant:

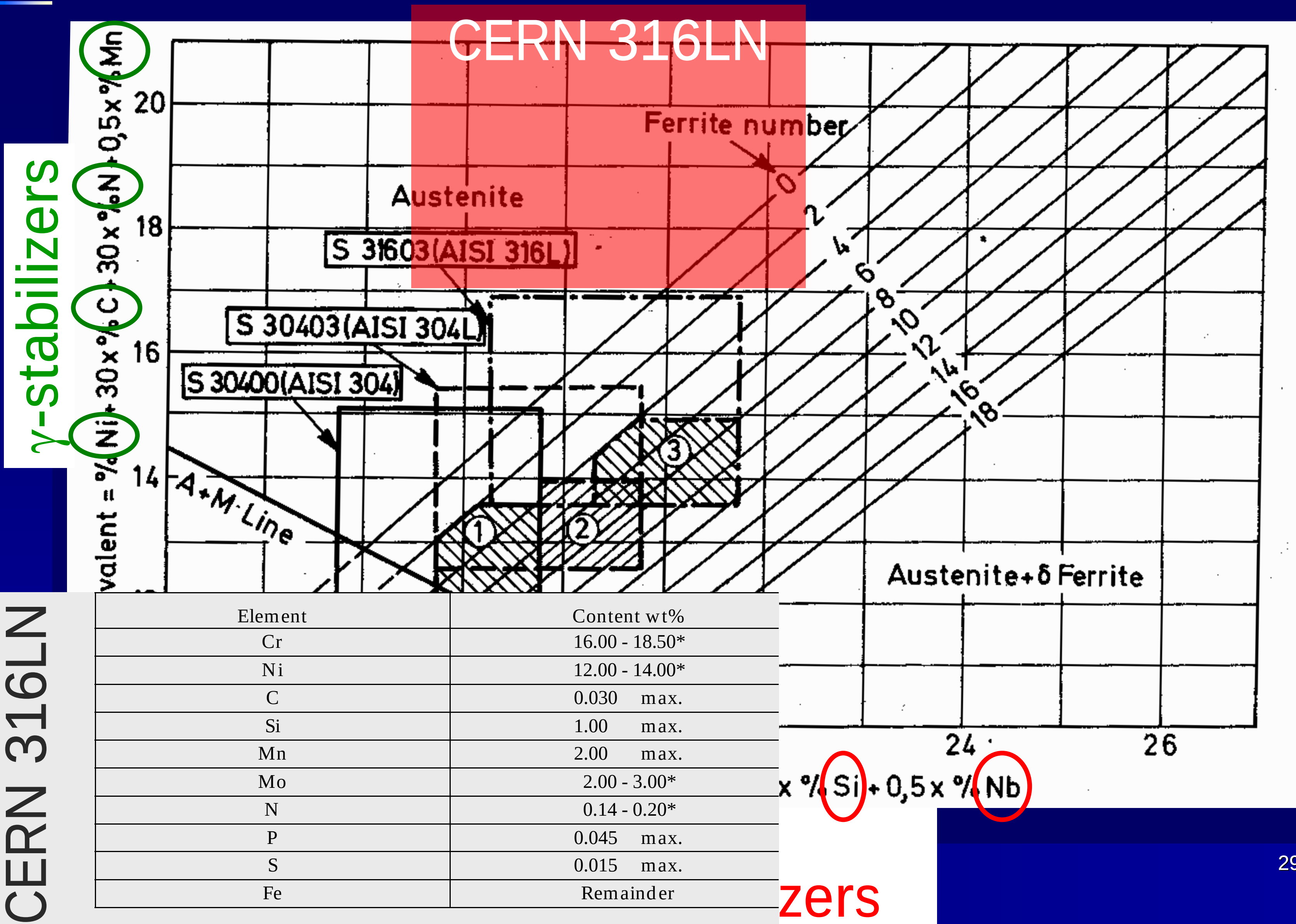
PESR, at a working pressure of 42 bars, to allow nitrogen alloying

casting

ESR & VAR

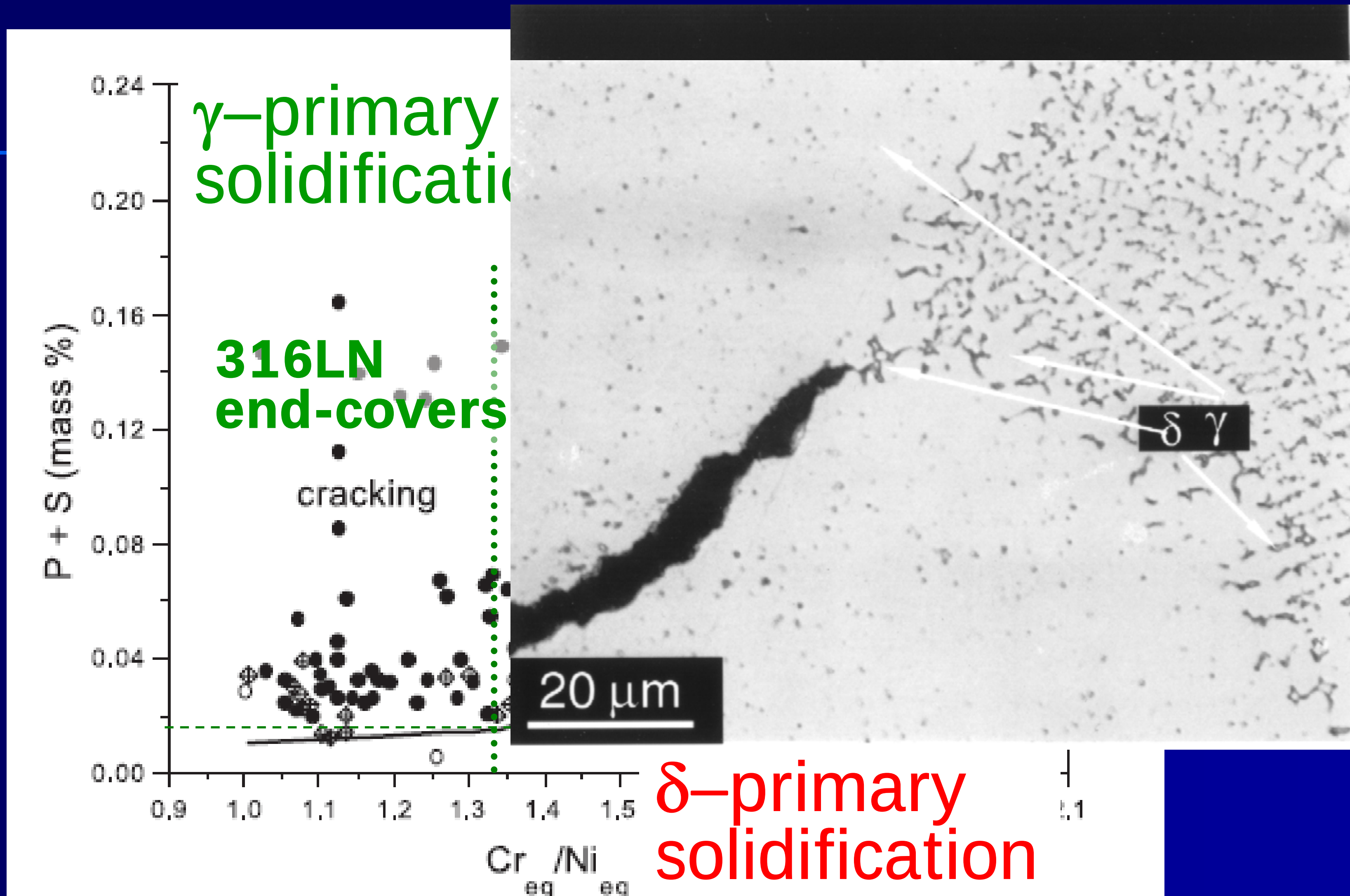
Courtesy of Breitenfeld Edelstahl / AT

2.a Stainless steels, welding metallurgy



CERN 316LN

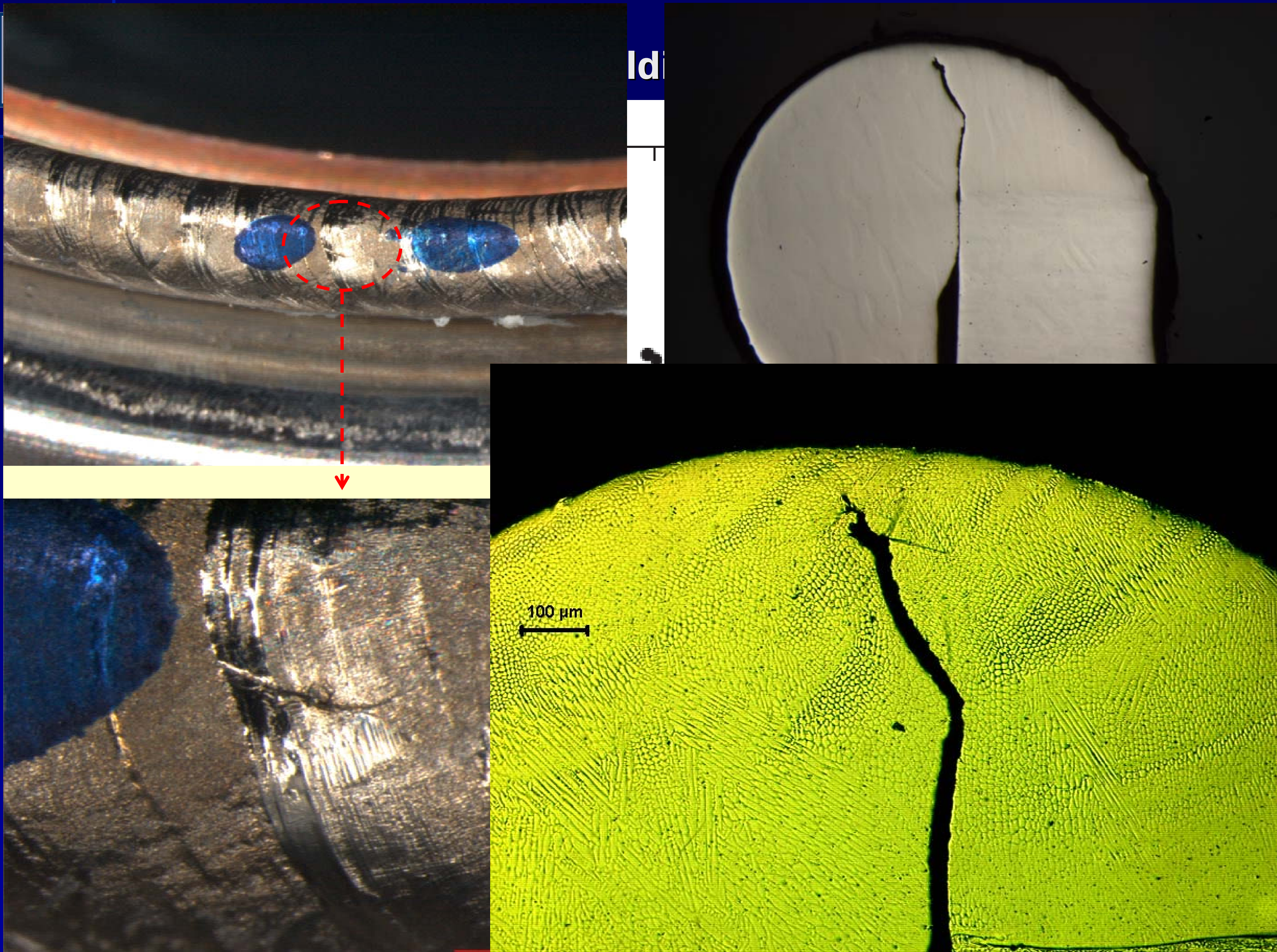
Element	Content wt%
Cr	16.00 - 18.50*
Ni	12.00 - 14.00*
C	0.030 max.
Si	1.00 max.
Mn	2.00 max.
Mo	2.00 - 3.00*
N	0.14 - 0.20*
P	0.045 max.
S	0.015 max.
Fe	Remainder



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

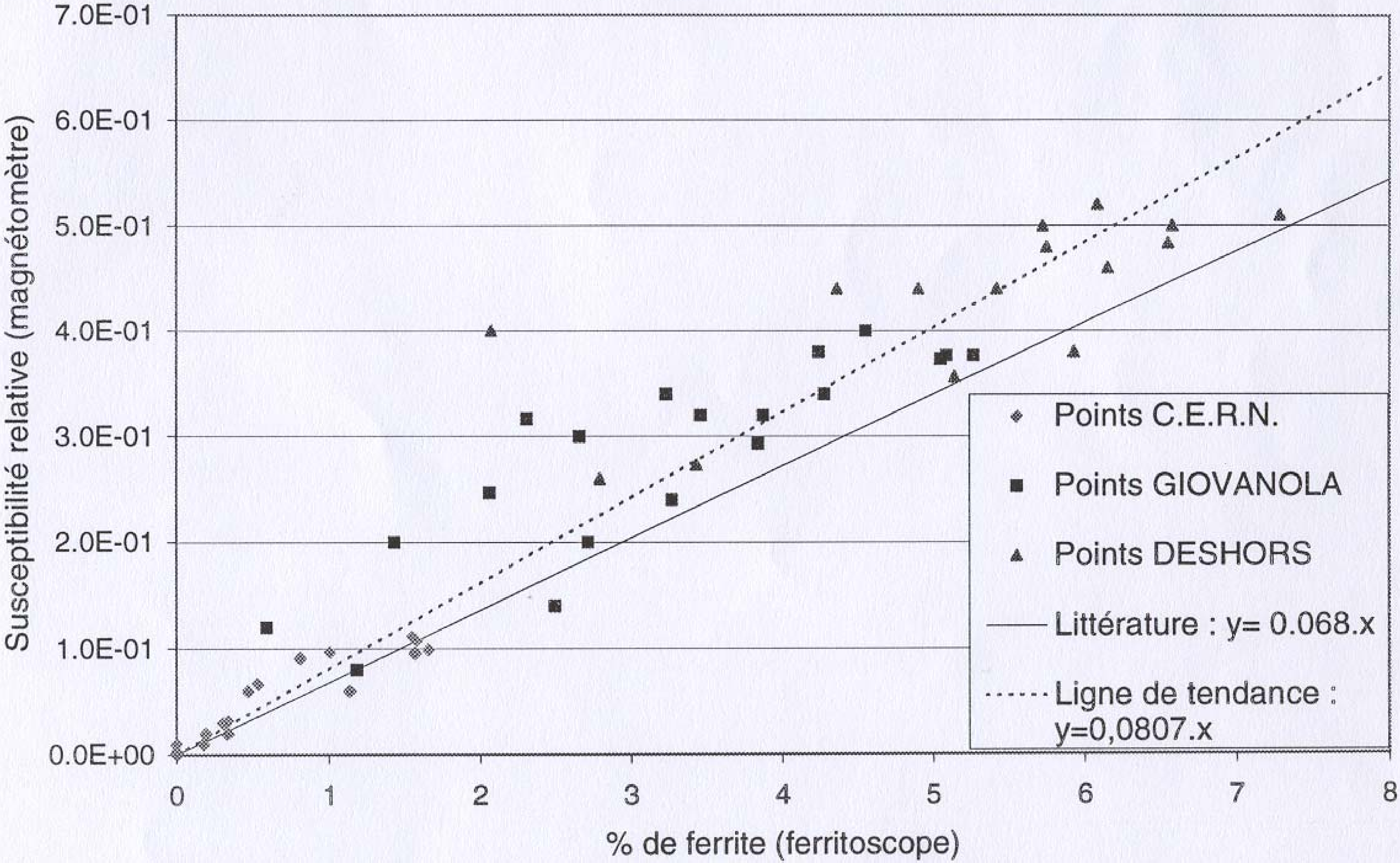
$$Cr_{eq} = Cr + 1.5Si + 1.37Mo$$

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


100 µm

2.a Stainless steels, effect of delta-ferrite on magnetic susceptibility

S. SGOBBA, C. BOUDOT, Matériaux et Techniques **95**, n°11-12, p. 23 (1997).



Other phase transformationd and their influence on magnetic behaviour

Martensitic transformations

Antiferromagnetic transitions

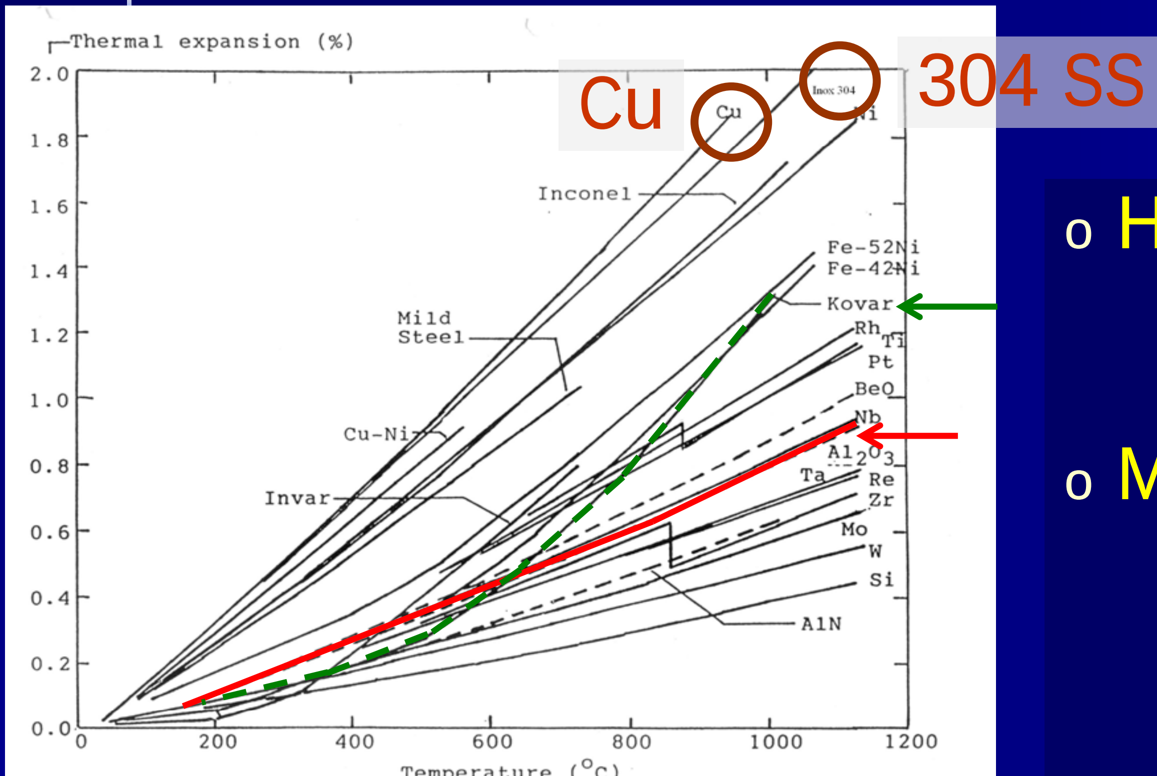
see:

1) S. SGOBBA and G. HOCHOERTLER : A New Non-Magnetic Stainless Steel for Very Low Temperature Applications, Proceedings of the International Congress Stainless Steel 1999: Science and Market, Chia Laguna / IT, 6-9 June 1999, Vol. 2, p. 391-401

2) S. Sgobba, Magnetic Properties of Materials and Phase Transformations, CERN Technical training EMAG-2005, 4-14 April 2005,

\\cern.ch\dfs\\Divisions\EST\Groups\SM\Metallurgy\Internal\Sgobba\Magnetic materials\Sgobba_seminar_final.ppt

2.a Stainless steels, brazeability to ceramics

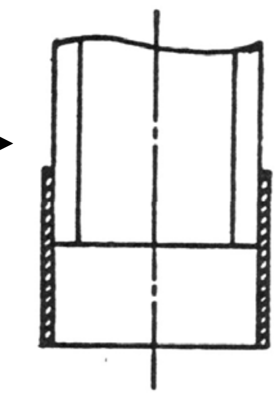


THERMAL EXPANSION CURVES OF SELECTED METALS AND CERAMICS

N. Anderson

- High T (> 500 °C) vacuum brazing
- Metal/ceramic matching expansion coefficient (Kovar), and/or
- Ductility of the "unmatched" metal

cs



sterdam, 1996

- Anisotropy of ceramics

- 96% Al_2O_3 , UTS compression, RT = 2070 MPa
  tensile, RT = 180 MPa
  tensile, 1100 °C = 90 MPa

2.b) Al

Wrought ... ignations

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	

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.

Base Alloys	Characteristics / 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	W
319.0, 333.0, 354.0, 355.0, C355.0, 380.0	2319			B A A A A A	B A A A A A		
	4043	B A A A A A	B A A A A A	C C B C A A	C C B C A A	B B A A A A	B
	4145	A A B A A A	A A B A A A	A B C B A A	A B C B A A	A A B A A A	A
413.0, 443.0, 444.0, 356.0, A356.0, A357.0, 359.0	4043	A A A A A A	A A A A A A	B B A A A A	B B A A A A	A A A A A A	A
	4145	A A B B A	A A B B A	A A B A A	A A B A A	A A B B A	
	5356						
7005, 7021, 7039, 7046, 7146, A712.0, C712.0	4043	A A C A A	A A C A A	B B A A A	B B A A A	A B C A A	A
	4145			A B A A	A A B A A		
	5183	B A B A A	B A B A A			B A B A A	B
	5356	B A A A A	B A A A A			B A A A A	B
	5554						C
	5556	B A B A A	B A B A A			B A B A A	B
	5654						C
6061	4043	A C A A	A A C A A	B B A A A	B B A A A	A B C A A	A
	4145	A D B A	A A D B A	A A B A A	A A B A A	A A D B A	B
	5183	B A B A	B A B A			B A B A	B
	5356	B A A A	B A A A			B A A A	B
	5554						
	5556	B A B A	B A B A			B A B A	B
	5654						
6005, 6063, 6101, 6151, 6201, 6351, 6951	4043	A A C A A	A A C A A	B B A A A	B B A A A	A B C A A	A
	4145	A A D B A	A A D B A	A A B A A	A A B A A	A A D B A	B
	5183	B A B A	B A B A			B A B A	B
	5356	B A A A	B A A A			B A A A	B
	5554						
	5556	B A B A	B A B A			B A B A	B
	5654						
					A A A A A	A B C C A	A

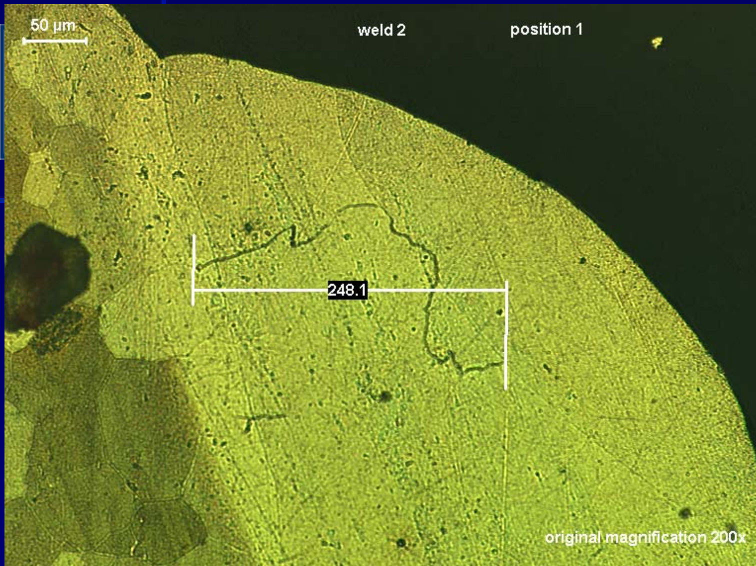
Legend

Filler alloys are rated on the following characteristics:

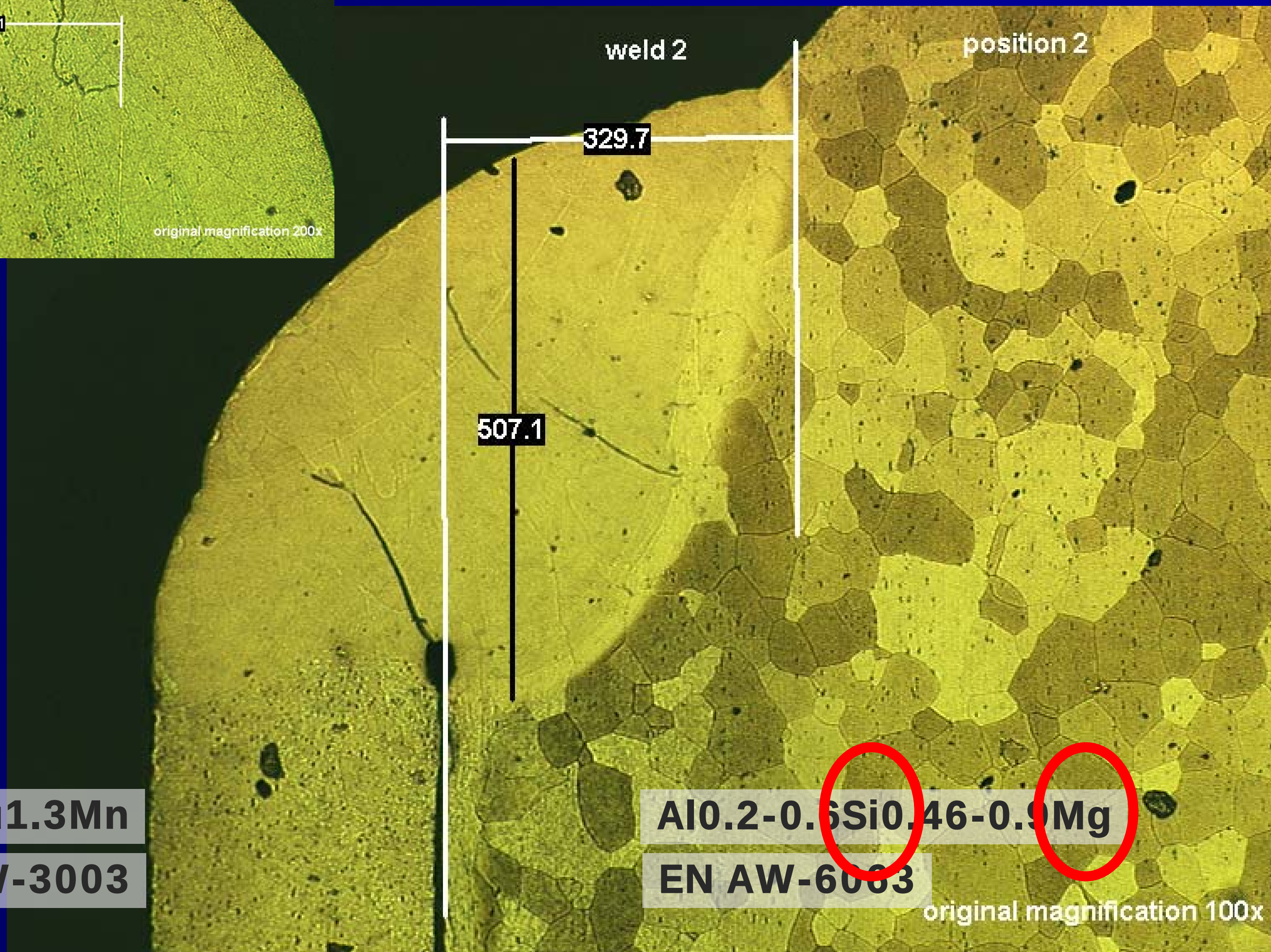
Symbol	Characteristic
W	Ease of welding (relative freedom from weld cracking.)
S	Strength of welded joint ("as welded" condition.) (Rating applies particularly to fillet welds. All rods and electrodes rated will develop the specified minimum strengths for butt welds.)
D	Ductility. (Rating is based upon 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.

d alloys, weldability



EN AW-6063



Al0.15Cu1.3Mn

EN AW-3003

Al0.2-0.6Si0.46-0.9Mg

EN AW-6063

2.b) Aluminium and alloys

Heat treatable **Non heat treatable**

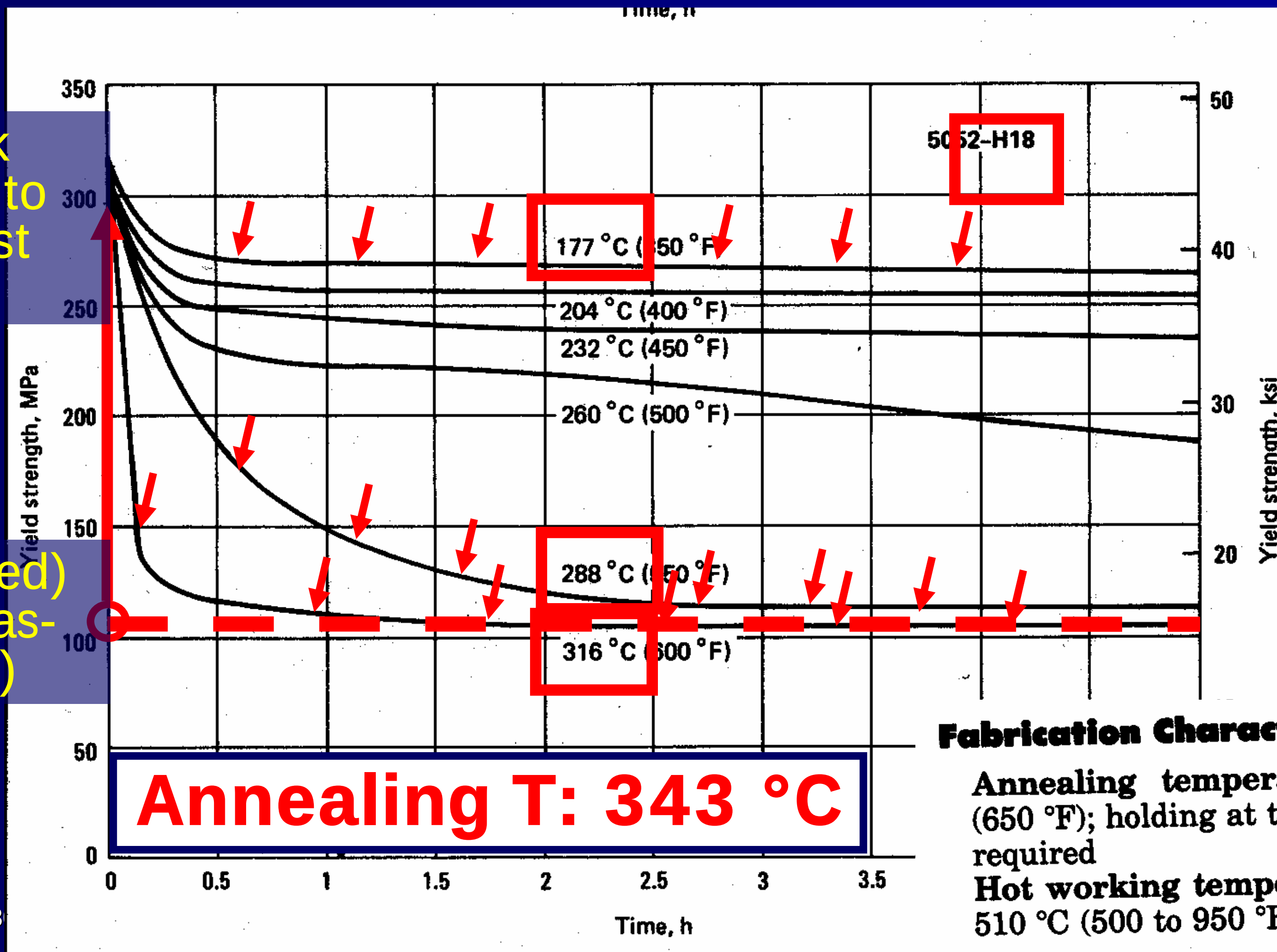
Alloy Group	Designation AA
Pure aluminium	1xxx series
Al-Cu	2xxx series
Al-Mn	3xxx series
Al-Si	4xxx series
Al-Mg	5xxx series
Al-Mg-Si	6xxx series
Al-Zn	7xxx series
Al+other element (Li)	8xxx series

(⇒)

Non heat treatable

H18 (work hardened to the hardest state)

O (annealed) or H111 (as-fabricated)



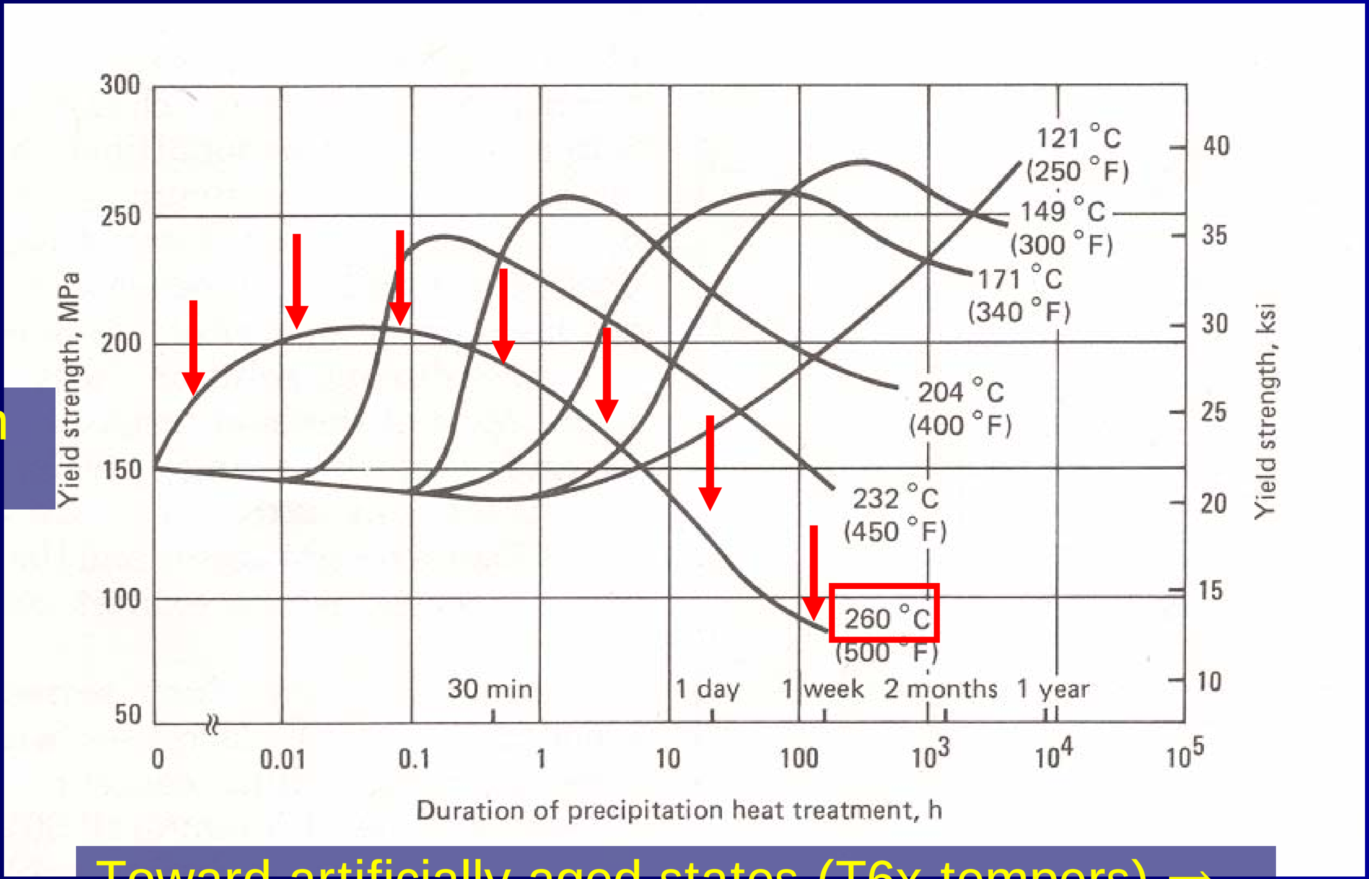
Fabrication Characteristics

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

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

2.b) Aluminium and alloys

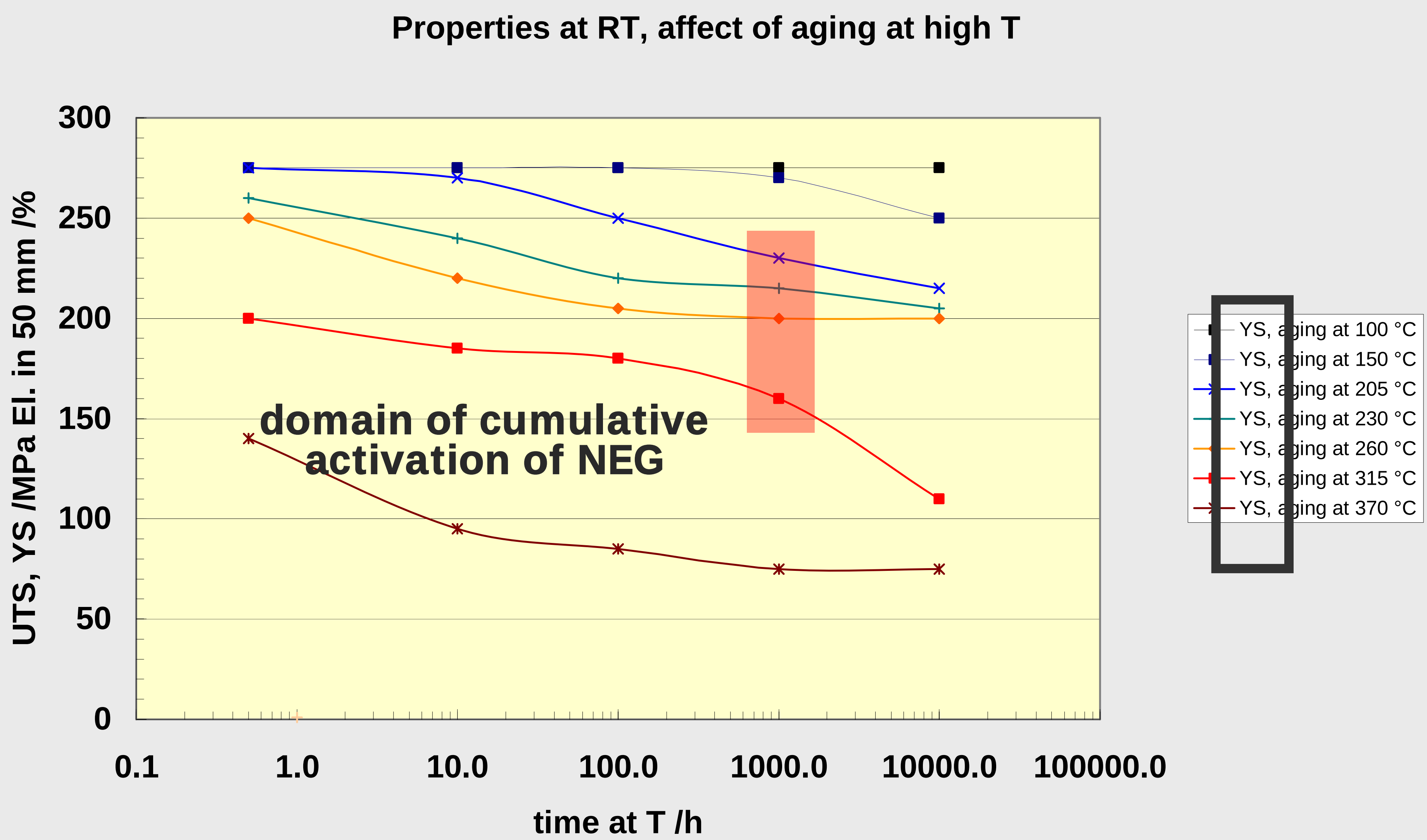
EN-AW 6061



O (solution annealed)

Toward artificially aged states (T6x tempers) ⇒

2.b) Aluminium and alloys, EN AW 2219



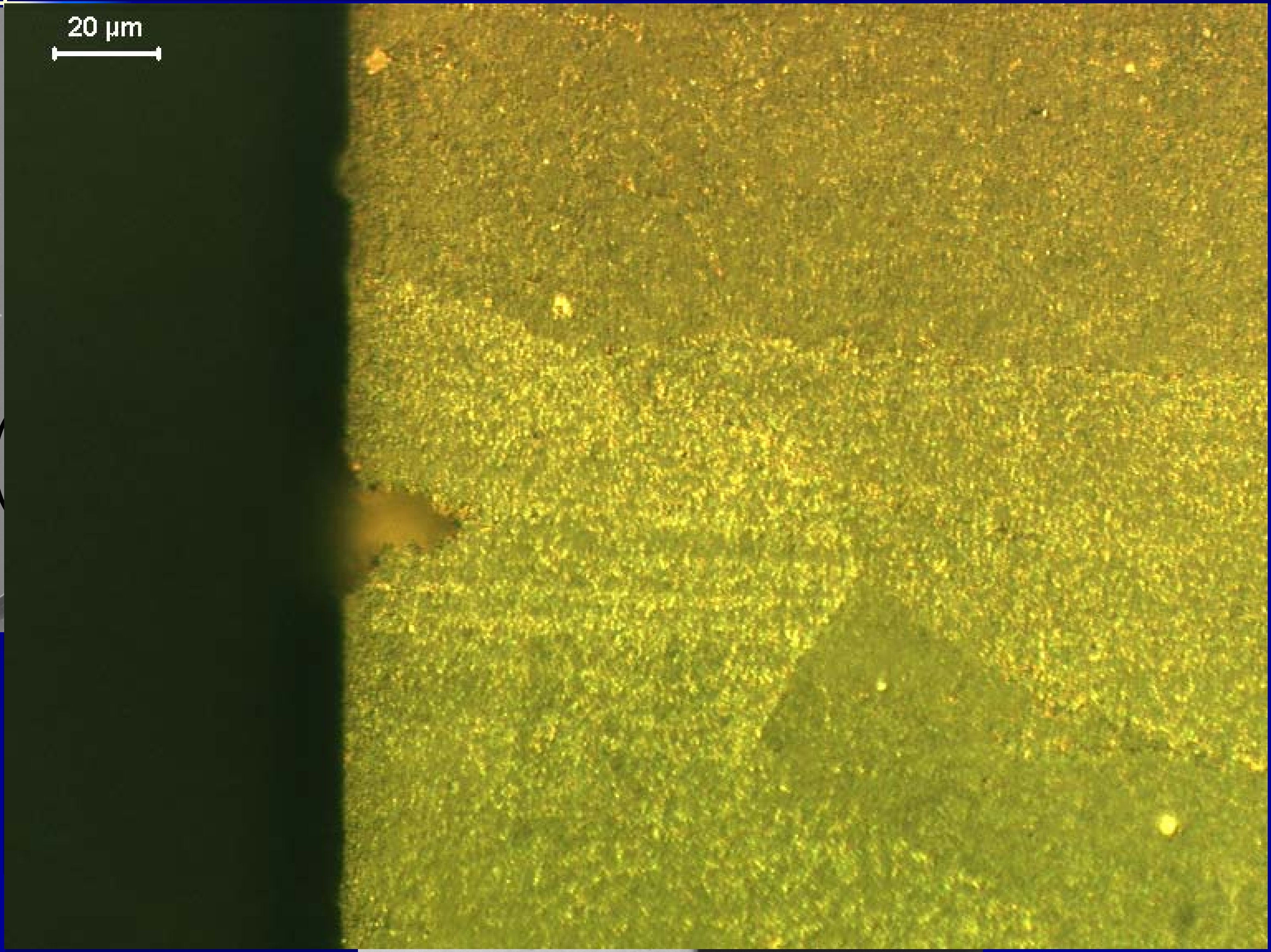
Failure of thin walled Al-alloy bellows for the LHCb experiment

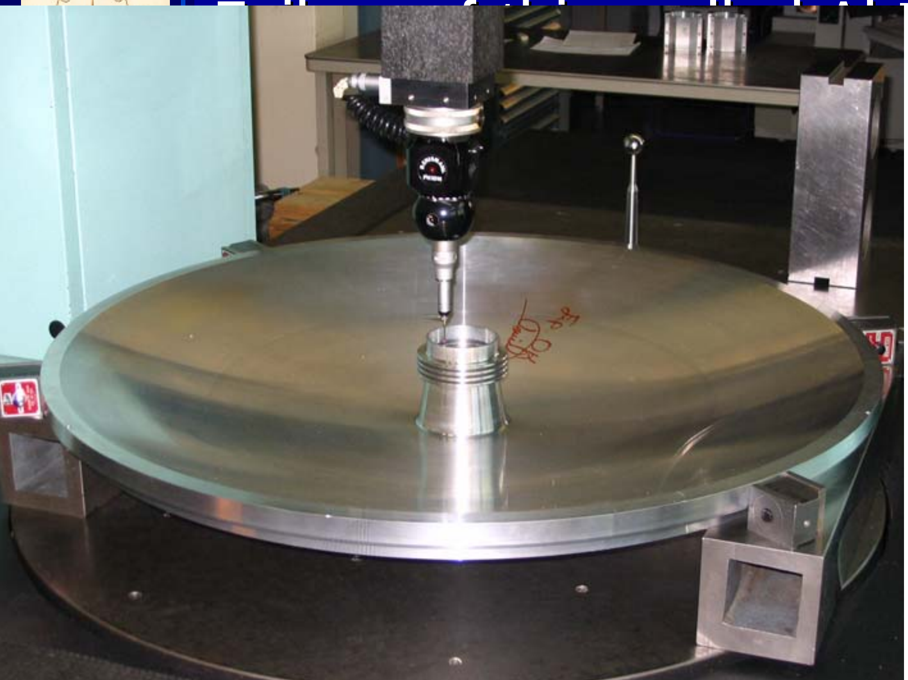
- EN AW 2219 bellows
- machined from forged round blocks
- welded assembly (2 flanges + 2 bellows + 1 tube)
- for the LHCb experiment

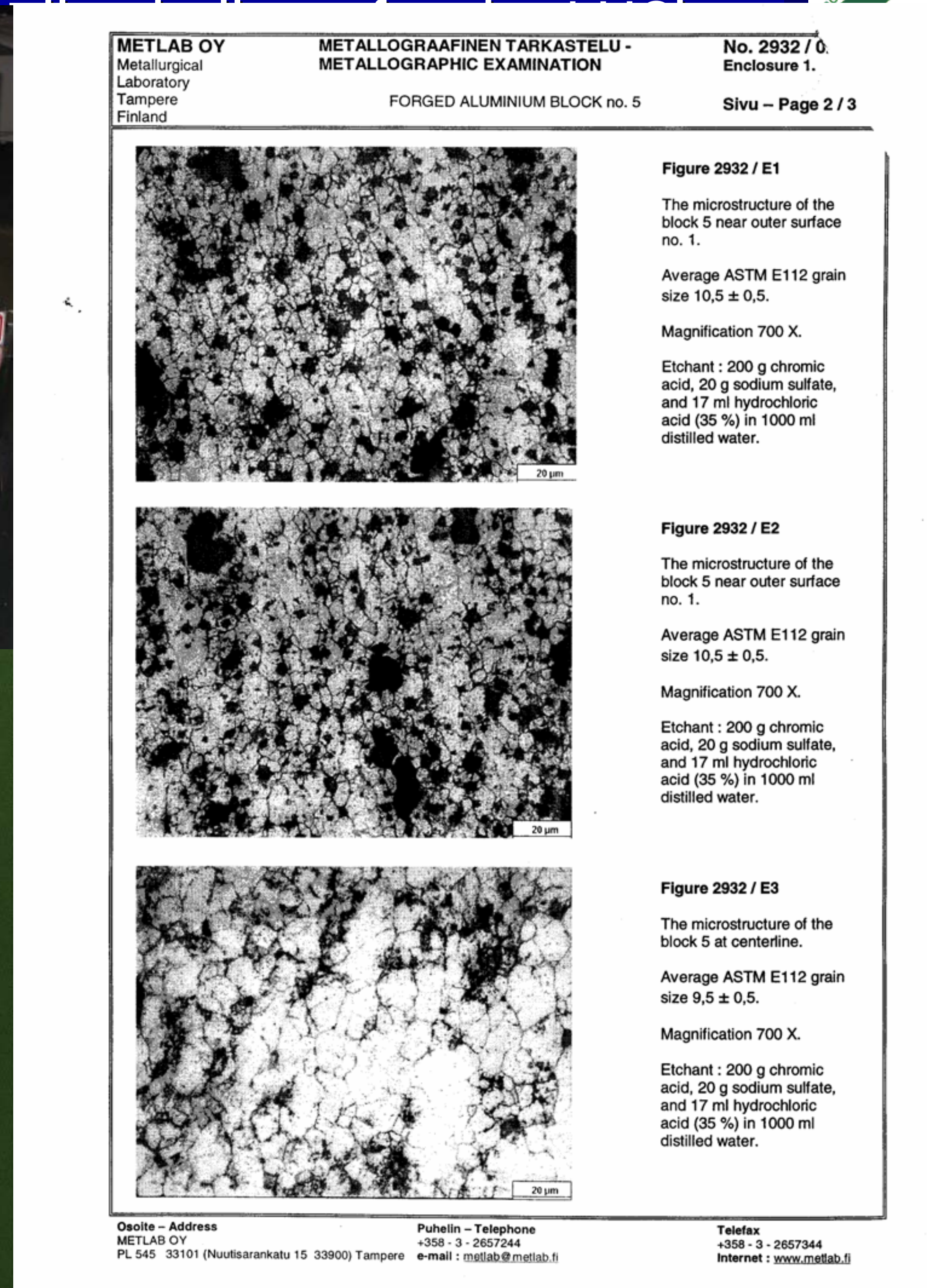
- leaks detected on a significant fraction of bellows

see EDMS Nr.: 681631

Failure of thin walled Al-alloy bellows for the LHCb experiment







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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PL 545 33101 (Nuutisarankatu 15 33900) Tampere

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Internet : www.metlab.fi


200 µm

"electrical coppers"

high strength copper alloys
Cu-2%Be, C17200
Cu-0.3%Be-0.5%Co, C17410

Generic name	UNS No.	Composition
Wrought alloys		
Coppers(a)	C10100–C15815	>99% Cu
High-copper alloys(b)	C16200–C19900	>96% Cu
Brasses	C20100–C28000	Cu-Zn
Leaded brasses	C31200–C38500	Cu-Zn-Pb
Tin brasses	C40400–C48600	Cu-Zn-Sn-Pb
Phosphor bronzes	C50100–C52480	Cu-Sn-P
Leaded phosphor bronzes	C53400–C54400	Cu-Sn-Pb-P
Copper-phosphorus and copper-silver-phosphorus alloys(c)	C55180–C55284	Cu-P-Ag
Aluminum bronzes	C60800–C64210	Cu-Al-Ni-Fe-Si-Sn
Silicon bronzes	C64700–C66100	Cu-Si-Sn
Other copper-zinc alloys	C66300–C69710	Cu-Zn-Mn-Fe-Sn-Al-Si-Co
Copper nickels	C70100–C72950	Cu-Ni-Fe
Nickel silvers	C73500–C79830	Cu-Ni-Zn

70Cu-30Ni, C71500
"70-30 cupronickel"

Alloys containing:

- **Zn**
- **Pb**
- **Cd**
- **Se**
- **S...**

might result in unsuitable vapour pressures

(J. O'Hanlon, A User's Guide to Vacuum Technology, Wiley, 2003)

2.c) Copper and alloys

ASTM B 170

TABLE 1 Chemical Composition[A]

Element	Grade 1	Grade 2
Copper, min %	99.99[B]	. . .
Copper (including silver), min %	. . .	99.95
	ppm, max	ppm, max
Antimony	4	. . .
Arsenic	5	. . .
Bismuth	1	. . .
Cadmium	1	. . .
Iron	10	. . .
Lead	5	. . .
Manganese	0.5	. . .
Nickel	10	. . .
Oxygen	5	10
Phosphorus[C]	3	. . .
Selenium	3	. . .
Silver	25	. . .
Sulfur	15	. . .
Tellurium	2	. . .
Tin	2	. . .
Zinc	1	. . .

[A] ...ytical uncertainty is not incorporated into the specified limits.
[B] Copper is determined by the difference of impurity total from 100.
[C] Refer to Section 13.

brazeability, weldability

OFE, OF Cu, respectively

CERN

Materials Technical Specification (SPL-LS)

TECHNICAL SPECIFICATION

N° 2001 - Ed. 3 - 02.08.1999

BAR

COPPER OFE

4. *MANUFACTURING PROCESS*

In accordance with the diameter, the bars shall be given the necessary treatment to allow delivery in the **HALF-HARD** state.

5.2 HOMOGENEITY

The homogeneity of the bar shall be ultrasonically inspected solely to detect continuity faults.

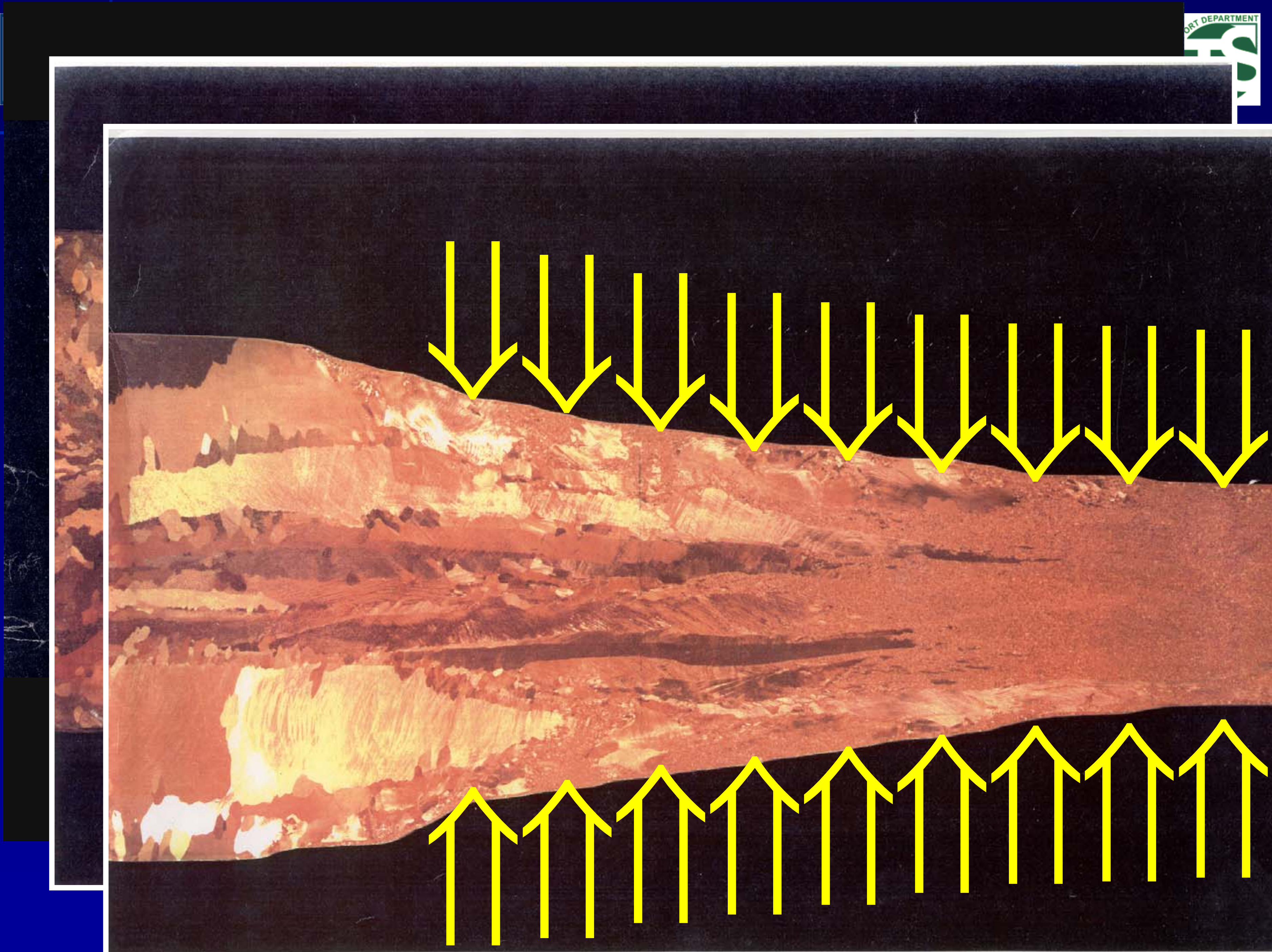
Each copper bar shall be ultrasonically tested at frequencies ≥ 4 MHz, depending on the thickness. If the attenuation is:

> 20 % Rejected.

The details of the ultrasonic inspection will be agreed upon between the manufacturer and CERN as a function of the product.

0 µm shall be

of a specific



data for:

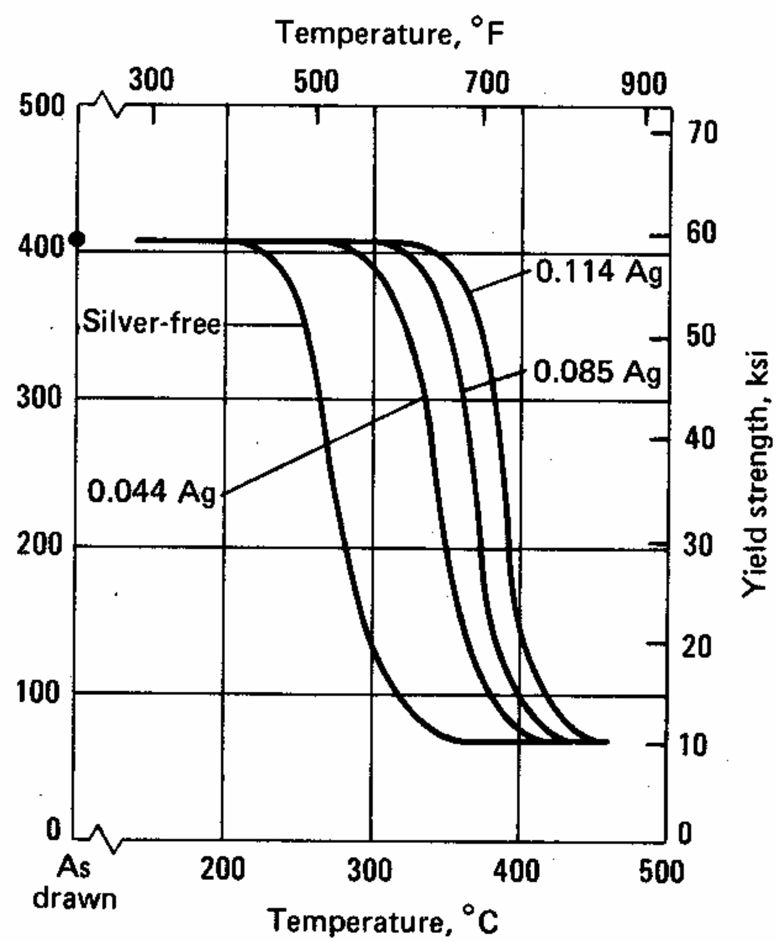
- Cu wire
- CW 90 %
- to 2 mm diam.

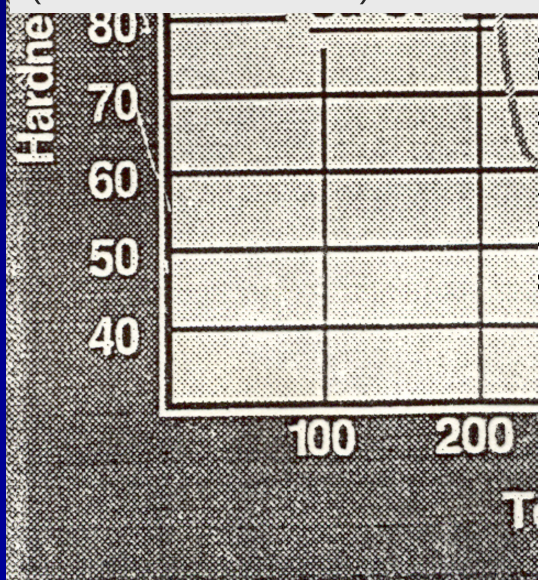
then

- annealed ½ h at various T

(source ASM Handbook)

Fig. 3 Softening characteristics of oxygen-free copper containing various amounts of silver





2.c) Copper and alloys

- **Copper base dispersion str**

  Oxide Dispersion Str
  GlidCop® Dispersi

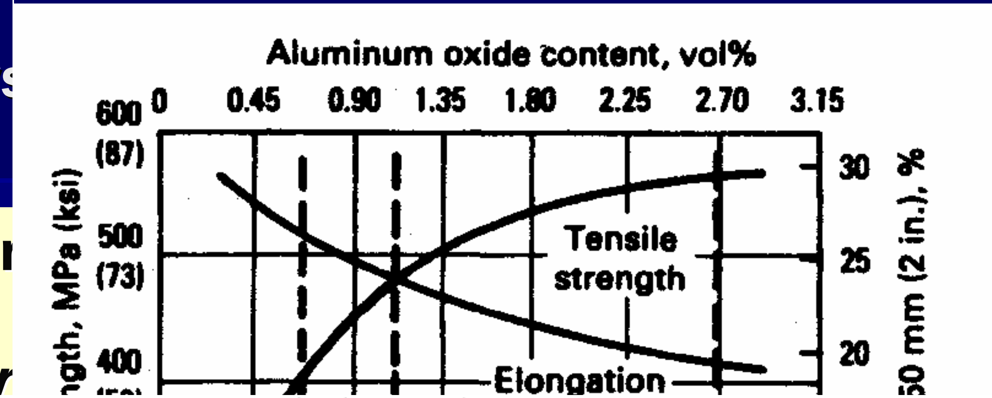
- **GlidCop, trademark of S**
  of metal powders
  Based on a Cu-Al_2(

- **Oxides immiscible in liqu**
  thermomechanical

  Internal oxidation

  (Mechanical mixing
  (Coprecipitation fro
  (Selective internal o

Nadkarni, Mechanical Properties of Metallic Components, 1993, p.297



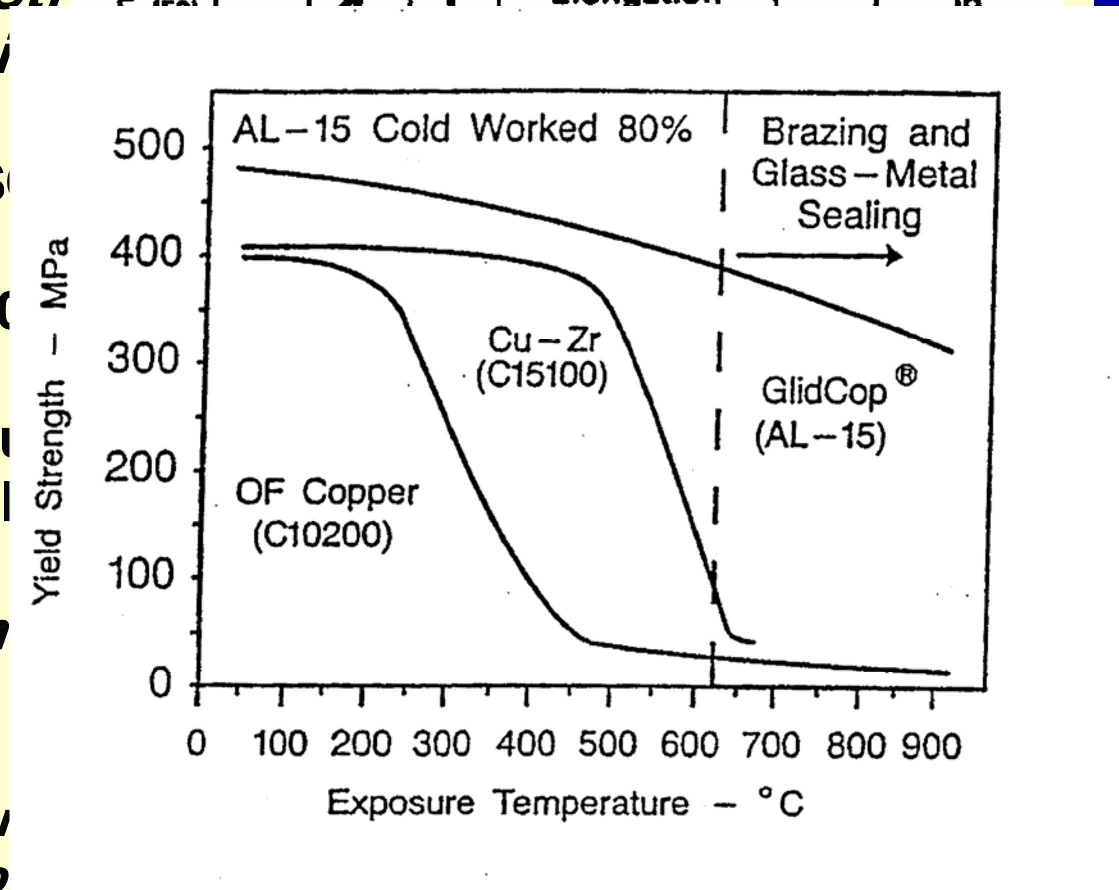


Figure 1: Softening resistance of GlidCop AL-15 versus OF copper and Zirconium Copper. (Note: Properties measured at room temperature, after exposure to elevated temperatures for one hour.)

North American Höganäs tech. data sheet no. 700A (rev. 2003)

- **GlidCop® AL-25**
- **based on a thermally stable reinforcement (Al_2O_3)**
- **acts as barrier to dislocation movement and to recrystallisation**

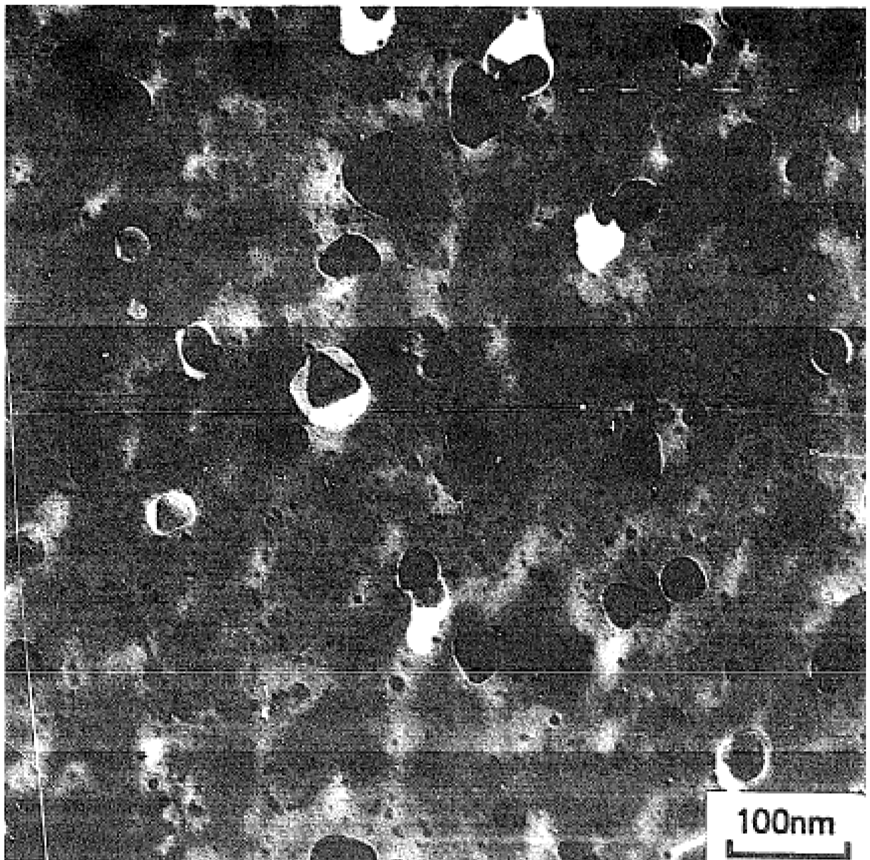
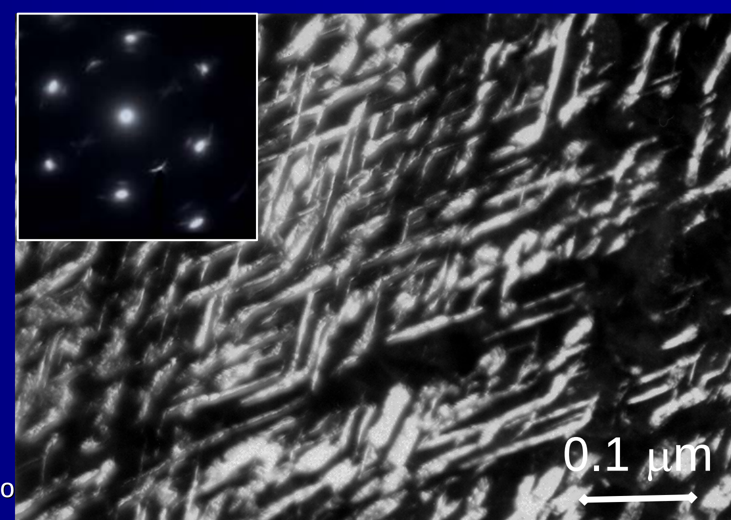


Fig. 1. Bright field TEM micrograph of a Cu–Al 25 alloy showing different sizes of alumina.

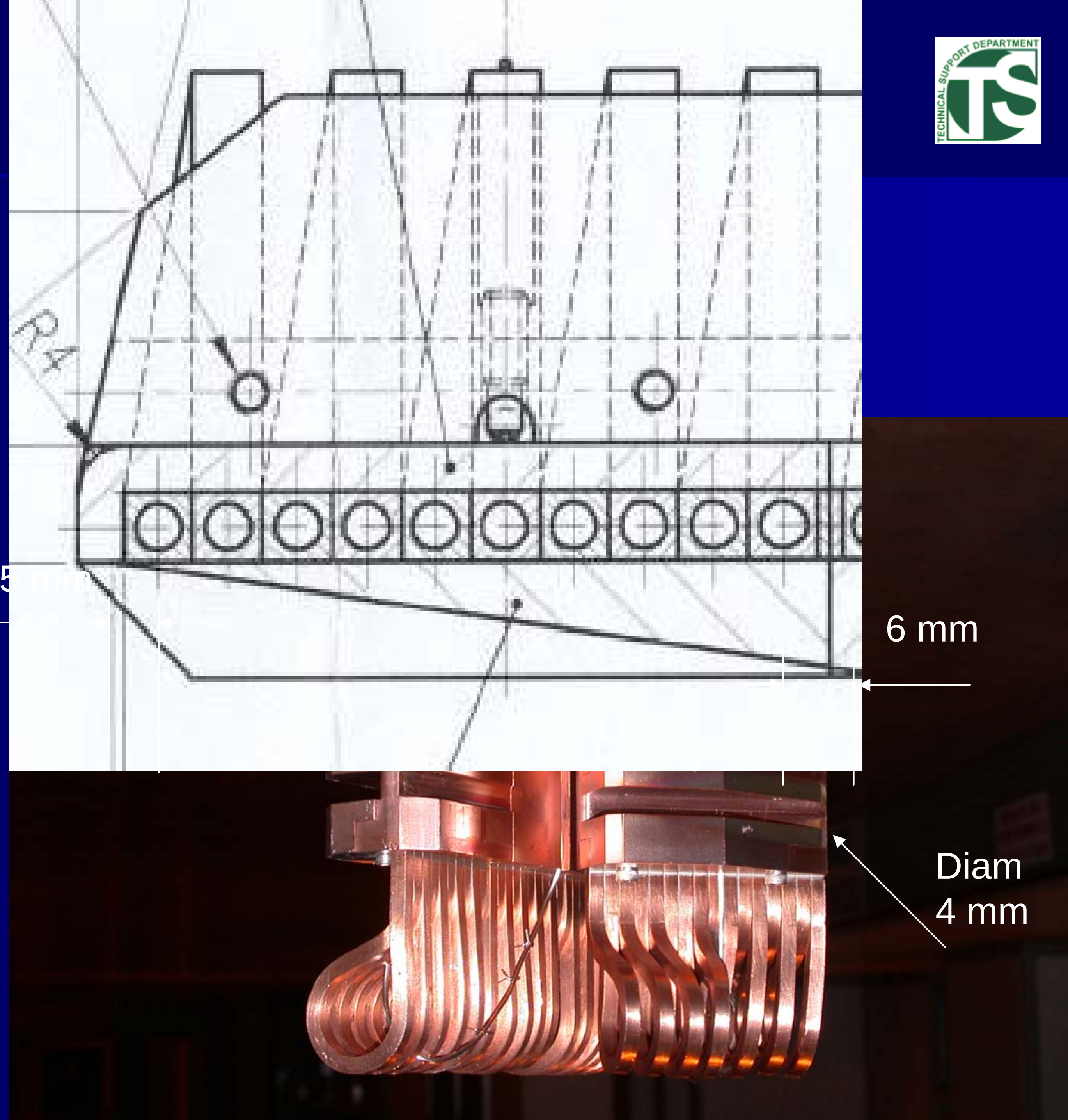
F. Zhu, L. Jiao, N. Wanderka, R.P. Wahi and H. Wollenberger, *FIM atom probe study of an Al_2O_3 dispersion strengthened copper alloy*, Surface Science 266 (1992) 337-341

- **Cu-2 % Be, aged 360 °C, 6h**
- **based on the usual GP $\Rightarrow$ (γ'') $\Rightarrow \gamma' \Rightarrow \gamma$ precipitation (Rioja and Laughlin, 1980)**
- **thermally unstable system (diffusion controlled)**

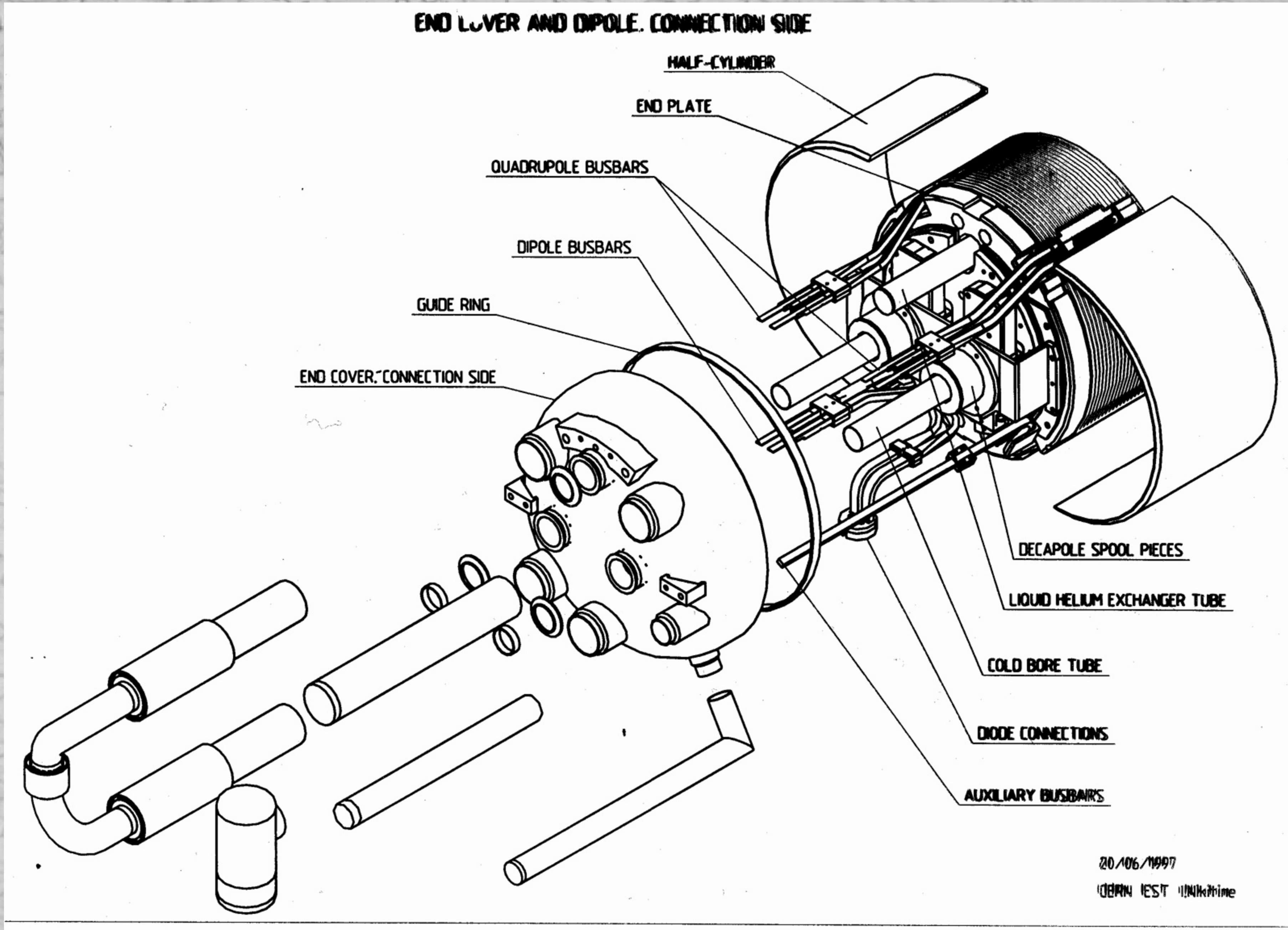


S. Sgobba, thèse EPFL n° 1215 (1994)

Bending Magnet Radiation



Courtesy of R. Kersevan

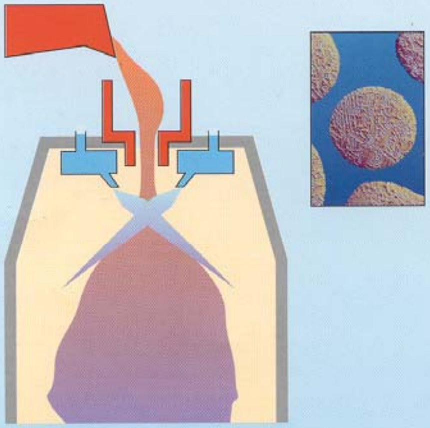

END LᴗVER AND DIPOLE. CONNECTION SIDE
HALF-CYLINDER
END PLATE
QUADRUPOLE BUSBARS
DIPOLE BUSBARS
GUIDE RING
END COVER: CONNECTION SIDE
DECAPOLE SPOOL PIECES
LIQUID HELIUM EXCHANGER TUBE
COLD BORE TUBE
DIODE CONNECTIONS
AUXILIARY BUSBARS
20/06/1997
CERN EST

HIPed AISI 316LN end covers for CERN LHC project (courtesy of Metso)

After capsule removal by pickling and heat treatment, before machining

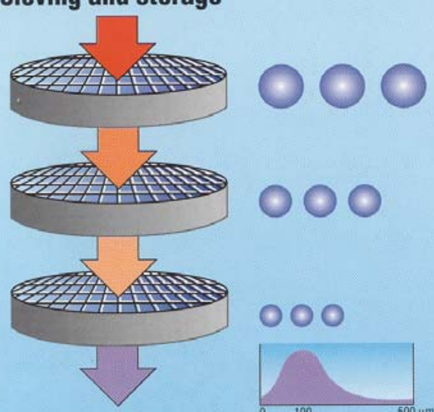
Powder production

Melting and gas atomizing



Melted and refined steel is fed through special nozzles into a high-speed inert gas flow, which atomizes the molten steel into fine, spherical solidified powder particles.

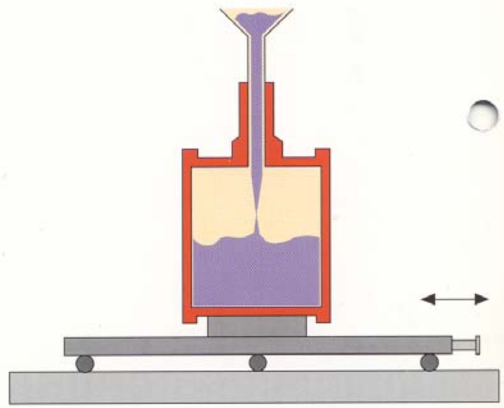
Sieving and storage



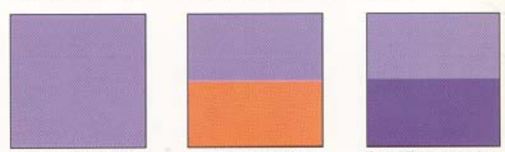
The atomized powder is sieved according to its particle size into separate fractions for a variety of applications. The powder will be carefully stored to guarantee its cleanliness.

Capsule making

Capsule making and compaction

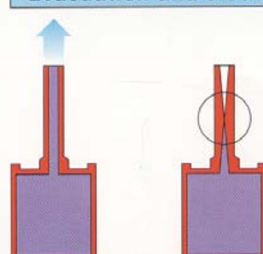


The production capsule for each component will be made out of thin plate by shaping and welding. This capsule will then be filled with gas atomized powder by vibrating the capsule. The capsule is oversized, to allow for the shrinkage which occurs during the powder compaction.
If the end product is designed to comprise of different materials, the powders will be encapsuled separately into different sections of the capsule. The other material can also be a solid product, such as a casting to be coated with special material.



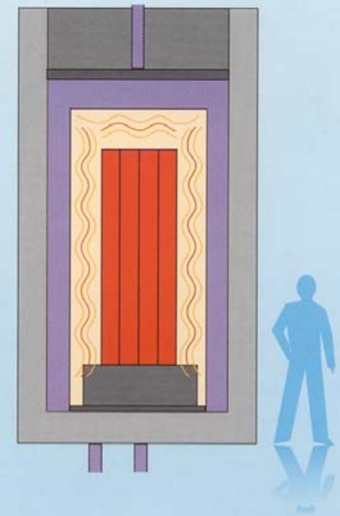
One powder material | Powder/solid | Two different powders

Evacuation and closing



After the capsule has been filled with powder, the air will be evacuated and the capsule closed tightly.

Hot Isostatic Pressing (HIP)

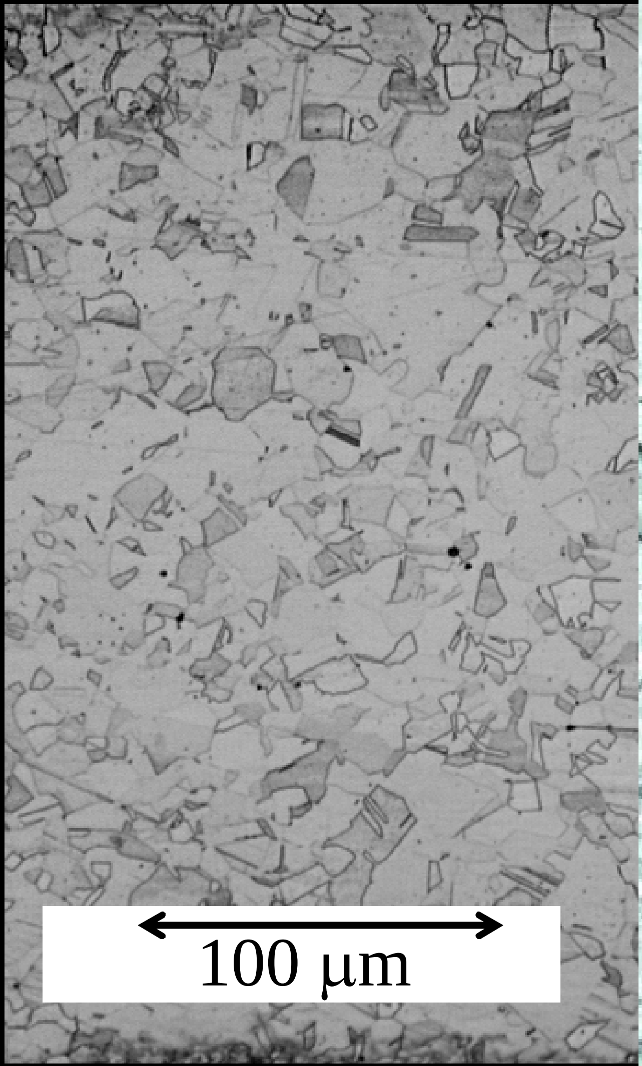


The temperature/
pressure cycle of the hot isostatic pressing:

The sealed capsules are moved to a pressure vessel used in the HIP-process. With the aid of high-pressure Ar-gas the capsule is subjected, in the pressure vessel, to an isostatic pressure, which by means of high temperature (about 70% of the melting point of the material being used) turns the powder into a 100% compact material.
The homogeneity of the end product is the same as that of the powder. The properties are even and do not depend on the orientation.

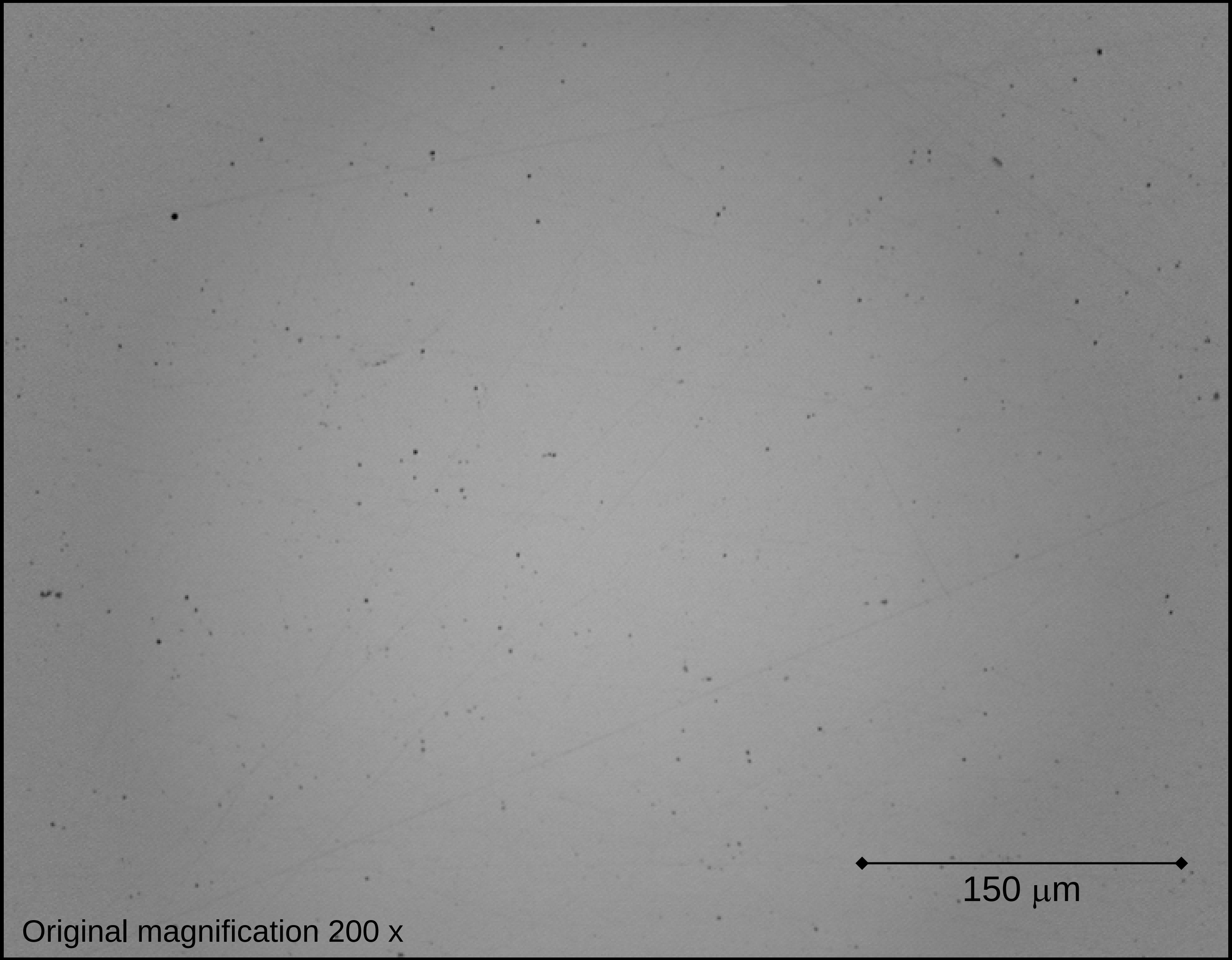
PM 316 LN,

Grain size according t

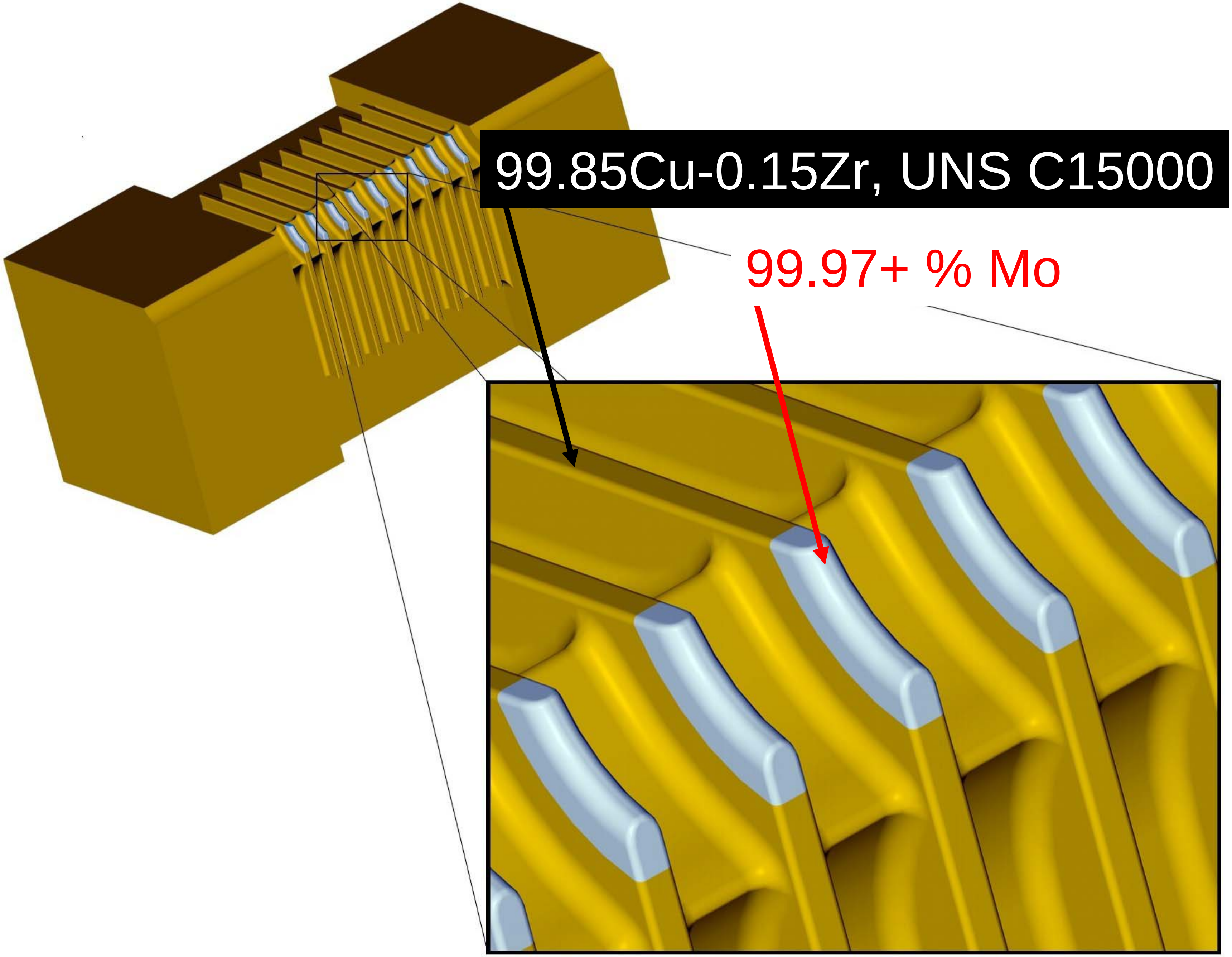


S. SGOBBA, F. SAVARY, J. LIIMATAINEN AND M. KUMPULA, A Powder Metallurgy Austenitic Stainless Steel for Application at Very Low Temperatures: Proceedings of the 2000 Powder Metallurgy World Congress, Nov. 12-16, 2000, Kyoto, Japan, vol. 2, p. 1002-1005

Inclusions



Mainly globular-type


99.85Cu-0.15Zr, UNS C15000
99.97+ % Mo

Bimetallic structures

Stainless steels

- 304L, general purpose ⇒ 5 sFr/kg
- 304L, vacuum applications ⇒ 8.50 sFr/kg
- 316LN, vacuum applications ⇒ 16-18 sFr/kg
- 316LN, blanks ⇒ 50 (up to 135) sFr/kg
- P506, 316L convolutions ⇒ 40-80 sFr/kg

b) definition and extent of the controls

Coppers

Special materials or bimetals

- Mo, 99.97% (CLIC) ⇒ 1800 sFr/kg
- Mo/CuZr bimetal (CLIC) ⇒ 40000 sFr/m, ∅ 85 mm
- Ti grade 2, CNGS end windows ⇒ 54 sFr/kg
- Nb (ILC cavities) ⇒ 270 sFr/kg

- Glidcop ⇒ 42 $/kg

(bellow convolutions vs. end flanges)

Al alloys

- plates EN AW 1050 ⇒ 5 sFr/kg
- plates EN AW 5754 ⇒ 7 sFr/kg
- plates EN AW 6082 ⇒ 6.50-8 sFr/kg
- special forgings, EN AW 6061, velo windows ⇒ 18 sFr/kg

3) Conclusions

- **Proper selection should keep into account:**
  - ***a) availability (Ti grade 2 plates for the CNGS end windows, EN AW 2219…)***
  - ***b) ease of fabrication into a given form (EN AW 6082…)***

- **Selection as a function of properties and further operations**
  - ***a) strength, ductility as a function of T (cryogenic applications, NEG activation, baking…)***
  - ***b) weldability (Al-alloys…), machinability (pure Cu…)***

- **Corrosion issues**
  - ***a) thin walled components (LHCb velo windows, bellows, ATLAS Pixel cooling circuit…)***
  - ***b) use of halogen-activated fluxes to be avoided in a SS environment***

3) Conclusions

- Consider the material aspects at the beginning of a project:
  - *a) availability (more than 1 y delay for a special SS, P506 for the beam screen)*
  - *b) interest of considering alternative techniques, including near net shaping (PM for the end covers of LHC dipole magnets)*

- New projects will eventually force into less conservative solutions:
  - *bimetals by HIP assisted diffusion bonding, explosion bonding (CLIC, ILC)...*