Recent AHSS Developments for Automotive Applications: Processing, Microstructures, and Properties

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Colorado School of Mines
Golden, Colorado

Workshop: Addressing Key Technology Gaps in Implementing Advanced High-Strength Steels for Automotive Lightweighting
February 9 - 10, 2012
USCAR Offices, Southfield, MI

*ASPPRC: An NSF Industry/University Cooperative Research Center - Est. 1984
http://aspprc.mines.edu/
Scope of Today’s Presentation

• AHSS historical perspective – very brief
• Status of recent AHSS developments
• Identify opportunities
  • Enhanced first generation AHSS
  • New Third generation processing routes
• Observations and suggestions
DP Developments – 1970’s to …..

• 1960’s – 1970’s: HSLA steel
  • Thermomechancial processing + microalloy additions

• 1970”s – 1980’s: Dual-phase steel
  • Fundamentals identified
  • **Basis for AHSS developments**

• 1990’s --- TRIP (Transformation Induced Plasticity) and other AHSS developments, leading to “3rd Generation AHSS”
**Dual-Phase Steels: “The Early Days”**

**Significant Parallel Research Activities**

- **Nippon Steel**
  - **1975:** S. Hayami and T. Furukawa, Microalloying ’75

- **GM**
  - **1976:** M.S. Rashid, SAE + others

- **Ford**
  - **1978:** R.G. Davies, Met. Trans. + others

**M.S. Rashid, SAE, (1977)**
DP Steel Processing

• Initially conceived based on “simple” processing routes for hot and cold rolled steels
  • Microstructures more complex than simply ferrite + martensite and contained retained austenite + ??

![Graph showing temperature and time with phases labeled: Ferrite + Martensite, Dual Phase, A1, A3, Overage/Galvanize]
...Lessons Learned from “Early” DP Steels

- Processed as dual-phase steel
- Observed microstructures more complex than ferrite + martensite

“...the ductility could be further improved by increasing the amount of retained austenite...” A. Marder (1977)

A. Marder, “Factors Affecting the Ductility of Dual-Phase Alloys,” TMS, (1979)
However, in a different study: “…retained austenite did not have a measurable effect” due in part “to the fact that the first few percent plastic strain eliminated … austenite from the microstructure.” *Eldis, TMS, (1979)*
TRIP Steel Processing – “modified DP”

- Isothermally transform or control cool
- Austenite in high strength matrix (e.g. fine grain ferrite, martensite, bainite, …)
...Lessons Learned from “Early” DP Steels

• Strength = f(MVF, ferrite grain size)

\[ \sigma_T = V_f \sigma_f + V_M \sigma_M \]

• Basic TRIP steel requirements identified
  • Control amount of retained austenite at room temperature.
  • Control austenite mechanical stability

• Microstructures are “complex”

• “First Generation AHSS”
Microstructural Classes: 1st Generation AHSS

- **Mild Steels**
- **Conventional HSS**
- **First Generation AHSS**

The diagram illustrates the relationship between tensile strength and elongation, with different microstructural classes such as DP, CP, TRIP, HSLA, IF, and BH. The graph is compiled from various sources: Huang 1989, Bruce 2003, Cornette 2005, and Säglitz 2008. For more information on steel properties, visit [AISI: www.steel.org (2006)].
**Future Opportunities for AHSS**

**Predicted to contain:**
- High strength constituent
- Retained austenite with controlled stability

**Goal:** Formable steels with increased strength and ductility

**Third Generation AHSS:** Affordable Multiphase Steels: Unique Microstructures**

Enhanced Dual-Phase Steels

Example approaches:

- Control heating rate
- Thermal cycling to refine grain size
- Alter ferrite strength to control ferrite/martensite strength ratio
- ...other....
Heating Rate: CMnSiCr DP600 Steel

Heating Rate = 2 °C/s

Heating Rate = 200 °C/s

Heated to 800 °C; Soak for 30 s; Quenched

Process Control: Ultra-Fine Grain DP Steels

Steel: 0.17C, 0.74Mn

(1) 1000 °C-30min

(II) 550 °C-60min

(III) 550 °C-75min

(IV) 750 °C-5&10s

(V) 300 °C/s

IBQ: Ice Brine Quench
WQ: Water Quench
CR: Cooling Rate

Martensite
Tempered Martensite

Process Control: Ultra-Fine Grain DP Steels

Steel: 0.17C, 0.74Mn

Temperature

1000 °C-30min

Ac₃

750 °C-5&10s

Ac₁

300 °C/s

550 °C-60min

550 °C-75min

5 µm

Process Control: Ultra-Fine Grain DP Steels

MVF = 0.42
Island size ≈ 2 μm

**Advanced DP Steels - Optimization**

- Processing for higher strength & enhanced performance
  - High volume fraction of martensite uniformly dispersed as fine particles
    - May need to control martensite strength
  - Fine grain ferrite
    - Modified to control martensite to ferrite strength ratio
  - Minimize banding
- *However, Third Generation AHSS not achievable by enhanced DP steels!!!
Multi-phase Modeling to Design “Third Generation AHSS”

(1) Constituent volume fractions
(2) Constituent properties
(3) Austenite Stability

Approaches:

• Ideal Composite Model
• Micromechanical Models
  • FEA Based
  • …other…
Application of Composite Model to Identify New Multiphase AHSS Steels (2006)

- Assume each “constituent” described by flow curve:
  \[ \sigma = K \varepsilon^n \varepsilon^m \]

- Apply rule of mixtures for composites (assumes “Isostrain”)
  \[ \sigma_T = \sigma_1 V_1 + \sigma_2 V_2 + \ldots \]

- At Instability \[ \frac{d\sigma}{d\varepsilon} = \sigma_U \]

**Constituent properties from the literature**

- High Mn Austenite (*assumed stable*)
- Martensite

<table>
<thead>
<tr>
<th>Constituent</th>
<th>UTS (MPa)</th>
<th>Uniform True Strain</th>
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<tbody>
<tr>
<td>Ferrite</td>
<td>300</td>
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</tr>
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<td>640</td>
<td>0.6</td>
</tr>
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Comparison to "3rd Generation" AHSS (2006)

\[ e_{\text{Total}} = e_U + e_{\text{Post-U}} \]

Stable Austenite + Martensite

Ferrite + Martensite

**Property Assessment: Metastable Austenite**

**Initial Microstructure:** Ferrite + Austenite  
**Initial Metastable Austenite = 0 to 85 %**

### Calculation Approach

- Assume austenite stability described by saturation function
- Assume function depends on alloying, microstructure, T, etc.
- Consider only “static hardening”
- Vary initial austenite content in ferrite-austenite composite


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Micromechanical Modeling: Korea (2009)

- Assumed TRIP, multi-phase steel – varied vol. fractions
- Applied a general kinetic model for the mechanically induced transformation of austenite to martensite

Micromechanical Modeling: PNNL (2010)

- FEA Model - utilize “Representative Volume Element” (RVE) to describe TRIP Steel microstructure
- RVE based on actual microstructures
Summary of Model Predictions

• “Big-Picture” predictions independent of modeling approach

• New (e.g. “3rd Generation”) AHSS will require:
  • High strength constituents
    e.g. Martensite, fine grained ferrite, bainite…
  • Austenite with controlled stability
    • e.g. transformation to martensite

• Additional Predictions: Steels with improved resistance to localized fracture obtained by
  • Refined microstructures
  • Minimized property gradients
Advances in Steel Processing

New 3rd Generation AHSS Processing Examples

(1) “Enhanced” TRIP Steels with high austenite volume fractions

(2) Q&P Steels produced by Advanced Processing = f (T, t)
Mn-Modified TRIP Steels

Design Approach:

• Add alloying elements
  • Mn or N or C or …. to stabilize austenite

• Increase ferrite strength
  • Decrease Ferrite Grain Size by TMCP (Thermomechanical processing)

• Increase austenite volume fraction > 20%
  • Fine and uniformly distributed

• Acknowledge: NSF, CMMI Grant # 0729114

**Experimental Approach**

- **Material** – 7.1 Mn

- **Partition Mn:**
  - long-time intercritical heat treatments

- **Predict heat treatments**
  - Use ThermoCalc:
    - TCFE2 Data (1999)
  - Austenite composition
  - Austenite fraction

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<table>
<thead>
<tr>
<th>wt pct</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.099</td>
<td>7.09</td>
<td>0.13</td>
</tr>
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Microstructure

- Heat treat for 1 week
  - 575 to 675 °C
- Retained austenite measured by neutron diffraction (*Lujan Center at the Los Alamos National Laboratory*)

• Constant engineering strain rate

• ASTM E-8 sub-sized samples
  • 32 mm reduced section

• Initial austenite contents in (%)

Strain-dependent Austenite Transformation

Ferrite-Austenite: Mn-Modified TRIP Steels

- Intercritical annealing:
  - Enhances Mn partitioning
  - Increases austenite stability

- Cost efficient ways to enhance partitioning need to be identified

- …Research is ongoing……..

- Acknowledge: NSF, CMMI Grant # 0729114
Quenching and Partitioning
“Q&P”
**TRIP Steel Processing**

- Isothermally transform or control cool
- Austenite in high strength matrix (e.g. fine grain ferrite, martensite, bainite, ...)

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![Diagram]

- Ferrite-Bainite-Austenite
- Ferrite + Martensite
- "Dual Phase"
- "TRIP"
Interrupted Cooling: The “Q&P” Process

- Novel method to produce high strength material with significant amounts of retained austenite
- Processing path to 3rd Generation AHSS

Quenching and Partitioning (Q&P)

- Fundamentally new approach developed by Prof. John G. Speer at ASPPRC/CSM with automotive collaborators
- Designed to produce enhanced AHSS with retained austenite in controlled martensite/ferrite matrix

Q&P: Unique Designed Microstructures

(1) Annealing temperature controls amount of initial ferrite

(2) Quench temperature (QT): controls amount of initial martensite

(3) Alloying controls carbide stability

(4) Partitioning temperature and time: control austenite stability

(5) Result: unique combinations of martensite + austenite + ferrite + ..other..

“Q&P” Alloying and Processing

- Alloying: e.g. Mn Si Al C Mo
- ... to control critical temperatures: $M_s$, $M_f$ ...
- ... to suppress cementite formation

Properties of Q&P
Summary and Comparison with AHSS

International Interest in the “Q&P” Process

• Initially conceived, 2003
• Ongoing R&D at:
  • Universities
    • 21 in 13 countries
  • Research Institutes
    • 13 in 7 countries
  • Companies
    • 14 in 10 countries
Current Status of
AHSS Developments
Example representative property combinations for automotive market


AHSS Development Status


Enhanced DP
Ultrafine DP
Modified TRIP
Matsumura
Micro-alloyed TRIP
TRIP Type Bainite
TRIP-DUAL
Interrupted Quench

Bainite
Bhadeshia-Edmonds
Mihikinen-Edmonds
Caballero
Garcia-Mateo

Quenching & Partitioning
Jun-Fonstein
Streicher
De Moor
Li
Wang - ind. trial

Rapid Heating and Cooling
flash process

Lower Mn TWIP/TRIP
Frommeyer
Dastur-Leslie
Merwin
AHSS Development Status

Matsumura et al. (1987, 1992)
0.39C, 1.2Mn, 1.2-1.5Si

Q&P
De Moor et al. (2008, 2009)

Mn Partitioned
Gibbs et al. (2011)
Merwin (2006)

Flexible Processing Lines and the Production of New AHSS
Baosteel's Special Flexible HSS Line

- Opened March 2009
- Multi-purpose processing
  - CR and GI
  - Flexible heating/cooling

<table>
<thead>
<tr>
<th>Cooling medium</th>
<th>Max Cooling ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%H2+95%N2</td>
<td>40°C/s</td>
</tr>
<tr>
<td>75%H2+25%N2</td>
<td>140°C/s</td>
</tr>
<tr>
<td>water</td>
<td>2000°C/s</td>
</tr>
</tbody>
</table>

Baosteel: Q&P from New Line

Q&P1000:
Composition (wt pct)
0.2C, 1.5 Si, 1.8 Mn

Li Wang and Weijun Feng, “Development and Application of Q&P Sheet Steels,” Advanced Steels, Y. Weng et al. (eds), Springer-Verlag, Berlin, (2011)
Formability Limited by Fracture
Tensile Properties... NOT the Whole Story...

Formability Limited by Fracture

Images Courtesy of Jim Fekete, GM (2006)

Dünckelmeyer et al., Slovika (2009)
Tensile Properties... NOT the Whole Story...

Void Nucleation: DP 740 MPa

Banding: DP980

Hole Expansion

Shear Fracture Test

Lee et al. ASPPRC/Posco 2005 after Cho, Pusan Nat. U., 200

<table>
<thead>
<tr>
<th>Steel (780 MPa)</th>
<th>Tensile Elong.</th>
<th>Stretch-flangeability (HER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>19 %</td>
<td>60 %</td>
</tr>
<tr>
<td>TRIP</td>
<td>30 %</td>
<td>40 %</td>
</tr>
</tbody>
</table>

A. Hudgins, et al. ASPPRC 2010
Hole Expansion Tests: Summary

- Hole Expansion Ratio (HER) = f(microstructure)
- Improved microstructural homogeneity = higher HER

Microstructural Effects on AHSS Fracture

Bending Under Tension

**Commercial Steel Matrix**

**Bending Under Tension Data**

\[ \frac{R}{t} \] = measure of formability

\[ \frac{R}{t} \] = formability (i.e. susceptibility to shear)

Application of Nanoindentation Techniques

- 0.1C-1.0Mn-0.3Si DP
- Vary intercritical T
- Vary MVF and martensite hardness
- Determine “hardness ratio”
- Result: $R/t_{critical}$ decreases with a decrease in the martensite to ferrite hardness ratio

Summary: Shear Fracture Susceptibility

- Formability (as measured by R/t) increased with a decrease in hardness ratio between martensite and ferrite.

- Other variables evaluated
  - Martensite morphology (limited effect)
  - Banding (effect orientation dependent)

Alternate Processing Routes:
Press Hardening
Press Hardened Steels (PHS)

- Production of high strength (1500 MPa) parts
- Martensitic microstructures; boron alloys
Press Hardened Steels (PHS)

T. Altan, 2007
www.stampingjournal.com

Press Hardened Steels (PHS)

Heated Blank

[Image]

Blank in Die

[Image]

PHS for High Strength Structural Components

[Image]


kam-stampingguru.blogspot.com/2011
Press Hardening

• Enhanced press hardening steels still maturing

• Cost (e.g. heating, etc) and surface finish continue to be issues for consideration

• Steel developments leading to alternate processing routes for similar strength parts are of significant interest
  
  • e.g. Q&P, bainitic, ...
  • Cold or warm forming
AHSS Closing Comments

• Approaches to potentially produce Third Generation AHSS have been identified

• Need optimized production routes to control:
  • Constituent volume fractions, size, distribution
  • Constituent mechanical properties
  • Austenite stability
  • …other

• Possibility for national research processing facility???
AHSS Closing Comments

• AHSS: Additional Important Points
  • Welding and Joining
  • Formability – Springback
  • Surface Finish
  • Coating
  • Hydrogen effects
  • ……..
  • TWIP steels???
    • Significant government funding in Germany and Korea
AHSS Closing Comments

- AHSS developments need to optimize time to implementation!!!
  - ...DP Steels, 35 years +...
    - “Most Important” AHSS
  - ...TRIP Steels, >20 years
  - ...Q&P ≈ 7+ years
  - .......

- ...The Competition Continues...
AHSS -- “Beyond Automotive”

• Multiple inquires received at ASPPRC - Examples:
  
  • Lightweight military vehicles
    • DOD/DOE workshop
      Detroit, July 2011
  
  • Blast resistant surfacing – US Army
  
  • Metal storage cabinets (shipping costs!)
  
  • Personal hand tools
  
  • ….others…..
The support of the Advanced Steel Processing and Products Research Center corporate partners, listed below, is gratefully acknowledged.

**Steel Producers**
AK Steel
ArcelorMittal Steel
Baosteel
Essar Steel Algoma Inc.
Evraz Inc., N.A.
Gerdau
Nucor Steel Co.
POSCO
SABIC
Severstal NA Inc.
SSAB Enterprises, LLC
Tata Steel Europe
The Timken Co.
United States Steel
voestalpine Stahl GmbH

**Heavy Equipment Mfg.**
Caterpillar Inc.
Deere & Co.

**Automotive Manufactures**
Chrysler Group LLC
General Motors Co.
Toyota

**Suppliers**
Bekaert
Johnson Controls
Tube Investments of India

**Other**
East Metals N. Amer. (Vanadium)
Los Alamos National Lab
Precision Cast Parts Corp.
Reference Metals (Niobium)
The Advanced Steel Processing and Products Research Center (ASPPRC) is dedicated to attaining excellence in the study of steel. The Center was initially established by the National Science Foundation as one of over fifty Industry/University Cooperative Research Centers. Thanks to corporate supporters from all over the world, the ASPPRC is now self-sufficient. Cooperation and frequent communication between industrial sponsors and the faculty, staff and students involved in the center forms the basis of the ASPPRC's success.

Today students at the ASPPRC study primarily three types of steel: bar and forging steels, sheet and coated steels, and plate and hot rolled steels. Students conduct research to work towards either a Master’s of Science or Doctorate of Philosophy. In addition to research, the students work closely with corporate sponsors.

In more recent news, the ASPPRC is also excited to announce the installation of the new Gleeble 3500!

http://aspprc.mines.edu/