REPORT:

DRAFT
Advanced High Strength Steel Workshop

held

October 22-23, 2006
Arlington, Virginia, USA

by

Robert H. Wagoner, Organizer

George R. Smith Chair
Department of Materials Science and Engineering
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Columbus, Ohio, USA

Advanced High-Strength Steels (AHSS) Workshop

A two-session workshop held on October 22 and 23, 2006, in Arlington, Virginia, brought together a diverse group of 60 scientists and engineers to discuss research issues surrounding Advanced High Strength Steels (AHSS), to recommend ways to address the outstanding issues, and to establish a vision for a path forward for the adoption of such materials. The workshop was funded by the National Science Foundation, Department of Energy, and the Auto/Steel Partnership.

AHSS offer amazing combinations of strength (performance) and ductility (manufacturability). They are particularly promising for crash-resistant autobody structures, where stiffness, strength, and energy absorption are required in stamped parts. Many fundamental technical questions must be answered before 2nd and 3rd generation AHSS can be adopted, thus allowing the potential benefits to be achieved. Progress in these fundamental areas will benefit other metals and alloys as well.

2nd generation AHSS offer the promise of unprecedented combinations of strength and ductility, but their cost is prohibitive for widespread adoption because of costly alloy content (e.g. Ni or Mn). The to-be-developed 3rd generation AHSS are envisioned as affordable alternatives to 2nd generation AHSS, but will trade some mechanical properties, still being much more effective than current, 1st generation AHSS.

The first set of workshop recommendations deal with fundamental technical issues. These were generated during breakout sections (8 tables), then presented to the full group for discussion. These recommendations appear in their entirety in appendices, and are summarized below in three inter-related areas: 1) alloy development issues, and 2) widespread adoption issues, and 3) linkages between these sets of issues and various length scales:

Alloy Development Issues

- Predictive micro-level models (phases, grains) of material behavior, particularly those involving twinning and phase transformation
- Predictive atomic-level models of interfaces, twinning, and phase transformation
- Predictive meso-level models / ability to treat large numbers of dislocations with computational feasibility
- Particularly *ab initio* tools and in-situ TEM, SEM experiments
- Properties of complex phases and microstructures, related fracture nucleation
- Choice of approach for 3nd generation AHSS: target phases and microstructures
    - ultra-fine ferrite matrix with bainite/martensite
    - stabilized, high austenite fractions
    - layered composite microstructures
    - nano-precipitates
- Basic knowledge of phase stability and phase transformations, particularly martensitic
- Knowledge of interface properties among phases, related fracture nucleation
- Rigorous methods for 2D and 3D microstructural characterization

Widespread Adoption Issues

- Accurate, verified constitutive equations informed by basic material models as well as macro tests (especially incorporating hardening laws for complex strain paths)
- Numerical procedures for accurate springback simulation in realistic times
- Limited material behavior data under multi-axial and complex strain/stress paths
- Unknown springback behavior, particularly involving modulus changes and generalized Bauschinger effect
- Unknown fracture behavior, particularly shear failure which is not predicted by existing FLD models
- Need to consider wide range of properties: weldability, toughness, cost, corrosion, high-rate deformation, fatigue.
- Development of forming processes optimized to needs of AHSS (elevated temp, rate, etc.)

Linkage Issues

- Multi-scale models to link phenomena from atomic to grain to continuum scales
- Homogenization schemes beyond averaging to inform continuum constitutive equations
- IP agreements, large project coordination
- Funding mechanisms for teams addressing AHSS issues (fundamental vs. applied)
- Education in steels and other supposedly traditional materials is disappearing in the U.S.
- Government / NSF policy r.e. manufacturing (vs. nano, bio, info).

The second set of workshop recommendations centered on the kinds of cooperation required to make 2nd generation AHSS a reality, as well as improving the fundamental knowledge for other alloys and their development. There was a strong consensus that a sustained effort over multiple years will be needed, both single-investigator work and larger cooperative projects. The cooperative projects will likely need to involve academia, steel companies, automotive companies, and government labs, with the grouping dictated by the problem and the most likely approach to solving it. Sponsorship will need to broad in order to address the range of issues (NSF – various programs, DOE, government labs, industry, other)

The workshop discussed in particular the EFRI program (Emerging Frontiers in Research and Innovation) of the NSF Engineering Directorate, as introduced by Dr. Realff. The parameters for the program seem most appropriate for the subject of 3rd generation AHSS, as follows:

Tranformative: Steels have been considered a mature area for many years, but recent advances are exciting, innovative, and offer the potential of materials with heretofore impossible combinations of properties and cost. The so-called banana chart illustrates the typical trade-off between strength and ductility that has been taken as gospel by generations of faculty, students, and engineers. The ability to increase both of these properties simultaneously with AHSS is indeed a technical paradigm shift of the highest order.

A second paradigm shift, in application, is also in progress. The national goals of energy conservation, increased safety and security, and protecting the environment have translated into substitutions of lower-density materials (e.g. polymers, composites, aluminum, magnesium) into automotive structures. The innovative leap of AHSS allows meeting of these goals in an economically feasible manner (and thus much more widespread impact) with stronger, stiffer materials. This is certainly a paradigm shift that has implications beyond the automotive industry.

National Need / Grand Challenge: Clearly the potential for a great advance and many societal benefits is promising. The workshop participants identified a variety of fundamental issues that must be addressed before the potential benefits can be realized. These occur at all length scales, and range from the most basic issues, to more applied challenges.

Community Response: The original driving force behind the AHSS Workshop was the Auto / Steel Partnership (A/SP)[*], a long-standing consortium that organizes research and develops projects related to their constituency. The existence of the A/SP, which is not reproduced in other material / manufacturing sectors, provides a unique opportunity to build on existing relationships and mechanisms for continued cooperation.

A/SP has long partnered with DOE to carry out applied and developmental research of common national interest. These two groups recently realized that 3rd generation AHSS required fundamental advances to couple with existing development activities, hence providing part of the motivation for this workshop. The response by the academic and government / private laboratory community to the AHSS workshop can only be described as overwhelming. Originally envisioned as an open-attendance event with a target attendance of 50 individuals, an acceptance rate by invitees of over 80% met the maximum capacity for the event (60). This effectively closed off further attendance. There were many requests to attend after the capacity had been filled, indicating a strong and deep interest in this new and exciting area.

Engineering Leadership: As shown by the range of workshop issues (and attendees), the focus of the NSF Engineering Directorate is central to the overall thrust. Research areas, such as the fundamentals of shear failure and fracture, multi-scale modeling, predictive models for fracture, springback and processing, thermo processing, and design theory for new materials, are all in the heart of various areas that engineering divisions support. Furthermore, NSF/MPS directorate (e.g., DMR) can be a strong partner in this topic in terms of atomic-level models and experiments, at one extreme, DOE has interests and funding in the applications and industrial trials, and ONR can be interested in this for their steel applications in ships.

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[*] The workshop presentation by Roger Heimbuch, Director of the Auto/Steel Partnership, introduces the organization and its goals. This presentation appears as an appendix to this report.

List of Appendices

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Appendix 4: Sponsor Presentations

- *Welcome Remarks*, Roger Heimbuch, Auto/Steel Partnership:
- *NSF Goals and Funding Procedures*, Mary Lynn Realff, National Science Foundation (DMI)
- *DOE Goals and Funding Procedures*, Joseph Carpenter, Department of Energy (Freedom Car)

Appendix 5: Technical Presentations

- *Overview of AHSS*: Debanshu (DB) Bhattacharya, Mittal Steel
- *AHSS Microstructures, Fffect on Failure*: David K. Matlock, Colorado School of Mines
- *AHSS Continuum Modeling Issues*:
    - *Part A, Springback*: Thomas B. Stoughton, GM Research and Development
    - *Part B, Forming*: Cedric Xia, Ford Research Laboratory

Appendix 6: Table Group Presentations, 1-8

Appendix 1: AHSS Workshop Schedule and Organizing Committee

October 22, 2006 – Hilton Arlington & Towers, Master Ballroom

5:30p Welcoming reception (A/SP hosted)

7:30p Dinner (hosted by the Auto/Steel Partnership)

Welcome Remarks, Roger Heimbuch, Auto/Steel Partnership:

NSF Goals and Funding Procedures, Mary Lynn Realff, National Science Foundation (DMI)

DOE Goals and Funding Procedures, Joseph Carpenter, Department of Energy (Freedom Car)

Workshop Organization, Robert H. Wagoner, The Ohio State University

October 23, 2006 – NSF Building, 4201 Wilson Blvd., Arlington VA 22230

8:00 Breakfast, Introductions

8:15 Opening Remarks

8:30 State of AHSS

- 8:30 *Overview of AHSS*: Debanshu (DB) Bhattacharya, Mittal Steel
- 9:00 *AHSS Microstructures, Fffect on Failure*: David K. Matlock, Colorado School of Mines
- 9:30 *AHSS Continuum Modeling Issues*:
  - *Part A, Springback*: Thomas B. Stoughton, GM Research and Development
  - *Part B, Forming*: Cedric Xia, Ford Research Laboratory

10:00 Break

10:15 Breakout sessions

12:30 Lunch

1:15 Breakout session reporting & discussion

3:00 Compilation of workshop results and recommendations

3:30 Adjourn

Organizing Committee

Robert H. Wagoner, Ohio State University (Chair)

Jian Cao, Northwestern University

Tom Stoughton, General Motors Research

Roger Heimbuch, Auto-Steel Partnership

Mary Lynn Realff, National Science Foundation, DMI

Bruce MacDonald, National Science Foundation, DMR

Clark Cooper, National Science Foundation, CMS

Joseph Carpenter, US Department of Energy

Appendix 2: Workshop Assignments

R.H. Wagoner
October 12, 2006

AHWW Workshop: Work Assignments & Table Assignments

Plenary Questions (All Groups to Answer)

1. What are the principal technical obstacles to the creation of third-generation AHSS?

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

4. What specific, <u>applied</u> (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

A. Modeling vs. Experimental (2 Groups)

1. What kinds of modeling are most needed to push AHSS forward? What length scales and techniques are likely to be the most important?

2. What kind of experimental information is needed by modelers in order to inform and validate their models?

3. What are the principal holes in experimental knowledge for second and third generation AHSS?

4. What kinds of established, new, or novel experiments or characterization techniques are most important to help inform models and understanding of properties?

B. Focus Application: 3rd Generation AHSS (2 Groups)

1) Which classes of 3rd Generation AHSS are most promising? What is the expected time frame to commercialization?

2) Identify critical issues related to developing a 3rd generation of AHSS.

3) What are the best mechanisms for addressing these issues?

4) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

C. Focus Application: Sheet Forming Simulation (2 Groups)

1) Identify critical issues related to numerical simulation of forming with AHSS

2) What are the best mechanisms for addressing these issues?

3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

D. Focus Application: Fracture / Failure (2 Groups)

1) Identify critical issues related to new or unusual fracture / failure behavior of AHSS, microstructural and mechanical.

2) What are the best mechanisms for addressing these issues?

3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

AHSS Workshop: Seating Chart and Table Arrangement

Front of Room: Screen

Table 1 **(D, Fracture)** Realff Spanos Gao Putnam (dinner) Acharya Matlock Thomas Wagoner	**Table 3** **(C, Forming Simul.)** Stoughton MacDonald Sun Haezebrouck DeArdo Kalidindi Mao	**Table 5** **(B. 3rd Generation)** Chong Essadiqi Santella Agnew Garmestani Pan Welsh Speer	**Table 7** **(D. Fracture)** Conner Simunovic Keeler Wu Altan Funkenbusch Michal Wierzbicki
Table 2 **(B, 3rd Generation)** Heimbuch Carpenter Gan Bhattacharya Lorincz (dinner) Balaji Pourboghrat Van Aken	**Table 4** **(C, Forming Simul.)** Xia Balaguru White Shi Beaudoin Jonas Shen J. Wang	**Table 6** **(A, Model v. Expt.)** Fekete Chopra Losz Anand Ghosh Khraisheh Li Miles	**Table 8** **(A. Model v. Expt.)** Du Cooper Khaleel Sun Cao Khan P. Wang

Appendix 3: AHSS Workshop: Attendee List and Table Assignments

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Appendix 4: Sponsor Presentations

- *Welcome Remarks*, Roger Heimbuch, Auto/Steel Partnership:

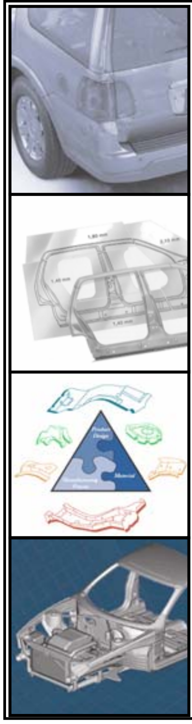
- *NSF Goals and Funding Procedures*, Mary Lynn Realff, National Science Foundation (DMI)

- *DOE Goals and Funding Procedures*, Joseph Carpenter, Department of Energy (Freedom Car)

A/S P Auto/Steel Partnership

Advanced High-Strength Steels: Fundamental Research Issues Workshop

Sunday, October 22, 2006
Arlington, Virginia

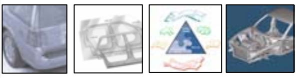


An Overview of the Auto/Steel Partnership and Research Needs

Roger Heimbuch
Executive Director
Auto/Steel Partnership

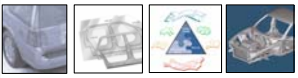
A/S P Auto/Steel Partnership

www.a-sp.org



OUTLINE OF PRESENTATION

- Overview of the Auto/Steel Partnership (A/SP).
- Connection to Department of Energy.
- Advanced High-Strength Steel Research Needs.



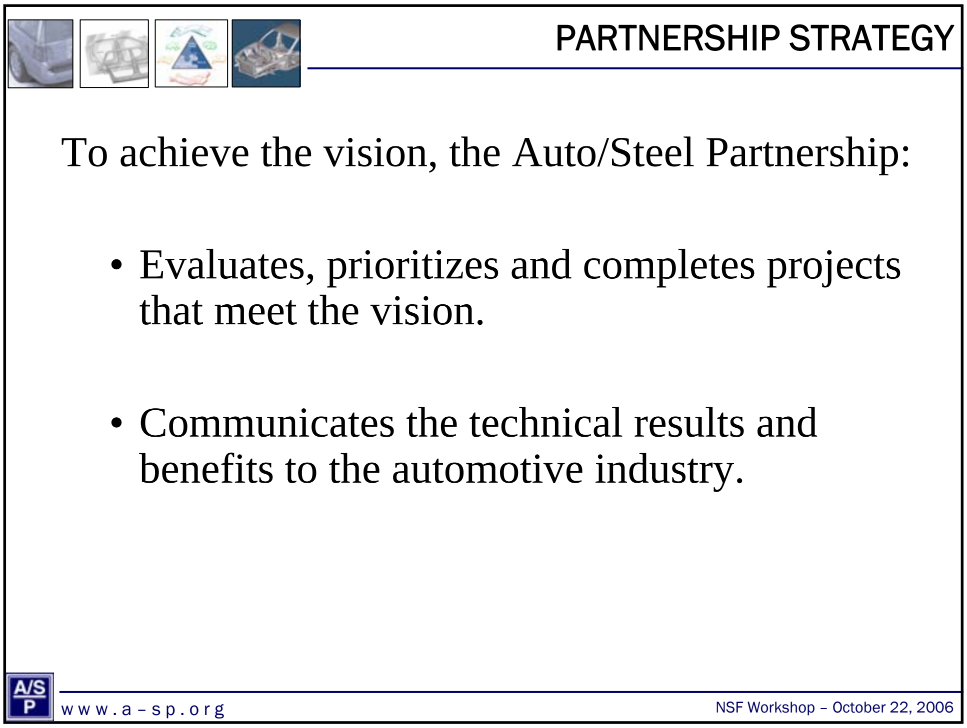
MEMBERS OF A/SP - Chartered in 1987

DAIMLERCHRYSLER
Ford
GM
AK Steel
DOFASCO
MITTAL
NUCOR
SeverStal North America
USS

PARTNERSHIP VISION

The Auto/Steel Partnership:

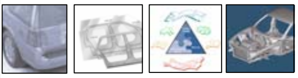
- Leverages the resources of the automotive, steel and related organizations.
- Ensures that steel remains the "competitive material of choice" in a changing automotive market.



PARTNERSHIP STRATEGY

To achieve the vision, the Auto/Steel Partnership:

- Evaluates, prioritizes and completes projects that meet the vision.
- Communicates the technical results and benefits to the automotive industry.



THE ACTIVE PARTNERSHIP PROJECTS

Lightweighting Initiatives

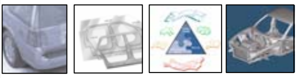
- Lightweight Closures
- Lightweight Front End Structures
- Lightweight Chassis Structures
- Future Generation Passenger Compartment
- MEARS

Enabling Projects

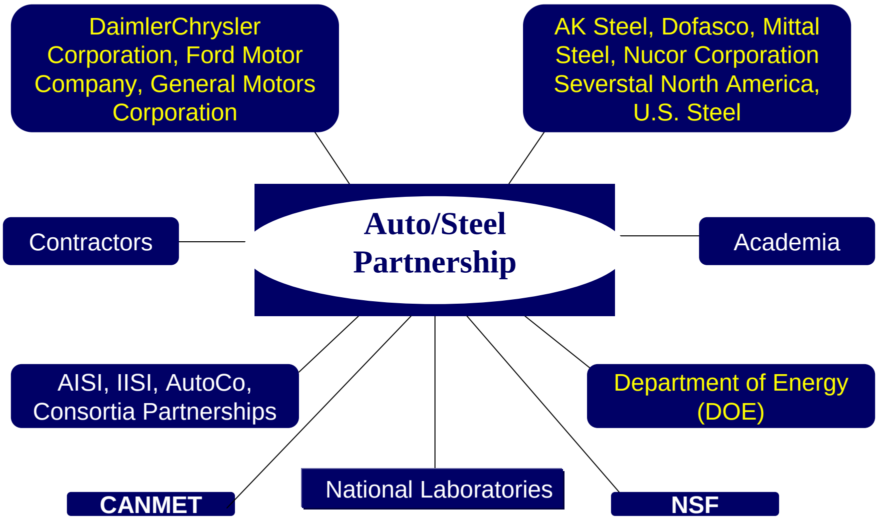
- High-Strength Steel Stamping
- Hydroforming
- High-Strength Steel Joining
- Fatigue Characteristics
- Strain Rate Characterization
- Tribology

On-Going Activity

- NAAMS Stamping Tooling Standards
- NAAMS Assembly Tooling Standards
- AHSS Application Guidelines
- Body Systems Analysis
- Common Qualification Procedures
- Technology Transfer



THE PARTNERSHIP LINKAGES



Auto/Steel Partnership

DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation

AK Steel, Dofasco, Mittal Steel, Nucor Corporation Severstal North America, U.S. Steel

Contractors

Academia

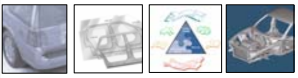
AISI, IISI, AutoCo, Consortia Partnerships

Department of Energy (DOE)

CANMET

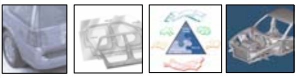
National Laboratories

NSF



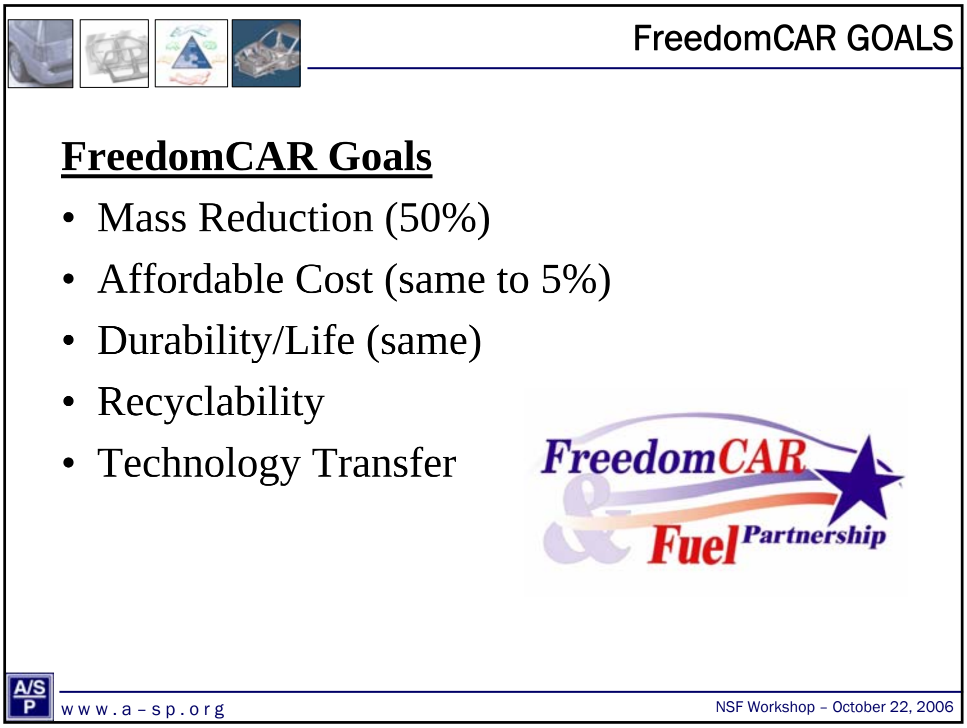
TERMINOLOGY

FreedomCAR & Fuel Partnership	DOE and USCAR Collaborative Automotive Research Program
USCAR UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH	United States Council for Automotive Research
USAMP UNITED STATES AUTOMOTIVE MATERIALS PARTNERSHIP	United States Automotive Materials Partnership – AMD: Automotive Metals Division – ACC: Automotive Composites Consortium – A/SP: Auto/Steel Partnership



FreedomCAR & FUEL PARTNERSHIP ACTIVITIES

- Fuel cell power systems.
- Hydrogen storage systems.
- Production and distribution of hydrogen.
- Integrated systems analysis.
- Technical basis for codes and standards to support hydrogen vehicles and infrastructure.
- Electric propulsion systems applicable to both fuel cell and internal combustion/electric hybrid vehicles.
- Lightweight materials.
- Electrical energy storage systems.
- Advanced combustion and emission control systems for internal combustion engines.



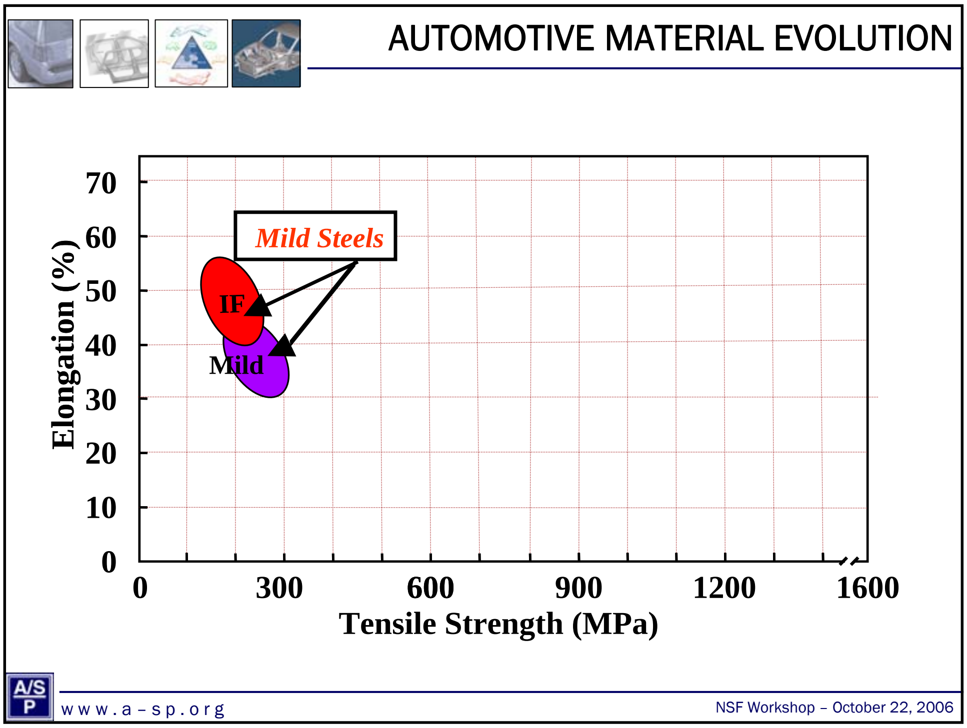
FreedomCAR GOALS

FreedomCAR Goals

- Mass Reduction (50%)
- Affordable Cost (same to 5%)
- Durability/Life (same)
- Recyclability
- Technology Transfer

www.a-sp.org

NSF Workshop – October 22, 2006



AUTOMOTIVE MATERIAL EVOLUTION

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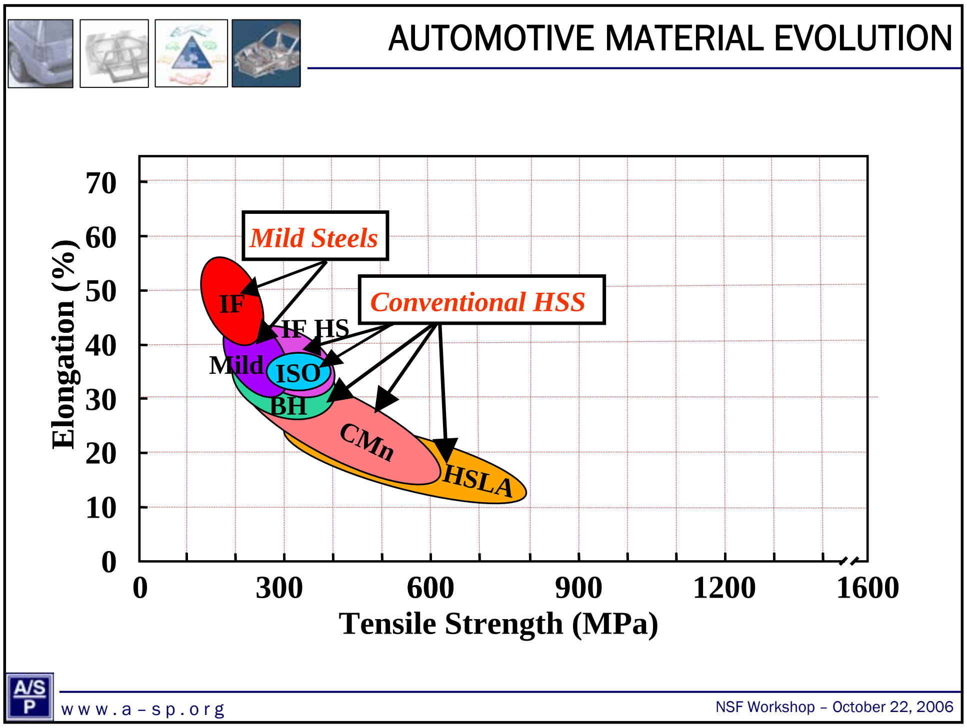

AUTOMOTIVE MATERIAL EVOLUTION

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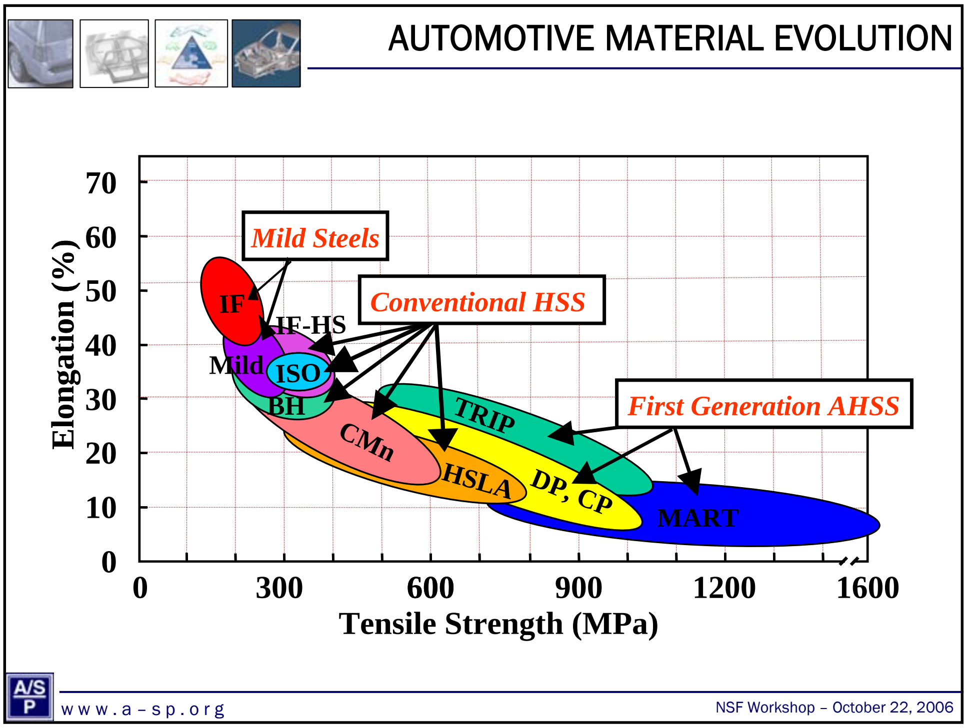

AUTOMOTIVE MATERIAL EVOLUTION

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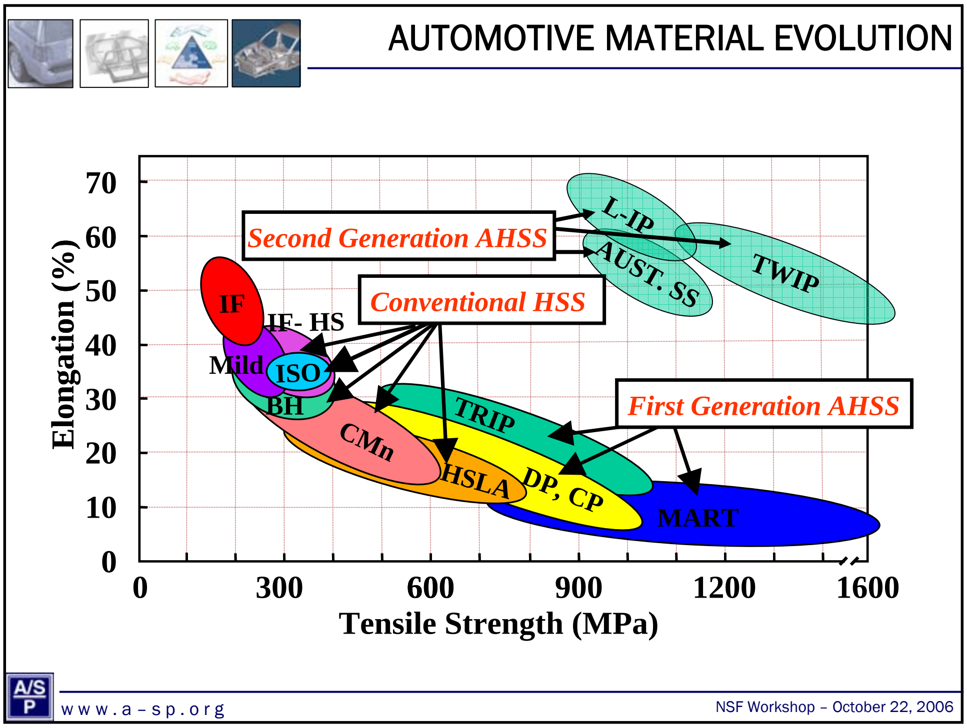

AUTOMOTIVE MATERIAL EVOLUTION

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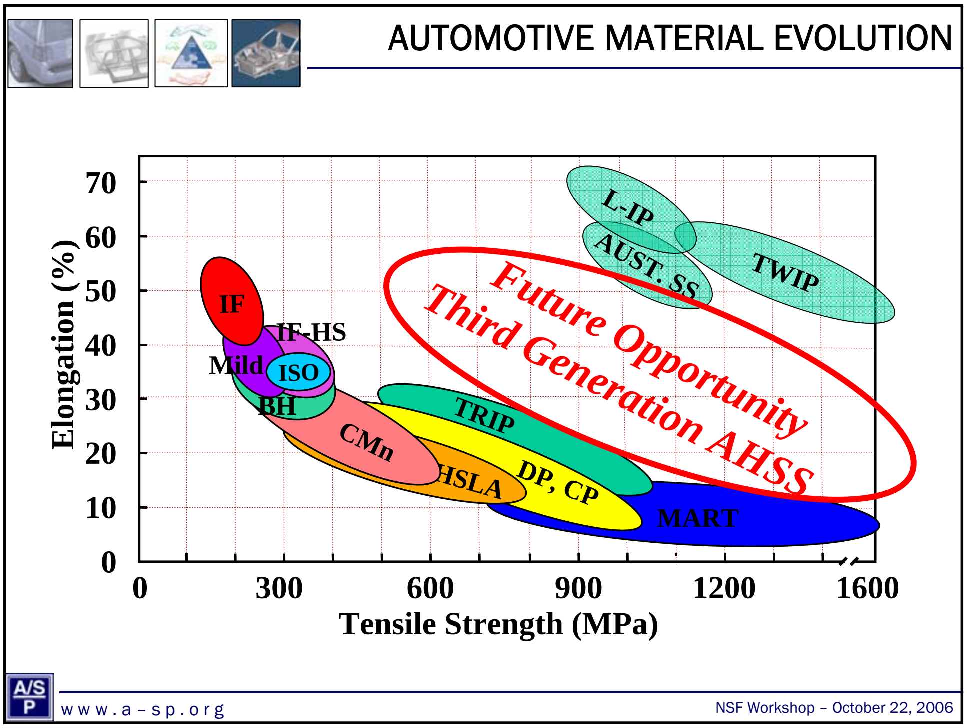
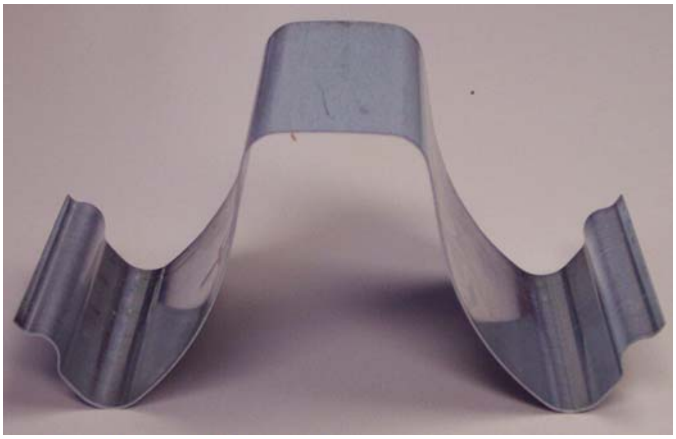


AUTOMOTIVE MATERIAL EVOLUTION

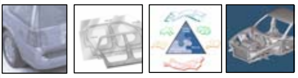
www.a-sp.org

NSF Workshop – October 22, 2006

SPRINGBACK OF DP600 CHANNEL DRAW

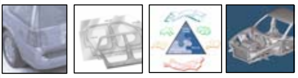


FRACTURES IN APPLICATION: DP780



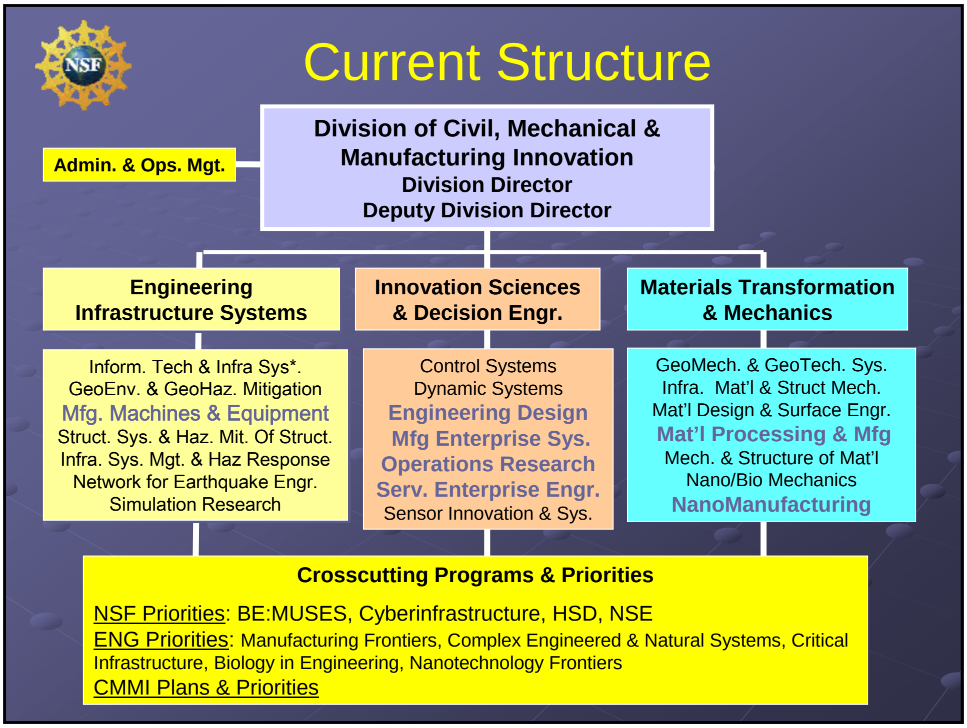
SUMMARY

- Auto/Steel Partnership is dedicated to developing and applying advanced steels to cars and trucks.
- Auto/Steel Partnership leverages a wide range of resources to accomplish that goal.
- Department of Energy support has accelerated Auto/Steel Partnership technology development.
- Auto/Steel Partnership believes there are needs and opportunities in steel research.



AUTO/STEEL PARTNERSHIP WEBSITE

- For more information visit the Auto/Steel Partnership website at: www.a-sp.org
- Contact: Dr. Roger Heimbuch
  Executive Director
  Auto/Steel Partnership
  248.945.4770
  rheimbuch@a-sp.org



Current Structure

Admin. & Ops. Mgt.

Division of Civil, Mechanical & Manufacturing Innovation
Division Director
Deputy Division Director

Engineering Infrastructure Systems

Inform. Tech & Infra Sys*.
GeoEnv. & GeoHaz. Mitigation
Mfg. Machines & Equipment
Struct. Sys. & Haz. Mit. Of Struct.
Infra. Sys. Mgt. & Haz Response
Network for Earthquake Engr.
Simulation Research

Innovation Sciences & Decision Engr.

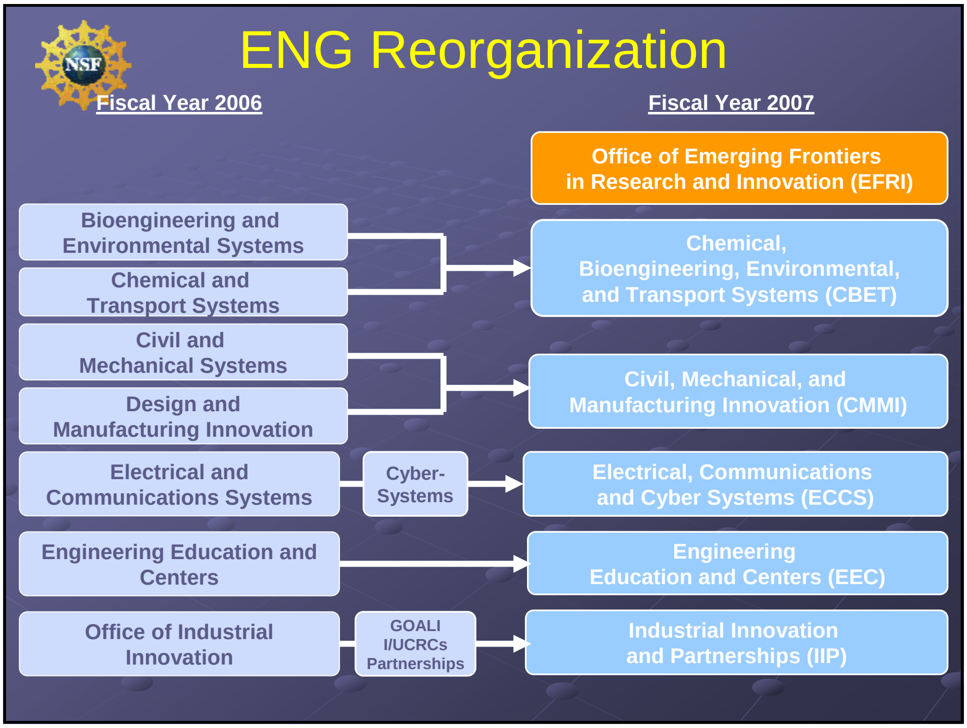
Control Systems
Dynamic Systems
Engineering Design
Mfg Enterprise Sys.
Operations Research
Serv. Enterprise Engr.
Sensor Innovation & Sys.

Materials Transformation & Mechanics

GeoMech. & GeoTech. Sys.
Infra. Mat'l & Struct Mech.
Mat'l Design & Surface Engr.
Mat'l Processing & Mfg
Mech. & Structure of Mat'l
Nano/Bio Mechanics
NanoManufacturing

Crosscutting Programs & Priorities

NSF Priorities: BE:MUSES, Cyberinfrastructure, HSD, NSE
ENG Priorities: Manufacturing Frontiers, Complex Engineered & Natural Systems, Critical Infrastructure, Biology in Engineering, Nanotechnology Frontiers
CMMI Plans & Priorities



ENG Reorganization

Fiscal Year 2006

Fiscal Year 2007

Office of Emerging Frontiers in Research and Innovation (EFRI)

Bioengineering and Environmental Systems
Chemical and Transport Systems
→ **Chemical, Bioengineering, Environmental, and Transport Systems (CBET)**

Civil and Mechanical Systems
Design and Manufacturing Innovation
→ **Civil, Mechanical, and Manufacturing Innovation (CMMI)**

Electrical and Communications Systems — **Cyber-Systems** → **Electrical, Communications and Cyber Systems (ECCS)**

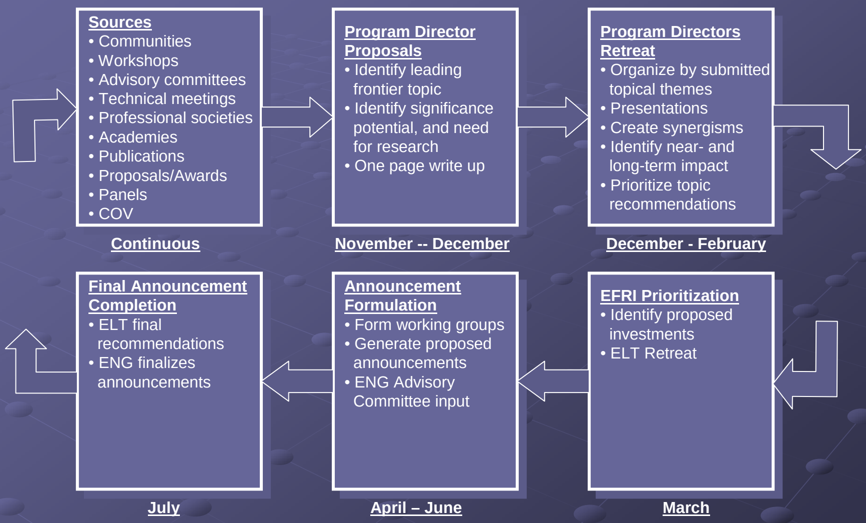
Engineering Education and Centers → **Engineering Education and Centers (EEC)**

Office of Industrial Innovation — **GOALI I/UCRCs Partnerships** → **Industrial Innovation and Partnerships (IIP)**

EFRI Mandate

EFRI will serve a critical role in helping the Directorate for Engineering <u>focus on important emerging areas in a timely manner</u>. EFRI will recommend annually a prioritization, fund, and monitor initiatives at the emerging frontier areas of engineering research and education.

EFRI Annual Process



<u>Sources</u>
- Communities
- Workshops
- Advisory committees
- Technical meetings
- Professional societies
- Academies
- Publications
- Proposals/Awards
- Panels
- COV

<u>Continuous</u>

<u>Program Director Proposals</u>
- Identify leading frontier topic
- Identify significance potential, and need for research
- One page write up

<u>November -- December</u>

<u>Program Directors Retreat</u>
- Organize by submitted topical themes
- Presentations
- Create synergisms
- Identify near- and long-term impact
- Prioritize topic recommendations

<u>December - February</u>

<u>EFRI Prioritization</u>
- Identify proposed investments
- ELT Retreat

<u>March</u>

<u>Announcement Formulation</u>
- Form working groups
- Generate proposed announcements
- ENG Advisory Committee input

<u>April – June</u>

<u>Final Announcement Completion</u>
- ELT final recommendations
- ENG finalizes announcements

<u>July</u>

EFRI Criteria

- **TRANSFORMATIVE**- Does the proposed topic represent an opportunity for a significant leap or paradigm shift in a research area, or have the potential to create a new research area?
- **NATIONAL NEED/GRAND CHALLENGE**- Is there potential for making significant progress on a current national need or grand challenge?
- **BEYOND ONE DIVISION**- Is the financial and research scope beyond the capabilities of one division?
- **COMMUNITY RESPONSE**- Is the community able to organize and effectively respond? [but not in very large numbers; i.e., it is an "emerging" area]
- **ENG LEADERSHIP**- Are partnerships proposed, and if so, does NSF/ENG have a lead role?

Areas for 2007 EFRI Solicitation

- **AUTO-RECONFIGURABLE ENGINEERED SYSTEMS ENABLED BY CYBERINFRASTRUCTURE**
  - **Key idea:** Autonomously reconfigurable engineered systems robust to unexpected/unplanned failure events
- **CELLULAR AND BIOMOLECULAR ENGINEERING: CONTROLLING MOLECULAR, CELLULAR, AND INTERCELLULAR/INTERFACIAL BEHAVIOR**
  - **Key idea:** Comprehensive modeling, measurement, and control of coupled biological, chemical, electrical, mechanical, and thermal processes at the cellular and biomolecular level under multiple stimuli.

Auto-Reconfigurable Engineered Systems Enabled by Cyberinfrastructure (ARES-CI)

- Cyberinfrastructure and other engineering advances now provide the capability to embed reconfigurability into systems.
- Design of autonomously configurable engineered systems integrating physical, information and knowledge domains
- Novel methods to sense, self-diagnose, and auto-reconfigure the system to function uninterruptedly when subject to unplanned failure events
- Auto-reconfigurability will provide robustness to unanticipated/unplanned failure events in the same way Complexity provides it to anticipated failure events.

Cellular and Biomolecular Engineering (CBE)

- Develop and validate experimental and simulation tools to model and measure the interaction of multiple stimuli (force, electrical current, biochemical reaction rate, etc.) on cellular and biomolecular interfacial responses;
- Build on integrative knowledge of cellular functions to develop biomolecules to achieve tunable biological, chemical, and mechanical functions;
- Design materials interfaces and biomolecules to control the role of external stimuli on biological activities to regulate cellular functions, identify and neutralize undesired substances, or produce desired substances.

FY07 EFRI Solicitation

- Single Solicitation (two topics) http://www.nsf.gov/pubs/2006/nsf06596/nsf06596.pdf
- Team Proposals
  - Three or more PIs
  - Multiple disciplines
- Up to 4 years in duration
- Up to $500K/year
- Require short (~5-page) pre-proposals followed by invited Full Proposals
- Preliminary Proposal Deadline: Nov. 17, 2006
- Full Proposal Deadline Date: April 30, 2007

11, $2M Standard Awards

Post-EFRI Support

Possible Routes

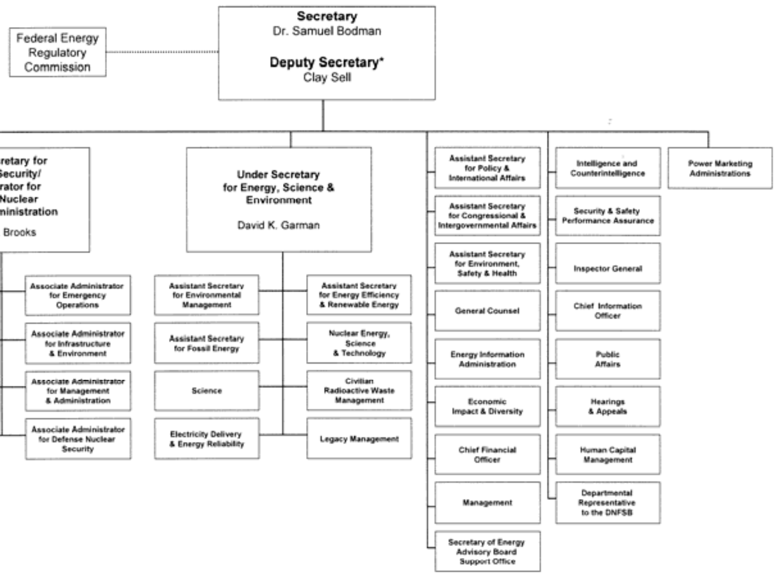
- ERC Program
- New Program in a Division
- Change/Restructure an existing Program
- New Program at interface of Divisions

- Who am I?
  - Dr. Joseph A. Carpenter, Jr.
  - Technology Area Development Manager, FreedomCAR Automotive Lightweighting Materials
  - U.S. Department of Energy (US DOE)
  - Energy Efficiency and Renewable Energy (EERE)
  - Office of FreedomCAR and Vehicle Technologies (OFCVT)

- What do I want from this workshop?
  - Identification of NSF-like fundamental research that can advance the state-of-the-art of technologies for automotive steels in the mid- (<5 years) to long- (>5 years) terms.

- How would the research be funded?
  - Through joint solicitations with NSF
  - Directly through FreedomCAR

DEPARTMENT OF ENERGY



Secretary
Dr. Samuel Bodman

Deputy Secretary*
Clay Sell

Federal Energy Regulatory Commission

Under Secretary for Nuclear Security/ Administrator for National Nuclear Security Administration
Linton F. Brooks

- Deputy Administrator for Defense Programs
- Deputy Administrator for Defense Nuclear Nonproliferation
- Deputy Administrator for Naval Reactors
- Deputy Under Secretary for Counter-terrorism
- Associate Administrator for Emergency Operations
- Associate Administrator for Infrastructure & Environment
- Associate Administrator for Management & Administration
- Associate Administrator for Defense Nuclear Security

Under Secretary for Energy, Science & Environment
David K. Garman

- Assistant Secretary for Environmental Management
- Assistant Secretary for Fossil Energy
- Science
- Electricity Delivery & Energy Reliability
- Assistant Secretary for Energy Efficiency & Renewable Energy
- Nuclear Energy, Science & Technology
- Civilian Radioactive Waste Management
- Legacy Management

- Assistant Secretary for Policy & International Affairs
- Assistant Secretary for Congressional & Intergovernmental Affairs
- Assistant Secretary for Environment, Safety & Health
- General Counsel
- Energy Information Administration
- Economic Impact & Diversity
- Chief Financial Officer
- Management
- Secretary of Energy Advisory Board Support Office

- Intelligence and Counterintelligence
- Security & Safety Performance Assurance
- Inspector General
- Chief Information Officer
- Public Affairs
- Hearings & Appeals
- Human Capital Management
- Departmental Representative to the DNFSB

- Power Marketing Administrations

* The Deputy Secretary also serves as the Chief Operating Officer

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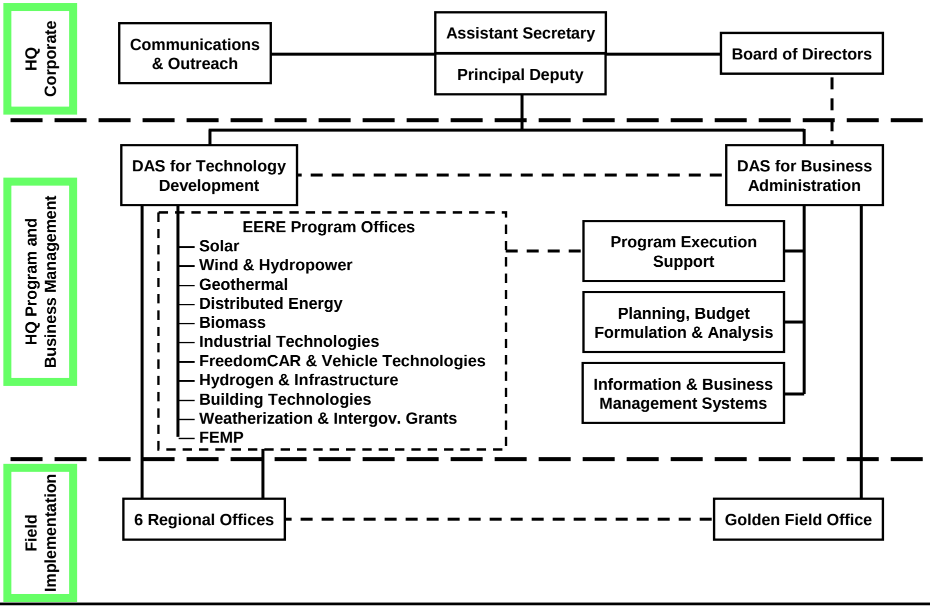
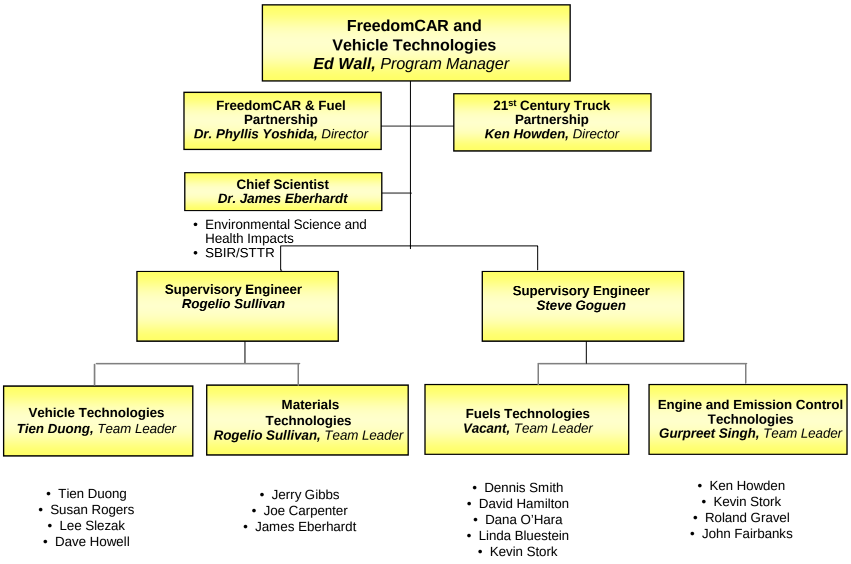
U.S. Department of Energy
Energy Efficiency and Renewable Energy

EERE Organization

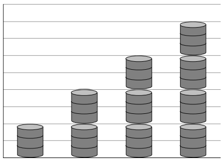


FreedomCAR & Vehicle Technologies Organization

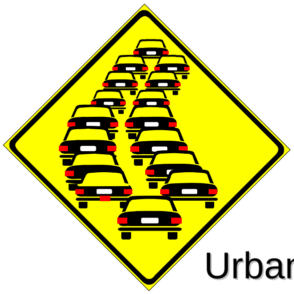


The Challenges Facing Us…

Materials Technologies



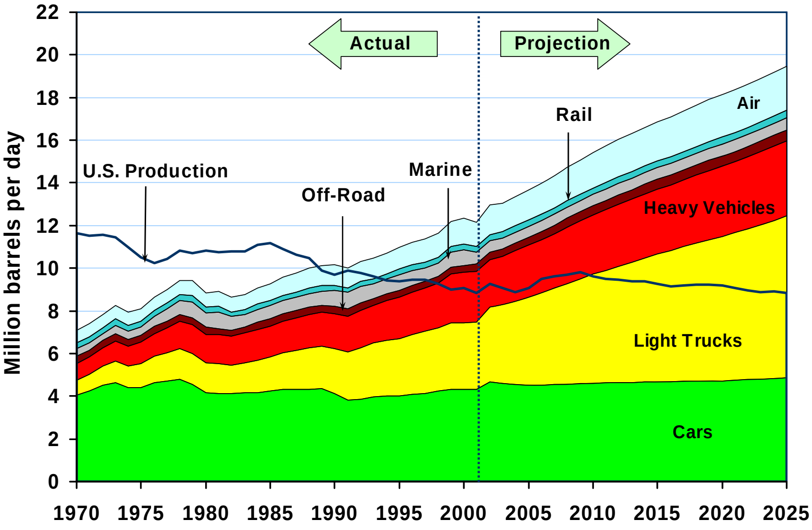
Growing Petroleum Consumption



Urban Pollution

Global Climate Change

USA Transportation Petroleum Use by Mode (1970-2025)
2003 Total = 13.42 mbpd



Note: Domestic production includes crude oil, natural gas plant liquids, refinery gain, and other inputs. This is consistent with EIA, MER, Table 3.2. Previous versions of this chart included crude oil and natural gas plant liquids only.
Source: Transportation Energy Data Book: Edition 24, ORNL-6973, and EIA Annual Energy Outlook 2005, Preliminary release, December 2004.

HISTORY

Materials Technologies

- 1970 (to present) – In response to environmental movements of the 1960's, the Clean Air Acts established *de facto* standards for criteria emissions (carbon monoxide, hydrocarbons, nitrogen and sulfur oxides, and particulates) from transportation vehicles and other sources.
- 1975 to 1986 (and to present) - Energy Policy and Conservation Act of 1975 establishes Corporate Average Fuel Economy standards for light-duty vehicles.
- 1993-2002 – President Clinton's Partnership for a New Generation of Vehicles (PNGV) between US government agencies and "Big Three" automakers indicates that high-fuel efficiency (33 km/l) family autos are probably technically viable at fractional cost premiums through use of alternate power plants (mainly diesel-electric hybrids), advanced design and lightweighting materials, probably spurs automotive technology worldwide, and provides US model for government-industry cooperation.

HISTORY - continued

Materials Technologies

- 2002 -- PNGV transitioned by President Bush to FreedomCAR with more emphases on fuel-cell vehicles, all varieties of light-duty vehicles ("CAR" stands for Cooperative Automotive Research, not "car") and limited to USCAR and DOE.

  -- Twenty-First Century Truck (21CT) Initiative forms aimed at heavy-duty vehicles.
- 2002-2005 – President Bush rejects Kyoto Treaty on economic bases but pledges large R&D efforts to provide technological solutions to climate change
- 2003 – FreedomCAR expanded to include the Hydrogen Fuels Initiative, becomes FreedomCAR and Fuels Partnership, to **explore** technologies for producing and delivering hydrogen for transportation and other uses (the "hydrogen economy"). Energy-supply industry joins. International Partnership for the Hydrogen Economy formed.

FreedomCAR and Fuel Partnership

FreedomCAR & FUEL Partnership

H_2

GM

Ford

DaimlerChrysler

bp

ChevronTexaco

ConocoPhillips

ExxonMobil

FreedomCAR Strategic Approach

- ☐ Develop technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles and assure the hydrogen infrastructure to support them
- ☐ Continue support for hybrid propulsion, advanced materials, and other technologies that can dramatically reduce oil consumption and environmental impacts in the nearer term
- ☐ Instead of single vehicle goals, develop technologies applicable across a wide range of passenger vehicles.

Weight Savings and Costs for Automotive Lightweighting Materials

Materials Technologies

Lightweight Material	*Material Replaced*	*Mass Reduction (%)*	*Relative Cost (per part)**
High Strength Steel	Mild Steel	10-25	1
Aluminum (Al)	Steel, Cast Iron	40 - 60	1.3 - 2
Magnesium	Steel or Cast Iron	60 - 75	1.5 - 2.5
Magnesium	Aluminum	25 - 35	1 - 1.5
Glass FRP Composites	Steel	25 - 35	1 - 1.5
Carbon FRP Composites	Steel	50 - 60	2 - 10+
Al matrix Composites	Steel or Cast Iron	50 - 65	1.5 - 3+
Titanium	Alloy Steel	40 - 55	1.5 - 10+
Stainless Steel	Carbon Steel	20 - 45	1.2 - 1.7

**** Includes both materials and manufacturing.***

Ref: *William F. Powers, Advanced Materials and Processes, May 2000, pages 38 – 41.*

Key Activities and Budgets

Materials Technologies

	Budgets ($M) FY05	FY06	FY07 (Request)
Propulsion Materials Technology			
Automotive Propulsion Materials	1.9	1.8	1.9
Heavy Vehicle Propulsion Materials	4.6	4.3	3.9
Lightweight Materials Technology			
Automotive Lightweighting Materials (light-duty)	16.3	18.3	18.7
High-Strength Weight Reduction Materials (truck)	7.4	2.7	0
High Temperature Materials Laboratory	5.9	7.2	4.4
Total	36.1	34.3	28.9

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Automotive Lightweighting Materials R&D

- Largest Focus Areas
  - Production of low-cost carbon fiber (+)
  - Production of low-cost carbon-fiber-composite components (+)
  - Low-cost forming of Mg components (+)
- Smaller Focus Areas
  - Low-cost Ti-matrix composite processes (=)
  - Ti metal and alloys production and fabrication (+)
  - Forming AHSS steel components (=)
  - General manufacturing (viz., NDE) (+)
  - Glazing (glass) (+?)
  - Crashworthiness of advanced materials and structures (=)
  - Recycling of light metals and composites (=)

Major ALM Partners

Materials Technologies

- United States Council for Automotive Research (USCAR)
  - United States Automotive Materials Partnership (USAMP) Advanced Metals Division (AMD)
  - Automotive Composites Consortium (ACC)
  - Vehicle Recycling Partnership (VRP)
- Auto/Steel Partnership (A/SP)
  - Through USAMP
- CANMET (Natural Resources Canada)

Recent ALM Steel Projects

Materials Technologies

- “Enablers” - Applied Fundamentals Studies

  Die Face Engineering for Advanced Sheet Forming (AMD 408).
  Enhanced Forming (A/SP 040).
  High Strength Steel Stamping (A/SP 050).
  Active Flexible Binder Control for Robust Stamping (AMD 301).
  Tribology (A/SP 230).
  Hydroform Materials and Lubricants (A/SP 060).
  High-Strength Steel Tailor-Welded Blanks (A/SP 210)
  Sheet Steel Joining (A/SP 070).
  Friction Stir Spot Welding of High-Strength Steels (ORNL and PNNL).
  Forming Limits of Weld Metal in Al and AHSSs ((PNNL).
  Ultrasonic Phased Array System for Resistance Spot Weld Inspection (AMD 409 and LBNL).
  NDE Inspection of Adhesive Bonds in Metal-Metal Joints (SNL).
  In-Line Resistance Spot Welding Control and Evaluation System Assessment for Light Weight Materials (AMD 605 and PNNL)
  Strain Rate Characterization of Steels (A/SP 190 and ORNL).
  Dynamic Characterization of Spot Welds for AHSSs (AMD ??? (USoCar) and ORNL).
  Evaluations of Manufacturing Effects on TRIP Steels (PNNL).
  Characterization of Thermomechanical Behaviors of AHSSs (ORNL and PNNL).
  Sheet Steel Fatigue (A/SP 160).

  ⇩ ⇧ ⇩ ⇧ ⇩ ⇧ ⇩

- “Focals” – Validation of and Guidance for Enablers’ Technologies

  Lightweight Closures (A/SP 090).
  Lightweight Front End Structures (A/SP 110).
  Future Generation Passenger Compartment (A/SP 240).
  Lightweight Rear Chassis Structures (A/SP 601).

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Office of Energy Efficiency and Renewable Energy

http://www.eere.energy.gov

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Appendix 5: Technical Presentations

- *Overview of AHSS*: Debanshu (DB) Bhattacharya, Mittal Steel
- *AHSS Microstructures, Fffect on Failure*: David K. Matlock, Colorado School of Mines
- *AHSS Continuum Modeling Issues*:
  - *Part A, Springback*: Thomas B. Stoughton, GM Research and Development
  - *Part B, Forming*: Cedric Xia, Ford Research Laboratory

An Overview of Advanced High Strength Steels (AHSS)

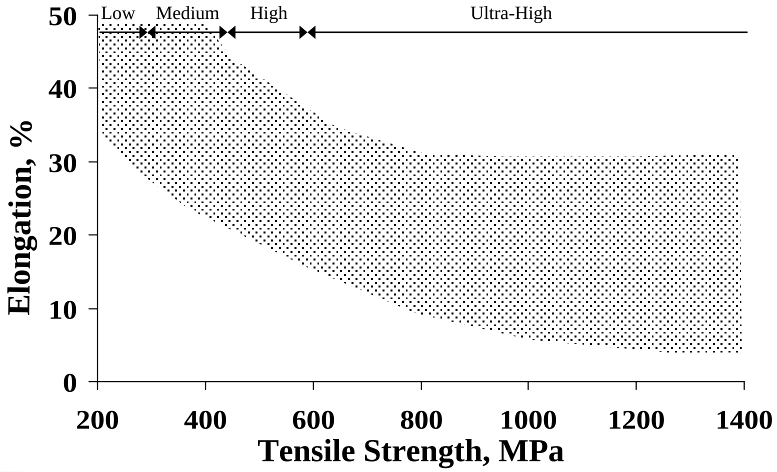
Dr. Debanshu Bhattacharya
Arcelor Mittal Research & Development Center
East Chicago, Indiana, USA

Outline

- **Definitions**
- **Multi-Phase (Complex-Phase) Steels**
- **Dual Phase Steels**
- **TRIP Steels**
- **Martensitic Steels**
- **X-IP (TWIP, SIP etc.) Steels**
- **Issues**

Sheet Steels Design

- Balance between Strength and Formability



Definition

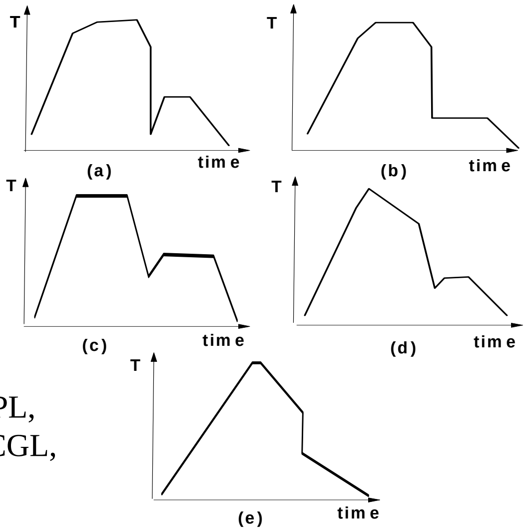
- **Advanced High Strength Steels (AHSS)**

Steels with > or = 500 MPa tensile strength and complex microstructures such as bainite, martensite, retained austenite etc. and excluding the classic HSLA steels

Product Development Concepts

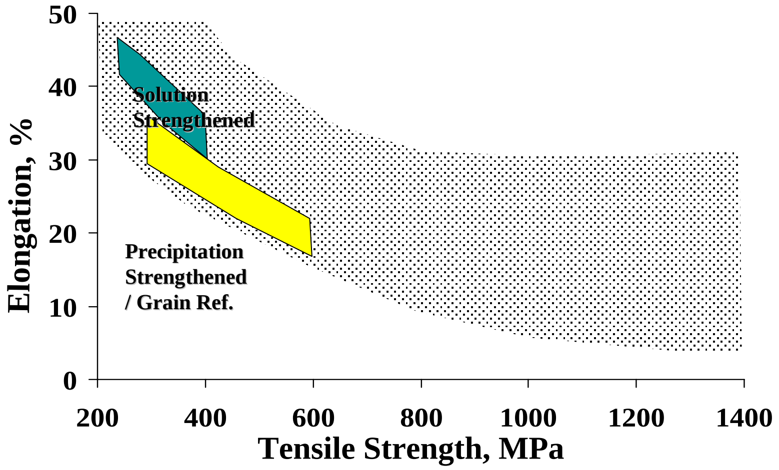
- Solid Solution Strengthening
  - – C, Mn, Si, P
  - – Solute C for bake-hardening steels
- Precipitation Strengthening
  - – Carbides, Nitrides (Nb, Ti, V etc.)
- Grain Refinement
  - – $\sigma_{LYS} = \sigma_0 + K\, d^{-1/2}$
- Phase Transformation
  - – Single, Dual-phase,
  - – Multi-phase, TRIP

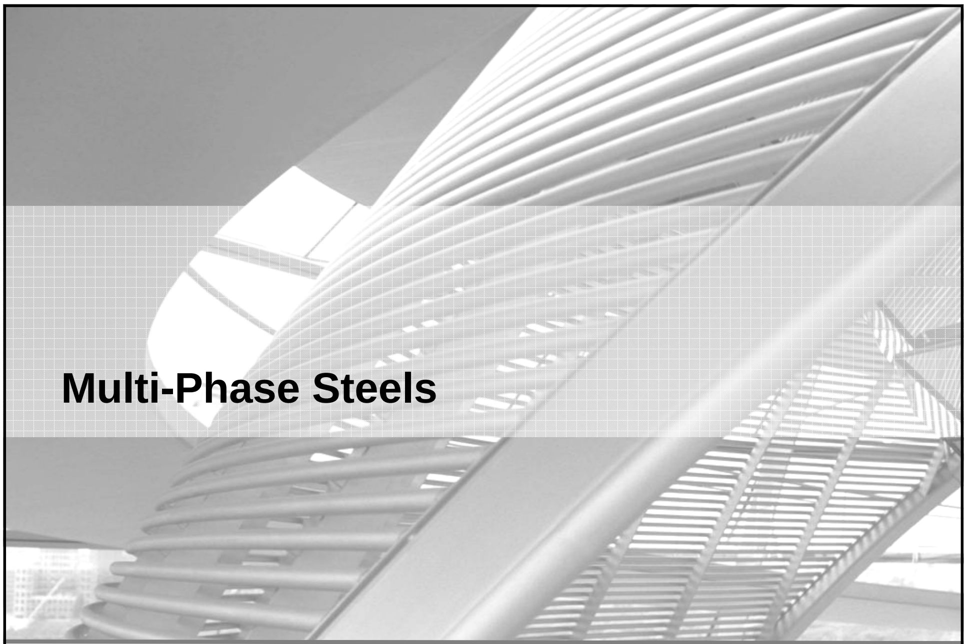
Available Annealing/Coating Cycles



a:CAL,b:CAPL,
c:KCGL,d:5CGL,
e:3CGL(ZQ)

Product Development

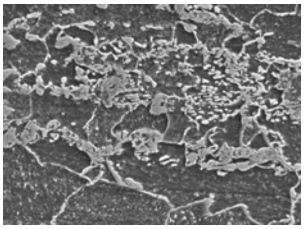




Multi-Phase Steels

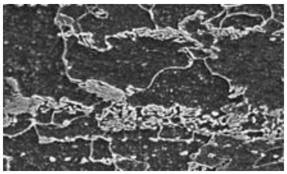
Multi-Phase Steels

- C < 0.15 wt%
- Ferrite + Bainite + Pearlite
- Strengthening
  - Phase Transformation
  - Solid Solution
  - Precipitation & Grain Refinement
- Higher Strength, Moderate Formability
  - TS: 440-590 MPa, YS: 300-500MPa, T-El: 35-20%
  - Some Stretch Flangeable, HE: >100 %

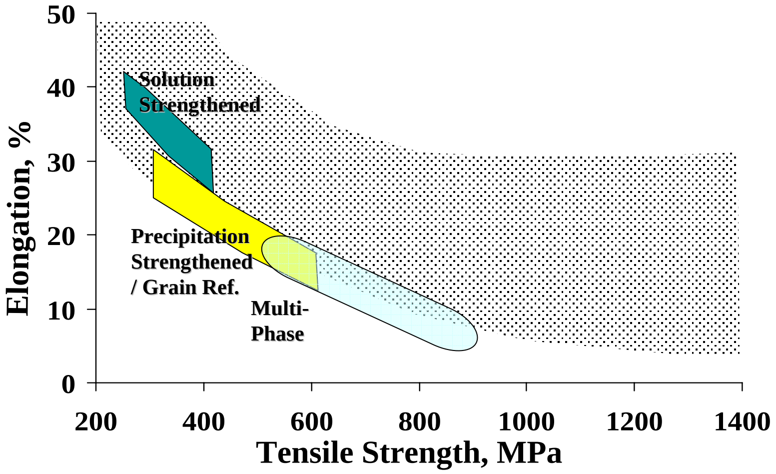


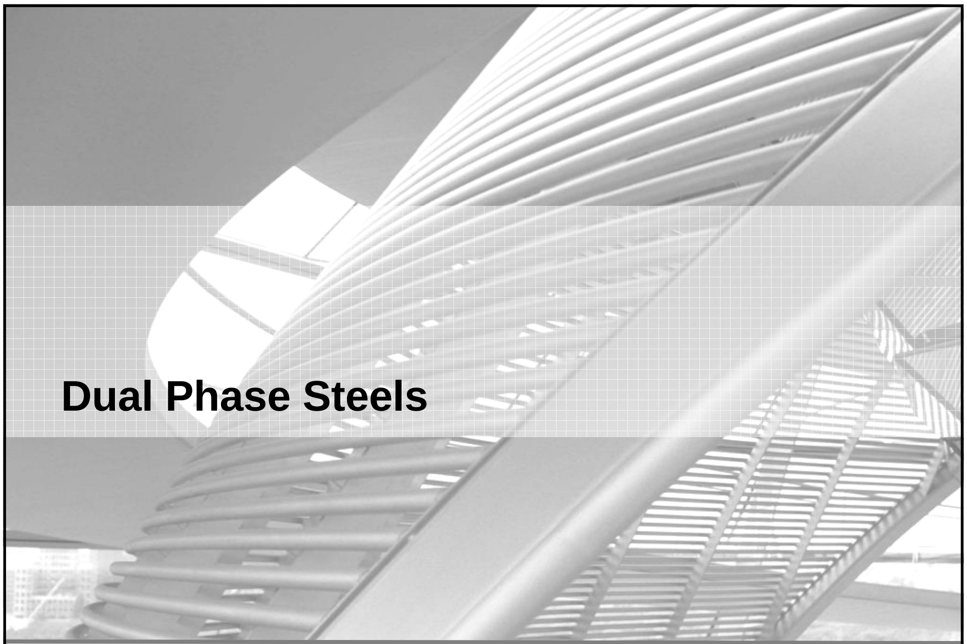
Mechanical Properties of Multi-Phase Steels

Product	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)
HR 590 SF	590	510	28
CR 590 HY	690	515	23
CR 980 HY	1005	795	15
GA 590 HY	620	505	26



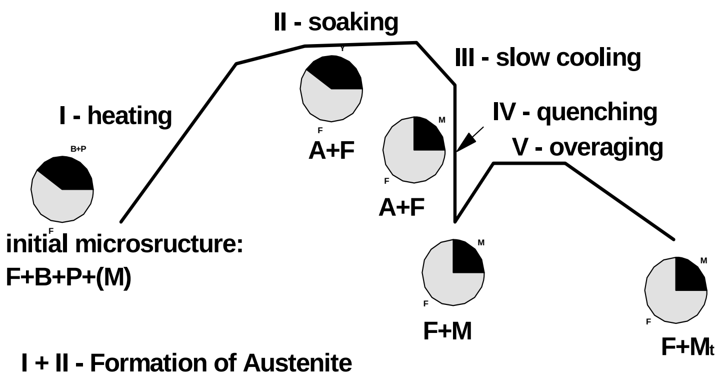
Product Development





Dual Phase Steels

Metallurgical Concept to obtain DP Structure on CAL

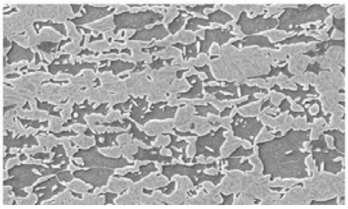


I + II - Formation of Austenite
III - Formation of Ferrite
IV - Formation of Martensite/Bainite
V - Tempering of Martensite/Bainite

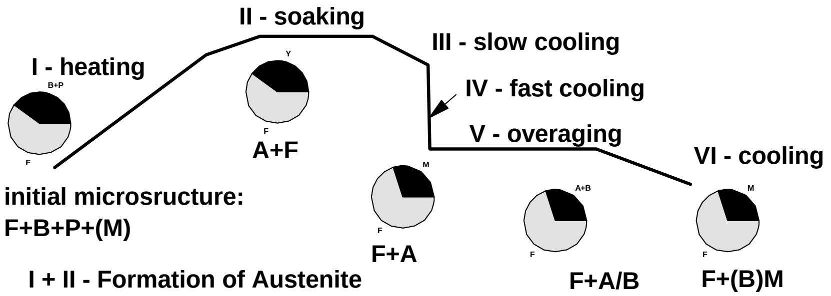
Mechanical Properties & Microstructure of CR DP 980

Chemistry(wt %) : 0.15C-1.5Mn-0.3Si

	YS, MPa	TS, MPa	UE, %	TE, %	YPE, %	Bend, 90º, (r/t)
Properties	675	1030	8	13	0	3.0
Target	580-730	> 980		> 8		



Metallurgical Concept to obtain DP Structure on CAPL



I - heating

II - soaking

III - slow cooling

IV - fast cooling

V - overaging

VI - cooling

initial microsructure:
F+B+P+(M)

A+F

F+A

F+A/B

F+(B)M

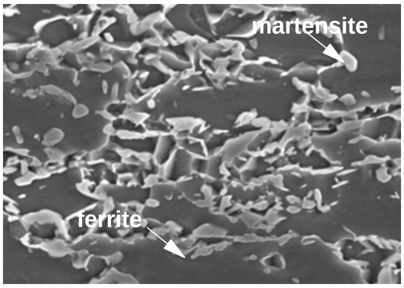
I + II - Formation of Austenite
III - Formation of Ferrite
IV - Retention of Austenite
V - Formation of Bainite and/or Retention of Austenite
VI - Transformation of Austenite to Martensite

Microstructure and Properties of EG 500 DP

- **Mechanical Properties (Avr. for 38 coils)**

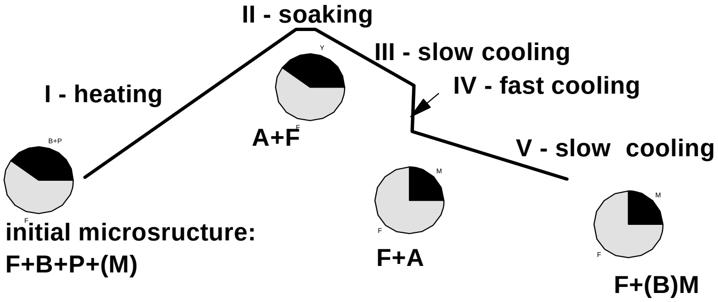
YS, MPa	TS, MPa	TE, %	n_{4-6}
315	547	31	0.220

x1000



x5000

Metallurgical Concept to obtain DP Structure on #3CGL



II - soaking

III - slow cooling

IV - fast cooling

I - heating

A+F

V - slow cooling

initial microsructure:
F+B+P+(M)

F+A

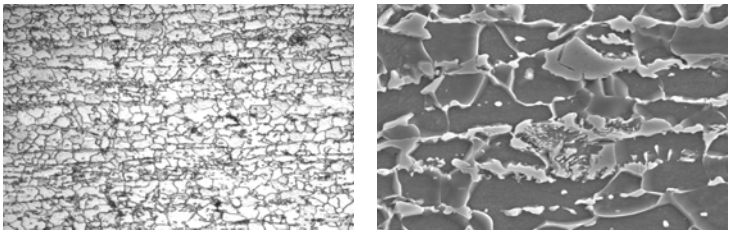
F+(B)M

I + II - Formation of Austenite
III - Formation of Ferrite
IV - Retension of Austenite
V - Transformation of Austenite to Martensite/Bainite

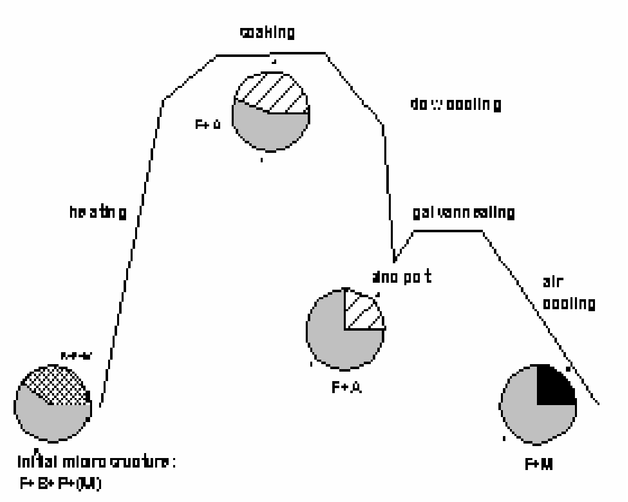
Typical Mechanical Properties & Microstructure

Steel Grade	TS, MPa	YS, MPa	TE, %
GI DP 600	625	320	26
Target	>600	340-410	>20

-



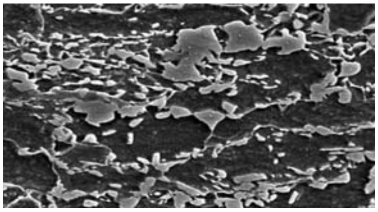
Metallurgical Concept for Galvannealed Dual Phase Steels



Typical Mechanical Properties & Microstructure

Steel Grade	TS, MPa	YS, MPa	TE, %
GA DP 590	620	355	26

Target	**>590**	**388**	**26**



Dual Phase Steels

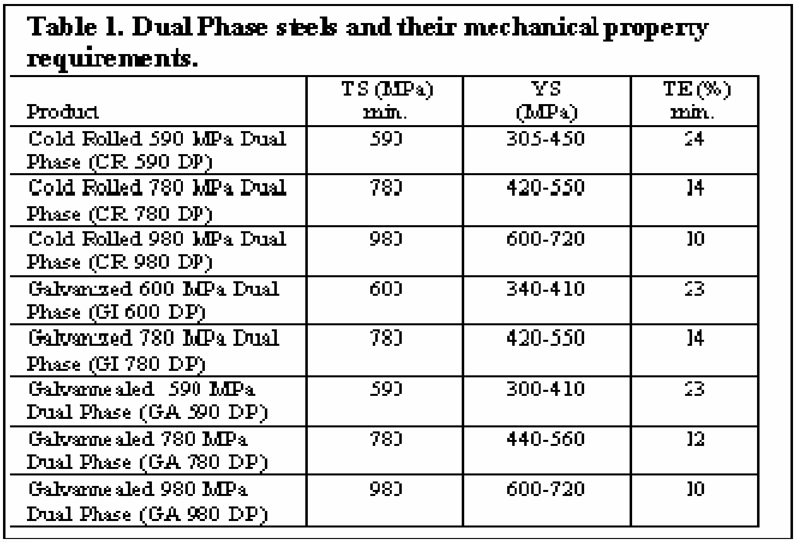
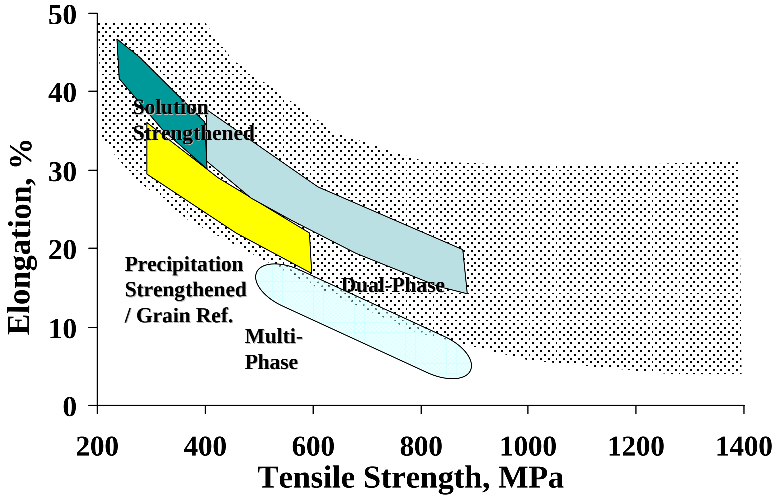
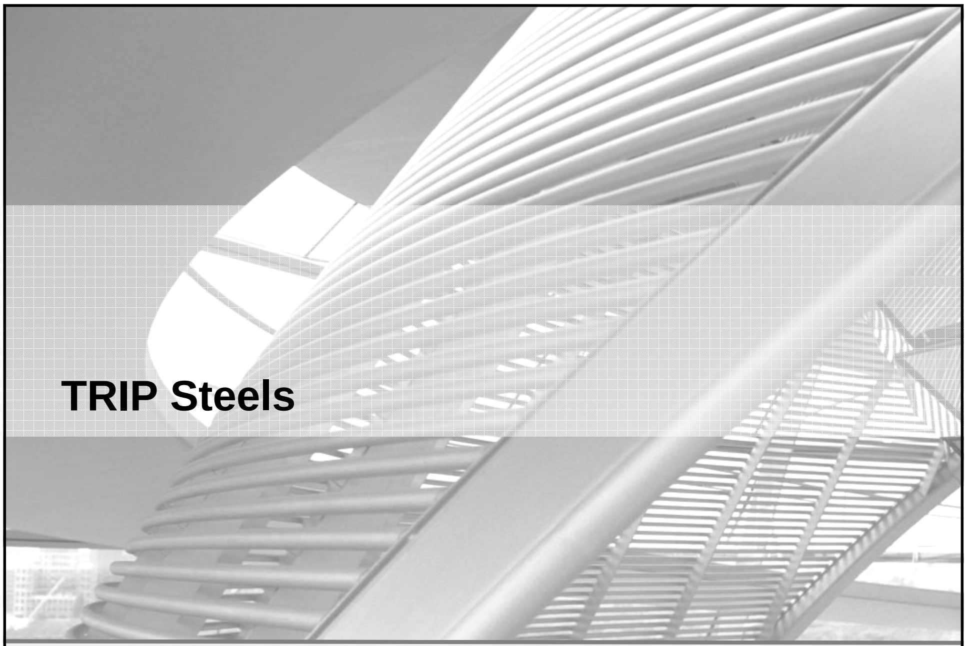


Table 1. Dual Phase steels and their mechanical property requirements.

Product	TS (MPa) min.	YS (MPa)	TE (%) min.
Cold Rolled 590 MPa Dual Phase (CR 590 DP)	590	305-450	24
Cold Rolled 780 MPa Dual Phase (CR 780 DP)	780	420-550	14
Cold Rolled 980 MPa Dual Phase (CR 980 DP)	980	600-720	10
Galvanized 600 MPa Dual Phase (GI 600 DP)	600	340-410	23
Galvanized 780 MPa Dual Phase (GI 780 DP)	780	420-550	14
Galvannealed 590 MPa Dual Phase (GA 590 DP)	590	300-410	23
Galvannealed 780 MPa Dual Phase (GA 780 DP)	780	440-560	12
Galvannealed 980 MPa Dual Phase (GA 980 DP)	980	600-720	10

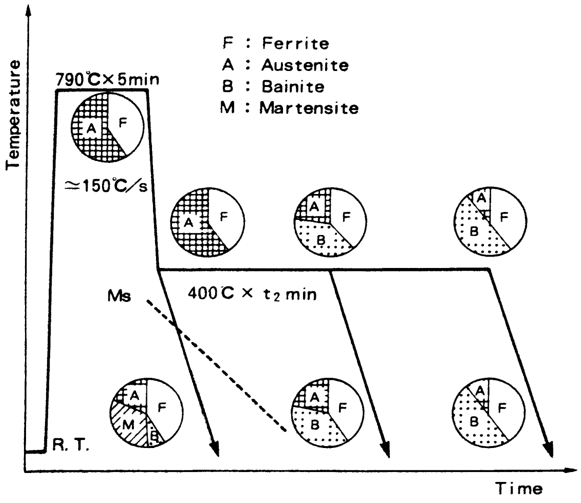
Product Development





TRIP Steels

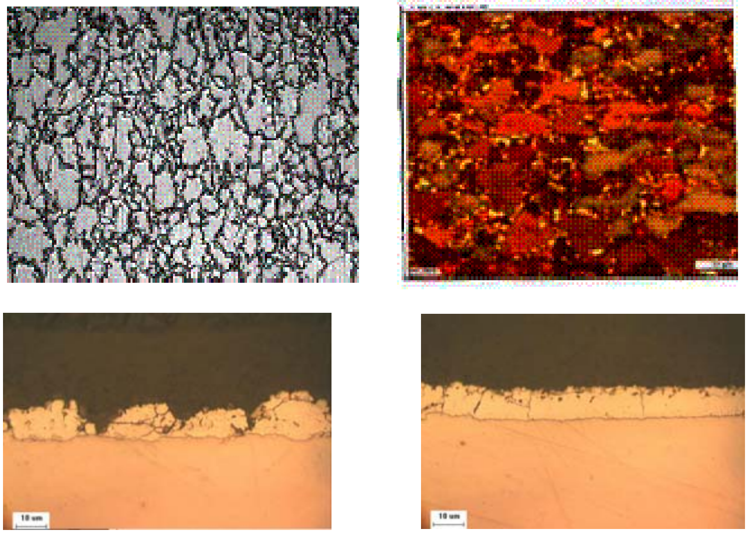
Metallurgical Concept to obtain TRIP Steels



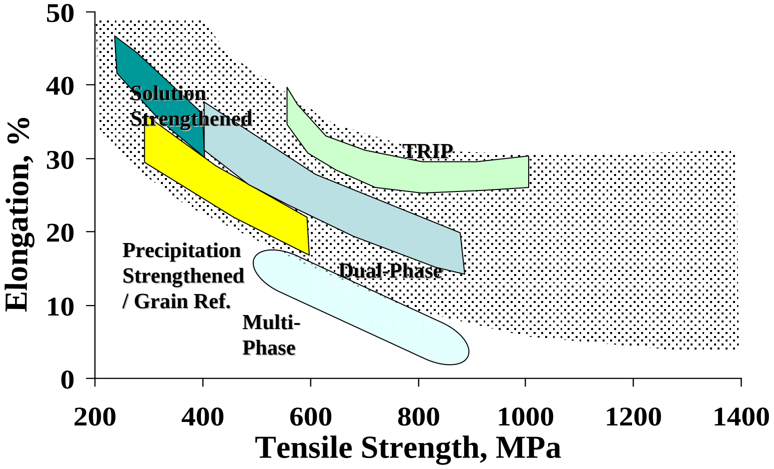
Target Mechanical Properties of TRIP Steels

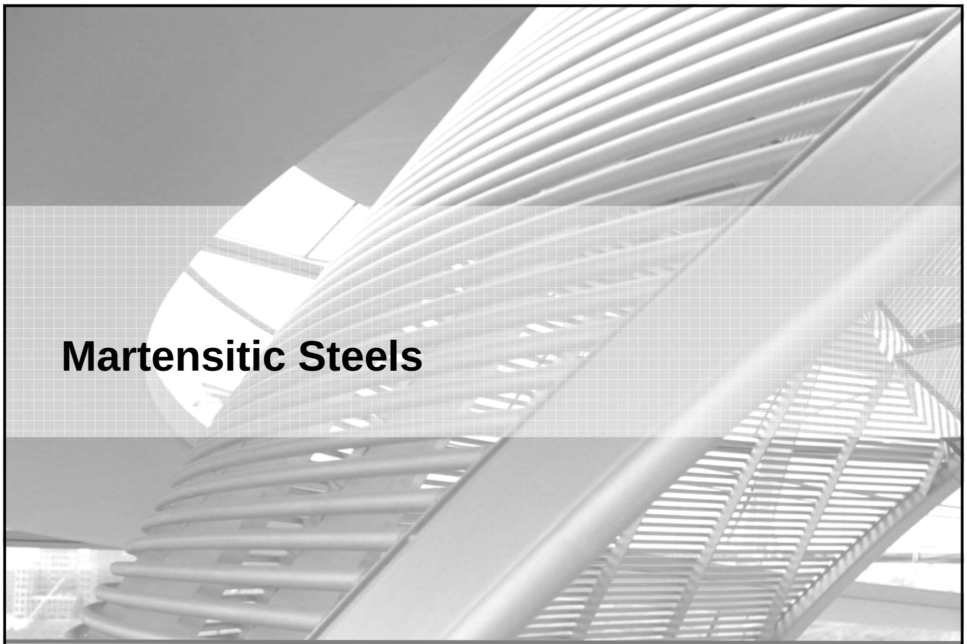
Product	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)
Cold Rolled 590 TRIP	590 Min	350 – 495	31
Galvannealed 590 TRIP	590 Min	360 - 510	26
Galvanized 590 TRIP	590 Min	380 - 480	27
Cold Rolled 780 TRIP	780 Min	410 – 500	21
Galvannealed 780 TRIP	780 Min	410 - 560	19
Galvanized 780 TRIP	780 Min	440 – 500	21

Microstructures of TRIP Steel



Product Development

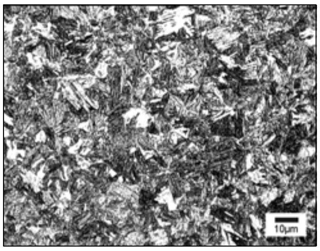




Martensitic Steels

Martensitic Steels – CR (+EG)

- C < 0.25 wt%
- Martensite Matrix
- Strengthening
  - Phase Transformation
  - Solid Solution

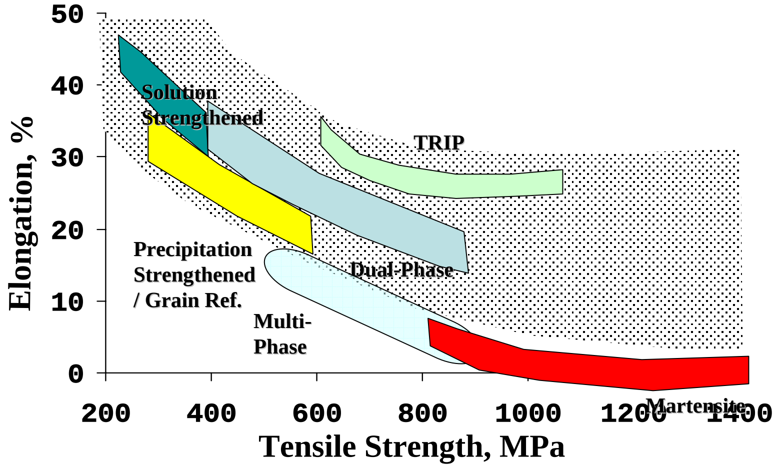


- Ultra-High Strength, Low Formability
  - TS: 960-1550 MPa
  - YS: 900-1330 MPa;
  - T-El: 5%

Typical Mechanical Properties of Martensitic Steels

Product	Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)
M130	1054	923	5.4
M160	1178	1020	5.1
M190	1420	1213	5.1
M220	1585	1350	4.7

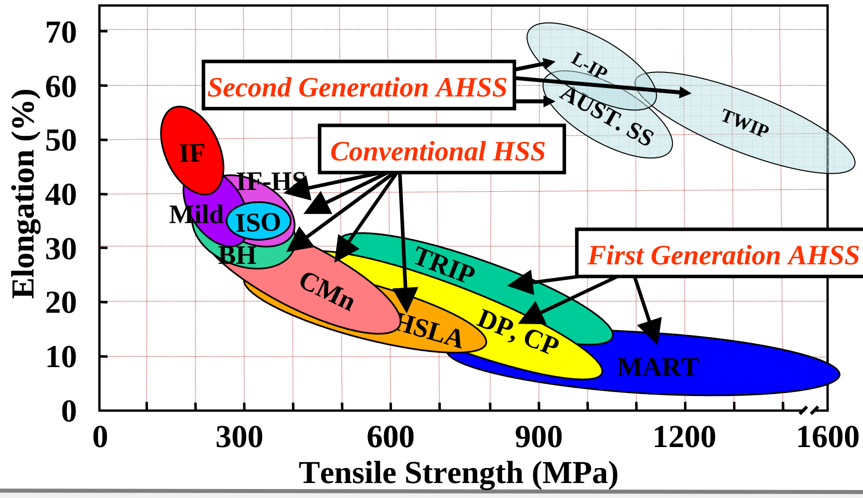
Product Development



X-IP (TWIP, SIP…) Steels

TWIP Steels

- Known TWIP C-Mn-S-Al composition
  - Tensile strength of 800MPa-1000MPa; Elongation >50%; Low YS/TS
  - Redesign of processing route may be required to achieve higher YS for crash performance and passenger safety cage
- Aim - to develop a *commercially viable* **high yield ratio** TWIP or quasi-TWIP steel for *structural application* with
  - Tensile strength of ~ 1000 MPa (800-1200 MPa)
  - Minimum 40% elongation
  - YS/TS of ~ 0.7



Issues for Steel manufacturing

- Steelmaking Control: Very tight control of C and Mn are needed to achieve the strength ranges specified
- Casting: Because of peritectic C at higher sterngth as well high Al casting without cracks is a challenge
- Hot Rolling: Because of additions of significant amounts of alloying elements. High temperature deformation is high and hot rolling to widths and gauges needed could be an issue
- Cold Rolling: If thin hot bands can not be obtained because of hot mill limitations, high cold reduction then becomes the problem
- Finally due to expensive alloys such as Mo, V etc. these could be high cost products

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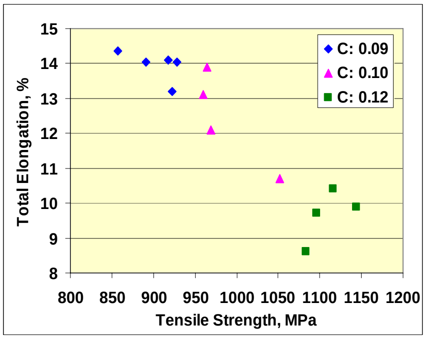
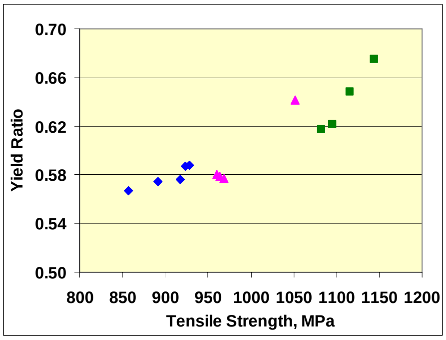
Effect of Carbon

Strength-Ductility Balance and Yield Ratio

1.6% Mn, 0.16% Mo, 0.0020% B



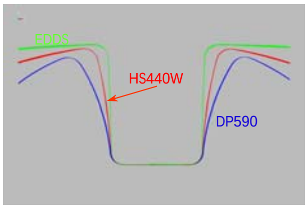
Soak: 800°C, Overage: 200°C

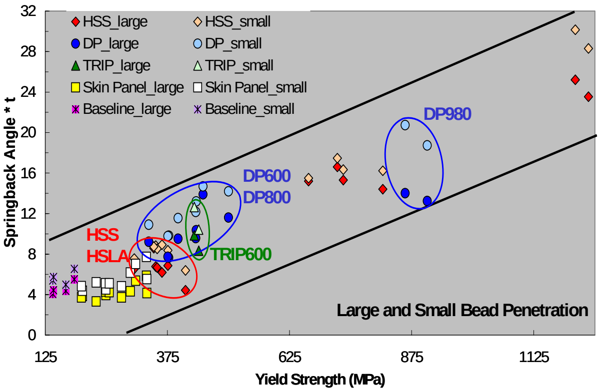


Issues for the End User

- Weldability: Addition of elements such a C, Al Si Mn pose a chellenge for welding
- Spring-back: Spring-back increases with strength so that control of spring-back is difficult in these steels
- Shear-edge Cracking: High stretch flangeability is often required and may not be compatible with the microstructure
- Hole Extrusion: Effects of strength and microstructure undermines this aspect
- Cracking at Tool Radius: Need to work with die designers to solve this problem
- Finally cost of product

Implementation Barriers - Springback

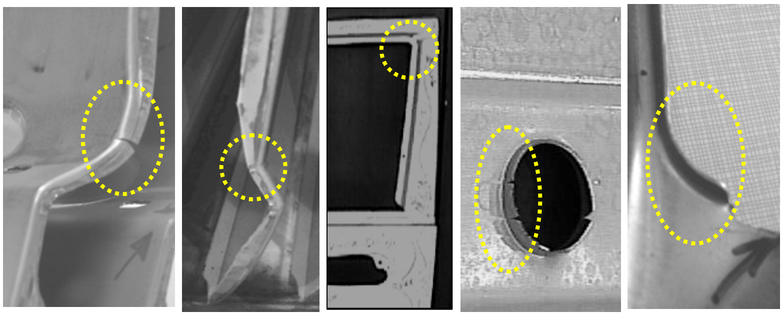




Springback has been systematically studied at Mittal Steel
(from AISI Technology Roadmap Project 0012)

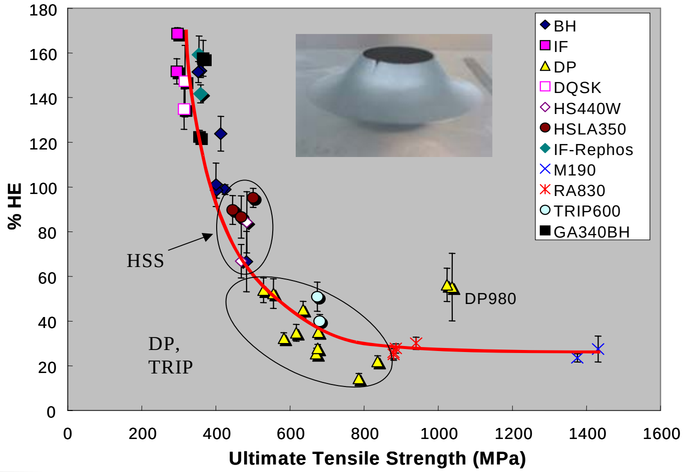
Implementation Barriers -
Springback Control

Implementation Barriers –
Shear Edge Cracking

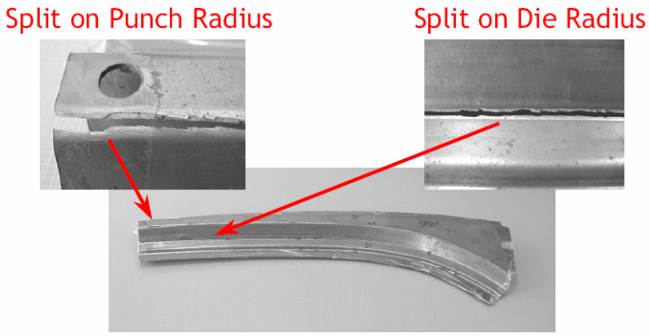


Stretch flange is a common feature in automotive parts

Implementation Barriers –
Hole Extrusion (effect of UTS and microstructure)



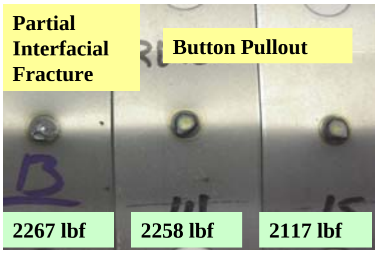
Implementation Barriers - Cracking at Tooling Radius



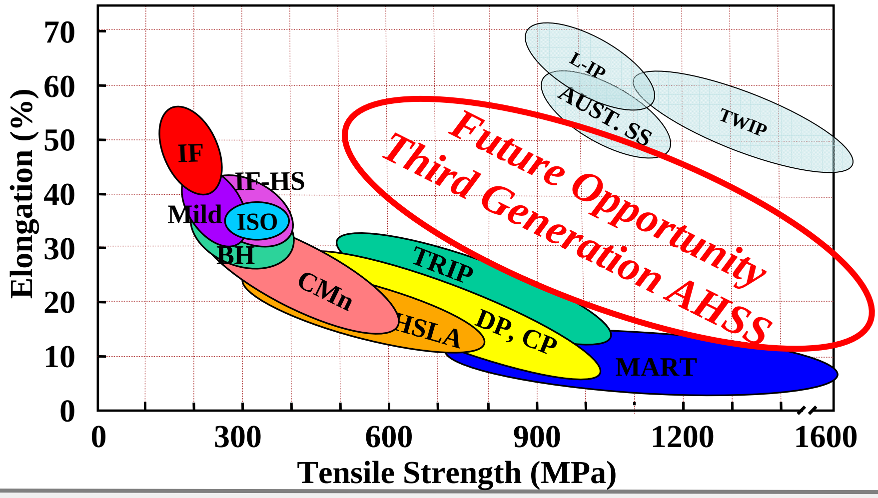
- Working jointly with customers to develop solutions
- A great deal of research work is in progress

Weldability (RSW)

- Optimization of welding parameters
  - ✓ High electrode force
  - ✓ MFDC power source
- Investigation of interfacial fracture
  - ✓ Strength not necessarily low
  - ✓ Optimizing carbon equivalent



Cross Tension Tests



Microstructural Aspects of Advanced High Strength Sheet Steels

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AHSS Workshop -- October 23, 2006

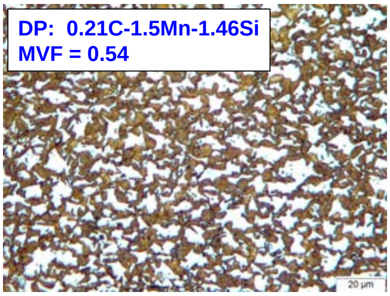
David K. Matlock
Advanced Steel Processing and Products Research Center*
Colorado School of Mines
Golden, Colorado

***An NSF Industry/University Cooperative
Research Center - Est. 1984**

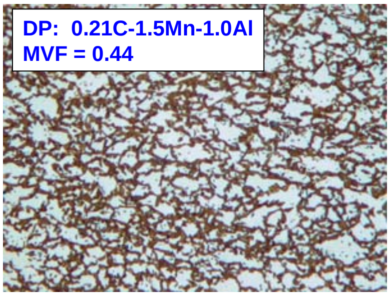
AHSS: Microstructural Classes

- **Conventional High Strength (ferrite-based)**
  Bake Hardenable (BH) HSLA
- **"1st Generation": ("ferrite"-based)**
  Dual Phase (DP) TRIP
  Complex Phase (CP) Martensitic
  Bainitic
- **"2nd Generation": ("austenite"-based)**
  Austenitic stainless steels
  TWIP - Twinning Induced Plasticity (TWIP)
  L-IP® - Lighter Weight Steels with Induced Plasticity
  …others…..
- **"3rd Generation": New (?) multiphase**

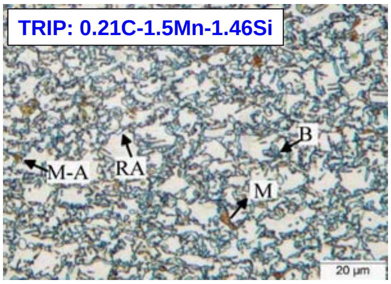
AHSS: Example Microstructures



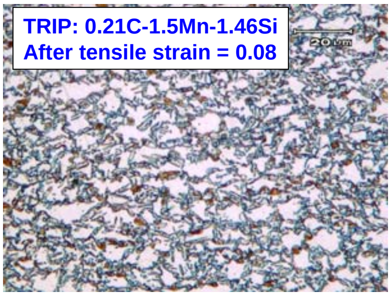
DP: 0.21C-1.5Mn-1.46Si
MVF = 0.54



DP: 0.21C-1.5Mn-1.0Al
MVF = 0.44



TRIP: 0.21C-1.5Mn-1.46Si



TRIP: 0.21C-1.5Mn-1.46Si
After tensile strain = 0.08

De, Speer, Matlock (2004): supported by AISI/DOE TRP Program

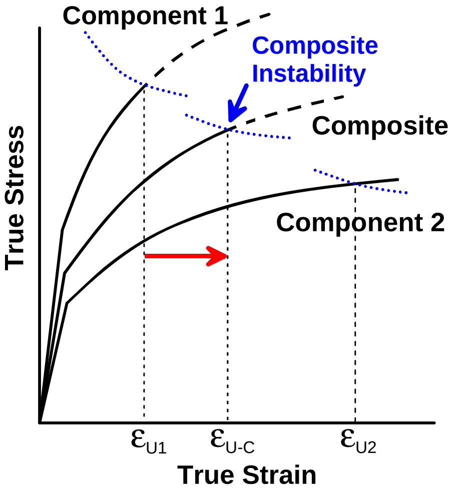
Application of Composite Model to Identify New Multiphase AHSS Steels

- **Assume each "constituent" described by flow curve:**

  $$\sigma = K\varepsilon^n$$

- **Apply rule of mixtures for composites *(assumes "Isostrain")***

  $$\sigma_T = \sigma_1 V_1 + \sigma_2 V_2 + \dots$$



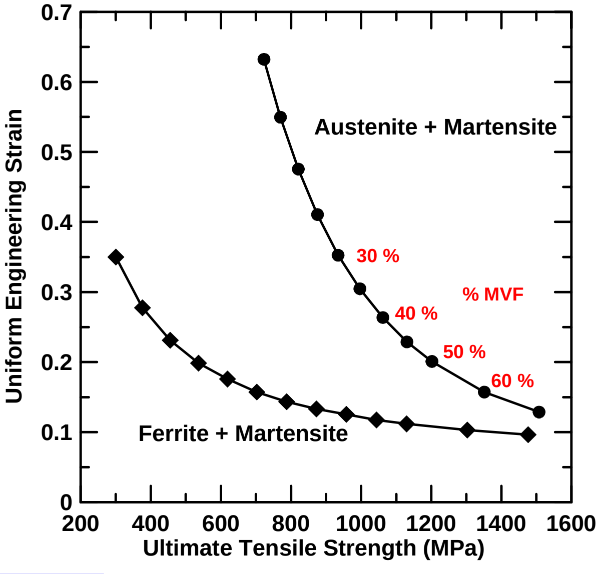
REF: "The Tensile Strength and Ductility of Continuous Fibre Composites" S.T. Mileiko, J. Mat. Sci., (1969)

Example Application: Stable Constituents

Constituent properties from the literature

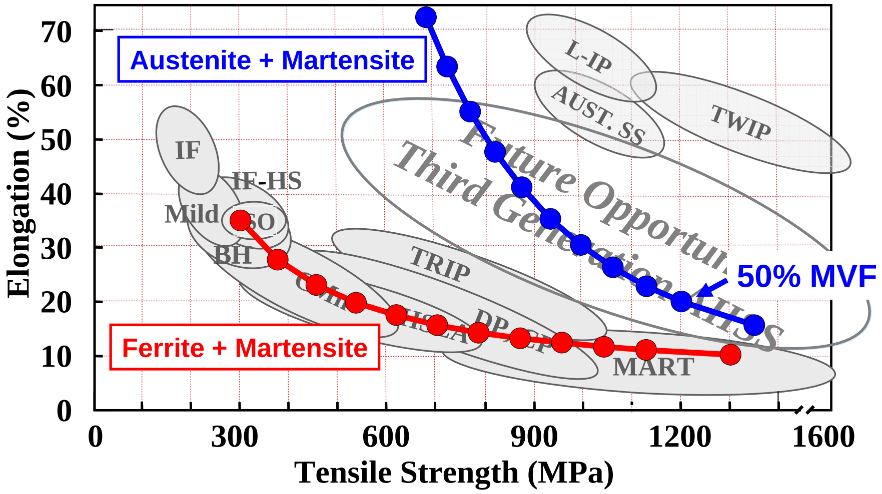
- IF Steel
- High Mn Austenite (*assumed stable*)
- Martensite

Constituent	UTS (MPa)	Uniform True Strain
Ferrite	300	0.3
Austenite	640	0.6
Martensite	2000	0.08



Matlock and Speer: ICASS 2006

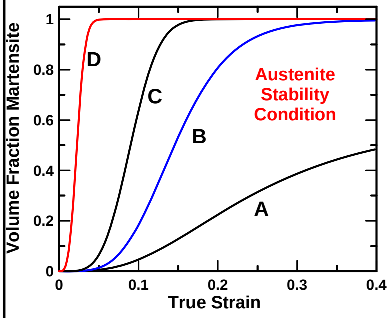
Comparison to "3rd Generation" AHSS

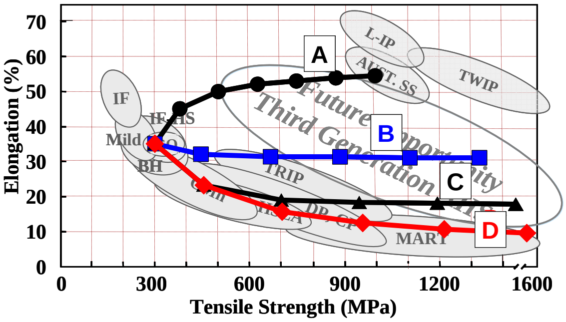


Matlock and Speer: ICASS 2006

Property Assessment: Austenite Stability

Initial Microstructure: Ferrite + Austenite
Initial Meta-stable Austenite = 0 to 85 %





Constituent	UTS (MPa)	Uniform True Strain	Uniform Engineering Stain
Ferrite	300	0.3	0.35
Austenite	640	0.6	0.82
Martensite	2000	0.08	0.08

Matlock and Speer: ICASS 2006

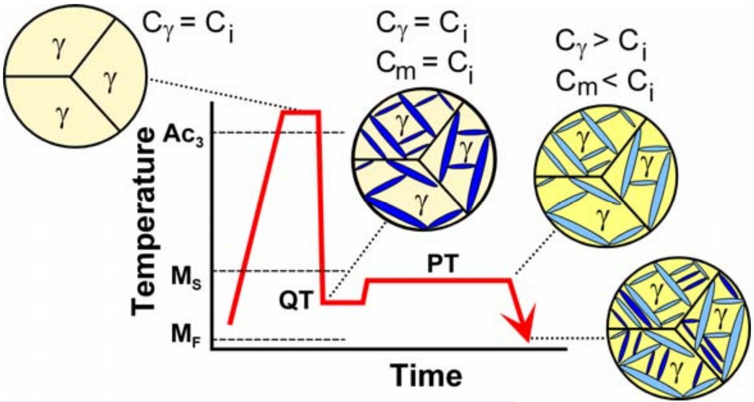
Summary: AHSS Developments

- **“3rd Generation” AHSS will require significant amounts of a high strength constituent**
  e.g. Martensite, fine grained ferrite, …

- **Opportunities exist for fundamental analyses leading to novel alloying/processing methodologies – examples:**
  - **Quenching and Partitioning**
  - **TMCP to produce 2 μm ferrite with 25% γ**
  - **………**

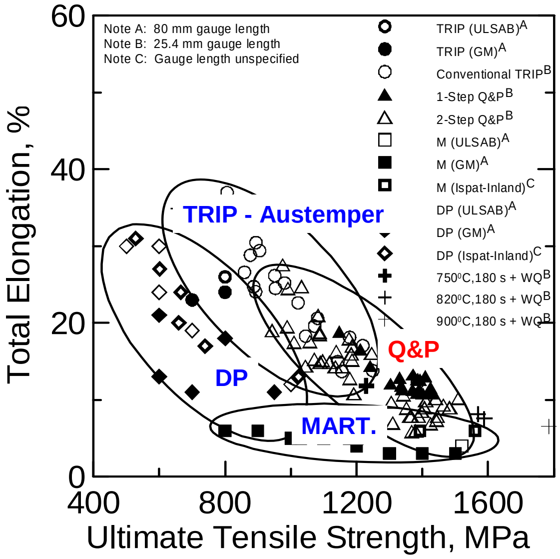
Quenching and Partitioning (Q&P)

- **Quench to T > RT (quench T = QT)**
  to form martensite + austenite
- **Enrich austenite (i.e. partition at T > or = QT)**
- **Result, controlled MVF with retained austenite**



Speer, Matlock, *et al.* (Supported by NSF-DMR)

Properties of Q&P
Summary and Comparison with AHSS



Clarke, Speer, *et al.* (Supported by NSF-DMR)

Low Temperature TMCP

Add alloying elements, e.g. Mn or N or …. to stabilize austenite

0.2C, 2Mn, 2Si

2 µm ferrite GS 25% austenite

UTS = 1050 MPa Uniform strain = 0.18

(Ref: Waikita *et al.*, Sumitomo, Thermec 2006**)**

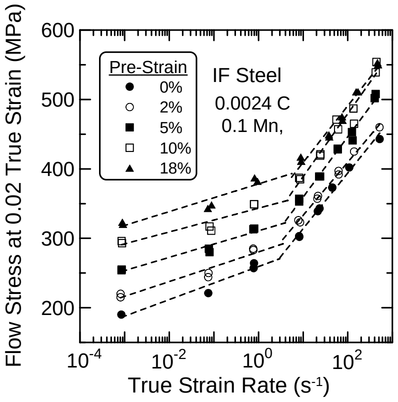
Other Approaches to produce high strength multi-phase microstructures………….

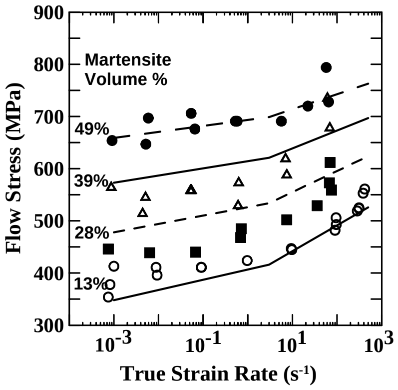
High Strain Rate Properties of Dual Phase Steels with High MVF

$$\sigma_F\,(Dual\ Phase\ Steel) \;=\; V_M\,\sigma_M(\varepsilon,\dot{\varepsilon}) \;+\; (1-V_M)\,\sigma_\alpha(\varepsilon,\dot{\varepsilon})$$

$$\sigma_M(\varepsilon,\dot{\varepsilon}) = \text{constant} = 1100\ \text{MPa}$$

$$\sigma_\alpha(\varepsilon,\dot{\varepsilon}) = \text{described by IF steel}$$



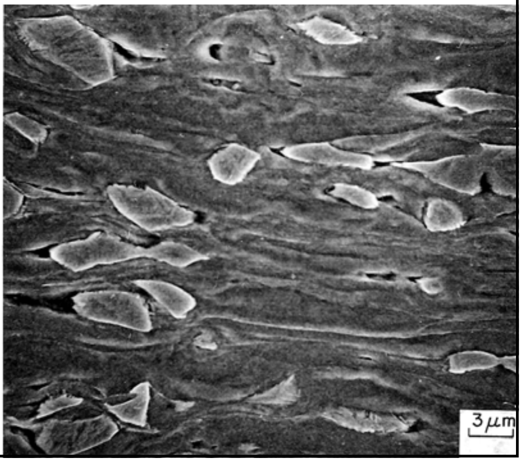


Supported by: AISI/DOE TRP Program

Implications of Fracture

- Lack of "Isostrain Condition"
  i.e. Non-uniform strain
- Void nucleation due to high strength second phase
- Fracture

SEM Micrograph



EXAMPLE: 1008 Steel Processed to DP Microstructure
True drawing strain= 1.39

Korzekwa *et al*., Scripta Met (1980)

Example Failures: Formability Limited by Fracture

Fractures often referred to as "Shear Fractures"

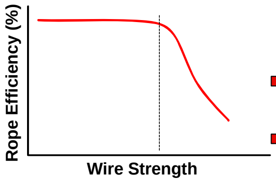
Images Courtesy of Jim Fekete, GM, and Matt Walp, DaimlerChrysler

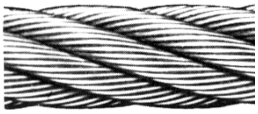
Other Shear Fracture Examples

Wire Rope Efficiency (P)

Stress State Effect

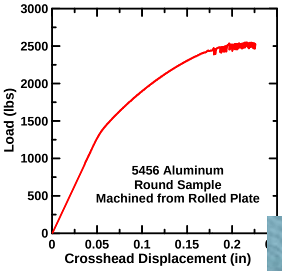
$$P = \frac{\text{Rope Strength}}{\sum(\text{Wire Strengths})}$$





5456 Aluminum Plate

Texture Effect

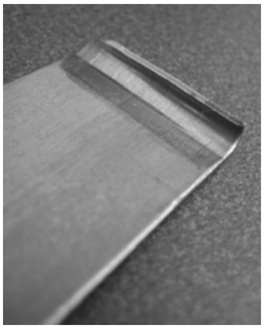


Research Needs: Shear Fracture

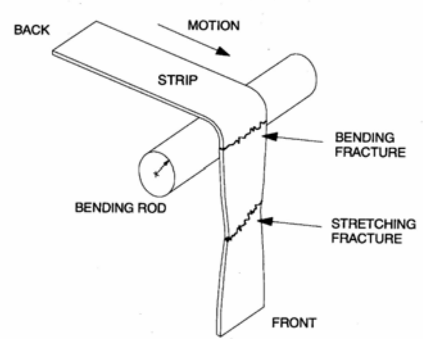
- **Laboratory Techniques to Experimentally Assess Susceptibility to Shear Fracture**
  - **Properties (e.g. Plane strain tensile …)**
  - **Formability (e.g. Stretch bend ….)**

- **Theoretical Analyses to Predict Damage**
  - **Geometry-based (e.g. instability)**
  - **Microstructure-based**
    - **Strain distribution**
    - **Critical fracture criteria**

Shear Fracture: Bending Under Tension



Characteristic shear failure: parallel to, and near the die.



A. Hudgins, ASPPRC, 2006

Fundamental Fracture studies

1) Identify ductile fracture criterion for heavy deformation conditions; predict effect of deformation mode and stress state on mechanisms.

2) Determine microstructural influence on ductile fracture:

Internal damage accumulation model which can explain influences of second phase type and distribution.

3) Identify favorable microstructures for good formability in high strength sheet steels

Ductile Fracture

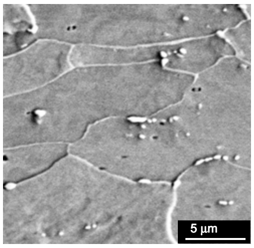
Void Formation – Interface Control

Steel	Microstructure	Interface
IF steel	Ferrite	Grain Boundary
Low C steel	Ferrite + GB Fe_3C	Ferrite/Fe_3C
Medium C steel	Ferrite + Pearlite	Ferrite/Fe_3C
HSLA steel	ppt. Hardened Ferrite + Pearlite	Ferrite/ Fe_3C Ferrite/ ppt.
TRIP steel	Ferrite + Retained Austenite	Ferrite/Austenite
DP Steel	Ferrite + Martensite	Ferrite/Martensite

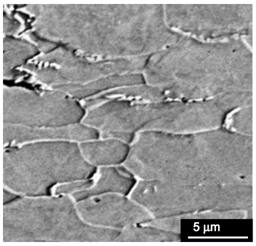
Lee *et al*. ASPPRC/Posco 2005

Internal Damage

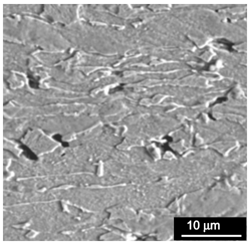
Example Micrographs: Microscopic Damage in Tension



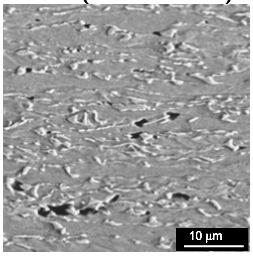
Low-C (uniform area)



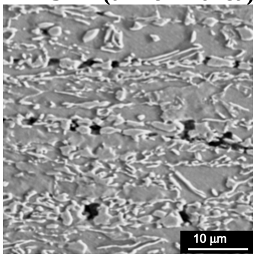
HSLA (uniform area)



DP steel (neck)



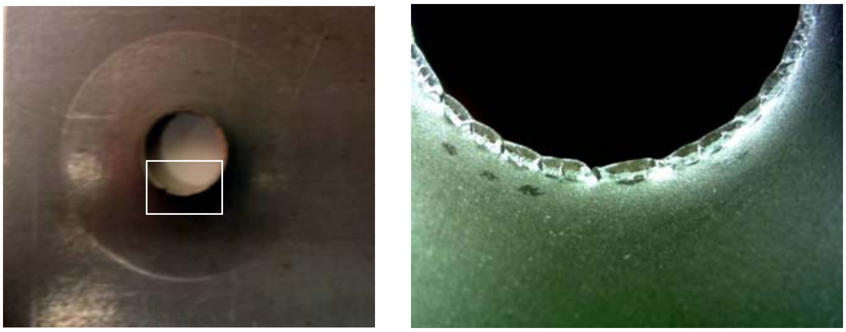
TRIP steel (neck)



TRIP steel (neck)

Lee *et al*. ASPPRC/Posco 2005

Hole Expansion Ratio: High Local Strain



Microstructure (780 MPa grade)	Tensile El.	Stretch-flangeability (HER)
Ferrite + Bainite	18 %	80 %
Ferrite + Pearlite	21 %	65 %
Dual Phase	19 %	60 %
TRIP steel (ferrite + retained γ)	30 %	40 %

Lee *et al*. ASPPRC/Posco 2005

After Cho, Pusan National University, 2000

"Damage Accumulation" - Instability Criterion

Damage accumulation rate (DAR)

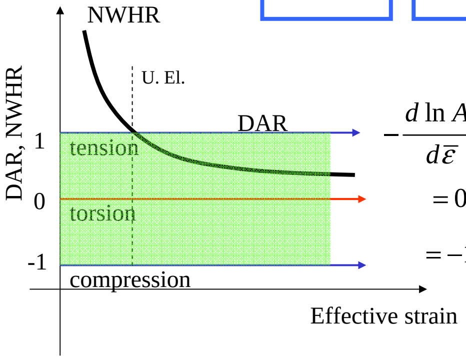
Normalized work hardening rate (NWHR)

$$-\frac{d\ln A_t}{d\varepsilon} = \frac{1}{\sigma_n}\frac{d\sigma_n}{d\varepsilon}$$

@ Pure tension

$$-\frac{d\ln A_t}{d\gamma} = \frac{1}{\tau}\frac{d\tau}{d\gamma}$$

@ Pure torsion



$$-\frac{d\ln A_g}{d\bar{\varepsilon}} = 1$$

$$= 0$$

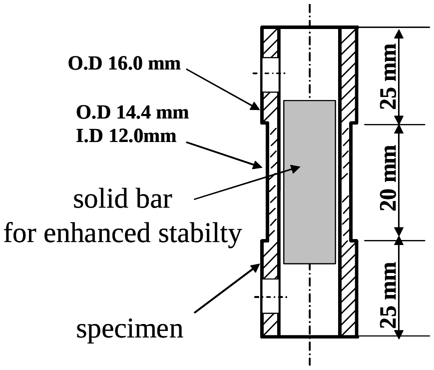
$$= -1$$

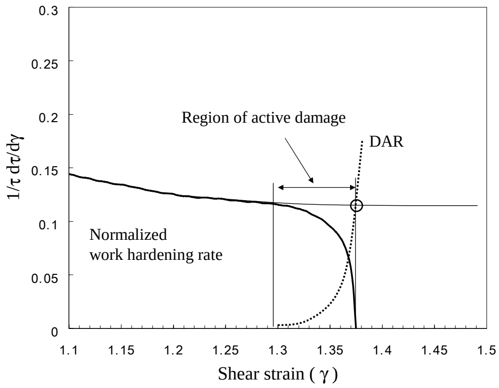
Forming limit in shear and compression determined by microstructural damage, not geometry

Lee *et al*. ASPPRC/Posco 2005

Torsion Test: Shear Fracture

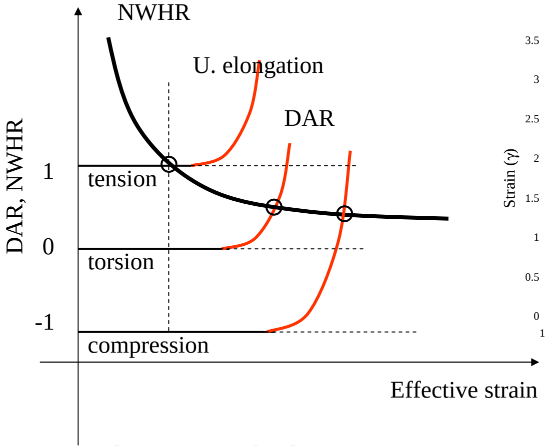
Torsion test
No cross section change
Pure Shear
Pure internal damage effect

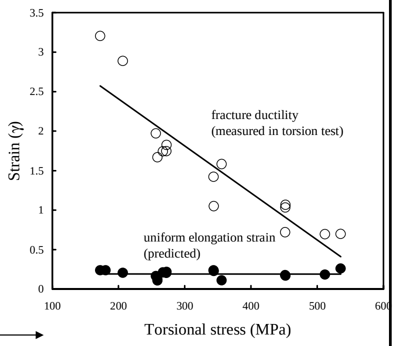




Lee *et al*. ASPPRC/Posco 2005

Internal Damage Effect





- **Lee model extended to**
  - **Include strain path effects – Hole Expansion Ratio**
  - **Interpret microstructure and work hardening**

Lee *et al*. ASPPRC/Posco 2005

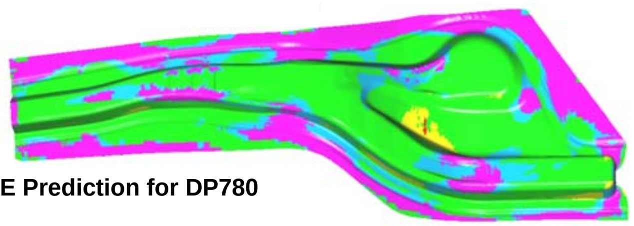
Summary: Research Needs

- Identification of critical microstructures based on strength, ductility, and fracture resistance
    - *Materials will contain large volume fractions of high strength constituent*
- Analysis of unique alloying and processing methodologies to produce new materials
- Analysis of fracture susceptibility
    - Models to assess strain distribution between constituents and critical fracture events
    - Models of damage accumulation
        - Include strain path effects
    - Laboratory methods to assess model predictions

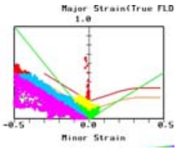
Challenges for Constitutive Models for Forming of Advanced Steels

Thomas B. Stoughton,	General Motors Corporation
Cedric Xia,	Ford Motor Company
Changqing Du,	DaimlerChrysler Corporation
Ming F. Shi,	United States Steel Corporation

Finite Element Simulation is used early in the design process to avoid tearing, wrinkling, and minimize or compensate for springback in automotive products



CAE Prediction for DP780



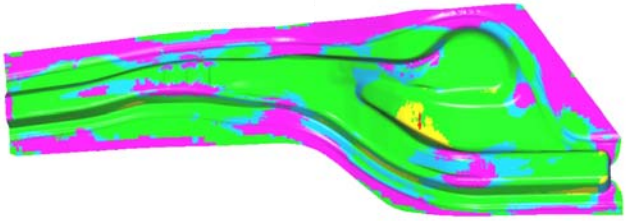
Springback of DP600 Channel Draw

Tryout Panel* of DP780 Front Rail

*Provided by USCAR DFE Project Team

Factors affecting formability of sheet metal products

1. Number of forming stages
2. Tool geometry for each stage
3. Boundary constraints
4. Lubrication conditions
5. Material variability
6. Product changes

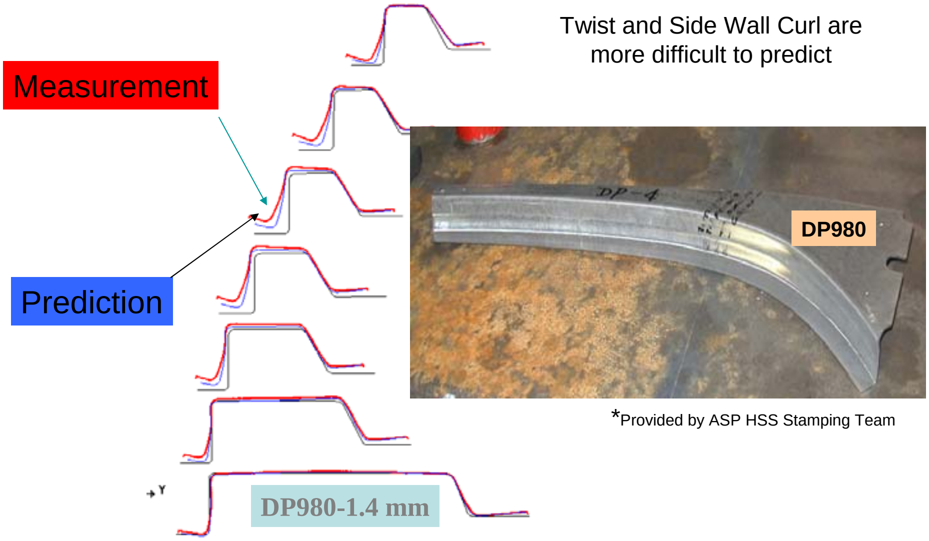


- ➢Multiple Analyses
- ➢Computationally Expensive
- ➢Usually there are ways to manufacture any product, but only one or a few that are economical for mass production

---

Springback Challenge with AHSS

Twist and Side Wall Curl are more difficult to predict



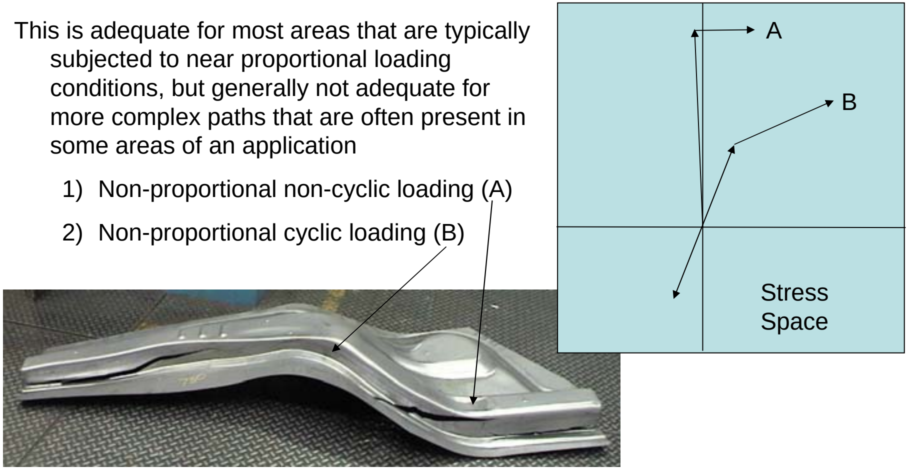
*Provided by ASP HSS Stamping Team

Challenges for phenomenological-based FEM simulation

Modern continuum-level constitutive models are accurate for proportional loading conditions and if they account for kinematic hardening, are also accurate for uni-directional cyclic loading conditions.

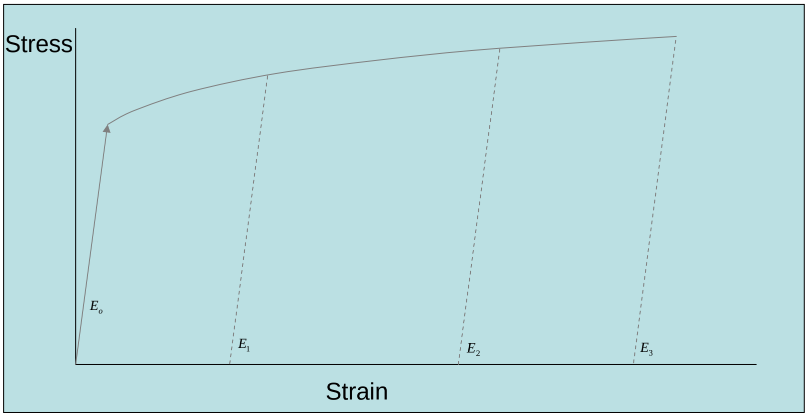
This is adequate for most areas that are typically subjected to near proportional loading conditions, but generally not adequate for more complex paths that are often present in some areas of an application

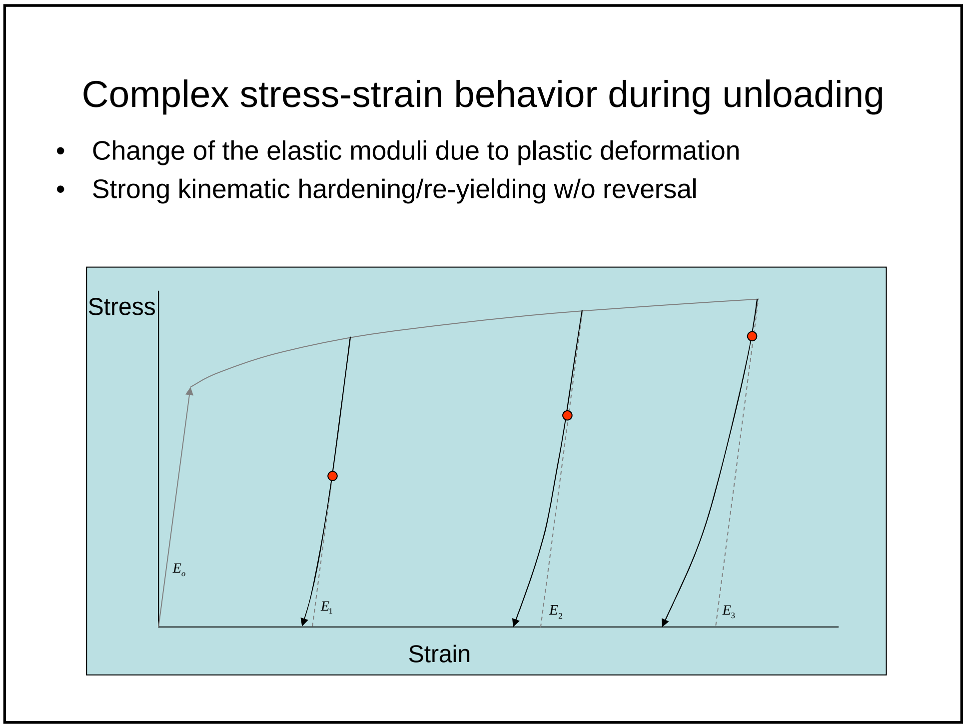
1) Non-proportional non-cyclic loading (A)
2) Non-proportional cyclic loading (B)



Complex stress-strain behavior during unloading

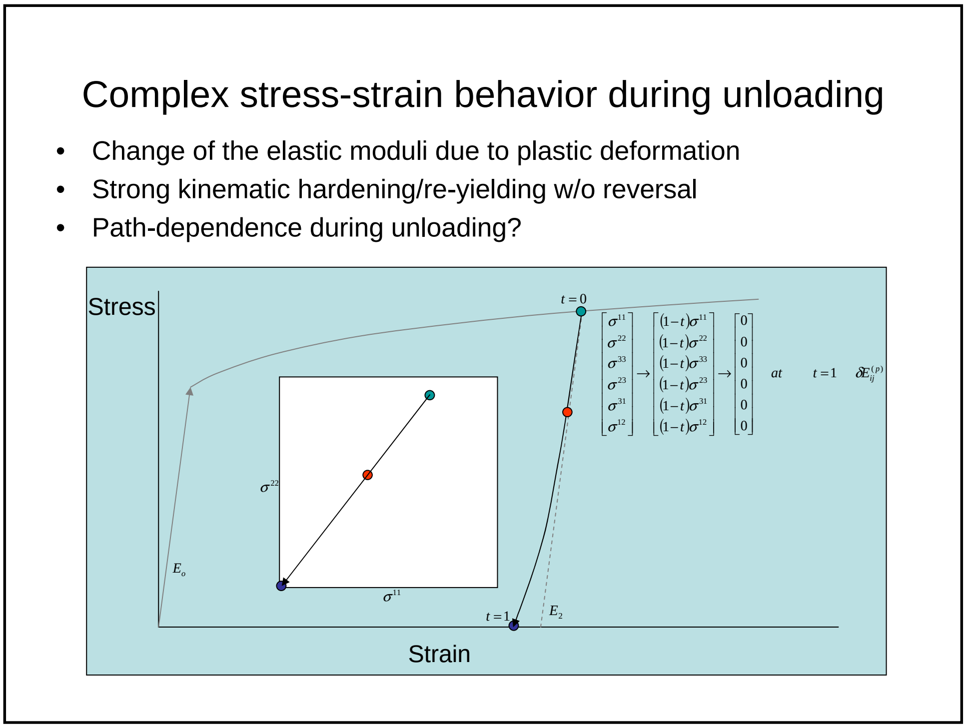
- Change of the elastic moduli due to plastic deformation





Complex stress-strain behavior during unloading

- Change of the elastic moduli due to plastic deformation
- Strong kinematic hardening/re-yielding w/o reversal



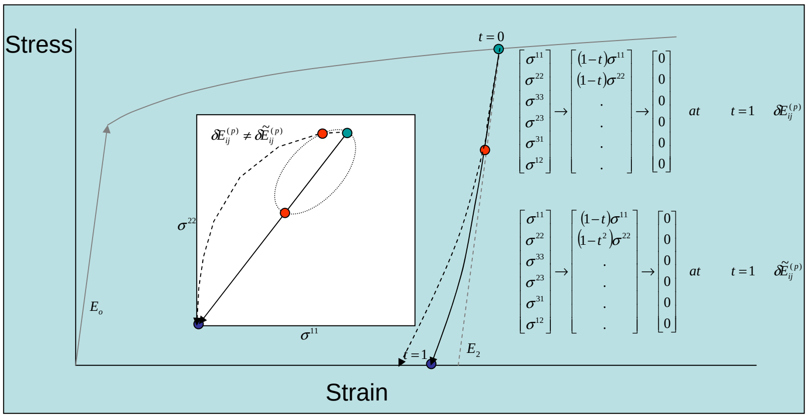
Complex stress-strain behavior during unloading

- Change of the elastic moduli due to plastic deformation
- Strong kinematic hardening/re-yielding w/o reversal
- Path-dependence during unloading?

$$\begin{bmatrix} \sigma^{11} \\ \sigma^{22} \\ \sigma^{33} \\ \sigma^{23} \\ \sigma^{31} \\ \sigma^{12} \end{bmatrix} \rightarrow \begin{bmatrix} (1-t)\sigma^{11} \\ (1-t)\sigma^{22} \\ (1-t)\sigma^{33} \\ (1-t)\sigma^{23} \\ (1-t)\sigma^{31} \\ (1-t)\sigma^{12} \end{bmatrix} \rightarrow \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad at \qquad t=1 \quad \delta E_{ij}^{(p)}$$

Complex stress-strain behavior during unloading

- Change of the elastic moduli due to plastic deformation
- Strong kinematic hardening/re-yielding w/o reversal
- Path-dependence during unloading?



$$\begin{bmatrix}\sigma^{11}\\ \sigma^{22}\\ \sigma^{33}\\ \sigma^{23}\\ \sigma^{31}\\ \sigma^{12}\end{bmatrix} \rightarrow \begin{bmatrix}(1-t)\sigma^{11}\\ (1-t)\sigma^{22}\\ .\\ .\\ .\\ .\end{bmatrix} \rightarrow \begin{bmatrix}0\\ 0\\ 0\\ 0\\ 0\\ 0\end{bmatrix} \quad at \quad t=1 \quad \delta E_{ij}^{(p)}$$

$$\begin{bmatrix}\sigma^{11}\\ \sigma^{22}\\ \sigma^{33}\\ \sigma^{23}\\ \sigma^{31}\\ \sigma^{12}\end{bmatrix} \rightarrow \begin{bmatrix}(1-t)\sigma^{11}\\ (1-t^2)\sigma^{22}\\ .\\ .\\ .\\ .\end{bmatrix} \rightarrow \begin{bmatrix}0\\ 0\\ 0\\ 0\\ 0\\ 0\end{bmatrix} \quad at \quad t=1 \quad \delta\tilde{E}_{ij}^{(p)}$$

- Continuum level constitutive models are adequate to predict manufacturability and enable springback control of most products made from conventional steels.

- Our ability to make accurate predictions are challenged with the use of advanced high strength steels:
  - Stresses are higher
    - stress prediction is typically not as accurate as strain prediction
  - The role and evolution of microstructure may be more important and not within the context of existing models –
    - texture
    - deformation induced phase transitions
    - microstructure related localization mechanisms
    - Inhomogeneous distributions of microstructure across sheet thickness
  - The unloading process appears to be far more complicated than most models can handle

Options for constitutive modeling for FEM simulation

Phenomenological-Based Approach

- Advantages
    - Fewer degrees of freedom
    - Good strain and failure prediction under proportional loading
- Challenges
    - Non-proportional loading (beyond model calibration limits)
    - Stress prediction (especially for AHSS)
    - Springback prediction
    - Novel effects
        - deformation induced phase transformation
        - microstructural based instability factors

Options for constitutive modeling for FEM simulation

Micro- Mechanics (Polycrystal) Approach

- Advantages
    - Understanding of failure and strain localization mechanisms
    - Opportunity to account for texture and multiple phase materials
    - New alloy development
    - Aid development of improved continuum level models
- Challenges (for use in die tryout/product design simulation)
    - Include all essential physics and microstructure features?
    - Valid for large strain deformations
    - Predict observed large-strain non-proportional loading effects?
    - Predict observed unloading effects?
    - Cost Effectiveness

Complexity of the Loading and Unloading Behavior wrt Springback

- Some evidence that elastic constants change with deformation in ways that are significant
- Micro-yielding seems to start in very early stages for AHSS and conventional yield stress determination method may not be appropriate.
- Unloading behavior may be more complex than conventional definitions of yielding can accommodate
- Experimental observation of unloading behavior seems to be more complex than linear elasticity assumes, which is exacerbated for advanced steels.
- High quality experimental data are limited and conflicting theories are published on the origin and mechanism of the unloading behavior
- We would like to see more basic research in this area that will enable more accurate springback prediction and thereby enable the use of advanced high strength steels in the automotive industry.

Basic Science/Technology Gaps

- Quantification of unloading behavior under various loading and time dependent conditions and identification of contributing factors and micromechanisms.
- Integration of these results into plasticity models for unloading that apply for arbitrary loading history and conditions.
- Definition and determination method of unloading yield point.
- Cost effective solutions to high t/R ratios, high normal stress, solid/shell/hybrid elements

Discussion Issues

- What experiments are necessary to determine the evolution of elastic and plastic properties during loading and unloading, considering:
  - Dependence on large strain deformation for anisotropic materials
  - Dependence on non-proportional loading with and without unloading
  - Dependence on single and few-cycle non-proportional loading
- Is it feasible to consider development of a micro-level model that has enough of the critical physics that it can be used to due virtual experiments for development of a more general continuum level model?
  - What mechanisms should be considered in the micro-level model approach?
  - How can such a model be validated?
  - Once validated, what numerical experiments are useful for improving continuum level modeling?
- What effect do the following issues/mechanisms have on springback determination,
  - Definition of yield (% offset, micro-strain offset, proportional limit) at both loading and unloading
  - Evolution of the elastic constants, texture, and voids
  - Microplasticity/Yield Surface Distortion/Anisotropic Transient Hardening
  - Anelasticity, Creep
- Is it practical to develop a model to predict/handle all of these effects?
- What possible cost-effective solutions are possible for incorporating benefits of shell and solid elements to deal with areas where high strength steels are flowing over sharp radii under significant forming pressures

A-SP/NSF Workshop on AHSS Steels

Challenges in Failure Prediction in Forming Advanced High-Strength Steels

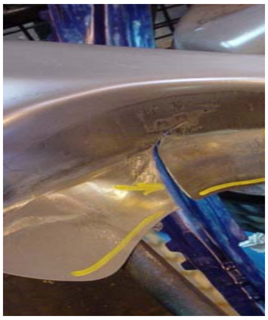
Z. Cedric Xia, Ford Motor Company
Tom B. Stoughton, General Motors Corporation
Changqing Du, DaimlerChrysler Corporation
Ming F. Shi, United States Steel Corporation

Oct. 23, 2006

Failure Issues in Forming Advanced High-Strength Steels

Failure under Stretch-bending

(DP780 steel Shown)



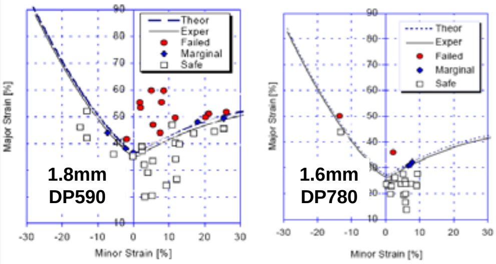
Edge Cracking

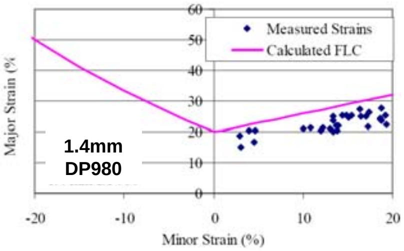
(DP600 steel Shown)

Forming Limit Diagrams (FLD) and other methods based on localized necking are no longer provide satisfactory predictions for stretch-bending and edge cracking in forming Advanced High-Strength Steels

Forming Limit Diagram for AHSS

- **FLDs have been working well in most cases up to now, with a safety margin added for industrial practice to account for path dependent and/or bending effects.**
- **Experimental data confirm that the Keeler-Brazier empirical formula for FLD is a reasonable approximation for most steels, including Advanced High-Strength Steels such as TRIP and Dual-Phase.**





A. Konieczny, SAE 2001-01-3075

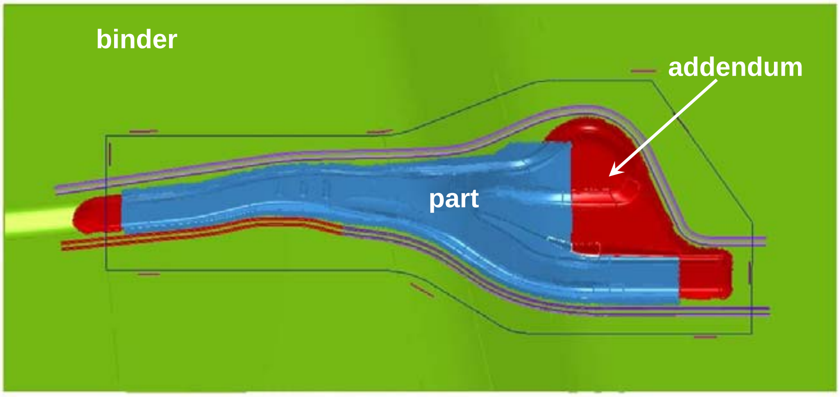
(US Steel)

M.F. Shi & S. Gelisse, IDDRG'06

(US Steel)

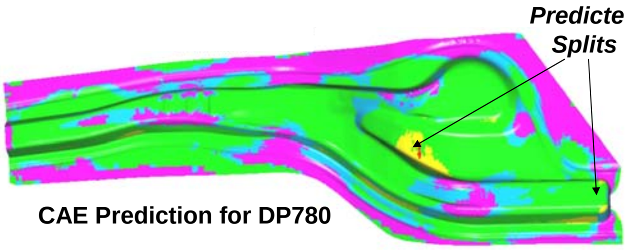
Traditional methods such as FLDs for predicting localized necking under biaxial loading seem to be equally applicable for Advanced High-Strength Steels!

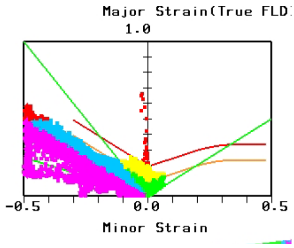
Industrial Experiences with AHSS – An Example



- **DoE Sponsored, USCAR "Die Face Engineering" project. Participants including DaimlerChrysler, Ford, GM, US Steel and ALCOA.**
- **Materials include DP600, DP780 and AA5754-O, all 1.6mm thick.**
- **Forming simulations were performed for all materials.**

Failure Prediction of Dual-Phase Steels

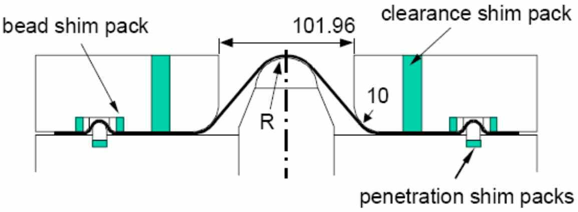


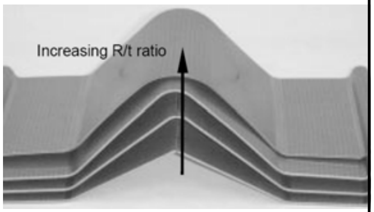


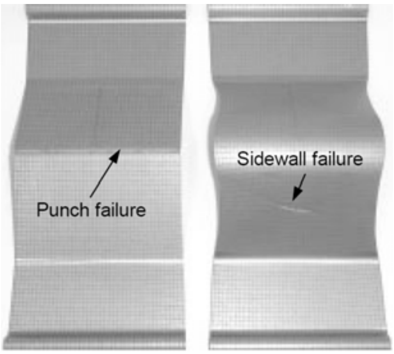
- **CAE simulation could not predict the failure for DP780 while the behavior for DP600 and AA5754-O were accurately predicted.**

Failure appears to be initiated from stretch-bending around tight radii before localized necking limits are reached elsewhere. No predictive criteria exist yet for such failure.

Angular Stretch Bend Test: Experiments





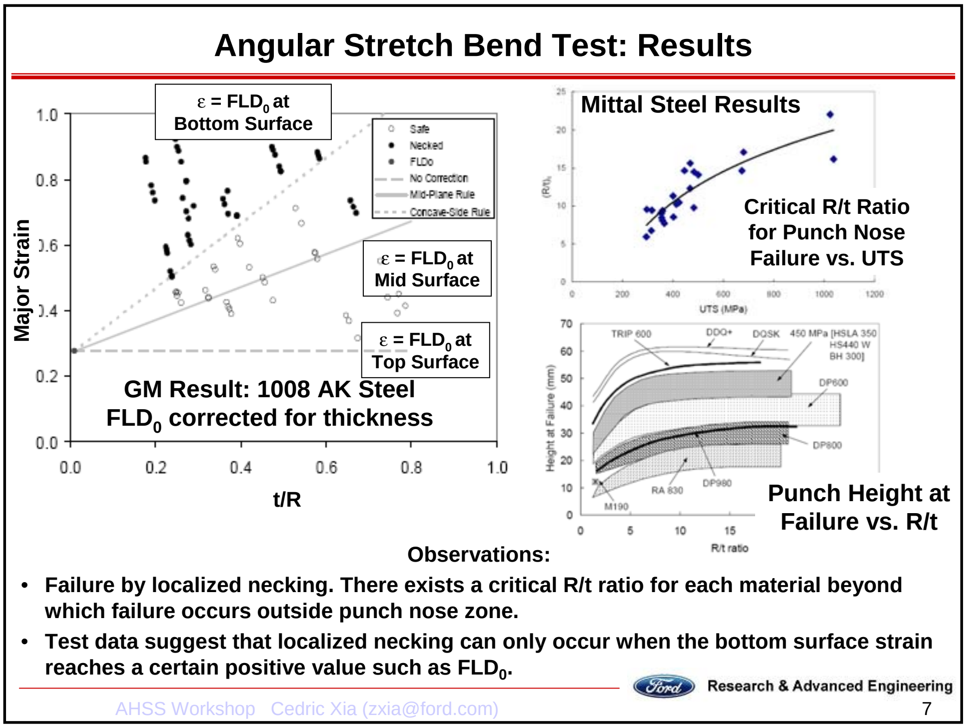


GM Study (*Tharrett & Stoughton SAE 2003-01-1157*)

- Material: 1008 AK Steel with thickness of 0.69mm, 0.92mm and 1.04mm.
- Punch Tip Radius: 0.508, 1.016, 1.524, 2.032, 2.540, 3.175, 4.750, 6.350, 9.525, and 12.70 mm.
- Photogridded on both sides (0.508mm square grid).

Mittal Steel Study (*Sriram et al. SAE 2003-01-1151*)

- AISI/DoE sponsored.
- Materials: 40 steel grades/thicknesses from multiple companies, including traditional steels and advanced high-strength steels.
- Punch Radius: 1.5, 5.0, 10.0 and 25mm



Angular Stretch Bend Test: Results

GM Result: 1008 AK Steel
FLD$_0$ corrected for thickness

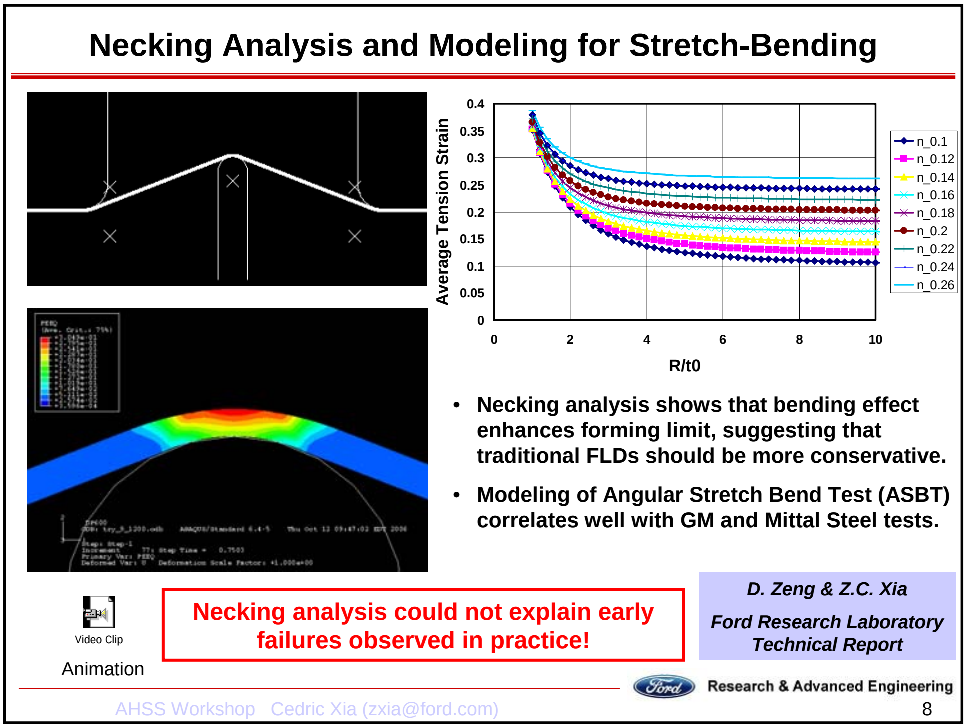
Mittal Steel Results

Critical R/t Ratio for Punch Nose Failure vs. UTS

Punch Height at Failure vs. R/t

Observations:

- **Failure by localized necking. There exists a critical R/t ratio for each material beyond which failure occurs outside punch nose zone.**
- **Test data suggest that localized necking can only occur when the bottom surface strain reaches a certain positive value such as FLD$_0$.**



Necking Analysis and Modeling for Stretch-Bending

- **Necking analysis shows that bending effect enhances forming limit, suggesting that traditional FLDs should be more conservative.**
- **Modeling of Angular Stretch Bend Test (ASBT) correlates well with GM and Mittal Steel tests.**

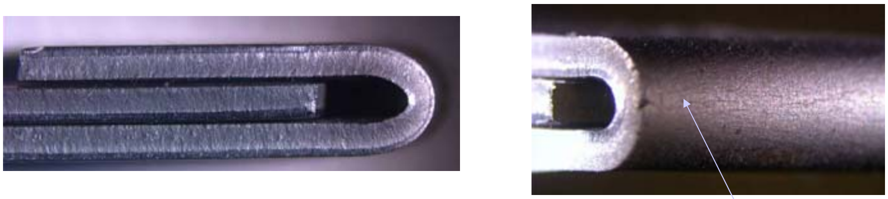
Animation

Necking analysis could not explain early failures observed in practice!

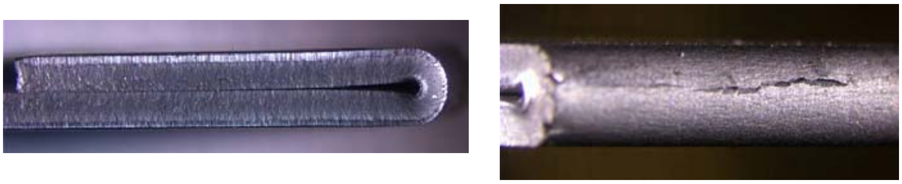
D. Zeng & Z.C. Xia

Ford Research Laboratory Technical Report

Bendability of Advanced High-Strength Steels



1.5mm DP780 3T Hemming



$$\int_0^{\varepsilon_f} \sigma_f\left(\sigma_{ij},\varepsilon_{ij}\right) d\varepsilon_f \equiv C$$

1.5mm DP780 2T Hemming

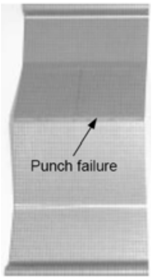
Note: DP600 can be flat hemmed to itself without fracture.

Fracture under bending-only starts from stretched surface at much higher strain than that of stretch-bending!

Z.C. Xia, P.A. Friedman and C. Miller
Ford Research Laboratory Technical Report

Issues for Failure under Stretch-Bending

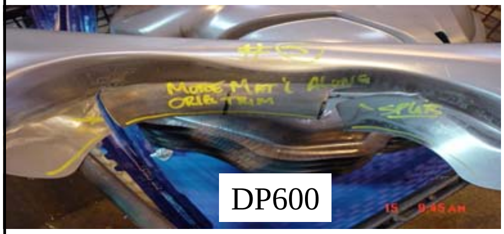
- **Localization Mechanisms:**
  - ***Traditional localized necking incorporating bending?***
  - ***Shear band formation? Effect of surface roughness and texture?***
  - ***Inhomogenuity, anisotropy and other mechanical properties associated with microstructures, both in-plane and through-thickness?***
- **Fracture Mechanisms:**
  - ***Ductile fracture through void nucleation and coalescence?***
  - ***Micro-crack initiation and growth from the surface?***
  - ***Shear strength reduction induced by microstructures? Shear delamination/peeling?***
- **Failure Prediction from Continuum Mechanics Computation:**
  - ***Predictive criteria bridging different failure mechanisms?***
  - ***Experimental tests and procedures required to establish such criteria?***
  - ***Quantitative characterization of microstructures?***
  - ***Complex deformation path and stress state? Strain rate effect?***
- **Fracture Prevention/Enhancement through Alloy and Process Design**

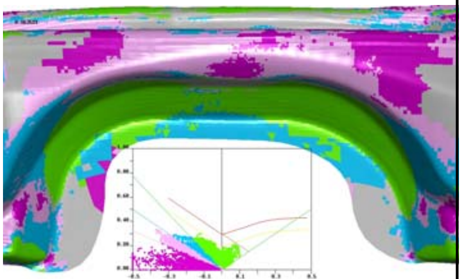


Failure by localization

Failure by Fracture

Edge Cracking





Formed Part
Showing Edge Cracking

Forming Simulation:
Strains at Failed Edge below FLC

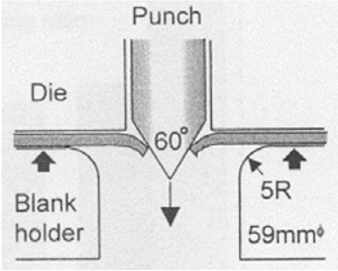
- **Materials at edges are generally under uniaxial stretch. FLDs in uniaxial direction are traditionally used for predicting necking failure.**
- **Such predictions often fail for AHSS.**

M. F. Shi & X. M. Chen

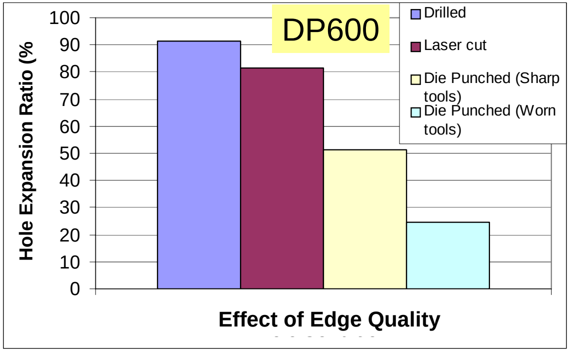
"Stretch Flangeability Limits of Advanced High-Strength Steels"

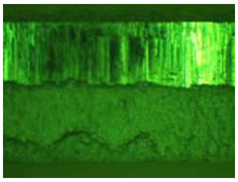
US Steel

Hole Expansion Test

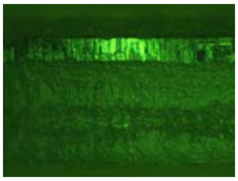


Hole Expansion Ratio

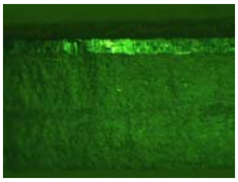




87.3%
(1.4mm HSLA)



58.5%
(1.4mm DP600)



15.7%
(1.4mm DP780)

Shi & Chen

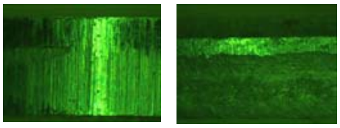
(US Steel)

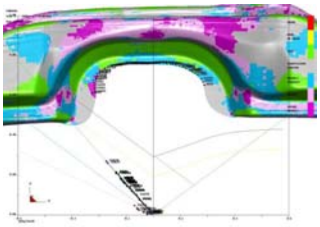
Konieczny and Henderson

(US Steel)

(Under Same Process Condition)

Issues for Edge Cracking





Mechanisms for Edge Cracking:

- *Localized necking?*
  - *Effect of Strain gradient?*
  - *Effect of In-plane Curvature?*
- *Micro-crack initiation and growth?*
  - *Shear edge quality and micro-crack characterization?*
  - *Effects of martensite size, shape and content/distribution?*
- *Coupling Mechanisms?*

Predicting edge cracking from continuum mechanics computation:

- *Macro-based predictive criteria for edge cracking? Incorporating microstructure parameters?*
- *How to characterize edge quality?*
- *Is hole expansion an adequate test to establish such criteria? Effects of contact vs. non-contact conditions during flanging?*
- *Incorporate prior deformation history (such as forming/trimming)? Thickness and strain-rate effect?*

Appendix 6: Table Group Presentations, 1-8

Advanced High-Strength Steels:
Fundamental Research Issues Workshop

TABLE 1:

Realff
Spanos
Gao
Acharya
Matlock
Thomas
Wagoner

Group D Questions: Fracture

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Need to identify microstructures (phases etc.) of potential interest
- Alloy/processing methods needed to produce desired microstructures
  - Use existing data base of various steels
  - Predictive models for new alloys and processing methodologies

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Not cost effective
- Not processing friendly

---

3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Microstructure:
  - Accurate, quantitative, consistent characterization methods
  - Correlation of critical microstructure features that dictate strain localization, fracture, etc.
- Predictive microstructural models driven by final material performance
  - All required properties simultaneously up front - strength, elongation, toughness, weldability, high strain rate (safety)
- See “Page 6” for more – all “fundamental ideas”

4. What specific, <u>applied</u> (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Scale up form the laboratory to production level heats, processing, etc.

D1) Identify critical issues related to new or unusual fracture / failure behavior of AHSS, microstructural and mechanical.

- Microstructural
  - Accurate quantitative characterization techniques to relate to properties - as a function of alloy content, processing, etc. - in a consistent and quantitative way
  - Determine critical microstructural features (phases, distributions, geometries) that dictate the important properties – strain localization, fracture, etc. (not defined by simple flow curves)
  - Tie in to large body of existing work on microstructural evolution models

- Fracture/Failure
  - How does development of a heterogeneous microstructure (phase trans., dislocation density, etc.) affect ductile crack initiation, residual stress initiation, etc.?
  - What are the critical fracture nucleation and growth events, stress requirements, etc. associated with these new microstructures?
  - What are the contributions of strain localization mechanisms to fracture?

- Proper communication between various communities – modelers, metallurgists (microstructure), and theorists
- Being able to calculate internal stresses as a function of heterogeneities
- Evolution of dislocation density leading to plasticity
- Modeling of deformation and failure/fracture across multiple length and time scales (dislocations, phases, macro)
- Methods for predicting evolution of mixtures of non-linear materials (intrinsic and deformation induced microstructure)

D2) What are the best mechanisms for addressing these issues?

- Fracture/Failure
  - How does development of a heterogeneous microstructure (phase trans., dislocation, density, etc.) affect ductile crack initiation, residual stress initiation, etc. – critical experimental and modeling studies
- …… See page 6
- Publishing benchmark (global) experimental studies – include composition, processing, microstructure, fracture, spring-back, etc. for a given, complete case study

---

D3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- Collaborations between single investigators
- Teams efforts – team members working more directly together from the various types of organizations (universities, industry, etc.)
- Sustained commitment of support over multiple years

Advanced High-Strength Steels:
Fundamental Research Issues Workshop

TABLE 2:

Heimbuch
Carpenter
Gan
Bhattacharya
Balaji
Pourboghrat
Van Aken

Group B Questions: 3rd Generation

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Fundamental science of new material development
- Interface between material development and material processing
- Development of accurate constitutive models for the 3rd generation AHSS
  - Material properties for the modeling
- Interface characterization

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Cost
- Availability
  - Mass production

3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Bainitic ferrite
- F + stabilized A
- Nano-precipitate based steel (cementite?).
- Ultra-fine grained steels
- Macro-composite

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Bonding of sheet layers
  - Can it be made
    - Roll bonding
    - Adhesive
    - Cladding
  - Cost-effective
- Weldability
  - Brazing
  - Friction Stir Welding
  - Heat treatment (pre and post)

- Forming
  - Microstructure based models
    - Strain partitioning/heterogeneity
    - Crystal plasticity
  - Springback
    - Prediction and compensation
  - Cracking
    - Prediction
    - Microstructure based models
  - Friction and tribology
    - Coating effects

B1) Which classes of 3rd Generation AHSS are most promising? What is the expected time frame to commercialization?

- F + stabilized A
  - Stabilize austenite:
    - Chemical: Al, Mn, Co, Nitrogen, C. Combination of elements? MD effects?
    - Thermal
    - thermo-mechanical,
    - microstructure (nano)
  - Cost effective
  - 5-15 years

- Bainitic ferrite
  - Speed up the manufacturing process?
  - Alternate to carbon stabilization of austenite, Mn-N effects?
  - Already commercialized, but long process times to obtain nano-scale. Cost is a issue.

- Nano-precipitate/ composite based steel (borides vs cementite others?).
  - Boundary bonding
  - Nano scale explanation

- Ultra-fine grained steels
  - High speed rolling

- Macro-composite or laminar products
  - Composite steel adhesive bonding
  - Roll bonding of 1st and 2nd generation steels

B2) Identify critical issues related to developing a 3rd generation of AHSS.

- 1 F + austenite
  - Cost
  - Manufacturing ability (high speed)

- 2 Bainitic ferrites
  - Cost
  - Manufacturing ability (high speed)

- 3 Nano precipitate/composite microstructures
  - Knowledge base
  - Processing issue

- 4 Ultra fine grain steels
  - Processing

- 5 macrocomposite or laminar product
  - Manufacturing
  - Forming

- Weldability
- Formability

B3) What are the best approaches for addressing these issues?

- Computational methods
  - Molecular dynamics
  - Phase field
  - Physical properties

- Experimental

B4) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- Data sharing between academic and manufacturing
  - Steel, auto companies, National labs, universities
- Access to facilities for processing new materials
- Computational and experimental facility access

Advanced High-Strength Steels:
Fundamental Research Issues Workshop

TABLE 3:

Stoughton
MacDonald
Sun
Haezebrouck
DeArdo
Kalidindi
Mao

Group C Questions: Forming Simulation

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Lack of a micro-structure based failure criteria
- Identification of more meaningful material performance criterion
- Defining properties of these materials
- Defining the processing constraints for manufacturing these steels
- Challenges due to the highly constrained manufacturing options (eg. Available coating lines, chemistry, and thermomechanical paths)
- Lack of basic thermomechanical and kinetic data for likely candidate alloy systems

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Weldability
- Coatability
- Affordable manufacturing cost
- Lack of microscale or phenomenological models (with sufficient accuracy) for twinning, phase transformations or other effects that are involved with these materials

---

3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Microstructural and strain-path dependent ductile fracture model
- Rigorous quantification of microstructure, (eg. 3D , spatial correlations)
- After identification of ideal microstructure, what’s the recipe,
- What are the fundamentals of phase transformation including austenite stability
- Multi-scale modeling (eg. with advanced homogenization theories) suitable for multiphase materials
- Development of new test equipment to obtain required data.

4. What specific, <u>applied</u> (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Identify target applications for specific materials
- Perform experiments and correlation studies
- For existing HSS, identify ways to maximize homogeneity (eg. Mn banding), that could be extended to 2nd and 3rd gen
- Effect of chemistry and processing on variability of microstructure and properties (identify causes of supplier or batch dependency)
- Factors contributing to and improve weldability; what are acceptance criteria

---

C1) Identify critical issues related to numerical simulation of forming with AHSS

- Microstructural and strain-path dependent ductile fracture model
- Post forming properties and performance simulation (crash, dent, structure)
- Fast and efficient material models that can handle material behavior under complex loading
- Accurate springback prediction
- Use of inverse methods for application design AND/OR for materials design

C2) What are the best mechanisms for addressing these issues?

- Form teams (Nat Lab, industry and academia) of critical mass with sufficient scope of expertise for the following topics
  - Material Design (Chemistry, Microstructural Design, Process Design)
  - Simulation Technology and Modelling
  - Micro-structural characterization

C3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- Clarification of IP agreements
- Umbrella and Project Management Structure
- Understanding of responsibilities
- Lobbying for more resources

Advanced High-Strength Steels: Fundamental Research Issues Workshop

TABLE 4:

Xia
Balaguru – not present
White
Shi
Beaudoin
Jonas
Shen – not present
J. Wang

Group C Questions: Forming Simulation

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Determining the family of alloy compositions which reliably and “inexpensively” stabilize austenitic
  - Ni, Mn, N, C
  - Impacts on weldability

- Determine processing methods which are appropriate to the various alloy compositions
  - Uniform distribution of phases throughout the strip
  - Through-thickness issues, banding

- Identify constitutive relationships and, using those relationships, formulate a fracture model
  - Including void formation and coalesence
  - Anelasticity

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Reducing baseline material cost – impact of less expensive alloying elements required to achieve austenitic compositions
- Identify constitutive relationships and, using those relationships, formulate a fracture model
  - Including void formation and coalesence
  - Anelasticity

- Majority of conventional North American steelmaking infrastructure not designed for high-volume production of 2nd generation AHSS
  - Methods to convert existing mills to effectively produce 2nd AHSS
  - New processes/process technology with “relatively” capital investment.

- Impacts on other processing
  - Weldability
  - Transfer press capacity,
  - die wear
  - lubrication

---

3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Develop forming process techniques which take advantage of the higher ductility of these materials
  - Giving designers greater flexibility allows them the opportunity to compensate for, or allow for, springback in part designs
  - This provides a near-term advantage, particularly in the absence of predictive models for springback behavior
- Development/design of post-stretch forming and other approaches which are less sensitive to variability in process and composition
- Developing of modeling of two and multiple-phase materials, based on local equilibrium/microstructural models
- Modeling of damage mechanisms
- Develop partitioning models for interstitials (low-T), precipitate formation and other methods of driving the required balance of microstructures required for 3rd generation AHSS
- Kinetics and characterizations of weak obstacles, and development of inelastic response
- Experimental characterization of internal stress
- Evaluating unloading effects in microstructral based models

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Leveraging existing DOE models on strain rate and temperature effects for both crash-impact, and forming application
- Development of experimental approaches and data relating to failure criteria of emerging AHSS
- Studies on materials joining
  - Processability
- Accomodating effects of joining processes on structural models

---

C1) Identify critical issues related to numerical simulation of forming with AHSS

- Availability of constitutive models
- Forming tools that include strain induced transformations
- Forming tools for complex microstructures
- Forming tools for heterogenous deformation (slip bands)

- Methods that capitalize on materials properties, then incorporate those properties into microstructural simulation

- Modification of numerical analysis methods/computational mechanics to reduce the processing time required to execute complex analyses
  - Development of specialized elements
  - Use of high-performance computing - Blue Collar Computing
    - HPC analyses to develop techniques
    - Simplified interfaces for HPC

- Incorporation of shear failure into forming models
- Computer simulations for shearing and blanking

C2) What are the best mechanisms for addressing these issues?

- Develop incentives for broad teaming
  - Multi-disciplinary teaming
  - Multiple institutions
  - Industry/government/academia and research institutions

- Mechanisms to encourage direct interaction between researchers and industry

- Regular joint reviews and updating of progress
  - Technology transfer
  - Updating the roadmap
  - Possibly in coordination with other relevant conferences (SAE, TMS, ASTM)

C3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- Continuation of these discussion groups
- Coordination of funding cycles and funding initiatives across agencies
- Incorporation of industry representation in the call development and peer review processes
- Use of ASPP and NSF websites, updated on a reqular basis

Advanced High-Strength Steels: Fundamental Research Issues Workshop

TABLE 5:

Chong- not present
Essadiqi
Santella
Agnew
Garmestani- not present
Pan
Welsh
Speer

Group B Questions: 3rd Generation

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Can you get a ferritic matrix (low cost) to meet 3rd Generation requirements ?
- Stabilizing austenite with a **lean-alloy** approach (C, Mn, high-N in low-alloy steels, etc…)
- Steel processing of totally new grades.
- Alloying effects on austenite deformation behavior
- High temperature in-line austenitizing capability for light gage sheet
- Joining limits alloy selections
- Microstructure developers need to understand multiaxial behavior and relationships between ductility/fracture/constitutive behaviors (mechanics / materials interface…)
- Understanding effects of microstructure anisotropy/morphology on key properties needed.
- Predictive data for damage (crack/void) initiation. Better void growth prediction.
- Ab initio: fundamental understanding of alloying effects to inhibit cementite and transition carbide phases (allows carbon to be used for austenite stabilization).
- Can one reduce the density (and/or increase modulus) of the steel in a useful way ?

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Multiaxial plasticity understanding will allow better product tuning, following uniaxial behavior first.
- Understanding of strain-path changes on mechanical behavior
- Higher forces challenge all aspects of manufacturing, from steel rolling to forming tools to welding fixtures, etc.
- More complete mechanical behavior characterization of new steels
- Accurate fracture prediction and springback models (microstructure effects on Bauschinger phenomema, etc.)
- New joining and galvanizing processes?
- Strain-rate effects
- Bridging length scales between microstructure and continuum.
- Ab initio: interface strengths for fracture models and microstructure engineering.
- Experimental techniques for developing necessary and credible data
- Understanding of internal stresses and stress partitioning between phases.

3. What specific, fundamental (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Develop and evaluate new microstructure/processing approaches.
- Deformation mechanisms in complex microstructures and multiphase materials
- Improved martensite transformation models: composition, morphology, strain/stress, etc.
- Detailed microstructure characterization via new instrumentation
- Constitutive material models (and associated data and techniques) appropriate for multiaxial complex non-proportional, etc. loading
- Ab initio studies on phase stability (carbides) and interface properties
- Understand properties of new alloys (thermophysical properties, etc)
- New process development (rolling, heat treatment
- Fundamental galvanizing responses (base microstructure, surface interactions, etc.)
- Coatings with intrinsic mechanical contribution
- Improved bainite transformation models

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- New process development (rolling, heat treatment ideas, etc)
  - Rapid heat treating…
- Transition from micromechanics models to continuum (usable by industry) models
  - Forming, springback, high rate, fracture
- Welding and joining technologies
- Help integrate DOE Lab capabilities into other researchers' programs…
- Support new processing demonstration/prototyping…flexibile pilot facilities for innovative steel production and processing
- Explore new methods of sheet forming – both evolutionary and revolutionary, including tubes
- Develop ancillary technologies (casting practices, mold powders, etc)

B1) Which classes of 3rd Generation AHSS are most promising? What is the expected time frame to commercialization?

- UFG ferrite or bainite/martensite matrix
- High austenite fractions
- New precipitation strengthening approaches
- Layered (composite) microstructures

B2) Identify critical issues related to developing a 3rd generation of AHSS.

- Next generation of professionals (metallurgical/manufacturing scientists/engineers disappearing)
- Funding priority for steel research relative to other parts of the world
- Govt policy toward manufacturing ?

B3) What are the best mechanisms for addressing these issues?

- Cooperation/collaboration – industry/govt/academia
- Develop and support LONGER RANGE programs
- Promote basic industries to students (manufacturing is sexy)

B4) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- High level political support on the importance of these activities.
- More exchange of professionals between the different constituencies
- Coordinate materials/mechanics interface (workshops like this)…

Advanced High-Strength Steels: Fundamental Research Issues Workshop

TABLE 6:

Fekete
Chopra
Losz
Anand
Ghosh
Khraisheh
Li
Miles

Group A Questions: Model v. Experiment

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Lack of guiding principles and concepts for processing (see A1)
- Highly trial and error based
- How to increase ductility

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Banana chart may be too simplistic (elongation no longer complete measure for forming application, need new quantitative measures unknown at present)
- Axi-symmetric versus Sheet metal (1-2mm) plane strain condition (n value)
- Lack of validated constitutive models and failure criteria

---

3. What specific, fundamental (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- New concepts and guiding principles for interface design (materials science principles) to prevent grain boundary/interface decohesion (sliding and separation) triple-junction failures
- Prediction of shear instabilities and attendant failures under low triaxiality conditions.
- Development of new experimental techniques to probe material response at microstructural length scales – twinning, phase transformations, interface response
- Identify governing macroscopic measures for realistic prediction of deformation and failure under complex forming conditions at both quasistatic and high strain rates

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Predictive finite element models incorporating microstructural damage paramters
- Predictive FLDs for AHSS steels from microstructure-based models
- Large scale warm forming
- New forming and joining technology: Explore fusion (RSW) and solid-state (friction stir welding, riveting, adhesive joining) technology in joining
- Benchmark forming problem set for testing models:
  (a) **grand challenge** (i) forming problem, (ii) crush/crash problem
  (b) **speciific experiments**: dome, bulge, flange, rail like stamping like crush test at high rate

---

A1. What kinds of modeling are most needed to push AHSS forward? What length scales and techniques are likely to be the most important?

Deformation Issues
- How the phases deform/transform/crack and interact with each other. Phase-interfaces, voids nucleation. Slip/twin/phase transformation interactions with interfaces.
- TWIP, TRIP: Models that describe how deformation induces transformation: twinning and other transformations. Twin-slip interactions. Stacking-fault energy dependence.
- Microstructure model: how to design microstructure - different microstructure – phenomenological – physics unknown length scale from dislocation scale to part geometry scale :
- Lack of suitable constitutive model for yielding damage accumulation in changing strain path
- Phase distribution and microstructure, morphological anisotropy
- Modeling microplastic strain – see most unloading in high strength materials – inelastic springback – small dislocation motion. Residual stress near martensite – relief.
- Leverage recent models for nanocrystals
- Computational efficiency, reducing microstructure-sensitive models to bulk forming model.

Fracture Issues:
- Energy absorption model in fracture
- Multi-axial loading – damage accumulation in microstructure in phases
- Go beyond principal strains for microstructure-sensitive shear banding and eventual failure and/or fracture criterion
- Modeling coupled effects of shear localization and hole-growth and coalescence.

Calibration of material parameters in constituive/failure models:
- How to efficiently extract parameters from experiments for advanced models.

A2. What kind of experimental information is needed by modelers in order to inform and validate their models?

- Deformation induced evolution of anisotropy and damage/failure
- Multi-axial experiments (e.g. stretch-bending, compression-shear, bulge test) to validate microstructure based models.
- Establish the right physics from experiments – detailed microstructure characterization of agents of damage: Slip/twin/phase transformation interactions with interfaces, void nucleation, dislocation density, interfacial decohesion and transformation structure – TEM/SEM work in different loading and failure modes.
- High-strain-rate experiments effects of adiabatic heating (1000/s)
- Experimental information for building constitutive model for yielding damage accumulation in changing strain path
- Temperature and strain rate history effects on formability
- Experimental work on energy absorption – characterize crack population – separate from deformation contribution.

A3. What are the principal holes in experimental knowledge for second and third generation AHSS?

- Be able to create desired microstructure, and somehow manufacture them on demand
- Damage accumulation for multi-phase in changing stress path
- In situ TEM, SEM experiments
- Both macro and micro-level experiment s
- Microstructure evolution, damage/crack initiation
- How different failure mechanisms couple.

Advanced High-Strength Steels:
Fundamental Research Issues Workshop

TABLE 7:

Conner
Simunovic
Keeler
Wu
Altan
Funkenbusch
Michal
Wierzbicki – not present

Group D Questions: Fracture

---

1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Cost effective alloying elements needed to generate new microstructures.
- Develop methods to define the microstucture required to deliver a desired set of mechanical properties
- Defining a cost effective thermomechanical processing scheme to generate the required microstructure.

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Develop a more uniform structure
- Stamping technology has not been considered as a system
  - Materials
  - Tooling
  - Equipment
  - Tribology
- Robustizing
- Reliability of process model predictions
- Difficulties in coating and joining

---

3. What specific, fundamental (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Reliable tests to determine variability of work-hardening and elastic properties as a function of strain path.
- Flow stress determination under multi-axially conditions.
- Effect of microstructure on loading and unloading behavior.
- Reliable FEM modeling that includes the above for robust and agile prediction.

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- In situ characterizations of materials and processes
- Develop FEM formulations and large scale computations necessary to couple length and time scales for the models

D1) Identify critical issues related to new or unusual fracture / failure behavior of AHSS, microstructural and mechanical.

- What are the proper testing methods for identifying mechanisms of fracture in AHSS?
- What are the micromechanics and microstructure origins of material deformation and fracture in AHSS (1st, 2nd, 3rd generation)?
- Strain partition in different phases and interfaces
- Through-thickness variation
- Initiation and propagation of fracture
- Properties of different constituents
- Shift from bulk-driven properties to interface-based properties
- Linking of various micro mechanisms and length scales into practical continuum models/fracture criteria
- Identify the critical subset of data that needs to be obtained from testing and microstructural analysis (Testing example: current subset is tensile testing, what's next—perhaps bulge test?)
- Variability of material obtained from different sources impacts fracture performance. This is both intrinsic to the material and a result of supplier's methods.

D2) What are the best mechanisms for addressing these issues?

- Experiments/Tests
- Find novel testing methods to examine multiaxial stress and strain loading representative of applications.
- Determine methodology and validity through coupled experiments and tests.
- Develop standardized testing methods as a result of the studies on these novel testing methods.
- Establish initial material state (microstructure and surface), follow stress-strain path during use (or in-situ test)
  - Process modeling for initial material state
  - Interrupted and in-situ tests
- Robustness in alloy design and processing to counteract material variability

- Modeling
- Develop improved/new constitutive models based on underlying micromechanics processes
- Develop friction models
- Build robust models such that results do not vary for a given test
- Develop new FEM formulations

D3) What specific kinds of cooperation is needed among funding agencies, steel companies, auto companies, and the research community? (Money, of course, but what else?)

- Organize workshops between academia, industry and US government research laboratories to coordinate research

- Develop joint research between the above institutions to leverage respective research capabilities and strengths

- Increase sharing of information between different research institutions and industry
  - Material databases
  - Experiments
  - Standards
  - Simulations

Advanced High-Strength Steels:
Fundamental Research Issues Workshop

TABLE 8:

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Group A Questions: Model v. Experiment

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1. What are the principal technical obstacles to the creation of third-generation AHSS?

- Define/expand technological aims/goals beyond strength and ductility. Additional considerations include formability, cost, manufacturability, weldability, coatability, fracture toughness, resistance to fatigue crack growth, *etc*.
- Identification of appropriate microstructures– “hard phase” vs. “soft phase” volume fractions
- Technical requirements based on application requirements including but not limited to sheet materials. Examples include components within the suspension system.
- Cost effective thermo-mechanical process modeling that is related to composition
- Predictive modeling tools, especially first-principles, *ab initio* type, are needed to simulate and predict the behavior of AHSS

2. What are the principal technical obstacles to the widespread usage of second-generation AHSS?

- Cost
- Manufacturability, including coatability, weldability, repairability, *etc*.
- Secondary processing, such as fracture, formability
- Industrial use of simple models and uniaxial data to predict complex, multi-axial processes

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3. What specific, <u>fundamental</u> (i.e. NSF-like) research is needed to make push forward second and third-generation AHSS? (i.e. Identify priority areas for NSF-like research in this area.)

- Bridge gaps / establish links between various relevant disciplines, such as mechanical engineering, materials science and metallurgical engineering
- Experimental methods to identify fracture under multi-state loading
  - Methods should replicate shear-failure behavior in stamping process
  - Important tool in materials selection and design of stamping tools and their process
- Fundamental experimental studies to enhance understanding the relationship among thermal/mechanical processing, alloying, microstructure and properties.
- Fundamental studies on failure mechanisms
- Material constitutive law for anisotropy and cyclic loading
- Fundamental studies to elucidate states of residual stress that result from processing
- Development of strain-rate and temperature-dependent yield and failure criteria for multi-axial loading
- Prediction and understanding of springback mechanisms

4. What specific, applied (i.e. DOE-like) research is needed to make second-and third-generations practical and widely used? (i.e. Identify priority areas for DOE-like research in this area.)

- Material informatics, including access to various databases (such as DoE database)
- Castability to increase the yield of materials
- Coatability
- Post-process properties to identify incipient and actual failures
- Formability / re-formability / workability, weldability, other joining methods, corrosion
- Duplication of failure mode prior to placing materials and components in production and end use

A1. What kinds of modeling are most needed to push AHSS forward? What length scales and techniques are likely to be the most important?

- Inverse modeling to go from desired engineering properties to microstructures
- Micro-mechanical and multi-scale, first-principles-based models to be embedded into / integrated with continuum-based models
- Phase transformation models
- Computationally efficient, simple-to-use, accurate predictive models that are amenable with multi-pass processes
- Incorporation of parameters that are absent from current generation models to represent measurable microstructures
- Models to account for friction, contact stresses, and microstructural effects during forming / rolling processes

A2. What kind of experimental information is needed by modelers in order to inform and validate their models?

- Statistical description / measures (two- and three-point correlations) of microstructures, residual stress
- Deformation mechanisms (dislocation motion, twinning, etc.)
- Surface stress during contact considering microstructures
- Response of material under multi-axial loading, e.g., kinematic and isotropic hardening

A3. What are the principal holes in experimental knowledge for second and third generation AHSS?

- Response of materials under multi-axial stress state, temperatures, and strain rates
- *In situ* experiments to identify failure and deformation mechanisms
- Low-cost method to determine properties and characteristics
- Enhanced knowledge of weldability