Roadmapping for Innovation in Sheet Metal Forming

Workshop Summary Report

May 4, 2015
Rebecca Crown Center, Hardin Hall, Northwestern University

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Sponsored by:

NIST AMTech, NADDRG, Northwestern NIST CHiMaD Center
Acknowledgments

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**Speakers and Panelists**

- Timothy Foecke, *NIST*
- Garth Boyd, *Deringer Ney*
- Edmund Chu, *ALCOA*
- Thomas Stoughton, *GM*

**Workshop Sponsors**

- Jean-Louis Staudenmann, *NIST*
- NIST AMTech Program
- CHiMaD (Center for Hierarchical Materials Design), Northwestern/NIST

**Key Partners**

- ALCOA / ArcelorMittal / College of Lake County / Deringer-Ney / EWI / Ford / OMI (Ohio Manufacturing Institute) / Oregon State University / NADDRG (North American Deep Drawing Research Group) / NCAL (NIST Center for Automotive Lightweighting) / Northern Illinois University / Texas A&M / University of New Hampshire
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EXECUTIVE SUMMARY

In conjunction with the Spring 2015 North American Deep Drawing Research Group (NADDRG) meeting, a workshop entitled, Roadmapping for Innovation in Sheet Metal Forming Workshop was held at Northwestern University in Evanston, IL. This workshop was convened to launch a roadmapping process that could guide and stimulate actions to enhance the global competitiveness of the US sheet metal industry. This workshop is part of a broader initiative sponsored by the U.S. National Institute of Standards and Technology (NIST) AMTech program to develop national technology roadmaps in a wide range of industries.

A select group of over 70 key academic and leaders from a cross-section of the industry identified critical gaps, key challenges and linked technology advancements and innovations that could transform sheet metal forming. Seven thrusts were identified that would propel the industry to the next level of excellence in the 21st century.

1. Prediction of flow stress reflecting anisotropy (25%)
2. Consistent modeling for a material (19%)
3. Springback prediction (15%)
4. Control of manufacturing factors (12%)
5. Fast forming technology development (12%)
6. In-line sensing & interpretation (9%)
7. Information conduit connecting supply chain (8%)

The envisaged Sheet Metal Forming (SMF) consortium will require a governance structure including a means to add new thrusts, clarify existing thrusts, and delete thrusts once work is completed or new technology or circumstances renders them irrelevant.

Participants agreed that governmental funding and support would be essential at the initial organization and formation incubation stage (i.e., near term) including promotion of emerging technologies and education of for new and incumbent workforce as well as addressing the systemic issue of STEM literacy to create the workforce of tomorrow. Initial achievements combined with comprehensive project sequels to implement and exploit early successes will provide the business case to encourage industry support.

Long term benefits to consortium participants and level of participation can be tailored to attract and retain key elements from all levels of the supply chain. The SMF consortium has the benefit of reviewing and adopting the best elements of the membership structure and governance of National Network for Manufacturing Innovation (NNMI) among other potential models.

The planned next step is the formation of task forces, one for each of the three challenges (modeling & prediction; standardization, data sharing & education; and novel manufacturing processes.) Though focused on technical needs, the three challenge task forces will also be charged with considering related non-technical barriers such as training. The task forces will produce a roadmap for each challenge with a rough order of magnitude budget for near-term needs. A fourth task force will compile a working draft consortium design and governance structure. The roadmaps and draft governance structure will be sent to potential charter consortium members with the goal of validation and consolidation into a comprehensive cross-cutting roadmap. This will be further enabled by a follow-on workshop to ratify the key activities and confirm and balance the estimated resources identified by the task forces. Next stage supplemental funding may be requested from NIST, or another Federal agency, as appropriate.
INTRODUCTION

Overview

Widely used in many products, sheet metal forming is responsible for more than 7% of U.S. GDP. It plays an essential role in enabling global market competitiveness and manufacturing by how it impacts cost, development cycle and energy use; and has been identified as one of the eleven critical technology areas in the 2012 President’s Council of Advisors on Science and Technology (PCAST) report to the President. Sheet metal forming faces rapidly emerging new technologies impacting diverse mix of materials including advanced high strength steel (hot forming), titanium alloys, lubrication, coatings, forming equipment (servo presses), automation, sensors, data analytics, numerical simulations, and related skills training - in both mass produced products by large OEMs and in small-medium enterprises (SMEs) where smaller lot size flexibility and agility is key.

Attaining a tightly aligned value chain with focused and transformative innovation is hampered by a diverse and complex spectrum among industry sector knowledge “silos”, by process and, particularly application e.g., food and beverages; medical and electronic products; aircraft; automobiles; and more. The goal of this workshop was to launch a roadmapping process to support pre-competitive collaboration and guide technology planning and investments toward common challenges, such as global competition, emerging manufacturing alternatives to forming, alternate technology paths, and transition from legacy systems, emerging new markets with new dimensional and materials requirements. Some notable examples include emerging energy storage, distributed energy light weighting in sea air and ground transportation, etc. This workshop is an important element to develop more comprehensive national sheet metal forming technology roadmap is sponsored with support by the U.S. National Institute of Standards and Technology (NIST) AMTech program.

Northwestern engaged firms across the supply chain and associations in diverse industries, along with relevant faculty in order to develop an integrated technology roadmapping effort. This activity will focus on cross-cutting, multi-disciplinary challenges and stimulate a systems approach with linkages between company and university researchers. The roadmapping effort will monitor emerging technologies, market end environmental changes and related training needs. A strong team has been assembled that can launch, support and bring the consortium into sustainability. The team combines academic and practice experts with deep knowledge and demonstrated competence in both forming (Cao) and roadmapping (Strauss), complimented by seasoned industry experts in diverse technical specialties. The project team collaborates with leading professional/industry organizations like the NIST Center for Automotive Lightweighting (NCAL), the North American Deep Drawing Research Group (NADDRG), Ohio Manufacturing Institute (OMI), Chicago Metro Metal Consortium (CMMC), Edison Welding Institute (EWI), and two newly established manufacturing institutes, the Digital Lab (DMDII) based in Chicago and the Lightweight Metal (ALMMII) based in Detroit as well as leading academic forming groups at the University of New Hampshire (UNH), Texas A&M, and Oregon State University. Knowledgeable supply chain leaders include material suppliers such as ALCOA and Arcelor-Mittal, small-medium manufacturer such as Deringer-Ney (DNI specialized in precision metal components), a large OEM manufacturer Ford, and as the College of Lake County (CLC) with its connection to other community colleges for their key role in addressing workforce training. As seen in Appendix 3,
the composition of participants was well balanced between academia (45%), industry (47%), and government (8%); students were excluded from this ratio. Therefore, this report reflects opinions from a wide range of stakeholders.

Over 90% of the workshop evaluation responses rated the program as helpful with an average score of 5.6 out of a maximum of 7, with. Nearly one third (32%) of the free responses identified government funding is appropriate to support university-industry collaboration, solve important issues, and educate next-generation engineers.

**Workshop Scope and Process**

The NIST Roadmapping for Innovation in Sheet Metal Forming workshop, brought together a select group of key academic and industry leaders, representing a cross-section of the industry, to discuss and identify critical gaps, challenges, technology advancements, and innovations that could transform sheet metal forming. The program launched a roadmapping process to guide and stimulate action to enhance the industry and U.S. competitiveness; the graphical scheme is provided in Figure 1.

Broken into five groups as indicated in Figure 2, workshop participants addressed three broad domains across the supply chain: materials, equipment, and control, plus modeling and simulation tools. Each group was assigned recorders with laptops to take notes on discussion and complete templates. Moderators were selected to keep the group on task during each of three sessions and assure all group members had an opportunity to contribute. Each participant received copies of the template for each session for personal note taking. Flip charts provided a visual means to help accurately capture input for each part of the template as well as colored stickers to signal time horizon. After each session, the participants selected a different group member to present a short summary of their group conclusions in the plenary session to capture other perspectives including competing priorities from the broader audience. The following reflects the guidance given, but, reflecting the variance in group make up, each group approached their assignments differently and made varying degrees of progress. Nonetheless, taken together, significant and useful input was obtained and evaluations confirmed interest in further collaboration by the majority of participants.

![Figure 1. Graphical scheme of workshop process.](image-url)
SESSION 1 (90 min) - Challenges, Opportunities, Options, and Requirements

1. First, the participants were guided to brainstorm key drivers, defined as customer needs that was pushing and guiding technology/development path selection. As a discussion starter, the following statement had been suggested as one driver; “The sheet metal industry is under growing pressure to improve application utility, reduce waste, lead time and cost, enable energy efficiency and address changing market needs.”

2. Afterwards, the participants went deeper in brainstorming challenges/constraints. For example:
   a. Knowledge of sheet metal and alloy behavior resides in diverse, industry-specific silos (aerospace, beverage industry, automotive, appliance). Cross-industry/cross-disciplinary exchange and applied research cooperation is needed.
   b. Forming entails high capital cost. Corporations must make hard-to-reverse choices of technology direction, market position and investment with significant uncertainty over future developments.

3. The participants were then requested to narrow down to the top five issues and list them on the provided flipchart sheet section.

4. The issues were prioritized by the participants. Each group member indicated their rank order on the flipchart.

5. Similarly, they were guided to brainstorm opportunities. For example:
   a. flexibility in low-volume production can be increased by eliminating time and expense of solid tooling, (3D models of parts could be downloaded; freeform rolling mill software utility can convert solid model to 3D freeform model), increasing the economic lot size for tool-less forming, decreasing the minimum feature size for micro-fluidic applications, or optimizing supply chains with distributed manufacturing platforms.
   b. Emerging technologies can improve mass production efficiency
      i. New sensors enable active feedback rolling mill control for new designs or retro-fit: next generation performance mills
ii. Enhanced economical computing
iii. Multi-scale simulation modeling
iv. Improved understanding of materials
v. Improved understanding of processes
vi. Advanced tribology technology lessens interface friction and wear
c. Participants were urged to identify non-technical as well as technical challenges and opportunities

6. The opportunity issues were narrowed down to the top five and listed on the provided flipchart sheet section, and then prioritized in the similar manner.
7. Afterwards, the participants brainstormed options (including alternative technology development paths) for addressing challenges and leveraging opportunities. They considered associated requirements, including workforce and other resources, and noted gaps in their availability as well as technical or other barriers or bottlenecks.
8. For all of the above, the organizers and moderators guided the following:
   a. Specify when (near term, mid-term, long term) you expect to see these becoming relevant (or changing). Use colored stickers to signal timing. Start with the estimate of near term being 1-2 years, mid: 3-4, and long term more than 4, but consider in discussion of uncertainties and the nature of industry products, whether these should be revised.
   b. Identify (and list) any important variations for different industry segments, supply chain positions, or applications
   c. Identify (and list) trends, assumptions, potential external changes and uncertainties that could significantly alter planning (including the above). Changes could include technology developments (by others including from other industries), regulations, competitor activity, market demands, etc.

SESSION 2 (90 min) – Targets and Tasks

1. The participants brainstormed technical (and a few non-technical) targets and listed them.
2. The targets were prioritized by narrowing down to the top five. Each group member was requested to indicate on the flipchart sheet their rank order. It was recommended to consider risks and potential payoffs to aid in prioritizing.
3. The participants were then guided to define tasks required to reach targets. They associated the tasks with the targets and indicated sequence. How tasks may require other tasks (interdependencies) was discussed as well.
4. For each task, the organizers and moderators guided the followings:
   a. Specify when (near term, mid-term, long term) the target will be viable and when the task must be undertaken/completed. Start with the estimate of near term being 1-2 years, mid: 3-4, and long term more than 4, but consider in discussion of uncertainties and the nature of industry products, whether these should be revised.
   b. Identify (and list) any important variations in impact and implications (including who must do what) for different industry segments, supply chain positions, or applications
c. Identify (and list) relevant trends, assumptions (assess implications if wrong), potential external changes and uncertainties, that could significantly alter targeting or tasks (including sequence). Changes could include technology developments (by others including from other industries), regulations, competitor activity, market demands, etc.

SESSION 3 (60 min) – Resources, Complementary Activity, Recommendations, and Consortium Design

1. For tasks defined in Session 2, the participants brainstormed and detailed supports needed.
2. They were guided to identify examples of relevant existing initiatives (including roadmapping) by government, associations, industry groups, schools, etc., and critical gaps.
3. The design of services and structure for a consortium were envisaged to, for example, reach across industry segments and engage the diverse stakeholders, stimulate collaboration with universities to support cross-cutting research, monitor relevant domestic and international activity, provide education and training, and continue roadmapping. The participants brainstormed how this consortium would be run and sustained, how all stakeholders including government, associations and related existing consortia could be engaged, and what services should be offered.
4. The participants were requested to take part in the following actions:
   a. Discuss the impact of trends and uncertainties identified in earlier sessions
   b. Specify (with colored stickers) when (near term, mid-term, long term) they see varying types of support to be needed and phases of the consortium needing to be implemented. Start with the estimate of near term being 1-2 years, mid: 3-4, and long term more than 4, but consider in discussion of uncertainties whether these should be revised.
   c. Related to the discussions above but thinking broader, what would the participants recommend for government agency/legislative support and policy?
ISSUES AND PRIORITIES
During Session 1: Challenges, Opportunities, Options, and Requirements, the five groups identified key drivers and issues related to sheet forming industry. As expected, some issues were repeatedly mentioned by different groups. To prioritize all issues suggested in the workshop, points were assigned to each item; 5 to 1 points were allocated to the item depending on their priority determined by each group, which were then sorted from highest to lowest priority.

![Top Seven SMF Challenges](image)

*Figure 1: Top Sheet Metal Forming Thrusts*

<table>
<thead>
<tr>
<th>Points of Importance</th>
<th>Prioritized Issues in the Workshop</th>
<th>Suggesting group(s)</th>
<th>Weighted Point Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Prediction of flow stress reflecting anisotropy</td>
<td>1, 3, 5</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>Accurate and consistent modeling for a material</td>
<td>3, 4, 5</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>Control of manufacturing factors</td>
<td>1, 4</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>Prediction and reduction of nonlinear springback</td>
<td>1, 3, 5</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>In-line sensing</td>
<td>1, 5</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>Information sharing between suppliers, manufacturers, researchers, and simulators</td>
<td>2, 3</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>New, fast, and innovative manufacturing/ forming technology</td>
<td>1, 2, 3</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Lightweighting</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Understanding of wear mechanism and wear fatigue life</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Profitability and technological leverage</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
If the data are weighted by the number of groups testifying to a subject, the range of scores increases four fold with the last five topics less than half as important as the first seven. These top needs are elaborated in the paragraphs below. The topics specified by only one group are considered as minor issues; they were placed in Appendix 4 to keep the main thoughts in focus.

**Property Prediction Reflecting Anisotropy (25%)**
A number of participants emphasized the importance of accurate, reliable, and cost-effective prediction of mechanical properties that include flow stress, fracture, and failure mode. The consensus is that this topic should be considered as a mid- to long-term issue. Simulation & Design Tools (Group 5) further suggested a failure prediction and micromechanical modeling on the basis of integrated computational materials engineering. The participants also agreed with the necessity of developing accurate material modeling as both factors (i.e., material modeling and prediction) were directly linked to each other. These top needs are elaborated later in this report.

**Development of Accurate and Consistent Material Model (19%)**
Participants pointed out certain material parameters were treated as less important, or often ignored, in current material models. For example, Global Materials (Group 3) proposed that residual stress should be considered more deeply in innovative material modeling, although the measurement and analysis of residual stress may be difficult and hence require very long-term research. Equipment, Control & Lubrication (Group 4) emphasized that friction model shall consider the presence/property of lubricant and material/die roughness. Simulation & Design Tools (Group 5) suggested the coupling of material effect such as anisotropy and phase transformation as a mid-term issue. It is generally accepted in materials science and engineering that these factors indeed have a great influence on mechanical behavior. For example, some anisotropic materials, such as titanium and magnesium alloys, exhibit a totally different tensile behavior depending on the deformation direction. A yield stress of a material can be significantly modified by simply reducing a grain size or precipitating second phase particles. More active collaborations between mechanical engineering and materials science was suggested to solve this issue.

**Control of Manufacturing Factors (12%)**
Ferrous Materials (Group 1) set the control of friction and wear properties as the important long-term issue to be resolved. Equipment, Control & Lubrication (Group 4) suggested the similar opinion, although it mainly paid attention to wear and fatigue life. The cross-discussion among the groups also suggested tool material properties, edge defects, and coating as other important manufacturing factors to be controlled. Participants also commented that we should consider machine accuracy, stiffness, die alignment, chatter, etc. to precisely control the manufacturing factors.
Prediction and Reduction of Nonlinear Springback (15%)
Ferrous Materials (Group 1), Global Materials (Group 3), and Simulation & Design Tools (Group 5) agreed on the importance of the springback issue, although their opinions varied on timing - both materials groups suggested this should be mid-term, while Simulation & Design Tools (Group 5) viewed the issue to be near-term. Springback is defined as the tendency of deformed sheet metal parts to change its shape upon unloading, which is an important issue due to its potential problem in assembly and manufacturing processes. In spite of its importance, however, the springback phenomenon has been controlled by a trial and error procedure, rather than an accurate and reliable prediction for two reasons. First, a lot of processing parameters and interactions among them affect the elastic recovery phenomenon (i.e., the origin of springback), including tool shape, forming temperature, material properties, frictional condition, etc. As a result, the springback phenomenon is strongly case-dependent, which makes it difficult to provide a generalized prediction model. Second, the nonlinearity and process complexities decrease the accuracy of prediction. Large corporations have developed their know-how in dealing with springback prediction and compensation in die geometry, however, such knowledge needs a systematic integration such that it can be easily transformed when new materials are used and can be adopted by suppliers.

Connections and Information Sharing between Suppliers, Manufacturers, Researchers, and Modelers (12%)
Non-Ferrous Materials (Group 2) and Global Materials (Group 3) suggested the establishment of system/platform to connect suppliers, manufacturers, researchers, and simulators. Both groups were highly interested in this topic. This system/platform will bring up the technical base of industry, make communication easier, and thus help all members mentioned above. According to the discussion, the system/platform shall link and transfer knowledge between corporations, universities, workforces, apprenticeship, and trainees. When discussing education to graduates, some participants mentioned the adoption of European model: EU companies are more willing to train apprentices, and thus post-graduate training may require less cost. It was also proposed to make material information into a database style format, which would allow easier sharing of information among the members. Some participants in both groups did not fully accept this idea. One of them indicated that few people would provide their intellectual property for free and others raised the challenges of evaluating the quality of those data.

In-Line Sensing: Interpretation of Interactions between Die and Workpiece (9%)
Ferrous Materials (Group 1) and Simulation & Design Tools (Group 5) proposed the in-line sensing issue as a key driver. It is essential to measure physical quantities of a machine and workpiece in any sheet metal forming process to improve the processing quality and decrease cost and time. For example, many researchers have investigated the in-line sensing of punch force because the parameter is directly related to failure of stamped metal sheet. However, most force-displacement measurements are often just global measurement or independent of local forming temperature, which needs to be improved.
# CHALLENGES & CLASSIFICATION

During *Session 2: Targets and Tasks* and *Session 3: Resources, Complementary Activity, Recommendations, and Consortium Design*, the participants continued discussion of issues identified in the first session but also raised new issues refining concerns into categories and prioritization. The groups exchanged views and cross-discussed at the end of this session, sharing common consensus. As several issues were discussed simultaneously in certain integrated categories, this report summarizes them in three categories, or challenges: (1) *Modeling & Prediction*, (2) *Standardization, Data Sharing & Education*, and (3) *Novel Manufacturing Processes*. The issues are classified into these keywords on the basis of relevance shown in the workshop.

## MODELING & PREDICTION CHALLENGES

Material modeling and short-run/cost-effective prediction have attracted the most attentions in the workshop. There are significantly wide variations in target impact and task roles here, thus the participants focused on general and macroscopic direction (i.e., roadmap) rather than the specifics. The general consensus was that the development of accurate material modeling would be indispensable to establish the innovative prediction method. Table 2 summarizes the targets and tasks suggested by the five groups in near-, mid-, and long-terms.

### Table 2: Thrusts for Modeling & Prediction Challenge

<table>
<thead>
<tr>
<th>Thrusts</th>
<th>Near Term (1-2 yrs.)</th>
<th>Mid Term (3-4 yrs.)</th>
<th>Long Term (&gt; 4 yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material characterization &amp; modeling</td>
<td>Identify required data and material tests</td>
<td>Identify level of complexity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield surface evolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advanced material characterization</td>
<td>Create the microstructural model including phase transformation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Data mining/analysis for material model</td>
</tr>
<tr>
<td>Short-run &amp; cost-effective prediction</td>
<td>Identify and develop promising prediction models</td>
<td>Implement standardized material models</td>
<td>Validation</td>
</tr>
</tbody>
</table>

### Advanced Material Characterization & Modeling Thrust

An advanced material model is required to capture material behavior in different conditions. Participants pointed out that such a model should integrate materials science and mechanical engineering. One suggested example is information about phase transformation. The type and fraction of phase have a critical influence on mechanical properties. For instance, the total
 elongation can double by introducing a small fraction of martensite in a titanium alloy. Furthermore, several materials adopted by the industry change their microstructure during a forming process, such as transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) steels. TRIP steel contains retained austenite, which is transformed into hard martensite under plastic transformation. Similarly, TWIP steels experience the onset of twinning during straining that leads to considerable work hardening and mechanical performance. Large deviations are found between experiments and simulations using a standard model in these alloys, thus many researchers and suppliers have paid attention to new material modeling nowadays. All groups agreed that this would be a long-term project.

The industrial members also considered the speed of material characterization as an important factor for different companies and applications. They emphasized the importance of a simple test to address material variability in contrast to the present methods with long (e.g., 6 month) testing phase. One of the participants even remarked that calculation time is sometimes the biggest factor in the industry.

**Short-Run & Cost Effective Prediction Thrust**

The problem discussed in the material modeling is also applicable in establishing a prediction model. Simulation is deviated from actual results when putting the basic parameters. Some industrial members highlighted the need for accommodating friction, lubricant distribution, die wear, and springback as these factors are not well considered in the present predicting models in spite of their importances. Participants expected that state-of-the-art computing would enhance simulation power at multiple manufacturing scales.

Not surprisingly, their interest in mechanical properties was highly dependent on the industry (e.g., formability in the automotive industry and fatigue in the aerospace industry). Effective measurement of residual stress is also an important factor, but it may not be the factor that OEMs are most concerned with; attendees suggested to start studies at the academic level for this topic.

**STANDARDIZATION, DATA SHARING & EDUCATION CHALLENGES**

Both academic and industrial members showed a strong interest in these topics. The qualified data should be obtained from different researchers, manufacturers, and suppliers by standardized testing procedures. They will be gathered and accumulated in a searchable gigantic database. Members of the consortium will learn how to access the database and utilize the data. Table 3 summarizes the targets and tasks suggested by the five groups in near-, mid-, and long-terms.

**Table 3: Thrusts for Standardization, Data Sharing and Education Challenge**

<table>
<thead>
<tr>
<th>Thrust</th>
<th>Near Term (1-2 yrs.)</th>
<th>Mid Term (3-4 yrs.)</th>
<th>Long Term (&gt; 4 yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardization of searchable database</td>
<td>Make a platform</td>
<td>Standardize testing procedures</td>
<td>Generate and accumulate data in database</td>
</tr>
</tbody>
</table>
**Standardization Thrust**

It is not surprising at this stage that one obtains different results for the same material and process in different laboratories. The participants indicated the need for standardization of tensile, forming limit diagram (FLD), and digital image correlation (DIC) tests in the field of sheet metal forming. They stressed that this work would be essential for proceeding to other tasks discussed above, such as advanced material modeling and innovative prediction method. The suppliers in the consortium will be requested to use the standardized procedures to ensure consistent product quality.

**Data Sharing Thrust**

The authority to access the database gave rise to much controversy. Some participants insisted the database should be open access to prevent companies from keeping secrets of the best standards in order to gain market access. On the other hand, others anticipated that suppliers may not be willing to share their data for free. They instead suggested establishing a tier membership in the consortium with different accessibility to the database. The conventional membership system, requiring several thousand dollars to be a member, was expected to limit motivation of the industry to participate in the consortium.

It is also important to decide which organizations take the lead in establishing the database and who has physical management/authority over the database. There were no concrete answers in this workshop. Nevertheless, people agreed with the necessity of a committee listening to the needs of industry and community. Some participants also suggested an organizing institute must work with NIST and their renowned facilities in metrology.

It was also proposed to utilize data mining, or knowledge discovery in databases (KDD), after establishing the database. Data mining is a collection of techniques based on advanced analytical models to find novel patterns in a large amount of data. Mining the usable data set will offer great opportunities for academia and venture businesses. However, people posed two questions about this idea. First, they raised the problem of data quality; it may be very difficult to determine which data are trustworthy for the analysis. One participant asked how to deal with the variation of data depending on each institute and company. This is related to the standardization issue. Second, they
pointed out the lack of educations and skill sets for this work. This is connected with how to ensure the workforce understands these techniques, i.e., education discussed below.

**Workforce Education Thrust**
One group asserted that North America or USA does not have sufficient man-power to get traction and initiate standards/fundraising. Another question was how to disseminate existing/new information to wider audiences and how to encourage interest in this information. These discussions raise the necessity of education for the application of database as well as new technologies. The education will help workforce to understand new materials, equipment, and technologies and to overcome the challenges in their supply chain and company. Massive open online course (MOOC) was suggested as a potential platform. To achieve this objective, there should be profit involved to increase motivation of workforce, as people may see no reason to participate in the education. In addition, one group threw a doubt if companies would willingly make the investment in training and apprenticeships despite potentially low retention rates. Which tasks to focus on first is not an easy decision since many factors are related to each other. Finally, a critical need is to provide enough training and education for undergraduate and graduate ME students to understand detailed material characterization.

**Strategic Tasks**
Participants also discussed two additional strategic tasks. The first one is to expand the standardized testing procedures to the world. A participant pointed out that the ASTM standard would not be applied outside US. He mentioned each country/region was developing their own localized standard, such as JSTP in Japan and SEP1240 in Europe. Another eventual strategic task is to standardize not only the testing methods but also equipment and machine. Although these issues have lower priority in comparison to the others in the above charts, they may be worthwhile to be considered later.

**NOVEL MANUFACTURING PROCESSES CHALLENGES**
Many groups mentioned the development of novel manufacturing processes, which can be classified into two groups: sensing and forming. Table 4 summarizes the targets and tasks suggested by the five groups in near-, mid-, and long-terms.

<table>
<thead>
<tr>
<th>Thrust</th>
<th>Near Term (1-2 yrs.)</th>
<th>Mid Term (3-4 yrs.)</th>
<th>Long Term (&gt; 4 yrs.)</th>
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<tbody>
<tr>
<td>Improved equipment/model-based sensing</td>
<td>Develop improved sensors</td>
<td>Establish a model for improved sensors</td>
<td>Real-time/in-situ material characterization</td>
</tr>
</tbody>
</table>
Improved Equipment/Model-Based Sensing Thrust
This issue consists of three phases: development of sensor, establishment of model, and real-time/in-situ material characterization. Such a sensor is expected to be installed inside the die or press. One good example regarding this issue is a draw-in sensor in a sheet metal stamping process. The draw-in is defined as the movement of workpiece between the binder and die, which should be precisely controlled for successful stamping process. Insufficient draw-in induces splits and thinning, while the excessive results in wrinkles and surface defects. The in-line draw-in sensors have been developed to continuously and reliably measure the amount of draw-in without interference by other factors during the stamping. Meanwhile, one participant proposed the measurement of residual stress using flash DIC and XRD. Another participant expected that the improved hardware performance would keep pace with sensing accuracy and speed. The improved sensing can give rise to intelligent equipment possessing better interaction between computer and hardware as well as real-time and closed-loop control based on strain distribution.

Advanced Thermo-Mechanical Forming Processes Thrust
In this workshop, participants suggested challenges as an example of advanced thermo-mechanical forming processes. The challenges are listed below with background information about each forming process.

Electromagnetic Forming (EMF)
EMF, also known as magnetic pulse forming, is a high-energy-rate metal forming technique using a high-velocity electronic pulse to form a workpiece without heat effects and mechanical contacts. This process is applied to three methods, which are compression, expansion, and contour forming. EMF enables formation of a complex shape of sheet metal against a die. This process is also used to improve surface quality of sheet metals. The high forming rates achieved by EMF process (i.e., the order of 250 m/s) make the sheet stretched without fracturing even at room temperature in contrast to conventional sheet forming processes. In addition, the process is also reported to reduce springback and wrinkling.

Incremental Forming
Incremental forming is a novel forming process that applies step-by-step incremental feed to deform a sheet metal. Conventional sheet forming methods need dedicated tools with expensive and complex design. The incremental forming does not require dedicated tools but uses a simple deforming tool, which gives rise to the improved cost effect and productivity. A number of
incremental forming processes have been developed, such as single-point incremental forming (SPIF), double-sided incremental forming (DSIF), and hybrid incremental sheet forming (HISF).

**Ultrasonic Forming**
The superposition of ultrasonic waves is utilized to enhance the workpiece surface in various material forming processes. In case of sheet metal forming, ultrasonic forming technique can be adopted by pressing, deep drawing, and bending industries. The unique characteristics of ultrasonic forming is that the process effectively reduces the frictional forces between the die and workpiece. This gives rise to the suppression of harmful buckling, wrinkling, and cracking phenomena.

**Flexible Tooling**
Tooling exerts a critical influence upon a product quality in many metal forming processes. Computer support in designing and developing steps allows a high flexibility in metal forming tools. In particular, a prototyping process accompanies frequent changes of tool design and does not require extreme accuracy or long lifetime of tools. In such cases, flexible tooling can substitute for conventional hard tooling to save cost and time.

**Cryo-Rolling**
Recently, researchers have focused on sheet rolling at cryogenic temperature. By this method, a deformed metal easily gains nanostructure or ultrafine-grained structure in which a mean grain size is reduced to nanoscale. Such a microstructural evolution resulted in significant grain-boundary strengthening as well as improved high-temperature formability due to superplasticity. Moreover, cryo-rolling basically uses a conventional rolling machine, which makes this process to produce bulk metals applicable in the large-scale industry. This is a big advantage in contrast to severe plastic deformation processes generally used to fabricate laboratory-scale nanostructured/ultrafine-grained metals. There are still challenges in application of this new technique for not only academia but also industry.

**Hot Stamping**
This technology was introduced during the cross-discussion as a new requirement to form advanced high-strength steels (AHSS) for automotive light-weighting. However, this same technology is also applicable to shape memory alloys and high-strength titanium alloys. Compared to conventional cold stamping, this process provides homogeneous distribution of strength and hence reduces the springback. High-temperature environments also allow decrease in forming load and investment for presses/tools. Moreover, more complex geometries can be made by hot stamping which utilizes tailored blanks. The necessity of optimizing materials for this process was also mentioned as well as understanding phase transformations, as hot stamping requires more material information (e.g., critical cooling rate) due to complex thermo-mechanical conditions.
FUTURE VISION
The majority of participants agreed that governmental funding and support would be essential at the initial organization and formation incubation stage (i.e., near term). The need for government support for pre-competitive standardization and database was also signaled by many participants.

Early achievements and planned sequels as implementation proceeds provide the business case to encourage industry support in the near- to mid-term for projects that show promise for a return on investment for shareholders. For example, an OEM needing an open source validated model developed near-term would encourage a material supplier to provide data for the model anticipating future business.

The promotion and education related to newly developed technologies is another important issue. This needs to be addressed for incumbent workforce as well as considering the systemic issue of making STEM literacy fun and exciting to create the workforce of tomorrow.

It is necessary for the envisaged Sheet Metal Forming (SMF) consortium to target each of the identified seven thrusts in the three challenges. However, the governance structure will also require a means to add new thrusts, clarify existing thrusts, and delete thrusts once work is completed or new technology or circumstances renders them irrelevant.

Benefits to consortium participants and level of participation can be tailored to attract and retain key elements from all levels of the supply chain from materials suppliers (sheet metals as well as lubricants), equipment producers, enterprise resource integration, digital manufacturing simulation and quality control, Tier I systems manufacturers and their lower tier component suppliers, and OEM systems integrators. One such benefit may be exclusive access to intellectual property.

The SMF consortium has the benefit of reviewing and adopting the best elements of the membership structure and governance of long standing consortium like North American Deep Drawing Research Group (NADDRG), National Center for Manufacturing Sciences (NCMS), American Welding Society (AWS), Metallic Materials Properties Development and Standardization (MMPDS), and the newly formed America Makes (AM), Digital manufacturing and Design Innovation Institute (DMDII), Lightweight Innovations for Tomorrow (LIFT).

The next step will be the formation of task forces, one for each of the three challenges (modeling & prediction, standardization, data sharing & education, and novel manufacturing processes.) Though focused on technical needs, the three challenge task forces will also be charged with considering related non-technical barriers like training. The task forces will produce a roadmap for each challenge with a rough order of magnitude budget for near-term needs. A fourth task force will compile a working draft consortium design and governance structure. The roadmaps and draft governance structure will be sent to potential charter consortium members with the goal of validation and consolidation into a cross-cutting roadmap. This will be further enabled by a follow-on workshop to ratify the key activities and confirm and balance the estimated resources identified by the task forces. Next stage supplemental funding may be requested from NIST, or another Federal agency, as appropriate.
## Appendix 1 - Workshop Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>7:30 – 8:30 AM</td>
<td>Breakfast &amp; Self-Introductions</td>
</tr>
</tbody>
</table>
| 8:30 – 8:45 AM  | Welcome & Project Vision  
  Schedule, Approach, Objectives & Deliverables  
  Jian Cao       |
| 8:45 – 9:00 AM  | Roadmapping Description & Breakout Charge  
  Jeffrey Strauss |
| 9:00 – 9:45 AM  | Panel: Overall Perspectives  
  Timothy Foecke (NIST)  
  Garth Boyd (Deringer Ney)  
  Edmund Chu (Alcoa)  
  Thomas Stoughton (GM) |
| 9:45 – 11:15 AM | Breakout Session #1  
  Issues & Opportunities, Associated Challenges, Key Uncertainties |
| 11:15 AM – 12:15 PM | Breakout Session #1 Recap & Discussion  
  Summarize, Present & Cross-Discussion |
| 12:15 – 1:15 PM | Lunch                                                                |
| 1:15 – 2:45 PM  | Breakout Session #2  
  Targets & Tasks                                                   |
| 2:45 – 3:45 PM  | Breakout Session #2 Recap & Discussion  
  Summarize, Present & Cross-Discussion                             |
| 3:45 – 4:45 PM  | Breakout Session #3  
  Support Needs & Consortium Design                                 |
| 4:45 – 5:45 PM  | Breakout Session #3 Recap & Discussion                              |
| 5:45 – 6:15 PM  | Workshop Summary & Action Items  
  Jian Cao                                                         |
| 6:15 – 7:00 PM  | Evening Break, Off-Site                                              |
| 7:00 – 9:00 PM  | Dinner  
  Remarks:  
  Jean-Louis Staudenmann (NIST)  
  Hyunok Kim (EWI Forging & Forming)  
  Final Remarks from Participants |
Appendix 2 - Pre-Workshop Survey

**Forming Industry Group Consortia Survey**
( hosted by EWI, SME, PMA and Northwestern University )
52 Responses from October 2014 - April 2015

**Q1. Identification Details**

**Q2. Which of the following best describes your company’s top three business priorities? (Select Three)**

- Cutting expenses: 18%
- Improving customer loyalty: 20%
- Expanding to emerging markets: 22%
- Building a strong culture: 27%
- Recruiting and retaining talent: 33%
- Gaining market share: 39%
- Delivering new products or services: 59%
- Improving innovation: 61%

**Q3. What are the top three areas of business impact in your organization that are most affected by technical issues? (Select Three)**

- Lack of real-time sensing data (i.e., temperatures, tonnage and scraps): 26%
- Insufficient expertise in tool and die design: 30%
- Die wear and associated preventive & corrective maintenances: 30%
- Inconsistent material quality: 34%
- Lack or minimum use of prediction capability: 34%
- Downtime of the production due to the aged equipment or many trouble shooting issues: 34%
- Insufficient expertise in forming process design: 43%
- Insufficient information of the material formability: 55%

**Q4. What are the top three areas that are major challenges in developing new products in your organization? (Select Three)**

- Insufficient capability of suppliers: 37%
- Cost associated with low-volume prototyping: 41%
- Insufficient subject-matter expertise: 46%
- Insufficient information of the state-of-the-art sheet forming technologies: 48%
- Increased requirements of the product quality: 52%
- New emerging or less experienced materials: 57%
Q4. What are the top three areas that are major challenges in developing new products in your organization? (Select Three)

- New emerging or less experienced materials
- Increased requirements of the product quality
- Insufficient information of the state-of-the-art sheet-forming technologies
- Insufficient subject-matter expertise
- Cost associated with low-volume prototyping
- Insufficient capability of suppliers

Q5. What are the top three areas of business impact in your organization that are most affected by a "skills gap"? (Select Three)

- Inability to comply with external quality standard regulations: 31%
- Inability to keep good workers from moving to competitors: 40%
- Inability to maintain good quality on current product line: 57%
- Inability to compete with current business product line: 62%
- Inability to grow the business: 64%

Q6. What are the top three technical skills that are hardest to find within the skilled workforce? (Select Three)

- Heat Treatment: 7%
- Material removal: 12%
- Joining: 26%
- Electrical/Electronics: 31%
- Welding: 36%
- Fabrication: 40%
- Simulation skills: 50%
- Hot/Cold Forming: 55%

Q7. Please select three manufacturing job roles that are the most difficult to fill in your organization. (Select Three)

- Assembler: 7%
- CNC Programmer: 12%
- Electrical Technician: 19%
- Welder: 19%
- CNC Machinist: 23%
- Machine Operator: 28%
- Mechanical Technician: 28%
- Not applicable: 30%
- Tool Maker: 56%
March 25th, 2015, Northwestern University welcomed delegates from the **Japanese National Institute for Materials Science (NIMS)**. A survey sheet for these delegates was created to capture information similar to that on this Survey form. Their responses are compiled as follows:

**Material Characterization and Development**
- FEM is the most common modelling method used
- SEM and TEM along with uniaxial tensile and biaxial tensile tests and deep drawing are typical material characterization tests
- Control of texture and computer aided materials development are trends of material development
- Challenges in material characterization are non-destructive evaluation, high-through put, and multi-probe analysis

**Equipment and Lubrication**
- The most advanced sensors being used are multiaxial tube expansion tests and laser displacement sensors
- Challenges in equipment and lubrication are high temperature lubricant of metal forming.

**Process and Control**
- New finite element formulation is the emerging challenge for prediction of the springback in emerging lightweight materials like titanium, magnesium and advanced high strength steels
- Hot-stamping and control of microstructures in hot forming are the main challenges in process and control

**Simulation and Design**
- Material models and friction models are not considered as acceptably accurate, and simple and high performance models are required
- Realistic modelling using experimental data is a challenge in simulation and design.

**Business Eco-System**
- In application areas or sectors like the electric car, distributed energy, and health and medicine, the new sheet metal forming emerging challenges are sheet forming for high strength materials and texture control
- Size of market and uniqueness of technology are important differences in the needs for large and small firms
- The Iron and Steel Institute of Japan is an organization that offers support to the industry
Appendix 3 - Summary of Minor Issues

The followings topics were prioritized by only one group, and thus are regarded as less important issues, but, in keeping with the emphasis encouraged in roadmapping on “minority reports” which could be ultimately recognized as important, they are included here and will be regularly revisited.

**Lightweighting**

Ferrous Materials (Group 1) suggested this issue as the most important key driver. Reduction of the material weight is directly linked to energy efficiency and environment in both structural and functional material industries, such as energy generation, storage, propulsion, and transportation. For example, in the automotive industry, the demand for improved fuel efficiency has been increasing for a long time. Such a goal could be achieved by actively introducing lightweight materials (i.e., twinning-induced plasticity steel, titanium alloys, aluminum alloys, magnesium alloys) as well as by developing an innovative design and manufacturing process.

**Understanding Wear Mechanism and Fatigue Life**

Group 4 showed a great interest in wear mechanism and behavior. They suggested the understanding of wear as the most important issue. Wear is a serious cause of material dissipation, which is not intrinsic material properties but are induced in a tribological system. The friction and wear are not only an academic topic but also a critical issue in the industry for a long time. It was measured that the economic loss due to these phenomena were 1-2.5% of gross national product (GNP). The basic wear mechanisms are (i) abrasive wear, (ii) adhesive wear, (iii) fretting, (iv) corrosive wear, and (v) erosive wear. Abrasive wear indicates the phenomenon that a harder material removes a softer material when rubbing it. Adhesive wear occurs by welding-related micro-junctions. The high load applied to the rubbing surface adhere both materials to each other, leading to transfer of material part by its counterpart. Fatigue wear is caused by the repetitively applied load higher than the fatigue limit of a material. Fatigue cracks initiate at the material surface and then propagate into the subsurface, which are often separated and delaminated by the material pieces. Corrosive wear indicates the accelerated wear by corrosion due to the increased temperature and removal of oxide films on the surface. Erosive wear occurs when particles remove material pieces from the surface. The problem in wear behavior is that more than two wear mechanisms are combined in the industry, making it difficult to perfectly understand a certain wear problem.

**Getting To Market Fast With Non-Ferrous Materials**

Non-Ferrous Materials (Group 2 particularly emphasized the necessity of such an enabling system/platform because currently time to market is very slow due to lack of knowledge in non-ferrous materials. A potential problem suggested in the discussion is that smaller companies are not interested in investing (or able to invest) as much in research, and would rather make capital purchases. But, while OEM level work has been slowly moving down to smaller-tier organizations with 10-500 employees, transfer of material knowledge is not. Knowledge dissemination within large companies may be another problem. It was suggested that some of these problems may be resolved through Manufacturing Extension Partnership (MEP), a NIST program providing business and technical assistance to manufacturers.
Certification

Equipment, Control & Lubrication (Group 4) suggested the certification issue for manufacturers. Certification process is indispensable for new materials, designs, sheet-forming processes to be commercialized. This process is driven by contracts, requirements, external reviews, educations or assessments, which require significant expense (both cost and time) as well as an understanding of various factors about product, market, etc. The high cost of certification often prohibits the use of new materials or new designs in a complex system. In particular, such a risk is of critical importance for small manufacturing businesses associated with high mix-low volume manufacturing.
Appendix 4 - Workshop Evaluation

Attendees were asked to voluntarily evaluate the workshop. The evaluation consisted of six multiple-choice questions (Q1 to Q6) and eight free response questions (Q7 to Q14). The high (37%) response rate is consistent with an overall affirmative assessment as quantified below.

**Q1. How helpful was your participation in this workshop, to your organization?** (‘1-Not at all’ to ‘7-Very helpful’)

**Q2. Would you participate in a similar program again?** (‘1-Not likely’ to ‘7-Definitely’)

**Q3. How frequently should programs like this be conducted?** (1/4, 1/2, 1, 2, 5, 7 or 10 years)

**Q4. What do you think is the most appropriate group to organize programs like this?** (multiple responses allowed)

**Overall Evaluation (Q1)**

Over 90% of the responses rated the workshop as helpful with a score above 4, out of maximum of 7, reflects a high overall satisfaction rating.
Future Participation (Q2 to Q4)

It is encouraging that 96% of the responses expressed the strong desire (> 4) to participate in a subsequent roadmapping workshop (5.9/7). The respondents recommended a follow-up workshop from 3 months to 5 years (2.1 years in average). Half of them considers the next workshop may be held in two years. No one has answered for 7 years or more. Regarding an organizing group, 1. Industry association, 2. Consortium, and 3. University were evenly recommended. However, 4. Company or 5. Other groups were not considered to organize a program. 5. Other groups indicated a governmental institute, such as NIST.

Valuable Part (Q5)

While 40% of the respondents listed multiple aspects of the workshop having value, there was clear delineation with networking considered the most valuable (40% of the responses) followed by information and new ideas (30%) and breakout discussion (21%).

Q5. What was the most valuable part of the program? (multiple responses allowed)

Future Contribution² (Q6)

Almost half (47%) of the responses answered they would join task force focused on the issues identified. Over a third (37%) of the responses would attend another workshop. Despite the absence of a specific roadmap, about one sixth (16%) were prepared to submit letter of support.

Q6. What are you prepared to do to move roadmapping forward? (multiple responses allowed)

² Please note that this question allowed multiple responses.
The other questions were sought free response to help identify actions to prepare for the next workshop. The responses are compiled with each question below. It is noteworthy that nearly a third (32%) of the free responses identified funding to support university-industry collaboration, solve important issues, and educate next-generation engineers in Question 10.

Q7. What specific questions or issues were not addressed?

- Big picture narrative
- Funding
- New processes
- New material developments and applications
- Consolidation of suggested ideas into an action plan
- Details of friction
- Simple models for materials
- How to solicit government funding to start a consortium
- In contrast, one attendee answered that most of the important issues had been covered or discussed in this workshop
- Limitations in material and software
- Actionable next steps
- Constitutional models

Q8. How did the workshop change your thinking?

- Multiple perspectives helped to stimulate ‘big picture’ thinking
- The workshop provided an opportunity to network with people in the field
- More consideration on collaborating with companies
- In different cases, engineers must think in different aspects, which means we might be more open-minded
- Industry and academia are not reacting to the new requirements in the metal forming field in an organized way. This was not expected.
- Hopeful that more needed funding might be appropriated by government
- Not much, but the workshop reinforced the original thinking (from 2 respondents)
- Not much (from 1 attendee)

Q9. Are there categories of people that were missing as participants?

- Small- to medium-sized businesses (from 2 respondents)
- People from associations, such as AISI and SAE
- People from government, such as DOE, NSF representatives
- Lubricant experts
- Non-ferrous experts
- Tool designer/manufacturer
- Actual stamping companies
- More OEMs
- Manufacturing engineers from Auto OEMs
More participants outside of auto-industry (e.g., aerospace)
More experts in the field of experimental/theoretical modeling.
Part manufacturers for new material
Hiring managers who can speak to specific lack of skills of not just emerging students, but people going through mid-life/mid-career job changes
Industry practitioners
Meanwhile, four respondents answered no missing in the workshop

Q10. Can you suggest specific individuals that should become involved (and contact information)?
Several individuals were identified.

Q11. What are key next steps for today’s participants as a group?
- Release a workshop report/white paper/summary (from 7 respondents)
- Continue to develop an organizational plan (from 2 respondents)
- Give feedback as project progresses (from 2 respondents)
- Identify issues of academic and industrial interests
- Openness to new ideas
- Keep in touch and cooperation
- More practical collaborations
- Frequent deep dives of the narrow items we identified so that the broad divergent topics don’t keep derailing

Q12. What related initiatives does this group – or a consortium – need to carry out or offer to help address your needs?
- Contact communication with organizations that have resources available that could be useful or at least get initial feedback on willingly to be involved
- Publish or disseminate results
- Better communication of what is available in technology developments, workforce education, etc.
- Education and development of material models
- Research on hot stamping process
- Reduce paperwork and costs to participate
- OEM approval

Q13. What documentation or other resource/action would you need from us for you to be able to commit to working further on the roadmapping initiative?
- A workshop report to update and to announce the next workshop (from 5 respondents)
- Demonstration to upper management that defines the ‘value’ to my employer of participation in roadmapping
- Open accessible web information (e.g., document, video)
- Better sense of tangible outputs
Cost to participate

Q14. What critical action would you or your company want legislation to support?

- Funding to support university-industry collaboration, solve important issues, and educate next-generation engineers. (from 8 respondents)
- R&D
- Database management & development
- Press data mining
- Technology transfer
- Supporting the application of new material and process
- A common data architecture for the product development system