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Workshop on Addressing Key Technology Gaps in Implementing AHSS for Automotive Lightweighting

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Executive Summary

Customer demand and regulatory requirements continue to drive automakers to develop vehicles with higher levels of fuel efficiency and structural performance. There is a well-established need for additional research into advanced high strength steels (AHSS) to overcome technology gaps that are inhibiting the lightweighting potential of AHSS. In order to articulate the research directions needed, a workshop was conducted on February 9-10, 2012 in Southfield, Michigan on the topic of "Addressing Key Technology Gaps in Implementing AHSS for Automotive Lightweighting". The workshop brought together top engineers and scientists from automotive OEMs, steel companies, Tier 1 suppliers, government agencies and academia. The format included keynote presentations from industry and government leaders and state-of-the-art presentations from technical experts on the six technical areas deemed most important for this workshop. These presentations (where authorized by the presenter's company) are attached to this report.[1] After the presentations, breakout sessions were conducted where technical requirements and gaps, as well as research needs for the six areas, were discussed, identified and prioritized. These needs were presented during the closing session of the workshop.

[1] The presentations are also available at http://www.nist.gov/mml/materials_reliability/structural_materials/ahss.cfm

The six important technical areas were selected by the workshop organizing committee, a group of experts from the auto and steel industries, and scientists from several National Laboratories. These selections were based on areas where there were known technical gaps, which if closed would have high impact on accelerating vehicle lightweighting with AHSS. The selected areas were: Steel Development, Fracture, Plasticity, Delayed Fracture/Hydrogen Embrittlement, Modulus Characterization and Joining.

The main output of the workshop is contained within the breakout session reports, which summarize the technical requirements, engineering gaps and research needs. The breakout session reports are included below in the main workshop report. The three top research needs for each of the six technical areas covered in these sessions are given below:

Steel Development: 1) Identify steel microstructures to meet 3rd Generation AHSS, with post-processing cycles (e.g., softening, hardening, painting) comprehended. 2) Set up independent lab(s) capable of rapid prototyping of AHSS and 3rd Generation AHSS. 3) Develop welding/joining processes insensitive to steel composition.

Joining: 1) Develop reliable weld and joint modeling software to predict weld performance. 2) Update and develop guidelines for AHSS weld performance requirements. 3) Develop a cost effective and practical approach to improve weld fatigue.

Fracture: 1) Develop theoretical understanding of fracture mechanics of multiphase material under different loading conditions. 2) Identify drivers of shear fracture behaviors in order to begin improving both performance and uniformity of materials. 3) Understand what modes of deformation (manufacturing processes) and their associated variables control shear fracture with the goal of developing manufacturing processes that are more robust in resisting shear fracture.

Modulus Characterization and Application: 1) Characterize elastic behavior and develop standard tests that including unloading/reloading. 2) Develop and validate predictive multi-scale model to explain changes in elastic behavior, including: microstructural effects, texture, anisotropy, and processing effects. 3) Evaluate the QPE model to determine if it can correlate with mechanical elastic behavior for springback prediction and extend to more materials and load cases (e.g. biaxial).

Delayed Fracture/Hydrogen Embrittlement (HE): 1) Identify or develop appropriate test method(s) for assessing delayed fracture and HE. 2) Conduct basic microstructural research on HE sensitivity in high strength steels. 3) Develop an on-vehicle sensor to monitor in-service changes in hydrogen during operation of automobiles.

Plasticity: 1) Develop a fracture limit diagram, (distinct from the necking limit diagram) for AHSS. 2) Develop a cost efficient standard method to measure forming limits of AHSS under linear and nonlinear strain paths. 3) Develop improved constitutive models for AHSS currently used in BIW applications, and extend this work to 3rd Generation AHSS as they become available**.**

Several broad cross-cutting research themes can be identified by reviewing the breakout session results as a whole:

- There is a need for predictive modeling in all the research fields discussed here. Models that can correlate processing with microstructure and microstructure with properties are needed. Ideally the models would be based on metallurgical fundamentals; however, phenomenological models may be able to bridge the gap between current status and fully validated and correlated fundamental models.

This finding is in agreement with the recognized need for Integrated Computational Materials Engineering (ICME) that was identified in a recent report by the National Academy of Sciences[2].

- There is also broad agreement that the current suite of test methods used to characterize sheet steel will not be adequate to provide the data needed to support the modeling efforts mentioned above. In addition, new test methods will likely be needed to qualify these new materials for service and ensure their quality.
- Finally, there is a large need for data on these materials, on mechanical properties, physical properties, corrosion and many other characteristics. In order to develop these data, a path towards cost-effective production of prototype quantities of these materials is needed urgently. Successful model development will supplement this effort, but will not be able to replace it.

We expect this information will be used for internal program planning by the auto and steel industries, and will also form the basis for development of new industry/government/academia collaborations to address tasks of mutual interest with the goal of accelerating the use of AHSS for vehicle lightweighting.

Acronyms

AISI	American Iron and Steel Institute
AHSS	Advanced High Strength Steel
A/SP	Auto/Steel Partnership
BIW	Body-in-White
CAE	Computer Aided Engineering
DOE	Department of Energy
DP	Dual Phase (Steels)
FEA	Finite Element Analysis
GMAW	Gas Metal Arc Welding
HE	Hydrogen Embrittlement
HSLA	High Strength Low Alloy
ICME	Integrated Computational Materials Engineering
LW	Laser Welding
MPG	Miles per Gallon
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturers (vehicle producers)
PHS	Press Hardened Steel
QPE	Quasi-Plastic Elastic

[2] Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security, National Academies Press, available at http://www.nap.edu/catalog.php?record_id=12199

R&D	Research & Development
RSW	Resistance Spot Welding
SMDI	Steel Market Development Institute
SOTA	State-of-the-art
TRIP	Transformation Induced Plasticity (Steels)
TS	Tensile Strength
TWIP	Twinning Induced Plasticity (Steels)
USCAR	United States Council on Automotive Research
UTS	Ultimate Tensile Strength
YS	Yield Strength

Introduction

The need to improve vehicle fuel efficiency has never been greater. Current regulations will require carmaker fleet fuel economy averages to reach 34.5 MPG by 2016, and proposed regulations would require them to reach 54.5 MPG by 2025. In addition, regulations to curtail CO_2 emissions could become reality in the next decade, as the implications of elevated levels of CO_2 in the atmosphere become better understood. Vehicle lightweighting will become a key enabler for automakers to address the unprecedented doubling of fuel economy regulations. Although alternative materials, such as aluminum, magnesium and advanced composites have the potential to reduce vehicle weight, concerns about their cost and availability as well as the gaps in their ability to be economically fabricated into useful parts, and the energy requirements for their manufacture demand that steel continues to be a viable alternative for vehicle lightweighting. Although great progress has been made in implementing 1st Generation and developing 2nd and 3rd Generation AHSS for vehicles, recent industry studies have indicated that the ultimate lightweighting potential of AHSS has not yet been reached. The use of high strength and advanced high strength steels has increased by 60% over the past 15 years. These high performance steels have enabled increased safety and vehicle performance while keeping vehicle mass flat in a stable Corporate Average Fuel Economy environment. Developing the key engineering, manufacturing and material technologies to unlock the full potential of lightweighting possible through the strategic use of 3rd generation AHSS and beyond is imperative to keep pace with the sharp increase in fuel economy regulations over the next 15 years. These technology gaps, if overcome, would increase the usage of AHSS and accelerate its implementation and provide automakers with a cost effective, high performance, and environmentally sound option for vehicle lightweighting. The DOE has publically recognized this fact in several recent presentations, and this workshop was aimed at identifying the research topics and approaches that could be used to close the gaps. Ultimately, the results of this workshop would be used by investigators to develop proposals to execute the identified research.

The workshop, “Addressing Key Technology Gaps in Implementing AHSS for Automotive Lightweighting,” was held February 9-10, 2012, at the USCAR offices in Southfield, Michigan. The goal of the workshop was to develop research and applied technology topics aimed at overcoming the key technology gaps that are hindering the lightweighting potential of increased use of AHSS in automotive applications. The workshop brought together scientists and engineers from the steel and automotive industries, laboratories affiliated with several federal agencies, and universities.

Keynote Presentations

The workshop began with four keynote presentations[3] to frame the topics. These talks outlined the opportunities, roadblocks, threats and requirements for using steel products with strength levels above 1000 MPa to achieve lightweighting in future vehicles to attain upcoming fuel economy mandates, from automotive, steel and government perspectives. The presenters were:

1. Steel Industry – Presentation by Ron Krupitzer, Steel Market Development Institute, American Iron and Steel Institute
2. Federal Government – Presentation by Will Joost, U. S. Department of Energy
3. Automotive Industry – Presentation by Curt Horvath, General Motors Company
4. Automotive Industry – Presentation by Jim Dykeman, Honda Motors North America

Technology State-of-the-Art (SOTA) Presentations

After the keynote presentations, a series of technology state-of-the-art presentations were given by leading experts. These presentations assessed the state-of-the-art of key lightweighting technology areas, from the standpoints of 1) how to improve performance, 2) how to predict performance more accurately, and 3) what is needed from steel makers and processors, auto companies and the research community. The main focus was on steels with strength levels above 1000 MPa; however, other technologies that provided a pathway to lightweighting were also discussed. The SOTA presentations were followed by breakout sessions, that were held to discuss each technology area and develop recommendations for future research to move the state-of-the-art forward. Six topics were selected for SOTA presentations:

1. Steel Development – Presentation by Prof. David Matlock, Colorado School of Mines
2. Joining – Presentation by Dr. Zhili Feng, Oak Ridge National Laboratory
3. Fracture – Presentation by Dr. Xin Sun, Pacific Northwest National Laboratory
4. Modulus Characterization and Application – Presentation by Dr. Umesh Gandhi, Toyota Research Institute North America
5. Delayed Fracture/Hydrogen Embrittlement – Presentation by Dr. Donald Jordan, Ford Motor Company
6. Plasticity – Presentation by Dr. Thomas Stoughton, General Motors Company

Technology Development Breakout Sessions

After the SOTA presentations, the conference attendees convened in smaller, two-hour breakout sessions to discuss how to address the technology gaps. Each session was led by a facilitator selected by the organizing committee, and a member of the organizing committee acted as a scribe for each breakout session. The facilitators led the group discussions about the technology requirements, specific technology gaps identified and research needed to close those gaps. The final activity of each breakout session was to prioritize the list of research needs. Each breakout session was summarized by the facilitator at the end of the workshop.

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[3] Workshop presentations that were released by the speakers for public distribution are found in Appendix I and are available at http://www.nist.gov/mml/materials_reliability/structural_materials/ahss.cfm

Breakout Session Reports

Following the workshop, the facilitators and scribes combined their notes and prepared the following breakout session reports. These reports, plus the abstracts from the SOTA presentations are presented below.

I. Steel Development

A. SOTA Presentation

"Recent AHSS Developments for Automotive Applications: Processing, Microstructures, and Properties," David K. Matlock, John G. Speer, Emmanuel De Moor, *et. al*., Advanced Steel Processing and Products Research Center, Colorado School of Mines.

Abstract: The results of a recent review article entitled "Strategies for Third Generation Advanced High Strength Steel Development" will be presented and used to highlight processing strategies that have been identified as potentially applicable for the production of next generation AHSS. Sheet steels of interest involve novel alloying and processing combinations that produce unique microstructural combinations characteristic of property regions within those defined for 3rd Generation AHSS. Depending on the specific property range within the third generation band, different processing routes have evolved as prime candidates for being potentially successful in facilitating commercialization of new products. For example, medium Mn, enhanced TRIP steels exhibit properties characteristic of the higher ductility, lower strength (i.e. up to ~ 1 GPa) portion of the third generation property band. In contrast, Q&P steels (quenched and partitioned) and bainitic steels exhibit properties characteristic of the higher strengths (i.e. above 1 GPa) within the third generation property band. Specific research on the steel alloying and processing routes that have been identified as of primary interest will be presented to illustrate how the application of fundamental metallurgical principles has led to enhanced AHSS. Research has shown that the properties of interest are not limited to strength-ductility combinations and must also include assessments of other properties including effects on formability (e.g. hole expansion, spring back) and weldability. In addition, as part of this presentation and to provide further framework for future research, the status of selected AHSS developments around the world will also be discussed.

B. Discussion

Facilitator: Peter Mould - Automotive Steel Technologies, Inc.; Scribe: Bart DePompolo - US Steel Corp., Attendance: 30

a) Technical Requirements

The group was asked to define physical and mechanical property requirements for 3rd Generation AHSS to guide product development. Although only qualitative metrics (tensile strength, excellent global and local formability, good spot weldability, low variability and low cost) were defined, the group agreed that basic research is needed to identify the microstructure 'mixes' needed for the group of steels. Additionally, a need was identified for a sheet steel processing trial facility where new steels and processes can be optimized. Finally, a focus on developing robust welding/joining processes to achieve welding goals was preferred to addressing inherent steel weldability via carbon. Specific technical requirements were categorized into 1) General, 2) Economic Issues, 3) Manufacturing Issues and 4) Improved Performance.

In general, 3rd Generation AHSS are desired to replace Press Hardened Steel (PHS) by providing high strength parts that are manufacturable at room temperature. Therefore, 3rd Generation AHSS must be developed with post-processing cycles comprehended (e.g., softening, hardening, painting), and identification of mechanical properties (e.g., yield strength, tensile strength, elongation, hole expansion, bendability) and physical properties (e.g., thickness, width, surface texture) are necessary to set product development goals. In addition, increased thickness and width availability of AHSS and 3rd Generation AHSS are necessary to support down-gauging and lightweighting.

Economic issues are of large concern for these new grades of steel. Business cases are needed to support Research & Development (R&D) and low-cost AHSS and 3rd Generation AHSS steels are required to compete with alternative materials. In addition, affordable TWIP (Transformation Induced Plasticity Steels) with no delayed fracture is desired. It is also essential that all of these products are globally available.

There are several manufacturing issues that are also of significant concern. Formability to enable part consolidation is needed that will enable maximum weight reduction. It was also requested that hot rolled 1000 MPa Complex Phase steel with high hole-expansion be developed. Modeling capability in predicting localized necking will significantly improve die development. Finally, weldable 3rd Generation AHSS should be targeted.

The area of improved performance of new grades of steel received the most attention in the breakout session. The following performance metrics were listed:

- Low variability of mechanical properties and thickness is necessary to ensure that mass reduction is truly achieved in the final product.
- Corrosion protection for all AHSS and 3rd Generation AHSS is required because over 80% of the steel in today's vehicles demand it.
- Improved stiffness by use of steel laminates.
- Understanding of delayed fracture is imperative to enable the use of steels above 1000 MPa.
- High-modulus and low-density steels are desired.
- Identification of automotive parts that are stiffness-dependent will help determine target formability requirements.
- AHSS and 3rd Generation AHSS with no local softening resulting from welding heat input are desired.
- Finally, it is critical to have AHSS and 3rd Generation AHSS which are insensitive to hydrogen embrittlement.

b) Technical Gaps:

The technical requirements were consolidated and used to identify the following technical gaps:

- Exposed-quality AHSS and 3rd Generation AHSS are required
- Microstructures to attain 3rd Generation AHSS must be identified.
- Steel compositions and thermomechanical processes to attain the microstructures required for 3rd Generation AHSS must be identified.
- Computational models to develop future steels are needed.
- R&D studies need to be transferred to mill operating practices.
- There is a lack of independent labs capable of melting and processing sheet steels to optimize structures

and properties to support product development.

- There are not enough facilities to produce TWIP.
- 3rd Generation steel compositions and microstructures must be developed to allow thermal post-processing.
- Local heat treatment technologies must be developed for in-part hardening or softening.
- Multiple steel composites are needed to optimize stiffness.
- Acceptable alloys must be identified to avoid environmental issues.
- Warm-formable Boron steels are needed to reduce processing costs.
- Industry standards for measuring flatness must be developed, and flatness requirements for AHSS and 3rd Generation AHSS must be set.
- Expanded thickness capability for AHSS and 3rd Generation AHSS are necessary to support light-weighting.
- Modeling of forming and crash for AHSS and 3rd Generation AHSS must be developed to the same capabilities now available for mild and HSS.
- Ability to separate/recycle 3rd Generation AHSS rich in high-cost alloys must be considered.

c) Research Needs

Research needs were organized into the following prioritized groupings. The detailed descriptions from the group's input and the number of supporting votes for each research idea can be found in the Appendix. Ideas with no votes will also be found in the Appendix.

1. Identify steel microstructures to meet 3rd Generation AHSS, with post-processing cycles (e.g., softening, hardening, painting) comprehended.
2. Set up independent lab(s) capable of rapid prototyping of AHSS and 3rd Generation AHSS.
3. Develop welding/joining processes insensitive to steel composition.
4. Create computational models to develop new steels.

II. Joining

A. SOTA Presentation

"Challenges and Opportunities in Joining Advanced High Strength Steels", Zhili Feng, Oak Ridge National Laboratory

Abstract: AHSS are steels that are highly engineered through careful controls of chemistry and thermomechanical processing routes to achieve the specified properties. Joining of these AHSS can be challenging. For example, the HAZ softening of certain ultra-high strength steels may reduce the joint efficiency of the weld, and the insensitivity of weld joint fatigue life to the strength of AHSS would neutralize the weight-saving benefits of AHSS in fatigue/durability critical components. We will review recent data of AHSS welds, and discuss the fundamental factors contributing to the joining challenges. Approaches to address or mitigate welding-induced property changes, in particular, approaches to improve the weld joint fatigue life, will be suggested. Computational approaches to design and engineering the welded joints with the consideration of weld property changes will be discussed.

B. Discussion

Facilitator: John Fillion, Scribe: Zhili Feng, Oak Ridge National Laboratory. Attendance: 15

a) Technical Requirements

Welding/joining is an essential manufacturing technology in today's high-volume production of automotive vehicles. The body of a typical modern passenger vehicle is assembled together with 4000 to 5000 spot welds made by resistance spot welding (RSW) process. Other welding/joining processes, such as gas metal arc welding (GMAW), laser welding (LW), and weld bonding, are also widely used.

Welding and joining of advanced high-strength steels, especially the ultra-high-strength steel class, presents some unique technical challenges to both the steel suppliers and the auto end-users. It is well recognized that welding AHSS with existing welding practices for the conventional mild steels may not be the preferred approach to achieve the full benefits of AHSS. Due to their high carbon and alloying element contents, and specially tailored microstructures for combination of strength and ductility, AHSS are considerably more sensitive to the thermal cycle of welding than conventional steels. The weld region of an AHSS typically exhibits microstructures different from those of the base metal produced through carefully controlled steel processing route, thereby resulting in different performance characteristics. The degree of microstructure and property changes in AHSS welds can vary greatly, depending upon the steel chemistry, the microstructure of base metal, and the welding process and parameters used.

It is important to note that the steel chemistry and steel processing route are two of the many variables that govern the performance (static strength, fatigue life, impact properties, etc.) of a weld joint in an auto structure. The geometric features of a weld (such as the weld surface profile and weld size) also play an important role. Due to the increased sensitivity to the welding thermal cycle, the welding processes and parameters need to be carefully selected to match the metallurgical characteristics of a given AHSS, and different types of AHSS may require different welding conditions to realize the benefits of the steels.

b) Technical Gaps

Considerable progress has been made in joining AHSS auto-body structures since the introduction of AHSS for auto-body applications. However, reduced weldability and property degradation (static strength, impact strength, crashworthiness performance, and fatigue strength) in the weld region are still among the major challenges impeding the widespread adoption of the current generation AHSS for auto-body structure lightweighting. For example, the higher grade AHSS (e.g., DP800/1000, TRIP, boron) are more difficult to weld and more susceptible to formation of brittle microstructures and solidification-induced defects in the weld region. Due to the thermal instability of the hard-phase constituents in the multiphase microstructure, softening of the heat-affected zone (HAZ) can occur. These characteristic microstructure changes in the AHSS welds can greatly influence the static and impact performance of welded AHSS structures. AHSS RSW generally has higher load-bearing capacity, but can fail under different failure modes (button pullout, interfacial, or mixed). Impact experiments on joints and structural components have shown that RSW have different responses under static and impact loads. Furthermore, studies have revealed that the weld-fatigue performance of the current generation AHSS is largely insensitive to base metal composition, microstructure, and strength. The lack of inherent weld fatigue strength advantage of AHSS over conventional steels is considered to be another bottleneck for vehicle weight reduction through the use of AHSS.

To the end-users, making the strongest weld is certainly desirable. However, the real engineering challenge would be how to specify a weld to meet the target performance specifications of a welded component in the most cost-effective way. It involves more than merely selecting the “strongest” steel in the market. In many cases, the specification could be met by using less-expensive steel together with intelligent specification and control of weld geometric attributes and welding conditions, to achieve the total cost-effectiveness. It would be highly desirable if the quality and performance characteristics of the AHSS welds could be accurately specified in the design stage, to achieve significant cost-savings and reduction of design time. To this end, development of robust welding process and performance simulation tools capable of predicting the local microstructure and property changes in the weld region, and integration of such weld modeling tools into the auto-body computer aided engineering (CAE) tools, would be critically important in auto body-structure optimization for design and manufacturing, in weld process development and optimization, and in development of “welding friendly” AHSS (current generation and future generations).

c) Research Objectives

The joining break out session produced a wide range of suggestions and recommendations. Through further discussion and voting, the research needs were ranked and prioritized. The following six top-priority joining R&D topics are identified.

1. Develop reliable weld and joint modeling software to predict weld performance.
2. Update and develop guidelines for Advance High Strength Steel performance requirements.
3. Develop a cost-effective and practical approach to improve weld fatigue.
4. Study laser welding for chassis components.
5. Research and develop joining methods betwee advanced high strength steels and dissimilar materials.
6. Develop practical solutions for fusion and laser welding of coated steels to avoid splatter, porosity, and voids.

III. Fracture

A. SOTA Presentation

“Tensile Ductility and Localized Fracture of AHSS”, Dr. Xin Sun, Pacific Northwest National Laboratory.

Abstract: Vehicle weight reduction is a key enabler to reducing the fuel consumption of U.S. automobiles and light trucks. This can be cost-effectively achieved by using more advanced high strength steels (AHSS) in vehicles. However, a noticeable degree of inconsistent forming behaviors has been observed for AHSS in production, particularly when the strength level reaches around 1000 MPa. These inconsistencies appear to be associated with the inherent microstructure-level inhomogeneities for various AHSS. This indicates that the basic material property requirements developed for the mild steels and HSLA are no longer sufficient for today’s AHSS in vehicle manufacturing applications. This talk will focus on the various ductile fracture behaviors for different AHSS by use of an integrated experimental and modeling approach. The objective is to gain fundamental understandings on how different microstructure level features of AHSS can influence the behaviors of these steels subjected to deformation paths similar to those experienced in automotive forming operations. In addition, the correlation between the localized formability and hole expansion test is also presented for different DP980. The ultimate goal is to accelerate the cost-effective vehicle weight reduction through the increasing use of AHSS.

B. Discussion

Facilitator: Rich Cover - Richard J. Cover & Associates, LLC, Scribe: Xin Sun – PNNL

a) Technical Requirements

The ability to predict and mitigate fracture in vehicle structures is needed to promote widespread implementation of AHSS in vehicle structures. In order to accomplish this, the group agreed on the following technical requirements on fracture, which include both design and manufacturing aspects.

From the design perspective, the automotive industry will need to:

1. Establish design and forming guidelines associated with AHSS. To achieve this, predictive models for shear fracture by use of FEA must be developed and applied to the design tools.
2. Develop a robust fracture prediction capability in engineering analyses to accurately and efficiently predict fracture strength, edge-cracking strain limit, and valid forming limit diagrams for different strain paths, and implement these computational tools for commercial software, e.g., LSDYNA, ABAQUS.
3. Develop and implement fracture prediction for crash events, and incorporate manufacturing history and material characteristics into product in-service performance predictions.

From the vehicle manufacturing and operations perspective, the automotive industry will need to:

1. Develop very fast ways to predict when and where fracture will occur in a complex manufacturing process, including
    a. Multistage forming,
    b. Forming at elevated temperatures,
    c. Heat treatment (annealing between steps).
2. Characterize fracture limits of different AHSS grades and determine critical (influencing) parameters that correlate to fracture propensity.

b) Technology Gaps

There was strong agreement around the top technology gap. Fundamental research is primary and essential to being able to undertake more practical endeavors in understanding fracture. Once sufficient fundamental work is completed, the next priority will be to develop predictive models based on measureable material characteristics. The lack of correlation between traditional material characteristics and shear fracture behavior is a serious technology gap that needs to be overcome. Finally, once validated models are available, the next priority will be to develop design tools that could be derived from the learnings in the first and second priority areas, so that users could use AHSS, including future 3rd Generation products, with confidence in models related to manufacturing performance, dynamic loading and straining and crash events, irrespective of the area of probable fracture initiation sites.

Specific technology gaps, based on the priorities above, have been identified in fracture related areas based on the current state of the art. These gaps are grouped into two categories in terms of materials intrinsic properties and the associated measurement techniques.

Materials intrinsic gaps include:

1. Understanding why different steels have different shear fracture resistance.

2. Fundamental understanding on metal characteristics that control shear fracture for future development of steels with high shear fracture resistance (including edge fracture) and controlled property variability.
3. Methods to compare microstructure, composition, and in the future correlate crystal structure to shear fracture behavior.
4. Properly calibrated mechanical models for fracture when only traditional tensile property data are available.
5. Understanding the behavior of materials relative to shear fracture, in crash events, using dynamic properties of materials, rather than "as-shipped" properties.
6. Benchmarking programs to differentiate among steels that have varying degrees of shear fracture resistance.

Measurements, testing and data related gaps include:

1. Standardized fracture test methods for measuring drivers of shear fracture and also the shear fracture event.
2. Standard testing methods to distinguish and characterize different failure modes, e.g., edge fracture, hole expansion and constrained area shear fracture (middle of a part).
3. Consistent test methods to evaluate fracture performance of materials.
4. Measurement methods for plastic constitutive response of AHSS at large strains, high strain rates, and elevated temperatures. In discussions and in development, distinguish also between strain localization fracture (such as uniform elongations) and brittle fracture.
5. Industry-wide collaborations among steel makers on knowledge sharing.

c) Research Needs

The four research needs below were given equal and top priority, with the view that significant progress in fundamental research in all four areas must precede any other work.

1. Theoretical understanding of fracture mechanics of multiphase material under different loading conditions.
2. Identification of drivers of shear fracture behaviors in order to begin improving both performance and uniformity of materials.
3. Understanding of what modes of deformation in manufacturing processes, and their variables, control shear fracture, with the goal of then developing manufacturing processes that are more robust in resisting shear fracture.
4. Fundamental understanding of relationships among composition, phases, microstructure, crystal structure in controlling various modes of deformation that can lead to shear fracture.

IV. Modulus Characterization and Application

A. SOTA Presentation

"Investigation of Anisotropy in Elastic Modulus of Steel," Umesh Gandhi, Toyota Research Institute North America.

Abstract: One of the major reasons for using steel in vehicle structural components is its higher elastic modulus compared to other materials such as aluminum and composites. Higher stiffness helps in designing a stiffer structure. Vehicle handling as well as noise and vibration performance are highly dependent on the vehicle structural stiffness. In automotive application of steel, most design calculations are based on the assumption that the elastic modulus of steel is 207 GPa. However in practice, we have observed the actual values of elastic modulus ranging from 180 GPa to 220 GPa. This is a significant difference and can result in unexpected design performance. Clear understanding of elastic modulus of steel is very important to optimize vehicle design. In this presentation we will examine the variation in elastic modulus of steel, identify possible root-causes of the variations and discuss ideas on how to address these variations in future.

B. Discussion

Facilitator: Ron Krupitzer - SMDI, Scribe: Jim Fekete - NIST, Attendance: 20

a) Technical Requirements

The first requirement identified by the group was the need for appropriate data. An important distinction was identified between understanding the classic "elastic modulus" of a material and understanding the elastic response of a material under stress. The group agreed that the elastic modulus of steel could be measured and was well understood. However, this is insufficient to properly simulate the elastic behavior of vehicle structural elements during deformation. Thus, there is a need for a characterization method that defines the nonlinear elastic behavior of steel and captures the constitutive relation between stress and strain at stresses below the yield strength. The data are needed to incorporate non-linear elastic behavior in modeling used for formability, durability and crash performance prediction.

In addition, there is a need to understand how processing affects elastic modulus. This includes the effect of plastic deformation (i. e., from stamping) on steel's nonlinear elastic behavior. It is well known, as described in the SOTA presentation, that crystallographic texture can influence the elastic response of steel, and thus there is a need to incorporate crystallographic texture into models. If these relations can be understood, it may be possible to control material properties through manufacturing processes (material anisotropy and variations through geometry) to optimize elastic response.

Once the data issues have been addressed, there will be a need to update the modeling requirements for elastic response. This will include migrating away from linear models for unloading and reloading, and developing methods for predicting elastic deformation accurately in models (for torsion, bending and buckling). This will require constitutive models that link existing formability models to localized nonlinear strain models that incorporate anisotropy to multiphase steel micromechanical models currently under development.

The modeling effort will also require standardized methods for handling elastic response, including understanding of uncertainty. Some of the measurement questions include: 1) how to obtain the full elastic response tensor when needed, and 2) whether we should measure elastic behavior for each phase (separately) and use composite calculations to characterize materials response. Once a validated model is available, sensitivity analyses on the effect of varying elastic behavior on model response should be undertaken, with the ultimate goal of quantifying the potential benefit of a more accurate description of elastic behavior.

Finally, once this information has been developed, it will be important to work with the Finite Element Analysis (FEA) companies (e.g. LS-Dyna, ABAQUS) to implement the models and validate the resulting behavior.

b) Technical Gaps

The technical requirements were consolidated and used to identify the following technical gaps:

1. Modeling microconstituent (elastic) behavior in AHSS with appropriate constitutive equations.
2. Mechanical characterization of elastic behavior of AHSS grades.
3. Relate manufacturing processes (steel processes and automotive processes) to the control of the elastic behavior of AHSS.

c) Research Needs

Research needs were organized into the following prioritized groupings. The detailed descriptions from the group's input and the number of supporting votes for each research idea can be found in the Appendix. Ideas with no votes will also be found in the Appendix.

1. Characterize elastic behavior and develop standard tests, including unloading/reloading.
2. Develop predictive multi-scale model to explain changes in elastic behavior, including microstructural effects, texture, anisotropy and effects of processing, experimentally calibrated and validated.
3. Correlate the Quasi-Plastic Elasticity (QPE) model[4] with mechanical elastic behavior for springback prediction and extend it to more materials and load cases (e.g. biaxial).
4. Develop consistent methods to measure stress-strain for uniaxial and biaxial loading (to check anisotropy). Compare steels from various sources and test in different labs.
5. Model the effect of thermo-mechanical processing to predict sheet product properties through understanding of phase and grain orientation development during processing.
6. Complete a sensitivity analysis of elastic behavior to structural response (crash, stiffness, springback).

V. Delayed Fracture/Hydrogen Embrittlement

A. SOTA Presentation

"Technology State-of-the-Art: Delayed Fracture/Hydrogen Embrittlement," Donald L. Jordan, Ford Motor Company.

Abstract: Product development activity to enable continued lightweighting for improved fuel economy may introduce undesirable fracture modes that have been commonplace in other industries with long histories of using high tensile steels but have been rare in automotive body structure applications where such steels are only recently being considered. Rather than blindly transferring technology from other industries, it is proposed that the automotive body structure community carefully characterize contributors to the three components of the commonly accepted delayed fracture model (microstructure, stress, environment) for each individual application, then develop delayed fracture prevention strategies and material screening methodologies.

[4] See Bibliography for references

B. Discussion

Facilitator: Peter Mould - Automotive Steel Technologies, Inc., Scribe: Tim Foecke - NIST, Attendance: 28

a) Technical Requirements

Uniquely amongst the six breakout sessions, the topic of delayed fracture and hydrogen embrittlement problems in 3rd Generation AHSS is a prediction. It is known that delayed fracture occurs in currently used AHSS. It is believed this is caused, at least in part, by hydrogen embrittlement of the interfaces in the complex microstructures. It is further known that various steps in the manufacturing process (from fabrication of the sheet through coating and welding to finishing), and during vehicle use, can cause the steel to absorb undissolved hydrogen. It was assumed by the breakout session attendees that as steel strengths increase in the range of 1 GPa to 2 GPa, problems with HE are going to appear. The resulting microstructures of 3rd Generation AHSS will almost certainly contain many different types of phase boundaries, each with its own susceptibility to HE. Therefore, guidelines to avoid HE must be developed for all phases of manufacturing and for part design.

These are the technology requirements needed to diagnose and address delayed fracture and hydrogen embrittlement (HE) in 3rd Generation AHSS:

1. Understanding of the mechanisms of delayed fracture, whether resulting from HE or some other phenomena.
2. Identification of microstructure or other parameters that can describe susceptibility to HE.
3. Correlation of bench-scale testing to long term field applications. Several long term applications of parts having YS > 1000 MPa have not shown problems in the field. However, bench-scale sensitivity tests on the same steels show failure.
4. Delayed fracture and HE in AHSS and 3rd Generation AHSS are unacceptable.
5. Sources of hydrogen, whether from steel production/processing, part manufacturing and assembly, or during vehicle use must be understood.
6. Identification of realistic stress and environmental state under which steel is to be tested for HE susceptibility.
7. Design guidelines need to be established to avoid HE.
8. Development of 1000 to 2000 MPa YS uncoated and coated steels that are insensitive to HE during steel production, part manufacturing and assembly and in-vehicle use.
9. Identification of the sources of hydrogen and dissolved concentrations that cause HE problems.
10. Correlation of steel compositions/microstructures with HE.
11. Delayed fracture/HE sensitivity for all automotive vehicle types (Internal Combustion Engines, Electric Vehicles and Fuel Cell Vehicles) and influence of on-board storage of hydrogen in Fuel Cell Vehicles.

b) Technical Gaps

The technical gaps identified by the participants all revolve around the lack of knowledge of what is going on inside the steel during delayed fracture or HE. Fundamental understandings need to be developed as to where the hydrogen is coming from, how it is interacting with the microstructure, and how manufacturing processes interplay with these factors. In addition, straightforward methodologies for characterizing hydrogen concentrations in steel are seen as needed.

The technical requirements were consolidated and used to identify the following technical gaps:

1. Relevance of existing test methods for HE to automotive applications is not established.

2. Lack of fundamental understanding of the parameters that cause HE in the automotive environment.
3. How much hydrogen is soluble in different steel phases/microstructural constituents?
4. The environmental effects on the amount of absorbed hydrogen in steels.
5. Understanding of the stress states on delayed fracture of parts on the vehicle (e.g. welds).
6. Determine acceptable levels of hydrogen for known levels of stress (applied and residual, % of YS or UTS).
7. Lack of hydrogen measurement equipment with an accuracy of 0.1 ppm.
8. The amount of hydrogen that can be induced into different steels via a corrosion reaction is unknown.
9. The effect of paint baking (and aging) on delayed fracture/HE is not understood.

c) Research Needs

Research needs were organized into the following prioritized groupings. The detailed descriptions from the group's feedback and the number of supporting votes for each research idea can be found in the Appendix. Ideas with no votes will also be found in the Appendix.

1. Identify or develop appropriate test method(s) for assessing delayed fracture and HE, including examining the effects throughout the manufacturing process. In addition, it is necessary to first determine that amount of hydrogen that is acceptable and how to ensure that laboratory specimens contain a representative amount of hydrogen.
2. Conduct basic microstructural research on HE sensitivity in high strength steels
3. Develop an on-vehicle sensor to monitor in-service changes in hydrogen during automobile operation
4. Develop a test method to show 'weld susceptibility' to HE

VI. Plasticity

A. SOTA Presentation

"Challenges in Modeling the Constitutive and Forming Limit Behavior of AHSS", Thomas B. Stoughton, General Motors Global Research and Development Center.

Abstract: This presentation focuses on the current state of knowledge of plasticity, constitutive behavior, and forming limits, with emphasis on increasing the opportunities for application of AHSS by identifying the key roadblocks and challenges to manufacturing automotive components. The presentation gives an overview of the application of micro and macro-level modeling, with a proposal on how to best utilize the benefits of each approach to address the modeling challenges. The talk then presents several key challenges in using AHSS, including a rise in the hysteresis of loading and unloading, the neglected importance of distortional hardening, the effect of curvature on necking and fracture, and the importance of that effect for dealing with AHSS, and finally, the importance of nonlinear strain paths and overcoming the challenge of conservative solutions that are not so effective for AHSS. This presentation is one of several technical presentations intended to help stimulate discussion in the workshop breakout sessions that will follow presentation sessions.

B. Discussion

Facilitator: John Fillion, Scribe: Tom Stoughton, GM, Attendance: 15

a) Technical Requirements

Constitutive and forming limit models for AHSS are needed in the automotive industry to understand and develop new alloys for improved manufacturing and product performance, as well as to predict whether the metals can withstand the forming conditions required to form automotive products in a given process, with the objective of developing and validating a robust manufacturing process through simulation without unnecessary waste of material ductility, and to predict product performance with reliability to reduce dependence on physical tests.

b) Technical Gaps

The group recognized the need for parallel development of continuum and polycrystalline (or microstructural) models for constitutive behavior, necking and fracture, backed by a strong experimental program to develop and validate the models under complex manufacturing and combined manufacturing/product performance simulations. Interestingly, more than half of the comments, reflecting the focus of the group, dealt with experimental issues. The group also discussed challenges or obstacles to the development of advanced material models, necking and fracture criteria:

1) A serious impediment to development of advanced models is material variability. While this also presents challenges for manufacturing and product performance, if the material variability is known, it can be compensated in principal through process sensitivity simulations and robust design methods. However, material variability is a challenge for material model development and calibration. One solution is the co-development of reliable physics-based models that can be calibrated from non-destructive tests or a few destructive tests to avoid specimen-to-specimen variation in the material behavior.
2) Since 3rd Generation AHSS are not yet available, it was recommended not to wait for these steels to emerge, but to continue improving the capability of modeling AHSS's that will be the workhorse in BIW, and introduce 3rd Generation steels into the modeling effort as these new materials are introduced.
3) Springback prediction was noted to continue to be a significant problem and it was suggested that if the current state of the art in this area for AHSS were sufficiently documented, there would be a higher interest in funding development of advanced material models.
4) While not dealing with the subject of plasticity modeling, the issue was raised that the state-of-the-art of friction modeling is also primitive, and some or most of the benefits of improving constitutive models will not be realized unless effort is simultaneously put into improving models for friction.

c) Research Objectives

Following the discussion of the technical requirements and gaps facing these challenges, the group created a list of objectives for a research and development program in this area, along with a list of challenges and needs.

After brainstorming on the topic of plasticity modeling, the group's ideas are summarized in the following list of objectives for the metal forming industry in the area of metal plasticity modeling to increase the use of AHSS. The list was originally generated from the comments generated by the group (see Section C) and then later prioritized through a survey allowing each person the opportunity to distribute three votes for the three most important ideas. It was noted during this survey that several of these items are interrelated/co-dependent, so that a sensible research program developed from these ideas should consider ways to coordinate the approach to simultaneously deal with these items in a cohesive strategy. The numbers of votes given for each of the following items as a result of the survey are respectively, 5,3,3,3,3,2,2,2,2,1,1,0,0.

1) Some sort of fracture limit diagram, similar but distinct from the necking limit diagram, is needed for AHSS.
2) A cost-efficient standard method is needed to measure forming limits of AHSS under linear and nonlinear strain paths.
3) Improved constitutive models are needed for AHSS currently used in BIW applications, and this work is expected to be adaptable to 3rd Generation AHSS as they become available.
4) Combined manufacturing/product performance simulations are more challenging because they necessarily involve deformations at high strains under extremely nonlinear forming processes. These are also a challenge when using conventional forming limit (fracture) models that have not been validated under such extreme nonlinear deformation histories.
5) Another interesting idea is whether it is possible to develop design guidelines for part designers that can take into consideration advanced forming limit criteria based on stress.
6) Polycrystalline models, including improvements to model changes in microstructure, are considered to be of high value for new alloy development, as well as to support development and calibration of improved continuum level models.
7) Some sort of empirical or physics-based model(s) for damage (or strengthening) due to welding/joining and hole punching is needed for both manufacturing and product performance simulations - something that would be reliable under complex deformation histories.
8) A set of standard benchmarks, such as selected cases from Numisheet Benchmark Studies, should be adopted and maintained for evaluation of existing and new material model developments, as well as identify the existing gaps in the technology.
9) There seems to be too much variation in material testing methods, recommending establishing of standards including reporting requirements on sample characteristics, test details, etc.
10) It was proposed to consider ways to integrate microstructural mechanisms in continuous level plasticity models at low cost, to introduce fundamentally microstructural effects such as twinning.
11) A thorough analysis of the correlation (or lack thereof) to experimental results should be the basis to define the gaps and reliability of existing models
12) An interesting idea was proposed questioning whether we can adapt steel properties so that they change under complex deformations to yield improve performance? An example is the extra strengthening that arises in TRIP steel through the growth in the martensite content, but the question was posed to consider other properties and other mechanisms that can lead to property changes… perhaps some favorable grain structures?
13) A cost-efficient means to obtain reliable measurement of 3D stress and strain fields.

Bibliography

L. Sun, R. H. Wagoner, “Complex unloading behavior: Nature of the deformation and its consistent constitutive representation”, Int. J. of Plasticity 27 (2011), 1126-1144

J. H. Kim, J. H. Sung, K. Piao, R. H. Wagoner, “The shear fracture of dual-phase steel”, Int. J. of Plasticity 27 (2011) 1658-1676

Appendix I – Presentations

I. Keynote Presentations

Steel Industry – Presentation by Ron Krupitzer, Steel Market Development Institute, American Iron and Steel Institute – see attached file “TBD”

Federal Government – Presentation by Will Joost, U. S. Department of Energy – see attached file “2-Joost-Keynote.pdf”

Automotive Industry – Presentation by Curt Horvath, General Motors Company – see attached file “3-Horvath-Keynote.pdf”

Automotive Industry – Presentation by Jim Dykeman, Honda Motors North America – not available

II. SOTA Presentations

Steel Development – Presentation by Prof. David Matlock, Colorado School of Mines – see attached file “5-Matlock-SOTA.pdf”

Joining – Presentation by Dr. Zhili Feng, Oak Ridge National Laboratory – see attached file “6-Feng-SOTA.pdf”

Fracture – Presentation by Dr. Xin Sun, Pacific Northwest National Laboratory – see attached file “7-Sun-SOTA.pdf”

Modulus Characterization and Application – Presentation by Dr. Umesh Gandhi, Toyota Research Institute North America – see attached file “8-Gandhi-SOTA.pdf”

Delayed Fracture/Hydrogen Embrittlement – Presentation by Dr. Donald Jordan, Ford Motor Company – not available

Plasticity – Presentation by Dr. Thomas Stoughton, General Motors Company – see attached file “10-Stoughton-SOTA.pdf”

III. Supplemental Information

Modeling Capability at Sandia – Presentation by Dr. Brad Boyce, Sandia National Laboratory (presentation was given in the Modulus breakout – see attached file “11-Boyce-Supp.pdf”

Appendix II – Agenda

Addressing Key Technology Gaps in Implementing Advanced High-Strength Steels for Automotive Lightweighting

February 9 - 10, 2012 | USCAR Offices | 1000 Town Center, Suite 300 – Southfield, MI

AGENDA - Thursday, February 9, 2012

8:00 Registration/Continental Breakfast
8:20 Opening Remarks

Session 1 – Setting the Stage
These talks will outline the opportunities, roadblocks, threats and requirements for using steel products with strength levels above 1000 MPa to achieve lightweighting in future vehicles to achieve upcoming fuel economy mandates, from automotive, steel and government perspectives

8:30 Steel Perspective – Ron Krupitzer, Steel Market Development Institute
9:15 Government Perspective – Will Joost, U. S. Department of Energy
10:00 BREAK
10:15 Automotive Perspective – Curt Horvath, General Motors
11:00 Automotive Perspective – Speaker TBD
11:45 LUNCH

Session 2 – Technology State of the Art Presentations I
These presentations will assess the state of the art of key lightweighting technology areas, from the standpoints of 1) how do we improve performance, 2) how do we predict performance more accurately, 3) what do we need from steel makers and processors, auto companies and the research community? Although the main focus should be on steels with strength levels above 1000 MPa, these talks may include technologies applicable to other products if they provide a pathway to lightweighting.

12:30 Steel Development – Process/Microstructure – David Matlock, Colorado School of Mines
1:15 Joining – Zhili Feng, Oak Ridge National Laboratory
2:00 Fracture – X. Sun, Pacific Northwest National Laboratory
2:45 BREAK

Session 3 – Breakout Sessions I
Three concurrent breakout sessions will be held to discuss each state-of-the-art technology area, and develop recommendations for future research to move the state-of-the-art forward. The results of the discussion will be developed into a summary report which will become part of the workshop report. In addition, during the course of the breakout sessions, topics for research white papers may be identified, and if so, volunteers will be solicited to write them.

3:00 Breakout – Steel Development – Location 1
3:00 Breakout – Joining – Location 2
3:00 Breakout – Fracture – Location 3
5:00 END

AGENDA - Friday, February 10, 2012

7:30 Continental Breakfast
7:50 OPENING REMARKS/CHECK-IN

Session 4 – Technology State-of-the-Art Presentations II

8:00 Modulus Characterization and Application – Umesh Gandhi, Toyota
8:45 Delayed Fracture/Hydrogen Embrittlement – Don Jordan, Ford Motor Company
9:30 BREAK
10:00 Plasticity – Tom Stoughton, General Motors Company

Session 5 – Breakout Sessions II (includes working lunch)

10:45 Breakout – Modulus – Location 1
10:45 Breakout – Hydrogen – Location 2
10:45 Breakout – Plasticity – Location 3

Session 6 – Breakout Session Reports/Discussion

Each facilitator will briefly present the results from their breakout session and encourage open discussion among the participants, with significant comments collected for the final report.

1:00 Steel Development
1:20 Plasticity
1:40 Fracture
2:00 Modulus
2:20 Delayed Fracture
2:40 Joining
3:00 Wrapup/Assignments
3:30 END

Post-Workshop

A team member will complete the breakout session reports, which will be reviewed and approved by the Workshop Organizing Committee. These reports, together with the speaker's slides, a workshop summary and any white papers stemming from the sessions will be distributed to the attendees.

Appendix III – Topic Rankings and Additional Information Captured During the Breakout Sessions

This appendix contains facilitator notes, voting results and other captured information from each of the breakout sessions. With the exception of some formatting changes, it is presented as it was received from the facilitators, to preserve the intent of the session participants.

I. Steel Development

Top 3:	No. of Votes
1. Identify steel microstructures to meet Generation 3 steels, with post-processing cycles for softening, hardening, painting, etc. comprehended.	17
2. Set up independent lab(s) capable of rapid prove out/prototyping of AHSS and Generation 3 steels.	15
3. Develop welding/joining processes insensitive to steel composition.	11
4. Computational models to develop new steels.	11
Second Tier:	
5. Develop test(s) for edge stretch-ability and shear fracture	3
6. Evaluate the process capabilities at CAN MET	2
7. Develop a multi-dimensional Forming Limit Curve to address all sheet forming modes	1
8. Develop a standard test for delayed fracture	1
9. Develop process needs for exposed-capable AHSS	1
10. Develop better forming and crash models	1
11. Develop steels having lower densities	0
Additional Needs:	
12. Develop robust-weldable steels.	0
13. Develop local heat treating capabilities	0
14. Develop ‘warm formable’ PHS steels	0
15. Develop multiple-steel (other material) composites	0
16. Develop steels having higher modulus.	0

II. Joining

Technical Requirements – What do we want to do? (Three framing questions were used with group input below each question)

1. What are the basic requirements for joining/welding processes to join AHSS?
    1. Spot weld to 3 sheet stack having 0.6 mm galvanized IF steel as one outer layer
    2. Weld sacrificial coatings that are consistent with manufacturing processes
    3. Robust processes with the ability to account for variations in composition of the same type of steel e.g. DP980
    4. Strength – static and fatigue, proven robustness, process cost
    5. Consistency of alloys based on material names – each mill is different – based on mechanicals not chemistry
    6. Material information (alloy, microstructure, coating) to identify the joining limits
    7. To be able to weld with existing plant equipment
    8. To be able to inspect the welds easily and quickly
    9. To have useable weld schedules
    10. Definition of resistance welding for AHSS stack-ups
    11. Develop a welded joint that has low stress concentration, force failure mechanism away from the joint.
2. What are the properties and quality attributes of AHSS welds/joints to enable the use of AHSS?
    1. Most research is focusing on resistance welding not open surface joining technologies such as arc and laser
    2. Weld nugget size hardness across the weld
    3. Ability to weld thick to thin
    4. Ability to join a combination of grades of steel in a multi –t stock
    5. Mixed metal joining
    6. Consistent internal bulk resistance
    7. HAZ: No big differences/jumps e.g. in hardness that causes cracking
    8. Fatigue life proportional to material strength
    9. Durability/fatigue strength of weld joint at 80% or higher of the base metal
    10. Still need design engineers to understand materials and changes due to forming/welding
    11. HAZ softening and hardening, uniformity of Zn coating
    12. Insensitivity to LME with Copper alloys or Zn coatings
    13. Development of property database for AHSS stack-ups
3. How to design and engineering/specify AHSS welds/joins in the framework of design and optimization of body components/structure for light weighting and improvement of performance and safety offered by AHSS?
    1. Acceptable gap and orientation mismatch based on weld type
    2. Be able to weld the steels using a variety of joining methods
    3. Be able weld dissimilar grades and gauges
    4. Ability to join non ferrous sheets to an AHSS structure
    5. Subsystem level testing simulation (not just based on coupon testing)
    6. Pay more attention to weld location, weld orientation, weld start/stop locations, weld size
    7. Weld/manufacture a AHSS that doesn’t require a sacrificial coating
    8. Investigate different welding methods e.g. laser hybrid
    9. Design the body structure with joining requirements/guidelines
    10. Proliferation of welding processes with no differentiation of where they are optimized
    11. Develop continuous joining technologies to improve stiffness of reduce gauge steels
4. Other

1. Inexpensive quality testing in the plant(where button pull out doesn't work)
2. Warm mechanical fastening for AHSS
3. Now generation quality assurance according to MS
4. Wireless sensor technology for mass data collection

Technology Gaps – Why can't we do it? (Three framing questions were used with group input below each question)

1. What are the pressing issues in joining that severely limit the use of AHSS? Issues include the effects of welding thermal cycle on the microstructure changes in the weld region, the properties of weld/joint (static, fatigue and crash/impact) that might not be sufficient to support the increases in AHSS performance/properties, and the CAE tools and design rules for weld joint design.
    1. Predictable, better crash simulations for joints including HAZ effects
    2. Limitation in existing plant equipment
    3. Concerns about HAZ softening
    4. Insufficient database (knowledge) on fatigue properties about joints
    5. Decreased formability, increased strength and stiffness of AHSS makes part fit up more crucial and difficult
    6. Quick weldability prediction analytical tools
    7. Simulation of welding effects in product attribute models
    8. HAZ strength and fatigue performance
    9. Tier 1's for chassis parts are set in their ways, need to motivate them to invest in improved joining processes
    10. Heat affects degrade the properties and performance
2. Are there any particular grades/types of AHSS that are difficult to weld? Why?
    1. High carbon equivalent steel in chassis suspension applications
    2. Austenitic grades appear to LME in arc brazing
    3. UHSS at 1500 MPa due to martensitic microstructure – heat change the structure and properties
    4. Thermal process mapping for G3 steels to define joining requirements
    5. Why not 200 SS alloys? Steel mills do not make the grades so no interest to push
    6. Galvanized 780 TRIP reported to be difficult to weld
    7. Problems with LME
3. Are today's joining processes adequate to join AHSS? Will AHSS require development of new or improved joining processes to fully utilize the benefits of AHSS
    1. Hybrid processes for pre/post heating of AHSS
    2. Better piercing/riveting capability for AHSS
    3. Fusion welds not good enough
    4. Need method to reduce or eliminate overlapping weld flanges using butt welds for suspension /ladder frames
    5. Secondary Q/T pulse spot welding
    6. Defocused laser second pass to heat treat after laser welding
4. Other
    1. How to get fast access to the data for new alloys as they come

Research Needs – How do we close the gaps? (Prioritized: numbers in red indicate relative priority within each major question)

1. How to improve the joint durability to match that of AHSS?
    1. Development of warm mechanical fastening for AHSS 1

2. Examination of high productivity joining processes to high carbon grades of AHSS 1
3. Integrated approach for joint durability improvements – measure property attributes to fatigue performance of joints pre/post weld processes 3
4. NDE for welded fasteners 3
5. Laser hybrid welding study for chassis components 4
6. Cost-effective and practical approach to improve weld fatigue 4
7. Joint designs should look like Aluminum joint designs – wrap to neutral axis
8. MS1200 for SPR and other mechanical joining processes

2. How to deal with the HAZ softening in certain types of AHSS welds?
    1. The effect of micro alloying additions on the HAZ softening in AHSS grades 1
    2. Improve weld filler metal to match joint properties of base metal 2
    3. Resistance spot welding of metals having greatly different bulk resistance and Tm 2
    4. Update/develop design guidelines for AHSS welding/joining to meet performance requirements 5
    5. Research for joining methods to join AHSS to aluminum panels and other dissimilar materials 6
    6. Complex resistance spot weld processing for uniform AHSS microstructures
3. CAE and design tools for joining of AHSS?
    1. Development of welding guidelines for implementing AHSS into design including process selection guidelines 1
    2. Laser brazing steel to aluminum 3
    3. Quick weldability prediction tools and models with data required to support the above tools and models 3
    4. Reliable weld/joint modeling software to predict performance 5
    5. Practical simulation methodologies to account for joining effects in product attribute evaluation models
4. Fundamental understanding of factors governing the properties of AHSS welds 2
    1. Development of thermo mechanical processing requirements for AHSS grades 1
    2. Assessment of stack-up influence for AHSS 1
    3. A material characterization parameter that correlates with weldability. This parameter will probably depend both on microstructure and chemical composition 1
    4. Identify easy to measure material properties to predict weldability of AHSS 2
    5. Development of wireless sensors and algorithms for 100% spot weld quality assurance
    6. Influence of coating variation on weldability of AHSS
    7. Need to teach basic physical metallurgy and effects of alloying and processing. There is a general lack of knowledge on the physics behind the metallurgy
    8. Development of new carbon equivalent formula for AHSS
5. Other
    1. Joining AHSS with non ferrous materials such as aluminum and composites 1
    2. Mig brazing for some zinc coated AHSS due to LME 1
    3. Practical vehicle NDT methods to inspect spot welds 3
    4. Improved inspection process for on-line evaluation of RSW integrity and strength 3
    5. Develop practical solutions for fusion and laser welding of coated steels to avoid spanner, porosity, and voids 5

III. Fracture

Attendees had sufficient time to consider priorities, but had difficulty achieving clarity on priorities or how to establish them. Several came to the front to advocate favorite project ideas, but others did not join in consensus building around anyone else's ideas. It appeared that the session topic was so fertile for new research that the subject matter experts wanted “everything to happen at once”. However, the facilitator and author were able to discern key themes that fell in to certain logical priorities.

There was strong agreement around one priority-setting theme: Fundamental research, as described in the prior page, was essential and primary to being able to undertake more practical endeavors in addressing the technology gaps.

1. As a category, the four research needs on page 3 were given equal and top priority, with the view that significant progress in all four research areas must precede any other work.
2. The second priority, assuming completion of sufficient fundamental and preceding research, was to develop predictive models based on measureable material characteristics. The lack of correlation between traditional material characteristics and shear fracture behavior was viewed as a serious technology gap that needs to be overcome.
3. The third priority was to develop design tools that could be derived from the learnings in the first and second priority areas, so that users could use AHSS, including future Third Generation products, with confidence in models related to manufacturing performance, dynamic loading and straining and crash events, irrespective of the area of probable fracture initiation sites.
4. Finally, the group concluded, when viewing the flip charts near the end of the session that numerous specific projects could and should evolve from the needs that they had defined.

IV. Modulus

Top Grouping (Voted as a group of similar projects):	No. of Votes
1. Examine effect of deformation on modeled microstructures of AHSS and validate in mechanical experiments.	11
2. High accuracy modulus characterization at length scales from component level to microstructural level.	11
3. Create standard tests for elastic behavior.	11
4. Measure unloading/reloading constitutive behavior.	11
5. Develop standard test method for elastic behavior of steel from zero (strain) to failure.	11
6. 3D microstructure model using techniques similar to Sandia for different grades of steel	10
7. Do a multi-scale modeling project on DP and TRIP steels at least to the 1180 MPa level to explain the changes in elastic behavior.	10
8. A predictive multi-phase micromechanical model to connect texture and anisotropy to macroscopic stiffness/modulus; experimentally calibrated and validated.	10
9. Investigate process simulation to predict grain structure of steel. (Consider all processing. This can be a long-term project.)	10
10. Determine if the elasto-plastic behavior described by Wagoner can correlate with	7

mechanical elastic behavior of AHSS in, for example, predicting springback or part stiffness.

11. Further evaluation of Wagoner's model for stress strain and validate for more materials and validate for biaxial load.	7
12. Consistent method to measure stress-strain for uniaxial and biaxial loading (to check anisotropy). Compare steels from various sources and test in different labs.	4
13. Model the effect of thermomechanical processing to produce sheet product and its impact on phases and grain orientation.	2
14. Sensitivity analysis of elastic behavior to structural response (crash, stiffness, springback).	2
15. Examine models and constitutive relationships in AHSS with various amounts of retained austenite of different stabilities.	0
16. Constitutive models verified at micro-scales that accurately predict micromechanicals. (Model in micros-scale to verify macro-scale.)	0
17. "Commodity Experts" Scientist that will dedicate full attention to a system (multiphase steels, etc.) Don't move to the next material too fast.	0
18. Examine effect of dislocation locking (solute C) on non-linear elastic behavior through mechanical testing.	0
19. Next generation insitu characterization tools to measure micromechanical properties of multiphase steel at strain rates simulating stamping operations and crash events.	0
20. Understand the distribution of phases and grain orientations and their effects on formability and resultant properties / performance.	0

V. Hydrogen

Research Needs Discussion: Nearly all of the participants identified a research need into developing test methods to assess delayed fracture and HE in high strength steels, particularly in keeping the tests relevant to automotive applications. This might involve examining HE in welds, the effect of paint bake and other processing steps, and so forth. Also extensively discussed, as part of developing effective test methods, was a determination of how much hydrogen is a problem in steels and how to repeatably charge a lab test specimen with the required amount of hydrogen. Currently, hydrogen embrittlement samples are typically electrolytically charged with hydrogen to the point of exclusion, which likely results in concentrations tens or hundreds of times larger than those seen from atmospheric uptake. Also, as steels that can produce strengths in the range of 1 GPa to 2 GPa will potentially contain complex microstructures that will react to hydrogen in presently poorly understood ways, there was a strong consensus that more fundamental research aimed at understanding HE and DF in high strength steels is clearly indicated. Finally, if HE is to some extent unavoidable during steel and automotive manufacturing, what remediation techniques could be brought to bear to deal with the problem?

Summary Observations:

The group discussion reflected uncertainty about the occurrence and frequency of hydrogen-induced delayed fracture – as illustrated by failures in simulation tests but little documented fracture in on-the-road vehicles. However, the expectation that HE increases as the strength level of steels increases raises concern about the utility of Generation 3 steels (1000MPa to 2000 MPa yield strength) and hence there is a need to understand the scale of the HE 'problem' and associated mechanisms.

As a result of the above it was not surprising that most R&D recommendations centered around testing and test methods for HE.

Basic research was recommended to fully understand HE sensitivity to:

- Different microstructural features
- The presence (absorption) of hydrogen at different life stages; steel production/processing, auto parts manufacturing and assembly and in-vehicle use.

VI. Plasticity

The following list is a summary of comments submitted by members of the discussion group, which are assimilated in the above summary but retained here for completeness of the record.

- Scope needs to target a small group of steel grades that are going to be the workhorse steels in BIW applications, with a focus on AHSS. Then transfer to 3G steels as they emerge
- Fracture limit diagram development for AHSS (distinct from necking limit)
- Welding/joining and hole punching introduce additional damage not present in conventional forming. How to integrate into the model
- Need to address material variability to develop better models and calibrate them
- Development of standard test to generate forming limit diagram under linear and non linear strain path for AHSS
- We understand parameters that change material behavior under complex deformations, can steel grades be developed to leverage these parameters for improved performance
- Reliable and inexpensive methods for measuring local 3-D stress and strain
- We need a sensitivity study for the springback prediction errors based on known inaccuracy of current models. This will generate the interest needed to get funding
- Manage cost by assigning portions of the project to lead groups, AISI, Universities, and National Labs
- Create a reference set of benchmark tests for cross model comparison using a common data set; Examples may include selected Numisheet Benchmark Studies
- There are no established standards for material testing meta-data e.g. sample characteristics, test details, etc
- Benchmarking is needed to identify (and validate?) the gaps

- Require control correlation of models to experimental results before specifying the gaps and reliability of the existing models
- A unified model for the prediction of AHSS behavior under complex deformation – control parameters vs noise parameters
- How can we translate the stress/strain effects into crash behavior to accurately predict non-linear performance of parts
- Can there be new simple design guidelines to be used by part designers based on stress FLD with path
- Reliable, validated integration techniques for connecting first principles ab-initio results to microstructure or continuum models
- Microstructurally informed continuum level plasticity models for twinning in TWIP steels
- Simultaneous friction and material model improvement to reduce prediction error
- Polycrystalline modeling to support the continuum models with experimental data support
- Polycrystalline models to suggest alloy improvement as well as aid continuum models
- Development of microstructure transformation model could help the development and accuracy of plasticity models

Appendix IV - Attendees

Name		Affiliation
Robert	Amaro	**National Institute of Standards and Technology**
David	Anderson	**Steel Market Development Institute**
Dan	Baker	**Severstal North America**
Joe	Beckham	**Chrysler Group LLC**
Paul	Belanger	**General Motors Company**
Debanshu	Bhattacharya	**ArcelorMittal USA**
Brad	Boyce	**Sandia National Lab**
John	Bradley	**General Motors Company**
Marc	Carter	**Nucor Corporation**
Ed	Case	**AK Steel Corporation**
Bill	Charron	**Ford Motor Company**
Justin	Clark	**Toyota**
Rob	Comstock	**AK Steel Corporation**
Diane	Coopmans	**Chrysler Group LLC**
Jason	Coryell	**General Motors Company**
Rich	Cover	**Facilitator**
Adam	Creuziger	**National Institute of Standards and Technology**
Terry	Cullum	**Auto/Steel Partnership**

Name		Affiliation
Bart	DePompolo	**United States Steel Corporation**
Ajit	Desai	**Chrysler Group LLC**
Chang	Du	**Chrysler Group LLC**
Jim	Dykeman	**Honda**
Hesham	Ezzat	**General Motors Company**
Timo	Faath	**ThyssenKrupp Steel USA, LLC**
Dr. Fateh	Fazeli	**CANMET**
James	Fekete	**National Institute of Standards and Technology**
Zhili	Feng	**Oak Ridge National Lab**
John	Fillion	**Facilitator**
Tim	Foecke	**National Institute of Standards and Technology**
Umesh	Gandhi	**Toyota**
Luis	Garza	**AK Steel Corporation**
Jerry	Gould	**EWI**
Mark	Gugel	**General Motors Company**
Jody	Hall	**General Motors Company**
Josephine	Hlavna	**Toyota**
Curt	Horvath	**General Motors Company**
David	Hoydick	**United States Steel Corporation**
Mark	Iadicola	**National Institute of Standards and Technology**
Cindy	Jiang	**AET**
Will	Joost	**United States Department of Energy**
Don	Jordan	**Ford Motor Company**
Dean	Kanelos	**Nucor Corporation**
Menachem	Kimchi	**EWI**
Theresa	Klix	**Chrysler Group LLC**
Ron	Krupitzer	**Steel Market Development Institute**
Ed	Kustrzyk	**Cosma Eng.**
Steve	Logan	**Chrysler Group LLC**
Don	Malen	**University of Michigan**
Dave	Matlock	**Colorado School of Mines**
Paul	McKune	**ThyssenKrupp Steel USA, LLC**
Matt	Morgan	**Chrysler Group LLC**
Shawn	Morgans	**Ford Motor Company**
Peter	Mould	**Facilitator**
Carolyn	Philpott	**Steel Market Development Institute**
Bill	Pinch	**General Motors Company**
Joe	Polewarczyk	**General Motors Company**
Narayan	Pottore	**ArcelorMittal USA**

Name		Affiliation
Jon	Powers	**Severstal North America**
Jim	Quinn	**General Motors Company**
Ron	Radzilowksi	**Severstal North America**
Igor	Rimmer	**Chrysler Group LLC**
Chris	San Marchi	**Sandia National Lab**
Ken	Schmid	**General Motors Company**
Paul	Schurter	**ArcelorMittal USA**
Jody	Shaw	**United States Steel Corporation**
John	Siekirk	**Chrysler Group LLC**
J.P.	Singh	**General Motors Company**
Harry	Singh	**EDAG**
Andrew	Slifka	**National Institute of Standards and Technology**
Raj	Sohmshetty	**Ford Motor Company**
Tom	Stoughton	**General Motors Company**
Weiping	Sun	**Nucor Corporation**
Xin	Sun	**Pacific Northwest National Lab**
Elie	Tohme	**Chrysler Group LLC**
James	Truskin	**Chrysler Group LLC**
Murali	Tumuluru	**United States Steel Corporation**
David	Van Aken	**Missouri University Science & Technology**
Rob	Wagoner	**The Ohio State University**
Yu-Wei	Wang	**Severstal North America**
Bruce	Wilkinson	**ThyssenKrupp Steel USA, LLC**
Cedric	Xia	**Ford Motor Company**
Benda	Yan	**ArcelorMittal USA**
Matt	Zaluzec	**Ford Motor Company**
DJ	Zhou	**Chrysler Group LLC**