Can Stainless Steel Meet the Challenges of Future Cryogenic Engineering Systems?

Ignacio Avilés Santillana, Enrique Rodriguez Castro, Berta Ruiz Palenzuela, Stefano Sgobba

CERN EN / MME - MM

CERN

ENGINEERING
DEPARTMENT

Outline

Motivation

FXM-19

316LNH

P506

Comparison and perspectives

Conclusion

MOTIVATION

- Demands on cryogenic engineering systems continue to evolve with advancements in high-energy physics, novel fusion devices, and the expanding hydrogen economy.
- Relying in **superconducting magnet technology**, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high:

FCC-hh: The core of the hadron collider are the 16 T magnets


US magnet prototype at FNAL

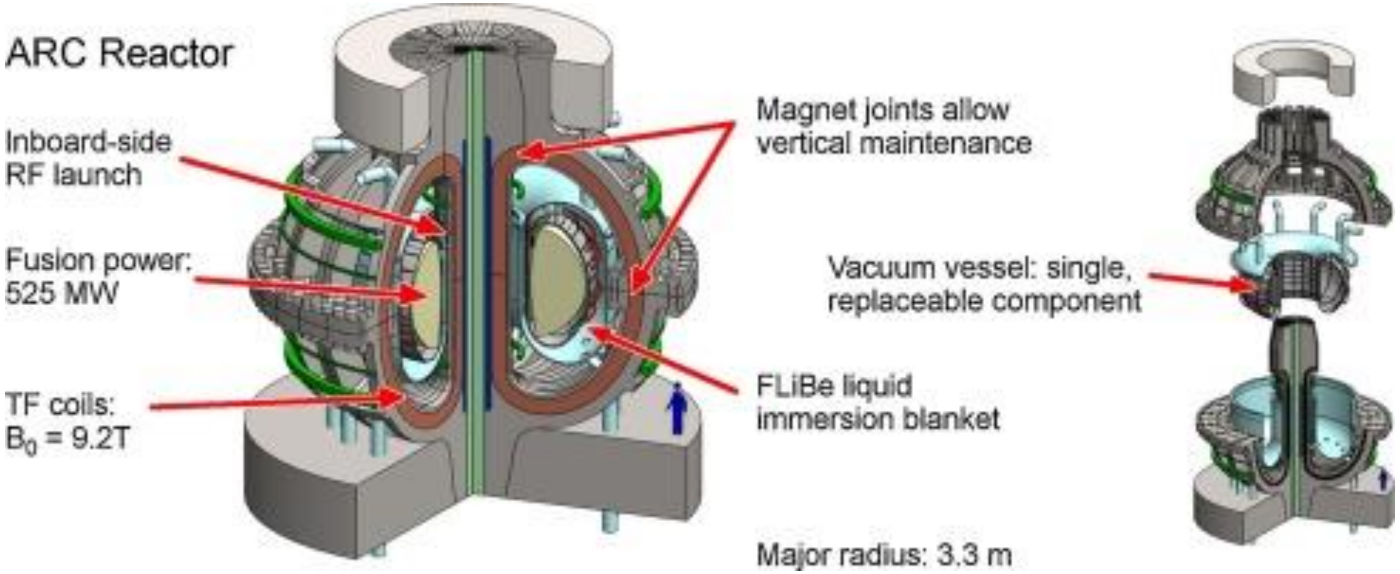

Enhanced racetrack coil at CERN

BENEDIKT, Michael; ZIMMERMANN, Frank. JACoW: FCC: Colliders at the Energy Frontier. 2018.

MOTIVATION

- Demands on cryogenic engineering systems continue to evolve with advancements in high-energy physics, novel fusion devices, and the expanding hydrogen economy.
- Relying in **superconducting magnet technology**, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high:

ARC : on-axis magnetic filed 9.2 T → 23 T peak field on coil



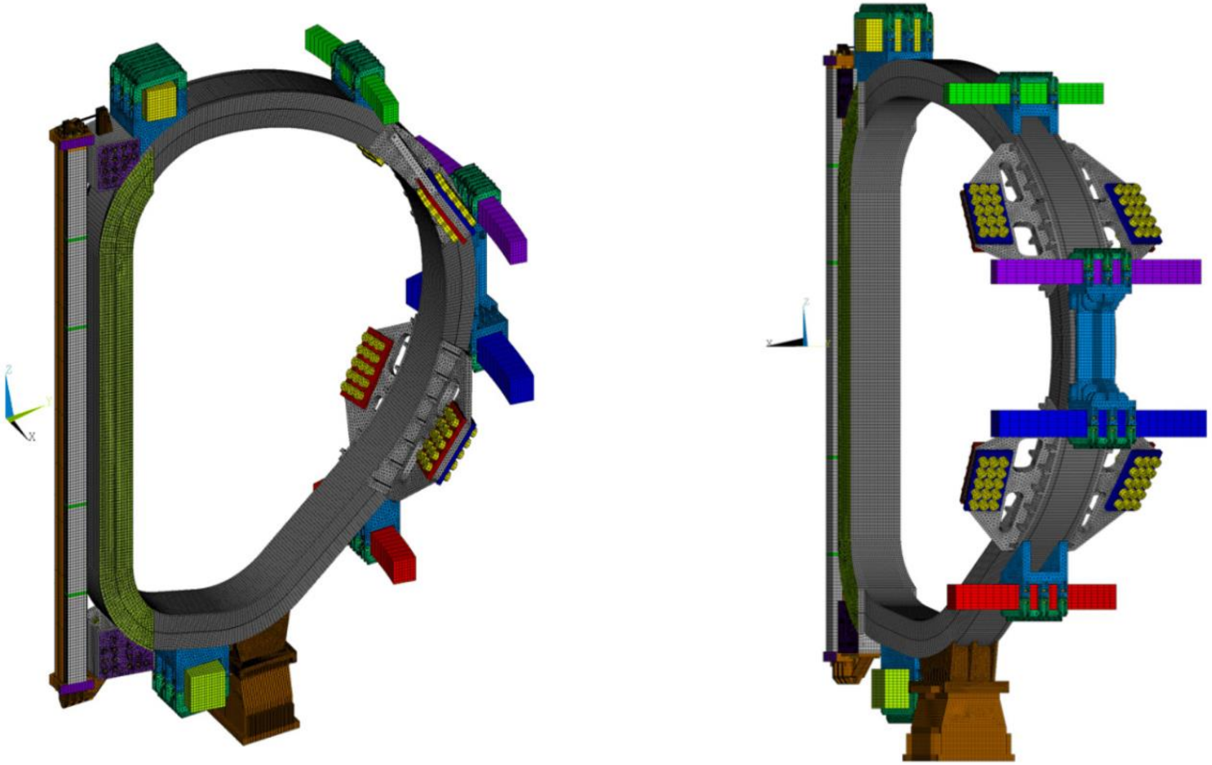
ARC fusion device

Sorbom, B. N., Ball, J., Palmer, T. R., Mangiarotti, F. J., Sierchio, J. M., Bonoli, P., ... & Whyte, D. G. (2015). ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets. Fusion Engineering and Design, 100, 378-405.

MOTIVATION

- Demands on cryogenic engineering systems continue to evolve with advancements in high-energy physics, novel fusion devices, and the expanding hydrogen economy.
- Relying in **superconducting magnet technology**, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high:

DEMO: 12 T, 66 kA magnets



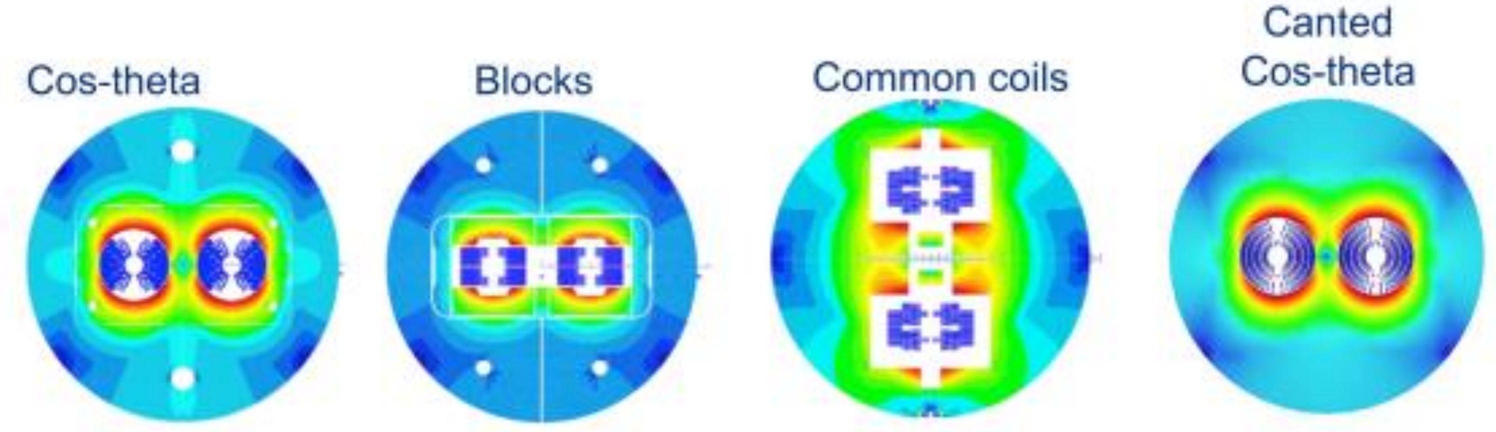
22.5-degrees sector of the machine with the PF, CS and TF coils, the inter-coil structures and the gravity support.

Giannini, L., Boso, D. P., & Corato, V. (2022). A combined electromagnetic and mechanical approach for EU-DEMO toroidal field coils. Applied Sciences, 12(6), 2766.

MOTIVATION

- Relying in superconducting magnet technology, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high.
- However, an increase in magnetic field is not accompanied by an increase in the size, thus **the need for high-strength structural materials becomes increasingly apparent**.

FCC-hh: Four types of high-field magnets designed and prototyped in the frame of EuroCirCol

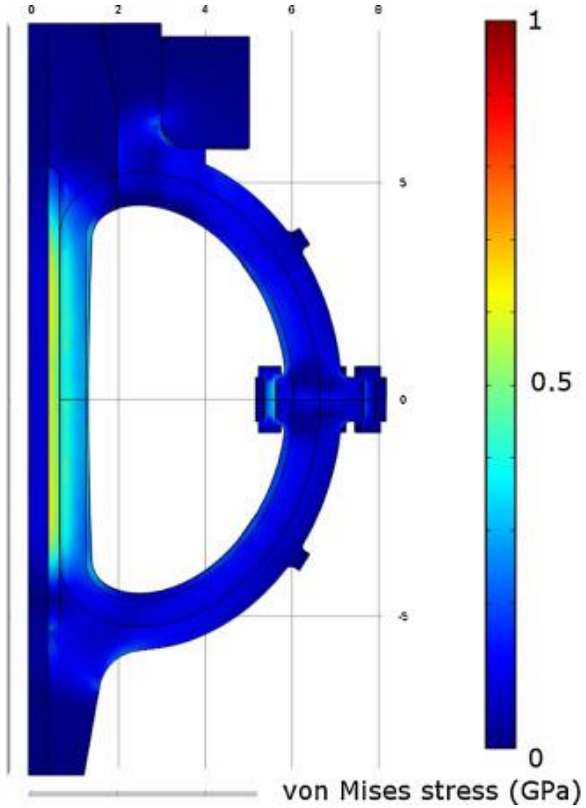


The goal is to raise the critical current density to 1500 A/mm2 , which would **reduce the size** of the coil area by almost a factor of two and allow for **greater compactness** plus lower cost.

BENEDIKT, Michael; ZIMMERMANN, Frank. JACoW: FCC: Colliders at the Energy Frontier. 2018.

MOTIVATION

- Relying in superconducting magnet technology, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high.
- However, an increase in magnetic field is not accompanied by an increase in the size, thus **the need for high-strength structural materials becomes increasingly apparent**.



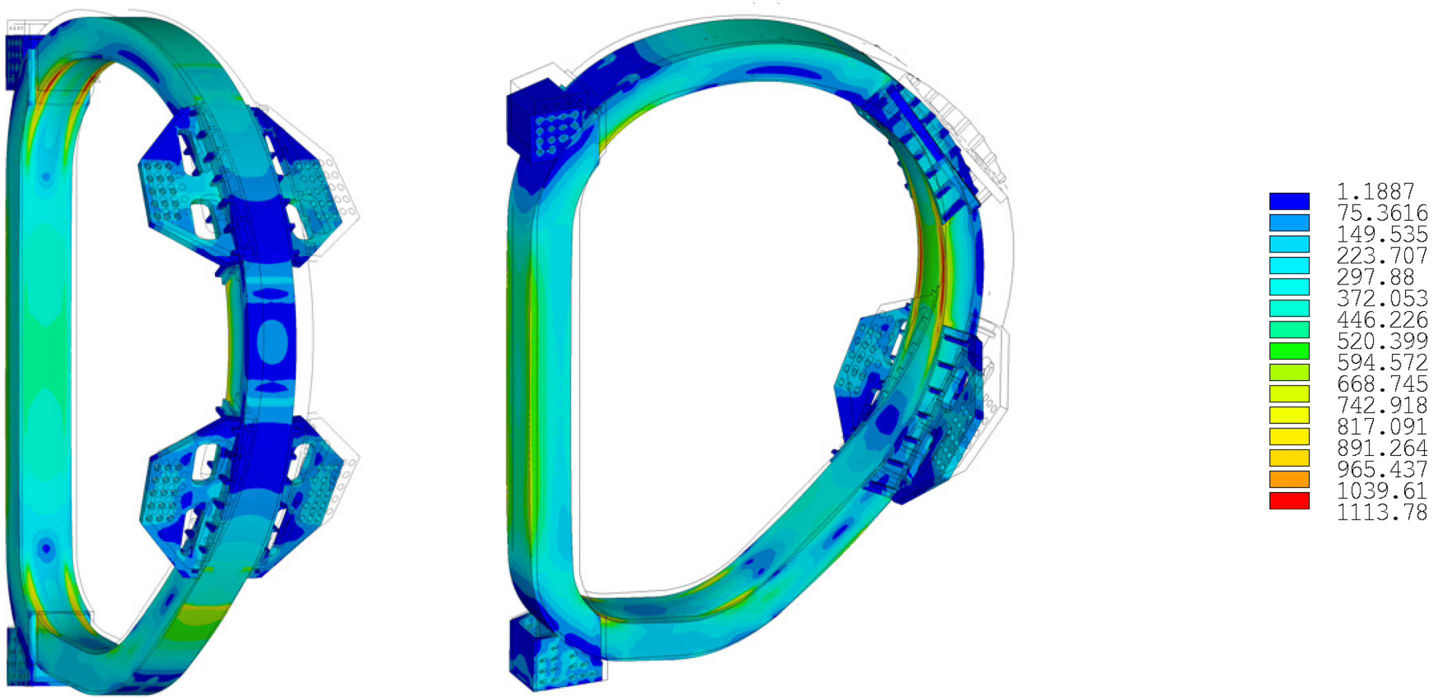
Stress simulations in the TF coils. The maximum stress in the stainless steel structure is 660 MPa

Sorbom, B. N., Ball, J., Palmer, T. R., Mangiarotti, F. J., Sierchio, J. M., Bonoli, P., ... & Whyte, D. G. (2015). ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets. Fusion Engineering and Design, 100, 378-405.

MOTIVATION

- Relying in superconducting magnet technology, the magnetic fields required for a variety of very ambitious engineering projects are increasingly high.
- However, an increase in magnetic field is not accompanied by an increase in the size, thus **the need for high-strength structural materials becomes increasingly apparent**.

DEMO TF coil casings during energization (equivalent Tresca stress)

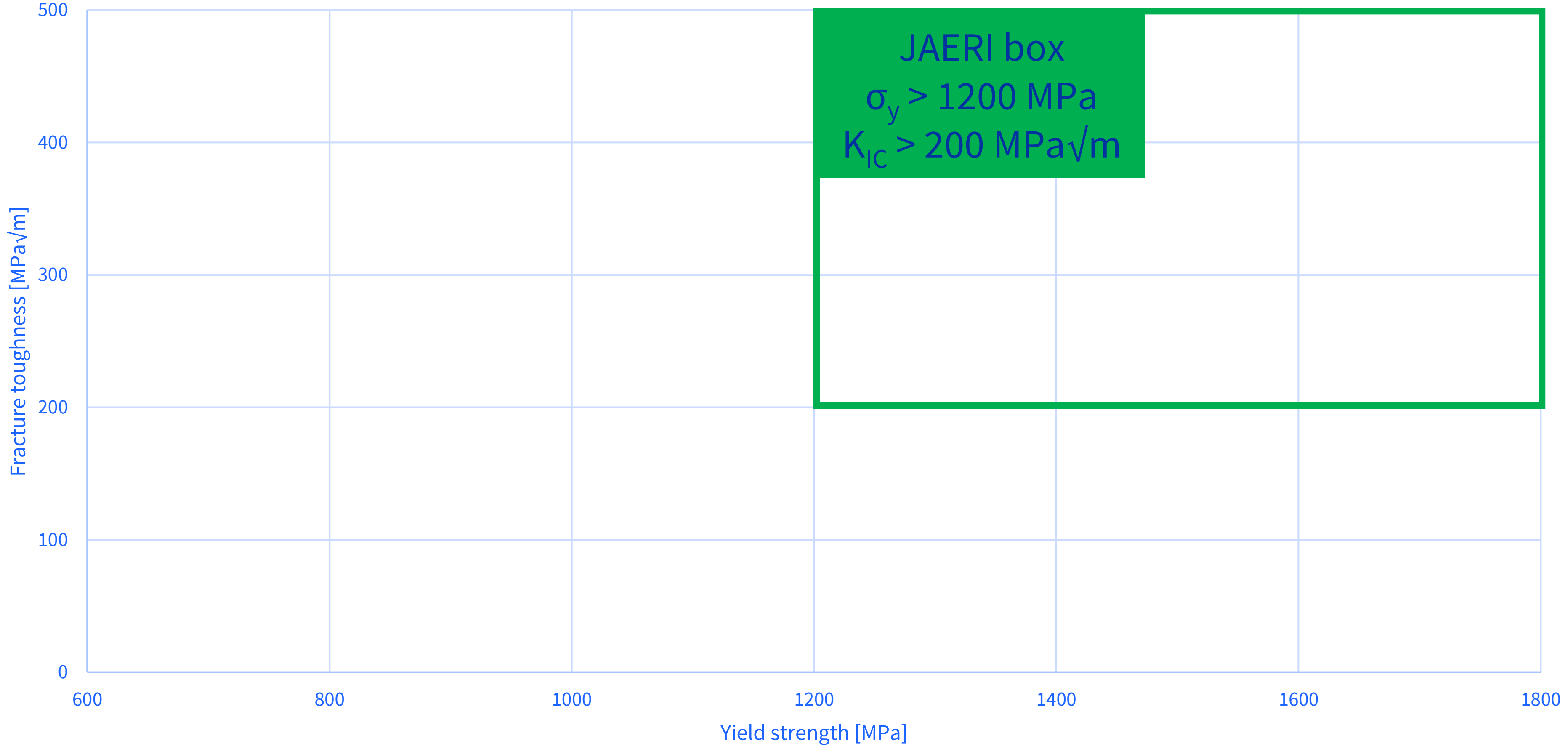


"…the TF case, for which a material with better performance is needed, with a **yield limit of 1000 MPa** and an ultimate strength of 1470 MPa"

Giannini, L., Boso, D. P., & Corato, V. (2022). A combined electromagnetic and mechanical approach for EU-DEMO toroidal field coils. Applied Sciences, 12(6), 2766.

MOTIVATION

- In order to have more reliable and safe systems, austenitic stainless steel should aim for and old ‘dream’: the JAERI box
- Are current austenitic stainless steels inside the JAERI box?



FXM-19

FXM-19

Very high strength alloy (both at RT and at 4 K)

Strengthened by **solid solution** (C, N) and by **precipitation** (Nb, V). Mn to increase N solubility

Steelmaking: first refining (AOD, VOD) + remelting (VAR, **ESR**).

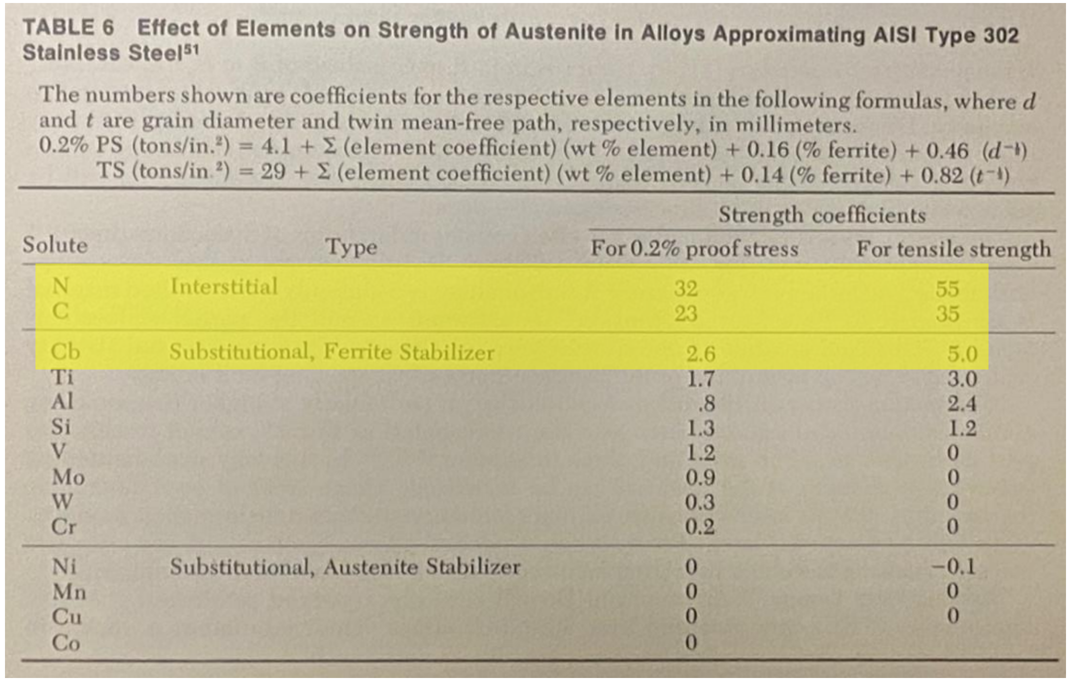


TABLE 6 Effect of Elements on Strength of Austenite in Alloys Approximating AISI Type 302 Stainless Steel[51]

The numbers shown are coefficients for the respective elements in the following formulas, where d and t are grain diameter and twin mean-free path, respectively, in millimeters.

$$0.2\%\ \text{PS}\ (\text{tons/in.}^2) = 4.1 + \Sigma\,(\text{element coefficient})\,(\text{wt \% element}) + 0.16\,(\%\ \text{ferrite}) + 0.46\ (d^{-\frac{1}{2}})$$

$$\text{TS}\ (\text{tons/in.}^2) = 29 + \Sigma\,(\text{element coefficient})\,(\text{wt \% element}) + 0.14\,(\%\ \text{ferrite}) + 0.82\ (t^{-\frac{1}{2}})$$

Solute	Type	Strength coefficients For 0.2% proof stress	For tensile strength
N	Interstitial	32	55
C		23	35
Cb	Substitutional, Ferrite Stabilizer	2.6	5.0
Ti		1.7	3.0
Al		.8	2.4
Si		1.3	1.2
V		1.2	0
Mo		0.9	0
W		0.3	0
Cr		0.2	0
Ni	Substitutional, Austenite Stabilizer	0	−0.1
Mn		0	0
Cu		0	0
Co		0	

From Peckner & Bernstein: handbook of stainless steel

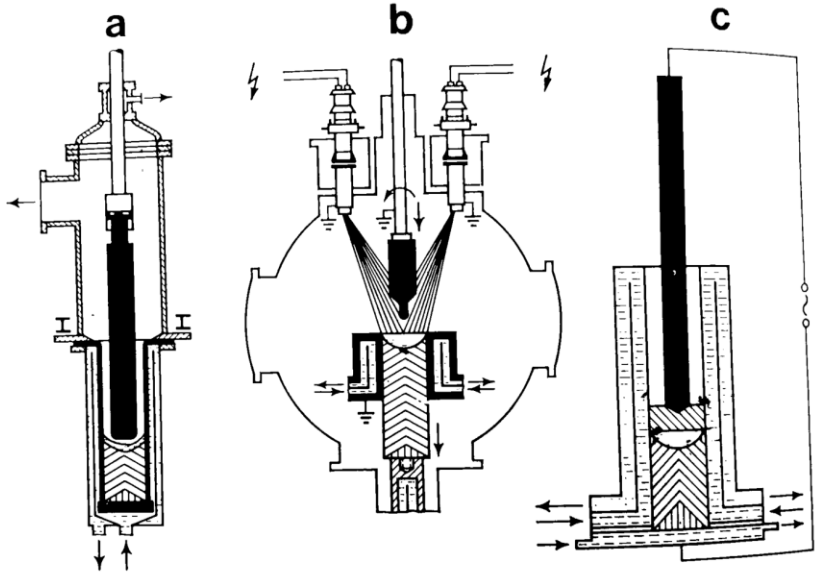
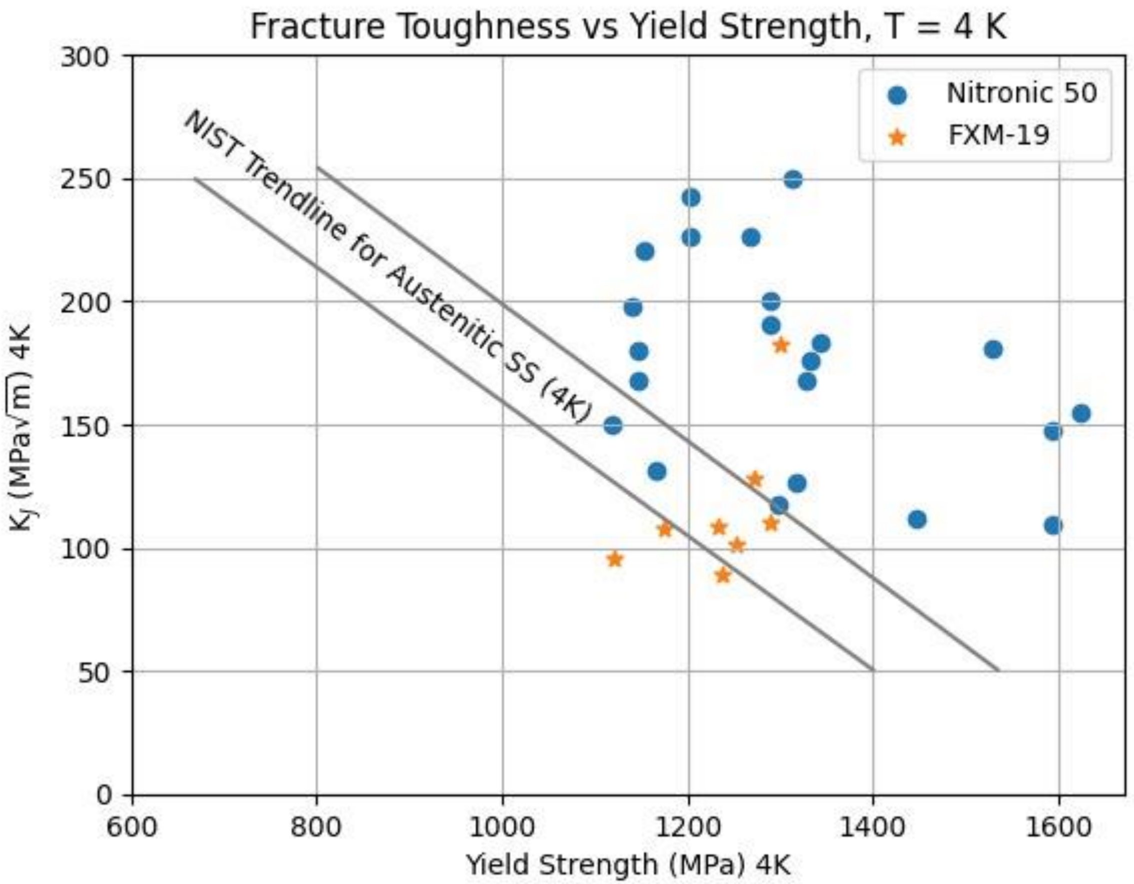


Fig. 38 Schematic diagram of various remelting processes. (a) Vacuum arc remelting. (b) Electron-beam remelting. (c) Electroslag remelting

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

FXM-19: mechanical properties



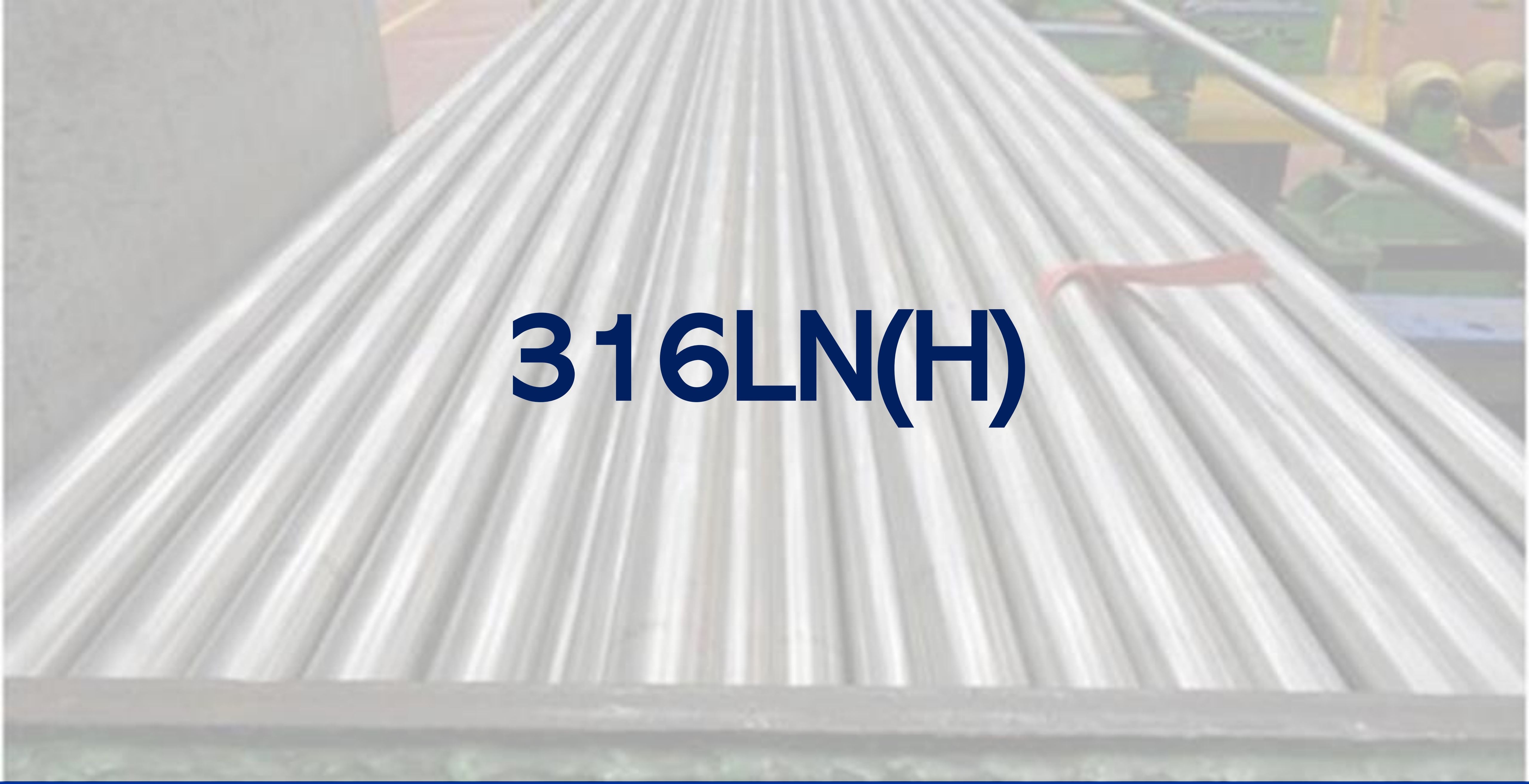
Latest results (FXM-19) show unstable crack propagation (see poster of E. Rodriguez Castro) for more details.

- Combination of solid solution strengthening + precipitation hardening makes:
    - Very high yield strength.
    - Large spread of mechanical properties (more evident for large pieces).

Weldability

	Specimen location	Specimen orientation	K_{IC} [MPa√m]	J_{IC} [N/mm]
Single piece forged	Head (top)	LT	170	130
	Head (bottom)	LT	190	161
		LS	197	172
	Tail (slab)	LT	188	157
		LT	226	239
Welded solution	weld	weld direction	112	62

From B. Walsh et al: Welded Tie Plate Feasibility Study for ITER Central Solenoid Structure (2014). Unpublished



316LN(H)

316LN(H)

Strengthened by **solid solution** (C, N) → N content at the upper bound of 316LN

Steelmaking: first refining (AOD, VOD) + remelting (**ESR**).

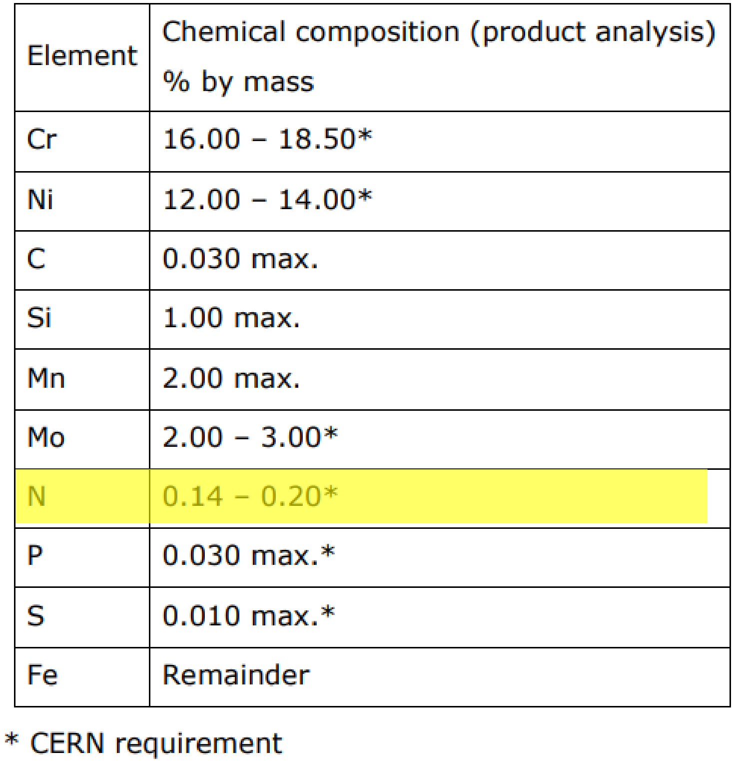
Example of composition of 316LN(H)
From material certificate

Element	**Wt.%**
C	0.02
Si	0.22
Mn	1.69
P	0.026
S	0.002
Ni	12.64
Cr	18.01
Mo	2.13
N	0.2016

Composition limits 1.4429
acc. to EN 10028-7

CRITERIA	VALUE	UNIT
C	≤ 0.03	%
Cr	16.5 – 18.5	%
Mn	≤ 2.00	%
Mo	2.50 – 3.00	%
N	0.12 – 0.22	%
Ni	11.0 – 14.0	%
P	≤ 0.045	%
S	≤ 0.015	%
Si	≤ 1.00	%

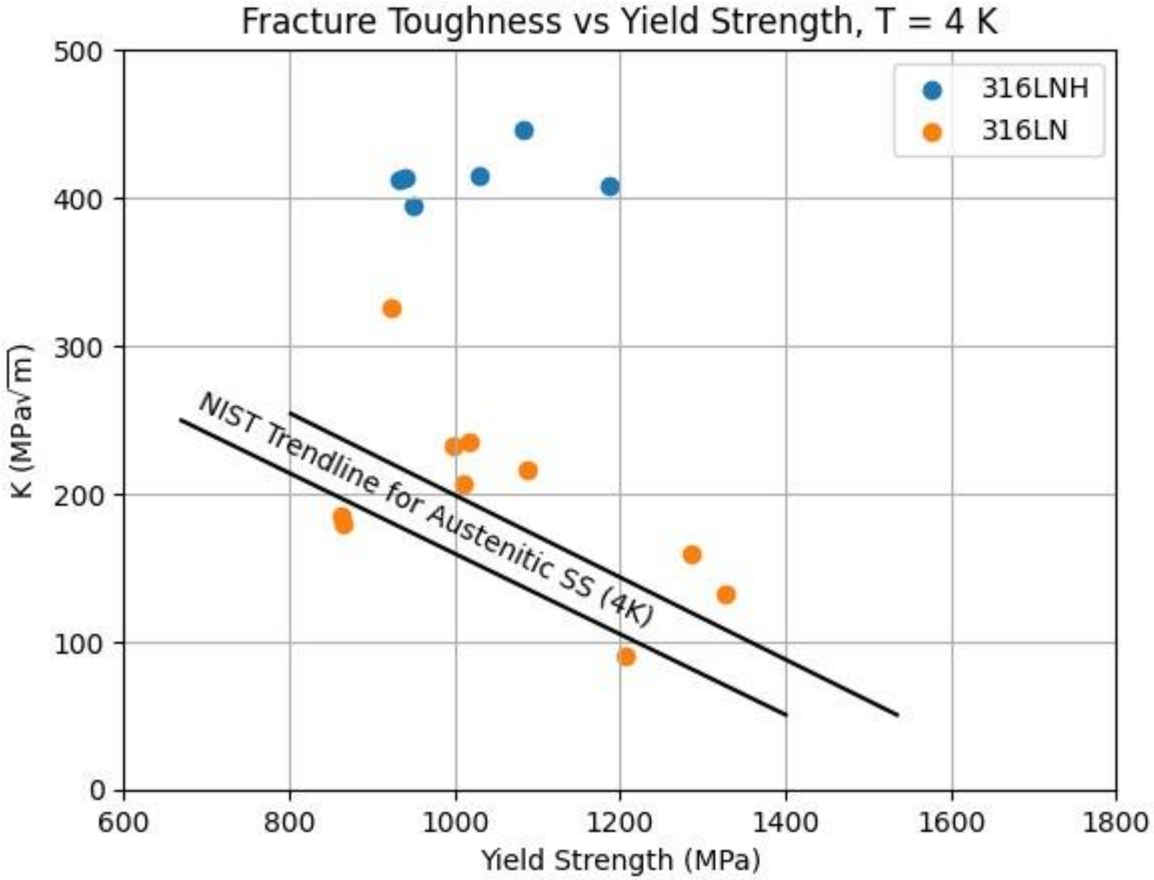
CERN tech. spec 316LN bars



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

316LN: mechanical properties



- Solid solution strengthening and high Ni content makes:
  - Moderately high yield strength.
  - Extremely high fracture toughness
- Stable crack tearing

Weldability

Technique	Filler	K_{IC}[MPa√m]
TIG	1.4453	262
TIG	1.4455	251
FSW	n.a	300

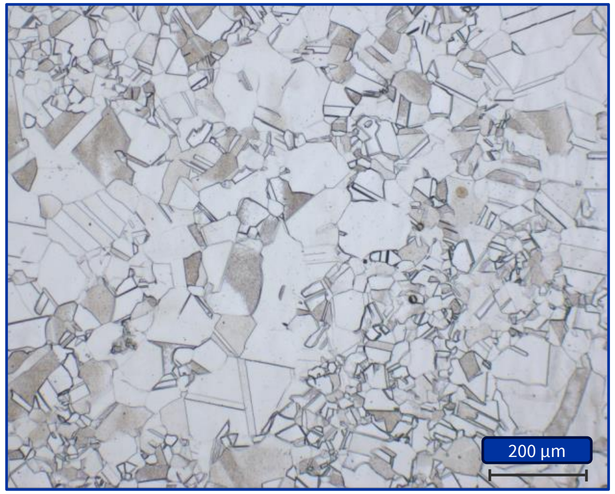
From I. Aviles Santillana: Assessment of production, materials and welds applicable at cryogenic temperatures to different components of ITER magnets, PD thesis (2018) and I. Avilés Santillana et al. Friction stir welding of AISI 316LN high strength austenitic stainless steel for cryogenic application. En IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2022. p. 012003.

P506

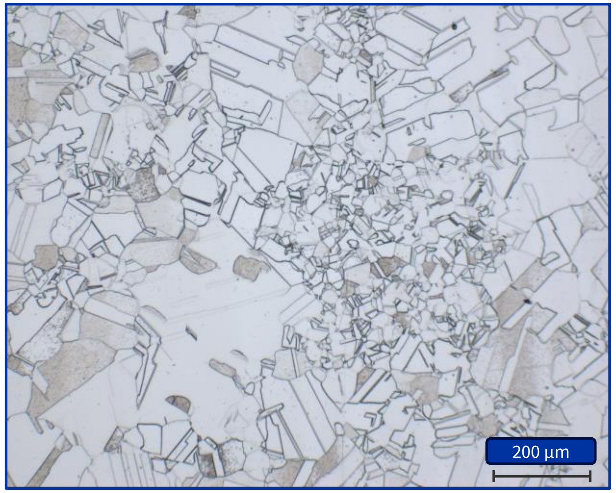
P506

Strengthened by **solid solution** (C, N). Mn increases N solubility

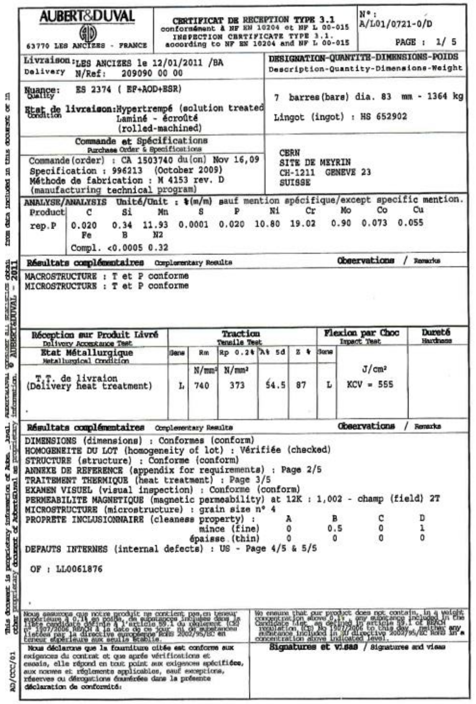
Steelmaking: first refining (AOD, VOD) + remelting (**ESR**).



Central-Longitudinal (1) zoom x100



External-Circumferential (4) zoom x100



AUBERT&DUVAL
63770 LES ANCIZES - FRANCE

CERTIFICAT DE RECEPTION TYPE 3.1
conformément à NF EN 10204 et NF L 00-015
INSPECTION CERTIFICATE TYPE 3.1.
according to NF EN 10204 and NF L 00-015

N° : A/L01/0721-0/D
PAGE : 1/ 5

Livraison: LES ANCIZES le 12/01/2011 /BA
Delivery N/Ref: 209090 00 00

DESIGNATION-QUANTITE-DIMENSIONS-POIDS
Description-Quantity-Dimensions-Weight

Nuance: ES 2374 (EF+AOD+ESR)
Quality

7 barres(bars) dia. 83 mm - 1364 kg

Etat de livraison: Hypertrempé (solution treated
Condition
Laminé - écroûté
(rolled-machined)

Lingot (ingot) : HS 652902

Commande et Spécifications
Purchase Order & Specifications

Commande(order) : CA 1503740 du(on) Nov 16,09
Specification : 996213 (October 2009)
Méthode de fabrication : M 4153 rev. D
(manufacturing technical program)

CERN
SITE DE MEYRIN
CH-1211 GENEVE 23
SUISSE

ANALYSE/ANALYSIS Unité/Unit : %(m/m) sauf mention spécifique/except specific mention.

Product	C	Si	Mn	S	P	Ni	Cr	Mo	Co	Cu
rep.P	0.020	0.34	11.93	0.0001	0.020	10.80	19.02	0.90	0.073	0.055
	Fe	B	N2							
	Compl.	<0.0005	0.32							

Résultats complémentaires Complementary Results — Observations / Remarks

MACROSTRUCTURE : T et P conforme
MICROSTRUCTURE : T et P conforme

Réception sur Produit Livré Delivery Acceptance Test	Traction Tensile Test					Flexion par Choc Impact Test		Dureté Hardness
Etat Métallurgique Metallurgical Condition	Sens	Rm	Rp 0.2%	A% 5d	Z %	Sens		
		N/mm²	N/mm²				J/cm²	
T.T. de livraion (Delivery heat treatment)	L	740	373	54.5	87	L	KCV = 555	

Résultats complémentaires Complementary Results — Observations / Remarks

DIMENSIONS (dimensions) : Conformes (conform)
HOMOGENEITE DU LOT (homogeneity of lot) : Vérifiée (checked)
STRUCTURE (structure) : Conforme (conform)
ANNEXE DE REFERENCE (appendix for requirements) : Page 2/5
TRAITEMENT THERMIQUE (heat treatment) : Page 3/5
EXAMEN VISUEL (visual inspection) : Conforme (conform)
PERMEABILITE MAGNETIQUE (magnetic permeability) at 12K : 1,002 - champ (field) 2T
MICROSTRUCTURE (microstructure) : grain size n° 4

PROPRETE INCLUSIONNAIRE (cleaness property) :	A	B	C	D
mince (fine)	0	0.5	0	1
épaisse (thin)	0	0	0	0

DEFAUTS INTERNES (internal defects) : US - Page 4/5 & 5/5

OF : LL0061876

Nous déclarons que la fourniture citée est conforme aux exigences du contrat et que après vérifications et essais, elle répond en tout point aux exigences spécifiées, aux normes et réglements applicables, sauf exceptions, réserves ou dérogations énumérées dans la présente déclaration de conformité.

Signatures et visas / Signatures and visas

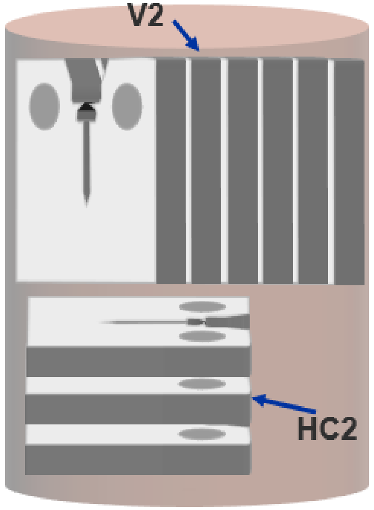
AD/CCC/01

The available semifinished product exhibits a dual microstructure.

Element	Fe	Cr	Ni	Mn	N	C	Si	S	P	Mo	Co	Cu	B
%wt	56.52	19.02	10.80	11.93	0.32	0.020	0.34	0.0001	0.020	.90	0.073	0.055	<0.0005

P506: mechanical properties

- Solid solution strengthening with very high N content makes:
  - Very high yield strength.
  - Unstable crack propagation?
- Other changes in composition:
  - Lower Ni content than 316LN → lower FT?
  - High Mn → lower FT? Unstable crack propagation?



	Rm (MPa)	A% after break	$Rp_{0.2}$ (MPa)
Specimen2_4K	1841.0	21.5	1379.2
Specimen6_4K	1860.0	22.2	1388.9
Average	**1850.5**	**21.9**	**1384.1**
S.DEV	13.4	0.5	6.9

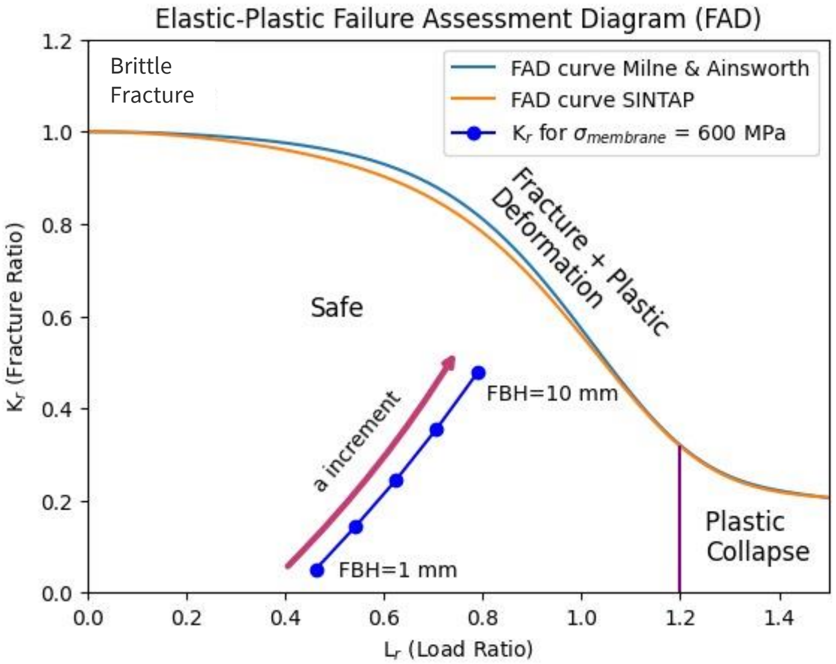
Specimen	K_{Ju} [MPa√m]
HC2 (C-R)	249
V2 (R-L)	127

- Results of tensile tests and FT @ 4 K of a non – optimized product show a promising combination of properties → considering the C-R direction for FT, we are indeed inside the JAERI box

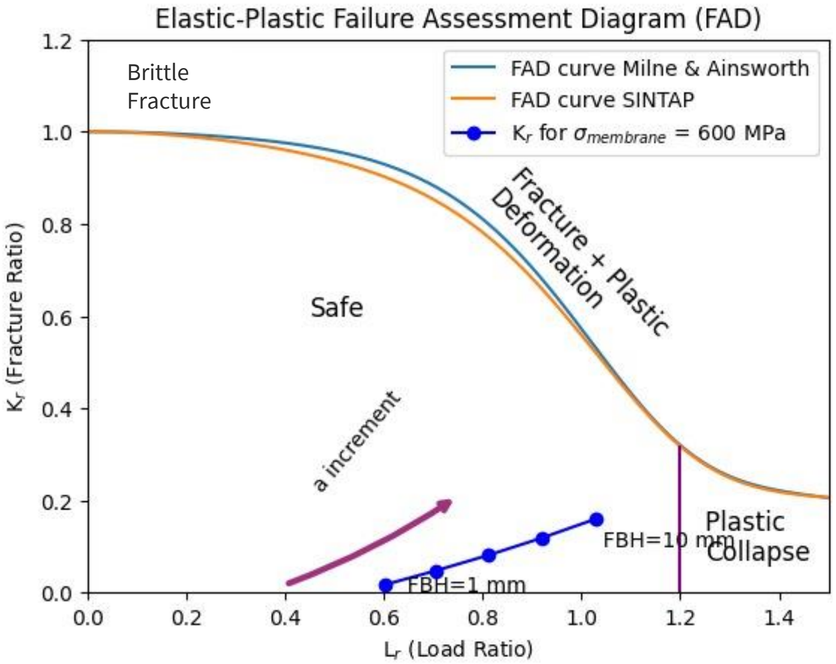
Comparison

- For a fair comparison of the cryogenic mechanical properties of the three grades, let’s use Failure analysis diagrams (FAD):

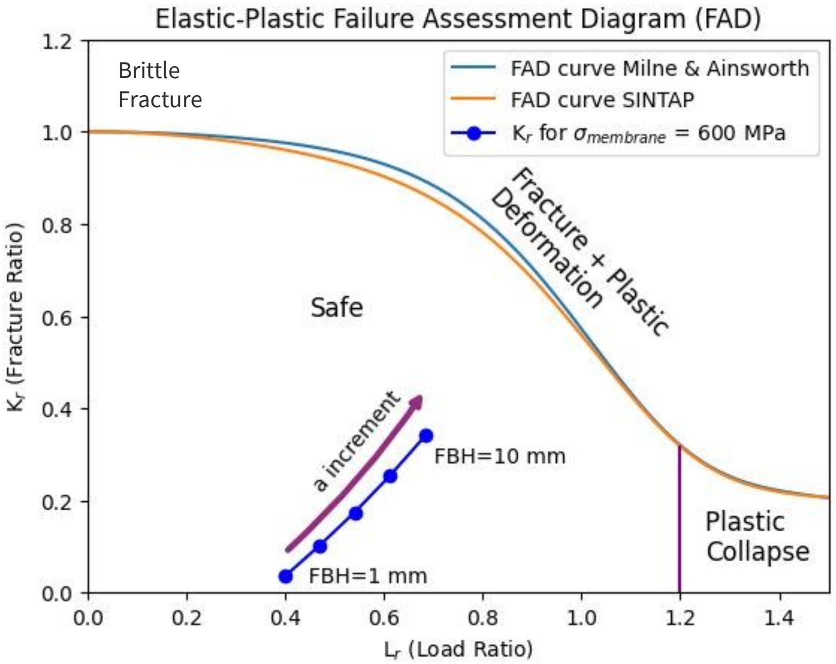
FXM-19



316LN(H)



P506



- 316LNH is too close to the plastic collapse (not recommended when very high stresses are foreseen.
- P506 (considering C-R direction) seems to be the most balanced combination of properties.

Conclusions

- FXM-19 has a great combination of mechanical properties at cryogenic temperature. However, studies in the direction of obtaining homogeneous and reproducible properties for very large components and thick walls should be conducted.
  - Its weldability is still a challenge (at least by fusion welding)
- 316LN(H) exhibits a remarkable fracture toughness at 4 K but lacks a bit of yield strength for very high stress applications. As a very known product, this high N version seems to be very well optimized.
  - Its weldability has been proven with different techniques and filler materials
- P506 seems to be a promising material for cryogenic structural applications. A first step would be to obtain an optimized product with a homogeneous microstructure to confirm it.
  - Its (laser) weldability has been proven, but the cryogenic mechanical properties of the welds have never been measured.
- It would be interesting to understand the origin of the unstable crack propagation.
- Alloying elements, can combine in undesired ways forming **brittle secondary phases** and **segregate** to preferential positions, thus it is crucial to understand and master the thermomechanical history of the parts.
- The **current challenge** is to have a **homogeneous, segregation free, fully austenitic microstructure** for very **large components** with thick walls.

CERN

ENGINEERING
DEPARTMENT

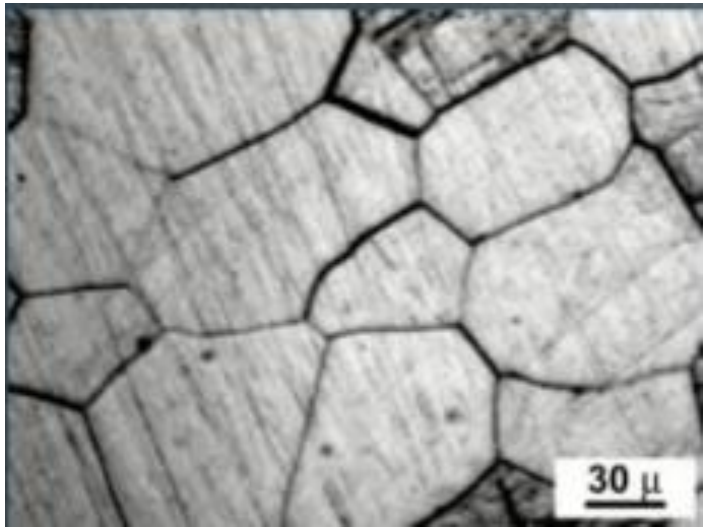
THANK YOU

QUESTIONS?

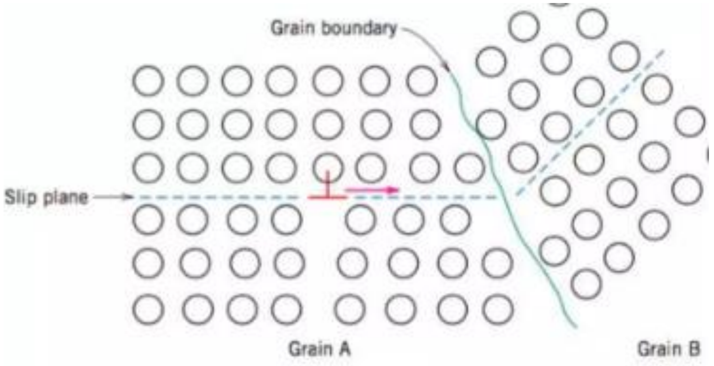
Strengthening mechanisms of austenitic stainless steel

- The capacity of a material to plastically deform depends on the ability of dislocations to move → strengthening mechanisms target the **restriction of dislocations' movement**.

Grain refinement



GBs act as a barrier to dislocation movement → the smaller the grains, more GBs → more strength.



Hall – Petch equation:

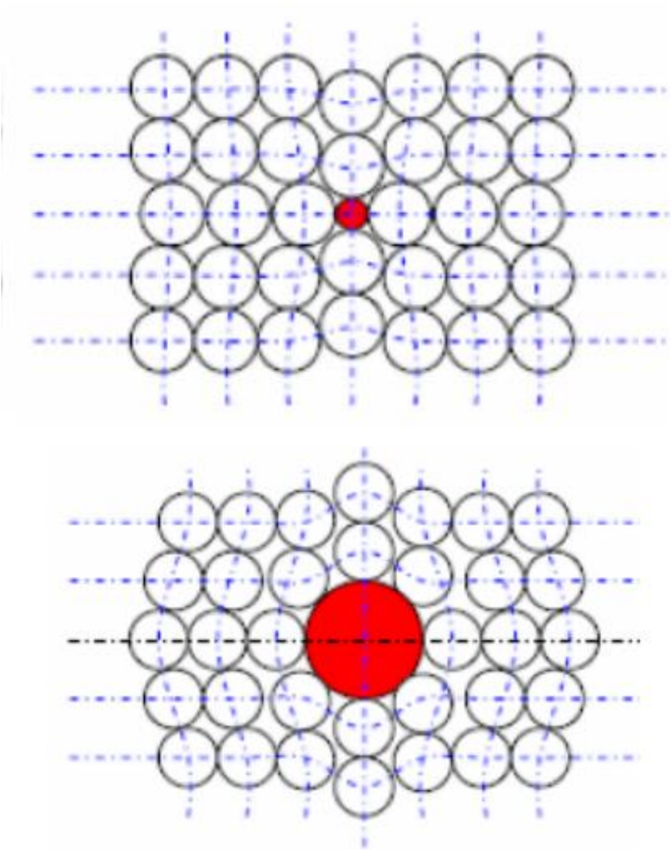
$$\sigma_y = \sigma_i + \frac{k}{\sqrt{D}}$$

Strengthening mechanisms of austenitic stainless steel

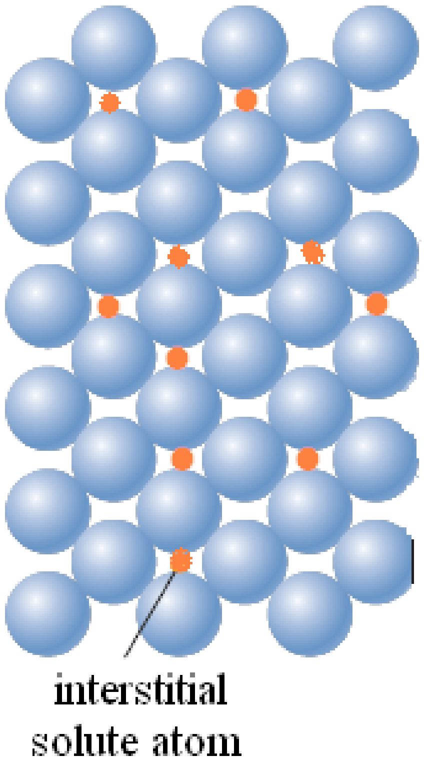
- Solute atoms produces **lattice strain**, either tensile or compressive, depending on the relative size of the solute atom (substitutional SS). They produce **local shear** that **opposes dislocation motion**.
- Smaller atoms fill empty spaces, hindering the movement of dislocations (interstitial SS).

Solid solution

Substitutional



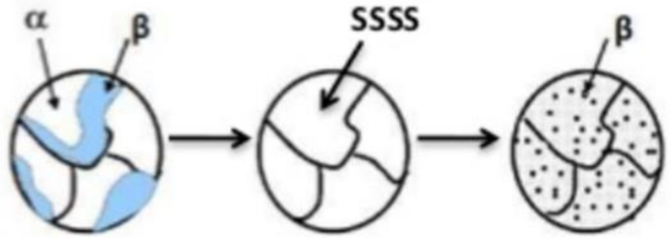
Substitutional



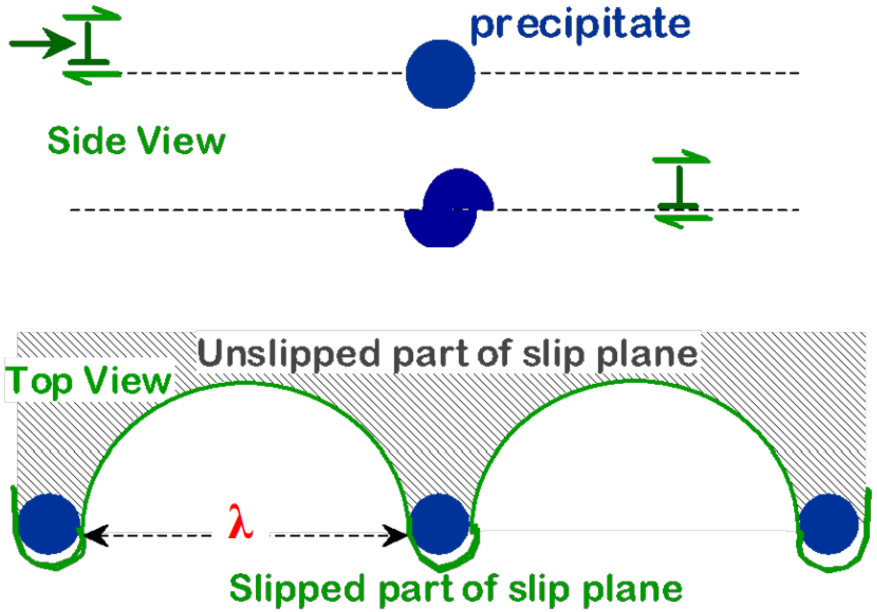
Strengthening mechanisms of austenitic stainless steel

- Requires a second phase, more soluble at high temperature than at low temperature. Three step process:

1. Dissolution of soluble phases at high temperature
2. Quenching: development of supersaturation
3. Age hardening: precipitation of finely dispersed precipitates



Precipitation & dispersion



Second phase particles impede the motion of dislocations by obliging them to surround precipitates or by obliging them to shear the precipitates.

METALLURGICAL ASPECTS

- A general increase of alloying elements protects against martensitic transformation (all coefficients are negative).

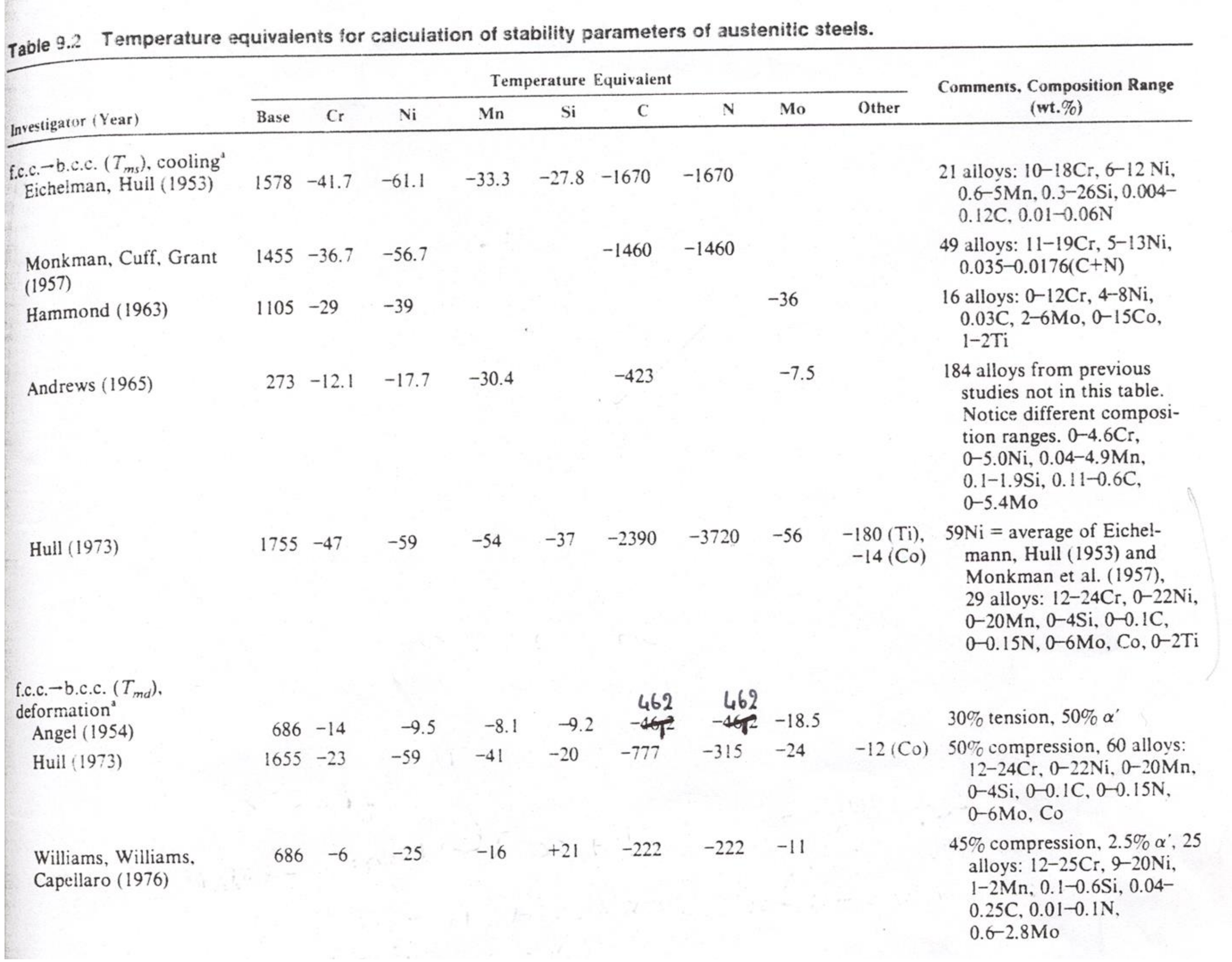


Table 9.2 Temperature equivalents for calculation of stability parameters of austenitic steels.

Investigator (Year)	Temperature Equivalent									Comments, Composition Range (wt.%)
	Base	Cr	Ni	Mn	Si	C	N	Mo	Other	
f.c.c.→b.c.c. (T_{ms}), cooling[a]										
Eichelman, Hull (1953)	1578	−41.7	−61.1	−33.3	−27.8	−1670	−1670			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[a]										
Angel (1954)	686	−14	−9.5	−8.1	−9.2	462 ~~−462~~	462 ~~−462~~	−18.5		30% tension, 50% α'
Hull (1973)	1655	−23	−59	−41	−20	−777	−315	−24	−12 (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

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

The work of Ul’yanin et al. (1969) suggests that **<u>Ni in particular improves ductility and toughness at cryogenic temperature</u>**, an effect that cannot be entirely ascribed to the stabilization of austenite.