Large Chunks of Extremely Strong Steel

52nd Hatfield Memorial Lecture
an apple weighs
1 Newton

= 1 Pa

1 m
Tensile Strength / MPa

Whisker Diameter / μm

Pure iron
Brenner, 1956
Scifer, 5.5 GPa and ductile

Kobe Steel
1 Denier: weight in grams, of 9 km of fibre

50-10 Denier

Scifer is 9 Denier
Claimed strength of carbon nanotube is 130 GPa

Claimed modulus is 1.2 TPa
Terrones et al., Phil. Trans. Roy. Soc., 2004
tethered space elevator

Arthur C. Clark (1979)
geosynchronous orbit
strength 130 GPa
modulus 1.2 TPa

<table>
<thead>
<tr>
<th></th>
<th>J g(^{-1})</th>
<th>m s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamite</td>
<td>4650</td>
<td>6000</td>
</tr>
<tr>
<td>Nanotube</td>
<td>5420</td>
<td>21500</td>
</tr>
</tbody>
</table>
data from Pan et al. 1999, Yu et al. 2000
An equilibrium number of defects.

Strength of a nanotube rope 2 mm long is less than 2000 MPa
Summary

• Strength produced by deformation limits shape: wires, sheets...

• Strength in small particles relies on perfection. Doomed as size increases.
Smallest size that can be achieved in a polycrystalline substance?

\[ \Delta G_V = \sigma S_V \]
\[ \Delta G_V = \sigma S_V \]

\[ |\Delta G_V^{\gamma \alpha}| \geq \sigma_\alpha S_V^\alpha - \sigma_\gamma S_V^\gamma \]

\[ |\Delta G_V^{\gamma \alpha}| \geq \frac{2\sigma_\alpha}{L_\alpha} - \frac{2\sigma_\gamma}{L_\gamma} \]
\[
\Delta T_{\text{max}} \approx \Delta H / C_\gamma
\]

Yokota & Bhadeshia, 2004
Summary

Thermomechanical processing limited by recalescence

Need to store the heat
Reduce rate
Transform at low temperature
Swallow and Bhadeshia, 1996
Fe-2Si-3Mn-C wt%
Low transformation temperature
Bainitic hardenability
Reasonable transformation time
Elimination of cementite
Austenite grain size control
Avoidance of temper embrittlement

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<td>0.98</td>
<td>1.46</td>
<td>1.89</td>
<td>0.26</td>
<td>1.26</td>
<td>0.09</td>
<td>&lt; 0.002</td>
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Temperature vs. Time

**Homogenisation**
- 1200 °C
  - 2 days
  - slow cooling

**Austenitisation**
- 1000 °C
  - 15 min
  - Air cooling

**Isothermal transformation**
- 125 °C - 325 °C
  - hours-months
  - Quench
$B_s \approx 350^\circ C$

$M_s = 120^\circ C$
Cooking temperature? 180 to 220 °C
X-ray diffraction results

Temperature/°C

Percentage of phase

bainitic ferrite

retained austenite
Conclusions

Low temperature transformation: $0.25 \, \frac{T}{T_m}$

Fine microstructure: 20-40 nm thick plates

Carbide-free

Designed using theory alone

Typical mechanical properties:
2300 MPa, 27 MPa m$^{\frac{1}{2}}$
Faster Transformation

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Cobalt (1.5 wt%) and aluminium (1 wt%) increase the stability of ferrite relative to austenite.

Refine austenite grain size.
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<th>Beginning</th>
<th>End</th>
<th>% Bainite</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>4d</td>
<td>9d</td>
<td>69</td>
<td>618</td>
</tr>
<tr>
<td>Co</td>
<td>2d</td>
<td>5d</td>
<td>79</td>
<td>690</td>
</tr>
<tr>
<td>Co + Al</td>
<td>16h</td>
<td>3d</td>
<td>78</td>
<td>690</td>
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<tr>
<td>Original</td>
<td>5h</td>
<td>3/4d</td>
<td>63</td>
<td>550</td>
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<tr>
<td>Co</td>
<td>4h</td>
<td>11h</td>
<td>77</td>
<td>640</td>
</tr>
<tr>
<td>Co + Al</td>
<td>1h</td>
<td>8h</td>
<td>76</td>
<td>640</td>
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<tr>
<td>Original</td>
<td>2.5h</td>
<td>1/2d</td>
<td>55</td>
<td>420</td>
</tr>
<tr>
<td>Co</td>
<td>1h</td>
<td>5h</td>
<td>66</td>
<td>490</td>
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Fe-0.34C-5.08Cr-1.43Mo-0.92V-0.4Mn-1.07Si wt%
excess carbon in solid solution in ferrite!
Peet, Babu, Miller, Bhadeshia, 2004
Peet, Bhadeshia, 2004

0.79C-1.59Si-1.94Mn-0.02Ni-1.33Cr-0.3Mo-0.11V wt%
Hammond and Cross, 2004

Stress / GPa

Velocity km s$^{-1}$
GRP
mild steel
“superbainite”
vehicle steel
GRP

Peter Brown (DSTL)
Dave Crowther (QinetiQ)
“more serious battlefield threats”
ballistic mass efficiency

consider unit area of armour

\[ BME = \frac{\text{mass of ordinary armour to defeat given threat}}{\text{mass of test material to defeat same threat}} \]


30 Tesla field, 485 HV
Francisca Garcia Caballero
Carlos Garcia Mateo
Mathew Peet
Kazu Hase
Pippa Swanell
Tomoyuki Yokota
Mohamed Sherif
Howard Stone
Suresh Babu
Daniel Crespo
Marimuthu Murugananth

www.msm.cam.ac.uk/phase-trans