American Metalcasting Consortium's

Casting Solutions for Readiness

Final Report

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A Cost Sharing Partnership

Volume I: CSR Projects Ending September 30, 2017

Program Executive Summary

Procurement agility is essential to the Defense Logistics Agency's (DLA) success supporting the combat readiness and welfare of the warfighter. Castings are an integral part to the operation of all combat weapon systems; however they represent a disproportionate amount of high costs and backorders for DLA. Enhancing DLA's capability to economically and rapidly procure metalcastings requires the development and transfer of advanced casting technology in materials, modeling, manufacturing, and procurement processes to ensure future success. The American Metalcasting Consortium's (AMC) *Casting Solutions for Readiness* (CSR) program has developed and implemented innovative technologies and processes for the procurement, design, and manufacture of cast spare parts to enable rapid support of items to the DLA and its customers.

AMC consists of the four leading metalcasting industry associations: American Foundry Society (AFS), North American Die Casting Association (NADCA), Non Ferrous Founders' Society (NFFS), and the Steel Founders' Society of America (SFSA), along with Advanced Technology International (ATI) as Program Manager. This unique consortium assures industry buy-in and access to over 1,900 domestic foundries. AMC represents every major casting process and material. The AMC CAST-IT team of engineers provides direct technical and procurement support to DLA. AMC's portfolio of projects under CSR are aligned with DLA's expressed technical areas of interest for casting research and support that has enabled U.S. foundries to manufacture cost effective, high quality cast spare and repair parts more quickly and DLA to better perform its mission. For over two decades AMC has been providing casting solutions to DoD.

AMC's industry-relevant and DLA-focused R&D projects have improved delivery times, quality, and cost efficiencies through innovative casting technologies and processes that provide rapid and nimble production, advanced material performance, reduced tooling and capital equipment investments, advanced casting design and modeling, and precision inspection tools. Impediments to technology commercialization and implementation have been neutralized by industry-evaluated and cost-shared projects that were centrally managed through AMC. ATI has managed the CSR program to ensure DLA's needs were coordinated with industry leadership, incorporated into appropriate DLA-needed research projects, and implemented into industry for supply-base efficiency enhancement.

Selected highlights include:

- The Integrated Casting Order Network (ICON) directed a monthly average of approximately 390 DLA bid solicitations worth $6.2M that contain cast metal components to capable metal casters. Actual contract awards made to ICON users averaged more than $1M per month.
- Pattern allowance predictions for steel casting enabled improved accuracy. The root mean square (RMS) error between measured and predicted pattern allowances for the new simulation capability is 0.29%, while pattern allowances based on previous production practices, known as the pattern maker's shrink rule, have a much larger RMS error of 1.31%.
- Application of an AlCrN permanent coating to a die surface that has dramatically reduced the amount of lubricant used by 83% - 92% in high pressure die casting. In addition to reducing the amount of lubricant used, the cycle time was reduced by about 12%, as the time required to spray the die was eliminated.

- The application of boron nitride (BN) was successfully used as a semi-permanent release agent for dies.
- Die thermal response was improved and cooling line design data was developed for reduced die lube spray cooling.
- Statistical based property data for sand cast high strength A206 aluminum and investment cast 15-5PH and 17-4PH stainless steels was developed for incorporation into the Metallic Materials Properties Development and Standardization (MMPDS) Handbook.
- A computer model was developed that determines the maximum flow distance and maximum fill time for die casting. It is now being used by die casters to facilitate the casting of thin-wall / lighter weight parts.
- Two new die casting alloys, considered to yield advantageous material properties, were registered with the Aluminum Association as F380 and B360.
- An improved Casting Alloys Data Search tool was upgraded with more data and additional data fields, including thermal-physical properties, thermal-mechanical properties, and strain life fatigue data. Additionally, data generated for more steel, aluminum and iron alloys was added to the database for process simulation modeling.
- A Steel Casting Wiki was developed that uses an online platform to provide both historical and current steel casting technology in one location. The Wiki has over 6,000 pages and approximately 4,800 technical references.

Introduction

The American Metalcasting Consortium's (AMC) "Casting Solutions for Readiness" program utilized a portfolio approach and distributed technology management among industry, research, and government resources to develop, leverage, deliver, and apply innovative technologies and processes in support of DLA's rapid procurement of cast components in weapon systems. AMC's strategic mission is to ensure a reliable casting supply chain for the rapid acquisition of high-quality, cost-effective parts for weapon systems. AMC is the only metalcasting consortium consisting of the leading metalcasting industry associations, their membership, and the premier metals / materials research universities in the United States. Structured as an integrated, cost-sharing collaboration, the CSR portfolio of projects addressed DLA's casting concerns, focusing on advancing the domestic supply base through DLA-relevant, industry-initiated R&D to improve lead times, costs, and quality in support of the warfighter. CSR also provided on-site technical and procurement support teams at DLA's Major Subordinate Commands. The consortium includes the four leading metalcasting industry associations (American Foundry Society (AFS), Non-Ferrous Founders' Society (NFFS), North American Die Casting Association (NADCA), and Steel Founders' Society of America (SFSA)), assuring industry buy-in and access to over 1,900 domestic foundries and the premier U.S. academic metalcasting / materials research universities.

The AMC CSR partnership with DLA is a cost-shared strategic alliance. The commitment of industry and the research community was evidenced by their 26% in value-added, in-kind cost share of the government-provided funding to the program. This is 13% over what was proposed.

AMC was formed by the leaders of the casting industry in 1992 to address the casting procurement problems experienced by DLA. These industry leaders selected the top academic talent in casting research from the nation's most respected casting research universities. The CAST-IT team, consisting of experienced metalcasting industry engineers, was assembled to address DLA's Major Subordinate Commands' real-time procurement problems of cast NSNs. CSR utilized the leaders in metalcasting, developers of innovative technologies, and existing relationships with DLA. The industry associations provided the involvement of industry, insight into R&D, and technology transfer. Researchers developed the needed technologies to help meet DLA objectives. The CAST-IT team provided procurement solutions for DLA using AMC technologies.

Approach

The core CSR team was comprised of ATI, AFS, NFFS, NADCA, SFSA, and America's premier metalcasting research universities. The core team has extensive experience in developing and implementing innovative technologies for the procurement, manufacture, and design of cast spare parts. The core team also provided access to state-of-the-art facilities and a strong knowledge-network infrastructure. ATI's role was that of business operations manager for the geographically distributed R&D teams. ATI supplied the CSR Program Manager who was responsible for the day-to-day operations of the program. All operating functions including financial management, scheduling, team communications, publicity, travel, and general program quality control were the Program Manager's responsibility.

AMC's CSR leadership came directly from the metalcasting industry. The chief executive officers of each industry association and elected industry representatives made up the AMC Board, and provided strategic direction and oversight for the CSR program. They worked closely with DLA managers and engineers to ensure the CSR objectives were focused on DLA priorities The DLA Program Manager and senior DLA executives had direct access to the AMC Board, and to the ATI

CSR Program Manager. This organizational structure provided effective and timely guidance for both policy and strategic program decisions.

AMC's Technical Advisory Committee (TAC) provided direct project technical oversight and monitored technical progress of all CSR activities, ensuring both DLA relevancy and industry acceptance. All aspects of CSR utilized information distribution channels that reached over 1,900 metal casters.

The CSR Program was funded as seven research elements:

- Task Order 1: Base Agreement
- Task Order 2: Tools for Streamlining Supply Chains: CAST-IT and Standards/Specifications
- Task Order 3: Procurement Solutions: Defense Casting for Supply Chain Integration and Statistical Properties for MMPDS Standard
- Task Order 4: Predictive Performance: Modeling of Steel Casting Performance – Dimensions and Distortion
- Task Order 5: Process Modeling: Lube-free Die Casting
- Task Order 6: Alternative Materials: Lightweight High Strength Cast Alloys Process Development
- Task Order 7: Rapid Tooling and Prototyping: On Demand Melting and Digital Radiographic (DR) Standards for Casting and Automated Image Analysis Techniques for New Radiographic Testing (RT) Standard

Task Order 2, CAST-IT, and Task Order 6, Welding of High Strength Steels, received no-cost extensions through June 30, 2018, at which time the final reports for those projects will be submitted. Task Order 7, On Demand Melting and Digital Radiographic (DR) Standards for Casting and Automated Image Analysis Techniques for New Radiographic Testing (RT) Standard was awarded in March 2016 with a period of performance through March 2019.

Results

The CSR projects completed through September 30, 2017 have developed and deployed agile, reliable solutions to support DLA’s procurement needs for cast metal parts. The CSR researchers have developed the tools and processes for metalcasters and machine shops/fabricators that support DLA’s procurement system. An executive summary of each project is provided below. Each project’s full final report is also available for detailed project results, conclusions, and information about transitions into industry.

The four metalcasting industry associations, with access to over 1,900 metalcasters, have promoted the newly-developed technology industry wide. The effectiveness of AMC’s approach has been demonstrated in the successful deployment and implementation of CSR technology efforts across the supply chain. CSR projects have been acknowledged by DoD and government officials at national conferences, and received recognition through both DoD and industry awards.

AMC recognizes that in order to maintain a healthy and vibrant supply base for DoD / DLA, a future workforce with a strong metals / materials / engineering education plays a critical role to sustain an agile and innovative metalcasting industry in the U.S. The CSR program encouraged university researchers to utilize their students to participate in this important R&D for the

metalcasting industry. Below is a list of students who supported the R&D, the degree they received or are pursuing, and where they are working:

University Students Supporting CSR Projects

Welding of High Strength Steels, Lehigh University

- Andrew Stockdale, received Ph.D., now working at Betis Atomic Power Lab, Pittsburgh, PA (a DOD Lab)
- Robert Hamlin, received Ph.D., now working at Knolls Atomic Power Lab, Schenectady, NY (also a DOD Lab)
- Brett Leister, received Ph.D., now working at Excelon Consulting, Los Angeles, CA
- Ally Fraser, undergraduate student, pursuing an M.S. degree at Lehigh

Modeling of Steel Casting Performance - Dimensions and Distortion, University of Iowa

- Daniel J. Galles, received his M.S. and Ph.D., now working in the Materials Manufacturing Technology Branch for the United States Army Research Laboratory

Lube-Free Die Casting, Colorado School of Mines

- Bo Wang, received his Ph.D. currently working for the coating company Ionbond, Chengdu, China
- Jie Song, post-doctorate, currently at Purdue University

Lube-Free Die Casting, Case Western Reserve University

- Sonni Lee, received B.S., currently employed by Nexteer, Troy, MI
- Bethani Cook, pursuing B.S. in Materials Science and Engineering
- Frances Seo, pursuing B.S. in Materials Science and Engineering

Acknowledgements

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Executive Summaries of CSR Projects Completed September 30, 2017

Task Order 2: Tools for Streamlining Supply Chains: Specifications and Standards / Design and Manufacturing Resources

a. Casting Alloy Data Search (CADS), American Foundry Society (AFS)

b. Development of Mechanical Properties for High Performance Die Casting Alloys , North American Die Casting Association (NADCA)

c. Steel Casting Wiki, Steel Founders' Society of America (SFSA)

Task Order 3: Procurement Solutions

a. Integrated Casting Order Network (ICON) Portal, Non-Ferrous Founders' Society (NFFS)

b. Statistical Properties for MMPDS Standard (AFS)

Task Order 4: Predictive Performance: Modeling of Steel Casting Performance – Dimensions and Distortion, University of Iowa

Task Order 5: Process Modeling: Lube-free Die Casting

a. Lube-Free Die Casting (Permanent Coating), Colorado School of Mines
b. Lube-Free Die Casting (Semi-Permanent Coating), Case Western Reserve University
c. Lube-Free Die Casting (Modeling), Ohio State University

Task Order 6: Alternative Materials: Lightweight High-Strength Cast Alloys Process Development

d. Thin-Wall and High-Strength Die Casting Alloys, Case Western Reserve University
e. Thin-Wall and High-Strength Die Casting Alloys (Modeling), Ohio State University

Task Order 2: Tools for Streamlining Supply Chains: Specifications and Standards / Design and Manufacturing Resources

a. Casting Alloy Data Search (CADS), American Foundry Society (AFS) Executive Summary

Accessing state-of-the-market technical, specification and training materials for castings is challenging. There is a need for better cast part design and specification data for longer service life, scrap reduction and improved performance. The American Foundry Society (AFS) is working to provide current and qualified information in a network friendly form to users of castings. This effort includes both archival and recent technical information in searchable databases. Specifications and standards are summarized, and the user is guided in their application. Tutorials covering the fundamental design concerns are also presented. These tools facilitate more effective and efficient procurement to both Department of Defense (DoD) and industry. Along with data from various AFS research projects, such as projects for the Development of Fatigue Properties Database, AFS has also incorporated the USAMP USAMP/USCAR Light Metals Materials Database properties and strain life fatigue data for CGI Grade 400 and a hi-alloy Class 40 Gray Iron into the AFS Casting Alloy Data Search (CADS) tool onto the AFS design website.

As part of the American Metalcasting Consortia (AMC) Casting Solutions for Readiness (CSR) program, a new project, Casting Alloy Data Search (CADS) tool was developed by AFS in partnership with PDA LLC and has been funded through the Defense Logistics Agency Research & Development Office. CADS, an online material design property database, is an enhancement of previous AFS AMC efforts to provide supply chain tools to facilitate reduction of lead time for castings and streamline the casting supply chain. This work builds on previous AMC, DOE, AFS, Steel Founders' Society of America (SFSA) and North American Die casting Association (NADCA) funded work, as well as on previous AFS sponsored research and DOE USAMP/USCAR work to develop material and physical properties benefiting designers. CADS greatly enhances the ability of the component design engineer to create the lightest weight and most efficient parts more quickly and at lower cost. The work planned under this project will add design properties for 4-5 additional cast metal alloys per year, while continuing to upgrade the CADS online database.

Industry users of this website will find CADS easy to use with step by step instructions on the website. Information has been disseminated through metalcasting industry associations via conferences, committee meetings, research reviews, periodicals, specification standards, webinars, and web sites. Presentations have been given at the AFS Casting Congress, Casting Design Conference, AFS Cast Iron Committee, SAE Fatigue chapter, and Investment Casting Institute conference. The AFS publication Modern Casting has included articles introducing readers to CADS. A webinar is also planned to introduce CADS users to the database and how to use it.

This work is valuable for the DLA supply chain by providing capable suppliers and enhanced supply base to ensure availability of critical cast parts to keep weapons systems operational. It also assists with obtaining optimized cast part performance and light-weighting.

b. Development of Mechanical Properties for High Performance Die Casting Alloys , North American Die Casting Association (NADCA)

The objective of this project was to collect information from North American die casting companies on new alloy compositions that might exhibit better mechanical properties than conventional aluminum die casting alloys. Cast-to-size tensile bars were produced from these alloys, and mechanical properties measured in three tempers, as-cast, T5 heat treated (low temperature age) and T6 heat treated (solution heat treat, water quench and age).

End users of die castings are starting to utilize die castings for structural applications, and so structural modeling such as Finite Element Analysis (FEA) is becoming more common. However, die castings typically have a heterogeneous structure, and so tensile samples machined from actual castings can exhibit inferior properties to the cast-to-size tensile bars normally used to characterize properties. Therefore, a second objective of this project was to provide a comparison between the mechanical properties of cast-to-size tensile bars and bars machined from commercial castings. Production castings were made from the new alloy compositions, tensile bars machined from these castings, and mechanical properties measured. A third objective of this project was to seek Aluminum Association registration for alloy compositions found to provide better mechanical properties than the conventional die casting alloys.

The fourth and final objective of the project was to transfer information from the project to industry. Project information was transferred through various presentations to North American Die Casting Association (NADCA) Chapter regions, during plant visits, and at meetings and conferences. In addition, the mechanical property data generated in this study will be transferred to industry through incorporation in the NADCA Product Specification Standards for Die Castings, as well through inclusion in NADCA's educational webinars and classes.

c. Steel Casting Wiki, Steel Founders' Society of America (SFSA)

The Steel Founders' Society of America (SFSA) is a not-for-profit trade association founded in 1902 to serve the steel foundry industry through advanced research and innovation. SFSA is uniquely positioned through its industry leadership in steel R&D to assume a prominent role in the development of industry-ready, performance-steel technology. SFSA is an approved supplier of steel R&D to the steel industry and the markets they support.

A major obstacle facing designers, purchasers, and producers of cast steel parts is a lack of both availability and accessibility of rapidly updated state-of-the-art technology information. Much of the historical steel casting technology that is relevant today is only available in print which limits the availability of the information and a means to keep it current incorporating new technology.

The objective of this project was to provide an accessible and efficient web-based resource tool in a Wikipedia format for SFSA members, any United States Government or Military personnel, and suppliers to the US Military to access information about steel castings. The Steel Casting Wiki uses an online platform to provide both historical and current steel casting technology in one location.

The framework of the steel casting wiki site is based on the contents of the Steel Castings Handbook 6th edition. As the wiki content and user base evolved, several additional technical reports and training resources were incorporated to make the wiki a robust casting technology resource for Government and industry. Additional resources include:

- SFSA Research Reports, National Technical and Operating (T&O) Conference Papers, and other SFSA Publications
- SFSA Surveys Prompted by Member Questions
- Artisan Program
- Webinar Training Courses
- Steel Castings Handbook Supplement 2 Update
- Technical Summaries

The Wiki currently has over 6,000 pages and approximately 4,800 technical references.

- Wiki content pages: 6,493
- Users: 428
- Uploaded files: 4,808
- Page edits: 8,321
- Carbon & Low Alloy Research Reports: 120
- High Alloy Research Reports: 13
- Special Reports: 33
- Technical Service Reports: 26
- SFSA Research Foundation Reports: 8
- Steel Founders' Research Journals: 59
- Journal of Steel Castings Research: 94 files containing 871 articles
- SFSA Technical Folios: 43
- Steel Castings Handbook Supplements: 11
- Other SFSA Publications: 31
- Steel Foundry Facts (Papers presented at SFSA Technical & Operating Conferences prior to 1983): 2,110
- Technical & Operating Conference papers 1983-2016: 1,230
- Results of SFSA surveys prompted by member questions: 63 in 16 subject areas

- SFSA Artisan Program requirements pages: 30
- Webinar training courses: 26

Task Order 3: Procurement Solutions:

a. Integrated Casting Order Network (ICON) Portal, Non-Ferrous Founders' Society (NFFS)

The Non-Ferrous Founders' Society (NFFS) is a 501(c)6 not-for-profit trade association that represents the non-ferrous foundry industry in the United States and Canada. NFFS is part of the American Metalcasting Consortium (AMC), which is a DLA ManTech funded program that provides the expertise and resources that are essential to the sustainment of a domestic metalcasting supply base that provides superior and affordable cast components to ensure warfighter readiness. The current NFFS projects aim to address the lack of visibility and response regarding metal castings in the DLA's supply chain.

Castings represent a significant portion of backordered parts in the current procurement system according to DLA supply centers. This is often due to fragmented supply chains that arise from a lack of understanding of underlying manufacturing processes and where to source qualified contractors, lost or unknown tooling locations, and a diminishing domestic manufacturing supply base. The result is increased lead-times, higher costs, creation of unnecessary duplicate tooling and a reduction in supply chain readiness. The Integrated Casting Order Network (ICON) Portal was designed to address these issues and to provide solutions using the following functionalities in one convenient internet portal:

- Automated Solicitation Matching and Distribution – a customizable Inbox for ICON users containing DLA solicitations that match the users Bid-Matching Settings. The portal will identify bid solicitations that contain a metal cast component via the FLIS dataset and match it to potential suppliers based on their bid matching settings and provide it to them via their Inbox. The Inbox allows users to quickly and easily sort through bid solicitations and view any solicitation details and technical data package information associated with the solicitation.
- Bid Matching Settings – allows ICON users to input their company manufacturing capabilities and to update their defense related tooling records within the ICON portal, to allow the system to match bid solicitations to their capabilities. Companies may include capabilities such as materials cast, casting processes utilized, minimum order quantity and minimum estimated contract values.
- Defense Tooling Locator – an online searchable database which enables a buyer or contractor to identify and locate tooling for defense castings that currently reside in prime contractor and sub-tier metalcasting facilities, thus eliminating the cost of duplicating tooling and reducing administrative and production lead-times for part acquisition.
- Defense Casting Supplier Database – a comprehensive database of metal casters that can be queried by alloy, casting process, business and federal classifications and other relevant capabilities. The database will enable DLA personnel and defense contractors to quickly identify qualified casting manufacturers by searching plant capabilities and technical specifications.

By implementing a suite of functionalities and features in one convenient location for DLA contractors and metalcasting suppliers to use, the quality and quantity of industry response from industry to the DLA increases dramatically. These efforts are being transitioned into industry by incorporating these items into the ICON portal, and by increasing the number of foundries using the ICON portal to find and fulfill DLA bid solicitations for castings.

As of September 2017, there are over 350 metal casters enrolled in the ICON Portal who possess more than 23,000 pieces of tooling for confirmed National Stock Numbers for Defense and Military components. On average, approximately 390 DLA bid solicitations that contain cast metal components are directed to capable metal casters, valued at over $6,200,000 per month. Actual contract awards made to ICON users average more than $1,000,000 per month, and continue to increase in number and value. Considerable cost savings on contracts awarded to ICON users have been documented, and the ongoing cost savings generated by the ICON portal for metal casting contract awards are now being included in DLA Cost Savings Reports for both the DLA Aviation (Richmond, VA) and the DLA Land and Maritime (Columbus, OH) Supply Centers.

b. Statistical Properties for MMPDS Standard (AFS)

The Cast High-Integrity Alloy Mechanical Property Standards (CHAMPS) Statistical Properties Project goal is incorporation of material property design data for additional cast alloys, A206 high strength aluminum for sand casting in the initial phase and then 15-5PH and 17-4PH stainless steels for investment casting in the second phase, into the Metallic Materials Properties Development and Standardization (MMPDS) handbook, which replaced Mil-handbook 5, so that this material can be specified and used to design and manufacture flight critical components in military and civilian aircraft. This builds on the original American Metalcasting Consortium (AMC) E357 effort of establishing a framework to design a series of test specimens that encompass the various section thicknesses used in these applications utilizing process simulation software, validating the approach metallographically, coordinating the collection of required samples from a consortium of qualified foundries, and submitting the data for statistical analysis and approval by the MMPDS board for incorporation into the MMPDS standards. The benefit to the Defense Logistics Agency (DLA) is the development of statistical-based property data to permit the use of castings across a broader range of applications and will allow the Engineering Support Activities (ESA) at the DLA to make cast alloy conversion / replacement decisions with assurance using statistical data on tensile, compressive, shear, and bearing properties from the Federal Aviation Authority (FAA) recognized source, the MMPDS Handbook. This will also reduce lead times with cast components competing on an equal basis with forging and assemblies from sheet, plate, and extruded mill products.

As with the E357 project, the intended outcome is cast A&B design property allowables for the alloys selected for inclusion in the MMPDS to meet FAA requirements. This allows aerospace design engineers to specify castings without using design safety factors. Various working groups actively looked at melt practices, test casting gating and filling, heat treatment parameters, testing protocol and weld repair standards. The initial casting trials followed the approach taken for E357 and conducted for 1.5 x 2.5-in plate cast in both horizontal and vertical gating approaches, and a heat treat study was conducted at various participating foundries. These plates were tested for tensile properties and microstructural evaluation was conducted. For the A206, the plate was 16” x 8” and the section thicknesses were ½ - 2”.

Some of the benefits of listing A206 high strength aerospace alloy are:

- Adds additional cast high strength aluminum alloy into available materials that can be specified and procured.
- Using higher strength, light-weight aluminum alloys results in weight reduction
- Overcomes part-by-part validation process
- Aligns with the goal of the Joint Defense Manufacturing Technology Panel (JDMTP):

  "Encourage community to collect and store data to build pedigreed data for MMPDS design allowables." --Stephen Luckowski, 17 April, 2014

It is noteworthy that as a result of the work performed on this project, the solution heat treatment specified for sand cast A206-T4 per AMS 4236B and A206-T71 per AMS 4235B was modified making the step solution treatment required.

Task Order 4: Predictive Performance: Modeling of Steel Casting Performance – Dimensions and Distortion, University of Iowa

Casting distortions are unacceptable dimensional changes resulting from stresses during solidification and cooling which can result in repair work or scrapped castings. Both the mechanical behaviors and properties of the steel and the sand mold affect the final casting dimensions through mold expansion, and by constraining the casting from free contraction, which introduces stresses and additional distortions. Distortions can lead to a lengthy trial-and-error process of modifying pattern allowances to meet dimensional requirements. In the past, foundries relied on rules-of-thumb, lengthy trial-and-error processes, and excessive machining allowances to meet dimensional tolerances. New dimensional predictive capabilities are especially needed for optimizing the dimensional performance of the thin-walled and light-weight steel castings needed in advanced weapon systems. The research and developments described here were undertaken to address deficiencies of computer models to predict final dimensions and distortions of steel castings. These deficiencies arise from mechanical properties for the mold and the steel not being known with sufficient accuracy, and the software not fully accounting for the mechanical and thermal interactions at the mold-metal interface. Resulting from this project, software tools and material properties necessary to perform such modeling were developed. The steel is modeled as an elasto-visco-plastic material, and the Drucker Prager Cap model is employed for the bonded sand. Properties and models are developed and calibrated with measurements from casting experiments. Steel properties and models are calibrated using steel bar castings that are strained by applying a force to bolts embedded in the bar ends. Restraint forces and the bars' length changes are measured in situ. The experiments are simulated by inputting calculated transient temperature fields into a finite element stress analysis that employs the measured forces as boundary conditions. Thermal strain predictions are validated using data from bar experiments without a restraint. The resulting calibrated mechanical property dataset is valid for the high-temperature austenite phase of steel. Bonded sand mold properties and material models are developed using two experimental setups by matching measurements and finite element stress analyses. The two casting experimental geometries used for this are a hollow cylinder and U-shaped bracket. The temporal evolutions of 1) the cylinder's inner diameter and 2) the gap opening between the bracket legs are measured in situ utilizing LVDTs (Linear Variable Differential Transformers) connected to quartz rods. By matching the predicted displacements with the measurements, a temperature dependent constitutive dataset is developed. The predictive capabilities of the properties and models are then demonstrated through case studies where dimensional changes and associated distortions for

production steel castings are predicted. Pattern allowances for ten casting features are measured and later used to validate the simulations in a case study reported here. Pattern allowances are predicted with good accuracy, as the root mean square (RMS) error between measured and predicted pattern allowances for the new simulation capability is 0.29%, while pattern allowances based on current production practices, known as pattern maker's shrink rule, have a much larger RMS error of 1.31%. Implementation and transitioning of this research for predicting casting dimensions and distortions to industry has been accomplished by undertaking demonstration case studies with industrial partners, implementation of its results in the MAGMAstress software available from MAGMA Foundry Technologies, through eleven publications and dozens of presentations to the steel foundry industry.

Task Order 5: Process Modeling: Lube-free Die Casting

a. Lube-Free Die Casting (Permanent Coating), Colorado School of Mines

During high-pressure aluminum die casting, a liquid lubricant is sprayed on the die surface prior to each shot to help release the casting, cool the die, and prevent soldering from occurring. However, spraying a large amount of liquid lubricant each shot not only reduces the quality of the castings, adds time to the casting cycle, and increases the cost of producing castings, it also generates effluent that has environmental ramifications. The overall objective of this work was to develop permanent hard coatings on the surfaces of die casting dies that result in no aluminum adhesion in the absence of using liquid-based organic lubricants. This new concept is called lube-free die casting. To achieve this goal, a simple laboratory method called the aluminum adhesion test (AAT) was developed to provide a quick quantitative evaluation of the adhesion/soldering strength of the cast alloy to various substrates and/or coatings. A number of hard coatings have been evaluated using the AAT. Several coatings were identified to have zero or negligible adhesion strength between the solidified alloy and the coating. To assess the efficacy of the candidate coatings screened by the AAT in preventing such alloy adhesion under actual die-casting conditions, both a coated die insert and a fully-coated die cavity have been tested in a series of four plant trials.

The results of laboratory testing and initial plant trials suggested that an AlCrN coating applied to the die surface has the potential for dramatically reducing die lubricant use. To date, more than 19,000 castings have been produced using a die coated with AlCrN, with die spraying reduced significantly (83-to-92% less) compared with the amount of spray used for an uncoated version of the same die. In addition to reducing the amount of lubricant used, the cycle time was reduced by about 12%, as the time required to spray the die was eliminated. In addition, T6 heat treatments trials have indicated that the reduction of spray dramatically decreased the amount of entrapped gases (porosity) in the castings, and although the reduction in entrapped gasses was not quantitatively measured in this study, porosity reduction due to reduced spraying is estimated to be greater than 50%. Finally, as aluminum die casting dies typically last longer than 100,000 shots, the plant trials have not progressed sufficiently to evaluate the impact of reduced die spraying on heat checking and die life. However, the metric in this project was to increase die life by 15%, and based on laboratory testing performed at Case Western Reserve University to evaluate the impact of die spray on die life, the 83-to-92% reduction in spray achieved in the plant trials should provide a die life extension of significantly more than 15%.

The results from the laboratory studies and the plant trials have been presented at the last two NADCA Congresses, and both congress sessions were well attended by industry personnel and

generated a lot of interest from attendees. In addition, the results from this research have been incorporated into a new NADCA booklet and webinar series entitled Applications of Surface Engineering for Die Casting Dies.

b. Lube-Free Die Casting (Semi-Permanent Coating), Case Western Reserve University

Die lubricants are used extensively in die casting and are expected to provide good part release, anti-solder and lubricity of the die and ejector pins. In many cases water based die lubricants are also applied to cool the die surface. While fulfilling these favorable roles, die lubricants have some undesirable consequences. Vapors from moisture left on the surface of the die after spraying can be trapped in the casting and cause excessive porosity. Decomposition of organic ingredients in the die lubricant can also cause porosity. Application of the die lubricant extends the cycle time. Unless properly addressed, die lubricant mist and residuals can pose environmental issues in the plant.

For these reasons, a lube-free die casting process is an attractive goal. To accomplish it, the functions of the die lubricant would need to be fulfilled by a substitute permanent or semi-permanent coating applied on the dies. The focus of this study was evaluation of boron nitride as a potential semi-permanent die casting coating. While expensive, boron nitride is recognized as an excellent release agent. As an inorganic substance, it is also thermally stable up to relatively high temperature. It does not react with molten aluminum, thus providing excellent protection from soldering.

The study confirmed the superior performance of boron nitride in preventing soldering, by conducting extensive exposure of boron nitride coated steel in molten aluminum. A novel test was developed to quantify the release stress during ejection of aluminum castings from the die. This test demonstrated low release stress during ejection when concentrated boron nitride coatings were applied. The release stresses increased when the concentration on the boron nitride was lowered, but were still significantly lower than in commercial die lubricants. Intermittent application of a boron nitride coating at longer intervals provided reduced yet satisfactory release. Preliminary evaluation in production at Mercury Marine provided encouraging results.

c. Lube-Free Die Casting (Modeling), Ohio State University

Lubrication free die casting generally means that surface spray is eliminated which eliminates one of the tools used for control of the die temperature. The primary objective of this work was to explore the implications of loss of spray cooling and evaluate strategies for cooling design to compensate for this loss.

It was known at the start of the project that good, well-engineered, internal cooling can compensate for the loss of spray and field tests performed as part of the project confirmed this fact. Die cooling system design principles have long called for sufficient internal cooling to accommodate the full heat load that is imposed on the die and some casters achieve this objective with good design but many lack the understanding of heat transfer necessary to achieve the objective or prefer to use spray.

This work demonstrated several of the physical principles that control the die thermal response. A one-dimensional (1-D) model that combines numerical and analytical solution techniques was used to perform several sensitivity studies that help visualize the tradeoffs inherent when spray cooling is reduced or eliminated. The 1-D model results are simple enough to display graphically for easy understanding but complete enough to provide needed engineering insight.

Several strategies intended to compensate for the elimination of spray were considered including "do nothing and letting the die run hot," increase the cycle time, and intermittent spray where spray is applied but not every cycle. While these approaches work in some cases, internal cooling is shown to be more effective.

Analysis of the heat transfer characteristics of internal cooling lines produced design relationships that relate the required heat transfer and temperature change in the coolant with cooling line design parameters. Methods used previously did not account for the temperature rise in the coolant.

Most results of the work are in the form of simple, graphical explanations of the heat transfer phenomena that occur in die casting dies. The 1-D transient and spatial die temperature results illustrate the effects of cycle time, thermal mass, cooling line placement etc. NADCA has course materials for both die design and die thermal management that will benefit from the inclusion of material in this form. A preliminary revision of course EC 415, Thermal Design and Control, has been completed including some of the spatial and transient response examples from this work and including the cooling line design relationships. Finalization of the presentation materials and revisions of the text material will be completed by early 2018.

Much of this work is also relevant to general computer modelling issues. Simulations generally do not explicitly model cooling lines as heat exchangers and the quasi-equilibrium phenomenon is not well understood. Results from this research that include these topics are included in three new NADCA computer modeling webinars that will be presented for the first time in the fourth quarter of 2017.

General modelling results, and especially the quasi-equilibrium results, were presented at the 2016 NADCA Congress and are included in the transactions (Miller 2016).

Task Order 6: Alternative Materials: Lightweight High Strength Cast Alloys Process Development

a. Thin-Wall and High-Strength Die Casting Alloys, Case Western Reserve University

NADCA has had success in developing a zinc alloy chemistry and processing parameters for thin-wall zinc applications. This project envisioned development of the same methodology to aluminum in order to produce thinner wall castings for light weighting. In addition, since higher fluidity is required for thin-wall casting, this project enables complex geometries to be made that cannot otherwise be successfully produced and allows scrap issues stemming from lack of fill to be reduced or eliminated.

Working with NADCA, the project team attempted to develop alloy composition(s) with high fluidity in aluminum by:

- Defining composition for a high-fluidity aluminum die casting alloy
- Measuring and optimizing fluidity of potential Al alloys
- Casting test bars to measure mechanical properties

An initial effort was dedicated to developing an instrument capable of measuring fluidity of aluminum alloys under conditions similar to die casting. This instrument was comprised of a vacuum reservoir connected to a vent block. The vent block was in turn connected to a silicon carbide riser tube immersed in molten aluminum. By applying vacuum to this system, molten aluminum is sucked into the vent block. The distance traveled by the molten alloy before it

solidifies is used as a measurement of fluidity. Using this instrument, a range of commercial aluminum alloys were evaluated. The high silicon 390 aluminum alloy had the highest fluidity. Increases in the silicon and copper in this alloy provided even higher fluidity, although the increase was very modest. In laboratory trials, boron nitride coatings applied on the vent block were also shown to improve fluidity. Preliminary in-plant trials were also conducted with a boron nitride coating. Additionally, the mechanical properties of alloys evaluated in this study were measured using test bars die cast at Premier Die Casting and are detailed in this report.

Parallel to the experimental work, a computational effort to predict influences of processing variables on fluidity was undertaken by Ohio State University. This work is described in a separate report. A relatively simple one-dimensional heat transfer model that incorporates part wall thickness, injection and die temperatures, gate speed plus the freezing range and fraction solid curve of the alloy was developed. The basic fluidity model was extended to incorporate varying speed and/or wall thickness. This extension enables analysis of prefill, or the situation where the cavity is partially filled before the onset of the fast shot or high-speed phase of cavity filling, and provides insight into the conditions under which prefill is beneficial and where it is not likely to be successful.

Several computation factorial experiments were performed using the basic model and analyzed to understand the relative importance of each factor as a contributor to flow distance. The results show that, while the alloy properties do affect the flow distance, flow distance or fluidity is largely a thermal issue controlled by the process conditions. This result provides support for the observation that the casting alloy should be selected to meet the functional requirements of the part without undue consideration of fluidity. The process conditions can then be optimized to produce an acceptable casting.

The computational work showed the injection velocity to be by far the most important variable in improving filling. The interfacial heat transfer between the die and the solidifying metal was also shown to have a significant impact on flow distance. This is an important takeaway, since it could be used by die casters to facilitate casting of thin-wall parts.

A subtask of the project addressed semi-solid metalcasting (SSM) casting of high-strength aluminum alloys. Standard high-pressure die casting (HPDC) of high-strength aluminum alloys such as 201 and 206 that are typically used in gravity pour methods is difficult due to the extremely low silicon content of these alloys. Because the flow and fill characteristics of semi-solid slurries are different than HPCD and because hot tearing is reduced due to lower pour temperatures, it was thought that it might be possible to cast these types of alloys in highly complex configurations by the semi-solid process. Although such alloys have been SSM cast, processing parameters that provide a wide operating window have not been established. This project evaluated SSM parameters designated for robust processing of high-strength alloys and demonstrated the process by casting test plates. Alternative compositions of aluminum 201 and 206 alloys for squeeze processing were identified from literature and mechanical properties were reported.

Partner companies such as General Die Casters, TCDC, Eck Industries, Mercury Marine and others have been steadily pushing the limits of thin wall die castings by introducing vacuum technology and optimizing the process parameters. Provided rigorous controls are in place, wall thickness sections of less than 1mm can be produced. The combined experimental and computational efforts put forth in this project are making a modest contribution to this industry-wide effort. They

demonstrate slight variations in fluidity to have a lesser impact on filling of thin wall die castings than process and thermal variables, such as shot velocity and heat transfer.

b. Thin-Wall and High-Strength Die Casting Alloys (Modeling), Ohio State University

Fluidity for casting is defined as the distance that the metal will flow before the onset of solidification stops continued flow. Fluidity is clearly an important issue when determining if a casting, particularly a thin walled casting, will fill. While both the properties of the cast alloy and the processing conditions impact the fluidity of the alloy, it is less clear what the relative contribution of the material, process, and the part itself are to the ability to fill the die cavity. A relatively simple one-dimensional heat transfer model that incorporates part wall thickness, injection and die temperatures, gate speed plus the freezing range and fraction solid curve of the alloy was developed to analyze this question. Determination of the gate area needed to successfully fill the die cavity at the minimum acceptable metal speed while maintaining an acceptable metal state at the end of fill was an unexpected benefit derived from this model.

The basic fluidity model was extended to incorporate varying speed and/or wall thickness. This extension enables analysis of prefill, or the situation where the cavity is partially filled before the onset of the fast shot or high-speed phase of cavity filling, and provides insight into the conditions under which prefill is beneficial and where it is not likely to be successful.

Several computation factorial experiments were performed using the basic model and analyzed to understand the relative importance of each factor as a contributor to flow distance. The results show that, while the alloy properties do affect the flow distance, flow distance or fluidity is largely a thermal issue controlled by the process conditions. This result provides support for the observation that the casting alloy should be selected to meet the functional requirements of the part without undue consideration of fluidity. The process conditions can then be optimized to produce an acceptable casting.

The fluidity model has been implemented and fully integrated in three web-based applications available on the NADCA Members Plus website. The three applications are:

a. PQ2

b. Max Flow Time Estimator

c. Gate Designer

The PQ2 application is used to properly size the in gate to the cavity to meet part quality requirements and to maximize the size of the operating window of the process.

The second of these applications estimates pre-injection heat losses, i.e. losses during ladling, pouring and residence of the metal in the cold chamber prior to injection. This set of calculations replaces a difficult to estimate quantity, the temperature of the metal at the gate, with estimates based on more easily obtained data.

The gate designer application is primarily intended for constructing gate geometries that facilitate metal flow into the cavity but the gate area calculation is included so that users who do not perform a PQ2 analysis first have access to the result.

The course presentations and text materials used for PQ2 and Gating have been revised to include the new results. The revised materials have been used for courses taught numerous times starting with the second quarter of 2016.