Solution strengthened ferritic ductile iron ISO 1083/JS/500-10 provides superior consistent properties in hydraulic rotators

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Indexator AB is a leading OEM producer of hydraulic

rotators (>15.000 /year) for forestry, piece goods & recycling,

and of tiltrotator **Rototilt®** (>3.000 /year) for excavator versatility

Swedish family-owned SME; turnover $ 70M; 220 employees

Currently used major materials in our products:

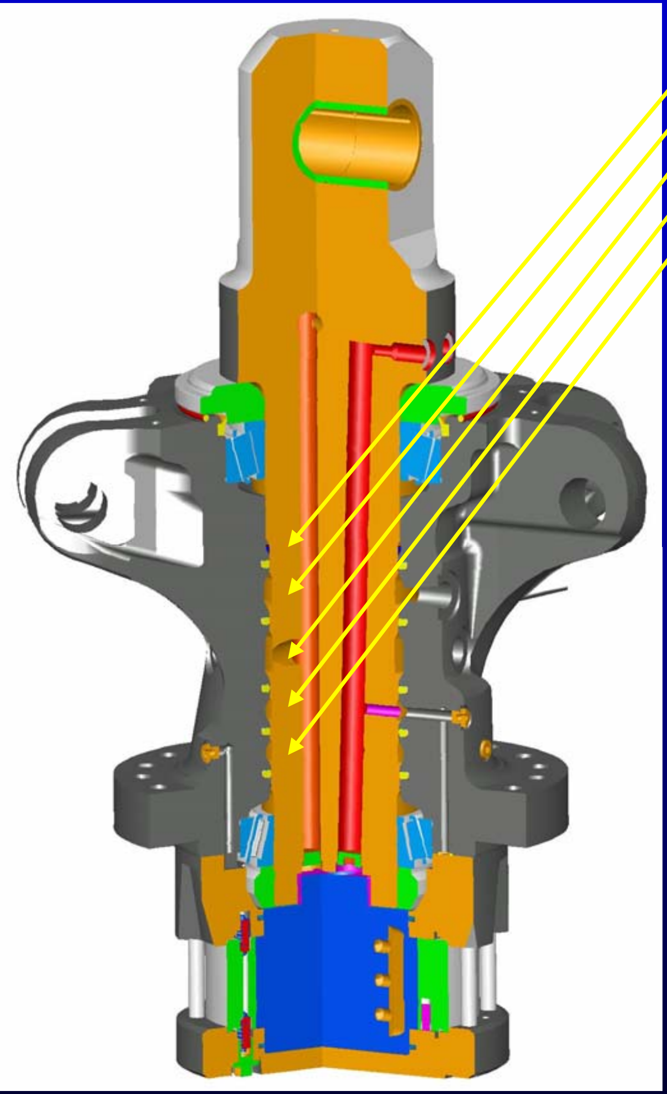
Rotators: ***Ductile iron*** >1.300 tonnes/year (≈1% of 1% of the global DI production!); currently ***conversion*** from ferritic-pearlitic ***to Si-solution strengthened ferritic DI***.

Rototilt: **Red** worm gear rotor housings are cast in ***Si-strengthened ferritic DI***; **black interfaces** to excavator and tools are *today in welded steel* (sheet + castings), but will at least partially be ***replaced by Ausferritic DI*** *(ADI)*.

Our first product in *Si-solution strengthened* DI:

Swivel housing (138 kg) cast **2005** in ISO 1083/JS/500-**10** (**3.7-3.8% Si**) for a rotator, integrated in a 5-claw recycling grapple for 20 tonne loads

Why replace ISO 1083/JS/500-**7** with JS/500-**10**?



Five seal grooves in the hydraulic swivel puts very high demands on tight machining tolerances <20 µm.

JS/500-**7** gave:

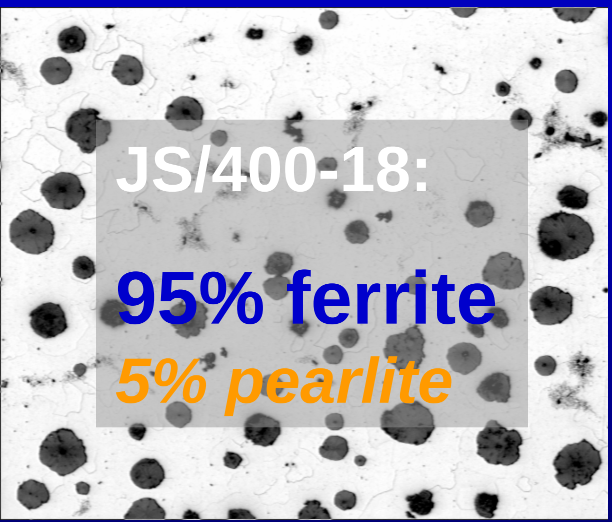
- Tolerances often out of spec., since *hardness variations* of 30-60 Brinell units *consume whole tolerance range!*
- *High reject rate*

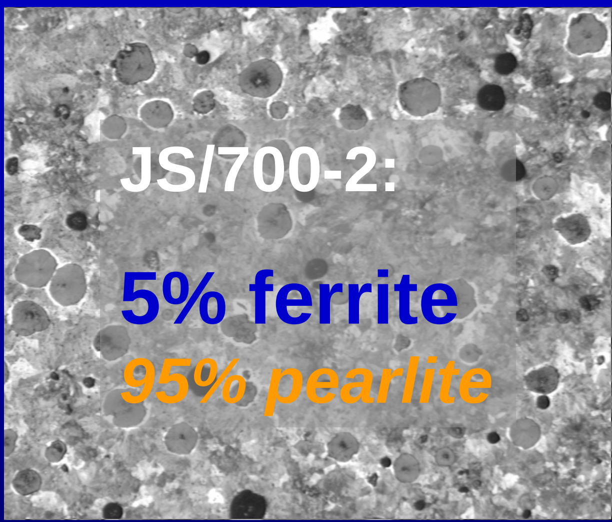
JS/500-**10** gives:

- ✓ ***Consistent*** properties (in HBW, etc)
- ✓ Tolerances within specification
- ✓ **Costs <80%** (time + tool wear + reject)

”Family” of ***structurally strengthened*** ductile irons:

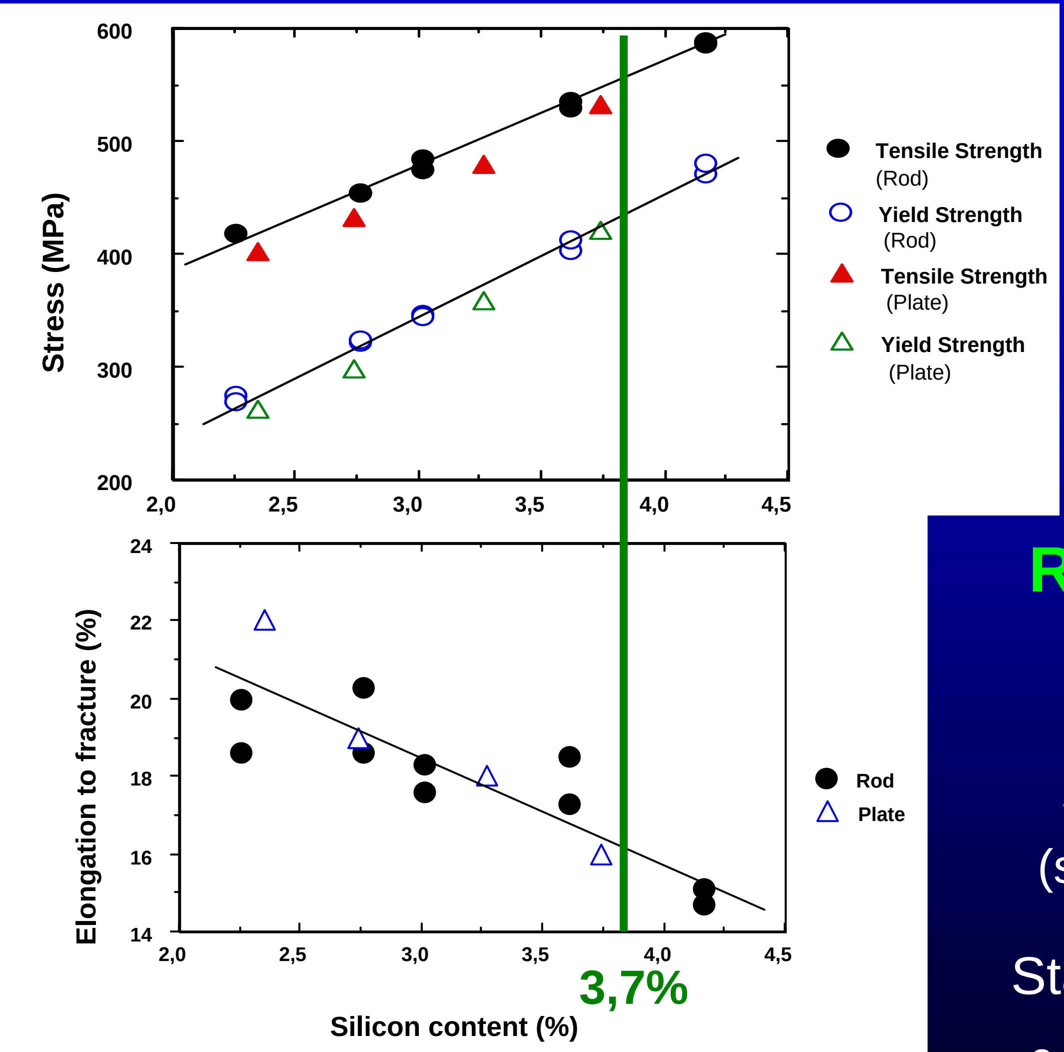
Conventional ferritic-pearlithic iron ISO 1083/JS/500-**7** shows large variations in properties due to ***varying pearlite content:***

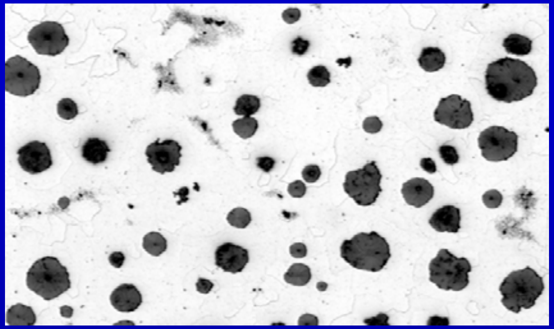




JS/400-18	JS/500-7	JS/700-2
H = 155 *±25* HBW	H = 200 *±30* HBW	*H = 265 ±40 HBW*
$R_{p0.2} \geq$ 250 MPa	$R_{p0.2} \geq$ 320 MPa	**$R_{p0.2} \geq$ 420 MPa**
$R_m \geq$ 400 MPa	**$R_m \geq$ 500 MPa**	$R_m \geq$ 700 MPa
$A_5 \geq$ 18%	$A_5 \geq$ 7%	*$A_5 \geq$ 2%*

Si-solution strengthened 100% ferritic DI:





Properties in 50 mm walls from four (4) first samples:

$R_{p0.2}$ = 402 – 415 MPa (≥360)

R_m = 515 – 534 MPa (≥500)

A_5 = 19.5 – 23.8% ! (≥10)

(standard minimas within parentheses).

Standardized as **SS 140725** (1998)

& as **ISO 1083/JS/500-10** (2004)

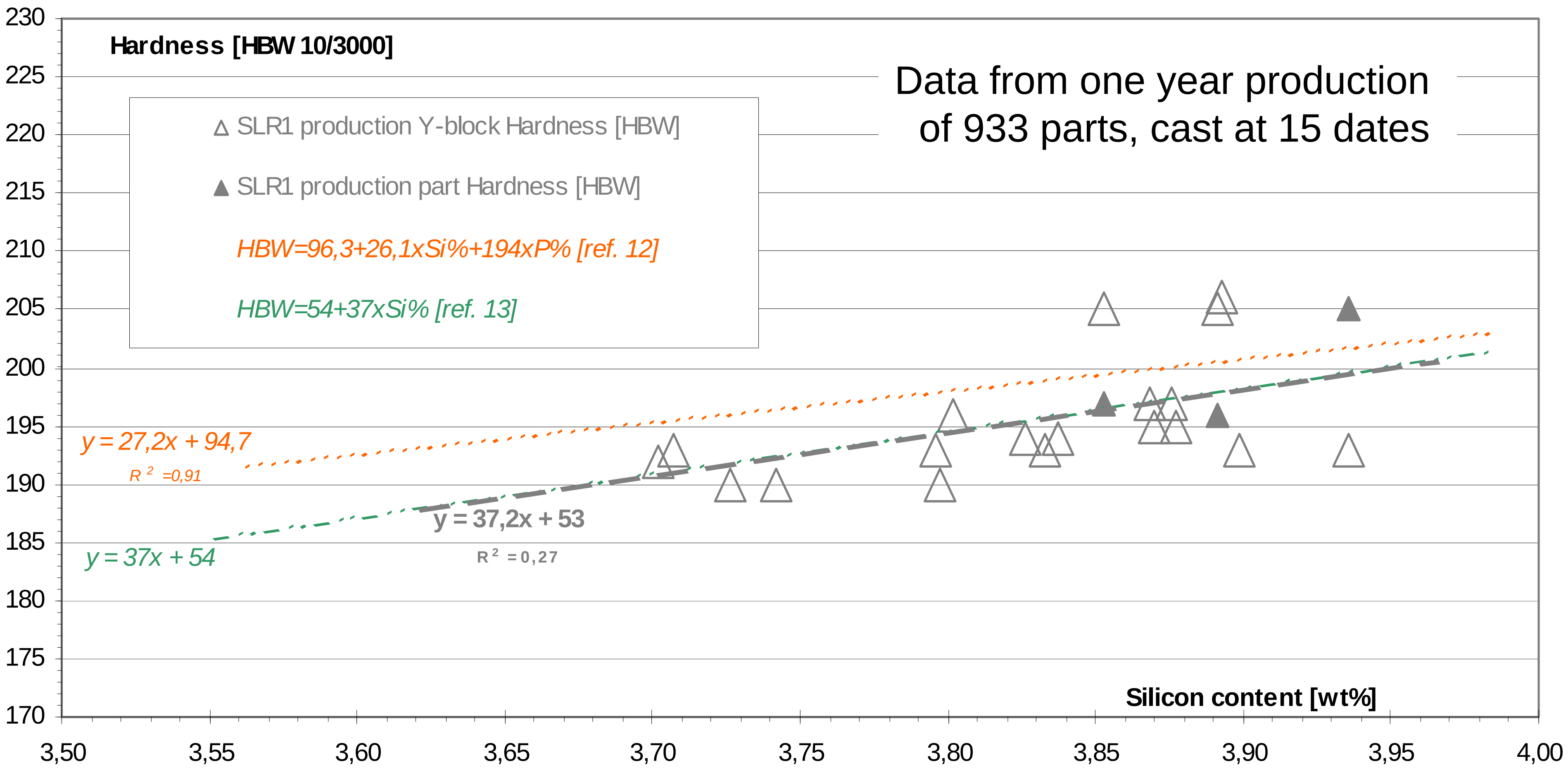
Gable: 201, 207, 201, 207, 212 212 179, 192, 212 HBW
Flange: 197, 201, 197, 192, 187

Gable: 187, 187, 187, 187, 187, 187, 187, 187 HBW
Flange: 192, 192, 192, 192 HBW

Hardness variation reduces by -75%, from ±10 HBW to **±2.6 HBW**

Machin-ability increase by 20-30%.

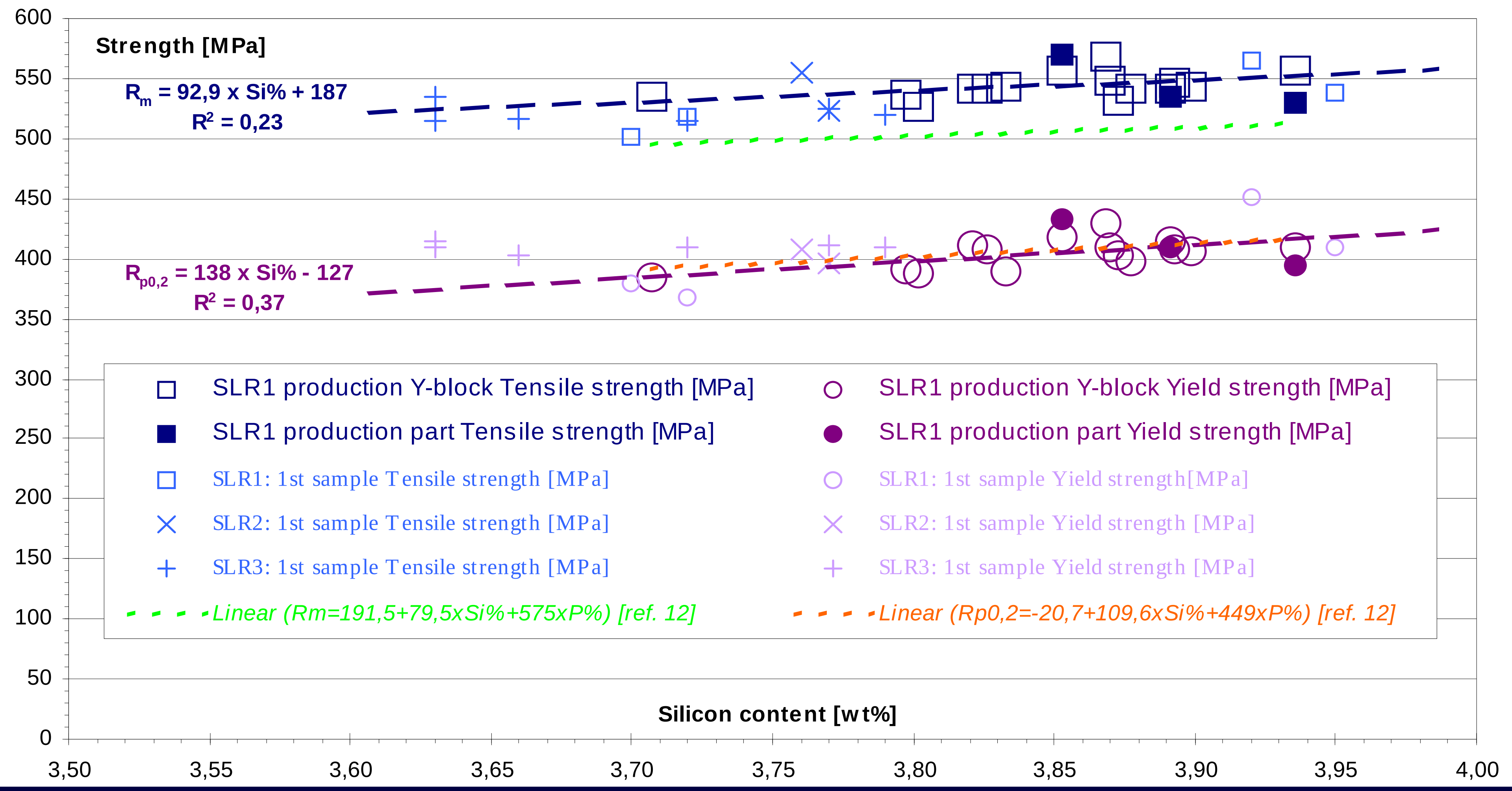
Hardness level vs. % Si during one year production:



Hardness level increases linearly with % Si (H = 54 + 37 x %Si), &

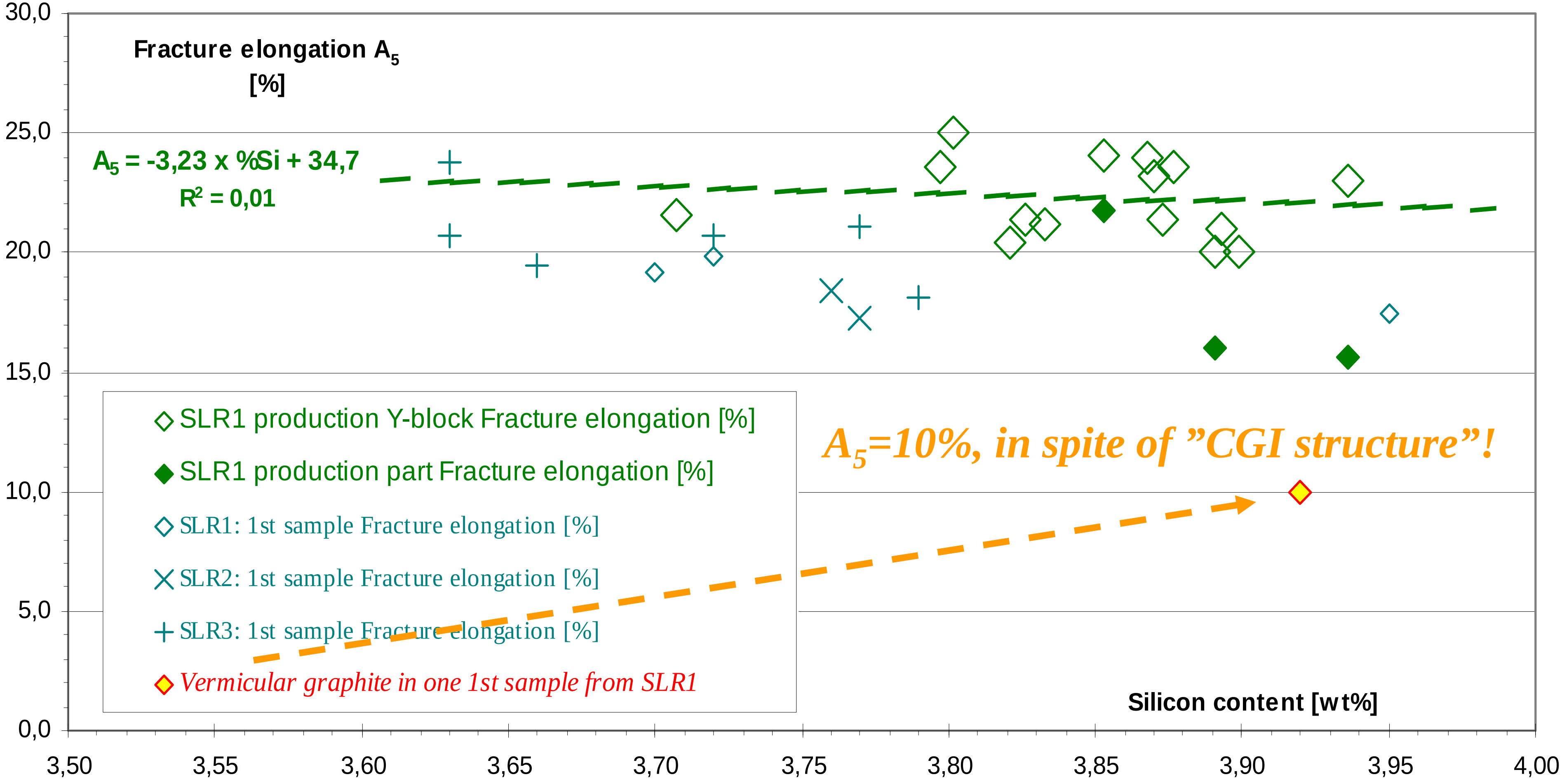
hardness scatter is drastically reduced (usually ±5 HB-units).

Strength levels vs. % Si during one year production:



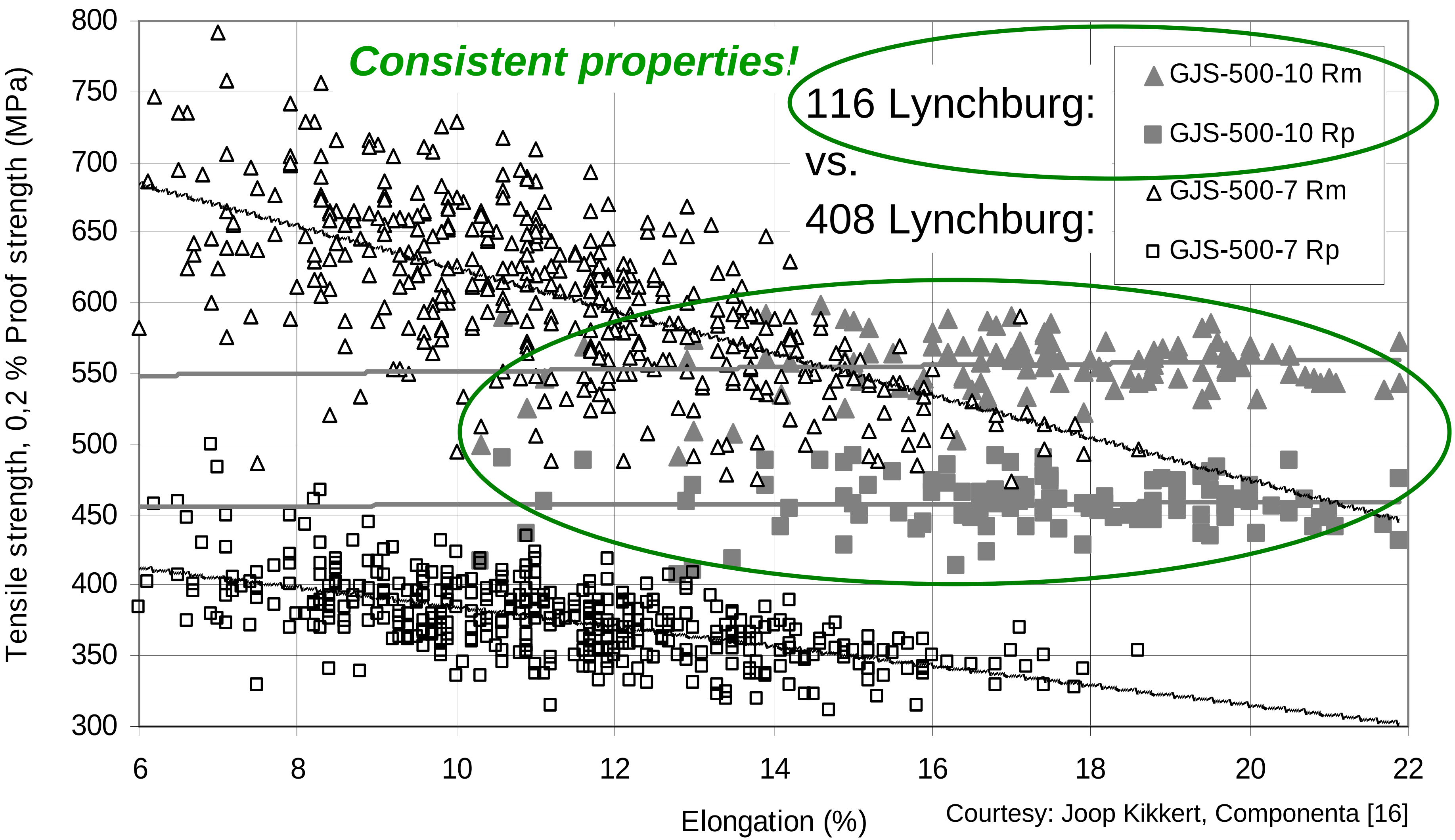
Strength levels increase linearly with % Si; $R_{p0.2}/R_m \approx 0.8$ (not 0.6).

Ductility level vs. % Si during one year production:



Ductility is *doubled* vs. JS/500-**7** & decreases linearly with % Si.

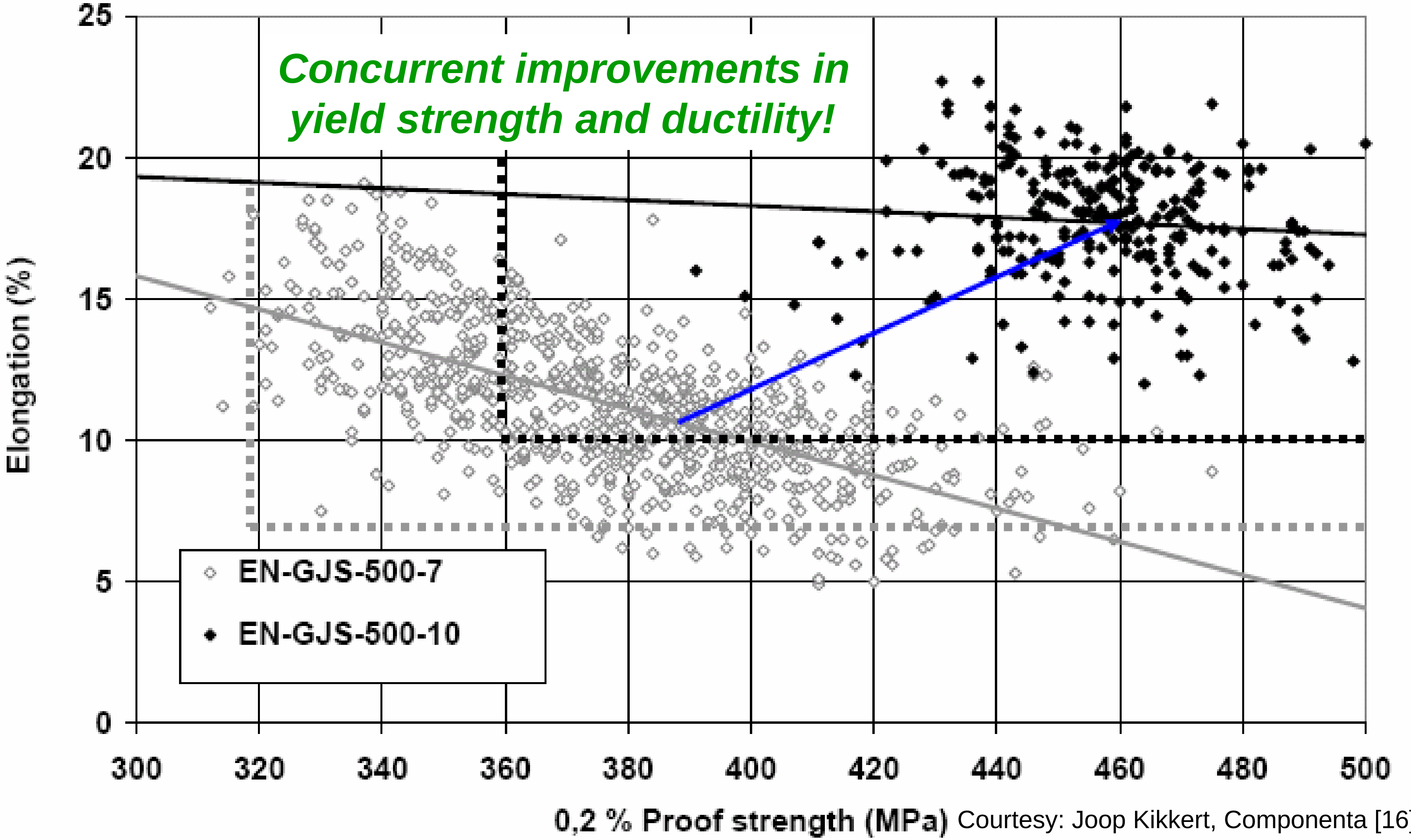
Comparison between JS/500-10 and JS/500-7:



Courtesy: Joop Kikkert, Componenta [16]

Scatter in ductility may, without pearlite, be attributed to graphite & porosity.

Comparison between JS/500-10 and JS/500-7:



Courtesy: Joop Kikkert, Componenta [16]

Prevailing ***misconceptions*** about raised Si-levels in DI:

#1: ”*High Si-levels makes ductile iron more* ***brittle*** *…”*

Already in the first ductile iron US Patent by Millis *et al* in 1949 [1], it was stated that *“… increasing the silicon content over these amounts (>2.5%) apparently lowers the mechanical properties, especially toughness, tensile strength and/or ductility …”.*

However, *all* iron alloys containing >2.5 wt% Si in their Tables V-VI (6 out of 54 alloys) *concurrently contained ≥0.8 wt% Mn, stabilizing* ***pearlite!***

This makes the conclusion about Si doubtful, especially since it was also stated that *“It is more preferred that the manganese content not exceed 0.3%, particularly when good ductility and/or high impact properties are desired”.*

High Mn levels (≥0.8 wt%) were probably also **responsible for low ADI ductilities (0.5-1.5%)** obtained in the pioneering austempering trials described in Table XIV of the same patent.

There is ***no doubt that solution strengthening by silicon has negative effects on reducing the impact energy of ferrite*** and increasing the notch-impact transition temp. ***N.B. Strain rates ≥5000 X slower in applications!***

This fact has commonly been presumed to represent a serious limitation, obviously *without considering that* the alternative & conventional path to reach higher strengths, namely to have a matrix with a substantial amount of harder but ***brittler*** **pearlite** ***also reduces notch-impact properties!***

At the *same* tensile strength level (500 MPa), ductile iron matrices with Si-solution strengthened ferrite vs. conventional structurally strengthened ferrite-pearlite show ***similar*** **Charpy behavior & energy levels** (while ferritic irons with lower Si & strength do show higher impact energies).

Regarding application-relevant properties **fatigue strength is *at least equal***, **fracture toughness** by J_{IC} & instrumented Charpy **is *slightly higher***, and as previously shown, **ductility is *considerably improved!***

Pearlite content embrittles far more at equal strength level!!

Prevailing ***misconceptions*** about raised Si-levels in DI:

#2: ”*High Si-levels increase risk for **chunky** graphite*”

The chunky graphite shape (instead of nodular) that may form in the interior of thicker castings may reduce $\mathbf{A_5}$ & $\mathbf{K_{IC}}$ by -50% and $\mathbf{R_m}$ & $\mathbf{R_{fatigue}}$ by -25%.

However, thicker castings are *usually loaded in bending* (not uni-axial tension), leading to *lower stress levels in the interior* where chunky graphite may form.

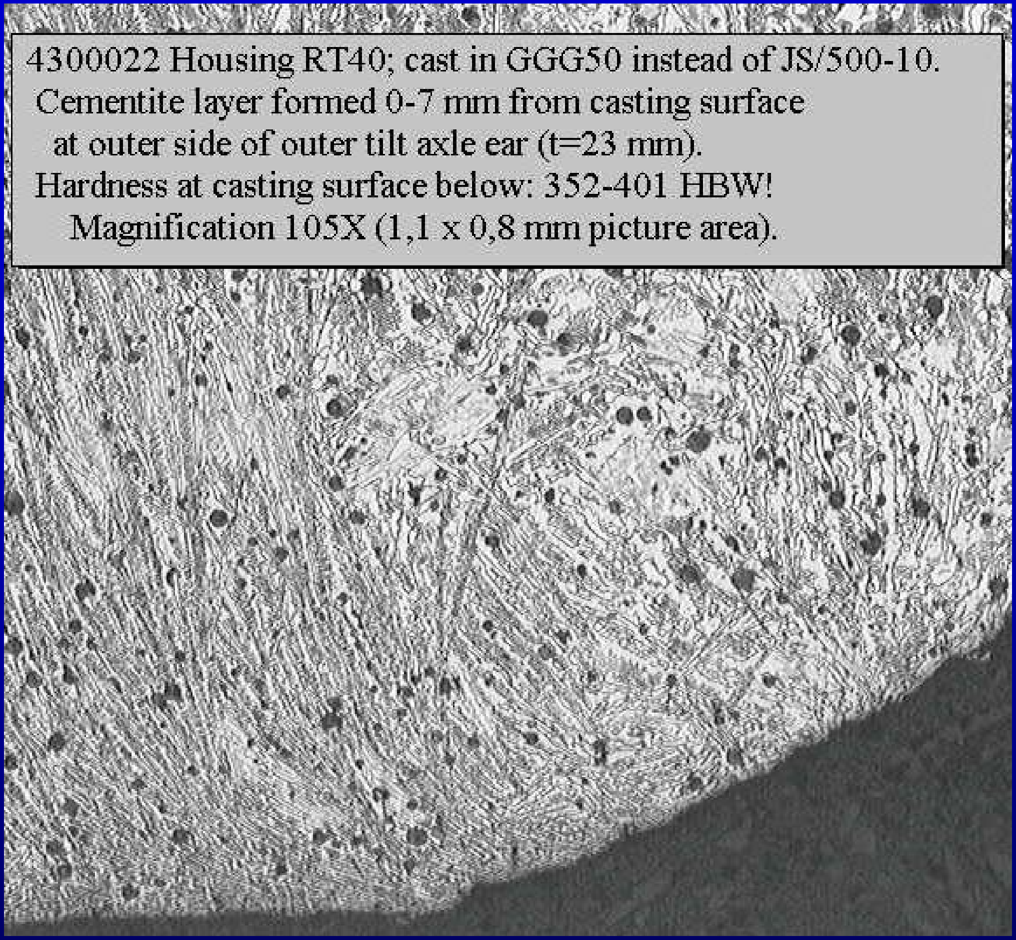
Further, according to the recent Swedish Dr.-Eng. Thesis by R. Källbom, ”*Chunky graphite in heavy section ductile iron castings*” (2006) [10], **the main reason is a too low oxygen content locally in the melt**, that can also be caused by other strong oxide formers like **Ce** & other RE, by Al & Ca.

To prevent chunky, it is recommended to **aim for a high nodule count**, to **use chills** (increased Si content reduces risk of white solidification!), to **avoid large risers** (partly substituted by less expensive chills!), and to **have balanced Ce + Sb contents**.

Recent ”porosity vs. Fe_3C” problem in JS/500-7:

Large cooling chills were used to avoid *shrinkage porosity in unsufficiently feeded* outer tilt axle ears.

This resulted in ***white*** *solidification* (cementite Fe_3C), making it brittle & very difficult to machine (400 HBW).



This is avoided when cast in JS/500-10, since silicon promotes grey solidification (graphite).

⇒ Greater freedom to use cheap chills, reducing costly feeders!

***Earlier shake-out (<750ºC) may also be possible*, since matrix will always be ferritic, independent of cooling rate at lower T!**

Another advantage: While pearlite-containing iron castings get a decarburized surface zone with lower strength (being ferritic with low Si), ferritic DI solution strengthened by silicon ***retains its strength out to the casting surface***, being especially valuable when as-cast surfaces are subject to fatigue loading.

Real **obstacles** for Si-solution strengthened DI:

#1: Large ***holding furnaces*** cause *difficulties for large Si changes (2.4%<=>3.7% Si)* between batches of different DI grades.

#2: Increased need for **low-alloyed scrap** (esp. low **Mn**), and maybe also some hypo-eutectic pig iron to keep CEL down when Si is raised.

#3: Lack of insight that the ***total production cost*** for manufacturing by machining of castings ***is the sum of three (3) categories*** *[11] :*

A. **Purchase price** (model cost + running part cost);

B. **Production cost** (strongly governed by ***consistent*** ***HBW & machinability***);

C. **Non-conformance cost** (interruptions & rejects related to castings, see B).

#4: ***Conservatism*** *&* ***Lack of knowledge*** at foundries & customers.

Other ”members” in Si-solution strengthened DI ”family”:

SS 140720 (3.2 % Si), standardized 1998 in Sweden: **(typical values)**

$R_m \geq$ 450 MPa (470-500); **$R_{p0.2} \geq$ 310 MPa** (70% of R_m) **(350-380);**

$A_5 \geq$ 12% (18-26); **H = 165-195 HBW (170-180).**

Test result with 4.44 wt% Si in thick sections:

R_m = 677 MPa; $R_{p0.2}$ = 557 MPa (83% of R_m)**; A_5 = 12.2%; H = 217 HBW.**

Compare with pearlithic-ferritic ISO 1083/JS/600-**3** (with $R_{p0.2} \geq$ **370** MPa)

and with fully pearlithic ISO 1083/JS/700-**2** (with $R_{p0.2} \geq$ **480** MPa)

Typical data for **SiMo irons** (3.7-5.2% Si + 0.6-0.9% Mo) for high temp. use:

R_m = 610-790 MPa; $R_{p0.2}$ = 460-630 MPa; A_5 = 16-7%.

Some increase in strength & decrease in ductility are here due to *Mo carbides*.

Conclusions:

For ductile irons with R_m = 500 MPa, **ductility is doubled** in Si-solution strengthened ferritic vs. conventional ferritic-pearlitic, combined with a **concurrent increase in $R_{p0,2}$**, raising $R_{p0,2}/R_m$ ratio from 0.6 to 0.8. Impact energy behavior is **comparable** & **fracture toughness is slightly better** vs. ferritic-pearlitic irons.

Ferritic ductile irons, solution strengthened by silicon to various superior combinations of mechanical and machining properties, ought to be entitled "***Second generation of ductile irons***".

The approaching ***"paradigm shift"*** towards the 2nd generation of ductile irons will, together with continued development of ausferritic ductile irons (ADI), further ***strengthen the cost-effectiveness of ductile irons & facilitate Lean Production***.

Thanks for Your attention!

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