Final Report (Feb. 1, 2013 – Mar. 31, 2017)

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SECTION 1: EXECUTIVE SUMMARY

The Integrated Computational Materials Engineering Development of Advanced High Strength Steel for Lightweight Vehicles project, herein referred to as the ICME 3GAHSS project, achieved the following objectives:

1) Developed a 3GAHSS ICME model, which includes atomistic, crystal plasticity, state variable and forming models. The 3GAHSS model was implemented in commercially available LS-DYNA and a user guide was developed to facilitate use of the model.
2) Developed and produced two 3GAHSS alloys using two different chemistries and manufacturing processes, for use in calibrating and validating the 3GAHSS ICME Model.
3) Optimized the design of an automotive subassembly by substituting 3GAHSS for AHSS yielding a design that met or exceeded all baseline performance requirements with a 30% mass savings. A technical cost model was also developed to estimate the cost per pound of weight saved when substituting 3GAHSS for AHSS.

The project demonstrated the potential for 3GAHSS to achieve up to 30% weight savings in an automotive structure at a cost penalty of up to \$0.32 to \$1.26 per pound of weight saved. This makes a compelling case for the development of 3GAHSS alloys for automotive applications. However, the manufacturing processes for making 3GAHSS are non-trivial. The development of the ICME 3GAHSS Model, which was validated for two distinctly different 3GAHSS alloys, is expected to be useful in helping the industry virtually develop new 3GAHSS grades, thereby reducing the time for steel alloy development. The 3GAHSS ICME Model enables the user to design 3GAHSS to desired mechanical properties in terms of strength and ductility.

SECTION 2: COMPARISON OF ACCOMPLISHMENTS WITH GOALS

The goal of the project was to successfully demonstrate the applicability of ICME for development and deployment of 3GAHSS for immediate weight reduction in passenger vehicles. To achieve this goal the project had to do the following:

> Objective #1: Demonstrate that 3GAHSS could achieve 35% mass savings in an automotive body assembly at a cost of no more than \$3.18 per pound of weight saved.
>
> Objective #2: Develop an 3GAHSS ICME model capable of predicting 3GAHSS properties within 15% of experimental results.

The project did not fully achieve Objective #1. The project selected a baseline side-structure sub-assembly from a 2008 model year sedan as the demonstration assembly and substituted two 3GAHSS alloys for all AHSS components in the sub-assembly. The team then optimized the 3GAHSS side structure by reducing component gauge thickness, eliminating joints, and optimizing component shapes. The final design had to meet all performance metrics of the baseline assembly for crash and stiffness. The final optimized design achieved a 30% mass savings versus the 35% target but met or exceeded all side-structure performance targets. The team concluded that additional mass savings was possible if the team could have optimized the full body-in-weight design rather than just the side-structure sub-assembly.

The project was able to achieve the cost target of first objective. The project demonstrated via a technical cost model that it was economically feasible to use 3GAHSS as a substitute to AHSS. A comparison between the estimated cost of the AHSS and the optimized 3GAHSS side structure sub-assemblies indicated that the use of 3GAHSS would have a cost increase of $0.32 to $1.26 per pound of weight saved, which was well below the target of $3.18 per pound of weight saved. The increased ductility and formability of 3GAHSS versus AHSS enabled improved design flexibility, which was needed to compensate for the reduced stiffness that comes with reducing gauge thickness.

The project was able to meet the second objective by developing and validating a 3GAHSS ICME Model. The 3GAHSS ICME model is an assembled model composed of a two principal material models, a crystal plasticity model and a state variable model, linked to a forming model. The project demonstrated that the assembled material models could accurately simulate the flow curves of a baseline AHSS and two 3GAHSSs. Furthermore, the project was able to use the output of the assembled material models, material cards, to simulate the forming of a T-shaped component, which is representative of the upper portion of an automotive side structure B-Pillar. Along limited strain paths, the project was able to show that the coupled 3GAHSS material and forming models could predict within approximately 15% the as-formed component microstructures, thereby meeting the second objective's accuracy target.

SECTION 3: SUMMARY OF PROJECT ACTIVITIES

The summary of project activities is broken down into the following activities:

1. Material Model Development, Calibration and Validation
2. 3GAHSS Experimental Heats
3. Forming Model Development and Validation
4. Design Optimization
5. Technical Cost Modeling
6. Data Model

The summary is a high-level overview reflecting principal accomplishments and inter-relationships between the activities. For more in-depth discussions, the reader is referred to technical papers and presentations given by the project participants.

3.1 Material Model Development, Calibration and Validation

The 3GAHSS ICME model is composed of a crystal plasticity model and state variable model and is best understood by reviewing the inputs and outputs of each model. For the crystal plasticity model the inputs consisted of material property information, such as atomistic simulations, microstructural phase volume fractions, critical resolved shear stress (CRSS), etc. The output of the crystal plasticity model, which is the input for the state variable model, is material microstructure with characteristic information, such as grain size, phase volume fractions, individual phase flow properties, texture, etc. The state variable model then processes this information and produces a material card, which describes the flow properties (i.e. stress / strain curve) of the composite microstructure.

At the onset of the project, there were limited material models for AHSS and no models for 3GAHSS as there were no commercially available 3GAHSS at the start of the project. This means there is limited experimental material property information available to develop and calibrate the crystal and state variable material models. Therefore, the project had to establish a baseline material that would be representative of a 3GAHSS from which needed material property information could be obtained. The project selected a QP980 steel (Quench and Partitioned, 980 MPa tensile strength steel) as the baseline material. This steel was composed primarily ferrite and martensite, which was expected to be the dominate phases in 3GAHSS. The project then characterized the QP980 steel, developed and calibrated both the crystal and state variable models resulting in a material card for QP980. As shown in Figure 1, the project was successful in calibrating the ICME Model for the QP980 steel where the experimental flow curve is in general agreement with the predicted flow curve. After completing this step, the project was able to move on to developing the ICME model for 3GAHSS materials.

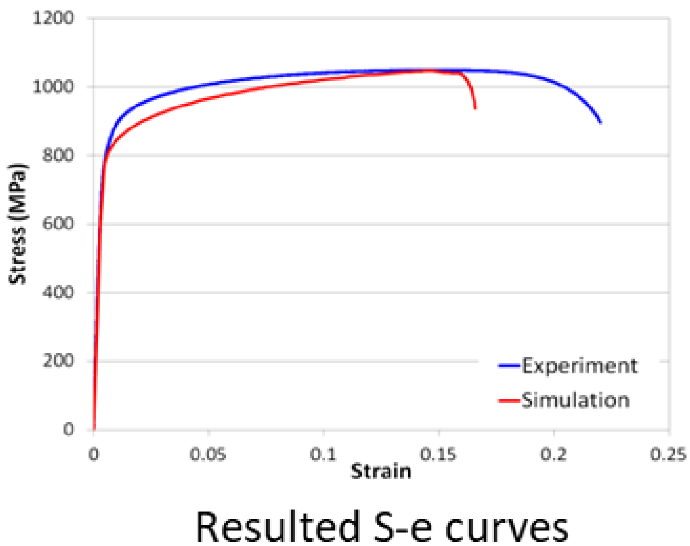


Figure 1: A Comparison Between Experimental and ICME Model Simulated Flow Curves for QP980 Steel

The calibration of the assembled material models for 3GAHSS was not as straightforward. The lack of commercially available 3GAHSS meant that there were no materials from which to obtain constitutive material property information needed to calibrate the material models. Fortunately, the project was able to successfully produce two 3GAHSS but the materials arrived late in the program, which limited the amount of testing that could be done. Furthermore, there were several issues that arose in the testing of the materials that impacted model calibration;

1. The grain size of the 3GAHSS was too small for accurate micro-pillar testing, which was used to derive individual phase critical resolve shear stress (CRSS) values. This forced the project to use alternative materials to derive representative CRSS values.

2. Unlike the dual phase nature of the QP980 baseline steel, the 3GAHSS materials used in this project were three-phase microstructures consisting of ferrite, martensite and retained austenite. The latter is a metastable phase that transforms to martensite as a function of strain and temperature.
3. One of the 3GAHSS had non-uniform post-yield behavior, which was later attributed to a complex inter-related deformation and phase transformation behavior. This issue resulted in the development a new experimental technique that utilized in-situ digital image correlation (DIC) and high energy X-ray diffraction (HEXRD) to characterize the transformation of retained austenite as a function of strain.
    a. A fourth phase, epsilon martensite, was discovered during the transformation of retained austenite to martensite for the same steel. The project did not have the time and resources to characterize this phase and would have been challenged to do so considering the limited volume faction, small grain size, and the phase's transitory and metastable nature.
    b. Twinning was found to occur in this steel as well, which was different than the traditional work hardening flow curves observed in the QP980 baseline steel and other 3GAHSS.
4. Due to the late arrival of the 3GAHSS, rapid strain rate testing of the 3GAHSS was late and the project was not able to calibrate the models for rate dependency. Furthermore, as shown in Figure 2, the High Strength, Exceptional Ductility steel is sensitive to strain rate, which could have a future impact on 3GAHSS application.

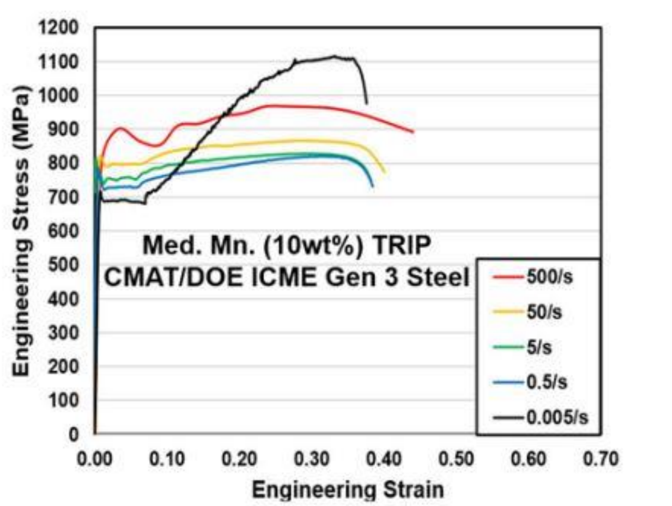
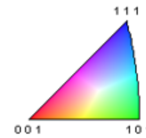
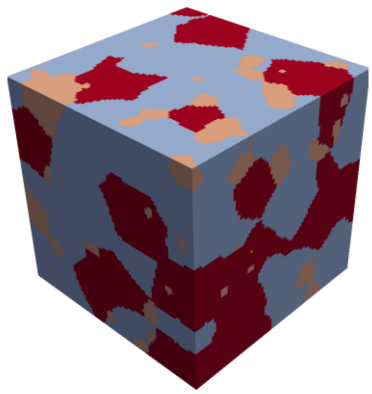
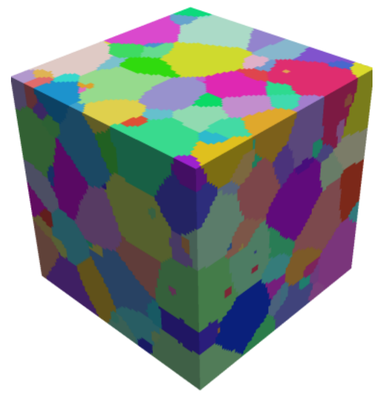
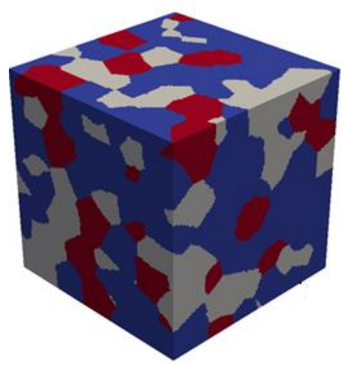
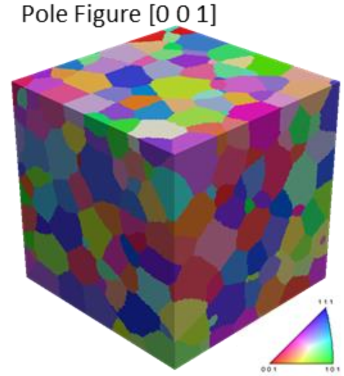
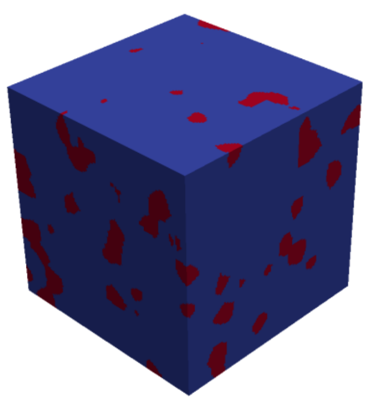
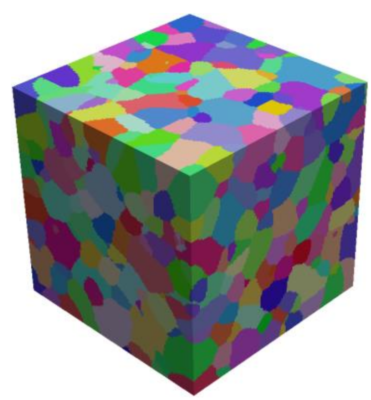


Figure 2: Strain Rate Sensitivity of the High Strength, Exceptional Ductility Steel (courtesy of GM)

5. Originally, the project had intended to map the steel microstructures using two-dimensional representative volume elements. The project decided that it would be better to use three-dimensional representative volume elements, 3DRVEs. The premise is that this would enable the material models to accommodate material anisotropy and texture. Two different software packages were tried with the team finally deciding upon

Dream.3D© software. Table 1 shows the 3D RVEs for baseline QP980 and two 3GAHSS.

Table 1: Generated Three- Dimensional Representative Volume Elements (3D RVE) for the Baseline and 3GAHSS materials

Steel	Phase Distribution	Pole Figure [0 0 1]
		
QP980 Martensite (49.48 %) Austenite (6.63 %) Ferrite (43.89 %)		
High Strength, Exceptional Ductility (CMAT Med. Mn 2.1) Tempered Martensite (57.4 %) Untempered Martensite (25.1 %) Austenite (17.5 %)		Pole Figure [0 0 1] 
Exceptional Strength, High Ductility (CMAT Q&P 2.2) Martensite (94.8%) Austenite (5.2%)		

Despite these challenges, the assembled 3GAHSS ICME model was able to produce flow curves that were in general agreement with the experimental results for both 3GAHSS alloys, as shown in Figures 3 and 4. The project team acknowledges that additional work is needed to fully calibrate the ICME 3GAHSS material models but the general agreement between predicted and experimental flow curves is encouraging.

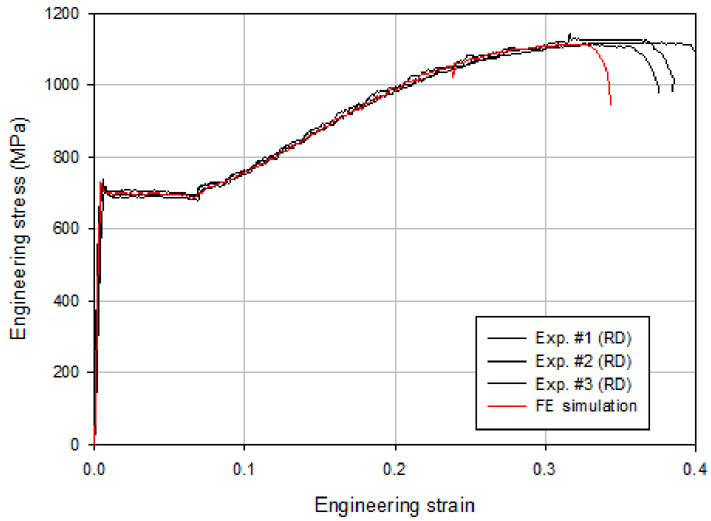


Figure 3: Flow Curve for the High Strength Exceptional Ductility Steel

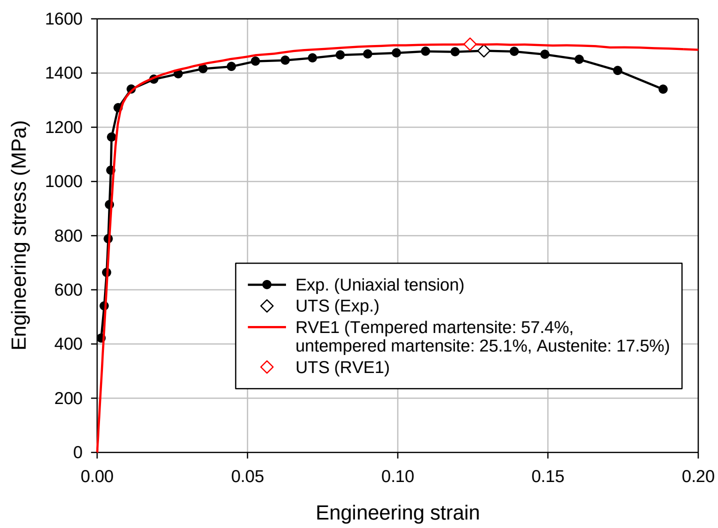


Figure 4 : Flow Curve for the Exceptional Strength, High Ductility Steel

The amount of experimental testing in this project was significant and included the following;

- Uniaxial tensile testing
- Hydraulic bulge test (balanced biaxial)
- Controlled biaxial testing (cruciform)
- Austenite-to-martensite transformation at different conditions
- Shear testing
- Formability testing -Nakajima/Marciniak
- Tension-compression testing
- Edge fracture (hole expansion test, center hole specimen tension test)
- Other (draw bend / stretch bending test, springback, etc. …)
- Electron Backscatter Diffraction

The results from the testing are posted in a database, which is currently managed by the National Institute for Testing and Standardization (NIST) and discussed in section 3.6. Below are a couple examples of lessons learned related to experimental testing.

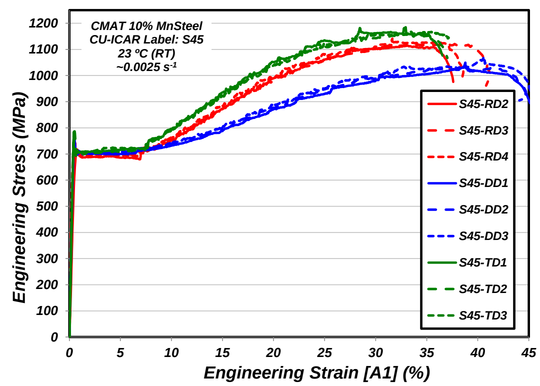
A. Digital image correlation (DIC) testing was used when applicable, such as in uni-axial tensile testing. The expectation was that DIC would improve the quality of the test data but several issues arose that required some adjustment. Corrective measures were needed to correlate the strain imposed by the tensile machine with observed strain measured by the DIC system. This was necessary to account for discrepancies in elongation noted between traditional tensile testing and DIC tensile testing

B. The DIC based tensile testing measures strain in the gauge area of a tensile coupon whereas traditional tensile testing measures strain as the change in length of the entire coupon. The more precise localized measurement of strain revealed non-homogenous deformation in the 3GAHSS samples. This was later attributed to the complex interrelated deformation and retained austenite phase transformation induced by increasing strain. Deformation bands were observed to travel through the 3GAHSS sample, which were matched by serrations in the post-yield flow curve. Further work is suggested to better understand the deformation and transformation mechanisms of the 3GAHSS.

C. The team had originally expected three phases in 3GAHSS, martensite, ferrite and retained austenite. However, EBSD testing revealed the presence of epsilon martensite in samples that had been strained. Indications are that this phases is a transitory phase between retained austenite and newly transformed martensite.

As shown in Figure 1, experimental data was essential for calibrating the ICME models for the QP980 baseline steel. The flow curve for the QP980 is very traditional with a definitive yield point and classic work hardening to failure. As shown in the first image of Table 2, the behavior of the TRIP based 3GAHSS; the High Strength, Exceptional Elongation Steel, does not exhibit similar behavior. As shown in the second image of Table 2, the flow curves predicted by the initial ICME model did not agree with experimental results. However, once the ICME model was calibrated with the material properties from the experimental steel, the predicted flow curves aligned well with experimental results as shown in the third image of Table 2.

Table 2: Calibrating the 3GAHSS ICME Model for the High Strength, Exceptional Elongation Steel

<table>
<tr><td>Experimental Results for the High Strength, Exceptional Ductility Steel (CMAT Med. Mn 2.1)</td><td>
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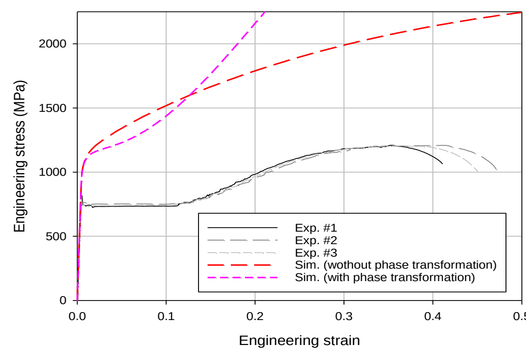
<tr><td>The initial Crystal Plasticity Model prediction did not match experimental results</td><td>
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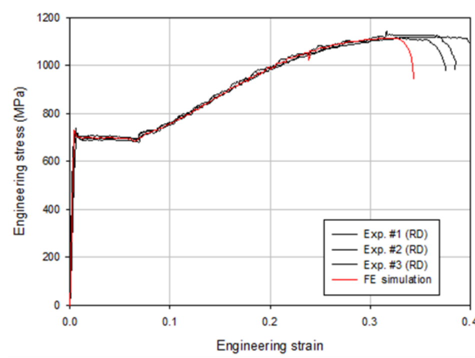
<tr><td>After calibration, the Crystal Plasticity Model prediction is in general agreement with experimental results</td><td>
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3.2 3GAHSS Experimental Heats

As stated previously, commercially available 3GAHSS did not exist at the onset of this project. To demonstrate that the material models were capable of simulating 3GAHSS, the project needed to produce steels from which constitutive material properties could be assessed and used for calibration and validation of the material models. The Department of Energy's (DOE)

Funding Opportunity Announcement (FOA) provided two 3GAHSS targets, a High Strength, Exceptional Ductility steel and an Exceptional Ductility, High Strength steel. The two targets are shown in Figure 5 with the target mechanical properties shown Table 3.

As demonstrated earlier, effective calibration of the ICME model required experimental materials with the similar microstructural constituents and flow behavior as the target 3GAHSS materials. But since the target 3GAHSS did not exist, the material microstructures had to be deduced from prior experimental work. Fortunately, previously published works indicated that there were experimental steel alloys with potential to achieve these properties. However, the works, based on limited volume heats of approximately one pound, suggested that the same steel process could not achieve both target steels. For the High Strength, Exceptional Ductility steel the project chose a Transformation Induced Plasticity (TRIP) process path and for the Exceptional Ductility, High Strength steel the project chose a Quench and Partitioning (QP) process path.

The goal for producing 3GAHSS wasn't necessarily to achieve the target properties, but rather to produce experimental steels with properties within the strength / ductility ranges that define a 3GAHSS and with microstructures and mechanical properties similar to those expected for the two target steels. Recipes were developed for both steels and the first experimental trials resulted in steels that came surprisingly quite close to the DOE targets. The AK Steel Medium Mn 2.1 represents one of the first trials for the High Strength, Exceptional Ductility steel where all target properties with the exception of yield strength were achieved. The AK Steel Q&P 1.2 steel represents one of the first trials for the Exceptional Strength, High Ductility steel, which met the ultimate tensile strength target but not the yield strength and ductility targets. Both trials heats were approximately 50 pounds in size.

The proximity of the two 3GAHSS to the DOE targets greatly improved the potential for the project to achieve the project objectives and suggested additional benefits. First of all, the work validated the 3GAHSS recipes and proved that the recipes were scalable from one pound to fifty pound heats. Secondly, the 3GAHSS material models could be calibrated to 3GAHSS steels with microstructures at or close to the DOE targets. Thirdly, the material models would be calibrated to 3GAHSS along two defined steel processes, TRIP and QP. Lastly, and most importantly, 3GAHSS materials were available for experimental work needed for model validation.

The first trial 3GAHS heats produced small volumes of 1.1 mm thick steel strips limited to 120 mm in width. This was sufficiently wide for experimental testing but not sufficient for making components. The project initiated a second trial to produce strips that were approximately 1 mm thick by 220 mm wide, which was of sufficient size to permit forming of small components. The second trial of the High Strength, Exceptional Ductility and Exceptional Strength, High Ductility steels, labeled CMAT Med. Mn 2.1 and CMAT Q&P 2.2 respectively had similar properties as those in the first trial as shown in Table 3. However, the second trial heats were approximately 450 pounds and, unlike the first trial heats, used production-like equipment. This reinforced the scalability potential of the two steels and suggested that the steels were manufacturable.

Table 3: 3GAHSS Experimental Alloys versus DOE Targets

Steel Alloy	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation	Uniform Elongation
High Strength, Exceptional Ductility	≥ 800	≥ 1,200	≥ 30%	≥ 20%
AK Steel Medium Mn 1.2	750	1,200	37%	34%
CMAT Medium Mn 2.1	693	1,042	35%	Not Measured
Exceptional Strength, High Ductility Steel	≥ 1,200	≥ 1,500	≥ 25%	≥ 8%
AK Steel Q&P 1.2	830	1,532	20%	Not Measured
CMAT Q&P 2.2 (McMaster)	1,218	1,538	20%	15%
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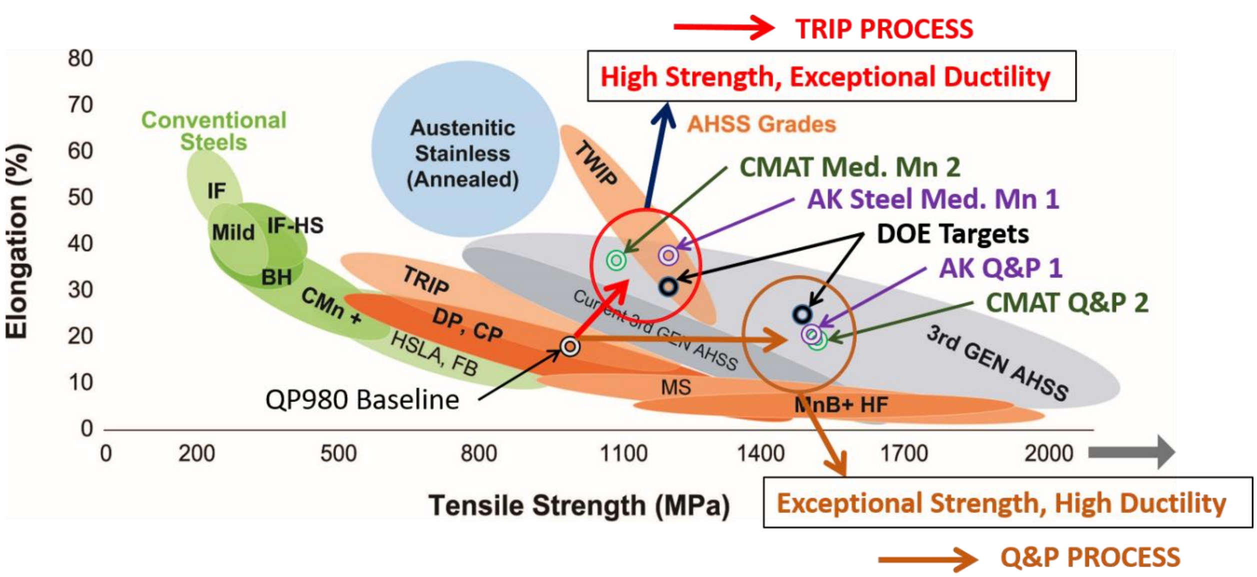


Figure 5: 3GAHSS Strength – Ductility Diagram showing Experimentally Produce 3GAHSS

3.3 Forming Model Development and Validation

The development and assembly of the material models (crystal plasticity plus state variable) encompasses the material length scales extending from the atomistic to the composite microstructure, or alternatively, the ICME model accommodates raw material and processing of the raw material into sheets. The next model element extends the ICME model to include the forming of the sheet into components.

Ideally, the project would use an actual automotive component but the 3GAHSS strip width limited the size of the component that could be formed. The project designed a pseudo-automotive component, called a T-Component, with features representative of the upper portion of a side-structure B-Pillar. Once designed, the project built a T-Component Die and used the die to make T-Components from the baseline QP980 and two 3GAHSS materials. Figure 6 shows three T-Components for baseline QP980 steel, the High Strength, Exceptional Ductility steel, and the Exceptional Strength, High Ductility steel. Full size T-Components were made from the QP980 steel and the High Strength, Exceptional Ductility steel but, due to heat treat processing limitations, the blank size for the Exceptional Strength, High Ductility Steel (CMAT Q&P 2.2) was too small to make a full-sized T-component.

QP980 T-Component | High Strength, Exceptional Ductility T-Component | Exceptional Strength, High Ductility T-Component

Figure 6: T-Components from the Baseline and two 3GAHSS materials

As with the material models, experimental work was used to support forming model development. The experimental data used for the forming model is listed below. The forming simulation was found to be in general agreement with formed T-Components in terms of dimensions, thinning and tearing.

1. Uniaxial tensile testing
2. Hydraulic bulge test (balanced biaxial)
3. Controlled biaxial testing (cruciform)
4. Austenite-to-martensite transformation at different conditions
5. Shear testing
6. Formability testing - Nakajima/Marciniak
7. Tension-compression testing
8. Edge fracture (hole expansion test, center hole specimen tension test)
9. Other (draw bend / stretch bending test, springback, etc. …)

The design of the T-Component is essentially a moving punch that projects into the bottom of the blank. Blanks geometries and designs can be used to achieve different forming modes and evaluate different strain paths. However, the depth of draw is the primary means of assessing the formability of the steels. Table 4 provides the draw depth for all three materials tested and it is evident that the High Strength, Exceptional Ductility 3GAHSS is more formable and the Exceptional Strength, High Ductility steel is less formable than the baseline QP980 steel

Table 4: T-Component Material Draw Depth

T-Component Material	Draw Depth
QP980	25 mm with no cracks
High Strength, Exceptional Ductility	25 mm with no cracks
Exceptional Strength, High Ductility	16 mm with cracks

The T-Component was an ideal component for this project due to its complex features, which requires different strain paths for forming such as uni-axial tension, bi-axial tension, bending, etc. The complexity of the design yielded another benefit. As discussed previously, a new experimental technique was developed to assess the transformation of retained austenite to martensite as a function of strain under uni-axial tension. The project team theorized that retained austenite transformation would be different for different strain paths. To prove this theory small pieces were extracted from areas of interest; areas with respect to strain paths (i.e. biaxial tension, bending, etc.) from the pre-form blanks and from as-formed 3GAHSS T-Components.

As shown in Figure 7, the transformation of retained austenite is influenced by strain path. Regions of similar equivalent strain but different strain path exhibited different retained austenite transformation behavior. The project team concluded that additional work was needed to better understand the deformation and transformation behavior of the 3GAHSS materials, that new experimental methods were needed to dynamically assess this behavior, and that this work would enable more precise post-formed mechanical properties as a function strain and strain path.

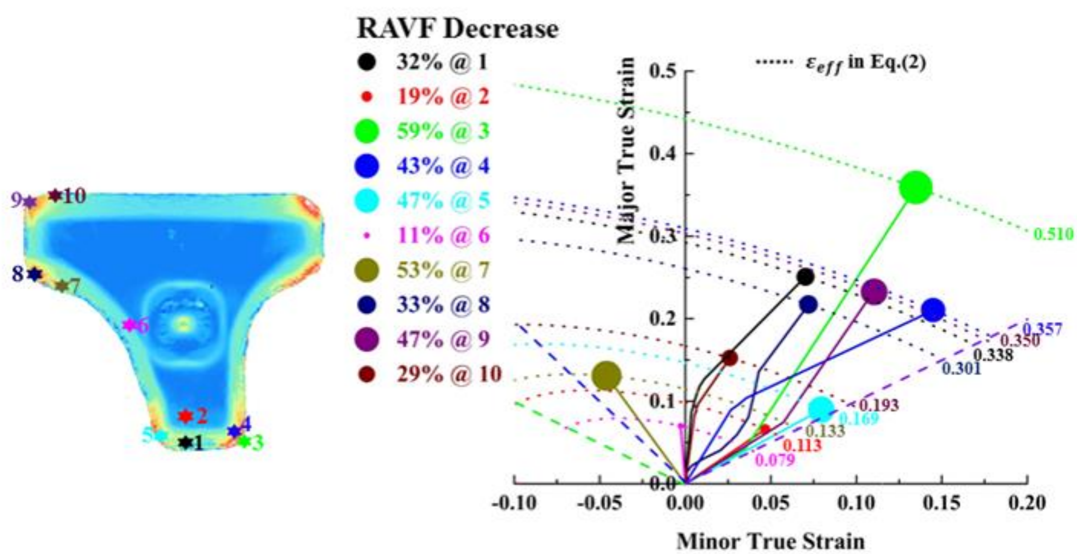


Figure 7: Using coupons extracted from formed t-components (left image), the project was able to show that the amount of retained austenite was not only a function of strain but also of strain path

The DOE FOA required the ICME Model to come within 15% of experimental results. Table 2, shown earlier, showed that the calibration of the ICME Model where predicted flow curves were in general agreement with experimental results. To demonstrate accuracy, the project could have chosen to assess the fit between predicted and experimental flow curves. However, this assessment is a composite assessment and does not specifically treat the different elements of the flow curve, elastic, plastic, work hardening, yield and final failure. The project chose to supplement this method by assessing the ICME Model's ability to predict 3GAHSS microstructure.

At the crystal plasticity level, the project had early on showed the ability to infer a material's initial mechanical properties from the microstructural phase composition. However, the mechanical properties change with strain, especially with the transformation of retained austenite to untempered martensite. The project chose to validate the ICME Model by assessing the ability of the model to predict retained austenite volume fraction. As shown in Figure 8, the ICME Model demonstrated that it could accurately predict retained austenite volume fraction within 15% of experimental result for uniaxial tension. This essentially provided a two-part validation method of comparing the fit between flow curves and comparing predicted versus experimental microstructures.

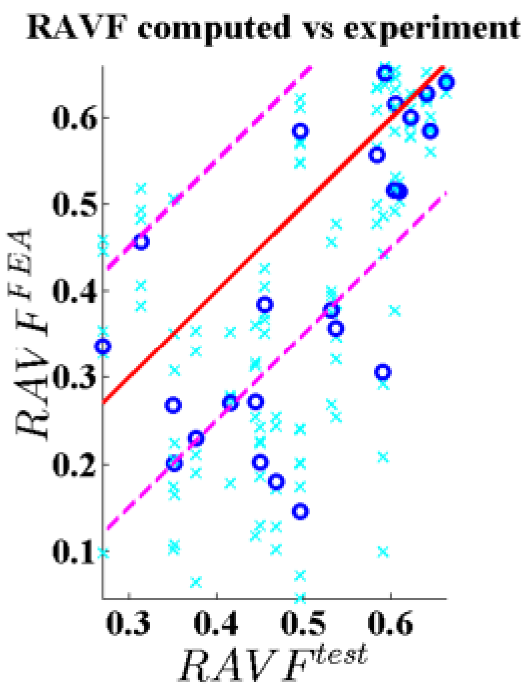


Figure 8: RAVF comparison - The cyan crosses show the 5 individual readings from FE for every coupon while the blue circles represent their mean. the dashed magenta lines represent +0.15 tolerances

3.4 Design Optimization

The DOE Funding Opportunity Announcement (FOA) required 3GAHSS to be substituted for four or more AHSS components in a selected baseline assembly from a 2006 model year or later production vehicle. The project team selected a side-structure subassembly from a 2008 model year sedan, which considered to be an ideal assembly for demonstrating the potential for 3GAHSS to reduce mass while meeting performance requirements. Side-structures are highly loaded safety critical assemblies, which have seen AHSS increasingly being selected to meet increasing vehicle crash requirements.

The selected side-structure contained 46 components, all of which were selected for replacement with 3GAHSS, which greatly exceeded the DOE FOA minimum requirements of four components. The project reasoned that the improved strength and ductility of 3GAHSS would enable reduced gauge thickness and more complex shapes not feasible in AHSS, which would be needed to meet the challenging 35% mass reduction requirement. The project produced a bill of materials, which detailed the material and gauge thickness for each of the forty-six components.

The first challenge for the design optimization team was determining the performance criterion for the side-structure assembly. Pole intrusion, side impact, rear impact, front impact, roof crush, bending stiffness and torsional stiffness were selected as the load cases for the assembly, however, all of these are vehicle-based performance metrics. To establish the side structure performance requirements, the team had to design a near-full vehicle body-in-white CAE model, apply the load cases, and measure performance. This introduced the second challenge; joining. The DOE FOA required a joining strategy for the eventual 3GAHSS assembly, but joining was not to be specifically addressed in this project. To eliminate joining as a factor in the comparison of the AHSS and 3GAHSS side-structure assemblies, the team decided to apply the same joining strategy for both assemblies, which was determined to be spot welding with a 35 mm pitch. The joining strategy was applied to the baseline assembly and substituted back into the vehicle CAE model, from which the baseline assembly performance was ascertained.

The next challenge was determining what properties to use for the 3GAHSS materials to be substituted into the side-structure assembly. The initial decision was to use the DOE FOA target properties for the Exceptional Strength, High Ductility steel and the High Strength, Exceptional Ductility steel. However the project had successfully produced two 3GAHSS materials with properties near the DOE targets so project used the experimental 3GAHSS material cards for design optimization. The Exceptional Strength steel was used for simple components that required strength and the Exceptional Ductility steel was used for more complex components where design flexibility was needed.

Design optimization was done in four stages. The first stage was to substitute the 3GAHSS materials and optimize the assembly for the maximum mass savings through gauge reduction without shape optimization, while still meeting crash performance requirements. This resulted in the design iteration #3, which yielded a 35.6% mass savings over the baseline assembly exceeding the 35% mass reduction target. Unfortunately, this design did not meet the stiffness requirements, which were 10% and 20% less for bending and torsional stiffness respectively.

The second stage was to conduct a stiffness sensitivity analysis to determine which components of the side-structure were most sensitive and least sensitive to stiffness. The unfortunate byproduct of reducing gauge thickness to achieve mass savings was to reduce component stiffness, which can only be compensated through shape optimization. The bending and torsional stiffness sensitivity analysis, shown in Figure 9, enabled the design optimization team to select candidates for shape and gauge optimization. For instance, the inner rocker panel (PANEL-RKR-INR-LH) was determined to be very sensitive to stiffness and therefore more difficult to reduce gauge. In contrast, outer frame panels (FRAME-BODY-SIDE-OUTER LH and RH) were less sensitive to stiffness and therefore more ideal for gauge optimization. From this study, the design optimization team produced design iteration #7, which met the bending and torsional stiffness requirements with a 19% mass savings, which was of course less than the 35% target.

Design iterations #3 and #7 essentially created the two bookends that illustrated the challenges of design optimization to reduce mass through gauge reduction, while meeting all performance requirements for crash and stiffness. Successive design iteration steps, which would focus on shape optimization, were constrained by stiffness but not crash performance. It should be noted, that all successive designs met the crash performance requirements.

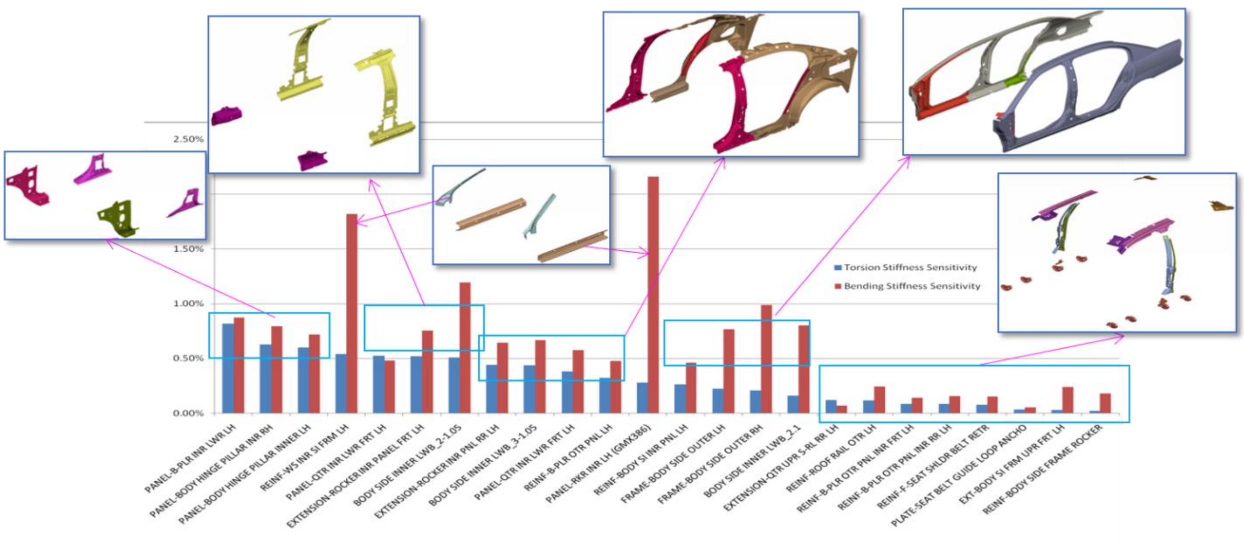


Figure 9: Side-structure bending and torsional sensitivity analysis

After a number of design iterations, which were mostly done using the National Renewable Energy Laboratory’s High Performance Computational Center, the final design (iteration #9) achieved a crash neutral design with 30% mass savings. This final design reduced the number for components from 46 components to 28 components, which was achieved by part consolidation, tailor welded blanks, and gauge and shape optimization. Figure 10, shows a comparison of the baseline, iteration 9, and 3GAHSS final design. The gauge thickness ranged from 0.5 mm to 2 mm. The team concluded that further design optimization of the side structure would not achieve the 35% mass savings target. However, the team was confident that the mass savings target could be achieved if the design could be expanded to include the full body-in-white. Despite not meeting the mass savings target, the final design did meet and exceed all crash performance requirements with 23%, 10%, 45% and 21% improvements in pole impact, side impact, rear impact and roof crush respectively.

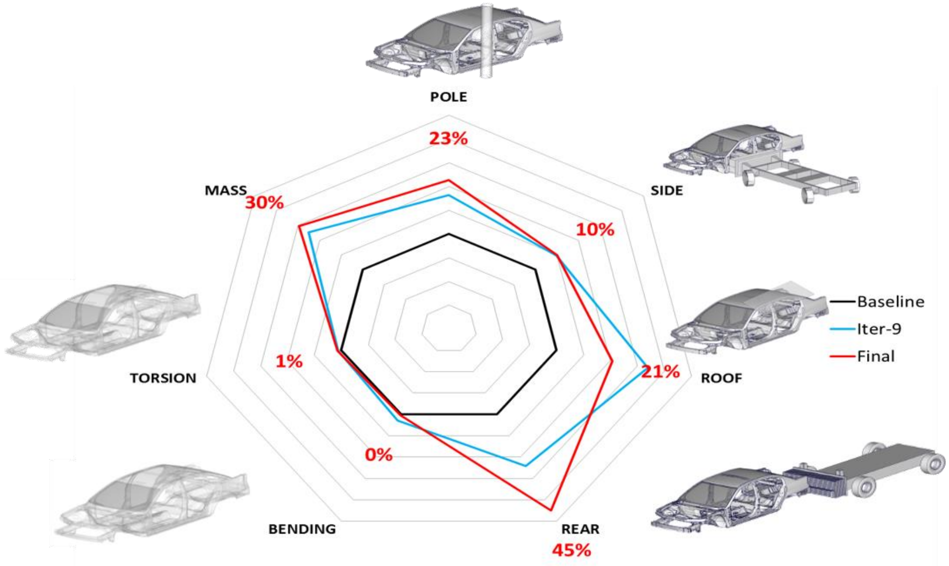


Figure 10: Spider graph comparing the Baseline, Iteration 9 and Final side-structure Designs for the seven defined load cases

3.5 Technical Cost Modeling

In addition to meeting 35% mass savings and performance requirements, the DOE required that the 3GAHSS automotive body assembly should not cost more than $3.18 per pound of weight saved. The project developed a process driven technical cost model to compare the costs of the baseline side-structure assembly against that of the final 3GAHSS side-structure. It must be noted that the cost estimates used in the model are not specific to any OEM or steel company and are based on industry estimates. Specific OEMs will have varying estimates that include (but not limited to) manufacturing flexibility, safety safe-guards, regional impacts, and vehicle variant manufacturing strategy etc. Furthermore it is necessary to outline the limits of the model.

The model is:

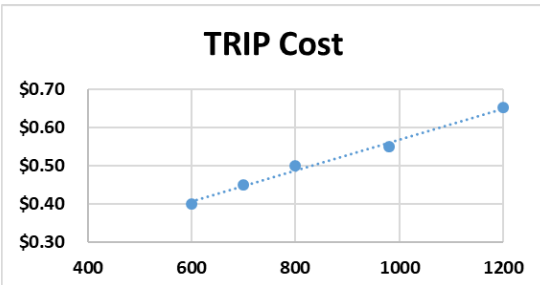
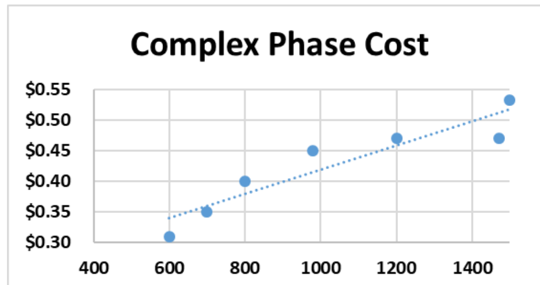
- An objective way to compare technologies, designs or manufacturing methods
- An analysis of manufacturing, equipment, tooling, labor, material, and energy costs
- A process to identify cost drivers
- A method to integrate piece cost, tooling cost and capital investment.

The model is note:

- A precise method to obtain commercial price
- A business case
- An analysis of non-manufacturing overhead, such as prototype costs, logistics, engineering and development costs

The steel costs used in the model were based off a five-year average costs of steel from 2010 to 2014, as published by PLATTS (www.platts.com). Steel costs are dependent upon the processes used to make the steel. Since the High Strength, Exceptional Ductility steel used the TRIP process, the price of this steel was extrapolated from lower strength commercially available TRIP steels, for which the costs showed a linear relation with tensile strength, see TABLE 5. The Exceptional Strength, High Ductility steel, which used the QP process, was more difficult to estimate as there were no commercially available QP steels. Instead, complex phase steels (CP) were used with the acknowledgement that the CP process was different than the QP process and therefore the costs may not be directly applicable, see Table 5.

Table 5: Cost estimate charts used to estimate 3GAHSS costs (cost versus tensile strength)

	
High Strength, Exceptional Ductility Steel Chart	Exceptional Strength, High Ductility Steel Chart

Based on the final 3GAHSS design, the technical cost model estimated that the cost of the 3GAHSS side-structure assembly would cost between $0.32 (actual estimate) and $1.26 (conservative estimate) per pound of weight saved, see Figure 11. This greatly exceeded the DOE target of $3.18 per pound of weight saved.

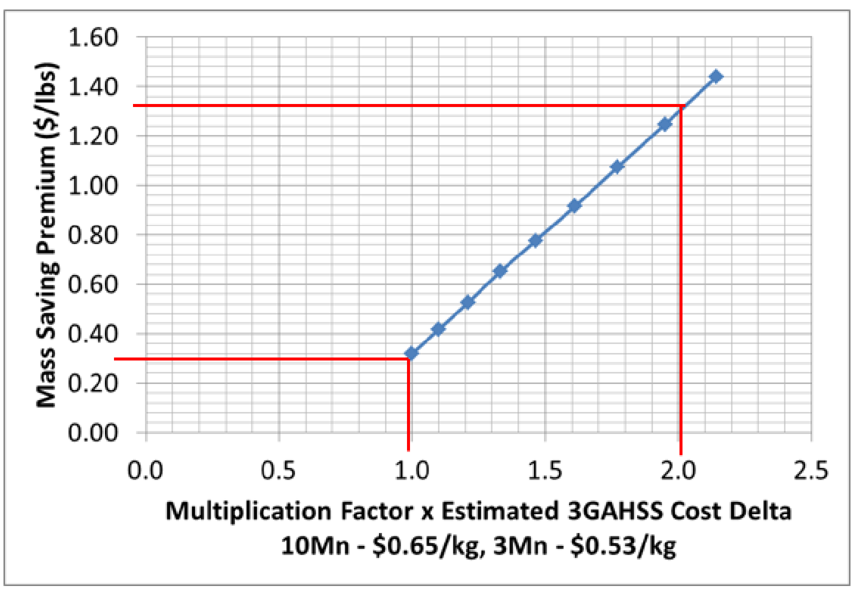


Figure 11: Technical Cost Model Projection for the final 3GAHSS Side-Structure Design

<u>Data Model</u>

The DOE FOA required a data model as one of the three project deliverables. The project developed a data model based on the three primary objectives:

1. A large database would be needed to store accumulated project data for material characterization and material, forming, and ICME model simulations.
2. The data stored in the database would have to be searchable and retrievable so that 1) modelers could obtain the data to calibrate material, forming and ICME models, 2) the data could be referenced in technical documents, and 3) the data would be available to the public upon project conclusion.
3. Associated metadata would be needed to adequately characterize and describe the data and how the data was obtained.

The project team selected the DSpace Data Repository managed by the National Institute of Standards and Technology as the basis for the data model. A data ontology was developed to store and curate the data to be stored in the database. As data was developed, project team members entered the data into the database with associated metadata. The database will be made available to the public within one year of project conclusion. The database can be accessed via the following link: ICME Approach to Development of Lightweight 3GAHSS Vehicle Assembly

ACCOMPLISHMENTS AND MILESTONE UPDATE

Accomplishments

The following accomplishments were achieved.

- Developed and produced two 3GAHSS alloys (High Strength, Exceptional Ductility, Exceptional Strength, High Ductility) using two different chemistries and manufacturing processes, for use in calibrating and validating the 3GAHSS ICME Model.
- Developed a 3GAHSS ICME model, which includes atomistic, crystal plasticity, state variable and forming models. The 3GAHSS model was implemented in commercially available LS-DYNA and a user guide was developed to facilitate use of the model.
- Developed and implemented a data model for the storage, curation, and retrieval of all test data and models developed in this project.
- Demonstrated the potential for 3GAHSS to achieve up to 30% weight savings in an automotive structure at a cost penalty of up to $0.32 to $1.26 per pound of weight saved.
    - Optimized the design of an automotive subassembly by substituting 3GAHSS for AHSS yielding a design that met or exceeded all baseline performance requirements with a 30% mass savings.
    - Developed a technical cost model to estimate the cost per pound of weight saved in using 3GAHSS versus AHSS.
- Developed a new test methodology for dynamically measuring the transformation of retained austenite to martensite by coupling digital image correlation, uniaxial tensile testing, and high energy X-Ray diffraction.
- Developed three-dimensional representational volume elements for the baseline and 3GAHSS materials.

Milestones

The Milestone Log is shown in Table 6. All milestones are due at the end of their respective billing periods. No milestones were scheduled for completion during this period of performance.

Table 6: Project Milestone Log

No.	NETL Milestone Title and Description	Planned Completion Date	Actual Completion Date
1	**Selection of Body Structure components/subassembly and identification of baseline materials complete**	**9/30/2013**	**9/15/2013**
2	**Meso-scale Computational Predictions:** **Validated meso-scale computational predictions from subtasks 5, 6 and 7.**	**1/31/2015**	**1/30/2015**

3	**Macroscopic Constitutive Models: Develop and validate macroscopic constitutive models for deformation and fracture**	**1/31/2016**	**Partially Complete 1/31/2016**
4	**Initial Forming Model:**	**1/31/2016**	**1/19/2016**
5	**3GAHSS Forming Model**	**1/31/2017**	**1/31/2017**
6	**Estimated Joint Properties**	**7/31/2016**	**7/31/2016**
7	**Baseline Assembly Design Defined**	**1/31/2014**	**1/16/2014**
8	**Optimized Design**	**3/31/2017**	**3/31/2017**
9	**ICME Model**	**3/31/2017**	**3/31/2017**
10	**Data Model**	**3/31/2017**	**3/31/2017**
11	**Technical Cost Model**	**3/31/2017**	**3/31/2017**

SECTION III: CHANGES IN APPROACH

ICME Model Development, Calibration and Validation

The original project plan was as follows;

1. Produce steels with mechanical properties within the strength and ductility range that defines 3GAHSS.
2. Develop a 3GAHSS ICME Model and calibrate it using the baseline and manufactured 3GAHSS steels
3. Run ICME Model simulations to determine the microstructural constituents needed to produce 3GAHSS with the DOE FOA target properties.
4. Produce 3GAHSS based on ICME Model Predictions to validate ICME Model predictions.

Unfortunately, the time and resources needed to produce small scale 3GAHSS did not allow for a third iteration of 3GAHSS production to validate the ICME Model predictions. Fortunately, the initial 3GAHSS production produced steels at or near the DOE FOA target mechanical properties. No simulation of the High Strength, Exceptional Ductility steel was needed since the mechanical properties of the experimental steel were nearly the same as the target properties. The differences in ductility between the experimental Exceptional Strength, High Ductility steel and the target steel, provided an opportunity to runs ICME Model simulations to increase the elongation from 20% to 25%.

The project ran several ICME Model simulations to increase ductility of the Exceptional Strength, High Ductility steel. Figure 12, an example of one such attempt, shows both the crystal plasticity model prediction for the material stress-strain curve (red) with experimental tensile test results (black) for the CMAT Q&P 2 steel. Figure 13 provides the composite representative volume element model (labeled RVE1) for this steel with the phase volume fractions listed in Table 7. There is general agreement between the model and experimental results with respect to the yield, ultimate tensile strengths and work hardening behavior. Disparities at the high strains are due to the absence of a fracture constitutive model in the simulation.

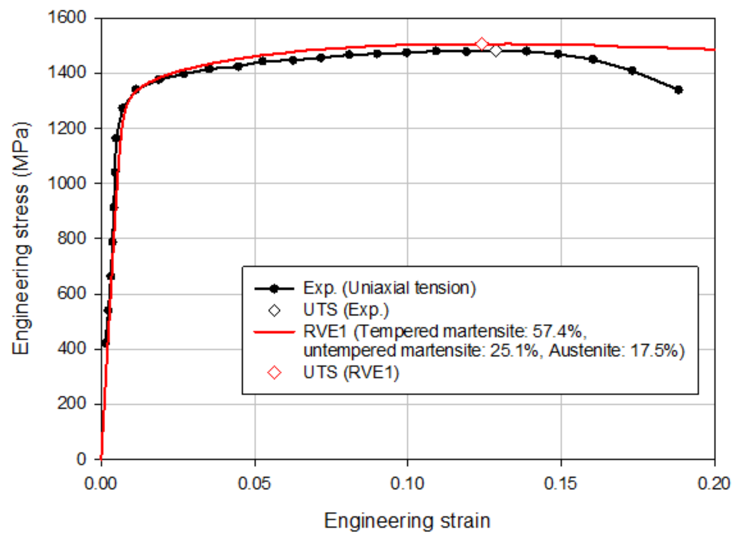


Figure 12: Simulated Stress-Strain Curve (RVE1) versus experimental test results (Exp.) for the CMAT Q&P 2 steel

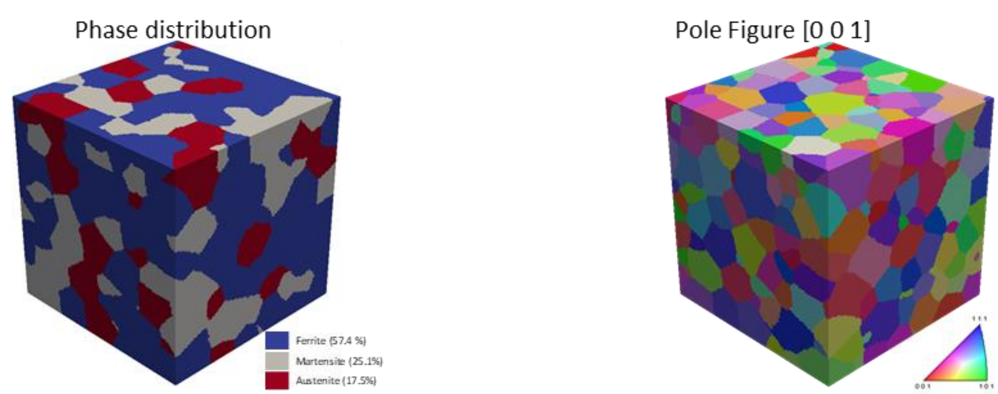


Figure 11: 3-D representative volume element for the CMAT Q&P 2 steel (RVE1)

Table 7: Volume phase fractions for the CMAT Q&P 2 and a hypothetical Q&P steels

Phase	Actual RVE for CMAT Q&P 2 Steel (see Figure 4, RVE1)	RVE for a hypothetical Q&P steel (see Figure 6, RVE2)
Tempered Martensite (α'_1)	57.4%	63.3%
Untempered Martensite (α'_2)	25.1%	19.0%
Retained Austenite (γ)	17.5%	17.7%

A hypothetical Q&P microstructure was postulated (labeled RVE2) with phase volume fractions shown in the third column to the right of Table 7. The amount of tempered martensite is increased by approximately 6% with a corresponding decrease in untempered martensite and a marginal impact on the percentage of retained austenite. The ICME Model then simulates the expected stress-strain curve for this steel, which is shown in Figure 12 (dashed blue curve) as contrasted against the actual simulated and experimental stress-strain curve for the CMAT Q&P 2 steel. The result is a predicted decrease in ultimate tensile strength with minimal impact on yield strength as a result of increasing the volume fraction of tempered martensite and corresponding decrease in untempered martensite. The composite representative volume element for the fictional Q&P steel is shown in Figure 6. This demonstrates one of the foundational aspects of ICME which is to generate hypothetical microstructures which can then be tested with the ICME model/process from simulation of coupon level experiments to simulation of forming to simulation of vehicle performance. Many additional such hypothetical microstructures can be generated and tested and hence the RVE2 microstructure is by no means definitive.

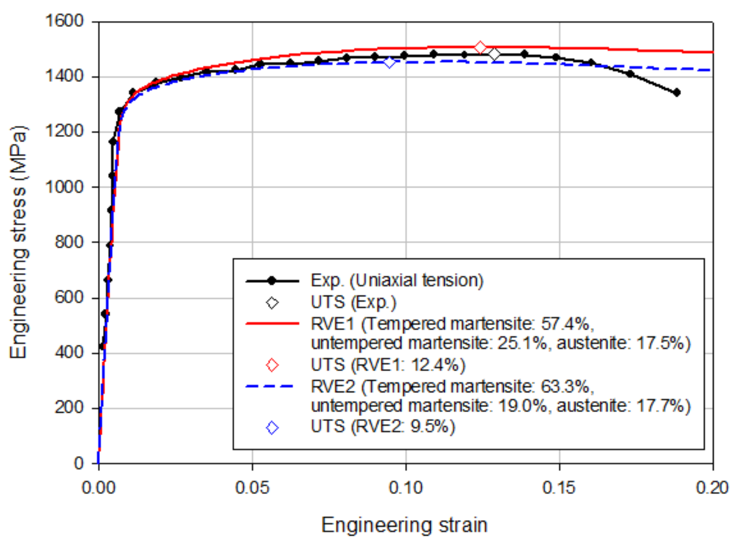


Figure 12: Simulated Stress-Strain Curves of the hypothetical Q&P steel (RVE2) versus contrasted against the actual Q&P 2 steel simulated (RVE1) and experimental (Exp.) stress-strain curves

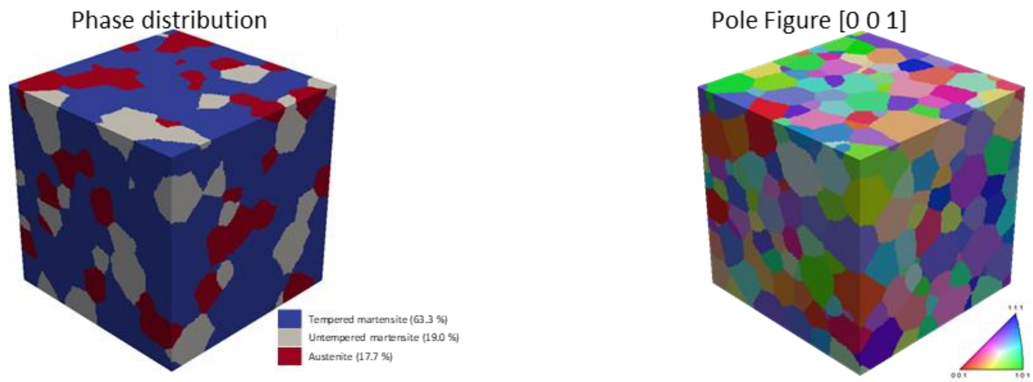


Figure 13: Hypothetical 3-D representative volume element for a hypothetical Q&P steel (RVE2)

Another gap that emerged in the project was the processing of 3GAHSS, which was not addressed in the DOE FOA. Early in the program, the team recognized that different steel processing paths were necessary to produce 3GAHSS to meet both DOE FOA targets. A TRIP process was recommended for the High Strength, Exceptional Ductility Steel and a QP process was suggested for the Exceptional Strength, High Ductility steel. This suggests that the 3GAHSS ICME Models developed are limited to the TRIP and QP process paths and may not represent alternative processing paths and may not encompass the entire strength and ductility space that defines 3GAHSS.

Lastly, the project assumed that assembly of the material models would enable the prediction of comprehensive material cards for use in forming, design optimization and performance modeling. Due to delays in producing 3GAHSS, not all experimental work could be completed and the experimental work was not sufficiently comprehensive to generate comprehensive material cards. For example, separate material cards for the High Strength, Exceptional Ductility 3GAHSS were developed for quasi-static behavior and rapid strain rate behavior. The former was used for forming simulations and the later for crash performance simulations. The same situation exists for AHSS and is only mentioned to acknowledge a gap in the integration of the material models into forming, design and performance models.

Crystal Plasticity Modeling

Initially, the project had planned to provide critical resolve shear stress (CRSS) values for all phases within the 3GAHSS microstructure using micro-pillar compression testing. Unfortunately, this work was constrained within the first two years of the project and before the 3GAHSS materials were fully developed and produced. Additionally, the micro-pillar compression test was limited to phases that were greater than two microns in size, which was larger than some of the phases observed in 3GAHSS materials. Therefore, alternate materials, such as stainless steel, were used to derived approximate CRSS values needed for atomistic and crystal plasticity modeling.

Since most prior ICME work was based on relatively homogenous single-phase materials, the project had assumed that two-dimensional representative volume elements would suffice for modeling. However, improvements in computational capabilities and the complex multi-phase nature of 3GAHSS suggested the use of three-dimensional representative volume elements. The project reasoned that this approach would yield and improved 3GAHSS ICME Model and the ability to simulate material anisotropy due to sheet processing.

Design Optimization

The DOE FOA require a demonstration automotive assembly from which 3GAHSS could be substituted for four existing AHSS parts. The initial assumption was that design optimization would be limited to four parts that may or may not be contiguous. However, the challenging performance and mass reduction targets suggested a more comprehensive approach where sub-assembly design optimization was more likely to achieve the DOE FOA mass and performance targets than individual component optimization. Early in the program, the project selected all forty-three AHSS components that made up side-structure assembly. Due to stiffness limitations, the project eventually added the rail and wheel housing bringing the total components of the side-structure to forty-six.

Data Model

Initially, the project intended to store all project data on the USCAR V-Room website or on the A/SP server. It was recognized early on that these resources were inadequate for the storage and retrieval of the large number and size of the files being produced by project experimentalists and modelers. PNNL provided access to the PNNL SharePoint website, which was used for the first couple of years until a more robust solution was provided. USAMP developed a CRADA with NIST to develop a DSpace database for the project that would allow the storage, curation, and retrieval of project data. The DSpace database had an advantage over the PNNL SharePoint website in that associated metadata could be stored with each data record and the data storage could be organized into a data ontology. Furthermore, this database was structured to satisfy the DOE FOA requirements for a data model, which included a plan to release the data to the public within one year of the project's conclusion.

SECTION IV: KEY PERSONNEL

There have been no changes in the team composition with respect to sub-recipient and vendor principal investigators. However, there were some changes in participant composition. ThyssenKrupp USA and United States Steel dropped out of the Auto/Steel Partnership, which resulted in some minor changes in project task team compositions. The principal investigator for Ohio State University was previously at Michigan State University. Other than minor time delays, this change had no discernable impact on the project. Table 7 provides the list of project sub-recipients and vendors. A list of principal investigators is available upon request.

Table 8: Project Participants

Universities / National Labs	Industry	Consortiums
Brown University	FCA US LLC	Auto/Steel Partnership
Clemson University	Ford Motor Company	United States Automotive Materials Partnership
Colorado School of Mines	General Motors Company	
Pacific Northwest National Lab	ArcelorMittal	
Ohio State University	AK Steel Corporation	
Univeresity of Illinois at Urbana-Champaign	Nucor Steel Corporation	

SECTION V: PROJECT OUTPUT

A. Publications

The project produced many publications, which are listed below. To assist the reader, the publications were sorted by task and by source where possible. The collaborative nature of the project complicated the sorting of the publications. Therefore, the principal author's affiliation was used as the primary sorting criterion.

Integrated Computational Materials Engineering

USAMP

- Hector Jr., L.G. (2013); "*Integrated Computational Materials Engineering Approach to Development of Lightweight 3GAHSS Vehicle Assembly*"; Presentation given at the 2013 DOE Annual Merit Review, Crystal City, Virginia, U.S.A.
- Hector Jr., L.G. (2013); Krupitzer, R.; Sachdev, A.K.; "*Integrated Computational Materials Engineering (ICME) for Third Generation Advanced High-Strength Steels: A New Four-year Project*"; In Proceedings of the International Symposium on New Developments in Advanced High-strength Steels, Vail, Colorado, U.S.A, pp. 341-349; AIST, Warrendale, PA.
- Hector, Jr., L.G. (2014); "Integrated Computational Materials Engineering (ICME) in the Automotive Industry: Successes and Opportunities"; Presentation to 2014 SAE World Congress, Detroit, Michigan.
- Hector, Jr., L.G. (2014): "*The Next Generation of Advanced High Strength Steels – Computation, Product Design and Performance, First Year Progress Update on the DOE ICME 3GAHSS Project*"; Presentation to 2014 Great Designs in Steel, Livonia, Michigan.
- Hector, Jr., L.G. (2014); "*Integrated Computational Materials Engineering Approach to Development of Lightweight 3GAHSS Vehicle Assembly*"; Presentation to the DOE Annual Merit Review, Bethesda, MD.
- Hector, Jr., L.G. (2014); "*Integrated Computational Materials Engineering (ICME) Approach to Development of Lightweight 3GAHSS Vehicle Assembly - Third Generation Advanced High Strength Steels*"; Presentation to Materials Genome Initiative - Data Workshop, Wright Brothers Institute, Tec^Edge, Dayton, Ohio
- Hector, Jr., L.G. (2014); "*Integrated Computational Materials Engineering (ICME) Approach to Development of Lightweight 3GAHSS Vehicle Assembly - Third Generation Advanced High Strength Steels*"; Presentation to the Fundamental & Computational Sciences Directorate PNNL, Richland, WA.
- Hector, Jr., L.G. (2014). "*Integrated Computational Materials Engineering (ICME) Approach to Development of Lightweight 3GAHSS Vehicle Assemb*ly"; Presented at the A/SP Technology Days.
- Hector, Jr., L.G. (2015): "*Integrated Computational Materials Engineering (ICME) of Generation Three Advanced High Strength Steels*"; Presented at the TMS Third World Congress on Integrated Computational Materials Engineering.

- Hector, Jr., L.G. (2015): "*Integrated Computational Materials Engineering (ICME) Approach to Development of Lightweight 3GAHSS Vehicle Assembly*"; Auto/Steel Partnership Technology Day, Livonia, Michigan.
- Hector, Jr., L.G. (2017); "*Bridging the Gap Between ICME Design and Implementation of Third Generation Advanced High Strength Steels for Automotive Applications," Symposium on ICME Gap Analysis*, TMS 2017, San Diego, CA.
- Hector, Jr., L.G. (2016); "*Integrated Computational Materials Engineering (ICME) of Generation Three Advanced High Strength Steels*," Society of Automotive Engineers (SAE) 2014 World Congress & Exhibition, Detroit, MI.
- Hector, Jr., L.G. (2016); "*Integrated Computational Materials Engineering (ICME) of Generation Three Advanced High Strength Steels*," Symposium ICME Infrastructure Development for Accelerated Materials Design: Data Repositories, Informatics, and Computational Tools, TMS, Nashville, TN.
- Hector, Jr., L.G. (2015); "*Integrated Computational Materials Engineering (ICME) of Generation Three Advanced High Strength Steels*," ASM International Detroit Chapter Meeting

LSTC

- Stander, N. (2015); Basudhar, A.; Basu, U.; Gandikota, I.; Savic, V.; Sun, X.; Choi, K.S.; Hu, X.; Pourboghrat, F.; Park, T.; Mapar, A.; Kumar, S.; Ghassemi-Armaki, H.; Abu-Farha, F.; Chen, M. "*Multi-scale parameter identification using LS-DYNA and LS-OPT*"; Proceedings of the 10th European LS-DYNA Conference.

Material Model Development, Calibration and Validation

Brown University

- Srivastava, A.; Ghassemi-Armaki, H.; Sung, H.; Chen, P.; Kumar, S.; Bower, A.F.; "*Micromechanics of plastic deformation and phase transformation in a three-phase TRIP-assisted advanced high strength steel: Experiments and Modeling*"; Manuscript submitted to Journal of Mechanics and Physics of Solids

Clemson University

- Abu-Farha, F. (2015); Alturk, J.; Hu, S.; Mates, W.; Luecke, L.; Zhang, J.; Carsley, J.; Ming, C.; Hector Jr., L. "*A Quantitative Comparison between Deformation Measurements with Different Digital Image Correlation Systems: Are we Reading the Same Strains?*"; Presented at the 2015 Society of Automotive Engineers World Congress.
- Hu, J. (2015); Abu-Farha, F.; Hall, J.; Hector Jr., L. "*Investigation of Temperature Effects on the Tensile Deformation Characteristics of a Quenched and Partitioned Steel using Digital Image Correlation*"; Presented at the 2015 TMS Annual Exhibition.
- Hu, J. (2015); Abu-Farha, F.; "*A Comparison between Different Digital Image Correlation based Techniques for Determining the Forming Limits of Sheet Metal*"; Presented at the 2015 Society of Automotive Engineers World Congress.
- Hu, J. (2015); Abu-Farha, F.; "*Adiabatic Heating and Its Effects on Material Deformation during Stamping of Quenched and Partitioned Steel*"; Presented at the 2015 Society of Automotive Engineers World Congress.

- Hu, J. (2015); Abu-Farha, F.; "*On the Use of Digital Image Correlation for Studying Deformation and Failure of Lightweight Materials at Various Temperatures and Rates*"; Presented at the 2015 Society of Automotive Engineers World Congress.
- Hu, J. (2015); Abu-Farha, F.; "*Developing the Forming Limit Curves for QP980 Steel Sheets*"; Presented at the 2015 Society of Automotive Engineers World Congress.
- Hu, J. (2015); Zhang, N.; Abu-Farha, F. "*Revealing Dynamic Banding during High Temperature Deformation of Lightweight Materials using Digital Image Correlation*"; Presented at the Society of Experimental Mechanics 2015 Annual Conference.
- Hu, X. (2017). Sun, X.; Hector, Jr., L.G.; Ren, Y.; "*Individual Phase Constitutive Properties of a TRIP-assisted QP980 Steel from a Combined Synchrotron X-ray Diffraction and Crystal Plasticity Approach*"; *Acta Materialia* 132, pg 230-244.
- Mates, S. (2015); Abu-Farha, F. "*Dynamic Tensile Behavior of a Quenched and Partitioned High Strength Steel using a Kolsky Bar*"; Presented at the Society of Experimental Mechanics 2015 Annual Conference.
- Abu-Farha, F. (2017); Hu, X.; Sun, X.; Ren, Y.; Hector, Jr. L.G.; "*Mechanical Stability of Austenite and Localized Phase Transformation in Third Generation Advanced High Strength Steels*"; *Met. Mat. Trans. A,* in review.

Colorado School of Mines

- Matlock, D. (2015); Thomas, L.S.; Taylor, M.D.; De Moor, E. Speer, J. "*Microstructural Developments Leading to New Advanced High Strength Sheet Steels: A Historical Assessment of Critical Metallographic Observation*"; The 2015 IMS Henry Clifton Sorby Award Lecture. The abstract citation is: Microsc. Microanal. Vol. 21 (Suppl 3), 2015, pp. 5-6.
- Rana, R. (2014); Gibbs, P.J.; De Moor, E.; Speer, J.; Matlock, D. "*A Composite Modeling Analysis of the Deformation Behavior of Medium Manganese Steels*"; Steel Research International, Special Issue: High Manganese Steels 2014, Vol. 86, No. 10, 2015, pp. 1139-1150.
- Rana, R. (2015); Gibbs, P.J.; De Moor, E.; Speer, J.; Matlock, D. (2015) "*A Composite Modeling Analysis of the Deformation Behavior of Medium Manganese Steels*"; Steel Research International, Vol. 85, 2015, currently available on-line DOI: 10.1002/srin.201400577.
- Rana, R. (2015); De Moor, E.; Speer, J.; Matlock, D.; "*Austenite Stability Controlled Mechanical Behavior of a Medium Manganese Transformation Induced Plasticity Steels*"; Presented at International Conference on Frontiers in Materials Processing, Applications, Research & Technology (FiMPART'15).
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3GAHSS Experimental Heats

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Design Optimization

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B. Technologies / Techniques

The following technologies and techniques have been developed since project inception:

- Two 3GAHSS grades were developed and produced. Production of these materials was scaled up from laboratory heats of approximately one pound to fifty-pound laboratory heats and finally in 150-pound production-like heats.
- The initial heat treatment of the Exceptional Strength, High Ductility steel was initially a limited salt bath process. An annealing simulator was used for the production-like heats suggesting industry potential for making this steel.
- Developed a new test methodology for dynamically measuring the transformation of retained austenite to martensite by coupling digital image correlation, uniaxial tensile testing, and high energy X-Ray diffraction.

C. Status Reports

- The project ended on March 31, 2017.

D. Media Reports

- The following media reports were released since project inception:
    - On January 5, 2017, USCAR released an announcement entitled, "USAMP Team Makes Significant Strides in Development of Third-Generation Advanced High-Strength Steels"

E. Invention Disclosures

- No inventions were disclosed since project inception.

F. Patent Applications

- No patent applications were submitted since project inception.

G. Licensed Technologies

- No licensed technologies were submitted since project inception.

H. Networks / Collaborations

- In addition to the project team, the following networks or collaborations were developed since project inception.
    - The team was granted use of Argonne National Laboratories Advanced Photon Source High-Energy X-Ray Diffraction to conduct work on material characterization and fracture analysis.
    - The team was awarded time at the National Renewable Energy Laboratory High Performance Computing center to conduct design optimization.

I. Websites Featuring Project Work or Results

- No websites featuring project work or results were developed or updated since project inception.

J. Other Products

- No other products were produced since project inception.

K. Awards, Prizes, and Recognition

- The American Metals Market awarded the project an "Innovative Process" award at its annual award ceremony on June 27, 2017 in New York City, New York.

SECTION VI: FOLLOW-ON FUNDING

- The project is complete and there is no follow-on funding. All funding is included in the Award Proposal and the approved budget is included in the Award.

SECTION VII: RECIPIENT AND PRINCIPAL INVESTIGATOR DISCLOSURES

- There are no recipient or principal investigator disclosures to report.

SECTION VIII: CONFLICT OF INTERESTS WITHIN PROJECT TEAM

- There are no conflicts of interest to report.

SECTION IX: PERFORMANCE OF WORK IN THE UNITED STATES

All work except the following was performed within the United States:

- CANMETMaterials produced experimental heats of the two 3GAHSS heats. Each heat was approximately 450 pounds and was hot and cold rolled into strips. The High Strength, Exceptional Ductility steel was fully processed at CANMET but the Exceptional Strength, High Ductility was sent to McMaster University for heat treatment.

SECTION X: PROJECT SCHEDULE STATUS

The Milestone Log is shown in Table 8 below. All milestones were fully completed by the project end.

Table 9: Milestone Log

No.	NETL Milestone Title and Description	Planned Completion	Actual Completion

		Date	Date
1	**Selection of Body Structure components/subassembly and identification of baseline materials complete**	**9/30/2013**	**9/15/2013**
2	**Meso-scale Computational Predictions:** **Validated meso-scale computational predictions from subtasks 5, 6 and 7.**	**1/31/2015**	**1/30/2015**
3	**Macroscopic Constitutive Models:** **Develop and validate macroscopic constitutive models for deformation and fracture**	**1/31/2016**	**3/31/2017**
4	**Initial Forming Model:**	**1/31/2016**	**1/19/2016**
5	**3GAHSS Forming Model**	**1/31/2017**	**1/31/2017**
6	**Estimated Joint Properties**	**7/31/2016**	**7/31/2016**
7	**Baseline Assembly Design Defined**	**1/31/2014**	**1/16/2014**
8	**Optimized Design**	**3/31/2017**	**3/31/2017**
9	**ICME Model**	**3/31/2017**	**3/31/2017**
10	**Data Model**	**3/31/2017**	**3/31/2017**
11	**Technical Cost Model**	**3/31/2017**	**3/31/2017**

SECTION XI: BUDGET STATUS – PRIME RECIPIENT

- The project is complete.

SECTION XI.B: BUDGET STATUS – FFRDC / GOGO

- Not applicable.