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

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Bhadeshia’s bainite phase transformation theory

\[ \gamma \rightarrow \alpha_b \]

Alloy Design process

- Homogenisation
- Austenitisation
- Isothermal transformation
- Bs
- Ms

Graphs showing:
- Vickers Hardness vs. Temperature
- Thickness vs. Temperature

Micrograph showing:
- \( \gamma \)
- \( \alpha \)

- 20 nm scale
- 200°C 10d
High density strong interfaces \textit{nano} \( \alpha+\gamma \)

Displacive (\textit{Dislocations, Nano-twins}) & Diffusionless

200 \( ^\circ \)C for 2 days.
Austenite morphologies

Very different C content as size ↓ –↑ C – better mechanical response

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

\[ \Delta \sigma \approx 115 (2t)^{-1} \quad \Delta \sigma \approx 7.34 \times 10^{-6} (\rho)^{0.5} \]

\[ \text{Strengthening contribution / MPa} \]

\[ \text{Transformation temperature / } ^{\circ}\text{C} \]

Big potential foreseen

R+D

Steel Makers

Final User

Industriallization of NANOBAIN

Nanobain
Fundamental & Industrial Design Considerations

- Carbide free microstructure
- Simple alloy system
- Reasonable transformation time

Hardenability
- 700 x 400 x 250 mm³ → Salt bath
- 200 x 20 x 30 mm³ → DryBainTM

High fraction of bainitic ferrite

Low transformation temperatures

Approach

- Addition of 1.5Si wt.%
- Fe-C-Si-Mn-Cr
- Reduction of PAGS
  \[ \Delta G_{\gamma \rightarrow \alpha} \]

\[
\ln \left| \tau \frac{(\Delta F_m)^p}{T^\tau} \right| = \frac{Q'}{RT} + C_4
\]

\[ V_\alpha = f(To \ line,T) \]

\[
\Delta G_m < G_N \\
\Delta G_{\gamma \rightarrow \alpha} < -G_{SB} \\
\Delta G_{\gamma \rightarrow \alpha} \left\{ M_s \right\} < G_N^{\alpha'}
\]
### NANOBAIN steel

**Simple alloy system ✓**

**Low transformation temperatures ✓**

*(220ºC-350ºC)*

**NANO (plate thickness t) ✓**

**High fraction of bainitic ferrite (Vb) ✓**

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

![Graph showing Vb/ % and t/ nm at various temperatures](image)
Faster transformation ✔️

Suffice hardenability ✔️
**Strength / Ductility (Tensile test)**

**UTS > 2 GPa**

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Strength/MPa</th>
<th>Elongation/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1C-Nb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1C-Mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1C-2.5Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6C-Cr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6C-Nb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6C-Mo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- UTS > 2 GPa
- YS: Yield Strength
- UTS: Ultimate Tensile Strength
- Uniform: Uniform Yield Strength
- Total: Total Yield Strength

**Temperature:**
- 250°C
- 240°C
- 250°C
- 270°C

**Summary:**
- Various steels tested at different temperatures to determine their strength and ductility properties.
- Steels show varying strength and ductility characteristics under different conditions.
- 0.6C-Nb and 0.6C-Mo steels exhibit higher strength and lower elongation compared to others at 250°C.
Twin discs wear test, 100 rpm, 5% slip, 300N load, 5h

Wear properties: rolling-sliding wear tests

Hardness (HV0.5) vs. SWR (mm³/N.m)

Materials:
- 1C-250C
- 1CSi-250C
- 08C-220C
- 08C-220C
- 08C-270C
- 06C-250C
- 06CMo-250C
- 06CNb-250C
- 1C-250C
- 06CV-220C
- 06CV-280C
- 100Cr6-std
- 100Cr6-950C-250C
- 100Cr6-950C-300C
- 40CrSi8
- 60CrSi9
- 60SiCr7-250
- 60SiCr7-300
- 60SiCr7-350
- 60SiCr7-N
- 42CrMo4-B350
- 42CrMo4-B400
- 42CrMo4-QT

NANOBAIN

Wear properties: high pressure abrasion

Hardox (SSA)
0.3C-0.7Si-1.6Mn-1.5Cr-1.5Ni-0.6Mo (%wt.)
HV = 500; Tempered Martensite + austenite

200N
Δt = 2.5s
t = 30 min

Relative HPA wear (ref.: Hardox 500)

Toughness x Relative HPA wear (ref.: Hardox 500)
Fatigue properties: rotation bending on notched specimens.

<table>
<thead>
<tr>
<th>Condition</th>
<th>UTS / MPa</th>
<th>$S_a$, 50% at $10^7$ cycles / MPa for $R = -1$, $K_t = 1.6$ by rotation bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>1CNb-220-FAT</td>
<td>2073</td>
<td>430</td>
</tr>
<tr>
<td>06C-250-FAT</td>
<td>2023</td>
<td>665</td>
</tr>
<tr>
<td>08C-270-FAT</td>
<td>2036</td>
<td>440</td>
</tr>
</tbody>
</table>

- 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

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<tr>
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<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1CSi-ind</td>
<td>1.00</td>
<td>0.75</td>
<td>2.50</td>
<td>1.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>0.6CV-ind</td>
<td>0.60</td>
<td>1.25</td>
<td>1.60</td>
<td>1.75</td>
<td>0.15</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Industrial heats casted

Before fabricating a component or demonstrator

Battery of tests
Wear: rolling-sliding wear tests

Twin discs wear test, 100 rpm, 5% slip, 300N load, 5h
Wear properties: high pressure abrasion

Toughness x Relative HPA wear (ref: Hardox 500)

- 0.6CV 280°C
- 0.6CV 220°C
## Fatigue properties: rotation bending

<table>
<thead>
<tr>
<th>Condition</th>
<th>UTS / MPa</th>
<th>Stress amplitude, $\sigma_a$ / MPa for $R = -1$, $K_t = 1.6$ by rotation bending</th>
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<tr>
<td>1CNb-220-FAT</td>
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<td>08C-270-FAT</td>
<td>2036</td>
<td>440</td>
</tr>
<tr>
<td>1CSI-ind-220-FAT</td>
<td>2224</td>
<td>550</td>
</tr>
<tr>
<td>1CSI-ind-250-FAT</td>
<td>2072</td>
<td>535</td>
</tr>
<tr>
<td>06CV-ind-250-FAT</td>
<td>2003</td>
<td>690</td>
</tr>
<tr>
<td>06CV-ind-270-FAT</td>
<td>1822</td>
<td>675</td>
</tr>
</tbody>
</table>

Graph showing the relationship between stress amplitude and number of cycles to failure.

0.6CV @ 270°C
Fatigue properties: notched tension-tension specimens

Representative of the functioning of heavily loaded diesel engines

Kt = 2
R (stress ratio) = 0.1

150Hz

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<tr>
<th></th>
<th>06CV-250</th>
<th>06CV-270</th>
<th>1CSi-220</th>
<th>1CSi-250</th>
<th>100Cr6 [TLi, 1998]</th>
<th>50CrMo4 [SSc, 2012]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS / MPa</td>
<td>2003</td>
<td>1822</td>
<td>2224</td>
<td>2072</td>
<td>2350</td>
<td>1180</td>
</tr>
<tr>
<td>$S_{a,50% \text{ at } N = 10^7 \text{ cycles / MPa}}$</td>
<td>350</td>
<td>330</td>
<td>205</td>
<td>245</td>
<td>355</td>
<td>305</td>
</tr>
</tbody>
</table>
Small component High pressure injection (demonstrator)

- Internal pulsating amplitude $\Delta p/\text{bar}$
- Number of cycles to failure, $N_f$

Graph showing the relationship between internal pulsating amplitude and number of cycles to failure for different materials.

- 06CV-250
- 1CSi-250
Big component
Scrap shear blades (component)

0.6CV @ 280°C

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.*

\[
\Delta G_m < G_N \\
\Delta G_{\gamma \rightarrow \alpha} < -G_{SB}
\]