Microstructural Stability and Long-term Creep Strength of Grade 91 Steel

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Creep Strength Evaluation: Grade 91

![Graph showing creep strength evaluation for Grade 91 at different temperatures (500°C, 550°C, 600°C, 650°C) over time to rupture (in hours)].

- **Stress, MPa**
  - 500°C
  - 550°C
  - 600°C
  - 650°C

- **Time to rupture, h**
  - 10^3 to 10^6
## Materials: Grade 91 steels

### Chemical composition of the tube & plate steels

<table>
<thead>
<tr>
<th>Code</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGA</td>
<td>0.10</td>
<td>0.38</td>
<td>0.40</td>
<td>0.015</td>
<td>0.001</td>
<td>0.12</td>
<td>8.53</td>
<td>0.96</td>
<td>0.21</td>
<td>0.076</td>
<td>0.010</td>
<td>0.050</td>
</tr>
<tr>
<td>MGB</td>
<td>0.09</td>
<td>0.34</td>
<td>0.45</td>
<td>0.015</td>
<td>0.001</td>
<td>0.20</td>
<td>8.51</td>
<td>0.90</td>
<td>0.205</td>
<td>0.076</td>
<td>0.02</td>
<td>0.042</td>
</tr>
<tr>
<td>MGC</td>
<td>0.09</td>
<td>0.29</td>
<td>0.35</td>
<td>0.009</td>
<td>0.002</td>
<td>0.28</td>
<td>8.70</td>
<td>0.90</td>
<td>0.22</td>
<td>0.072</td>
<td>0.001</td>
<td>0.044</td>
</tr>
<tr>
<td>MgC</td>
<td>0.10</td>
<td>0.24</td>
<td>0.44</td>
<td>0.005</td>
<td>0.001</td>
<td>0.04</td>
<td>8.74</td>
<td>0.94</td>
<td>0.21</td>
<td>0.076</td>
<td>0.014</td>
<td>0.0582</td>
</tr>
</tbody>
</table>

### Heat treatment condition of the tube & plate steels

<table>
<thead>
<tr>
<th>Code</th>
<th>Dimension</th>
<th>Normalizing</th>
<th>Tempering</th>
<th>Stress Relieving</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGA</td>
<td>50.8 mm OD 8.0 mm t</td>
<td>1045°C, 10 min. A.C.</td>
<td>780°C, 60 min. A.C</td>
<td>-</td>
</tr>
<tr>
<td>MGB</td>
<td>50.8 mm OD 7.3 mm t</td>
<td>1050°C, 60 min. A.C.</td>
<td>760°C, 60 min. A.C</td>
<td>-</td>
</tr>
<tr>
<td>MGC</td>
<td>50.8 mm OD 8.0 mm t</td>
<td>1050°C, 10 min. A.C.</td>
<td>765°C, 30 min. A.C</td>
<td>-</td>
</tr>
<tr>
<td>MgC</td>
<td>2,200 mm w 50 mm t</td>
<td>1060°C, 90 min. A.C.</td>
<td>760°C, 60 min. A.C</td>
<td>730°C, 504 min. F.C</td>
</tr>
</tbody>
</table>
Microstructural Stability and Long-term Creep Strength of Grade 91 Steel

- Background
- Tensile Strength Property
- Creep Strength Property
- Microstructural Evolution
- Changes in Precipitates
- Summary
Tensile Strength Property

0.2% offset yield stress

Tensile strength

ASTM Grade 91

Temperature, °C

0.2% offset yield stress, MPa

Tensile strength, MPa

MGA
MGB
MGC
MgC
Tensile Strength Property

Rupture elongation

Reduction of area

[Graphs showing the relationship between temperature and rupture elongation/reduction of area for different materials at various ASTM Grade 91 temperatures.]
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Creep Rupture Strength

- No difference in short-term creep rupture strength
- Large variation in the long-term, especially at 600°C
Minimum Creep Rate

![Graph showing minimum creep rate for different temperatures and materials.](image)
A part of the specimens of the tube steels indicate ductility drop in the long-term beyond 10,000h.
Monkman-Grant Plot

- Monkman-Grant plot indicates a common linear relationship.
- Scatter band increases in the long-term. It seems to have a correlation with heat-to-heat variation of creep rupture strength in the long-term.
Variation of Creep Strength

Large heat-to-heat variation in the long-term at 600°C
Nickel Dependence

The Higher Nickel, The Lower Creep Rupture Strength in the Long-term
Rapid Acceleration of High Ni Heat

Creep rate, h⁻¹

Time, h

0 20,000 40,000 60,000 80,000 100,000

10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸

MGA (0.12%Ni)  
MGB (0.20%Ni)  
MGC (0.28%Ni)

in progress

0.20Ni

0.28Ni

0.12Ni

ASTM Gr.T91
600°C - 80MPa

Time to rupture, h

30 10¹ 10² 10³ 10⁴ 10⁵ 10⁶

MGC

550°C

600°C

650°C
Influence of Nickel

- Nucleation and growth of Z-phase is promoted by nickel.  
  *Strang and Vodarek (1998)*

- Coarsening of precipitates is promoted by nickel.  
  *Fujita, Yamashita and Miyake (1980)*

- It has been considered that degradation during long-term creep exposure is promoted by nickel.

- Nickel is recognized as one of the factors which cause heat-to-heat variation of creep rupture strength in the long-term.
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Recovery of Microstructure

MGC heat: 600°C

100MPa, $t_R=34,141\,\text{h}$

70MPa, $t_R=80,736\,\text{h}$

Overall grain interior is covered by equiaxed subgrains.

Preferentially recovered area is observed along grain boundary.
Hardness Drop during Creep Exposure

- Large difference in hardness between grip and gauge portion indicates that softening is promoted by stress.
- Large drop in hardness is observed beyond 30,000h at 600°C and 70MPa.
Microstructural Evolution

MGC heat: 600°C-70MPa, $t_R=80,736\,\text{h}$
Microstructural Evolution

- Large drop in hardness is observed beyond 30,000 h.
- However, magnitude of changes in subgrain size and dislocation density in the same time range is very small.
- Significant change in those are observed in excess of 70,000 h.
Microstructural Evolution

- Good correspondence between increase in strain and growth of subgrain is recognized in excess of 70,000 hours.
- However, large drop in hardness in excess of 30,000 hours cannot be explained by subgrain growth and decrease in dislocation density.
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Distribution of Precipitates

ASTM T91 (MGC)

As tempered

crept for 9,992 h

crept for 30,030 h

600°C - 70MPa

crept for 50,064 h

crept for 70,000 h

$t_R = 80,736.8$ h
Number Density of MX & Z-phase

- Nucleation of Z-phase was recognized after creep exposure for 10,000 h.
- Number density of MX particles decreases in excess of 30,000 h.
- The precipitation of Z-phase takes place as a consumption of MX particles.
- Creep rupture strength in the long-term is reduced by dissolution and decrease in number density of MX carbonitrides particles.
Influence of Nickel

**MGC heat: 0.28Ni**
600°C • 70MPa $t_R = 80736.8\,\text{h}$

**MgC heat: 0.04Ni**
600°C • 90MPa $t_R = 78236.5\,\text{h}$

- $\text{M}_{23}\text{C}_6$
- MX(V-rich)
- MX(Nb-rich)
- Z-phase
- Laves

area 1

area 2

National Institute for Materials Science

8th Int. Charles Parsons Turbine Conf., Portsmouth, UK, Sep. 5-8, 2011
Heat-to-heat variation of long-term creep rupture strength and good correspondence with nickel content was observed.

Decrease in creep strength during long-term creep exposure is caused mainly by dissolution and decrease in number density of MX carbonitrides particles.

Nickel is recognized as one of the factors which cause heat-to-heat variation of creep rupture strength in the long-term, therefore, nickel content should be reduced in order to suppress a strength drop in the long-term.
Thank You for Your Attention

Creep lab. in Meguro Campus of NIMS