High Strength Steels Treated by Quenching and Partitioning Process

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National Science Foundation of China
National Basic Research Program of China (973 programs No. 2010 CB630800)

June 28@ University of Cambridge, UK
Shanghai Jiao Tong University

40,275  Total number of students
18,000  Graduate students
18,275  Undergraduates
4,000   International students
2912   Full-time Faculty
687    Full professors
1039   Associate Professors
15     Academicians of Chinese Academy of Sciences
18     Academicians of Chinese Academy of Engineering
9      Lead Scientists of the National 973 Programs
44     National “Changjiang” Chair Professors
38     Recipients of National Science Funds for Outstanding Junior Faculty

For 2010
OUTLINE

• Introduction
• Quenching and Partitioning Treatment
  – Processing and Alloying
  – Microstructure and properties
  – Competing Process and Kinetics Models
    • Carbide formation and suppression
    • Migration of the martensite/austenite interface
    • Carbon partitioning and partitioning kinetics
• Combination of QPT with Hot Stamping and Application Concerns
• Unresolved Issues
• Concluding remarks
More steel is used than all other metals combined

“Steel is strong, tough, easily formed and cheap. Its uses range from ships to paper clips. More steel is used than all other metals combined”.

M. F. Ashby, D. Cebon, Teaching Engineering Materials: the CES EduPack
Large Quantity of Steel Products in China

Annual steel production in 2011 is 696 million tons, about 45.5% of the World.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>128</td>
<td>151</td>
<td>182</td>
<td>222</td>
<td>282</td>
<td>353</td>
<td>419</td>
<td>489</td>
<td>500</td>
<td>560</td>
<td>627</td>
<td>696</td>
</tr>
<tr>
<td>World</td>
<td>848</td>
<td>850</td>
<td>904</td>
<td>970</td>
<td>1069</td>
<td>1147</td>
<td>1251</td>
<td>1351</td>
<td>1327</td>
<td>1200</td>
<td>1414</td>
<td>1527</td>
</tr>
<tr>
<td>%</td>
<td>15.1</td>
<td>17.7</td>
<td>20.1</td>
<td>22.8</td>
<td>26.3</td>
<td>30.7</td>
<td>33.4</td>
<td>36.1</td>
<td>37.6</td>
<td>46.6</td>
<td>44.7</td>
<td>45.5</td>
</tr>
</tbody>
</table>
Large Quantity of Automobiles in China

Automobile annual sale in 2011 is 18.51 million, ranked No.1 in the world.
Automobile lightweight and Safety——
Strive to develop advanced high strength steel

Automobile lightweight is urgent measure under the pressure caused by environment and resource.

➢ ~8% petrol saved if automobile weight reduced 10%*.

Advanced high strength steel is the first choice of automobile structure materials

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Steel</td>
<td>2,180</td>
<td>1,751</td>
<td>1755</td>
<td>1,314</td>
<td>Down 866 lbs.</td>
</tr>
<tr>
<td>HSS and Bake Hard</td>
<td>140</td>
<td>324</td>
<td>327</td>
<td>325</td>
<td>Up 185 lbs.</td>
</tr>
<tr>
<td>Advanced / Ultra HSS</td>
<td>--</td>
<td>111**</td>
<td>149**</td>
<td>403**</td>
<td>Up 403 lbs.</td>
</tr>
<tr>
<td>Iron</td>
<td>585</td>
<td>290</td>
<td>284</td>
<td>244</td>
<td>Down 341 lbs.</td>
</tr>
<tr>
<td>Aluminum (includes castings)</td>
<td>84</td>
<td>307</td>
<td>327</td>
<td>369</td>
<td>Up 285 lbs.</td>
</tr>
<tr>
<td>Plastic/Composites</td>
<td>180</td>
<td>335</td>
<td>340</td>
<td>364</td>
<td>Up 184 lbs.</td>
</tr>
</tbody>
</table>

*: Takehide SENUMA, ISIJ International, 2001, 41, 520-532
*3rd generation AHSS*

- UTS > 1000 MPa
- Elongation 20% or more
- Low cost (alloying elements, processing)

**Feasible microstructure?**

**Challenge Opportunity**

1st AHSS
- <15000 MPa

2nd AHSS
- 50000 MPa

3rd AHSS
- 20000 MPa

3rd AHSS target microstructures

Matrix Strengthening  TRIP  Precipitates Strengthening

**Hard(M) + Soft(RA) + Precipitates**

Lath martensite + retained austenite + nano scale precipitate

Microstructure control

Local VS Overall !

Interface (Block & Packet)

Fraction / morphology / size etc. for Soft RA
Why lath martensite (∼ 0.4 C%)?

• Complicated microstructure for lath martensite
  – prior austenite grain
  – packet (habit plane)
  – block (OR)
  – lath (low angle)

• Several possible strengthening mechanism
  – Substantial and interstitial solid hardening
  – Dislocation strengthening, i.e. work hardening
  – Fine twins
  – Grain size
  – Segregation of carbon atoms
  – Precipitation of iron carbons

AHSS with high alloying elements (high cost)

<table>
<thead>
<tr>
<th>Steels</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Co</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Al</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF 1410E</td>
<td>0.16</td>
<td>10.05</td>
<td>1.99</td>
<td>1.01</td>
<td>13.80</td>
<td>0.16</td>
<td>0.051</td>
<td>0.01</td>
<td>0.01</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>AerMet100</td>
<td>0.24</td>
<td>11.08</td>
<td>3.04</td>
<td>1.20</td>
<td>13.40</td>
<td>0.01</td>
<td>0.001</td>
<td>0.01</td>
<td>0.0099</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>4340</td>
<td>0.40</td>
<td>1.78</td>
<td>0.79</td>
<td>0.26</td>
<td>0.69</td>
<td>0.26</td>
<td>0.031</td>
<td>0.003</td>
<td>0.016</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Variation of yield and ultimate strength as a function of tempering temperature.

Box: AF 1410 E + 1Cr; diamond: AF 1410E; and triangle: AerMet 100.

Effect of tempering on Charpy notch toughness of AF 1410E and AF 1410E + ICr steels

Progress II: Steels with Enhanced Toughness

- 0.4C-2Si-1Cr-1Mo

**nanoprecipitation on suitable matrix**

<table>
<thead>
<tr>
<th>Processing</th>
<th>500-600°C tempering</th>
<th>500°C C+1.7 (Strain Ageing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS (MPa)</td>
<td>1770</td>
<td>1850</td>
</tr>
<tr>
<td>YS (MPa)</td>
<td>1470</td>
<td>1840</td>
</tr>
<tr>
<td>A (%)</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>VE (J)</td>
<td>14</td>
<td>226</td>
</tr>
</tbody>
</table>

Lath martensite + nano precipitate = “bamboo”

Dispersed nano precipitation

Progress III: Nano bainite steels

Nano scale microstructure

Nano ferrite + nano austenite = nano bainite

### Phase composition and grain size refinement

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Parameters</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single phase (Mild steel)</td>
<td>- Grain size &lt;br&gt; - Grain shape</td>
<td>$\alpha = $ ferrite</td>
</tr>
<tr>
<td>Two phase (Dual phase steel)</td>
<td>- Grain sizes &lt;br&gt; - Volume fractions &lt;br&gt; - Local chemical composition</td>
<td>$\alpha = $ ferrite &lt;br&gt; $\alpha' = $ martensite</td>
</tr>
<tr>
<td>Multi phase (TRIP steel)</td>
<td>- Grain sizes &lt;br&gt; - Volume fractions &lt;br&gt; - Local chemical composition &lt;br&gt; - Phase stability</td>
<td>$\alpha = $ ferrite &lt;br&gt; $\alpha_B = $ bainite &lt;br&gt; $\gamma_R = $ retained austenite</td>
</tr>
</tbody>
</table>

**Local chemical composition & Phase stability!**


Viewpoint: Routine for achievement of finer microstructure by combination of phase transformation and deformation in steels

Figure 1. Three different sequences combining phase transformation and plastic deformation for the fabrication of nanostructured metals. (i) Plastic deformation of the mother phase prior to phase transformations. (ii) Plastic deformation after phase transformation. (iii) Repetition of plastic deformation and phase transformation.

Figure 2. Three typical microstructures obtained by phase transformation in steels. (a) Ferrite structure. (b) Pearlite structure. (c) Martensite structure.


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* Schematic Process for QP & QPT

**Quenching:** Fraction of Martensite  
**Partitioning:** Carbon diffuse into residual austenite

- **C-Si-Mn**
- **Temperature**
- **Ac₃**
- **Ms**
- **Mf**
- **Cγ = Ci**
- **Cm = Ci**
- **Cγ > Ci**
- **Cm < Ci**
- **15000MPa·%**

**Tempering:** for precipitation

**Speer & Edmonds, 2003, QP**  
**T. Y. Hsu, 2007, QPT**

- Microalloying + tempering = strengthening by precipitation
- > 15000MPa·%
Although high carbon content is beneficial for strengthening, embrittlement is along with it, therefore, low carbon (<0.5wt%) is necessary. Krauss revealed that >0.5% of carbon content in carbon and low alloyed steels would lead quench and temper embrittlement resulted from cementite formation (G. Krauss. Metall. Trans., 2001, 32B: 205-221.)

1) Composition of steels feasible for QPT Treatment

Designed chemical compositions:
as <0.5C, 1.5Si(or Al), 1.5Mn with(or without) 0.2Mo and 0.02Nb(mass%).

fine lath martensite; dispersed complex or ε(η) carbide precipitated in martensite and retained austenite with certain carbon content, and considerable thickness as well as fine grain size of original austenite.
First try for a TRIP with high Si by J Speer et al

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Si</td>
<td>0.15</td>
<td>1.5</td>
<td>0.3</td>
<td>0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>High Si</td>
<td>0.15</td>
<td>1.5</td>
<td>1.6</td>
<td>0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>Al</td>
<td>0.15</td>
<td>1.5</td>
<td>0.1</td>
<td>0.005</td>
<td>1.9</td>
</tr>
<tr>
<td>P</td>
<td>0.15</td>
<td>1.5</td>
<td>0.3</td>
<td>0.1</td>
<td>0.03</td>
</tr>
</tbody>
</table>

% γ, before isothermal transformation at lower hase lower-carbon austenite. Microstructures Figure 5. At 300°C the microstructure is lath the holding time increased, the lath features in (b) and (c), presumably a result of an etching this temperature, in contrast to the behavior discussed above for the intercritically annealed condition. While retained austenite is usually not expected in 0.15 wt.% C martensite, a small amount was detected by x-ray diffraction, possibly indicating some carbon partitioning between the martensite and austenite prior to final cooling to room temperature.


96200

<table>
<thead>
<tr>
<th></th>
<th>Weight %</th>
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<tbody>
<tr>
<td>C</td>
<td>0.56-0.64</td>
</tr>
<tr>
<td>Mn</td>
<td>0.75-1.00</td>
</tr>
<tr>
<td>P</td>
<td>0.035 (max)</td>
</tr>
<tr>
<td>S</td>
<td>0.04 (max)</td>
</tr>
<tr>
<td>Si</td>
<td>1.80-2.20</td>
</tr>
</tbody>
</table>

1700 MPa @ 8 % for QT at 425°C

4) Evidence for carbon partitioning

TABLE I. Activation energies in kilojoule per mole associated with the observed exothermic DSC peaks.

<table>
<thead>
<tr>
<th></th>
<th>Peak 1</th>
<th>Peak 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q&amp;P 350 °C 10 s</td>
<td>92</td>
<td>172</td>
</tr>
<tr>
<td>WQ</td>
<td>170</td>
<td></td>
</tr>
</tbody>
</table>

TABLE II. Reported activation energies in kilojoule per mole for tempering stages, bainite formation, and element diffusion.

<table>
<thead>
<tr>
<th>Stage</th>
<th>E (kJ/mol)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempering stages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C clustering</td>
<td>67–91</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>68–94</td>
<td>7</td>
</tr>
<tr>
<td>e/η formation</td>
<td>102–135</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>111–118</td>
<td>7</td>
</tr>
<tr>
<td>γret decomposition</td>
<td>127</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>174</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>202</td>
<td>19</td>
</tr>
<tr>
<td>Cementite formation</td>
<td>233</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>227</td>
<td>14</td>
</tr>
<tr>
<td>Bainite formation</td>
<td>45</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>23</td>
</tr>
<tr>
<td>Diffusion in bcc Fe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe pipe diffusion</td>
<td>152</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>84</td>
<td>18</td>
</tr>
</tbody>
</table>

0.20C-1.63Mn-1.63Si

DSC heat flow as a function of temperature obtained after heating the CMnSi Q&P steel

associated with austenite decomposition

associated with carbon partitioning
Case 2) Quenching Tempering VS Quenching Partitioning

- 0.41C-1.27Si-1.30Mn-1.01Ni-0.56Cr

martensite

QP190-425-30s

QP190-425-30s

QP190-350-30s

QP190-350-30s

QP-190-425-30s

QP-190-350-30s

Q in water

Precise control of multi-scale structure

3) Epsilon precipitating during one-step QPT

Table 1 Chemical compositions of the steel in this study (wt.%)  

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>$M_s$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.41</td>
<td>1.27</td>
<td>1.30</td>
<td>1.01</td>
<td>0.56</td>
<td>277</td>
</tr>
</tbody>
</table>

QPT treatment for a medium carbon steel

Transition carbide precipitation in the midrib of plate martensite during quenching and partitioning at 180°C for 180s
4) Low bainite transformation during QPT treatment

- 0.41C-1.27Si-1.30Mn-1.01Ni-0.56Cr

Interior maintained at low level of carbon enable the bainite transformation during partitioning and tempering

Strengthening by Precipitation

TRIP 600
Fe-0.2C-1.53Si-1.46Mn

Fe-0.2C-1.5Mn-1.5Si-0.05Nb-0.13Mo
QT=220 C and PT=400 C (Ms=370 C)
1500MPa & 15%

Microstructure and properties for a medium carbon steel subjected to QPT


Fe-0.2C-1.5Mn-1.5Si-0.05Nb-0.13Mo
> 1500MPa & 15%

Low alloying elements
Low cost of processing

Martensite and austenite in nano scale
Nano precipitates

Low cost of processing

Multiphase Multiscale Metastable microstructure

Film-like retained austenite

Lath martensitic matrix

Secondary martensite

Island-like / bulky retained austenite

Submicron-scale lath martensite or bainite matrix within which uniformly distributed fine carbides with average size of several nanometers plus submicron-scale island-like metastable RA or polygonal ferrite and film-like RA with film width of dozens of nanometers.

Discussion
Third Generation AHSS property band

Tensile specimen geometry is well known to influence the measured value of total ductility.
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Combination with Hot Stamping

Control of microstructure through carbon partitioning!

1500 MPa
6 % elongation
Chemical compositions (wt. %) of both steels

<table>
<thead>
<tr>
<th>steel</th>
<th>steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>B</th>
<th>Al</th>
<th>P</th>
<th>S</th>
<th>Ms</th>
<th>Mf</th>
<th>Ae3</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>22MnB5</td>
<td>0.22</td>
<td>1.58</td>
<td>0.81</td>
<td>0.022</td>
<td>0.0024</td>
<td>-</td>
<td>0.0064</td>
<td>0.0014</td>
<td>378°C</td>
<td>265°C</td>
<td>800°C</td>
</tr>
</tbody>
</table>

CCT graphs for Steel A and Steel B with grain size 9 ASTM and austenitisation of 669.26°C.
22SiMn2TiB steel with $\text{Ms}=378^\circ\text{C}$ and $\text{Mf}=265^\circ\text{C}$
Preliminary results: Mechanical properties for specimens by combination of hot stamping and QPT

Table 1. The mechanical properties and amount of retained austenite after quenching at different temperatures.

<table>
<thead>
<tr>
<th>Quenching temperature (°C)</th>
<th>Partitioning time (s)</th>
<th>Volume fraction of retained austenite (%)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Yield strength ($\sigma_{0.2}$) (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>10</td>
<td>&lt;1</td>
<td>1632 ± 4</td>
<td>850 ± 3</td>
<td>6.6 ± 0.5</td>
</tr>
<tr>
<td>280</td>
<td>10</td>
<td>5.0 ± 0.5</td>
<td>1601 ± 5</td>
<td>720 ± 3</td>
<td>10.3 ± 1</td>
</tr>
<tr>
<td>300</td>
<td>10</td>
<td>10.1 ± 0.1</td>
<td>1576 ± 5</td>
<td>696 ± 3</td>
<td>11.3 ± 1</td>
</tr>
<tr>
<td>320</td>
<td>10</td>
<td>15.6 ± 1</td>
<td>1522 ± 5</td>
<td>665 ± 3</td>
<td>12.6 ± 1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>17.3 ± 1</td>
<td>1569 ± 5</td>
<td>660 ± 3</td>
<td>13.5 ± 1</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>18.5 ± 1</td>
<td>1510 ± 5</td>
<td>655 ± 3</td>
<td>14.8 ± 1</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>16.6 ± 1</td>
<td>1562 ± 5</td>
<td>658 ± 3</td>
<td>12.9 ± 1</td>
</tr>
</tbody>
</table>

### Finer Microstructure

#### Optical image

- Martensite

#### TEM for martensite

- Martensite
- Dislocations

#### Austenite in BF

#### Schematic representation of microstructure

<table>
<thead>
<tr>
<th></th>
<th>Austenitizing</th>
<th>After quenching</th>
<th>After partitioning</th>
<th>After Q&amp;P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Undeformed austenite</strong></td>
<td><img src="hexagon" alt="Diagram" /></td>
<td><img src="after_quenching" alt="Diagram" /></td>
<td><img src="after_partitioning" alt="Diagram" /></td>
<td><img src="after_Q&amp;P" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Deformed austenite</strong></td>
<td><img src="deformed_austenite" alt="Diagram" /></td>
<td><img src="deformed_austenite" alt="Diagram" /></td>
<td><img src="deformed_austenite" alt="Diagram" /></td>
<td><img src="deformed_austenite" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Preliminary result of laser welding

- 0.41C-1.27Si-1.30Mn-1.01Ni-0.56Cr

After QPT, 1800 MPa @ 14% El, **original**

Tensile strength of 1600 MPa and elongation of 5-6% **after laser welding**.
Fracture toughness measurement

Three point bend  SE(B)
Arc-shaped bend  A(B)
Compact  tensile  C(T)
DENT test

- Ductile tearing resistance measured by the essential work of fracture ($w_e$)
- Critical crack Tip Opening Displacement ($\delta_c$)
- Fracture toughness at cracking initiation ($J_{IC}$)
- Linear-Elastic Plane-Strain Fracture Toughness $K_{IC}$

Transformation Induced Plasticity (TRIP) steel sheet with thickness about 1.4mm
DENT specimens for tensile test

Transformation Induced Plasticity (TRIP) steel sheet with thickness about 1.4mm

# Q&P Properties

<table>
<thead>
<tr>
<th>PT-time °C-s</th>
<th>UTS MPa</th>
<th>YS MPa</th>
<th>EL %</th>
<th>$w_e$ KJ.m$^{-2}$</th>
<th>$J_{IC}$ KJ.m$^{-2}$</th>
<th>$\delta_C$ µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>260-60</td>
<td>1485.37</td>
<td>1021.92</td>
<td>7.8</td>
<td>$329 \pm 31$</td>
<td>$136 \pm 56$</td>
<td>$327 \pm 15$</td>
</tr>
<tr>
<td>280-60</td>
<td>1339.82</td>
<td>892</td>
<td>9.2</td>
<td>$317 \pm 27$</td>
<td>$182 \pm 41$</td>
<td>$382 \pm 8$</td>
</tr>
<tr>
<td>300-60</td>
<td>1220.05</td>
<td>858.5</td>
<td>11.54</td>
<td>$424 \pm 31$</td>
<td>$268 \pm 39$</td>
<td>$552 \pm 11$</td>
</tr>
<tr>
<td>320-60</td>
<td>1296.58</td>
<td>920.48</td>
<td>13.2</td>
<td>$451 \pm 26$</td>
<td>$283 \pm 35$</td>
<td>$699 \pm 6$</td>
</tr>
<tr>
<td>340-60</td>
<td>1314.79</td>
<td>901.03</td>
<td>12.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360-60</td>
<td>1239.72</td>
<td>875.48</td>
<td>12.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>380-60</td>
<td>1208.6</td>
<td>903.27</td>
<td>10.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Q&P steel QT=320°C for 60 seconds
Fractography

average volume fraction of retained austenite of TRIP steel

OUTLINE

• Introduction
• Quenching and Partitioning Treatment
  – Processing and Alloying
  – Microstructure and properties
  – Competing Process and Kinetics Models
    • Carbide formation and suppression
    • Migration of the martensite/austenite interface
    • Carbon partitioning and partitioning kinetics
• Combination of QPT with Hot Stamping and Application Concerns
  • Unsolved Issues
• Concluding remarks
Unsolved Issues

1. Quantitative modeling for work hardening of multi-phase steels correlated with TRIP effect
2. Strategy of designing/selecting process with proper alloying for automobile
3. Kinetics of competing processes
1. Quantitative modeling for work hardening of multi-phase steels

- TRIP-assisted: how quantitatively to evaluate cooperative effect of multi-phase
- Work hardening: how to optimize plastic deformation and transformation in order to beat necking
- Length scale / multi-scale
  - Precipitation VS effective grain or sub-grain size
  - Toughness VS strength
Deformation induced martensitic transformation and transformation induced plasticity

- Martensite morphology (lath or epsilon)
- Stability of austenite
- Temperature difference between $M_s$ and $M_d$ with $M_s(\sigma)$ just below ambient

I. Tamura
Metal Science Vol. 16 May 1982 245
TRIP effect for multi-phase system

- 15% * 0.15 = 2.25% directly from TRIP effect
- In addition to plastic deformation and TRIP effect, cooperative interaction between different phases may take effect!
- Partition of stress and strains

In a tensile test the effect of constraint due to the grips is to cause the sample to rotate [e.g. Ref. 5)] making $\mathbf{v} \parallel \mathbf{u}$ so that the net strain along the tensile axis is given by

$$1 - |\mathbf{v}| / |\mathbf{u}| = 0.15$$

Fig. 1. An invariant-plane strain with a shear $s$ and dilatation $\delta$. The coordinates $z_i$ represent an orthonormal set in which $z_3$ is normal to the invariant-plane and $z_1$ is parallel to the shear direction. (Z P Z) is the deformation matrix describing the strain.
Work hardening

- Plastic deformation / pile-up of dislocations
- Harder martensite induced by deformation
- Optimize the stability to beat the necking where unstable plastic deformation takes place
  - Especially in the late stage during deformation
  - Md30, temperature where half of austenite has been transformed to austenite under 30% true deformation strain
  - Designing by composition, effective phase size, location, morphology, so on of retained austenite
Optimizing the stability of retained austenite

Modified rule of mixture with damage model

Fig. 3. Martensitic volume fraction mechanically transformed under various stability conditions of retained austenite corresponding to Table 2.

Fig. 9. A design application of TRIP-aided multiphase steel.

Heung Nam Hana,* Chang-Seok Ohb, Gyosung Kimc, Ohjoon Kwonc Materials Science and Engineering A 499 (2009) 462–468
EFFECT OF RETAINED AUSTENITE ON THE YIELDING AND DEFORMATION BEHAVIOR OF A DUAL PHASE STEEL

ANIL K. SACHDEV

Metallurgy Department, General Motors Research Laboratories, Warren, MI 48090-9055, U.S.A.

Table 1. Chemical analysis and average tensile properties of the dual-phase steel used in this study

<table>
<thead>
<tr>
<th>Chemical analysis (wt.%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.12</td>
</tr>
<tr>
<td>N</td>
<td>0.007</td>
</tr>
<tr>
<td>Mn</td>
<td>1.44</td>
</tr>
<tr>
<td>Si</td>
<td>0.50</td>
</tr>
<tr>
<td>V</td>
<td>0.061</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tensile properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>367 MPa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>639 MPa</td>
</tr>
<tr>
<td>Uniform elongation</td>
<td>23%</td>
</tr>
<tr>
<td>Total elongation</td>
<td>32%   (50 mm gage)</td>
</tr>
</tbody>
</table>

Fig. 3. Incremental strain hardening exponent \( (n_i) \) vs true strain for the various testing temperatures. The solid circles indicate the uniform elongation measured at the maximum tensile load.
Mn-Duplex stainless TRIP steels with 1GPa@60%

\[(\text{Fe-19.9Cr-0.42Ni-0.16N-4.79Mn-0.11C-0.46Cu-0.35Si}, \text{ wt.\%})\]

Hot-rolling + Cold-rolling + Recrystalinzation

\(\text{Md}_{30}=64.0 \text{ C}\)

28.1C for 1.4362

C. Herrera, D. Ponge, D. Raabe
Acta Materialia 59 (2011) 4653–4664
Alternative mechanisms of plasticity/toughness due to retained austenite beside to TRIP

• Blocking crack propagation, BCP


• Dislocation absorption by retained austenite, DARA


Table 4.1 Microstructure parameters of martensite and retained austenite in tensile samples at different strain stages after the Q-P-T treatment

<table>
<thead>
<tr>
<th>Strain</th>
<th>$(\varepsilon_M^2)^{1/3}$ ($\times 10^{-3}$)</th>
<th>$\rho_{M1}$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$\rho_{M2}$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$\bar{\rho}_M$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$(\varepsilon_{RA}^2)^{1/3}$ ($\times 10^{-3}$)</th>
<th>$\rho_{s1}$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$\rho_{s2}$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$\bar{\rho}_s$ ($\times 10^{14}$ m$^{-2}$)</th>
<th>$V_{RA}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2.52±0.06</td>
<td>7.29±0.25</td>
<td>7.23±0.21</td>
<td>7.26±0.23</td>
<td>2.25±0.29</td>
<td>13.66±0.89</td>
<td>8.32±0.71</td>
<td>10.99±0.80</td>
<td>13.2</td>
</tr>
<tr>
<td>1%</td>
<td>2.36±0.06</td>
<td>7.01±0.23</td>
<td>6.24±0.18</td>
<td>6.63±0.21</td>
<td>2.53±0.25</td>
<td>16.46±1.32</td>
<td>20.83±1.44</td>
<td>18.65±1.38</td>
<td>11.3</td>
</tr>
<tr>
<td>3%</td>
<td>2.24±0.07</td>
<td>5.82±0.23</td>
<td>6.13±0.23</td>
<td>5.98±0.23</td>
<td>3.07±0.37</td>
<td>27.29±2.88</td>
<td>26.65±2.69</td>
<td>26.97±2.79</td>
<td>8.2</td>
</tr>
<tr>
<td>5%</td>
<td>2.19±0.09</td>
<td>5.86±0.26</td>
<td>5.55±0.24</td>
<td>5.71±0.25</td>
<td>3.42±0.44</td>
<td>37.31±3.20</td>
<td>30.56±3.43</td>
<td>33.94±3.32</td>
<td>5.5</td>
</tr>
<tr>
<td>7%</td>
<td>2.29±0.08</td>
<td>6.46±0.25</td>
<td>6.00±0.27</td>
<td>6.23±0.26</td>
<td>3.71±0.45</td>
<td>39.86±4.21</td>
<td>42.19±4.50</td>
<td>41.03±4.36</td>
<td>4.2</td>
</tr>
</tbody>
</table>

how quantitatively to evaluate cooperative effect of multi-phase
2. Strategy of designing/selecting process with proper alloying for automobile (AHSS)

- DP
- TRIP
- TWIP
- QP

Microstructure of Metastable Multi-scale Multi-phase

- Composition
- Processing


Effect of deformation on hydrogen trapping and effusion in TRIP-assisted steel

Joo Hyun Ryu\textsuperscript{a}, Young Soo Chun\textsuperscript{c}, Chong Soo Lee\textsuperscript{c}, H.K.D.H. Bhadeshia\textsuperscript{a,b}, Dong Woo Suh\textsuperscript{a,*}

\textsuperscript{a} Graduate Institute of Ferrous Technology, POSTECH, Republic of Korea
\textsuperscript{b} Materials Science and Metallurgy, University of Cambridge, Cambridge, UK
\textsuperscript{c} Materials Science and Engineering, POSTECH, Republic of Korea

Received 30 January 2012; received in revised form 3 April 2012; accepted 7 April 2012
Available online 18 May 2012
3. Kinetics of competing processes

• Decomposition of austenite
  – Precipitation
  – Bainite reaction

• Thermodynamically // Kinetically

A few processes concurrently take place at medium temperature for lean composition such as partitioning, precipitation and bainitic reaction et al.
2) Carbon partitioning from martensite to austenite

By comparison the calculated durations between the formation of lath martensite and carbon partitioning owing to the different solubility of carbon in martensite and austenite, with carbon concentration profile as shown in Figure 1, Hsu and Li in 1983 showed that the carbon partition may keep pace with, or slightly lag behind, the formation of lath martensite. The time required for equalization of enriched austenite is at least one order of magnitude slower than the formation of lath martensite.

Figure 1 Sketch of carbon concentration profile in martensite and retained austenite for quenched 0.27%C steel

1979, Thomas et. al  Hsu and Li in 1983
3) Kinetics for an athermal martensitic transformation

Koistinen and Marburger; Magee: kinetics equation for an athermal martensitic transformation

\[ f = 1 - \exp[-\alpha(M_s - T_q)] \]  \hspace{1cm} (1)

where \( \alpha = 1.10 \times 10^{-2} \) for carbon content 0.37 to 1.10 mass%.

\( \Delta G \) is a function of not only temperature but also the carbon content in austenite and the Magee’s equation, or the Koistinen and Marburger equation should be modified.

\[ f = 1 - \exp[\beta(c_2 - c_1) - \alpha(M_s - T_q)] \]  \hspace{1cm} (2)

where \( c_2 \) and \( c_1 \) represent the carbon contents in austenite before and after quenching.

Modified Koistinen-Marburger Equation

Koistinen-Marburger equation
\[ V_A = A \times \exp[-b(Ms - Tq)] \]

Koistinen-Marburger modified by Wildau [3]
b = 0.011
n = 0.663
\[ V_A = A \times \exp[-b(Ms - Tq)^n] \]

Fig. 11—Experimentally determined martensite transformation kinetic as well as modeled kinetic by the Koistinen-Marburger equation and by a modification of this equation.

Fig. 12—\textit{In situ} neutron diffraction results during heating (partitioning) of a 0.64C-4.57Mn-1.30Si steel after quenching to room temperature, showing phase fractions, austenite carbon concentration, and lattice strains\textsuperscript{[56,57]}

Interaction between carbon and dislocation
Activation energy  121KJ/mol (1.26eV)
Aneleastic peaks
Temperature
Broaden peak
Snoek-köster-like aneleastic peaks

Evidence from Internal friction
0.39C-1.56Si-2Mn-9.84Ni  730°C *30min+ water queching

First heating curve (DMA)

Second heating curve (DMA)

resolving capability:
Internal friction  $10^{-6}$
DMA  $10^{-4}$
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Conclusions

• **Ultimate tensile strength of >2000MPa and total elongation of >10%,** Microstructure in QPT steels generally contains ~5% **retained austenite**, with considerable thickness trapped between fine lath martensite embedded with **dispersed complex carbides** or η(θ) carbide

• Preliminary results show that combination of QP with hot deformation can improve the mechanical properties of AHSS. **Enhanced mechanical properties** and the total elongation of the steel increases from 6.6% to 14.8% compared with that of hot stamped and quenched steel.

• A few unresolved issues such as the multi-phase modeling of TRIP-assisted mechanical properties, designing strategy of AHSS targeting for automobiles and kinetics of competing processes.