ARL-SR-0427 ● APR 2020

Report of the 2019 Department of Defense Steel Summit

by Krista R Limmer, Daniel M Field, and Andelle G Kudzal, Katherine M Sebeck, Eric J Payton, and Matthew C Draper

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Report of the 2019 Department of Defense Steel Summit

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
April 2020	Special Report	7–8 November 2019

4. TITLE AND SUBTITLE Report of the 2019 Department of Defense Steel Summit	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Krista R Limmer, Daniel M Field, and Andelle G Kudzal, Katherine M Sebeck, Eric J Payton, and Matthew C Draper	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CCDC Army Research Laboratory ATTN: FCDD-RLW-MF Aberdeen Proving Ground, MD 21005	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-SR-0427
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
ORCID ID(s): Krista R Limmer, 0000-0003-4775-5876

14. ABSTRACT
The third annual Department of Defense Steel Summit was held 7–8 November 2019 at Aberdeen Proving Ground, Maryland, to bring together the government, industry, and academic communities working on defense-relevant steel development in order to more rapidly advance material development and implementation. This report contains the meeting agenda, abstracts, summary, and attendance roster. Appendices with copies of briefings and posters presented during the meeting are also included.

15. SUBJECT TERMS
steel, alloys, processes, defense applications, characterization, modeling, properties, performance

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Krista R Limmer
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (Include area code)**
Unclassified	Unclassified	Unclassified	UU	78	(410) 306-2039

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. About the Meeting

1.1 Meeting Overview

The 2019 Department of Defense (DOD) Steel Summit, held on 7–8 November 2019 at the Mallette Training Facility in Aberdeen Proving Ground, Maryland, was hosted by the Weapons and Materials Research Directorate (WMRD) of the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL). This was the third annual DOD Steel Summit, which stemmed from an expansion of the US Air Force Research Laboratory's (AFRL) Steel Munitions Summit. The primary objective of the summit was to bring together defense, industry, and academic communities engaged in the production, use, and research of steel alloys relevant to military applications to better advance the development and integration of steels to accomplish current and future Warfighter needs.

The 2019 summit comprised technical briefings, panel discussions, and poster sessions, as outlined topically in Table 1. The 19 technical briefings were presented in 5 different topical sessions and 4 panel discussions were held at the conclusion of the relevant technical sessions. There were two poster sessions during which 19 posters were presented by their authors. Dr Scott Schoenfeld, WMRD Chief Scientist and Senior Research Scientist for Terminal Ballistics, welcomed the attendees at the opening of the summit.

Table 1 2019 DOD Steel Summit agenda

Date	Start time	Description
7 NOV 2019	0830	Opening and Welcome
	0845	Session A: Development and Integration of New Steels in DOD Assets
	1130	Panel: Development and Integration of New Steels in DOD Assets
	1200	Lunch Break
	1315	Session B: Castings
	1430	Poster Session
	1530	Session C: Welding
	1645	Panel: From Material to Materiel: Casting Qualification, Welding, and Machining
	1715	Conclude Day 1
	1830	No-Host Dinner at the Greene Turtle
8 NOV 2019	0830	Session D: High Alloy Steels
	0945	Poster Session
	1045	Session D (continued)
	1135	Panel: Alloy Development and Characterization Challenges
	1205	Lunch Break
	1315	Session E: Additive Manufacturing
	1430	Panel: Agile Manufacturing in the DOD
	1500	Wrap-Up and Conclude

1.2 Meeting Attendance

The summit was attended by 140 persons representing more than 60 different government, academic, and industrial organizations (Appendix A: Meeting Attendance). The value of the summit to the attendees was enhanced by the experience and diversity brought to the briefings, through the posters and discussions by the attendees. The organizations represented by panelists or authorship of oral and poster briefings are shown in Fig. 1. A group photo was taken following the poster session on the second day (Fig. 2).

Fig. 1 Logos of organizations represented by panelists or authorship on oral and poster briefings

Fig. 2 Group photo from the second day of the DOD Steel Summit (93 of 140 attendees pictured)

Over the past three years, more than 200 different people have attended at least one DOD Steel Summit, with an increasing number attending each year as the summit content becomes more inclusive and the event becomes better publicized. The breakdown of new and returning attendees is shown in Fig. 3.

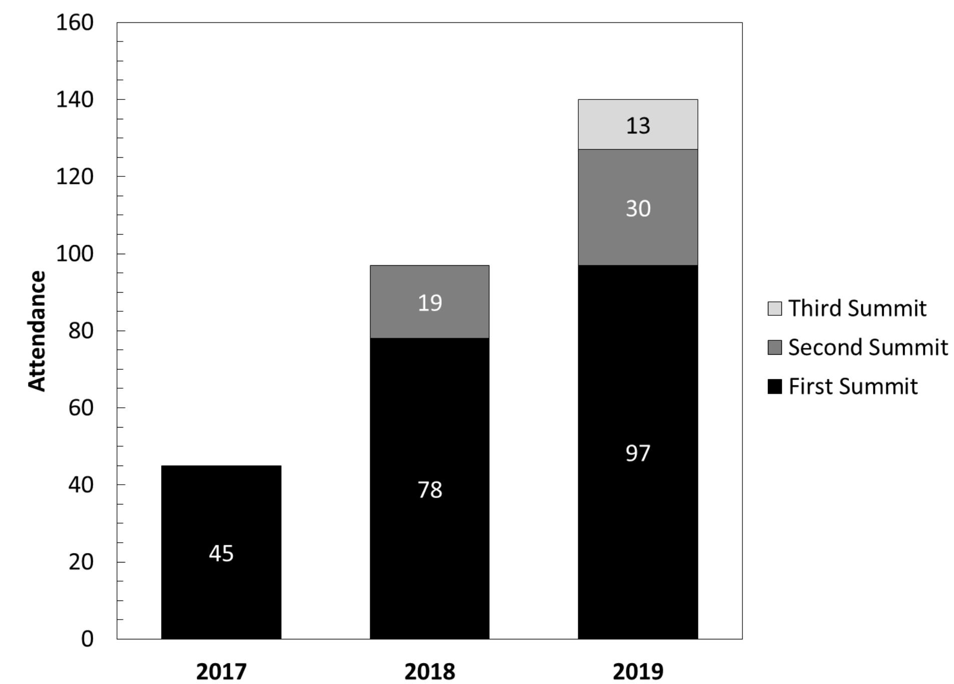

Fig. 3 DOD Steel Summit attendee profile history: new and returning attendees

The meeting attendee affiliation has consistently included the DOD, other government agencies (OGAs), industry, and academia (faculty, postdoctoral associates, and students), although the balance of each of these sectors has shifted, as seen in Fig. 4.

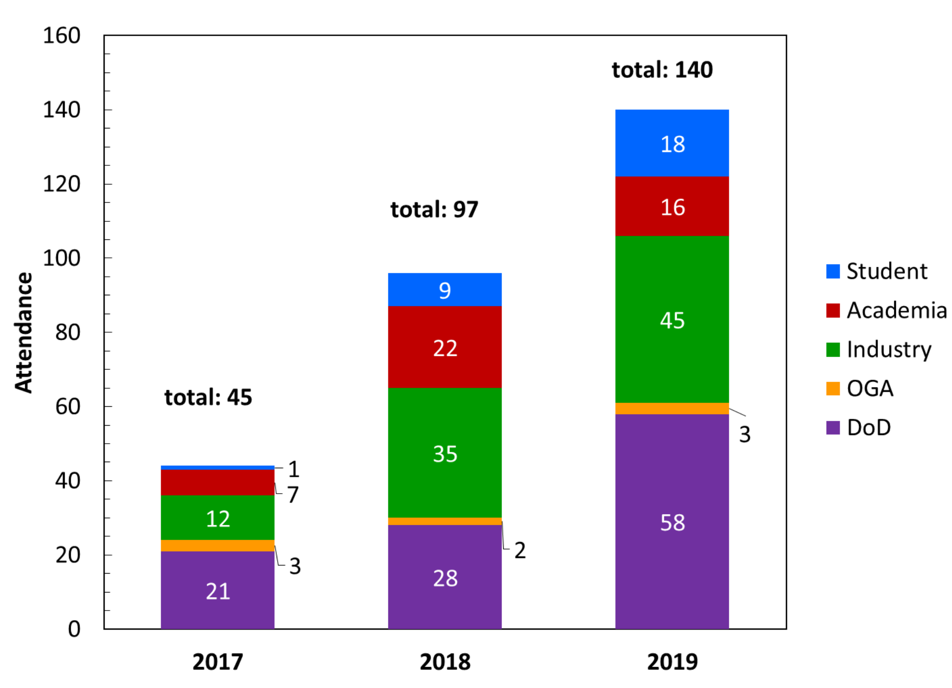

Fig. 4 DOD Steel Summit attendee profile history: affiliation

1.3 Attendee Feedback: Post-Event Survey

A post-event survey was sent out to all attendees the week after the Steel Summit to gauge the utility of the summit in various aspects as well as aid in planning future summits. Over the following two months, 71 responses were received from the 140 attendees indicating a 51% response rate. Attendees were invited to answer in a freeform format what their "primary objectives" were for the summit as well as what their "most important takeaway" was after having attended the summit. The primary reasons for attending the summit were the following: network, learn about current DOD steel research and research trends, and identify DOD material and technology development needs. The key takeaways reported by the respondents largely suggested that the attendees were successful in these objectives, with respondents commenting on their newly established network contacts, better understanding of service-specific constraints and application spaces, and optimism for the future of steel development and implementation in the DOD.

Respondents also commented on the things that went well and were generally consistent with responses such as the following:

- “It felt professional and well run. I liked the panels and poster section and the times when candid conversation was able to occur.”
- “Excellent mix and balance among DOD metallurgists, specifiers, steel suppliers, steel users, and academics. And the not-too-formal attitude taken by the moderators that facilitates questions and exchanges.”
- “Good and growing venue. Clearly this event is filling a vacuum.”
- “Gathering experienced scientist and engineers that push really interesting discussions.”
- “You have a winner. Make sure leadership knows. Let us know if we need to carry the message to anyone. Build on it. I guarantee you the Warfighter is going to see benefit form this is innovation speed, cost, and deployment.”

The feedback for improving the value of the summit was also beneficial but more scattered and often contradicted other suggestions. The organizers of the 2020 DOD Steel Summit will be working with this and other feedback as they begin the organization process.

To better interpret the survey responses, the respondent profile was also analyzed. Most of the responses were from individuals who attended both days of the Steel Summit (Fig. 5) and were generally more closely affiliated with the Army, although both the Air Force and Navy had substantial representation as well (Fig. 6).

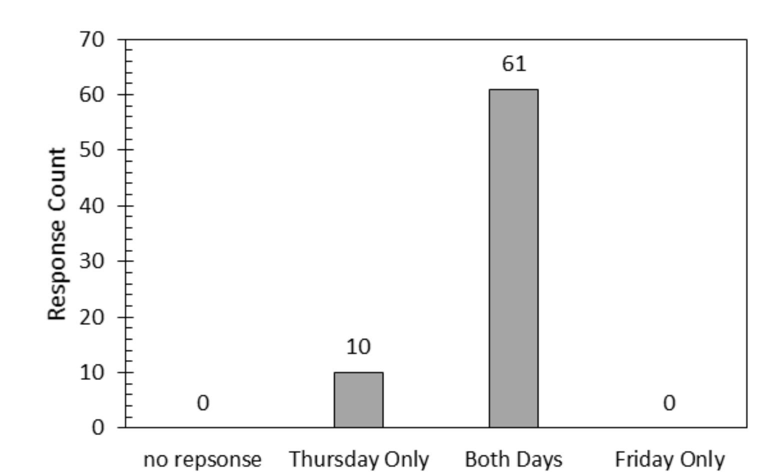

Fig. 5 Daily attendance as reported in the post-event survey

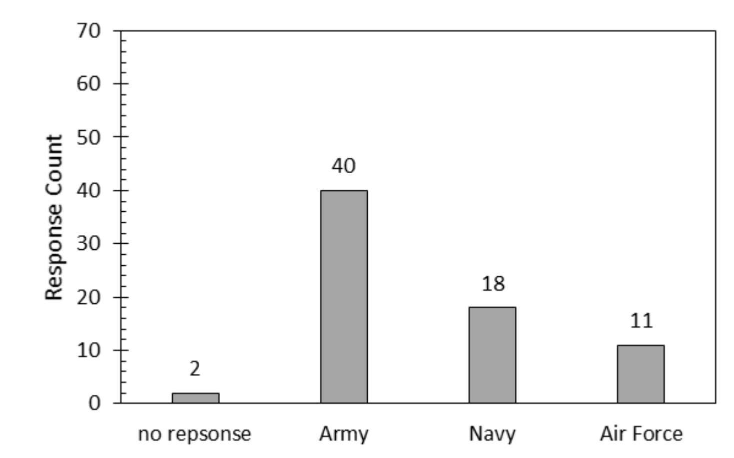

Fig. 6 Primary service affiliation as reported in the post-event survey

The survey respondents came from a broad range of experience both in the field and formal education (Figs. 7 and 8), as well as a wide geographic range (Fig. 9).

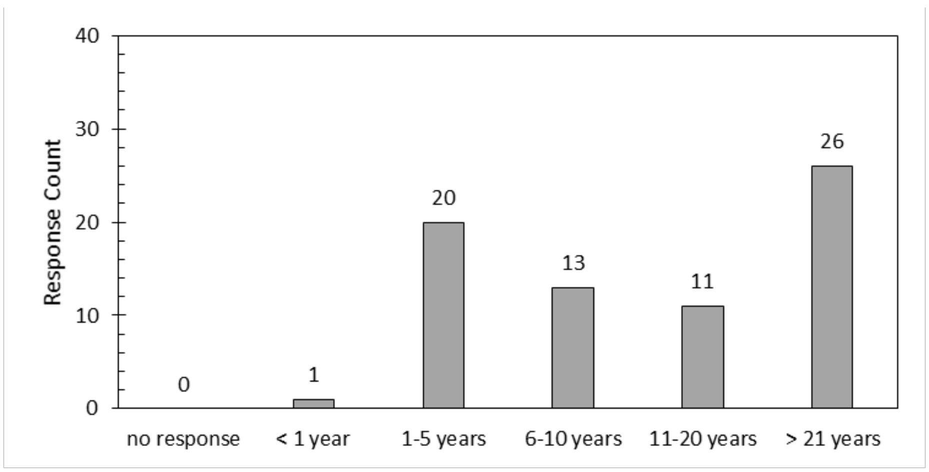

Fig. 7 Experience level of attendees based on the post-event survey

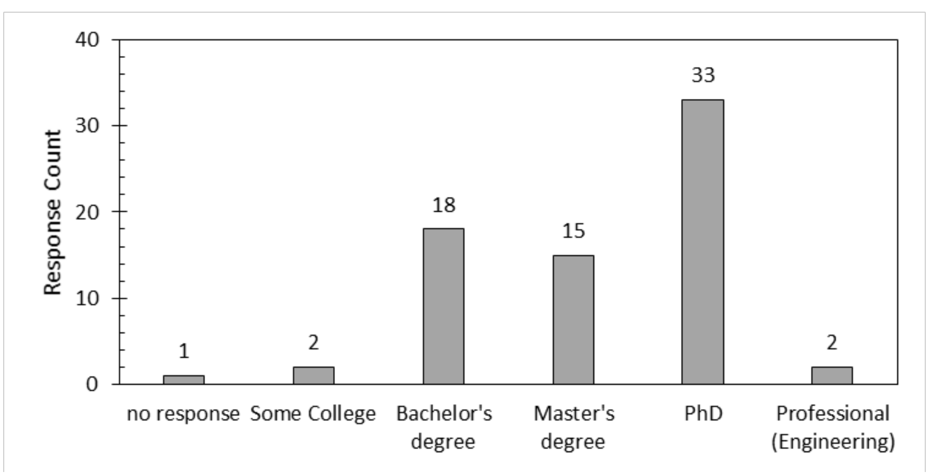

Fig. 8 Attendee education level as recorded by a post-event survey

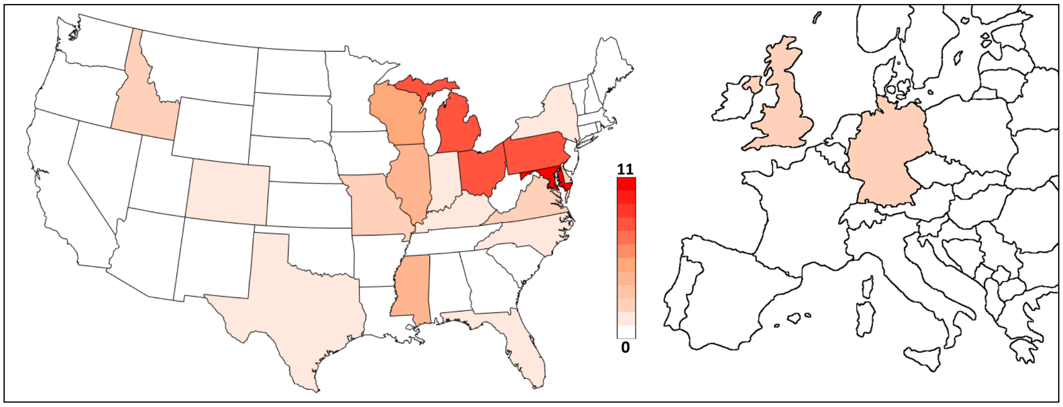

Fig. 9 Geographic distribution of attendees as recorded by the post-event survey

2. Technical Content

The two-day summit was divided into technical sessions with related oral briefings followed by a panel discussion and one poster session break each day, as outlined earlier in Table 1. The first day's morning session was related to the "Development and Integration of New Steels in DOD Assets" and the afternoon session's oral briefings were on the topics of casting and welding, with a closing panel discussion on "From Material to Materiel: Casting Qualification, Welding, and Machining". The second day of the summit opened with oral briefings on "High Alloy Steels" followed by a panel discussion on "Alloy Development and Characterization Challenges". The final technical session and panel discussion of the summit were on the topics of "Additive Manufacturing" and "Agile Manufacturing in the DOD".

2.1 Panel Discussion Summaries

A summary of each of the panel discussions along with the names of the panelists is provided. This is not intended to be a transcript of the dialogue, rather an overview of the topics discussed.

2.1.1 Development and Integration of New Steels in DOD Assets

Panelists:

- Jonathan Montgomery (Emeritus Researcher, CCDC Army Research Laboratory)
- Brian Placzankis (Specifications and Standards Lead, CCDC ARL)
- Manny Gonzales (Materials Engineer, AFRL/Materials and Manufacturing Directorate [RX])

Moderator: Matthew Draper (Materials Engineer, Naval Surface Warfare Center Carderock Division [NSWCCD])

The panel led off by considering the challenge of transitioning new materials developments to DOD assets, offering thoughts on strategies for bridging the "valley of death" between materials technology development and application. One proposed approach was to get the full specifications and data collected on the program manager's (PM's) radar so that a technology can "creep" into use if it is not immediately inserted. From the perspective of cost, it is easy to insert materials that are twice as good and cost half as much; however, when there is also a cost increase associated with the new material, it is often assumed that the additional initial cost translates to a proportional increased cost in all other material handling aspects, without a discount for increased longevity. Another consideration beyond cost and performance is risk reduction. The DOD is inherently risk-averse; materials that do not fit into existing specifications make the process of transition from basic research to applied tools to implemented technology higher risk and require more vocal advocates in the PMs. Also, we must consider whether the technology is a "tech pull" or a "tech push". Tech pulls are generally being developed and implemented in conjunction with a PM and/or original equipment manufacturer (OEM), which facilitates the development, testing, and evaluation processes to meet their rapid insertion timelines. Tech pushes require more effort on behalf of the company or organization developing the new material, process, or component. Coming to events like the Steel Summit to network is critical to get the technology on the DOD's radar, evaluate properties, gauge avenues for implementation, and/or initiate a more thorough evaluation with DOD partners. Partnerships with DOD research laboratories or centers can be completed through a cooperative research and development agreement (CRADA) or a test service agreement (TSA).

From the supply chain perspective, it is a risk to make specialty components with high-specification minimum requirements that have no other customers if the component does not meet the DOD minimums. Specified values such as V50s are critical numbers that must be met; however, there may be circumstantial waivers for other criteria, but these are difficult to obtain due to the risk associated with accepting a component that has not met all of the specifications. One of the challenges is then finding the DOD personnel who have the authority and are also willing to sign off on waivers. There was some interest expressed in developing fit-for-service qualification standards for noncritical components.

Finally, the panel considered a comment from a representative of a major defense contractor regarding frustrations in getting DOD components to follow up on potential technology transitions for which there is strong support from the National

Defense Industry Association. DOD civilians on the panel noted that DOD research laboratories (which take the lead in organizing this summit) are often not well positioned for assisting in interactions with DOD program offices. DOD manufacturing technology organizations may contain the personnel with the right connections and focus for performing this role, so their participation in summits such as this one are critical for developing the professional networks that facilitate such technology transitions.

2.1.2 From Material to Materiel: Casting Qualification, Welding, and Machining

Panelists:

- Matthew Draper (Materials Engineer, NSWCCD)
- Demetrios Tzelepis (Materials Engineer, CCDC Ground Combat Systems Center [GVSC])
- Jason Wolf (Materials Engineer, AFRL/RX)
- David Poweleit (Vice President of Technology, Steel Founder's Society of America [SFSA])

Moderator: Daniel Field (Materials Engineer, CCDC ARL)

The first major discussion point for this panel session was the topic of machining and how to include this critical step earlier in the materials development cycle. DOD applications often require high-toughness and high-strength alloys that make machining increasingly difficult. The panelists spoke toward their perspectives on removing this bottleneck. In 1906, FW Taylor introduced an empirical approach to establish optimum metal cutting conditions, which is still considered to be significant. Even today, the community is still working to nail down these processing windows outside of the current Edisonian practice. The integrated computational materials engineering (ICME) paradigm has generated a movement toward leveraging models to ease the experimental burden, but to date, this has not been sufficiently applied to machining of metals. Encouraging academic and industrial partners to consider machining earlier in the material development cycle is one avenue to reduce the bottleneck. Another approach would be to explicitly investigate cutting-tool development. Some DOD components may be able to be heat treated after finish machining, although depending on the tolerances allowed in the components and scale of the machined parts, this may not be an option. Electrical discharge machining (EDM) is another potential solution for difficult-to-machine components, although the OEMs generally do not use this process because it is comparatively slow and expensive. Near-net shape castings was also offered as a potential solution.

On the topic of quality control and qualification standards, one discussion point was that mandating additional inspections that seem superfluous implies that the system lacks integrity. One example given was taking a picture of a component in the furnace at the beginning and end of the heat treatment cycle. Many of these somewhat strange requirements stem from an incident in the past that may or may not still be a concern. Such qualification standards should be reconsidered before the reasons for their implementation are lost, especially if the workers who added these requirements retire. Such legacy requirements should be appropriately revised and/or removed. Stewarding 1960s technology is not sustainable and prevents the DOD from being competitive in the future—we must position ourselves to be more agile. An example of this shift is the Navy moving away from qualifying each cast component (e.g., 140 components on a Virginia class sub) to qualifying a single scalable part for universal qualification of a supplier for a specific alloy with a specific range of section thicknesses. A long-term vision of quality control (QC) may involve industries relying on the Internet of Things (IoT) and validating models using a significant body of process data. Because each service has different specific needs, a tri-service approach to solving these different dogmatic concerns may require implementing these design tools, philosophies, and QC measures in lower-risk applications (e.g., materials for unmanned systems).

2.1.3 Alloy Development and Characterization Challenges

Panelists:

- E Buddy Damm (Timken Steel)
- Dana Frankel (QuesTek Innovations)
- Fred Fletcher (ArcelorMittal, retired)
- Charlie Monroe (University of Alabama–Birmingham)

Moderator: Matthew Draper (Materials Engineer, NSWCCD)

Alloy design methods have evolved over the past few decades to include more low-length-scale experimentation, advanced simulations and computational methods, and coupled experimental–computational approaches such as ICME. An increasing amount of data is being generated, and databases and data interpolation tools including machine learning (ML) are becoming more common, raising questions about uncertainty quantification (UQ) of these computationally derived new alloys and products. This panel discussion probed many of these subtopics, with panelists offering their view of where alloy development and characterization currently are and where they should be as we continue to advance.

ICME, the recent paradigm for materials discovery and development, is being implemented in many academic and industrial settings to speed up the material discovery and implementation processes. ICME can be considered as one of the tools in the engineering toolbox—not a replacement for the other tools that already exist. ICME can be valuable to learn what is important in developing new materials but it is not going to replace engineers, just enhance their ability to approach problems in different ways. One of the keys to getting the desired ICME synergy is to establish the right team consisting of experts in modeling and experimental methods. Early in the design cycle, both parties should sit down and define what the relevant outcomes should be. In general, the modeling space evaluations should be efficient and enable down-selections to be validated experimentally. New computational tools are constantly being developed, with increasing levels of detail. When selecting specific tools to apply in the ICME framework, they must be fast enough to "integrate", not just shift the workload from the experimental to the computational; the efforts should be synergistic. It is also important to keep the target performance metrics in mind when designing or optimizing an alloy and know if the optimization is toward the limit of the manufacturing constraints or to actual performance objectives.

Current gaps and needs in the ICME community center around the balance between increasing complexity while producing faster outcomes. The current practice of ICME in the steel community is generally an attempt to fill in the middle ground between low-length-scale simulations (e.g., density functional theory) to make the models more capable and the experiments to calibrate the models to more closely reflect reality; the efficient linkages and integration between the computational and experimental tools are not well implemented. Although many computational tools exist to predict new alloys, the questions of properties and performance generally remain unanswered, due in large part to missing microstructural information (precipitate size, distribution, and morphology) or neglecting metastable processing conditions (e.g., quench and tempering response and kinetic constraints). More reliable prediction of these quantities and the subsequent linkage of this information into higher-length-scale models (e.g., finite-element method) to effectively predict their effect on properties and performance are critical. Model calibration is a critical piece of the ICME paradigm and depends on a reliable set of accurate evaluations. There is not currently a series of high-throughput tools to generate these data in an industrial setting to accelerate the evaluation of new alloys and products. The community should consider high-throughput testing and parametric studies alongside the more common deep-dives routinely investigated. Another approach to building these tools and the workforce may require training starting at the undergraduate level to become engaged with this method.

One approach to making more efficient models is to employ ML tools, with the expectation that ML methods will be used to enhance the mechanistic understanding rather than becoming a black-box shortcut. ML is commonly used in materials discovery, but is not often applied in the development space. ML is a powerful tool for interpolating and identifying areas of high return that are poorly understood or highly complex. Some suggested applications of ML in the defense-steel community include the following: predicting ballistic performance, optimizing advanced manufacturing (AM) processing parameters for new alloys and components, and predicting when low-length-scale experimental techniques (e.g., transmission electron microscopy [TEM], atom probe tomography [APT]) should be used. A challenge in directly applying the ML and ICME approaches is obtaining the necessary stochastic data. Metallurgists generate a lot of data that may be considered as "sparse data" rather than "big data", as all aspects of the data set are not complete or directly comparable due to differences in testing methods and/or requirements for the specific application.

One of the risks of ML is that it may hide the underlying physics and mechanics. More risk is generally assigned to materials and components predicted by ML instead of those predicted by experimental experts or more traditional calculation of phase diagram (CALPHAD) methods. Defining and reducing uncertainty when implementing new materials requires more statistical data and analysis. In-process data that feed into IoT could also be used to evaluate and reduce risk by reproducibly processing steels. Some of the "crazy" ML predictions are also worth further investigation if there is time and space to evaluate the outcomes. UQ models should not be neglected. Without quantifying the uncertainty in the models, they will remain in the "science" realm and not be adopted within "engineering" applications.

Metallurgists and materials scientists are not generally well versed in interpreting databases and their uncertainty. This is one area where funding to fill in tools or aid in education of the current and future workforce may be beneficial. Materials societies no longer focus on the development of public databases built on industry knowledge. The steel industry operates for profit and generally keeps more data internal to allow them the cutting edge on the market. When things do not make it to the market, the data fade until someone else rediscovers them years or even decades later. There also are fewer trained metallurgists in the workforce. There are still some consortium and centers at universities that bring together steel companies to build this foundational knowledge. Commercialized databases are generally proprietary, limiting the ability of the end-users to adjust the models to better fit with novel systems not used in the database training set and limiting the opportunity for advancement.

A challenge in steel development is to collect more effective data that are both cost and time efficient. Characterization of an alloy must be relatively complete yet also inexpensive and fast. Much of the science of metallurgy is in understanding the processing-structure–property-performance (PSPP) relationships, but from an engineering standpoint, there is a need for a measurable property that is directly related to the performance, a critical consideration of steel in defense applications. The migration of alloy development toward nanoscale structures and features that require APT and TEM to resolve has shifted the required tools from the hands of the industrial community into academic and research laboratories. Bridging this gap in the age of IP protections is key. If an industrial partner wants to use these tools for alloy development, they need to spend funds outside and seek additional funding from the consumers as well. Automated scanning electron microscopes (SEMs) for inclusion content are not uncommon in the industrial setting, but if more advanced tools (APT, TEM, synchrotron, etc.) are the critical tools moving forward, they must become more routine and ubiquitous. The lingering questions to the community are the following:

- How can we move the science and understanding forward with the smallest amount of data possible?
- What characteristics need to be measured and what techniques need to be developed and implemented to accomplish this?
- What is the most efficient way to set up research and development (R&D) centers?

2.1.4 Agile Manufacturing in the DOD

Panelists:

- Kyu Cho (Manufacturing Science and Technology Branch Chief, CCDC ARL)
- Vikas Sinha (Materials Engineer, AFRL/RX and UES Inc.)
- Alyssa Gafner (Materials Engineer, CCDC GVSC)
- Russ Cochran (Boeing)

Moderator: Eric Payton (Materials Engineer, AFRL/RX)

There is a general interest across the DOD in using AM techniques to promote readiness and modernization by decreasing the design limitations imposed by traditional manufacturing methods. System performance can be rapidly improved by combining advanced materials (lighter and/or stronger) with optimized complex parts, and, ideally, the time scale for implementation can also be shortened. “Advanced Manufacturing” was recently defined within Army Directive 2019-29 “Enabling Readiness and Modernization Through Advanced Manufacturing” as methods to enable modernization while simultaneously enhancing readiness by delivering tools to the Warfighter as fast as possible while maintaining quality and low cost:

> “Advanced manufacturing refers to activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences. It encompasses new ways to manufacture existing products and the manufacturing of new products resulting from advances in technology. It includes, but is not limited to, additive manufacturing (also known as three-dimensional (3D) printing), artificial intelligence, robotics, and advanced composite materials.” (US Army 2019)

AM methods are also intended to “address the readiness challenges posed by parts obsolescence, diminishing sources of supply and sustained operations in austere environments” (US Army 2019). Currently, only polymers are being printed in the field, not metals, and only for noncritical components (e.g., lens covers). One of the challenges for metals AM is the increased material and machine costs compared to polymer AM and traditional manufacturing methods. A strong case will need to be made for metals AM, including identifying specific parts that will likely need to be a low-risk insertion. A part of that consideration is the quality of builds currently produced in laboratory environments by highly trained professionals and the transition to less than ideal conditions.

As with most other traditional processing routes, there is the competition between cost and performance, and the effort to obtain the required properties and performance in a cost-competitive manner. One considerable advantage for AM in the field is that for low-risk components that may only require base functionality not superior performance; building the part onsite may be the low-cost option. The Army is largely cost-driven for components and not able to justify some of the high costs per component as the Air Force.

The long pull for AM is to get consistent properties from different alloys as well as across different vendors and platforms. There is not currently a large powder supply base, but even among those there is a large variation in the properties produced when printed on the same machine with the same parameters. This leads to a hesitancy to implement AM-produced components due to risk aversion. There must be some well-defined set of powder property allowables from a strong supply base. Ideally, AM production will rely on the supply base rather than in-house production, but the base has not been developed yet. Similar to the early days of composites, everyone is keeping the processing in-house until the supply chain becomes stable and reliable enough to make quality repeatable powders and printed components. This is a lesson already learned; let's not repeat the old mistakes.

A challenge for AM is the large uncertainty in the produced components that drives increased per part costs due to elevated levels of required testing and qualification for certification. This is due in part to not having a consistent method to qualify and certify parts for service. One area of improvement would be to develop and implement effective nondestructive testing (NDT) techniques. Most of the current techniques are affected by surface roughness requiring on-the-fly mechanical smoothing and still producing noisy results. Especially in large components, lack of fusion between the layers is a concern. NDT methods must be advanced to give people the confidence to use the parts. Compared with titanium (Ti) alloys, ex-situ characterization of steel components with computed tomography (CT) is limited due to the higher density. Another qualification pathway may include relying on *in situ* monitoring tools to identify the build quality of a part, although these tools are challenged by the high melting temperature of steel. ARL is looking toward developing a center to better address part qualification through pooling of resources and personnel in a collaborative space with industry, academic, and government all represented.

Beyond the overall framework for building and certifying components, the physical metallurgy of steel AM components is relatively young compared to traditional steelmaking. Prediction of the microstructure throughout the build by *in situ* monitoring is the stretch goal and will facilitate the seamless transferability of AM production of an alloy from one machine to another. Development of the combined knowledge base of ferrous metallurgy and AM methodology to understand how processing parameters affect the builds (i.e., PSPP relationships) must be developed further through the building of teams to rapidly produce, evaluate, and optimize AM, but the available workforce with these skill sets is limited. Funding has been increasing for AM and will likely continue to increase, this can be leveraged to grow the workforce and understanding.

When considering the ferrous alloys being used for AM currently, like other near-net shape production processes, they are all casting alloys. There are not currently any alloys designed specifically for AM, although some academic and corporate R&D centers are starting to work toward this. Steels represent a unique challenge for AM due to their tempering response not seen in Ti alloys or nickel superalloys. The high cooling rates observed in AM represent a quench followed by subsequent layer processing producing a tempering during the lower temperature heating. Another factor of importance for steels that must be considered is decarburization, similar to aluminum loss in the printing of the Ti-6Al-4V alloy.

2.2 Technical Abstracts

An abstract for each of the technical oral briefings and posters at the summit has been included here in the representative section. Oral briefing abstracts are organized by chronological order presented in the respective technical sessions. Poster abstracts are presented in alphabetical order by title. Presenting authors are indicated in bold text. Briefing slide decks and posters that have been cleared for public release in print form have been included as separate appendices as denoted at the end of each abstract. Abstracts have not been edited and appear as submitted by the corresponding authors.

2.2.1 Session A: Development and Integration of New Steels in DOD Assets

2.2.1.1 Army Armor and Armament Steel Historical Perspective, Part 2

Jonathan Montgomery (CCDC ARL)

I will again speak on historical Army programs on steel armor, projectiles, and guns. These have been programs which have solved Army-unique problems using steel metallurgy. As is usually the case, some of these solutions have been more successful than others.

This time I will talk about the development of dual-hardness steel armor, steel small-caliber projectile cores, and the erosion of 13-8 Mo PH stainless steel in the 155-mm regenerative liquid propellant gun. Each of these are unique Army applications that have had unique solutions.

Briefing included as Appendix B. Army Armor and Armament Steel Historical Perspective, Part 2.

2.2.1.2 New Armor Steel Specifications - FeMnAl Case Study

Krista Limmer, Daniel Field, and Bryan Cheeseman (CCDC ARL)
Katherine Sebeck (CCDC GVSC)

The development and qualification of new armor steels is a rigorous process that can take many years even after the alloy is optimized at a laboratory scale.

The case of FeMnAl, a low-density steel being considered as a drop-in replacement for rolled homogeneous armor (RHA), is discussed here. As a highly alloyed steel it does not meet the MIL-DTL-12560 carbon equivalence requirement, thus it becomes a greater endeavor to develop a new armor steel specification than qualifying it according to the existing specification. In this briefing the history and current status of FeMnAl armor steel maturation is discussed and the process of qualifying steel as armor steel is described.

Briefing included as Appendix C. New Armor Steel Specifications – FeMnAl Case Study.

2.2.1.3 Ballistic Testing of the French ArcelorMittal Industeel MARS Armor Steels

William Gooch and Denver Gallardy (CCDC ARL)
Damien Delorme and Antoine Proust (ArcelorMittal Industeel of France)

The French steel industry has a long-established production history with similar military-grade steels to US armor steels under RHA or high-hardness armor (HHA) military specifications. This presentation, however, will examine the French MARS specialty armor steels that are not readily available in the US with baseline ballistic data that can be used for engineering design. These steels generally exhibit higher alloying and are either oil/water quenched or normalized by air-cooling. Thicknesses below 0.1875 inch (4.7 mm) are generally coil-based. Some grades were used to expand updates to current US Military Specifications and have passed US first article certification; many grades also offer a greater range of thicknesses than available under US military specifications or production. The specific grades to be discussed include:

- MIL-DTL-12560K/Amendment 1. The current RHA specification for combat vehicles was updated in November 2018 for Class 1 plate from 0.098 inch (2.5 mm)–6.00 inches (152.8 mm), but the major change was seen in MIL-DTL-12560K of December 2013 when Class 4a RHA was defined as a liquid quenched and tempered grade with Class 4b as normalized or air-quenched. MARS440 Class 4 plate is offered in both grades and have been designed in blast applications for belly plates; plate is available up to 80 mm. Ballistic testing used to generate the US acceptance tables will be provided.

- MIL-DTL-46100E/Amendment 3. The current HHA specification was updated in November 2018, but the major change was seen in Amendment 2 with the reduction of the minimum ordered thickness to 0.098 inch (2.5 mm). The French oil-quenched/die-clamped MARS500 HHA in thicknesses from 0.102 inch (2.6 mm)–0.169 inch (4.3 mm) were used to generate the new acceptance curves. MARS500 HHA is available in thicknesses to 150 mm.

- MIL-DTL-32332A. The current ultra-high-hardness armor (UHHA) specification was updated in November 2018 for thicknesses from 0.098 inch (2.5 mm)–0.63 inch (16 mm) in two classes with a minimum hardness of 570 Brinell Hardness Number (BHN). The initial 2009 specification was fully based on testing of UHHA plate from France, Sweden, and Germany with later testing for MIL-DTL-32332A with French coil grades. MARS 600 (Class 1) in thicknesses up to 80 mm and MARS650 (Class 2) UHHA grades in thicknesses to 16 mm are produced with hardnesses up to 650 BHN and monolithic welded armor structures have been produced from both grades. Ballistic certification data will be provided.

Briefing included as Appendix D. Ballistic Testing of French ArcelorMittal Industeel MARS™ Armor Steels.

2.2.1.4 SECURE Steels: Highest Protection for Civil and Military Applications

Ross Auten and Robert Holt (thyssenkrupp Steel North America)
Stephan Scharf and Axel Gruneklee (thyssenkrupp Steel Europe AG)
Matthew Burkins (Burkins Armor Consulting LLC)

SECURE steels are quenched and tempered, low alloyed, and fine-grained carbon steels, which are characterized by their hardness levels. Their field of application consists of ballistic and blast protection.

In the first section of this presentation, details regarding the available dimensions, production routes, as well as the mechanical and processing properties of SECURE, thyssenkrupp Steel Europe's ballistic steel brand, will be discussed.

This will be followed by summarizing recent achievements and findings regarding the ballistic and processing properties of SECURE 600:

- Results of first article testing according to MIL-DTL-32332 will be presented and compared. Additional ballistic results for typical threats, carried out by a well-known US company, will also be presented.

- Narrow radii bending tests were carried out on SECURE 600 at the application technology center at thyssenkrupp Steel Europe. This was followed by running ballistic tests at a well-known Dutch company with high-velocity armor-piercing rounds on the bending radii sections.

Briefing included as Appendix E. SECURE Steels: Highest Protection for Civil and Military Applications.

2.2.1.5 Rapid Rolling/Forming Schedule Development for Emerging Steels

Thomas Lillo and Henry Chu (Idaho National Laboratory)
Victor Burgess (CCDC GVSC)

Computational methods in alloy design is accelerating alloy discovery. However, computational methods for forming these emerging alloys are currently lacking and thermomechanical processing (TMP), e.g., rolling, forging, etc., must rely on past experience with closely related alloys. Failure of ingots during forming is costly as is development/refinement of TMP schedules. Development of deformation processing diagrams is one way of identifying appropriate combinations of temperature and strain rate to safely form a specific alloy. In this presentation, we demonstrate the approach on emerging alloy, AF9628, a relatively new steel alloy originally designed for Air Force ordinance applications. The alloy has been found to be low cost and high strength with considerable toughness. Such attributes may make this alloy suitable for ballistic armor applications. However, for plate, rather than casting, a forging is required and no rolling experience with this alloy exists. Therefore, the Gleeble 3800 universal testing machine was used to obtain elevated temperature, strain-rate dependent compressive stress–strain curves on small samples (10 mm diameter by 12 mm long). A deformation processing diagram was developed using the approach of Prasad, 2003 from which potential rolling schedules were developed. These candidate rolling schedules were simulated also on the Gleeble 3800—again, using small samples (10 mm × 15 mm × 20 mm)—using a plane strain configuration. The simulated rolling samples were assessed for defects and used to down-select a final rolling schedule. The down-selected rolling schedule was then applied to 102 mm thick, as-cast ingots to successfully obtain plates with thicknesses down to 6.4 mm (~94% reduction in thickness) for future assessment of the ballistic properties.

Briefing included as Appendix F. Rapid Rolling/Forming Schedule Development for Emerging Steels.

2.2.1.6 Enhanced Performance through Hotformed Armor Steel Applications

Udo Klasfauseweh (BENTELER Lightweight Protection)

Hotforming of steel has been introduced to passenger cars more than 25 years ago. During the last years, more and more applications in military vehicles have been realized, and demonstrate the advantages of hotforming compared to traditional technologies.

Hotforming allows the production of complex shaped parts for a large variety of steel grades and provides therefore new design opportunities. In opposite to welded structures, were every weld seam requires special efforts with regard to quality assurance and inspection as well as to manage the changed properties in heat affected zones (HAZ), hotformed components allow the integration of single parts into large stampings with homogenous properties all over. This provides the precondition for achieving the following advantages for military systems:

- Reduced weight, since overlaps for weldseams can be deleted
- Better ballistic and mine/blast protection because of deleted weldseams
- Small shape tolerances allow a straightforward assembly and reduced effort
- Deletion of weld seam preparation, welding fixtures and rework reduces overall cost

After a brief process and material overview, advantages of hotforming will be demonstrated on various applications.

Briefing included as Appendix G: Enhanced Performance through Hotformed Armor Steel Applications.

2.2.2 Session B: Castings

2.2.2.1 The Use of Computational Methods in the Production and Optimization of Large Components

Jesus Talamantes-Silva (Sheffield Forgemasters)

This presentation highlights the importance of process modeling in the manufacture of bespoke, high integrity, critical components such as large forgings and castings. The production of such components with the appropriate combination of strength, toughness, and degradation resistance can be a difficult undertaking. Close control of key manufacturing parameters such as chemical composition, heat treatment temperatures, casting and forging route is, therefore, essential.

Material capability can be determined through process modeling; this practice can identify limitations from both an operational and material standpoint. When manufacturing and material capabilities are maximized, adopting new materials may be key to enhancing product performance and life. Again, computer simulations can give insight into material behavior and key characteristics. Of particular interest is the control of essential manufacturing parameters that determine product homogeneity in regions distant from test locations. In a production item, homogeneity and mechanical properties in these locations cannot be measured by testing or examination. Determination of the limits of material and process capability, required for operating tolerances, can only be realized by a holistic approach to computer simulation techniques well beyond the time, human, and financial constraints traditionally applied.

Of immediate consideration is the issue of realistic and repeatable manufacturing controls to provide a sustainable process. This process needs to lie within the limits of the computer simulated outcomes in order to contain process heterogeneity within prescribed tolerances. The use of computer simulations enables more flexibility in defining the characteristics of each component and helps to tailor the manufacturing process to suit. In addition, this also facilitates taking on more technical challenges and to look at entirely new ways of creating components, which allows for greater manufacturing efficiency and stronger, lighter, more complicated end products. This presentation uses cases studies to give an insight about the role of such simulation techniques from a manufacturing perspective.

This briefing has not been included as an appendix.

2.2.2.2 Update on Design, Manufacturability, and Reliability of Steel Castings (SFSA DID)

David Poweleit, Raymond Monroe, Diana David, and Ryan Moore (SFSA)

SFSA's Digital Innovative Design (DID) for Reliable Casting Performance program is advancing steel casting design from a legacy, heuristic approach with workmanship quality standards to two design strategies: a design allowable code-based process with embedded NDT and a lower bound modeling-based practice with quantitative NDT. The program utilizes fracture analysis and microstructure characterization along with statistical analysis of properties, such as Weibull distributions or Metallic Materials Properties Development and Standardization (MMPDS) A- and B-Basis, to develop these new design methodologies. In addition to design, the program is working on alloy development ranging from a 50-ksi carbon steel to AF96/HY/FeMnAl, and welding of steel castings. This briefing will cover a comprehensive program update along with summaries of projects under the program that will not be individually presented at the 2019 Steel Summit.

Briefing included as Appendix H: Update on Design, Manufacturability, and Reliability of Steel Castings (SFSA DID).

2.2.2.3 Development of Meaningful Relationships between Steel Casting Surface Inspection Results and Performance

Frank Peters, David Eisenmann, Sharon Lau, Daniel Schimpf, and Jeffrey Tscherter (Iowa State University)

Much effort is expended to improve the surface finish of steel castings but the impact of surface condition on performance is not well understood. Contributing to this lack of understanding is the measurement error inherent with current surface characterization methods, including both visual inspection and magnetic particle inspection (MPI). Current efforts are addressing this via three avenues. Past research has shown that the visual inspection process is very subjective and prone to measurement error. Furthermore, the casting surfaces are typically specified via standards (e.g., MSS SP 55 and ASTM A802) that rely on photographs or comparator plates of casting surfaces. These issues are being addressed via the development of a digital standard based on scanned data. The new standard will utilize a statistical variogram approach to quantify the surface condition. This method removes the underlying geometry and any surface abnormalities from the calculations. The second avenue being addressed is the reduction of measurement error in the MPI process. The impact that surface roughness has on the ability of MPI to detect indications on a casting is not well known. A modification of the Ketos ring was developed that also incorporates surface roughness so that this relationship can be understood. Finally, the effect of surface and near-surface indications on fatigue properties is being studied. Cast steel plates are produced and then inspected via visual, radiograph, and MPI to determine the optimal location of the test bars to study the impact of any indications identified during inspection. The test bars have the original casting surfaces on two faces and a waterjet surface on the sides. The combined goal of these efforts is to develop a relationship between the inspection results and casting performance. This will enable the component designer to choose a steel casting and have confidence that the inspection requirements will ensure the performance needed without an unnecessary cost to produce the specified surface condition.

Briefing included as Appendix I. Development of Meaningful Relationships between Steel Casting Surface Inspection Results and Performance.

2.2.3 Session C: Welding

2.2.3.1 Mitigation of Hydrogen-Induced Cracking and Mechanical Properties Enhancement Using Low-Temperature Phase Transformation Welding Filler Wire on Armor Steel

Demetrios Tzelepis (CCDC GVSC)
Jeff Bunn, Andrew Payzant, and Zhili Feng (Oak Ridge National Laboratory)

Hydrogen-induced cracking (HIC) has been a persistent issue in welding of high-strength steels. Fabricating HIC-free welded structures of high-strength steels, particularly the ultra-high-strength martensitic-grade steels can be difficult in field fabrication and repair. As a result, it is critical to control HIC. Four factors contribute to the HIC: susceptible microstructure, residual stress, hydrogen content and near ambient temperature. The current studies develop a proactive in-process weld residual stress mitigation technique, which manipulates the thermal expansion and contraction sequence in the weldments during welding process. When the steel weld is cooled after welding, martensitic transformation will occur at a temperature below 400 °C. Volume expansion in the weld due to the martensitic transformation will reduce tensile stresses in the weld and HAZ and in some cases produce compressive residual stress in the weld. Based on this concept, customized filler wire with martensite phase transformation during cooling was developed. Y-Groove testing showed new filler wire showed significant improvement in terms of reducing the tendency of HIC in high-strength steels. Neutron diffraction residual stress measurement revealed reduced tensile and compressive residual stress in welds made by new filler wires for the Y-Groove plates and for an additional multi-pass restrained joint configuration. In addition weld wire has shown mechanical property improvements over conventional weld wires.

Briefing included as Appendix J: Mitigation of Hydrogen-Induced Cracking and Mechanical Properties Enhancement using Low-Temperature Phase Transformation Welding Filler Wire on Armor Steel.

2.2.3.2 Fusion Welding of High-Strength Steels for Military Applications

John DuPont, **Erin Barrick**, **Rishi Kant**, and Jason Bono (Lehigh University)
David Seidman (Northwestern University)

High-strength steels that provide a balance of strength and toughness are required for many military applications. Fusion welding is often an important step during the fabrication of military hardware. Most high-performance steels acquire their unique balance of strength and toughness through thermomechanical treatments with carefully controlled temperatures under moderate heating/cooling rates to achieve the desired microstructure. By comparison, fusion welding involves a relatively wide range of peak temperatures with rapid heating and cooling rates. As a result, the base metal microstructure and resultant mechanical properties are often adversely affected in the fusion zone and HAZ. The phase transformations and concomitant properties in the weld must be understood in order to develop processing strategies to restore the mechanical properties in the weld. In this presentation, recent examples of property restoration in welds are described in several high-strength steels, including precipitation-strengthened steels, FeMnAl alloys, and 10 Ni steels. In each case, a combination of controlled thermal simulations is combined with microstructural characterization and property measurements to understand the cause for degradation in properties and develop strategies for property restoration.

Briefing included as Appendix K. Fusion Welding of High-Strength Steels for Military Applications.

2.2.3.3 Microstructural Characterization of High-Nickel Steel Weld Deposits with a Non-equilibrium Hierarchical Microstructure

Amir Farkoosh and David N Seidman (Northwestern University)
Daniel H. Bechetti, Matthew F Sinfield, and Jeffrey D Farren (NSWCCD)

Fabrication of steel structures invariably requires joining by fusion welding. As requirements for weight and cost savings drive increased demand for advanced high-strength, high-toughness structural steels, the ability to balance mechanical performance and microstructural robustness of steels for the spectrum of welding processes poses a significant challenge. One aspect of this challenge is material responses to reheating during multi-pass welding. Thermal transients induce extensive microstructural changes in prior weld passes, whose nature and magnitude are highly dependent on the specifics of the chosen welding processes. Herein, we present a new high-Ni steel, developed at NSWCCD, which exhibits a positive response to the intrinsic heat treatment imposed during multi-pass welding processes. We demonstrate that it is possible to produce a fine martensitic microstructure, without post-weld heat treatments, leading to high strength and toughness. Additionally, we study the effects of carbon concentration and various alloying elements on the microstructure and mechanical properties of the welds. We utilize optical microscopy, TEM, X-ray diffraction, electron backscatter diffraction (EBSD), and local-electrode APT to study the microstructural features over hierarchical length scales. The fundamental knowledge acquired in this study can also be used to optimize the alloy system for fabrication of structural components via additive manufacturing processes.

This briefing was cancelled and has not been included as an appendix.

2.2.4 Session D: High Alloy Steels

2.2.4.1 New High-Strength NiCr Steel Alloys, AerMet 310 ,340, 360 for Hypersonic Structure

Dan Roup, Paul Novotny, Humberto Raposo, and **Colleen Tomasello** (Carpenter Technology)

Hypersonic vehicles require materials that can withstand extreme loads to operate reliably. In the launch systems, cases and engines the DOD needs targeted ultra-high-strength materials that are ready now and commercially available. In anticipation of these challenges, Carpenter Technologies has invested considerable resources in expanding the well-known AerMet franchise of high-strength NiCrCo martensitic steels. Led by Paul Novotny, the co-inventor of AerMet 100, Carpenter Technologies now offering AerMet 310, 340, and in the future, 360 for applications that require "all the strength they can get", which occurs often in hypersonic structure. These alloys create a system of interlocking properties taking full advantage of the AerMet metallurgy to provide the design engineer the specific strength/toughness ratio required for their most challenging applications. Although these products are new to the world, Carpenter brings over 30 years of production experience in AerMet 100 to provide reliable source of supply form a company that has been serving the Warfighter for more than 100 years. In this session, Carpenter metallurgists and engineers will present critical design data and product specifications. Furthermore, case studies of the material in applications will be presented to generate design creativity OEMs.

Briefing included as Appendix L. New High-Strength NiCr Steel Alloys, AerMet 310, 340, 360 for Hypersonic Structure.

2.2.4.2 Modeling and Characterization of Experimental Austenitic Steels Strengthened by MC Carbides

Paul Lambert and Daniel Bechetti (NSWCCD)

Austenitic steels can possess a wide range of desirable mechanical properties, such as high strain hardening and excellent low-temperature toughness. Despite these desirable properties, use of austenitic steels is generally limited to applications where low yield strengths are allowable. Most typical industrially processed austenitic steels have yield strengths of 50 ksi (345 MPa) or lower, whereas much higher yield strengths can be realized in ferritic/martensitic steels with relative ease. As part of an Office of Naval Research initiative, several Department of the Navy (DoN) and academic collaborators have been working to accelerate the proliferation of ICME methodologies within the US Navy. This presentation will describe the progress on one portion of that initiative: the development of an ICME framework focused on rapid parallel development of new alloys and matching welding consumables. In this work, a model system of an austenitic steel hardened by MC carbide precipitates was chosen and design objectives of 80- to 100-ksi yield strength without sacrifice of other material performance characteristics were established. Results will be presented for the use of CALPHAD techniques to predict phase stability, precipitation kinetics, solidification behavior, weldability, and material response to processing for a range of prospective alloy compositions. Verification of the CALPHAD predictions via characterization of strategically chosen experimental heats of material will be presented.

Briefing included as Appendix M. Modeling and Characterization of Experimental Austenitic Steels Strengthened by MC Carbides.

2.2.4.3 Critical Performance Attributes for High-Strength Steel in Defense Applications

Kip Findley, John G Speer, Emmanuel De Moor, David K Matlock, Leslie Lamberson, Amy J Clarke, and Kester D Clarke (Colorado School of Mines)

While high-strength steels for many defense applications focus on ballistic and/or blast performance for applications such as armor and munitions, other performance metrics also remain vital. This presentation will focus on steel design for high strength in the context of potentially critical properties including hydrogen embrittlement (HE), strain-rate dependent strength, ductility, and toughness, and fatigue. High-strength steels typically consist of quenched and tempered martensite, which is a complex, multiscale microstructure. Advanced characterization of various aspects of the martensitic microstructure and their relationship to the properties listed above will be discussed. Additionally, the presentation will highlight recent research on high-strength steel microstructures tailored with other microconstituents such as retained austenite, microalloy precipitates, and bainite, and their effects on these critical properties. For example, the high strain rate behavior of third-generation advanced high-strength steels containing retained austenite and hydrogen embrittlement performance of alloys containing mixtures of martensite, bainite, and retained austenite will be addressed. Finally, comments on alternative microstructure design approaches, e.g., low-cost austenitic steels, will be provided for applications such as hull structures with considerations for HE performance and toughness.

Briefing included as Appendix N. Critical Performance Attributes for High-Strength Steel in Defense Applications.

2.2.4.4 Computational Design of a Fully Austenitic Steel for Naval Hull Applications

Amit Behera, Dana Frankel, and Greg Olson (QuesTek Innovations LLC)
Clay Houser (Northwestern University)
Matthew Draper (NSWCCD)
Steve Roberts (Goodwin Steel Castings)

As part of a Naval Research program, QuesTek Innovations LLC is utilizing its ICME tools and expertise to design/develop a next-generation fully austenitic transformation induced plasticity (TRIP) steel toward the Navy's requirements of high yield strength, high toughness, low magnetic response, and good weldability. A high-strength steel with a fully austenitic microstructure is desirable owing to its low magnetostriction and permeability. A systems-based approach toward such alloy design focusing on correlation of the alloy composition, its processing to the microstructural characteristics, and final resultant mechanical properties will be elaborated. A fully austenitic TRIP steel composition with optimized homogenization and annealing heat treatment cycle was designed using existing ICME models at QuesTek. The designed steel is predicted to have high strength due to gamma-prime precipitation in the austenite matrix and improved toughness due to the TRIP effect. Some of the other key design criteria are to avoid formation of detrimental secondary phases (such as eta or laves phase), achieve adequate weldability, and avoid excessive grain coarsening. The designed steel was experimentally prototyped and studied for its microstructural characteristics and mechanical properties after application of necessary heat treatments. For the cast material, an optimized homogenization heat treatment cycle was developed using Scheil solidification and DICTRA calculations. Experimental results from the homogenized as-cast material and after undergoing various aging heat treatments will be discussed. The calibration and validation of developed models to predict the microstructural features and mechanical properties using the experimental results will also be discussed.

This briefing has not been included as an appendix.

2.2.4.5 Hot Cracking Resistance Evaluation Using Cast Pin Tear Test in Lightweight Armor Steel Based on the FeMnAl-C Alloy System

Stanton Hawkes, William Evans, Rafael Giorjão, and **Antonio Ramirez** (Ohio State University [OSU])
Katherine Sebeck (CCDC GVSC)

Fe-Mn-Al-C steel alloys have been previously studied for their potential as an alternative steel alloy for RHA. Prior examination of the material system has shown promise in this capacity due to the high strength and reduced density of Mn steels as compared to RHA. In the present work, the alloy's susceptibility to hot cracking evaluation using the cast pin tear test was conducted. The cast pin tear test is a test designed to induce solidification cracking in susceptible materials. The test involves levitation melting a charge of material and dropping it into a mold. The material is then allowed to solidify under nominal conditions. This solidification method allows for solidification cracks to grow if the material is susceptible. Testing will be conducted utilizing button melting tests, autogenous spot welds, and cast pin tear testing. The testing results showed that the FeMnAl system in its current form has a susceptibility to both solidification cracking and to HAZ liquation cracking.

Briefing included as Appendix O. Hot Cracking Resistance Evaluation Using Cast Pin Tear Test in Lightweight Armor Steel Based on the FeMnAl-C Alloy System.

2.2.5 Session E: Additive Manufacturing

2.2.5.1 Additive Manufacturing and Casting of Ultra-High-Strength Maraging Steels

Russ Cochran (Boeing)

In recent years, there has been increasing interest in long-range guided projectiles launched by electromagnetic pulse as well as conventional howitzer blast. These launching methods put tremendous g-force loads on the projectile structural body and are the driving element of the airframe structure and material selection.

C300 maraging steel (300-ksi typical UTS) is a standard off-the-shelf powder from EOS for laser powderbed fusion (LPF) 3-D printers. Powders from higher strength C350 maraging steels are also being evaluated.

Since LPF methods of fabrication of these parts are slow and expensive, it is only a viable option for prototyping and other low quantities. Cast maraging steels are available for higher production rates, but are also expensive using traditional vacuum casting methods to prevent oxidation. Air melt castings poured with shielding gases are being evaluated for feasibility.

This briefing has not been included as an appendix.

2.2.5.2 Additive Manufacturing of AF9628 Steel via Laser Powder Bed Fusion

Vikas Sinha (AFRL/RX and UES Inc.)
EM Hager, RP O'Hara, and RA Kemnitz (Air Force Institute of Technology [AFIT])
PJ Flater (AFRL/Munitions Directorate [RW])
EJ Payton (AFRL/RX)

Low-alloy, high-performance martensitic steels are traditionally used in wrought product forms. In this experimental study, we investigated the fabrication of AF9628 (a low-alloy, high-performance steel) samples via additive manufacturing route. The samples for microstructural and mechanical property characterizations were fabricated with LPF method. The process parameters, including laser power and speed, were optimized via weld track inspections, microstructural characterizations, and quantification of porosities. The microstructures for the different processing conditions were characterized via EBSD and chemical etching followed by optical and electron microscopy. The mechanical properties, including tensile properties and Charpy impact toughness, were characterized for the different optimized processing conditions.

Water quenching of wrought AF9628 steel from austenitizing temperature does not result in cracking of specimens, whereas initial experiments on as-printed (i.e., without any stress-relief) AF9628 indicated that water quenching from austenitizing temperature can cause cracking in specimens. The locations of quench-induced cracks did not correlate with the pore distribution in additively manufactured AF9628. To assess whether the residual stresses in the as-printed material are responsible for cracking, a series of stress-relief heat treatments were conducted on the additively manufactured steel prior to austenitizing and water quench heat treatments. The influence of stress-relief heat treatments on the propensity to crack formation was evaluated and an optimum stress-relief heat treatment to avoid cracking during quench from an austenitizing temperature was determined. The specimens were stress-relieved under optimized conditions and subsequently subjected to the same heat treatment schedule that is typically used for wrought AF9628. The effects of heat treatments on microstructures and mechanical properties of additively manufactured AF9628 were examined. The microstructures and mechanical properties of as-printed and heat treated additively manufactured materials were compared and contrasted with the heat treated wrought AF9628 steel.

Hot isostatic pressing (HIP) is typically employed to reduce porosity and improve properties of cast as well as additively manufactured metallic components. The additive manufacturing of low-alloy high-performance martensitic steels, such as AF9628, is relatively new and therefore, the HIP conditions are currently not optimized for additively manufactured AF9628. In this study, the HIP conditions for additively manufactured AF9628 were also optimized.

This briefing has not been included as an appendix.

2.2.5.3 From Waste Steel to Materiel: Agile Production Enabled by Additive Manufacturing

Karl Sundberg, Raymond Monroe, **Jianyu Liang**, Diran Apelian, Brajendra Mishra, and Richard Sisson (Worchester Polytechnic Institute [WPI])
Jian Yu and Brandon McWilliams (CCDC ARL)

According to studies conducted by ARL and the Natick Soldier Research, Development, and Engineering Center from April 2014 to May 2015, the breakdown of metal waste generated from the force provider expeditionary camps is 60% ferrous, 36% aluminum, and 4% other metals. Thus, this Strategic Environmental Research and Development Program (SERDP) project aims to develop an agile manufacturing process that allows for reuse of ferrous scrap that could produce parts or repairs to ensure the Warfighter's in-field readiness. This process integrates the following three manufacturing steps: 1) a scrap sorting and molten-steel-composition control step, to produce ferrous alloys with desirable composition and properties; 2) a stereolithographic 3-D printing step, to create patterns for investment casting of mission-critical parts; and 3) a post-process treatment protocol, to control the quality of the final cast product. This effort will reduce the military's logistical tail through investigation of the feasibility of a field-capable and on-demand manufacturing process, which potentially will enable the reuse of waste iron.

Briefing included as Appendix P. From Waste Steel to Materiel: Agile Production Enabled by Additive Manufacturing.

2.2.6 Poster Session

2.2.6.1 3rd Generation Advanced High-Strength Steel through Quenching and Partitioning Process

Matthew Cagle, Christopher Barrett, Hongjoo Rhee, and Haitham El Kadiri (Mississippi State University [MSU]–Center for Advanced Vehicular Systems [CAVS])

Improved strength and ductility of a transformation induced plasticity steel were achieved in this study using a quenched and partitioned heat treatment process, creating a martensite and retained austenite microstructure. We used a Gleeble 3500 thermo-mechanical simulator to apply rapid heating and cooling rates to dog bone specimens, subsequently tested at quasi-static strain rate (0.001/s). One composition shows higher total elongation (38%) than other attempts at third-generation advanced high-strength steels owing to the location of retained austenite at martensitic grain boundaries. The presence of the ductile FCC phase between martensite grains is expected to substantially mitigate strain incompatibilities at grain boundaries known to be prone for hot spots and damage initiation. This effect explains the possibility of obtaining high-ductile steels through the quenching and partitioning process despite the low carbon content and could be the primary cause of the high uncertainty associated with the mechanical properties of quenching and partitioning steels as the fraction of grain boundary austenite is highly sensitive to the process parameters and grain microstructure.

This poster has not been included in the appendix.

2.2.6.2 A Study of Navy Hull Steel (HY80) Test Block Mechanical Properties

Stephen Roberts and Ryan Leese (Goodwin Steel Castings, Ltd.)

This presentation focuses on casting developments in high-integrity Navy hull steels. This work was undertaken by Goodwin Steel Castings Ltd. (United Kingdom) within a collaborative working group functioning under the framework of the DID FY19 project in support of ongoing efforts for the current Columbia, Virginia, and future US Navy submarine programs.

The incumbent series of cast hull steel for Navy submarines, HY80 and HY100, are manufactured to the stringent requirements of NAVSEA Technical Publication T9074-BD-GIB-010/0300 Revision 2, Appendix D. For these critical duty cast components the specification mandates heavy matching section test blocks to qualify the mechanical properties of associated tactical castings. For castings over 6 inches, in section test blocks are required to be poured within the same mold (flask) as the casting they represent. When pouring a series of individual molds from one heat, this will result in multiple test blocks being required with each individual casting representing a testing lot. The test blocks are large in order to reasonably represent cooling rates both during solidification and subsequent thermal treatments of the castings they represent and as a result absorb considerable resource to both manufacture and mechanically test.

To support future Navy programs in relation to cost reductions, a potential proposal is to pour one test block per heat qualifying all the tactical components from the batch provided all castings from the heat are heat treated together on the same furnace load. Further savings would result if a reduction in test block length was permitted. Currently, test block minimum dimensions are specified within the Tech Pub 0300 specification.

To investigate these potential new methodologies and better understand the relationships between when test blocks are poured and resultant properties, this presentation will detail initial work where test blocks where mechanically characterized and compared when poured at the beginning and end of a pouring sequence. To help to answer whether current specification compliant test blocks in future specification revisions could be reduced in length, the presentation includes a study of solidification and heat treatment cooling data for standard and reduced-length test blocks for a section sizes 6 to 14 inches.

This poster has not been included in the appendix.

2.2.6.3 Accelerated Creep and Creep-Fatigue Testing for the Rapid Qualification of Candidate Alloys

David Alexander IV, Robert Mach, Jacob Pellicotte, Md Abir Hossain, and Calvin Stewart (University of Texas at El Paso [UTEP])

Integrated computational materials science and engineering (ICMSE) and advanced manufacturing techniques such as additive manufacturing have enabled both the rapid identification of candidate material systems and the rapid manufacture of prototype alloys. These “designer” alloys are calculated to exceed the performance requirements of existing materials; however, there is a need to replace calculations with a “real” qualification of material response. There is a need for rapid, miniaturized, parallelized, and automated qualification of prototype alloys. These stream of data can be leveraged using ML to create reduced-order models for the prediction of the processing → structure → properties→ performance relationship in a specific candidate material system. This study focuses on the design of accelerated creep and creep-fatigue tests for the rapid qualification of material behavior. The time-temperature–stress-superposition theory is employed where increased stress and/or temperature are applied to accelerate the time to failure. Calculated time-temperature-transformation (TTT), time-temperature-precipitation (TTP), and deformation mechanism maps are consulted to select test parameters. Advanced constitutive models are leveraged to separate history effects from the isostress/isothermal mechanical properties. Wrought Inconel 718 alloy is evaluated in this study.

This poster is included in Appendix Q. Posters.

2.2.6.4 Adaptation of Ferrium® M54® for Personal Armor Applications

Thomas Kozmel (QuesTek Innovations)
Melissa Roth (CCDC Soldier Center)

QuesTek Innovations is currently working on a Phase II Small Business Innovation Research (SBIR) program to adapt its patented Ferrium M54 alloy for personal armor applications. This high-strength, high-toughness steel, already in use in applications such as hook shanks, has proven to be a promising candidate for property improvement via ausforming. During the ausforming process, metastable austenite grains are deformed such that upon quenching, a refined martensitic lath structure is obtained. Material produced with this technique has been evaluated for ballistic performance, and microstructures have been characterized.

This poster is included in Appendix Q. Posters.

2.2.6.5 Alloy Design and Characterization of High Hardness Grade Steels

David Salley, William Williams, Haley Doude, Wilburn Whittington, and Hongjoo Rhee (MSU–CAVS)
Daniel Field, Krista Limmer, and Kevin Doherty (CCDC ARL)

HE is a delayed failure mechanism causing unexpected failure of materials even below yield strengths. Since this event mostly occurs in high-strength steel grades including HHA and UHHA steels, which are commonly used for applique armor, modified leaner chemistries are proposed in this study. Multiple alloys were designed and manufactured, in-house, to satisfy MIL-DTL-46100E property requirements and to produce high-strength armor-grade steel with the hope of increasing resistance to HE susceptibility. The mechanical properties of these alloys were compared with commercially available high-hardness steel plates. Manufacturing simulations were also performed using a Gleeble 3500, a thermal-mechanical simulator, to acquire optimal process parameters with respect to chemistry. Mechanical test results revealed that the material produced in-house can meet most required specifications. The findings from the present study could aid in identifying the design methodology to reduce HE susceptibility for HHA steels.

This poster is included in Appendix Q. Posters.

2.2.6.6 Comparing Hydrogen-Enhanced Decohesion (HEDE) and Hydrogen-Enhanced Local Plasticity (HELP) through Molecular Dynamic Simulations

Bradley Huddleston, Doug Bammann, Raj Prabhu, Denver Seely, Anh Vo, Nayeon Lee, and Sungkwang Mun (MSU–CAVS)
Krista Limmer (CCDC ARL)

The effect of hydrogen on the mechanical behavior of steel through the dual mechanisms of hydrogen-enhanced decohesion (HEDE) and hydrogen-enhanced local plasticity (HELP) is explored through molecular dynamics simulations. Hydrogen's effect on deformation and failure was studied at 300 K through two different stress states: fixed wall tension and fixed end simple shear. Fixed wall uniaxial tension created a triaxial stress state promoting damage nucleation and growth, which highlighted the effect of hydrogen on damage nucleation. In contrast, fixed end simple shear is an isochoric deformation that promoted plastic strain and underlined the effect of hydrogen on increasing dislocation activity. The simulations were run on a set of nanoscale lath-like microstructures (~1 million atoms) representing a tempered martensite steel alloy. The structures contained approximately 0.8 wt% total carbon content divided between needle-like epsilon carbide particles about 5 nm long and the remainder at interstitial sites within grains or grain boundaries. Hydrogen atoms were also added at interstitial sites at concentrations ranging from 0 to approximately 100 ppm. Structures with greater hydrogen content were found to nucleate voids at lower strains in the tension simulations. Voids nucleated preferentially at ferrite–carbide interfaces, particularly when hydrogen was present. In the simple shear simulations, the material yielded at a lower stress and strain as hydrogen concentration increased. The lower yield was caused by preferential dislocation nucleation near hydrogen atoms and greater dislocation mobility as they traveled through grains near hydrogen atoms. Our study suggests that the HEDE and HELP mechanisms work in concert to hasten failure in highly triaxial loading conditions while in low triaxial loads HELP reduces yield and promotes plastic strain.

This poster has not been included in the appendix.

2.2.6.7 Comparison Study on the Susceptibility of High-Hardness Steels to Hydrogen Embrittlement

William Williams, Haley Doude, Wilburn Whittington, and Hongjoo Rhee (MSU–CAVS)
Daniel Field, Krista Limmer, and Kevin Doherty (CCDC ARL)

HE poses a risk for HHA steels (e.g., as specified in MIL-DTL-46100) and can lead to premature failure of components. Due to the wide chemistry specification allowed by MIL-DTL-46100, the sensitivity of armor steels to HE has not been fully identified. A study was performed to assess the sensitivity of hydrogen susceptibility across the spectrum of HHA steels. Several HHA alloys with different chemical compositions, meeting MIL-DTL-46100 specification, were studied. Steel plates were mechanically tested after being charged with hydrogen to observe the degradation of performance due to HE. This was observed by several iterations of slow-strain rate testing of tensile specimens that were charged with different levels of hydrogen. To better understand the uptake of hydrogen in the alloys, hydrogen permeation tests were also performed to determine the hydrogen diffusivity coefficient of each alloy and to observe the effect of any possible hydrogen traps within the material. Permeation samples were taken from mid-thickness, surface, and quarter-thickness to detect any variations of diffusivity within the material that could be caused by material processing. The evaluation of hydrogen susceptibility across the spectrum of various chemical compositions of HHA steels will aid in future design and mitigation of HE.

This poster is included in Appendix Q. Posters.

2.2.6.8 Development of Quenching and Partitioning (Q&P) Plate Steel Intended For Toughness Applications

Travis Marsh and John Speer (Colorado School of Mines)
Rainer Fechte-Heinen (thyssenkrupp)

In recent years, the 3rd generation of advanced high-strength steels has been developed for automotive sheet applications using quenching and partitioning (Q&P) as one of the heat treatments, developing a microstructure of martensite and retained austenite (RA). There is interest in exploring the application of a Q&P process to low-alloy plate steel because a microstructure of lath martensite and fine, interlath RA may have enhanced toughness and energy absorption as compared to tempered martensite microstructures generated by traditional quench and temper (Q&T) processes. The increased toughness and energy absorption in these microstructures is generally attributed to the TRIP effect caused by the transformation of metastable RA into martensite during strain.

In this work, design of low-alloy plate steel for Q&P processing has accounted for differences in cooling rate through the thickness during quenching in order to avoid microstructural inconsistencies. Additionally, modeling has been used to design Q&P heat treatments that could feasibly be applied using currently existing Q&T heat treatment facilities. Dilatometry experiments have been performed on a low-alloy steel to further develop Q&P heat treatments to obtain a microstructure of martensite and fine, interlath RA through the thickness of an 18-mm-thick plate. Full-scale Q&P heat treatments of plates are in progress and will be used to measure and compare properties to those achieved after traditional Q&T heat treatments.

This poster is included in Appendix Q. Posters.

2.2.6.9 Efficient Use of Multiple Information Sources in Material Design

Yu Liu, Xinzhu Zheng, and Ankit Srivastava (Texas A&M University)
Dongwei Fan (ArcelorMittal Global R&D)

ICME calls for the integration of computational tools into materials development cycle, while Materials Genome Initiative (MGI) calls for acceleration of the materials development cycle through a combination of experiments, simulations, and data. But, both ICME and MGI do not prescribe how to achieve the tool integration or how to efficiently exploit the simulations and experiments. Here, we present a general framework for the design/optimization of materials that is capable of accounting for multiple information sources available to the materials designer. We demonstrate the framework through the microstructure-based design of multi-phase microstructures. Specifically, we seek to maximize the strength normalized strain-hardening rate of a dual-phase steel through a multi-information source Bayesian optimal design strategy. We assume that we have multiple sources of information with varying degrees of fidelity and cost. The available information from all sources is fused through a reification approach and then a sequential computational design is carried out. The computational design seeks not only to identify the most promising region in the materials design space relative to the objective at hand, but also to identify the source of information that should be used to query this point in the decision space. The selection criterion for the source used accounts for the discrepancy between the source and the "ground truth" as well as its cost. It is shown that when there is a hard constraint on the budget available to carry out the optimization, accounting for the cost of querying individual sources is essential.

This poster is included in Appendix Q. Posters.

2.2.6.10 Evaluation of Surface Integrity and Tool Wear in Machining of AF9628

Julius Schoop and Ian Brown (University of Kentucky [UK])
Jason Wolf (AFRL)
Neal Ontko (Universal Technology Corporation [UTC] Dayton)

This presentation will build on the results of an ongoing machinability study of AF9628 under AFRL's MOTO effort. We will discuss experimental results obtained at UK, which supplement the corresponding machinability study carried out by TechSolve for the Materials and Manufacturing Directorates Manufacturing and Industrial Technologies Division. Program management for this effort is being conducted by UTC (Dayton, Ohio). At both TechSolve and UK, turning operations were carried out for hot rolled bar in the annealed (HRC 31) and hardened (HRC 51) conditions.

Typical machinability studies focus on determining process parameter ranges for maximum manufacturing productivity. However, optimum ranges of cutting feeds and speeds are also constrained by changes that occur in the workpiece material as a result of the machining process, i.e., process-induced surface integrity. Therefore, samples from an ongoing machinability study of AF9628 were systematically analyzed for surface and sub-surface damage, including white layers, microstructural changes, near-surface micro hardness profiles and surface morphology.

Using advanced 3-D white light scanning interferometry, tribological studies of friction, and wear mechanisms in machining of AF9628 were conducted across various cooling and lubrication strategies. Dry, flood-cooled, minimum quantity lubrication and cryogenic cooling were investigated. The results of this study are a foundation for future modeling and optimization efforts of cutting tool geometries, coatings, and cooling/lubrication strategy.

We will present our findings, as well as associated implications for more efficient machining of AF9628. By demonstrating the correlation between machining conditions and the resultant surface integrity characteristics, our results are expected to enable the industrial base to confidently adopt more productive machining parameters in AF96.

This poster has not been included in the appendix.

2.2.6.11 HH and UHH Steel in Complex, Formed Shapes for DOD Applications

George Tunis and Justin Gordon (Hardwire, LLC)
Alex Millar and Andy Roubidoux (EVRAZ)

Hardwire, LLC, using EVRAZ steels, has developed technology to form high-hard and ultra-high-hard steels into complex, shaped parts. Many military vehicle applications utilize high-hard steel or ultra-high-hard steel for force protection reasons. However, they face the challenges of welding, seam vulnerabilities, and cracking. Hardwire's unique processes for forming high-hard steel parts eliminate those issues by delivering net shape parts. This reduces the need for welded assemblies and eliminates/reduces seams or the need for ballistic doublers, all while still delivering the ballistic performance of high-hard or ultra-high-hard steels (up to 650 Brinell hardness).

The forming process entails rapid heating of the steel plate and solid-state quenching through what would be called a "retrogression re-aging process" in nonferrous metals. The forming process maintains the material and ballistic properties. The work to date has focused on forming sets of 3-D parts from low-cost tooling that is designed specifically for Hardwire's rapid quenching process. A variety of high-hard and ultra-high-hard steels and their properties are being compared in various forms, including certified control plates, flat plates, and formed 3-D parts. Thicknesses of interest range from 5 mm to 1 inch.

For DOD applications where complex parts would be optimal but are not currently attainable through traditional stamping or forging operations, the Hardwire forming process can reduce part count, eliminate manufacturing complexity, improve system performance, decrease maintenance burdens, and reduce costs.

This poster has not been included in the appendix.

2.2.6.12 Joining of Wrought Homogeneous Armor Steel Using Friction Stir Welding Technique

Scott Hunter, William Evans, Rafael Giorjao, Mike Eff, and Antonio Ramirez (OSU)
Martin McDonnell (CCDC GVSC)

Friction-stir welding (FSW) is a solid-state joining process (the metal is not melted) that uses a third body tool to join two facing surfaces. Heat is generated between the tool and material, which leads to a very soft region near the FSW tool. In this study, FSW parameters were developed and used to weld wrought homogeneous armor steel. Metallography, micro hardness indention, and thermal modeling was also employed to predict the joint's properties. Examining the micrographs and SEM images, the microstructure appeared to be fully martensitic. The martensite found in the stir zone (SZ) and HAZ has undergone auto-tempering as well. When examining the micro hardness profile of the weld, it appears that the SZ hardness is close to that of the base metal. This would indicate that some level of tempering is occurring during the welding process, leaving a tempered martensitic microstructure.

This poster is included in Appendix Q. Posters.

2.2.6.13 AF9628 Turning Machinability Study

George Adinamis and F Gorsler (TechSolve)
Neal Ontko (UTC Dayton)

The presentation will cover the results of a comparison of AF9628, an emerging material designed by Eglin Air Force engineers, with 4340 steel to provide a benchmark for soft and hard turning production. The objective of the project was to develop machinability data to facilitate implementation of AF9628 Steel for DOD weapons applications and reduce risk for materials transition. UTC (Dayton, Ohio) conducted the program management for this effort.

The Turning operations were conducted at TechSolve's M Eugene Merchant technology development center located in Cincinnati, Ohio. The machinability comparisons were carried out on hot rolled AF9628 in the annealed (HRC 31) and hardened (HRC 51) conditions, compared to hot rolled 4340 steel in the annealed (HRC 26) and hardened (HRC 46) conditions.

We measured tool wear, horsepower, cutting force, and surface finish using state-of-the-art instrumentation. The resulting comparisons include information on power requirements, chip formation, recommendations for cutting tool grades, geometries and operating conditions to achieve desirable metal removal rates and avoid less desirable conditions.

We also will discuss how machinability data drives the economics for machining optimization, including the interactions of various cost factors to assist in building a business case for AF9628 material substitution.

Separately, TechSolve used the parameters developed during the tool-life tests to generate metallurgical specimens for the study of potential subsurface effects by UK.

AFRL's Materials and Manufacturing Directorate, Manufacturing and Industrial Technologies Division at Wright-Patterson Air Force Base sponsored the effort.

This poster is included in Appendix Q. Posters.

2.2.6.14 Measurements and Predictions of Lower Bound Mechanical Properties of Cast Steels

Richard Hardin and Christoph Beckermann (University of Iowa)
Raymond Monroe and Diana David (SFSA)

From a data set containing well over 7000 specimens, statistical analyses are performed on tensile data collected by the SFSA from its members to establish lower bound mechanical design properties. These properties, lower bound allowables for yield and ultimate strengths, elongation, and reduction of area, are determined at the 1st and 10th percentiles of the data for normal and Weibull distributions at the 95% confidence level. These levels follow the MMPDS Handbook approach for the so-called "A" and "B" allowables, respectively. The lower bound allowables are determined by grouping the data by grade and heat treatment according to two specifications, ASTM A958 and the ASME BVP code. For the steels grouped by grade and heat treatment according to the ASTM A958 standard, design properties are determined for grades 8620, 8625, 8630, and 8635 in normalized and tempered, and quenched and tempered heat treatment conditions. For the data analyzed and grouped according to the ASME BVP code specification SA7487, lower bound allowables for grades 4A, 4B, and 4E are determined. Mechanical property predictions are presented using casting and heat treatment simulation results. Predicted results for cooling rate, thermal gradient, and carbon segregation are combined with software package predictions of mechanical properties to improve agreement with measurements. Best-fit models using predicted results are used to calculate yield strength, ultimate strength, elongation and reduction of area. Measured and predicted mechanical properties are compared for cast 8630 Q&T steel. Specimens taken from a range of casting section sizes and casting geometries are used in these comparisons in contrast to the SFSA dataset, which comprises mostly of keel block and other standard test coupon castings. A lower bound relationship is proposed for the property predictions based on the lower bound allowables determined from the SFSA member data.

This poster has not been included in the appendix.

2.2.6.15 Microstructure and Mechanical Properties of Lightweight Fe-Mn-Al-Ni Steels for Armor Applications

Michael Piston, Laura Bartlett, and Ron O'Malley (Missouri S&T)
Krista Limmer and Daniel Field (CCDC ARL)

Additions of nickel to high manganese and aluminum low-density austenitic steels have been shown to greatly increase strength by forming hard intermetallic B2 precipitants within the austenite matrix during hot rolling and subsequent annealing. Additional strengthening is provided by homogenous precipitation of kappa carbide within the austenite matrix during aging in the temperature range of 450 to 570 °C, resulting in a peak hardness greater than 50 HRC. This study investigates the influence of Ni contents between 5–8 wt% on the microstructure and mechanical properties in nominal composition Fe-(18-20)Mn-(8-9)Al-1C steels as a function of thermomechanical processing and subsequent heat treatment. Increasing Ni content produced a greater density of nanosized B2-type NiAl precipitates that precipitated uniformly within the austenite after annealing between 900–1050 °C. However, higher Ni levels or annealing temperatures can result in over-coarsening and undesirable precipitation of B2 on grain boundaries that can deteriorate notch toughness. Therefore, careful control of the composition and thermomechanical processing must be employed to avoid embrittlement and deleterious effects on notch toughness.

This poster is included in Appendix Q. Posters.

2.2.6.16 Probabilistic Reconstruction of Austenite Microstructures from Martensite EBSD Data

Eric Payton (AFRL/RX)
AF Brust, TJ Hobbs, and SR Niezgoda (OSU)
Vikas Sinha (AFRL/RX and UES Inc.)

Austenite grain size can affect the distribution of variants observable after a martensitic transformation in steels. A recently developed graph-cut based algorithm for probabilistic reconstruction of prior austenite microstructures from electron backscatter diffraction observations of the martensite phase at room temperature is employed to infer austenite grain sizes prior to quenching. Fewer variants are observed in smaller grains, posing a challenge for grain size quantification. Orientation relationships exhibited from the transformation also vary with local composition. The graph cut algorithm is found to be robust for alloys of varying compositional complexity. Challenges associated with fine microstructures resulting from thermal cycling, from deformed structures such as those that result from ausforming, and for additively manufactured structures will be discussed. These microstructures continue to pose a challenge for austenite reconstruction and grain size measurement.

This poster is included in Appendix Q. Posters.

2.2.6.17 TRISECURE – Ballistic Steels with Lightweight Potential

Ross Auten and Robert Holt (thyssenkrupp Steel NA)
Stephan Scharf and Axel Gruneklee (thyssenkrupp Steel Europe AG)
Matthew Burkins (Burkins Armor Consulting, LLC)

This is an introduction to thyssenkrupp Steel Europe's recently developed steel-grade TRISECURE, which is a multi-layered steel sandwich material composed of a layer of SECURE 450 sandwiched between two SECURE 650 outer layers. TRISECURE seeks to provide higher ballistic performance than ultra-high-hardness MIL-DTL-32332 steel and dual hardness MIL-S-46099 steel. TRISECURE provides much improved flatness over MIL-S-46099 dual hardness armor because the residual stresses are more balanced. The production process, the mechanical properties and ballistic performance, as well as some forming and bending results of TRISECURE, will be discussed.

This poster is included in Appendix Q. Posters.

2.2.6.18 Additive Manufacturing of Ultra-High Strength Steel AF9628

Raiyan Seede, David Shoukr, Bing Zhang, Austin Whitt, Alaa Elwany, Raymundo Arroyave, and Ibrahim Karaman (Texas A&M University)
Sean Gibbons and Phillip Flater (AFRL)

Ultra-high-strength steels have attracted increasing interest for their use in the automotive and aerospace industries, in mining equipment, and in defense applications due to their high yield strengths and reasonable ductility. AFRL recently developed a relatively inexpensive ultra-high-strength steel called AF9628. This martensitic steel can exhibit strengths greater than 2 GPa with more than 10% elongation with proper microstructural refinement, in particular via refinement in prior austenite grain size. In an effort to produce high-strength parts with a high degree of control over geometry, this work studies the effect of selective laser melting (SLM) process parameters on the mechanical properties of AF9628. In particular, a new protocol for determining processing windows in an accelerated fashion is first introduced. The protocol integrates an analytical thermal model with experimental characterization, then uses geometric criteria for determining processing parameters such that fully dense parts with minimal lack of fusion and keyholing porosity can be produced.

Using this framework, fully dense samples were achieved over a range of processing parameters, allowing the construction of an SLM processing map for AF9628. Flexibility in processing parameter selection while maintaining full density parts opens up the possibility of local microstructural refinement through processing parameter variation.

This poster is included in Appendix Q. Posters.

2.2.6.19 Atomistic Study on Hydrogen Segregation and Embrittlement at α-Fe Grain Boundaries and Ferrite–Carbide Interfaces

Nayeon Lee, Sungkwang Mun, Doyl Dickel, Bradley Huddleston, Douglas Bammann, and Michael Baskes (MSU–CAVS)
Krista Limmer (CCDC ARL)

We studied the interactions of hydrogen atoms with α-Fe grain boundaries (GBs) and ferrite–carbide interfaces using molecular dynamics simulations to understand the HE mechanism in tempered martensitic steel. Tempered martensitic steel is primarily composed of α-Fe and ε-iron carbides generated during the tempering process. Past research has shown that major trapping sites for hydrogens are the ferrite–carbide interfaces (Chan and Charles 1986; Ramunni et al. 2006). However, GBs also accumulate hydrogen resulting in intergranular crack propagation. We quantified and compared the segregation energy of a hydrogen atom at ferrite–ferrite grain boundaries of various misorientation and ferrite–carbide interfaces to examine the effect of the GB structure and interfaces on hydrogen accumulation.

In this study, calculations were carried out using the Modified Embedded Atom Method (MEAM) interatomic potential for Fe-C-H system. The potential parameters were calibrated to experimental data and first-principles calculations. We ran molecular statics simulations at zero temperature for three different interface cases: 1) ferrite–carbide interfaces, 2) pure α-Fe GBs, and 3) α-Fe GBs with carbon atoms. GB structures were constructed for the <100> symmetric tilt GB systems with misorientation angles of 18.86°, 28.07°, 36.87°, 43.60°, and 53.13°, and carbon atoms were inserted to energetically favorable sites using a Monte Carlo algorithm. Simulation results showed that GBs with higher GB energies tended to have greater segregation energies. Ferrite–carbide interfaces also had high binding energies, affirming that carbides can be strong hydrogen trapping sites. Our observations are consistent with experimental findings and can be useful to improve ductility and prevent embrittlement by engineering GBs or altering the alloy contents.

This poster is included in Appendix Q. Posters.

2.2.6.20 The Role of Metal Carbides in Austenite formation in a High-Ni Martensitic Steel

Chia-Pao Lee, Amir Farkoosh, and David Seidman (Northwestern University)
Paul Lambert (NSWCCD)

Research at NSWCCD by Dr X Jie Zhang, over many years, has demonstrated that a low carbon 10 wt% Ni steel with an appropriate quench-lamellarization-tempering (QLT)-type heat treatment can achieve an excellent combination of high strength, high toughness, and ballistic resistance (Jain et al. 2017). This family of 10 wt% Ni steels thus has the potential to deliver improved strength and ballistic protection for naval structural applications. The QLT heat-treatment produces a complex steel-microstructure containing reverted or precipitated austenite, martensite, ferrite, or tempered martensite, together with carbide precipitates contributing to precipitation-strengthening. Retained austenite, with a different composition than the reverted austenite, may also be present. Our previous research on 10 wt% Ni steels revealed that co-located and mixed MC/M2C-type carbides (M is Mo, Cr, V), comprising a M2C carbide shell and a MC carbide core, which form after the QL- and QLT-treatments (Jain et al. 2018). It is, however, unknown whether the metal carbides observed in the QL and QLT-treated samples play any significant role in austenite formation. To investigate this, we have designed a heat treatment that form carbides with different sizes and distributions within a martensitic matrix (intra-lath regions) prior to the lamellarization (L-step) and tempering (T-step) treatments. This multi-step heat treatment permits studying the role of carbides in austenite formation and possibly altering the size and distribution of austenite grains in the intra-lath regions, to further improve the mechanical properties of this steel. We utilize experimental characterization techniques, optical microscopy, SEM, synchrotron X-ray diffraction, APT, EBSD, plus ThermoCalc and DICTRA to follow the kinetics of phase transformations and the resulting microstructural features at different hierarchical length scales.

This poster is included in Appendix Q. Posters.

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Appendix A. Meeting Attendance

Table A-1 Attendees and their affiliations

Last name	First name	Affiliation
Adinamis	George	TechSolve
Alexander	David	University of Texas El Paso (UTEP)
Ankem	Sreeramamurthy	University of Maryland
Antillon	Edwin	US Naval Research Laboratory (NRL)
Anwar	Yusra	University of Maryland, College Park
Auten	Ross	thyssenkrupp Steel North America
Bakas	Michael	Army Research Office
Barrick	Erin	Lehigh University
Bartlett	Laura	Missouri University of Science and Technology
Bechetti	Dan	Naval Surface Warfare Center Carderock Division (NSWCCD)
Beyeler	Dana	Ellwood Group, Inc.
Bleckmann	Matthias	CCDC Army Research Laboratory (ARL)/WIWeB
Brown	Ian	University of Kentucky (UK)
Burkins	Matthew	Burkins Armor Consulting, LLC
Cagle	Matt	Mississippi State University (MSU)-Center for Advanced Vehicular Systems (CAVS)
Challa	Venkata	ArcelorMittal R&D
Cheeseman	Bryan	CCDC ARL
Chinella	John	CCDC ARL
Chizek	Philip	LIFT – Lightweight Innovation Institute
Cho	Kyu	CCDC ARL
Chu	Henry	Idaho National Laboratory
Cochran	Russ	Boeing Defense Systems - St. Louis
Cola	Gary	Flash Steelworks, Inc.
Czech	Peter	LIFT - Lightweight Innovation Institute
Damm	Buddy	TimkenSteel Corporation
Davenport	Tracy	PRL Industries, Inc
Doherty	Kevin	CCDC ARL
Doude	Haley	MSU–CAVS
Dowding	Robert	CCDC ARL
Draper	Matthew	NSWCCD
Dunsford	Kyle	Missouri University of Science and Technology
Dunstan	Matt	CCDC ARL
DuPont	John	Lehigh University
Edwards	William	Ellwood Group, Inc.
Eller	Ben	Nucor Steel
Enders	Paul	MetalTek international – Wisconsin Centrifugal Division
Farnin	Christopher	Lehigh University
Field	Dan	CCDC ARL
Findley	Kip	Colorado School of Mines
Fletcher	Fred	ArcelorMittal

Table A-1 Attendees and their affiliations (continued)

Last name	First name	Affiliation
Fonda	Richard	NRL
Fountzoulas	Constantine	CCDC ARL
Frankel	Dana	QuesTek Innovations LLC
Frichtl	Matt	Vision Point Systems
Gafner	Alyssa	CCDC Ground Vehicle Systems Center (GVSC)
Gallardy	Denver	CCDC ARL
Galuardi	John	University of Maryland, College Park
George	Jacob	ATI Flat Rolled Products
Gins	Richard	NSWCCD
Gonzales	Manny	Air Force Research Laboratory (AFRL)
Gooch	William	WA Gooch Consulting Inc,
Gordon	Justin	Hardwire, LLC
Green	Joshua	Nucor Steel
Hammond	Vince	CCDC ARL
Hardin	Richard	University of Iowa
Healy	Jonathan	NSWC Carderock Division
Holt	Robert	thyssenkrupp
Honecker	David	Freeport McMoRan (Climax Molybdenum)
Hoppel	Chris	CCDC ARL
Horwath	Ed	CCDC ARL
Houser	Clay	Northwestern University
Huddleston	Bradley	MSU–CAVS
Jackson	Eric	CCDC Armaments Center (AC)
Jones	Kristoffer	NAVSEA (Columbia Class)
Kant	Rishi	Lehigh University
Klasfauseweh	Udo	BENTELER Lightweight Protection
Kozmel	Thomas	QuesTek Innovations LLC
Kudzal	Andelle	CCDC ARL
Lambert	Paul	NSWCCD
Lee	Chia-Pao	Northwestern University
Lee	Nayeon	MSU–CAVS
Leese	Ryan	Goodwin Steel Castings Ltd
Liang	Jianyu	Worcester Polytechnic Institute
Lillo	Thomas	Idaho National Laboratory
Limmer	Krista	CCDC ARL
Lloyd	Jeffrey	CCDC ARL
Magness	Lee	CCDC ARL
Malachin	Julianna	CCDC AC
Marsh	Travis	Colorado School of Mines
Maxeiner	Michael	McConway & Torley, LLC

Table A-1 Attendees and their affiliations (continued)

Last name	First name	Affiliation
McCormick	John	US Army
McWilliams	Brandon	CCDC ARL
Meredith	Chris	CCDC ARL
Merrill	Marriner	NRL
Millar	Alexander	EVRAZ NA
Monroe	Charles	University of Alabama at Birmingham
Monroe	Raymond	Steel Founders Society of America (SFSA)
Montgomery	Jonathan	CCDC ARL
Morley	Matthew	Sheffield Forgemasters International Ltd.
Moy	Paul	CCDC ARL
Mroczka	David	US Army
Mullins	Bill	Office of Naval Research
Nath	Maya	NSWCCD
Nicholls	Ian	Sheffield Forgemasters International Ltd.
O'Brian	Danny	CCDC ARL
Ontko	Neal	Universal Technology Company
Payton	Eric	AFRL
Peters	Frank	Iowa State University
Pickens	Joe	Periodic Innovation
Piston	Michael	Missouri University of Science and Technology
Placzankis	Brian	CCDC ARL
Poweleit	David	SFSA
Pugliano	Victor	Office of the Secretary of Defense Research and Development (OSD R&D)
Ramirez	Antonio	Ohio State University
Raudenbush	Gregory	PRL Industries, Inc
Rawlett	Adam	CCDC ARL
Rinderspacher	Chris	CCDC ARL
Roberts	Stephen	Goodwin Steel Castings Ltd
Roshan	Hathibelagal	Maynard Steel Casting Company
Roup	Dan	Carpenter Technologies Inc.
Rusin	Daniel	CCDC HQ
Salley	David	MSU–CAVS
Scharf	Stephan	thyssenkrupp Steel Europe AG
Scherrer	Charles	McConway & Torley, LLC
Schoenfeld	Scott	CCDC ARL
Schoop	Julius	University of Kentucky
Schwarm	Samuel	NSWCCD
Seede	Raiyan	Texas A&M University
Sinfield	Matthew	NSWCCD
Sinha	Vikas	AFRL/UES, Inc

Table A-1 Attendees and their affiliations (continued)

Last name	First name	Affiliation
Slye	Bill	Carpenter Technologies Inc.
Srivastava	Ankit	Texas A&M University
Stewart	Calvin	UTEP
Strifas	Aphrodite	University of Maryland
Swoboda	Pat	CCDC ARL
Talamantes-Silva	Jesus	Sheffield Forgemasters International Ltd
Terrenzi	Edward	SSAB Inc
Thiel	Alexander	Oshkosh Corporation
Tomasello	Colleen	Carpenter Technologies Inc.
Tunis	George	Hardwire, LLC
Tuttle	Robert	Saginaw Valley State University
Tzelepis	Demetrios	CCDC GVSC
Vieau	Katherine	CCDC GVSC
von Mueller	Werner	BENTELER Lightweight Protection
Wabiszewski	Mike	Maynard Steel Casting Company
Walden	Clay	MSU–CAVS
Walter	Timothy	CCDC ARL
Williams	William	MSU–CAVS
Wolf	Jason	AFRL
Wrege	Michael	Oshkosh Defense, LLC.

Appendix B. Army Armor and Armament Steel Historical Perspective, Part 2

This appendix appears as a PDF attachment to the report.

Appendix C. New Armor Steel Specifications – FeMnAl Case Study

This appendix appears as a PDF attachment to the report.

Appendix D. Ballistic Testing of French ArcelorMittal Industeel MARS™ Armor Steels

This appendix appears as a PDF attachment to the report.

Appendix E. SECURE Steels: Highest Protection for Civil and Military Applications

This appendix appears as a PDF attachment to the report.

Appendix F. Rapid Rolling/Forming Schedule Development for Emerging Steels

This appendix appears as a PDF attachment to the report.

Appendix G. Enhanced Performance through Hotformed Armor Steel Applications

This appendix appears as a PDF attachment to the report.

Appendix H. Update on Design, Manufacturability and Reliability of Steel Castings (SFSA DID)

This appendix appears as a PDF attachment to the report.

Appendix I. Development of Meaningful Relationships between Steel Casting Surface Inspection Results and Performance

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This appendix appears as a PDF attachment to the report.

Appendix J. Mitigation of Hydrogen-Induced Cracking and Mechanical Properties Enhancement Using Low-Temperature Phase Transformation Welding Filler Wire on Armor Steel

This appendix appears as a PDF attachment to the report.

Appendix K. Fusion Welding of High-Strength Steels for Military Applications

This appendix appears as a PDF attachment to the report.

Appendix L. New High-Strength NiCr Steel Alloys, AerMet 310,340,360 for Hypersonic Structure

This appendix appears as a PDF attachment to the report.

Appendix M. Modeling and Characterization of Experimental Austenitic Steels Strengthened by MC Carbides

This appendix appears as a PDF attachment to the report.

Appendix N. Critical Performance Attributes for High-Strength Steel in Defense Applications

This appendix appears as a PDF attachment to the report.

Appendix O. Hot Cracking Resistance Evaluation Using Cast Pin Tear Test in Lightweight Armor Steel based on the FeMnAl-C Alloy System

This appendix appears as a PDF attachment to the report.

Appendix P. From Waste Steel to Materiel: Agile Production Enabled by Additive Manufacturing

This appendix appears as a PDF attachment to the report.

Appendix Q. Posters

This appendix appears as a PDF attachment to the report.

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
AC	Armaments Center
AFIT	Air Force Institute of Technology
AFRL	US Air Force Research Laboratory
Al	aluminum
AM	advanced manufacturing
APT	atom probe tomography
ARL	Army Research Laboratory
BHN	Brinell Hardness Number
C	carbon
CALPHAD	calculation of phase diagrams
CAVS	Center for Advanced Vehicular Systems
CCDC	US Army Combat Capabilities Development Command
Co	cobalt
Cr	chromium
CRADA	cooperative research and development agreement
CT	computed tomography
DID	Digital Innovative Design
DOD	US Department of Defense
DoN	Department of the Navy
EBSD	electron backscatter diffraction
FEM	finite-element model
FeMnAl	iron-manganese-aluminum
FSW	friction stir welding
FVL	future vertical lift
GB	grain boundary
GVSC	Ground Vehicle Systems Center
H	hydrogen

HAZ	heat affected zone
HE	hydrogen embrittlement
HEDE	hydrogen-enhanced decohesion
HELP	hydrogen-enhanced local plasticity
HHA	high-hardness armor
HIC	hydrogen-induced cracking
HIP	hot isostatic pressing
ICME	integrated computational materials engineering
ICMSE	integrated computational materials science and engineering
IoT	Internet of Things
LPF	laser powderbed fusion
LRPF	long-range precision fire
MGI	Materials Genome Initiative
ML	machine learning
MMPDS	Metallic Materials Properties Development and Standardization
Mo	molybdenum
MPI	magnetic particle inspection
MSU	Mississippi State University
NDT	nondestructive testing
NGCV	next-generation combat vehicles
Ni	nickel
NSWCCD	Naval Surface Warfare Center Carderock Division
OEM	original equipment manufacturer
OGA	other government agency
OSU	Ohio State University
PM	program manager
PSPP	processing-structure–property-performance relationship
Q&P	quench and partition
Q&T	quench and temper
QC	quality control

QLT	quench-lamellarization-tempering
R&D	research and development
RA	retained austenite
RHA	rolled homogeneous armor
RW	Munitions Directorate
RX	Materials and Manufacturing Directorate
SEM	scanning electron microscope/microscopy
SFSA	Steel Founder's Society of America
SLM	selective laser melting
S&T	science and technology
SZ	stir zone
TEM	transmission electron microscopy
Ti	titanium
TMP	thermomechanical processing
TRIP	transformation induced plasticity
TSA	test service agreement
UHHA	ultra-high-hardness armor
UTC	Universal Technology Corporation
UTEP	University of Texas at El Paso
UQ	uncertainty qualification
V	vanadium
WMRD	Weapons and Materials Research Directorate
WPI	Worchester Polytechnic Institute

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