Understanding hydrogen redistribution and designing a new hydrogen extraction method

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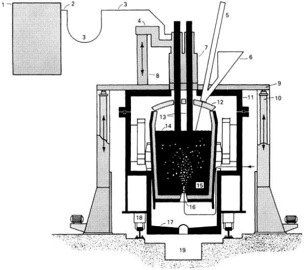
Embrittlement prevention methods



- At the design stage (material & component engineering)
- Extraction from liquid metal during refining (Vacuum, AOD, *et c.*)
- Extraction from solid at high temperature (very slow cooling & **directional cooling**: METAL2010, HSLA2011, Euromat2011, Steel & Hydrogen2014, *et c.*)
- Extraction by treating after cooling (Baking treatment: METAL2014)

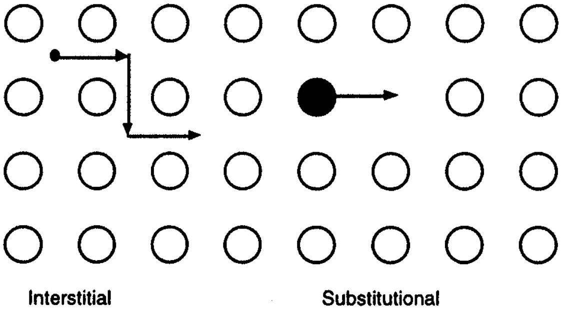
Can we still do anything else to reduce the incidence of hydrogen embrittlement in metals?

The Model

Let's start at the beginning:
Let's try and understand the redistribution of interstitial elements

An interstitial diffusion model

Interstitial diffusion: Hydrogen



Model: Diffusion

Characteristics of the model:

(METAL2010-2014, HSLA2011, EUROMAT2011, Steel& Hydrogen2014, *et c.*)

Thermal evolution and T gradients (Heat Equation)

Phase transitions from Liquid to α BCC (Thermodynamic Model)

Hydrogen diffusion as **random walk**, driven by **chemical activation** gradient

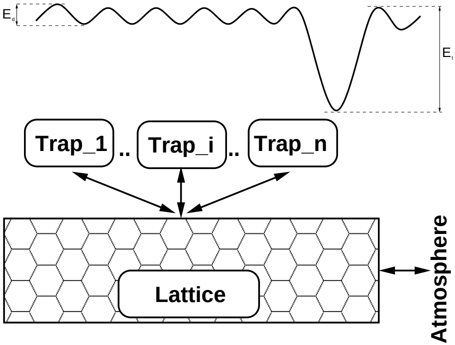
Interstitial solubility and saturation as function of temperature and matrix phase or trap type and distribution

Model: Trapping

Each trap type characterised by its characteristic release energy barrier

Interaction of each of the trap sites with lattice

Exchange with atmosphere at free surfaces: local equilibrium across the surface (Sievert's law)



Application to real processes

What can we do with this model? (Very briefly)

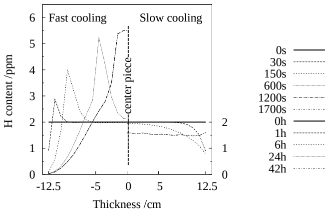
Analysis of Casting (or any cooling process)

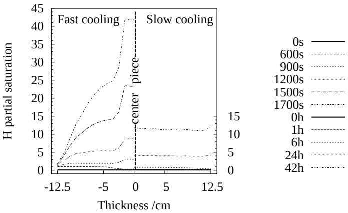
Development of new H extraction method

Analysis of Baking

... and much more!!

Analysis of Casting (or any cooling process)



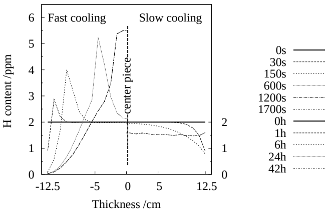


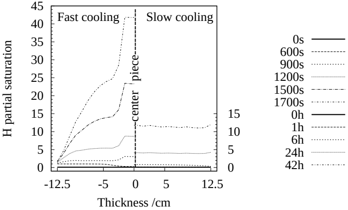
Steel: 25cm thick with 2ppm

Effect of cooling rate:

Fast cooling *vs.* Slow cooling

Analysis of Casting (or any cooling process)





Steel: 25cm thick with 2ppm

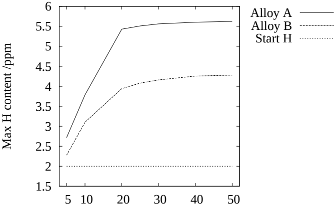
Effect of cooling rate:

Fast cooling *vs.* Slow cooling

Effect of thickness: (5-50cm)

Effect of FCC to BCC transformation temperature:

- Steel A: 700^{o}C *vs.* Steel B: 450^{o}C



Development of a new hydrogen extraction method

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"Understanding hydrogen redistribution during steel casting, and its effective extraction by thermally induced up-hill diffusion"
D. Gaude-Fugarolas, in: Journal of Iron and Steel Research International 18 supl.1.1 (2011) 159–163.

Also at proceedings: **High Strength Low Alloy (HSLA2011) International Conference, Beijing, China, 2011**.

Development of a new hydrogen extraction method

A severe temperature gradient forces hydrogen to flow towards the core region of a component, where it can reach severe supersaturation

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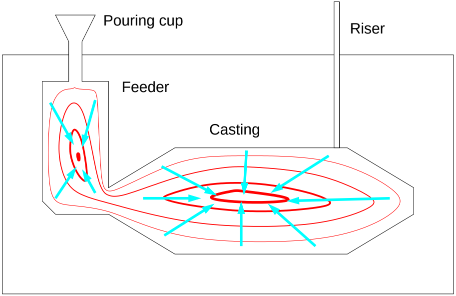
Actually, **NO!!**. The temperature gradient forces hydrogen to flow towards *higher temperature regions*!!

Then, why don't we try instead to redirect the hydrogen flux towards the surface?
(and eventually get rid of it)

Development of a new hydrogen extraction method

Standard casting operation: Interstitial element flux creates enriched regions at the core of the piece



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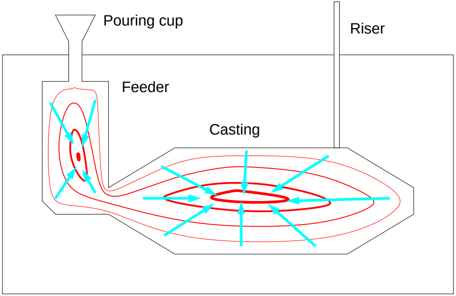
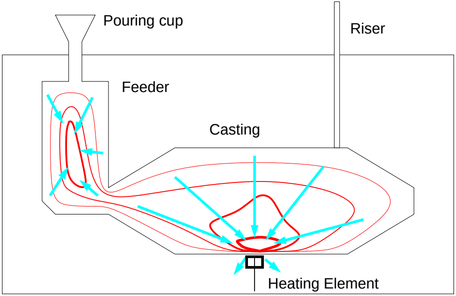
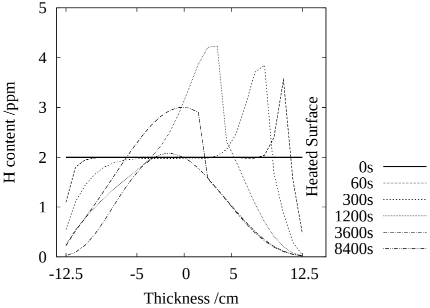
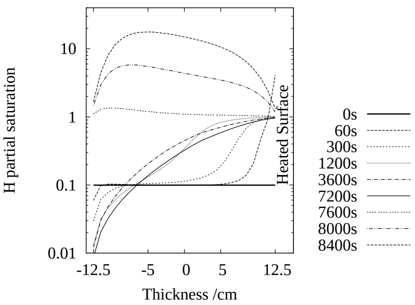


Modified casting operation with a severe thermal gradient towards the surface being imposed, eliminating interstitials



Development of a new hydrogen extraction method





Steel: 25cm thick with 2ppm

Surface I: Fast cooling

Surface II: Kept at high temperature (*i.e.* 1500°C)

Temperature gradient maintained 2h

Final H content 0.99ppm!! i.e 50% Reduction!!

Partial Saturation during treatment below 1.0 !!

Analysis of Baking

Analysis of Baking

"On the effectiveness of baking as hydrogen embrittlement reduction treatment"
D. Gaude-Fugarolas, in: Proceedings of METAL2014, 21-23 May, Brno, Czech Republic, 2014.

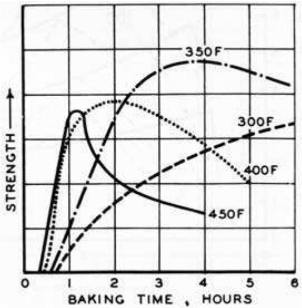
Treatment after cooling: Baking

Storage of the metal components in over at low warm temperature (typically 150-230 ^{o}C) for a long period, up to 24-48 hours.

The treatment aims to reduce internal stresses and to reduce hydrogen content.

If treatment is not performed immediately after casting and cooling, it might become ineffective.

Effectiveness of treatment varies.



Why does effectiveness of baking vary so much?

Analysis of Baking

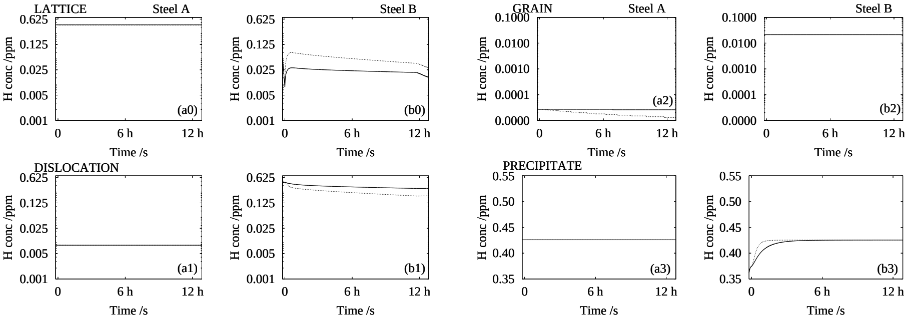
Hydrogen content: 1 ppm

Baking: 12h at 190^{o}C or 300^{o}C

Sites: Lattice, Dislocation, Grain boundary, Precipitate (& *Desorption to atmosphere*)

Steel A: Allotriomorphic Ferrite (725^{o}C), large grain, low dislocation density

Steel B: Bainitic/Martensitic Ferrite (450^{o}C), small grain, high dislocation density



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Conclusions on Baking

The success of baking depends of the **interaction** of hydrogen content, microstructure and trap distribution.

Some microstructures already **saturate** with low hydrogen contents, **making baking useless**.

In general, baking is only effective when the microstructure is **far below saturation**.

The **baking temperature** needs to be tailored to **trap type and H distribution**.

Some defects may even **increase** their H content during baking.

Future work

This is still work in progress...

- Surface defects
- Crack initiation
- H absorption from atmosphere

To be presented at, may be, **METAL2015, Brno, Czech Republic, May 2015.**

Conclusion

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To summarise...

- Small amounts of hydrogen can endanger the integrity of critical metal components.
- A physical model has been presented offering a correct description of hydrogen redistribution during manufacturing operations.
- Several methods exist to reduce hydrogen embrittlement in metal, but not always successful.
- A new method has been presented to reduce hydrogen content using of imposed temperature gradients.
- (**Patent** filed in US, Europe, China, *et c.*, Already **awarded** or in process, and open for **licensing**).

Thanks

Thank you for your attention!!

For more information, please visit (or email):
primeinnovation.net
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