

IT4009 Low carbon steel

MSCTM, August 27, 2015

LMF + Marco Buzio, Alexandre Gerardin,
Susana Izquierdo, Alessandro Parrella,
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ARMCO Pure Iron

- IT 4009, 1800 tonnes low carbon steel (magnetic/pure iron)
- Hot rolled 5.8 mm thickness. 650 x 3'000 to 4'000 mm.





- Magnetil® not available.
- Cold rolled << 5.8 mm thickness.

- ARMCO Pure Iron 5.8 mm
 - AK steel patent (USA)
 - Produced by Thyssen (DE) since 1917.
 - Grade 2 and 4.

- 3 sets of samples tested at CERN:
 - as received in may 2014,
 - annealed at 980°C in august 2014,
 - annealed at 750 and 850°C in june 2015.

Test report EDMS#1382378

May 2014
ARMCO Pure Iron
As received

CERN CH1211 Geneva 23 Switzerland	EDMS NO. 1382378	REV. 0.0	VALIDITY APPROVED
	REFERENCE HL-LHC/ R. Principe TE/ MSC		
 EN Engineering Department	Date: 30/07/2015		
	MME Mechanical & Materials Engineering		
Metallurgy Report			
Metallurgical analysis of ARMCO samples			
DOCUMENT PREPARED BY: A. Gerardin EN/MME/MM	DOCUMENT CHECKED BY: S. Sgobba EN/MME/MM	DOCUMENT APPROVED BY: S. Sgobba EN/MME/MM	

Material certificate



Letter of Compliance acc. to manufacturer's test report / mill certificate

AK STEEL SARL
2-6 rue des Bourets
Tour Ventoses

F-92150 Suresnes

Customer Order No. POFR-130443	AK Steel Order No 131328	AK Steel Contact Carmela Micciché	Telephone (Ext.) -12	Date 24 October 2013
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Product: ARMCO® Pure Iron, hot rolled plates, Tol. acc. to DIN EN 10029

Item	Qty	Size	Weight	Heat-No.	Chemical Composition, %												
					C	Mn	P	S	Cu	N	Si	Al	Cr	Mo	Ni	Sn	
	Pieces	mm	Kg		.003	.050	.005	.003	.009	.0051	.004	.003	.017	.005	.015	.002	
		5 x 1000 x 2000	632	402571 /B													

Mechanical Properties:	
Yield Strength, Rp 0,2	266 MPa
Hardness	87 HB
Elongation, A	57 %

This Letter of Compliance is based on the information and on the product responsibility of the manufacturer of the base material!

Manufacturer's Test Report No.: 1570899001, Date 23.10.2013

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Ulla Hahn
Ulla Hahn

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Local Court Cologne, HRB 18607

Tensile tests and Micro-optical

Average tensile tests results of the three samples for each direction:

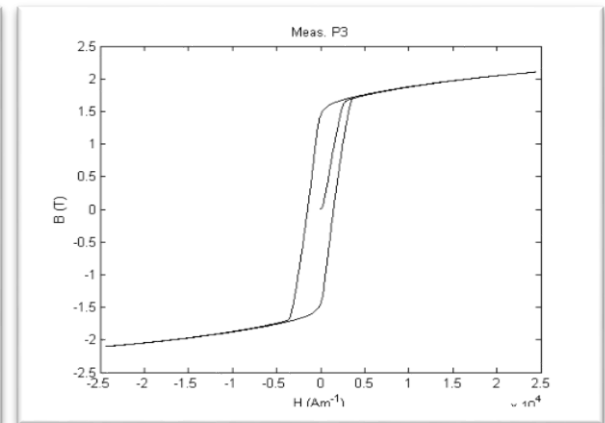
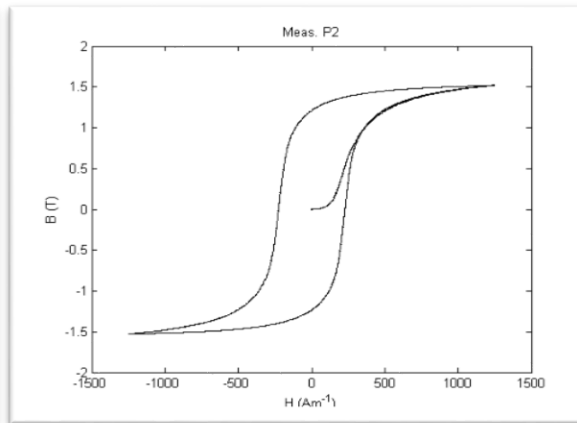
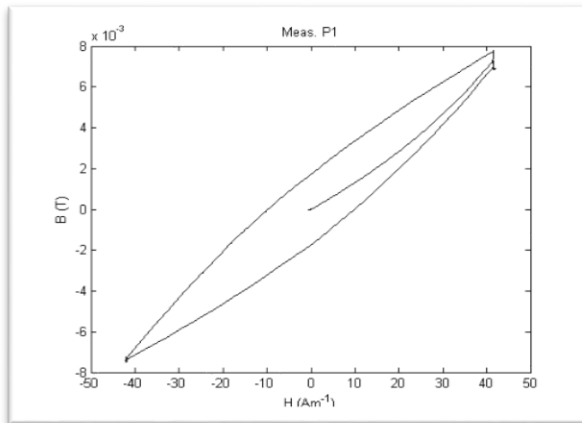
- Longitudinal direction:
 - $R_m = 305.0 \pm 2.3$ MPa (IT4009, $R_m < 280$ MPa/mm²)
 - $R_e = 237.5 \pm 6.5$ MPa
 - $A\% = 43.5 \pm 1.8$ %
- Transverse direction:
 - $R_m = 305.4 \pm 0.4$ MPa
 - $R_e = 233.2 \pm 4.4$ MPa
 - $A\% = 39.9 \pm 2.3$ %

Micro-optical observations and image analysis revealed:

- Average Grain size $G \approx 5$ in longitudinal direction
- Average Grain size $G \approx 7$ in transverse direction
- IT4009, $GS < 3.5$

Magnetic Measurement




	H (Am ⁻¹)	B (T)	B _{IT4009} (T)
P1	41.6	0.0076	0.2
P2	1246	1.519	1.5
P3	24360	2.102	2



Test performed by Marco Buzio and Giuseppe Montenero

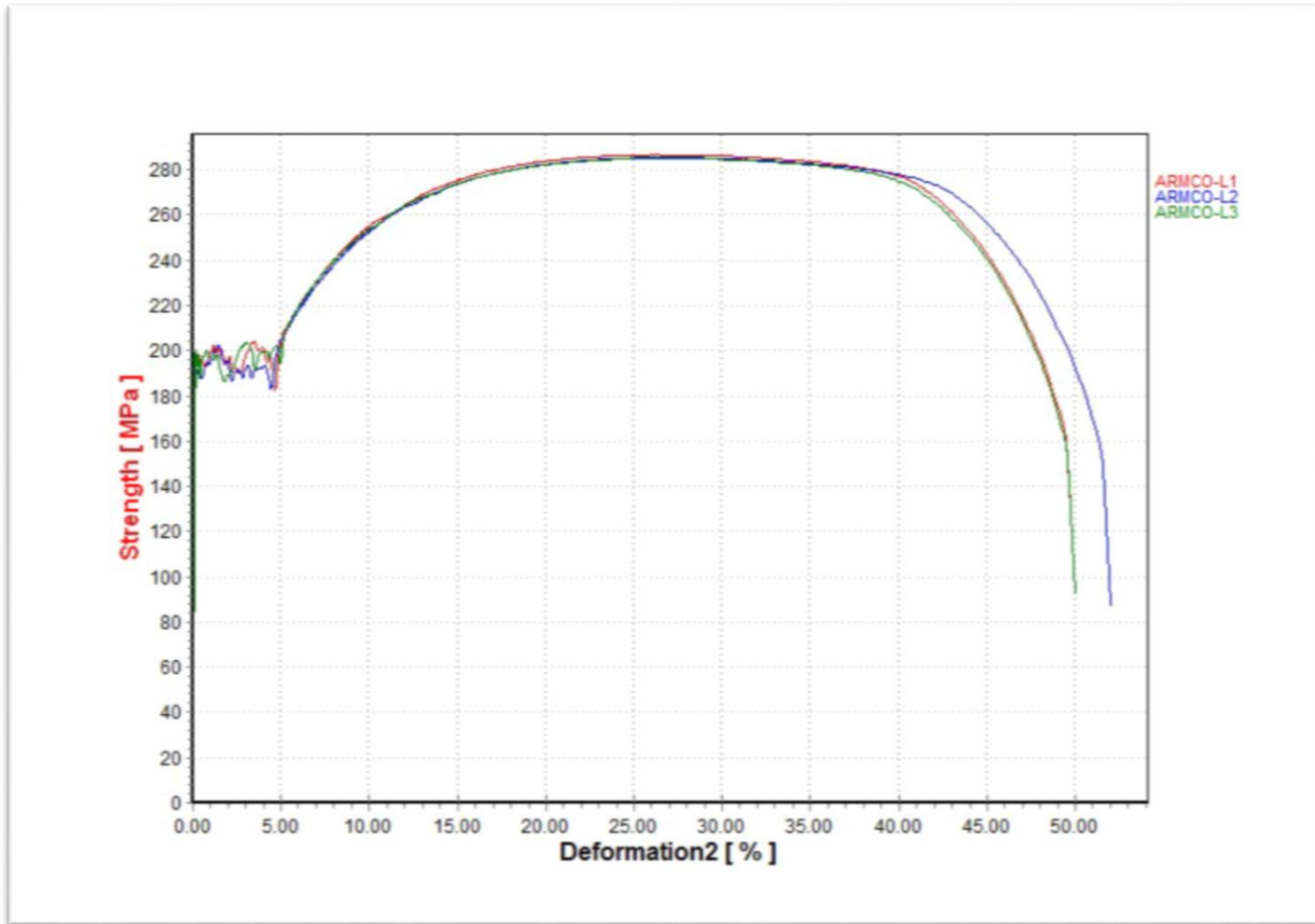
Test report EDMS#1408185

August 2014
ARMCO Pure Iron
Annealed at CERN
980°C 1hr.

CERN CH1211 Geneva 23 Switzerland	EDMS NO. 1408185	REV. 0.0	VALIDITY APPROVED
	REFERENCE HL-LHC/ R. Principe TE/MSC		
EN Engineering Department			Date: 12/09/2014
	MME Mechanical & Materials Engineering		
Metallurgy Report			
Metallurgical analysis of ARMCO samples -2-			
DOCUMENT PREPARED BY: A. Gerardin EN/MME/MM	DOCUMENT CHECKED BY: S. Sgobba EN/MME/MM	DOCUMENT APPROVED BY: S. Sgobba EN/MME/MM	

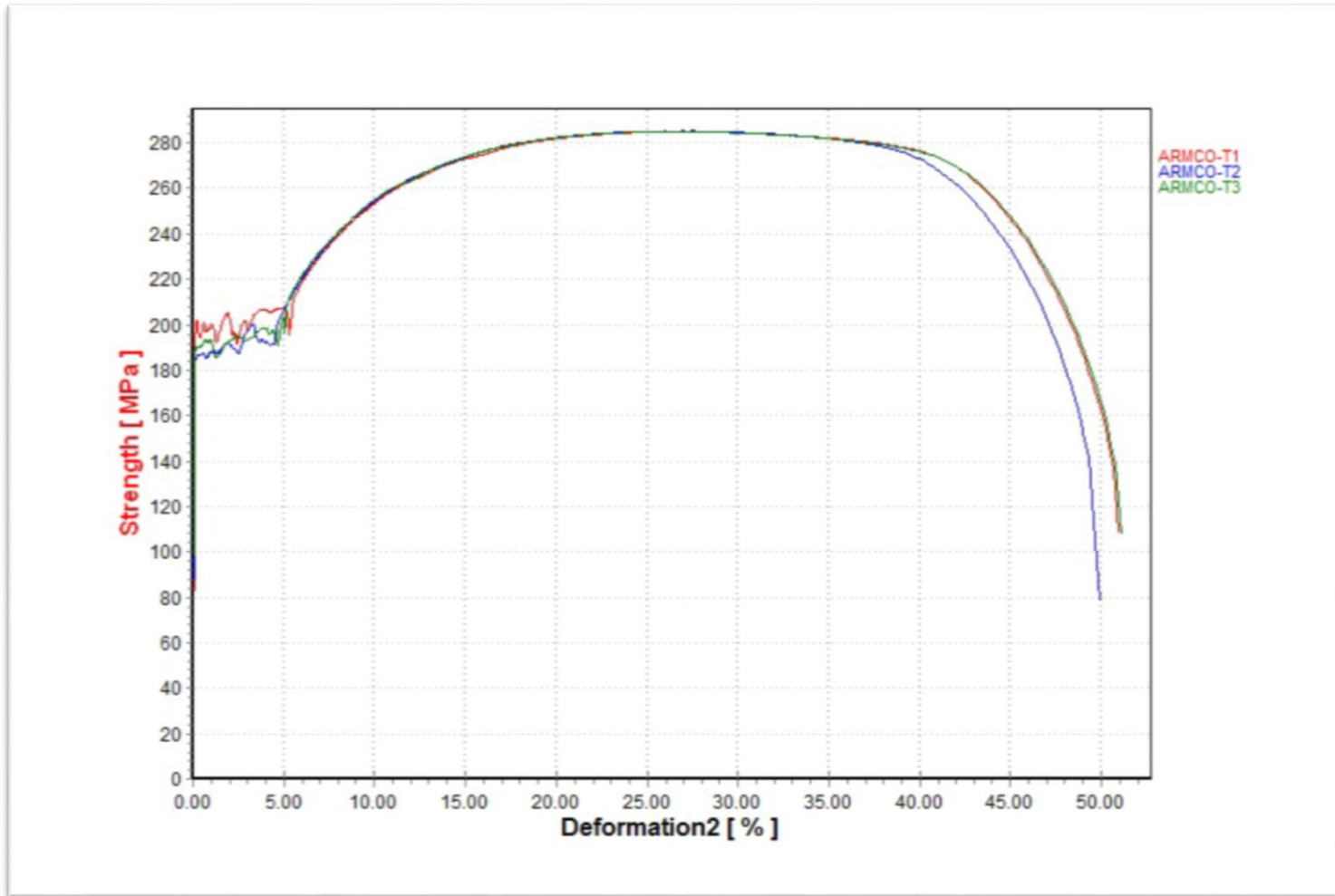
Yield and tensile strenght L

IT4009, $R_m < 280 \text{ MPa/mm}^2$, $R_e > 150 \text{ MPa/mm}^2$



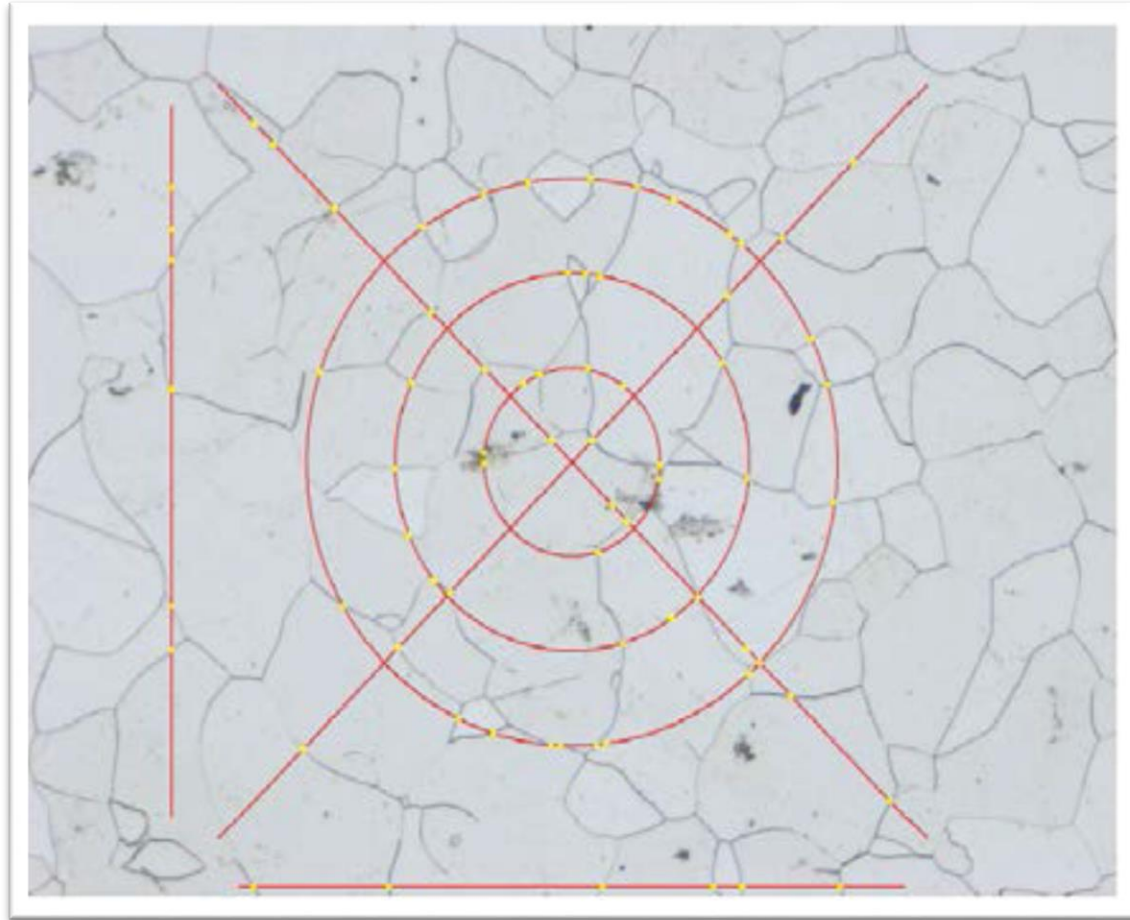
Yield and tensile strenght T

IT4009, $R_m < 280 \text{ MPa/mm}^2$, $R_e > 150 \text{ MPa/mm}^2$



Grain Size $L \approx 4$

IT4009, GS<3.5



Grain size $T \approx 4.5$

IT4009, GS<3.5



Tensile tests and micro-optical

Average tensile tests results :

- Longitudinal direction:
 - $R_m = 285.8 \pm 0.8 \text{ MPa}$ IT4009, $R_m < 280 \text{ MPa/mm}^2$
 - $R_e = 187.7 \pm 0.1 \text{ MPa}$ IT4009, $R_e > 150 \text{ Mpa/mm}^2$
 - $A\% = 50.2 \pm 1.2 \%$
- Transverse direction:
 - $R_m = 285.1 \pm 0.2 \text{ MPa}$
 - $R_e = 187.6 \pm 3.9 \text{ MPa}$
 - $A\% = 50.3 \pm 0.7 \%$

Micro-optical observations and image analysis revealed:

- Average Grain size $G \approx 4$ in longitudinal direction
- Average Grain size $G \approx 4.5$ in transverse direction
- IT4009, $GS < 3.5$

ARMCO chemical composition

ARMCO Pure Iron



Grade 2

Grade 4

Max. Analysis %	Avg. Analysis %	CHEMICAL COMPOSITION	Max. Analysis %	Avg. Analysis %
0.010	0.006	Carbon	0.010	0.0013
0.100	0.064	Manganese	0.060	0.048
0.010	0.005	Phosphorus	0.005	0.004
0.008	0.005	Sulfur	0.003	0.003
0.006	0.003	Nitrogen	0.005	0.004
0.030	0.012	Copper	0.030	0.007
0.005	0.004	Cobalt	0.005	0.002
0.010	0.002	Tin	0.005	0.002

IT4009 C<0.03

Average value last 7 years (max value C=0.0027)

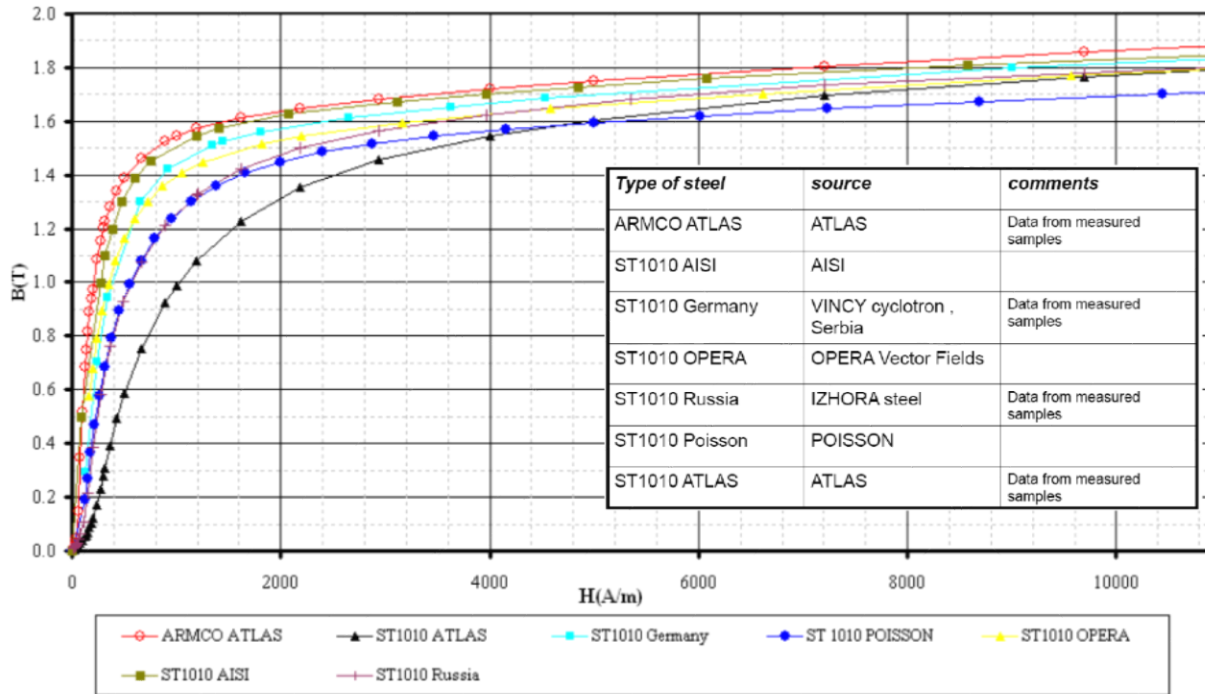
At CERN Co<0.1
ARMCO 50 times better

Steelworks product unique in its purity; all natural impurities have been largely removed

Fe = min 99,85 %

AISI1010 comparison

ARMCO® Pure Iron vs. Low Carbon Steel AISI 1010

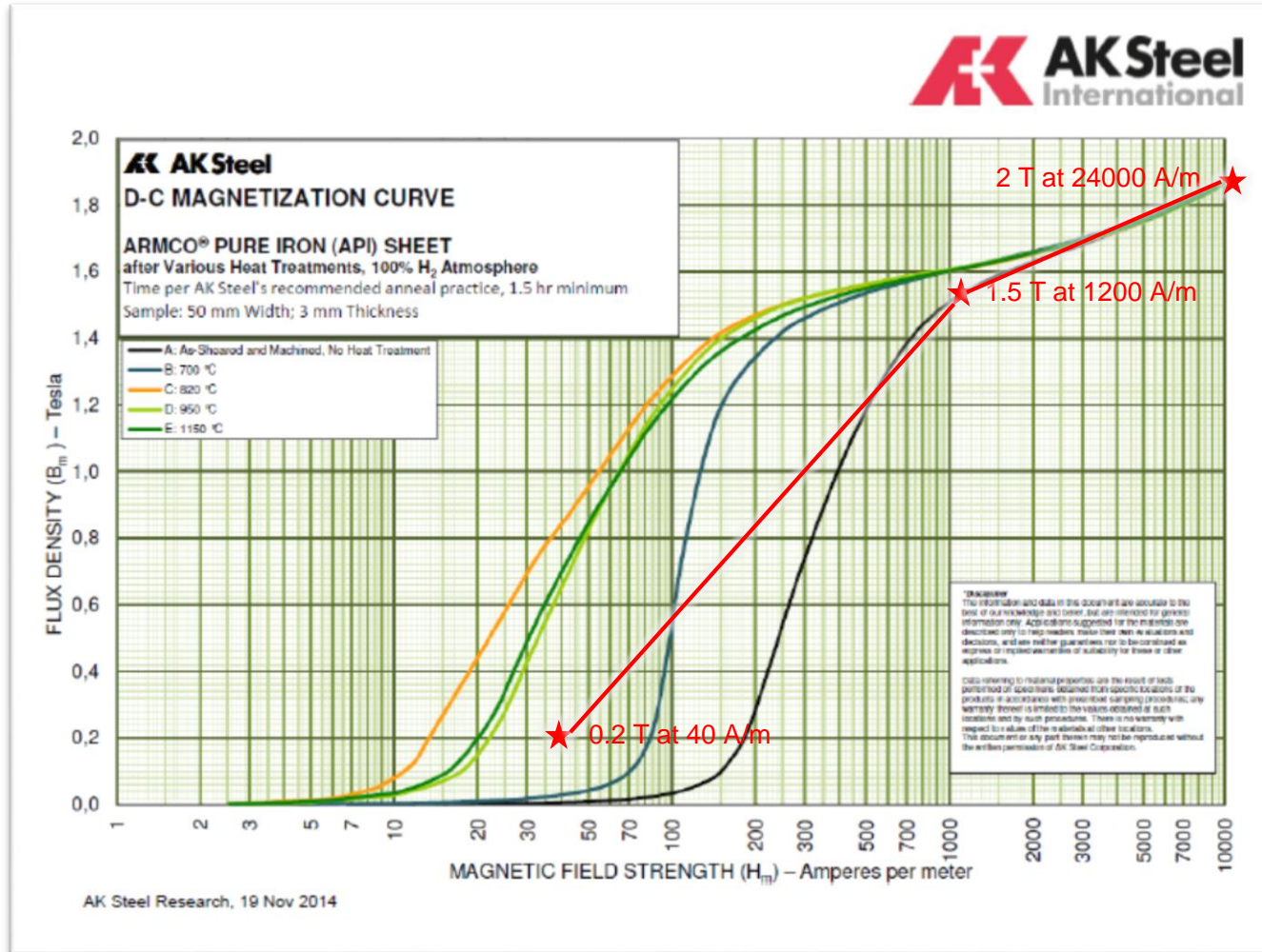


M. Modena, 27 April 2009

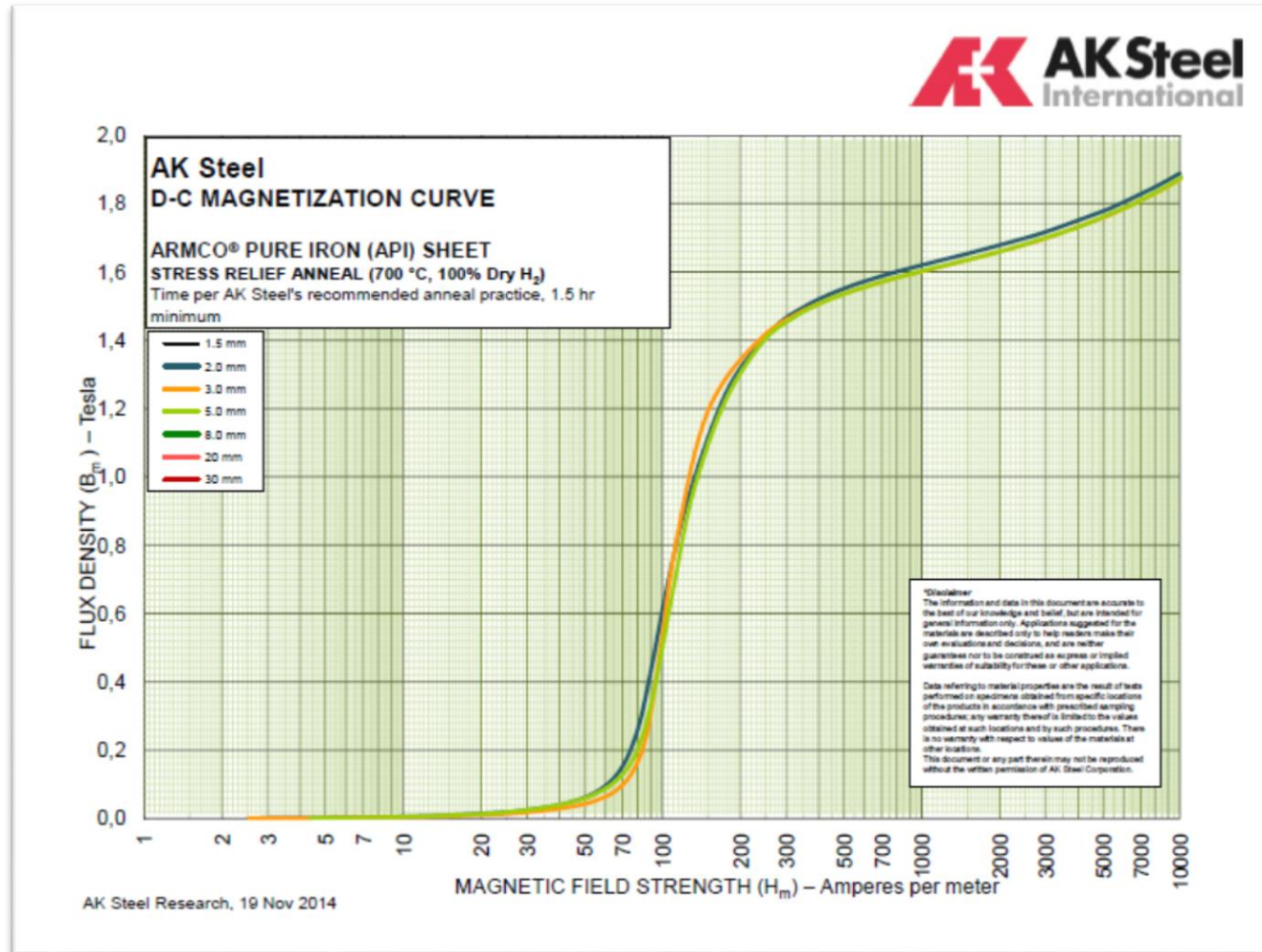
(Courtesy of A. Vorozhtsov)

Source : Physics & Measurements of Magnetic Materials II (S. Sgobba, CERN), CAS, Bruges, 2009

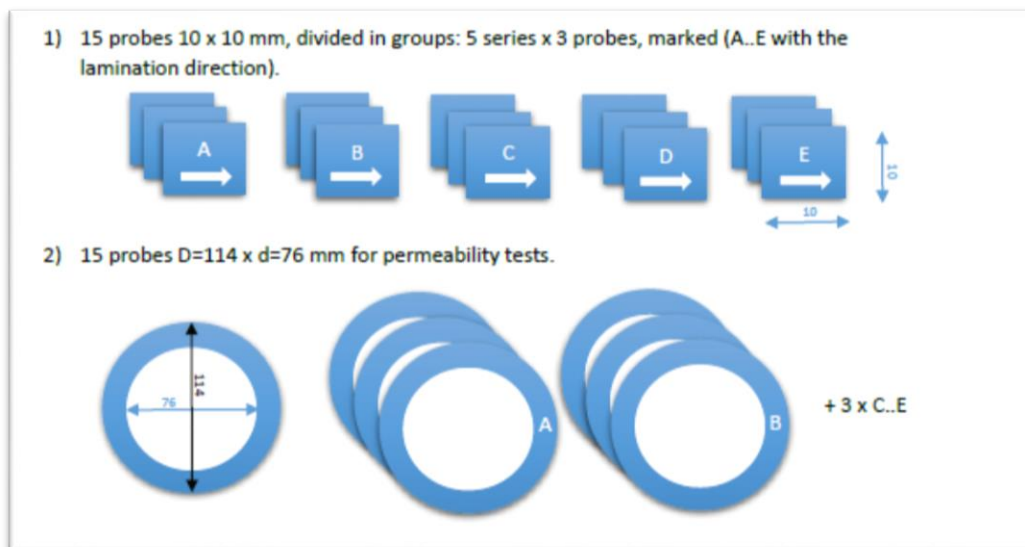
ARMCO B/H curves



B/H vs. thickness



ARMCO Pure Iron Grade 4



Probe	Annealing
A	Ref. value
B	750°C, 1h
C	750°C, 5h
D	850°C, 1h
E	850°C, 5h

Test report EDMS#1524264

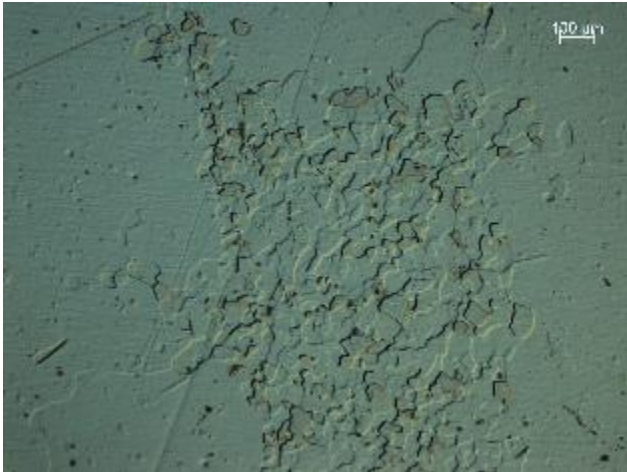
Samples	A (ref.)	B (750°C,1h)	C (750°C,5h)	D (850°C,1h)	E (850°C,5h)
HB 31.25/2.5	73	75.1	73	60.5	52.5
	72	75.1	73	54.8	54.8
	73	75.1	73	56.1	57.5
Average	72.7	75.1	73.0	57.1	54.9
Std dev	0.5	0.0	0.0	2.4	2.0
Equivalent Rm *	273	281	274	223	216

* based on conversion from NF A 03-172/173

Micro-optical observations and image analysis revealed:

- Average Grain for A, B and C, size $G \approx 7.5$ in longitudinal direction
- Average Grain for A, B and C, size $G \approx 7.5$ in transverse direction
- IT4009, GS < 3.5

GS for samples D and E



Sample D = 850°C, 1hr

- Few crystals \gg 1 mm
- Many crystals $<$ 20 μ m
- GS: beginning of recrystallization

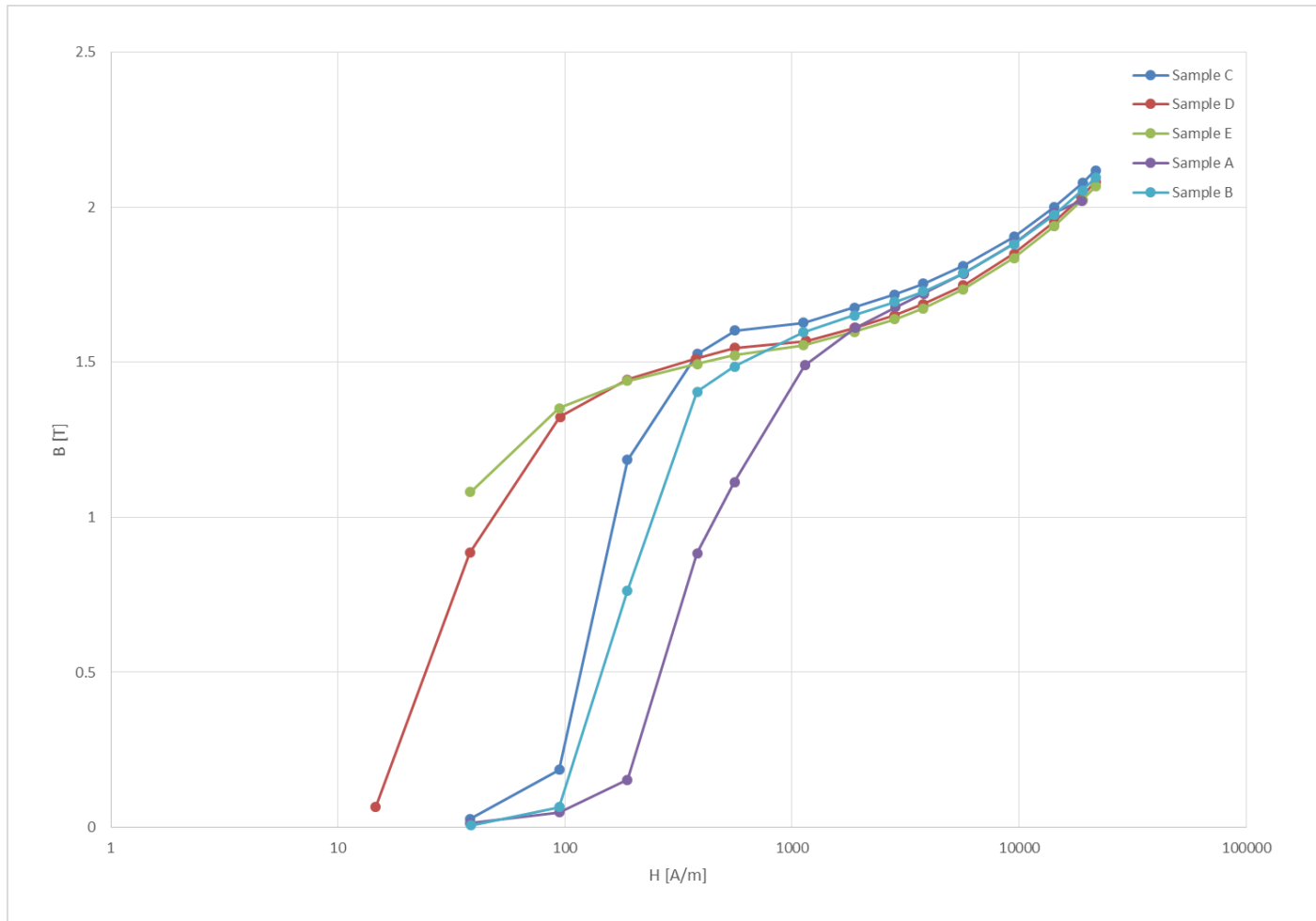


Sample E = 850°C, 5 hrs

- Very few small crystals
- Most of the crystals \gg 1mm
- GS very low

Magnetic measurements

(Alessandro Parrella and Marco Buzio)



H/B values

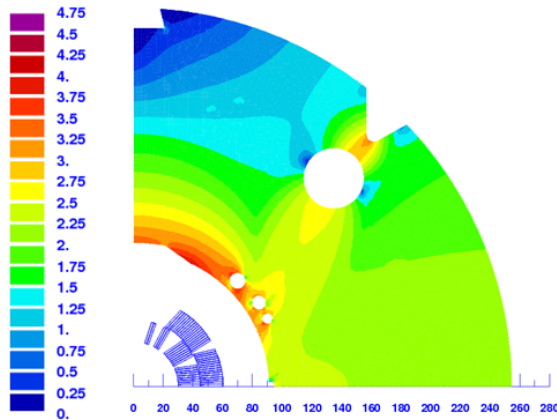
(Alessandro Parrella and Marco Buzio)

Sample A		Sample B		Sample C		Sample D		Sample E	
H [A/m]	B [T]	H [A/m]	B [T]	H [A/m]	B [T]	H [A/m]	B [T]	H [A/m]	B [T]
						14.65658	0.067115		
38.29423	0.014046	38.55988	0.007128	38.29126	0.027668	38.1083	0.884925	38.2618	1.081289
94.438502	0.048394	94.58309	0.065129	94.54471	0.185324	95.32979	1.324388	94.42068	1.351355
188.5346	0.152933	188.3662	0.76432	188.5611	1.184932	188.5522	1.444388	188.5789	1.440313
383.53154	0.884668	383.4498	1.404223	383.6331	1.526379	377.5054	1.511681	383.4375	1.494378
559.31106	1.113955	558.0063	1.486541	561.8116	1.602611	558.0533	1.545981	558.2316	1.522958
1137.8665	1.490956	1119.253	1.59693	1122.878	1.62733	1154.051	1.569319	1122.492	1.555243
1900.5945	1.610991	1879.756	1.651515	1883.261	1.676588	1879.072	1.610124	1883.395	1.59746
2857.2991	1.677706	2833.779	1.694854	2838.013	1.718807	2832.962	1.651394	2837.839	1.638939
3809.1214	1.721245	3784.017	1.728613	3787.854	1.753027	3783.249	1.686996	3788.399	1.674141
5718.6833	1.78633	5690.484	1.786377	5695.609	1.811015	5689.395	1.748503	5695.237	1.735524
9542.2634	1.88393	9505.052	1.88051	9511.762	1.905036	9498.417	1.849667	9511.514	1.836639
14311.996	1.981122	14266.09	1.975227	14275.45	1.999893	14265.06	1.952165	14274.04	1.938672
18859.278	2.021408	19033.57	2.054646	19042.49	2.078737	18849.62	2.034029	19043.8	2.024183
		21794.81	2.094648	21805.93	2.119094	21793.72	2.081749	21805.51	2.066464

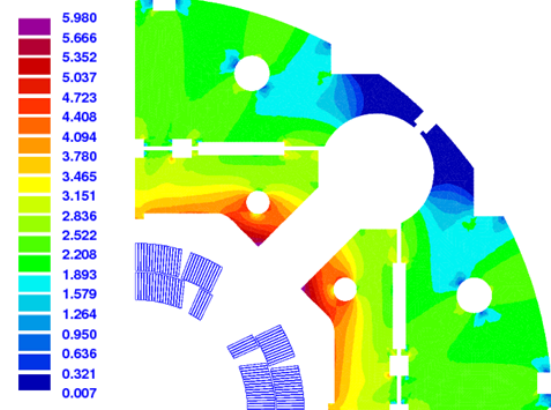
BH and field quality

(Susana Izquierdo and Ezio Todesco)

|Btot| (T)

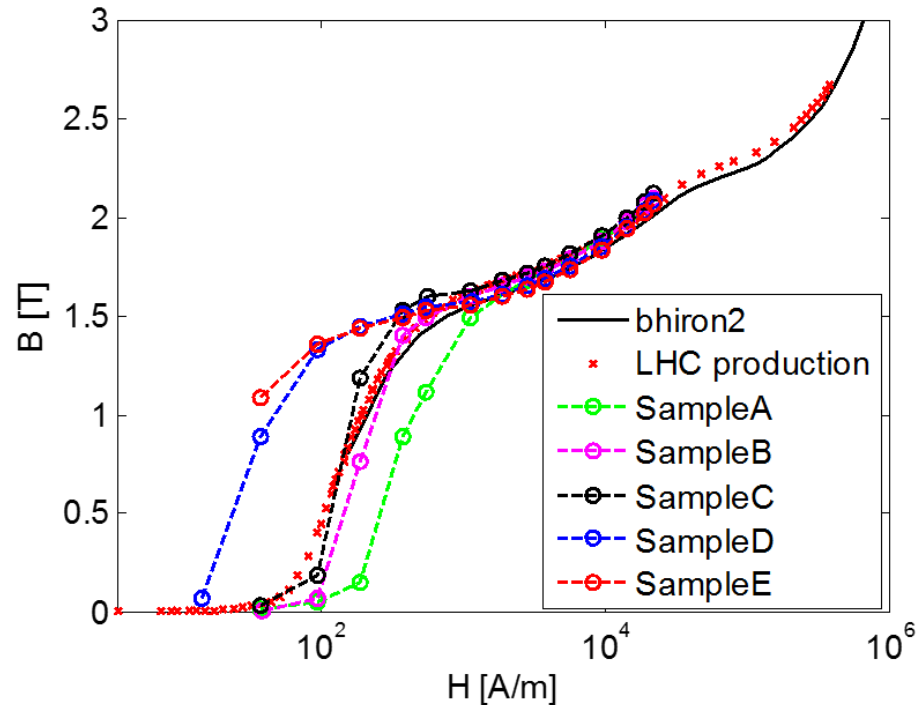


ROXIE_{10.2}



ROXIE_{10.2}

- Measurements up to $H = 20000 \text{ A/m}$ ($B \sim 2\text{T}$)
- For $H > 20000 \text{ A/m}$ “LHC production” data assumed
- The region $H > 20000 \text{ A/m}$ is critical for Hi-Lumi magnets, as the iron is heavily saturated ($B \sim 4\text{-}5\text{T}$)



BH and field quality: conclusions

(Susana Izquierdo and Ezio Todesco)

- The impact of the BH on the harmonics is negligible.
- There impact on the transfer function is dominated by the magnetic properties of the iron at *high field, which have not been measured.*

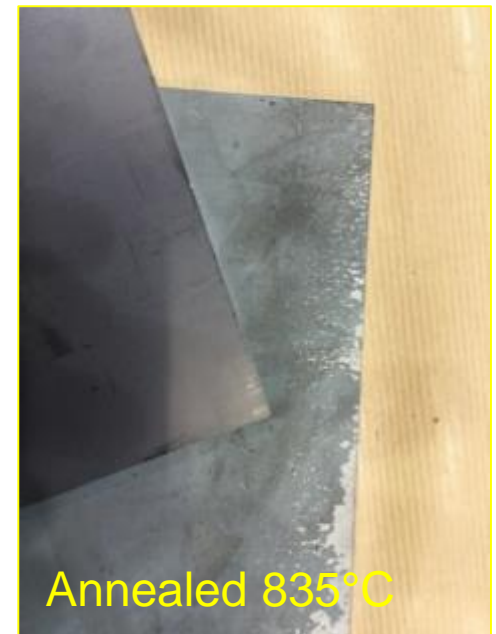
To be understood what is the impact of the annealing at higher field level:

- It will be only an issue if the reproducibility of the behaviour at high field is worse for the “non-annealed” case
- Would be good to measure the behaviour at higher field to have the full characterization

Surface coating

Annealed 835°C

As received



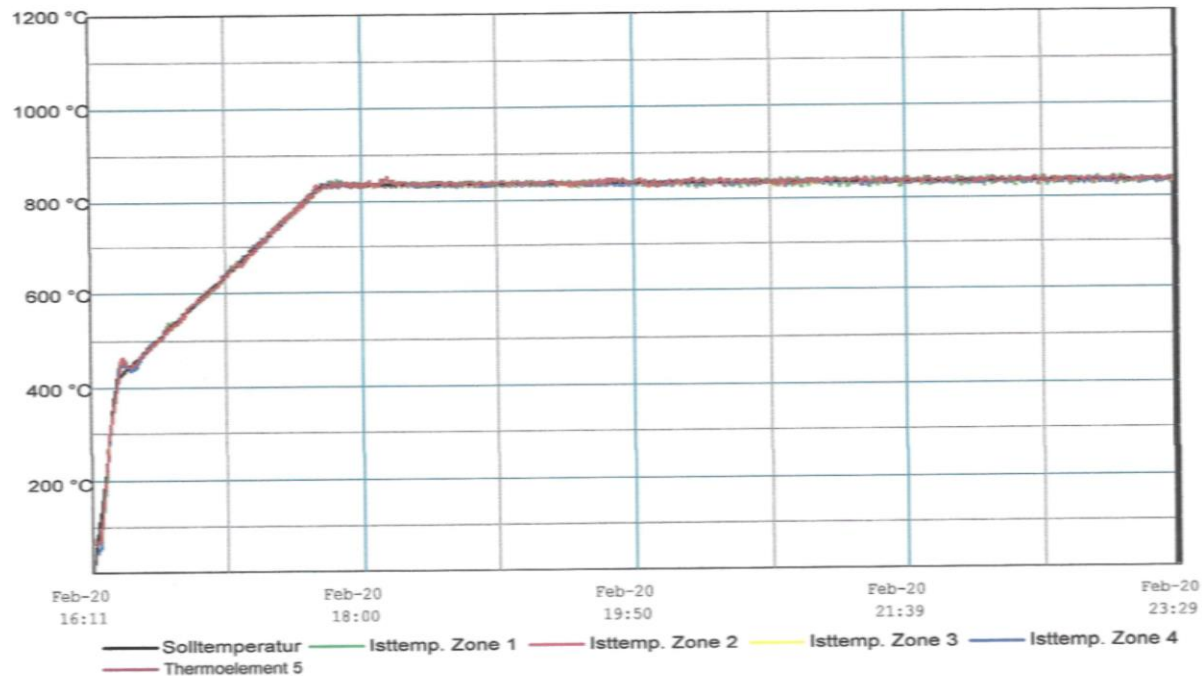
Annealing cycle

Ofennummer : 2
Glühergebnis : 4
Störung : ja

Wärmebehandlungsverfahren: 11
Wärmebehandlungstemperatur: 835 °C
Haltezeit: 60 min
Abkühlung nach Wärmebehandlung: 10
Einsatzgewicht (GEW - GES): 5.000 t
Walztafeldicke: 4.00 mm 156.00 mm

833 °C
59 min

Temperaturverlauf



Conclusion

ARMCO grade 4 (closer to the CERN specification)

C content acceptable (as received + annealed)

- Average C=0.0013; Max C=0.0027.
- AKS guaranteed C<0.0100 (IT4009 C<0.0030).

Co content ok (as received + annealed)

- Avg.Co=0.0020; Max Co=0.0050 (CERN Co<0.1)

Tensile and yield strenght ok (annealed)

- Warning for 850°C 5 hrs : annealing temp. and time vs. Rm critical (samples D and E → Rm very low).
- Suggest a test x two samples: 820°C 6 hrs + 980°C 2hrs.

Magnetic carachteristics ok (annealed)

Dimension: if annealed 780x4000x5.8 due to limitation of the edge trimming line in Huetteneim.

Coating

- Annealing curve to be better defined
- Temperature control do be discussed: natural cooling too fast, temp gradient not equally distributed on the sheet surface?
- Temp control affects the grain size and surface quality.

Urgent: storage

- Contract 1800 tonnes → 230 m³
- 15 to 25 tonnes per truck (70 to 120 trucks)
- Metal sheets 4000 x 650 (or 780) x 5.8
- Stack weight up to 2 tonnes
- Storage area 200 to 300 m².



www.cern.ch