Nanostructured Steel Industrialization: a plausible reality

C. Garcia-Mateo, T. Sourmail, F.G. Caballero, V. Smanio, C. Ziegler, M. Kuntz, R. Elvira, A. Lerio, E. Vuorinen, T. Teeri

cgm@cenim.csic.es

CSIC

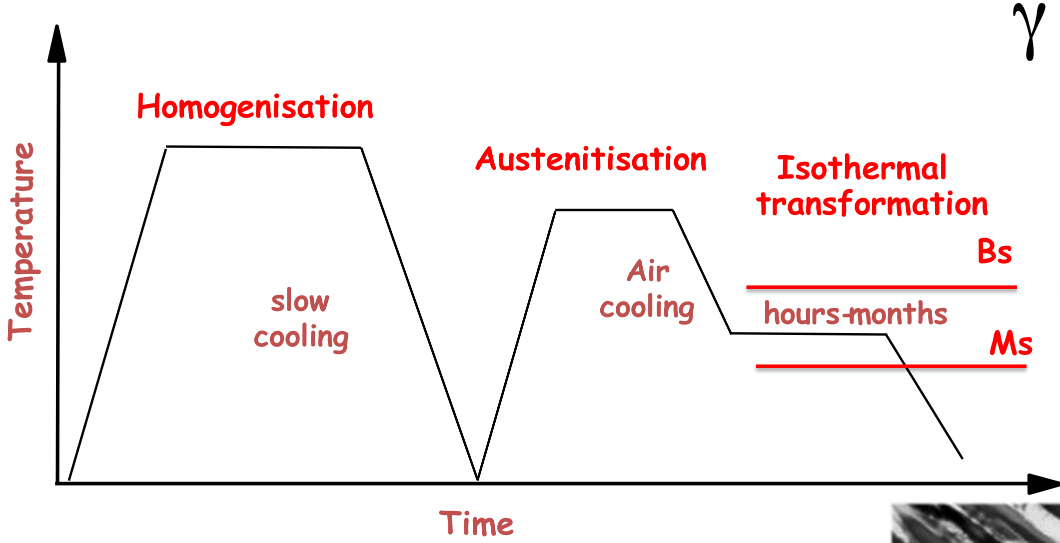
CENTRO NACIONAL DE INVESTIGACIONES METALÚRGICAS (CENIM)

Acknowledgements:
APM 2013 Conference Chair
European RFCS. RFSR-CT-2008-00022
MINECO MAT2010 - 15330

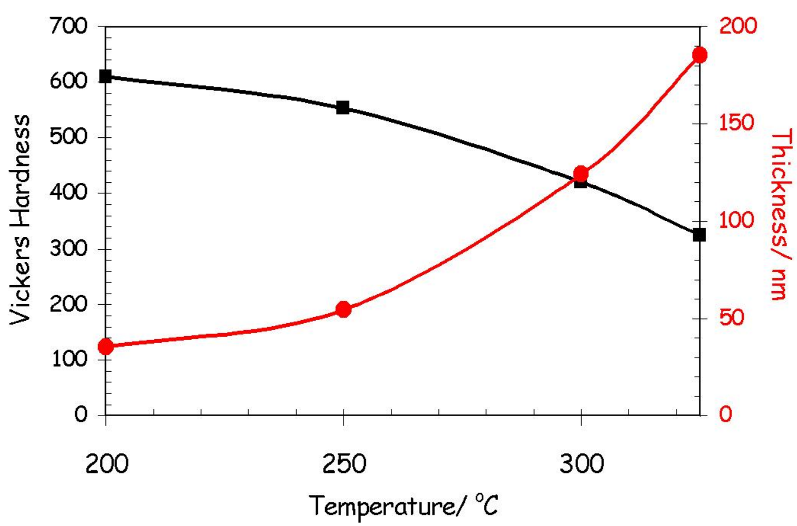
n-9
Nanobain
=
CENIM-CSIC
ASCOMETAL
ALD
BOSCH
GERDAU
LTU
METSO

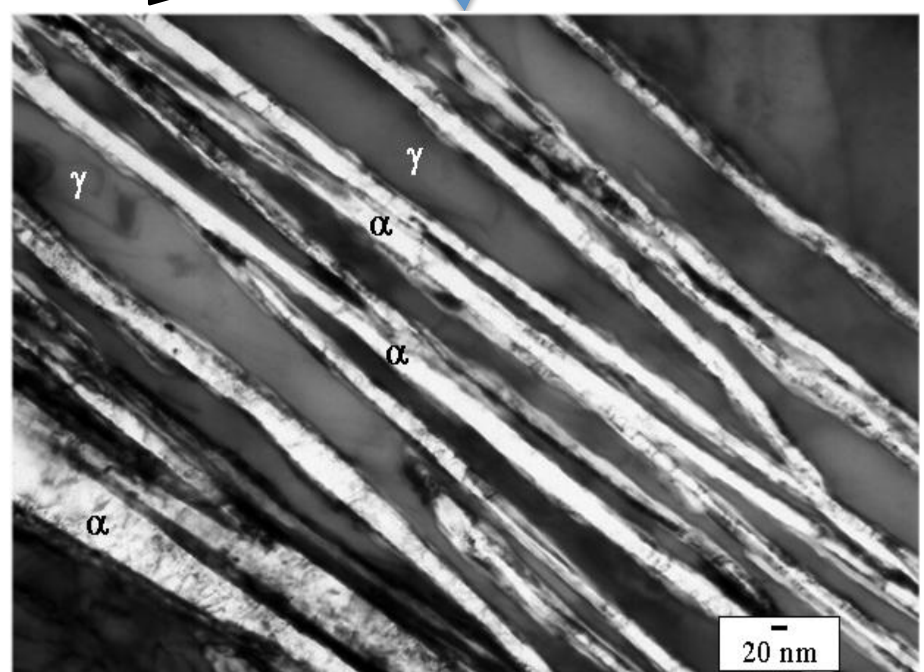
Bhadeshia´s bainite phase transformation theory

$\gamma \rightarrow \alpha_b$



Alloy Design process

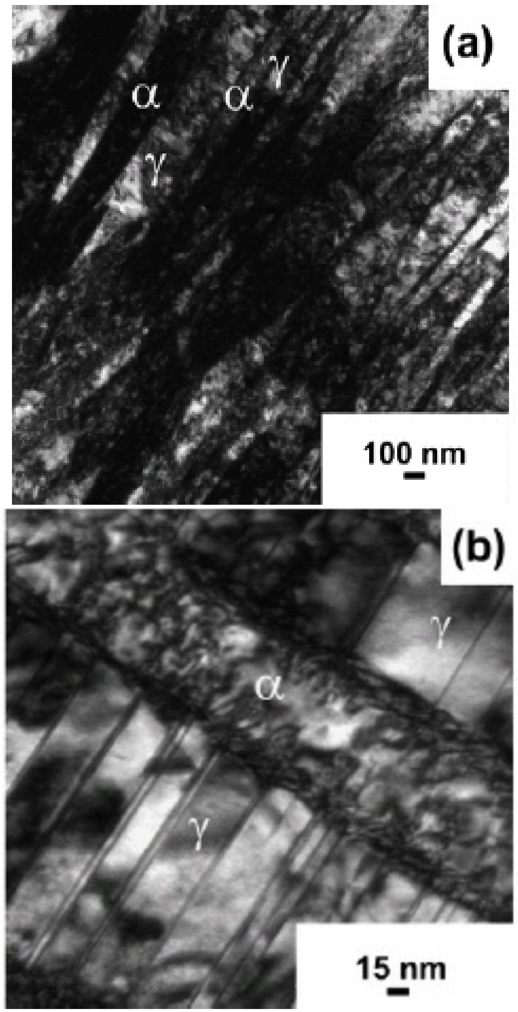


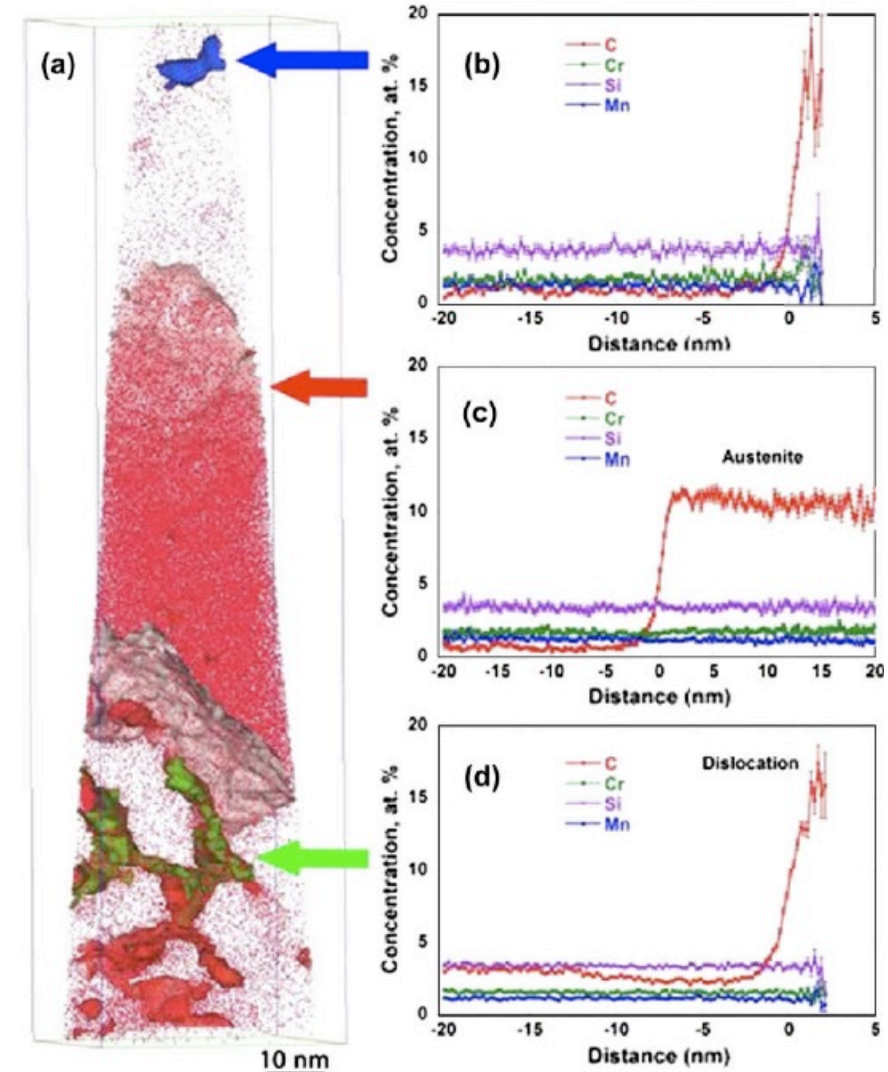


200ºC 10d

High density strong interfaces *nano α+γ*

Displacive *(Dislocations, Nano- twins)* & Diffusionless

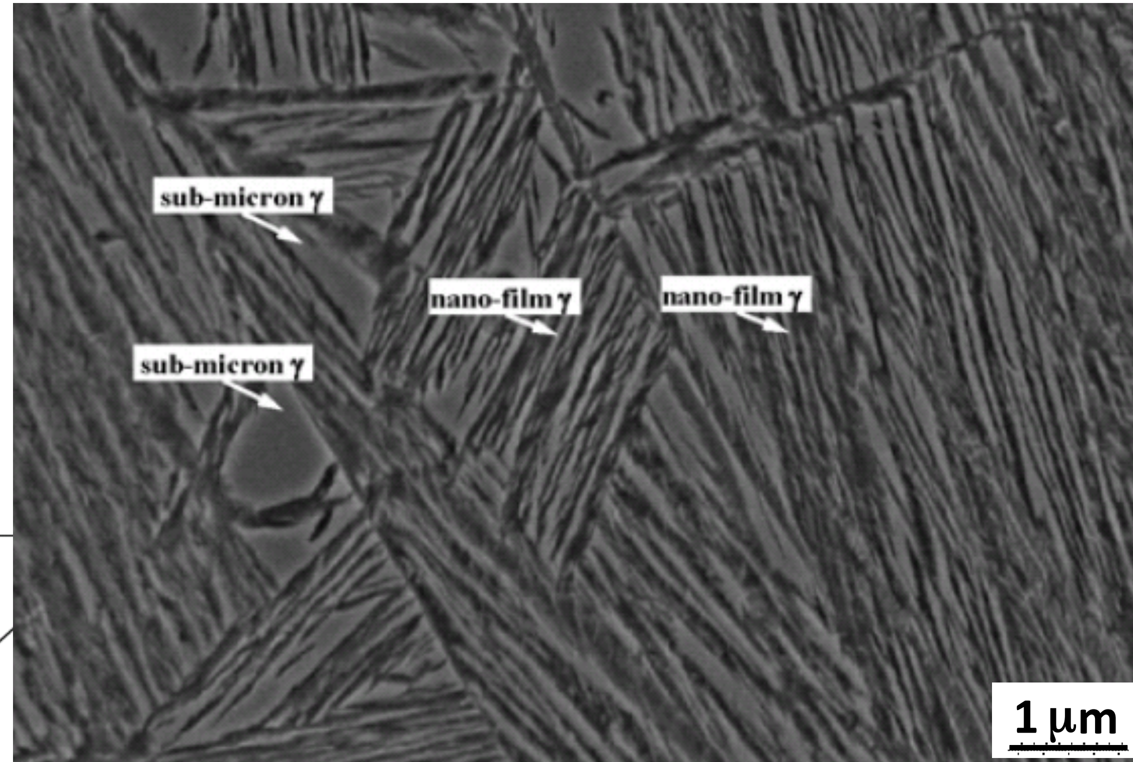


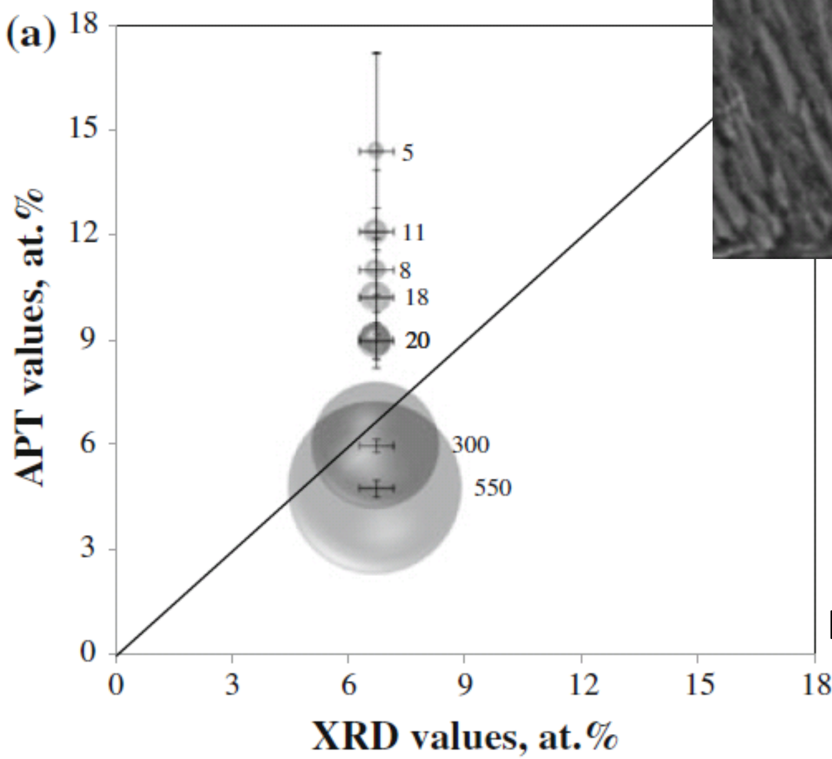


200 ºC for 2 days.

Caballero . Acta 2010 & 2011

Austenite morphologies



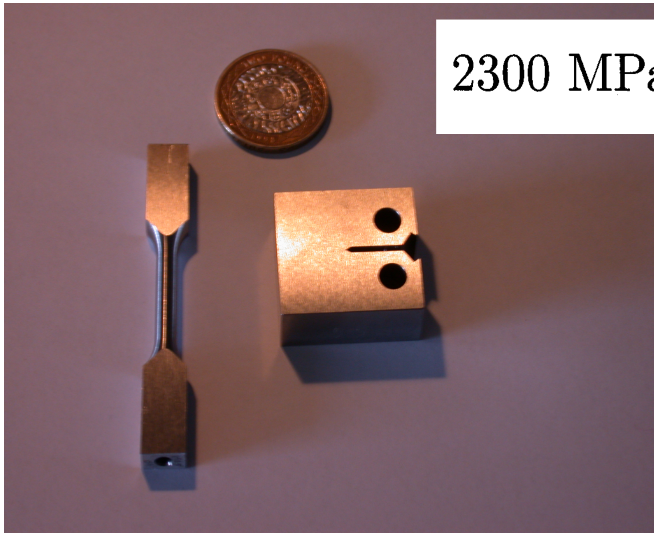


Very different C content

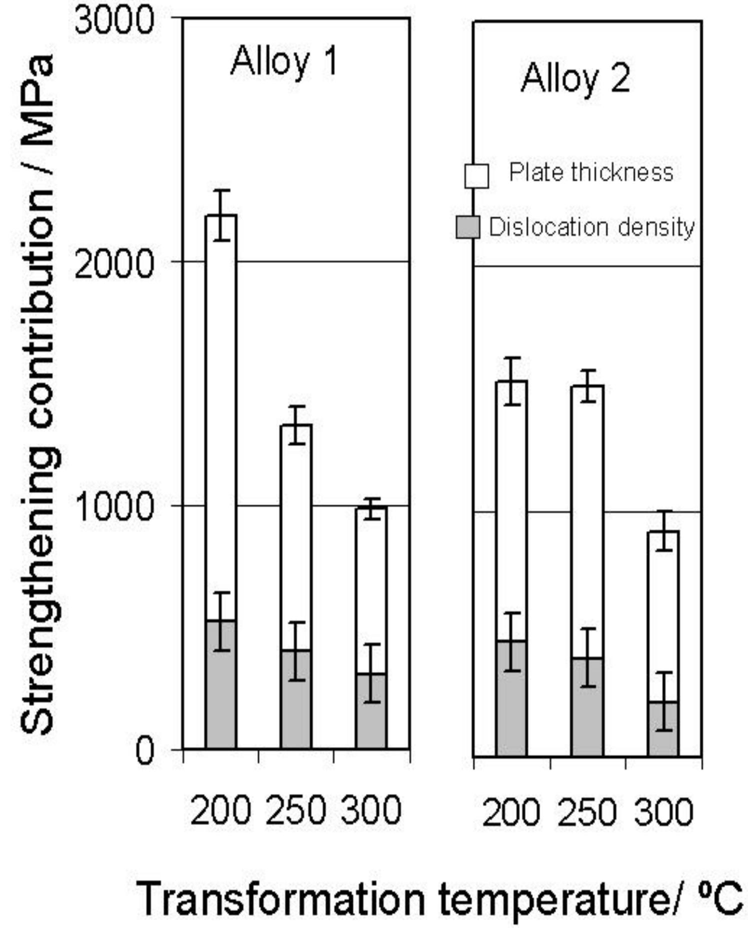
as size ⇩ ➔ ⇧ C ➔ better mechanical response

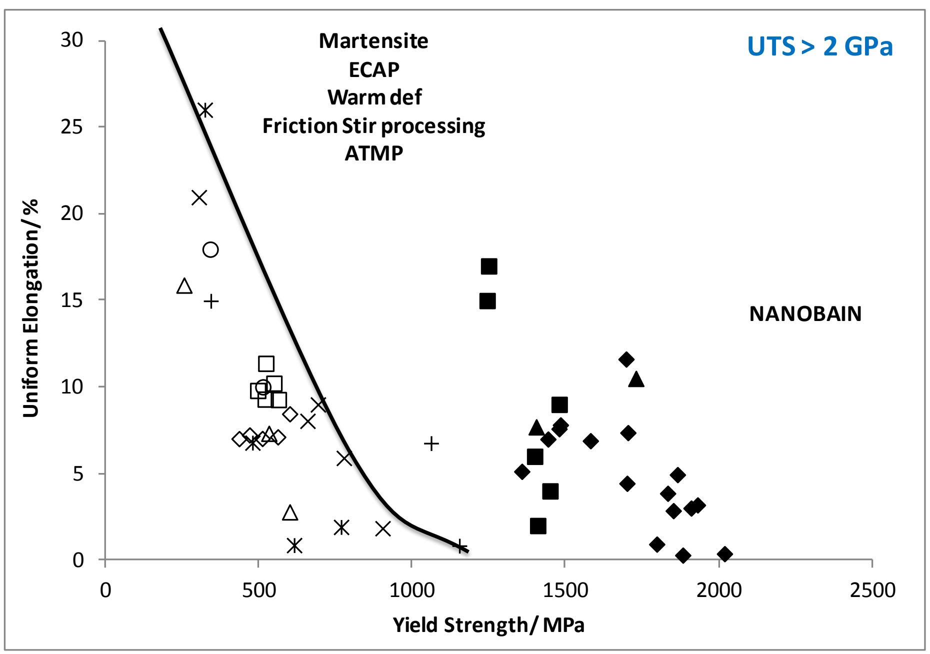
Garcia-Mateo, et.al. *Journal of Materials Science* ***2012***,
Bhadeshia, et al. *Metal Science* **1983**,

$2300\ \text{MPa},\ 27\ \text{MPa}\,\text{m}^{\frac{1}{2}}$



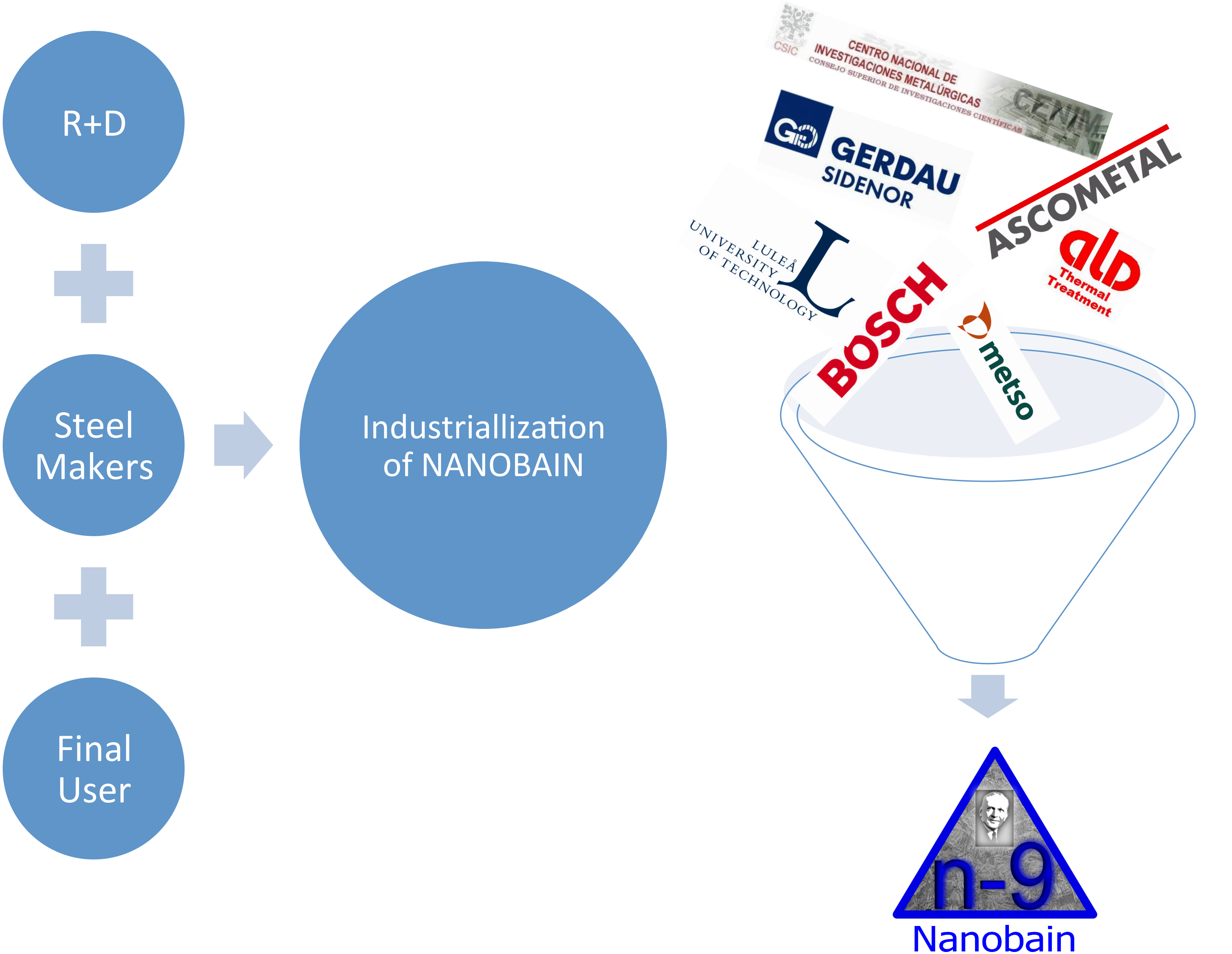
$\Delta\sigma \cong 115(2t)^{-1}$ $\Delta\sigma \cong 7.3410^{-6}(\rho)^{0.5}$





Big potential foreseen

Garcia-Mateo & Caballero, (2005 & 2007)


R+D
Steel Makers
Final User
Industriallization of NANOBAIN
CSIC
CENTRO NACIONAL DE INVESTIGACIONES METALÚRGICAS
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CENIM
GERDAU SIDENOR
LULEÅ UNIVERSITY OF TECHNOLOGY
ASCOMETAL
BOSCH
metso
Thermal Treatment
n-9
Nanobain

Fundamental & Industrial Design Considerations	Approach
Carbide free microstructure	*Addition of 1.5Si wt.%*
Simple alloy system	*Fe-C-Si-Mn-Cr*
Reasonable transformation time	*Reduction of PAGS* $\Delta G^{\gamma \rightarrow \alpha}$
Hardenabillity *700 x400x250 mm^3 ➔ Salt bath* *200x20x30 mm^3 ➔ DryBainTM*	$\ln\left\lvert \frac{\tau(\Delta F_m)^p}{T^z} \right\rvert = \frac{Q'}{RT} + C_4$
High fraction of bainitic ferrite	$V_\alpha = f(To\ line, T)$
Low transformation temperatures	*Bs* $\Delta G_m < G_N$ $\Delta G^{\gamma \rightarrow \alpha} < -G_{SB}$ *Ms* $\Delta G^{\gamma \rightarrow \alpha}\{M_s\} < G_N^{\alpha'}$

NANOBAIN steel

C	Si	Mn	Cr	Mo	Nb
0.99	1.58	0.76	0.45		
1.00	1.53	0.75	0.51		0.02
1.01	1.51	0.82	0.46	0.096	
0.98	2.90	0.77	0.45		
0.88	1.54	0.69	0.50		
0.67	1.6	1.25	1.50		
0.61	1.45	0.76	2.42		
0.64	1.60	1.27	1.5		0.03
0.58	1.63	1.29	1.43	0.1	

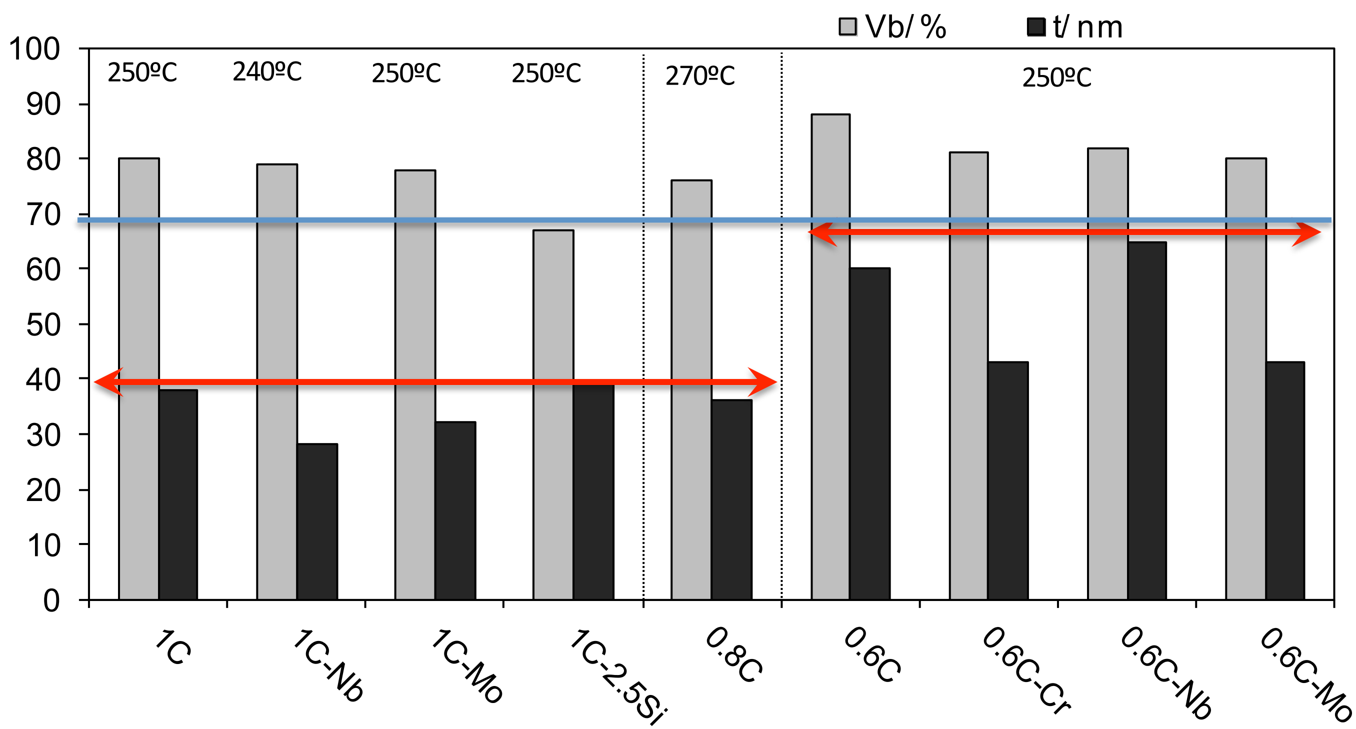
Simple alloy system ✓

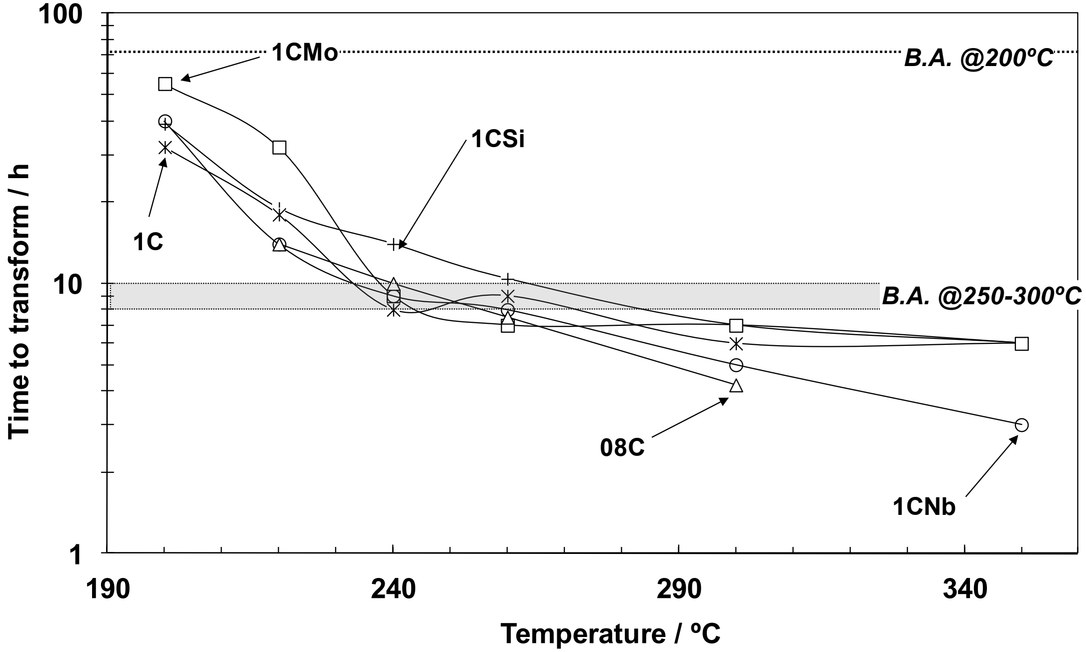
Low transformation temperatures ✓

(220ºC-350ºC)

NANO *(plate thickness t)* ✓

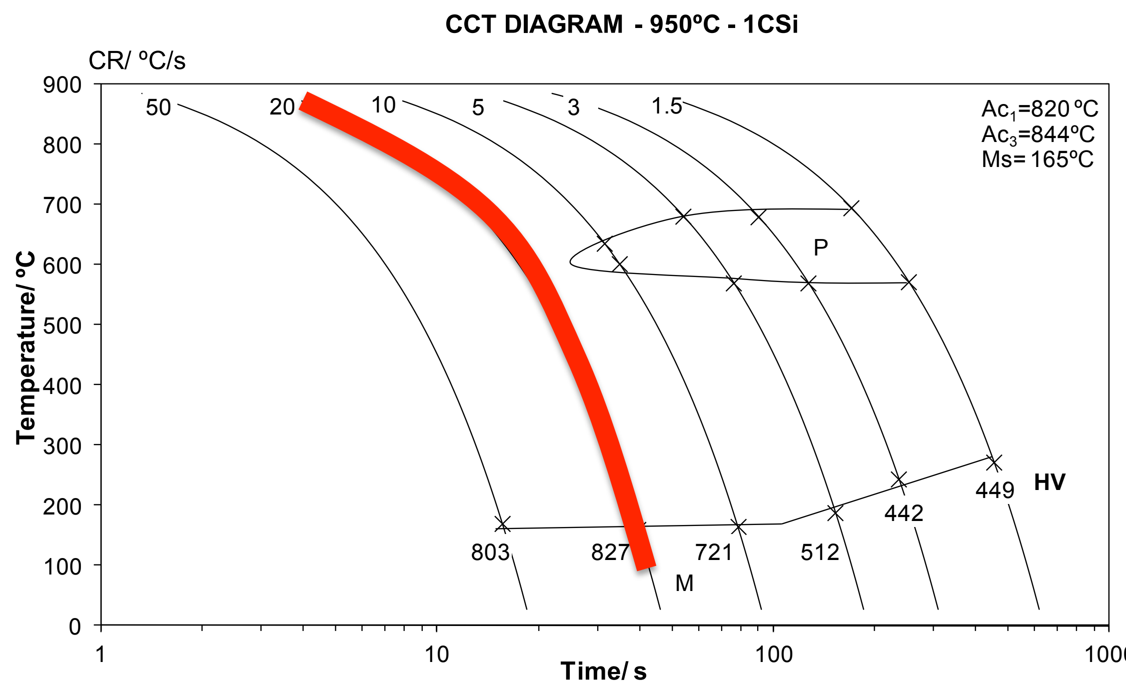
High fraction of bainitic ferrite (Vb) ✓

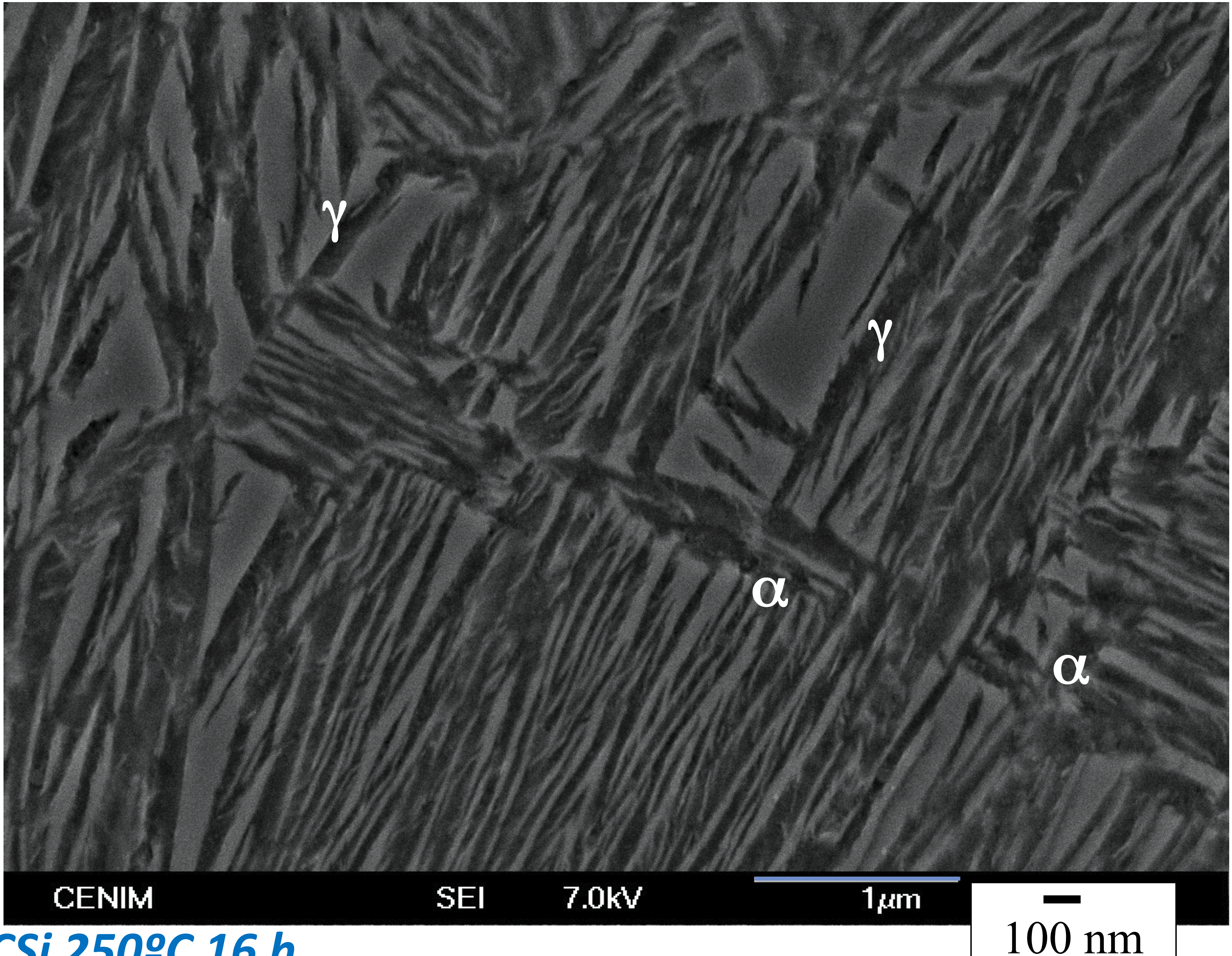




Faster transformation ✓

Suffice hardenability ✓

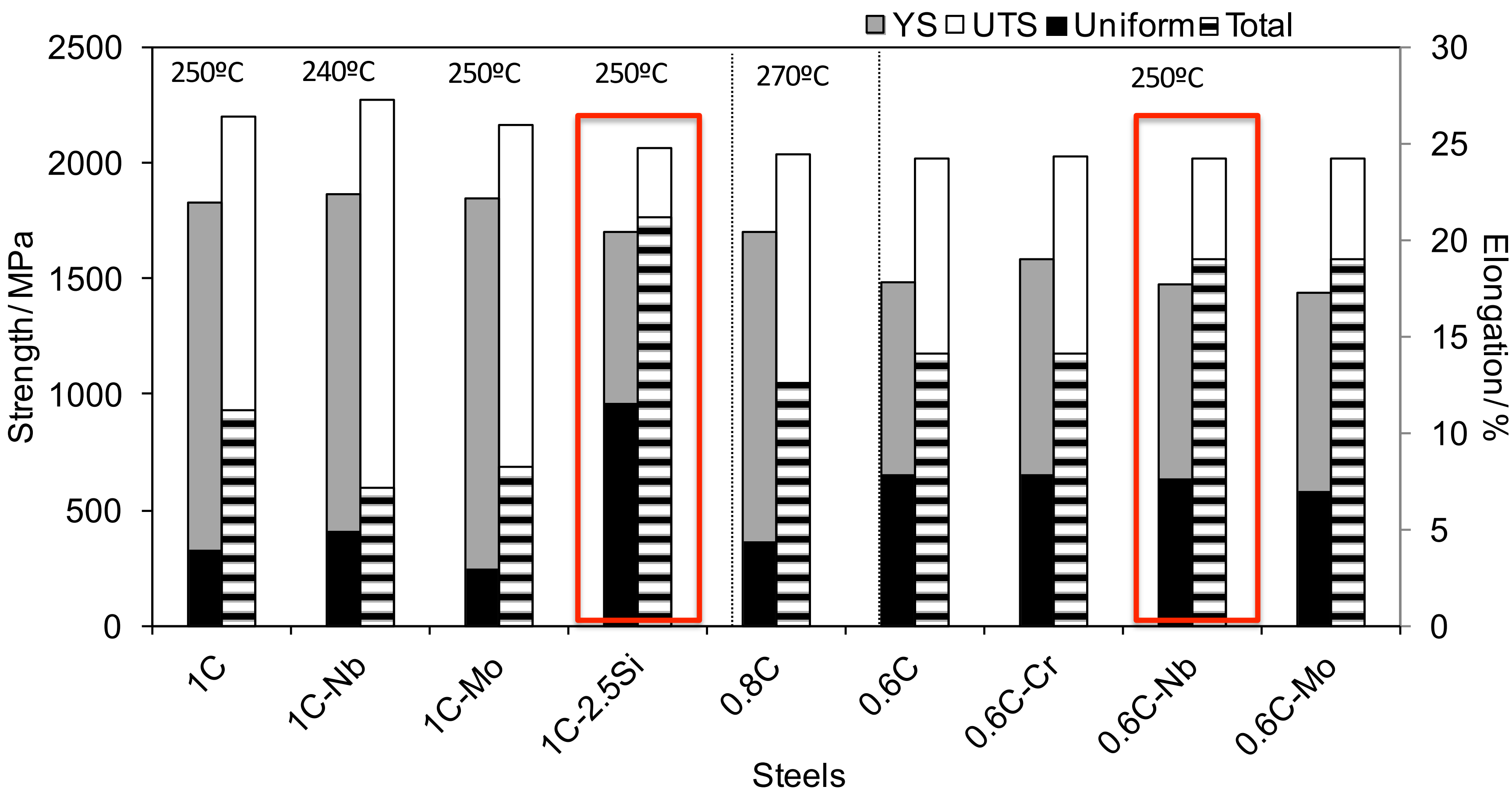




1CSi 250ºC 16 h

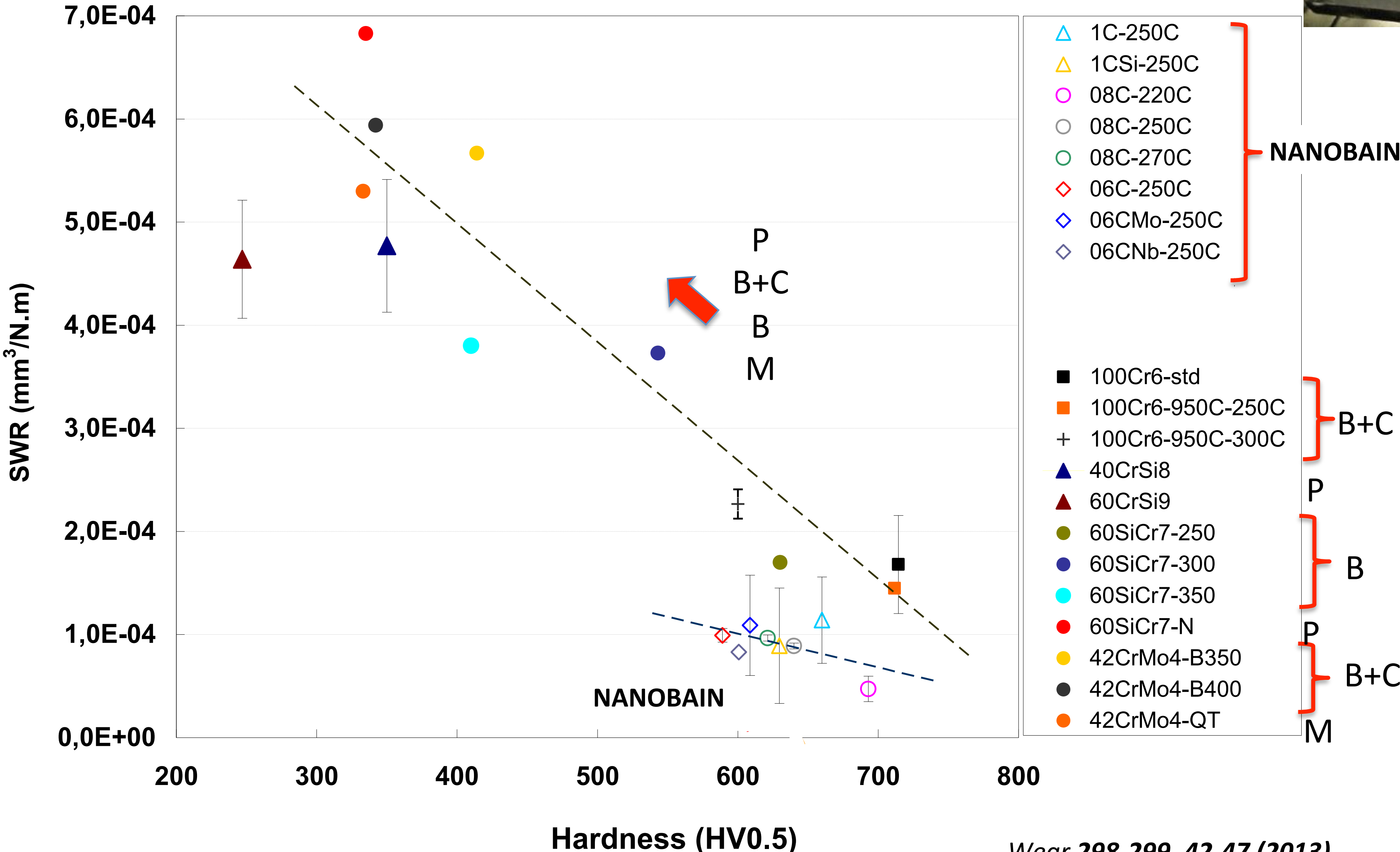
Strength / Ductility (Tensile test)

UTS > 2 GPa



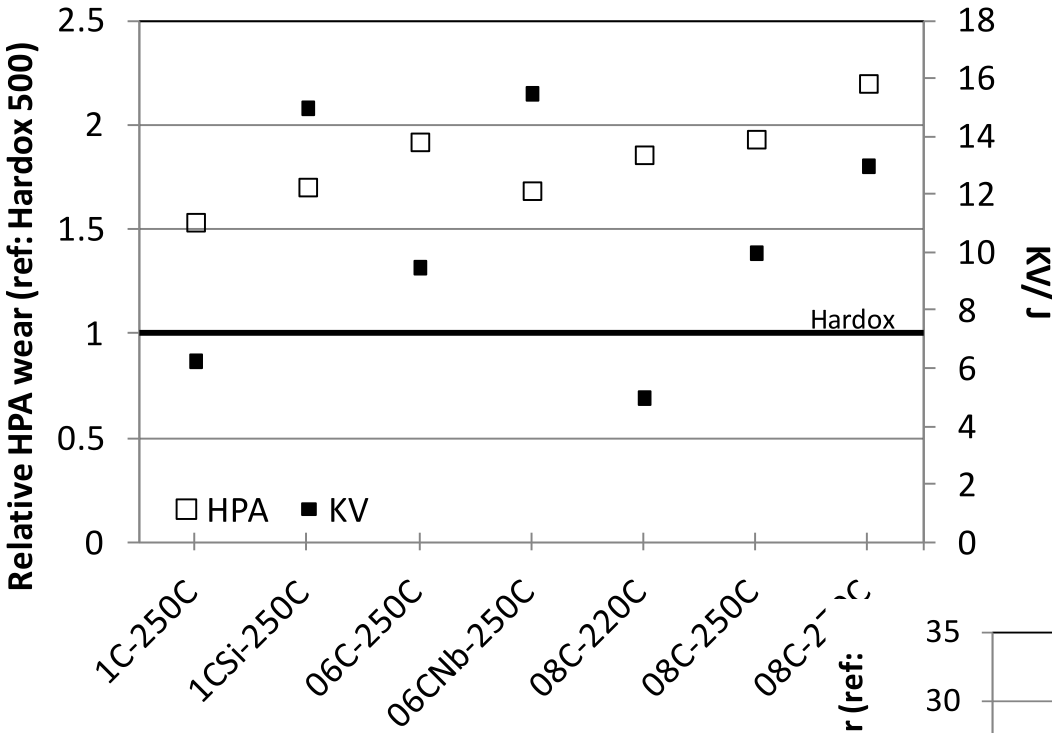
Wear properties : rolling-sliding wear tests

Twin discs wear test, 100 rpm, 5% slip, 300N load, 5h

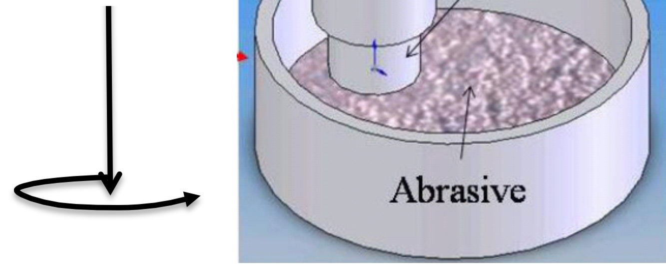


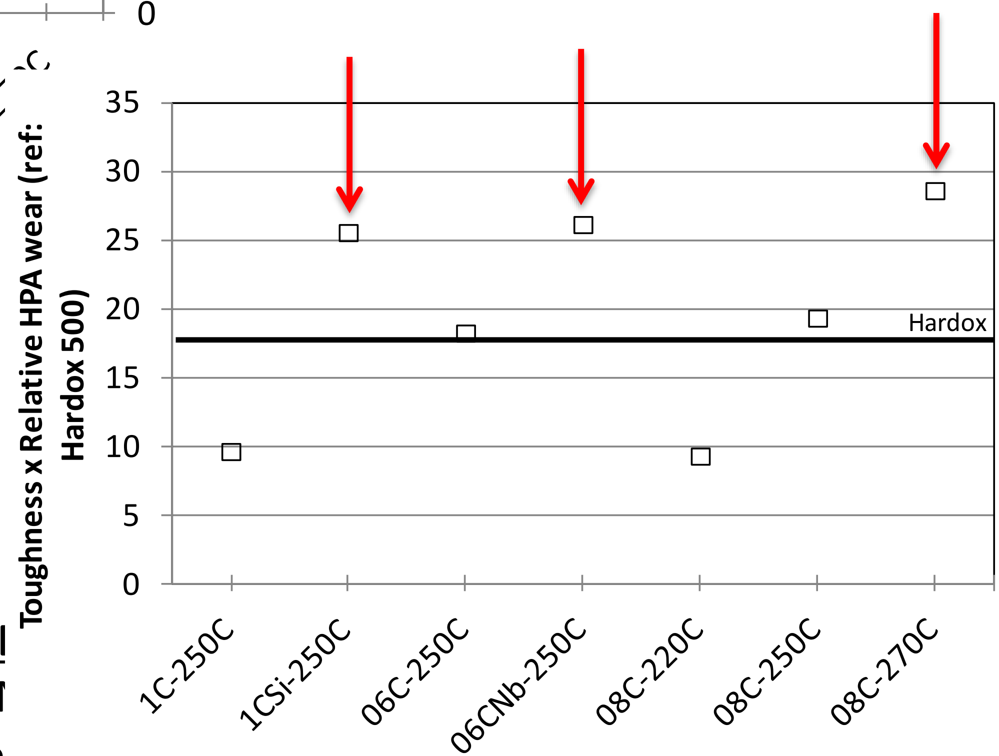
Wear ***298-299, 42-47 (2013).***

Wear properties : high pressure abrasion



200N
Δt = 2.5s
t = 30 min





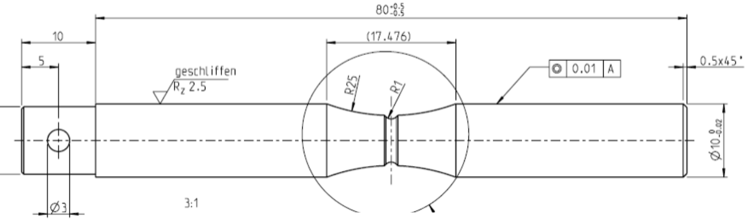
Hardox (SSAI

0.3C-0.7Si-1.6Mn-1.5Cr-1.5I

HV = 500 ; Tempered Marte

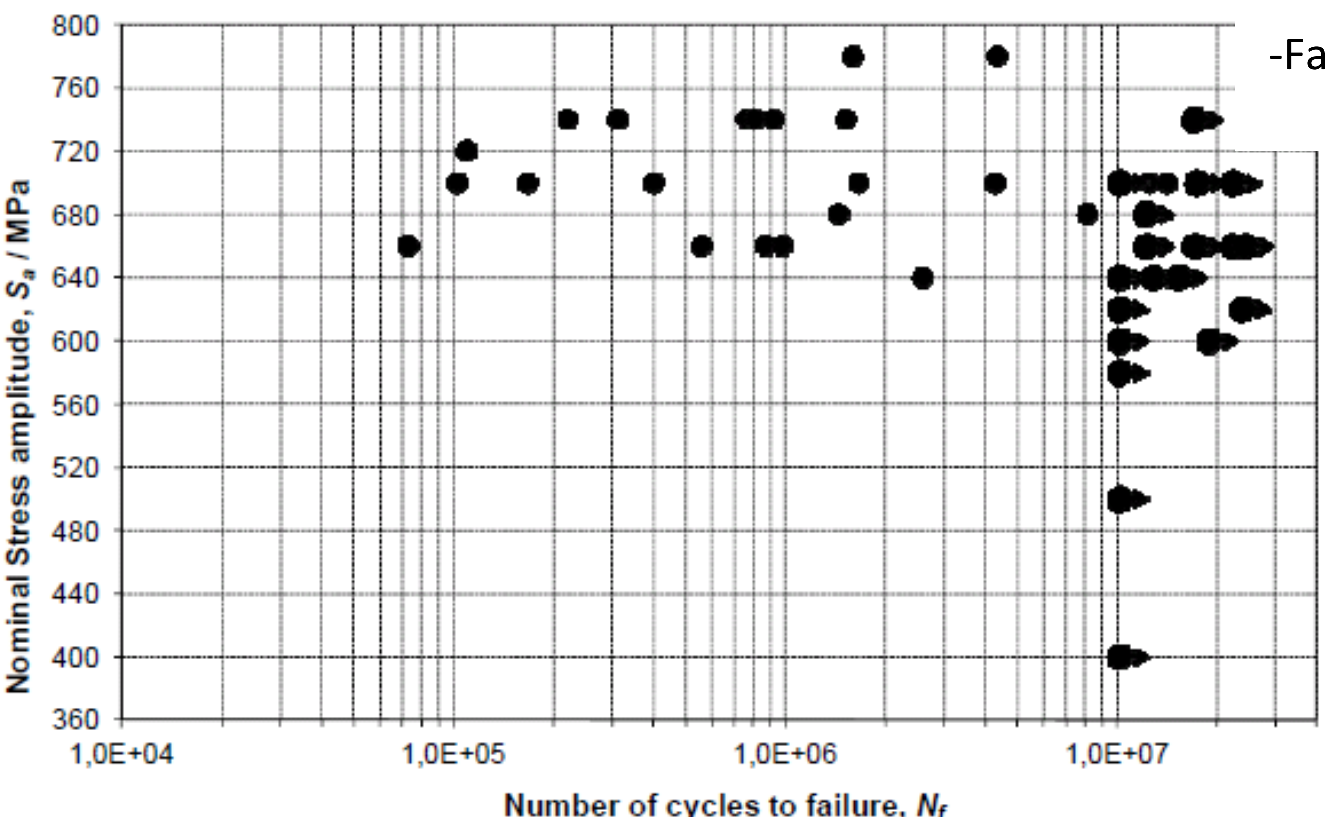
Fatigue properties : rotation bending on notched specimens.

Condition	UTS / MPa	Sa, 50% at 10^7 cycles / MPa for R = -1, Kt = 1,6 by rotation bending
1CNb-220-FAT	2073	430
06C-250-FAT	2023	665
08C-270-FAT	2036	440



Notch ?

-Application have stress concentrator



-Fatigue sensitive to austenite decomposition

0.6C @250ºC

(Industrial) Material selection

Strength ductility balance ➔ *small component* ➔ *1CSi*

HPA+Charpy performance ➔ *big component (hardenability)* ➔ *0.6 CNb*

0.6 CNb ⇔ *0.6 CV*

= *microstructure, HV & Bs/ Ms +* faster kinetics

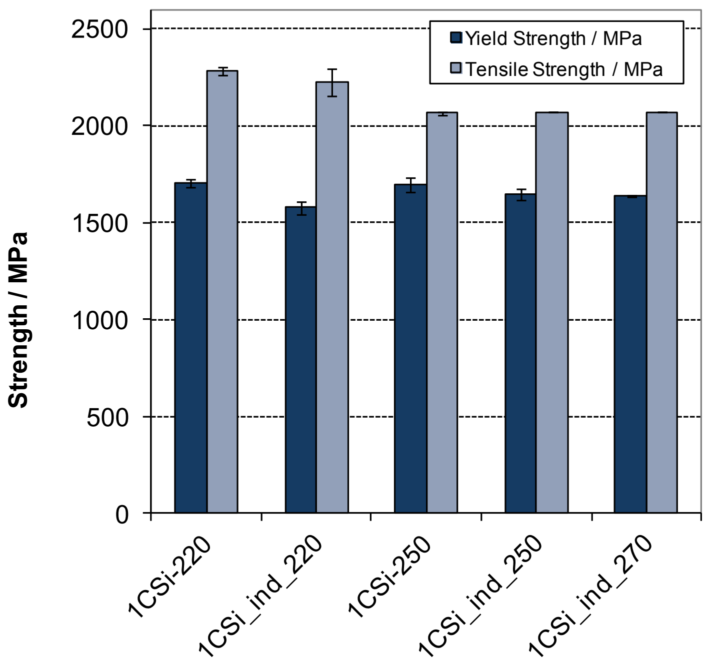
	C	Mn	Si	Cr	Mo	V
1CSi-ind	1.00	0.75	2.50	1.00	0.03	0.00
0.6CV-ind	0.60	1.25	1.60	1.75	0.15	0.12

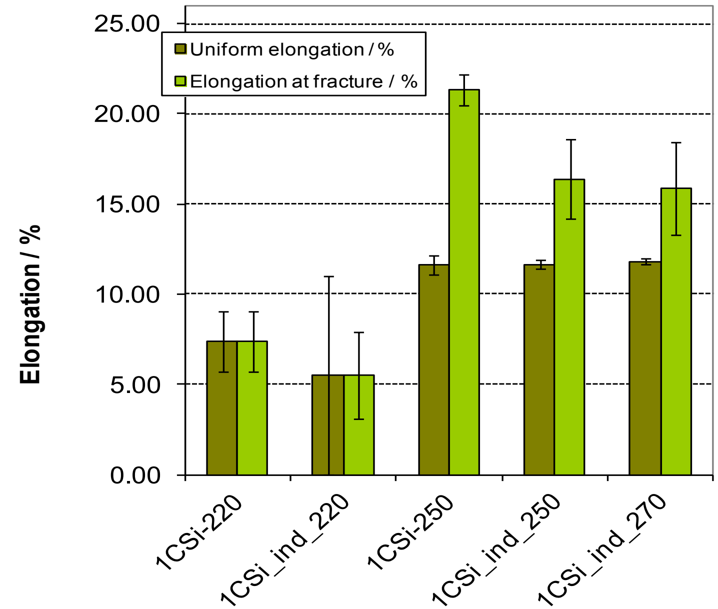
Industrial heats casted

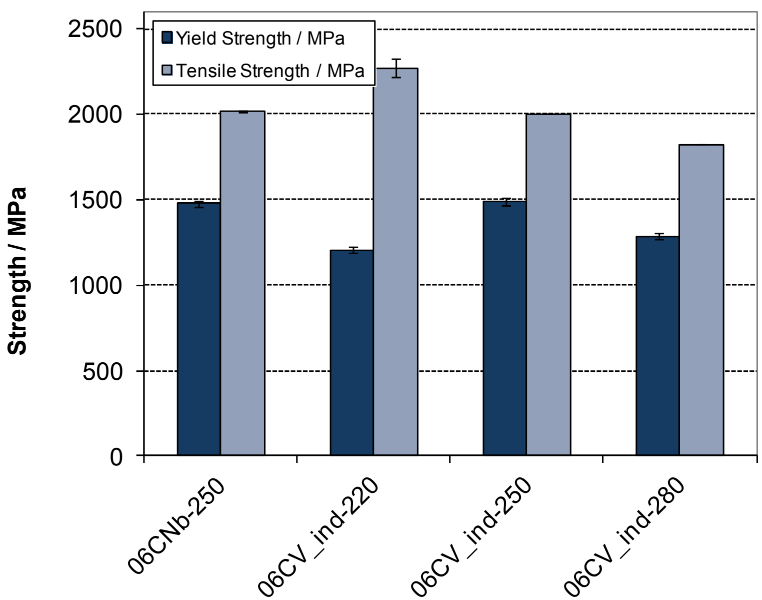
Before fabricating a component or demonstrator

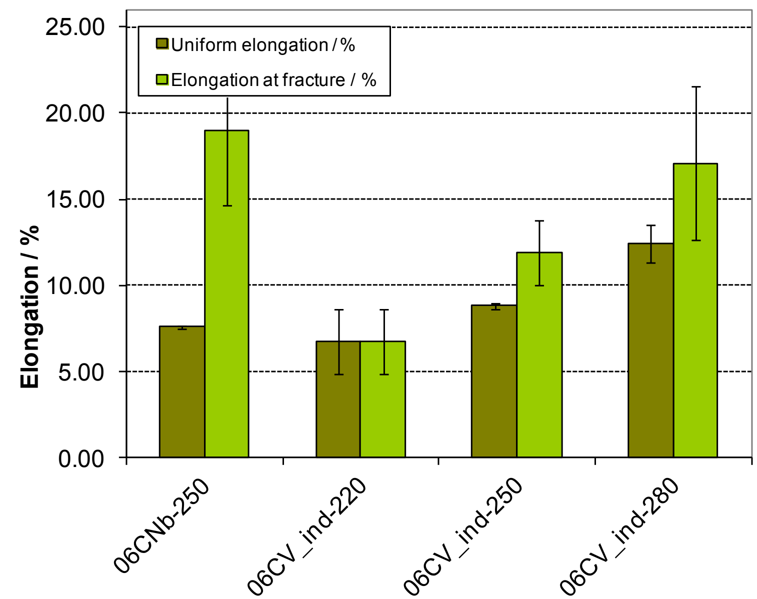
Battery of tests

Tensile Industrial Material



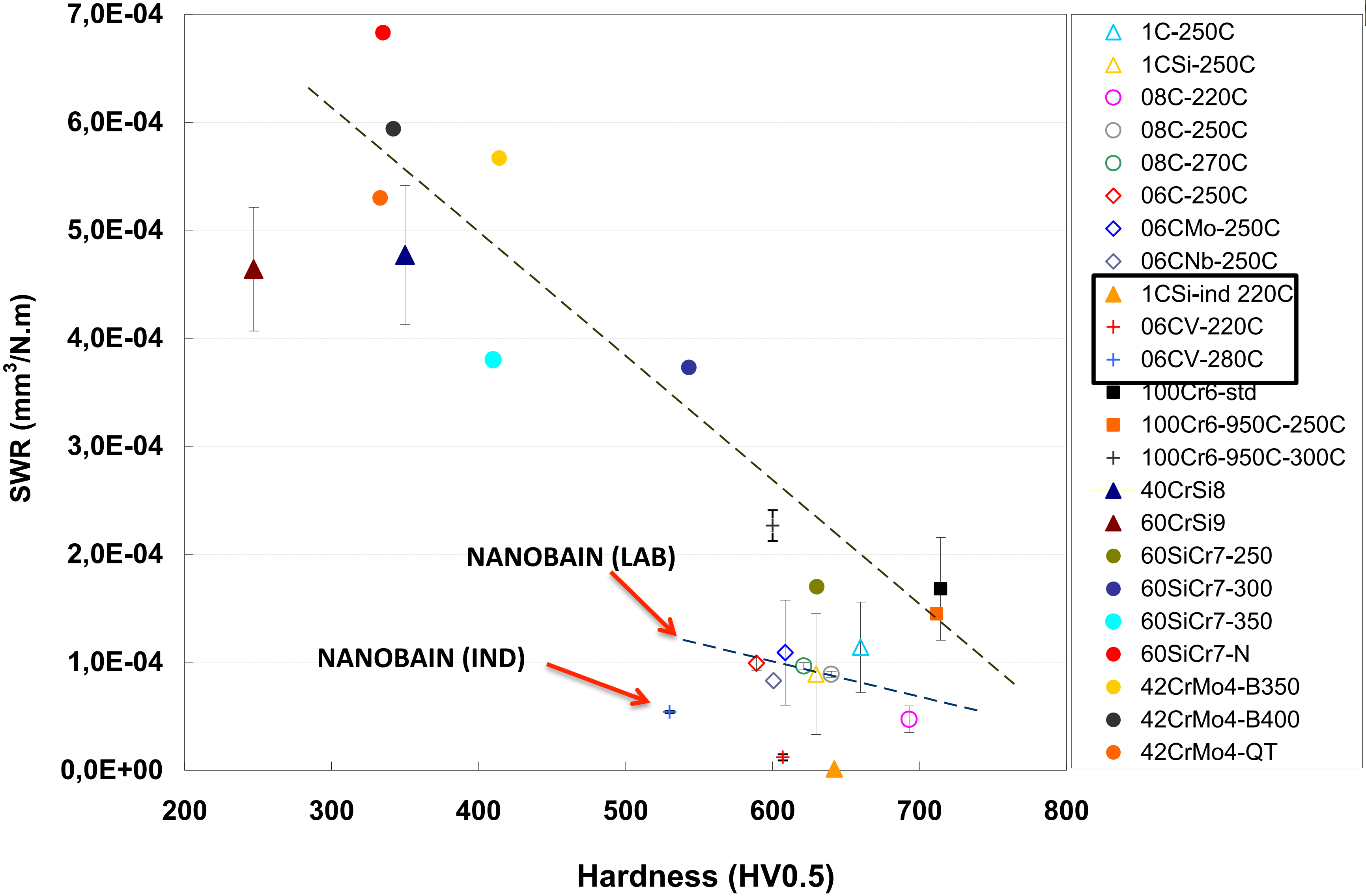




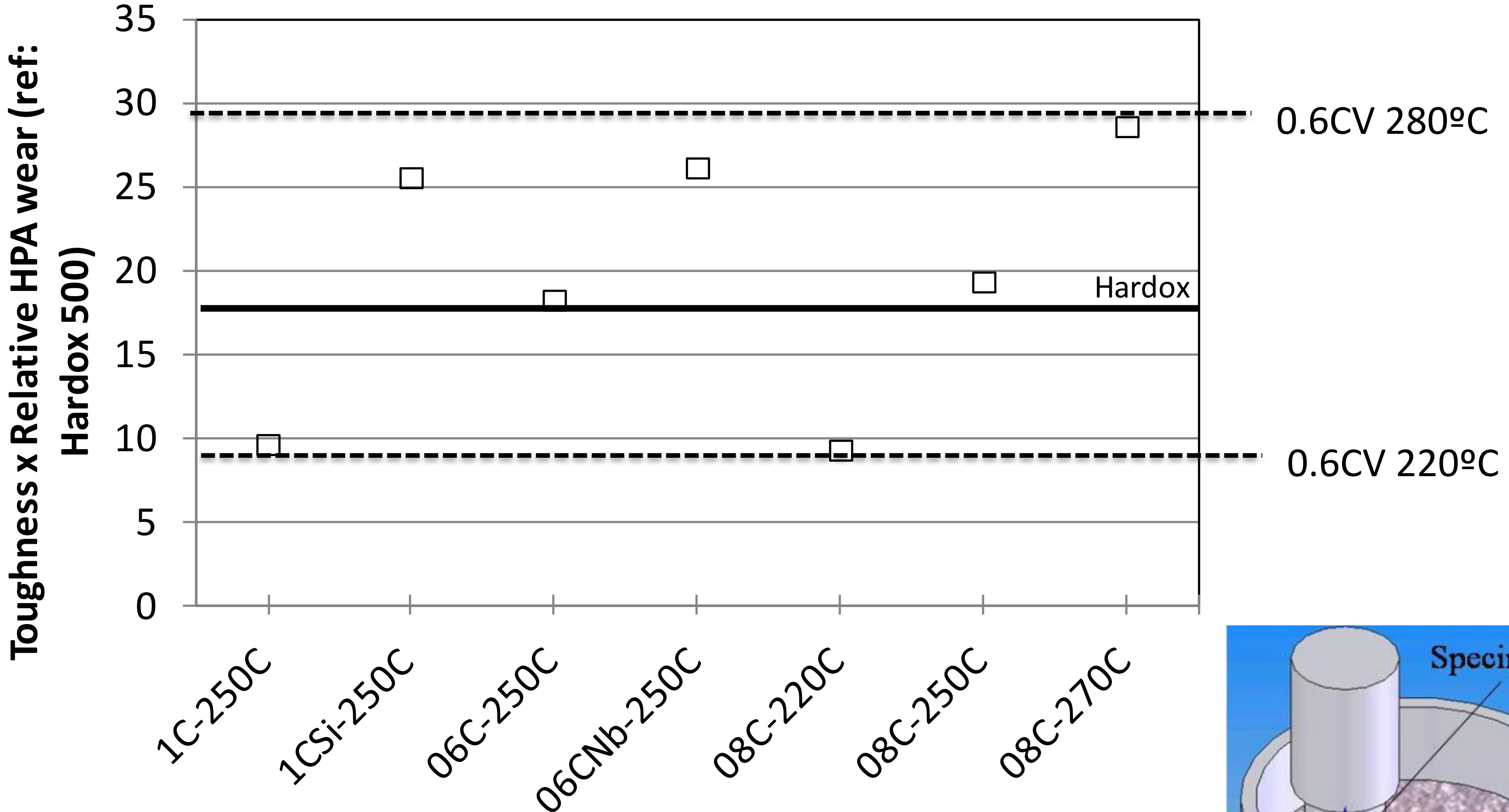


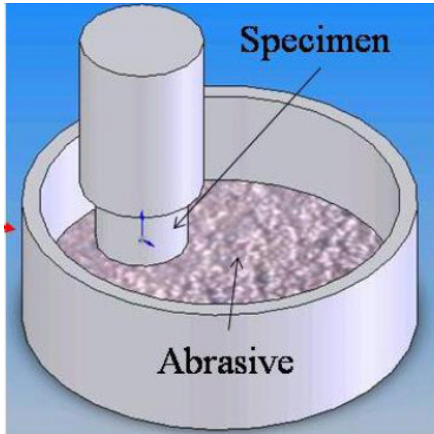
Wear : rolling-sliding wear tests

Twin discs wear test, 100 rpm, 5% slip, 300N load, 5h



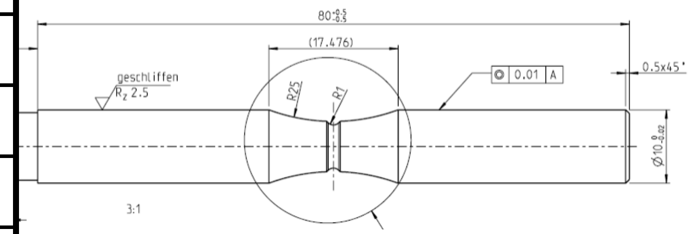
Wear properties : high pressure abrasion

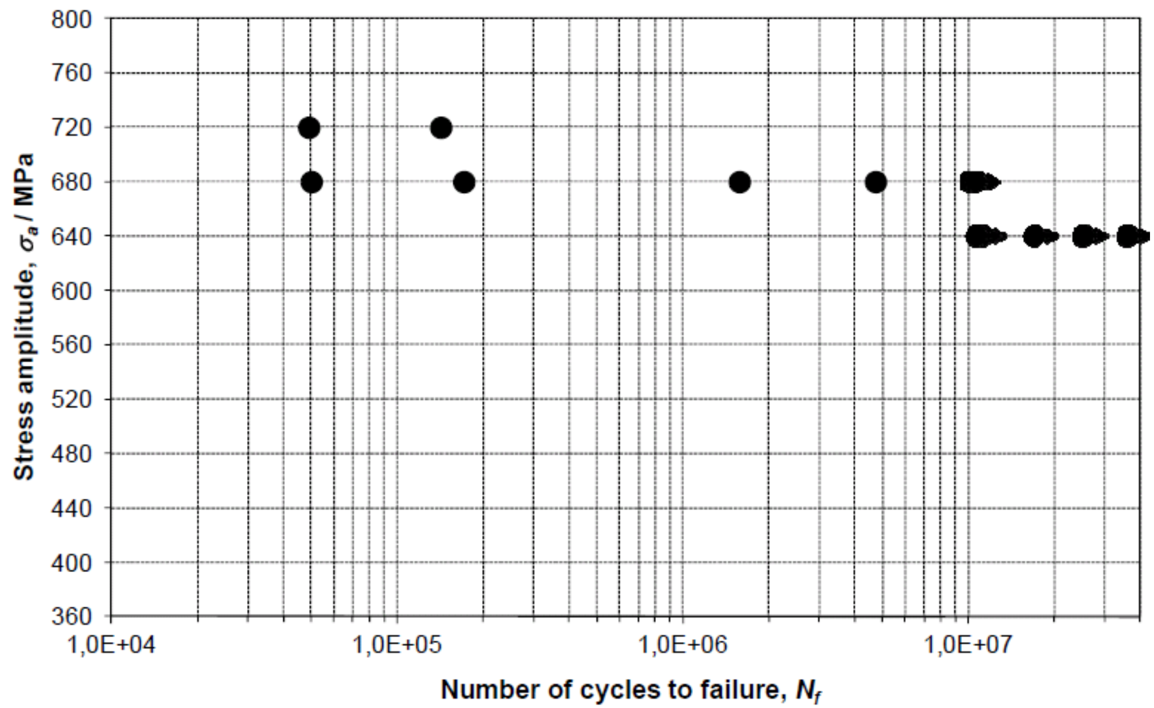




Fatigue properties : rotation bending

Condition	UTS / MPa	Sa, 50% at 10^7 cycles / MPa for R = -1, Kt = 1,6 by rotation bending
1CNb-220-FAT	2073	430
06C-250-FAT	2023	665
08C-270-FAT	2036	440
1CSi-ind-220-FAT	2224	550
1CSi-ind-250-FAT	2072	535
06CV-ind-250-FAT	2003	690
06CV-ind-270-FAT	1822	675

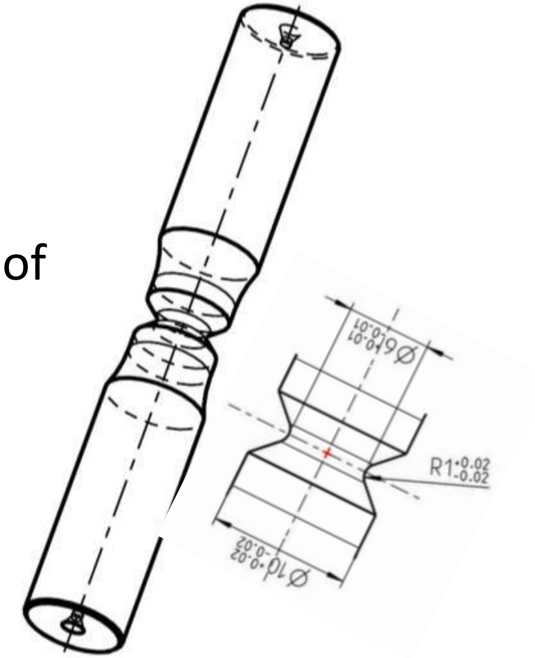




0.6CV @270ºC

Fatigue properties : notched tension-tension specimens

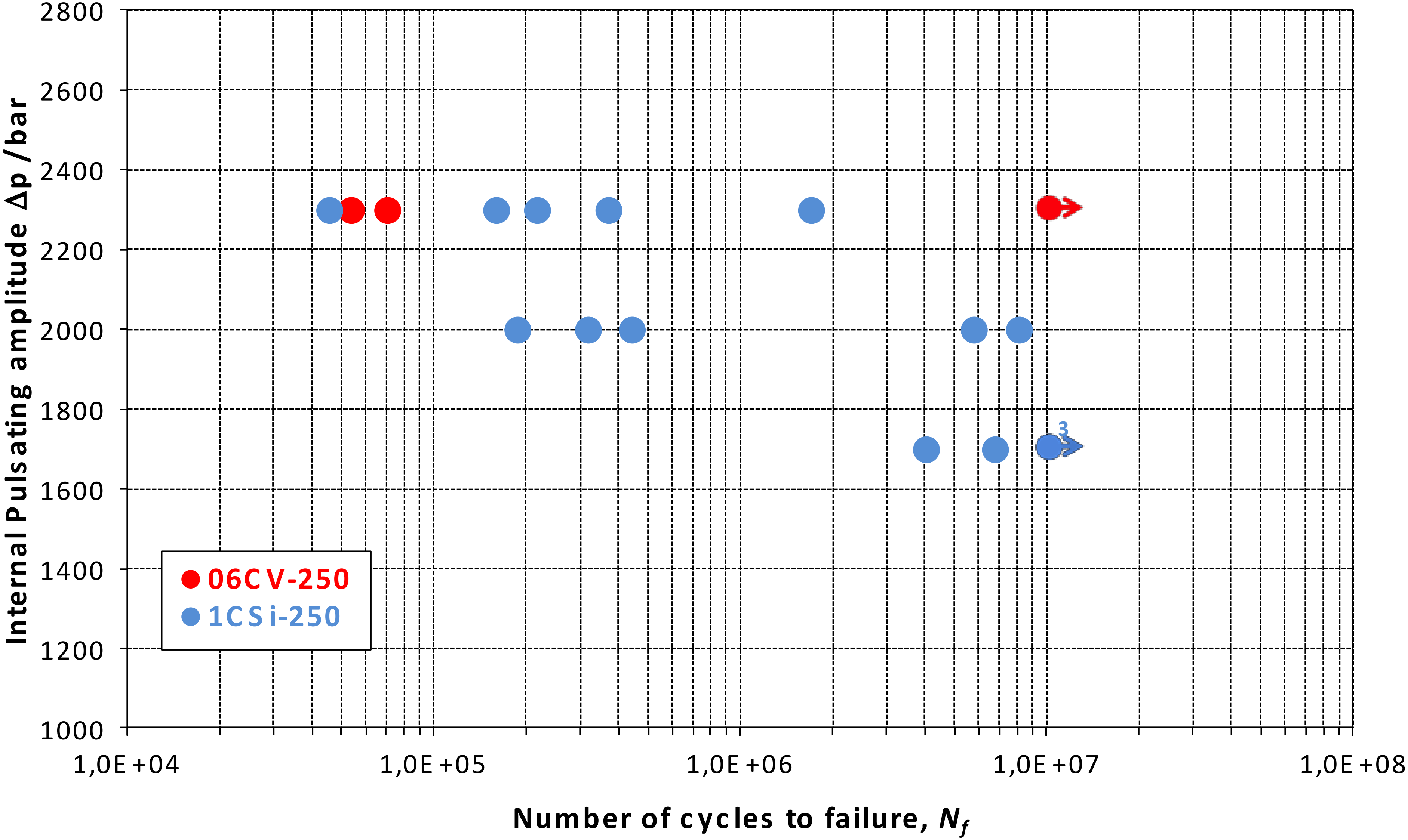
Representative of the functioning of heavily loaded diesel engines



Kt = 2
R (stress ratio) = 0.1
150Hz

	06CV-250	06CV-270	1CSi-220	1CSi-250	100Cr6 [TLi, 1998]	50CrMo4 [SSc, 2012]
UTS / MPa	2003	1822	2224	2072	2350	1180
$S_{a,50\%}$ at N = 10^7 cycles / MPa	350	330	205	245	355	305

Small component High pressure injection (demonstrator)



Big component
Scrap shear blades (component)

0.6CV @ 280ºC

	Surface		Core	
	Side	Middle	Side	Middle
Surface	545	535	542	541
Mid-thickness	541	535	542	543

30 kg load Vickers hardness for METSO's component. The hardness did not vary significantly with position.

Estimated potential gain 20%

due to the significantly cheaper material

Conclusions

- Design of ‘cheap’ steel grades adapted to low temperature bainitizing and application hardenability .
- Tensile properties : achieved excellent combinations of high strength and ductility. Unprecedented and unexpected 21% TE at UTS 2GPa.
- Fatigue tests, on par with 100Cr6 for one of the industrial grades, scope for improvement
- Large improvement in RS wear resistance, related to retained austenite decomposition

Achievement

In just over three years, the Nanobain project took the concept of nanostructured bainitic steels from a laboratory experiment to full scale industrial production and testing.

***Solely by means of phase transformation theory*.**

$$\Delta G_m < G_N$$

$$\Delta G^{\gamma \rightarrow \alpha} < -G_{SB}$$