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Report of the 2022 Department of Defense Steels Summit

by Krista R Limmer, Daniel M Field, Katherine M Sebeck, Manny Gonzales, Sujeily Soto-Medina, Matthew C Draper, Maya Nath, Andelle Kudzal, and Eric J Payton

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Report of the 2022 Department of Defense Steels Summit

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14. ABSTRACT
The annual Department of Defense (DoD) Steels Summit was held 15–16 November 2022 at Aberdeen Proving Ground, Maryland, to bring together the government, industrial, and academic community working on defense-relevant steel development to more rapidly advance material development and implementation. This report contains the meeting agenda, technical abstracts, and summary. Appendixes with proceedings and posters presented during the meeting are also included.

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tri-service, steel, manufacturing, industrial base, advanced steel solutions, Sciences of Extreme Materials

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Table 1 2022 DoD Steels Summit agenda 1

1. About the Meeting

1.1 Meeting Overview

The 2022 Department of Defense (DoD) Steels Summit held 15–16 November 2022 in the Mallette Training Facility at Aberdeen Proving Ground, Maryland, was hosted by the Army Research Directorate of the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL). This was the sixth annual DoD Steels Summit, returning to an in-person format after 2 years of virtual meetings during the COVID-19 pandemic. 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 2022 DoD Steels Summit comprised keynote and invited speakers, technical briefings, a panel discussion, and poster sessions, as outlined in Table 1. Sixteen technical briefings were presented in six different sessions, and a panel discussion was held to discuss the state of the steel industry. There were two poster session breaks at which 31 posters were presented by their authors. Dr Ernest Chin, Sciences of Extreme Materials Division Chief, welcomed the attendees at the opening of the summit.

Table 1 2022 DoD Steels Summit agenda

Date	Start time	Description
15 Nov 2022	0830	Opening and Welcome
	0900	KEYNOTE: COL Ryan Howell, PhD (US Army)
	1015	Session A: Structure–Processing–Property Relationships
	1115	Session B: Data Science and Modeling
	1155	Group Photo and Lunch
	1330	INVITED: Dr Rachel Abrahams (US Air Force)
	1400	Session C: Physical Metallurgy of Ultra-High Strength Steels
	1500	Poster Session
	1600	Session D: Additive Manufacturing of Ultra-High Strength Steels
	1700	Conclude Day 1
		No-Host Social, Prost German Restaurant
16 Nov 2022	0830	Session E: Degradation and Performance
	0945	Session F: Ballistic Performance
	1025	Poster Session
	1125	INVITED: Dr Glenn Daehn (The Ohio State University)
	1140	PANEL: Steel Industry of Today and Tomorrow
	1225	Concluding Remarks – end of open session
	1330	Closed Government Session
	1530	Conclude Day 2

1.2 Meeting Attendance

The summit was attended by more than 150 people representing more than 60 different government, academic, and industrial organizations. 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 meeting attendee affiliation has consistently included the DoD, other government agencies (OGAs), industry, and academia (faculty, postdoctoral associates, and students). The affiliations of the 2022 summit registrants are shown in Fig. 1 (consistent with previous summits).

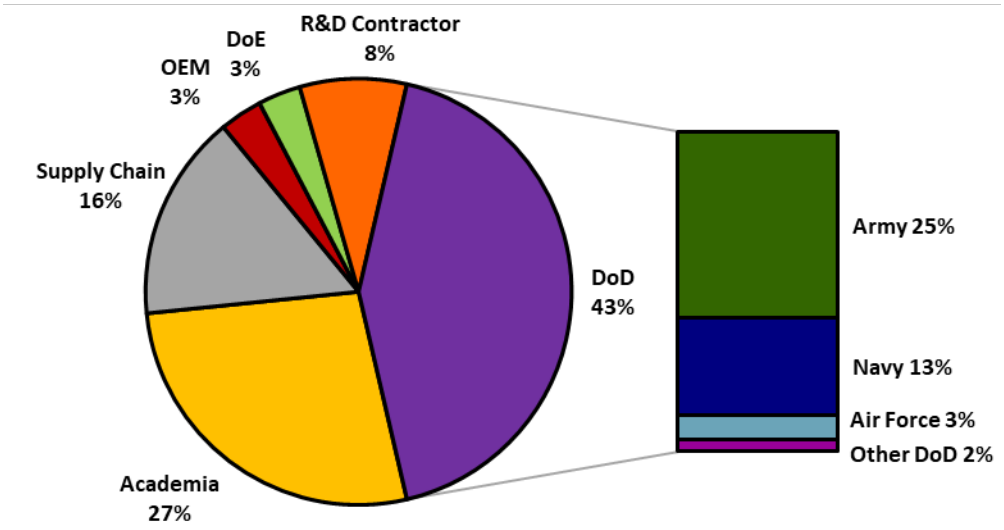


Fig. 1 DoD Steels Summit 2022 registrant affiliation

Although the general affiliation of attendees has remained relatively constant, the individuals in attendance are changing. The number and location of previous DoD Steels Summits attended by registrants are shown in Fig. 2. Almost half of the registrants (47%) had not yet attended a DoD Steels Summit. Of registrants who had previously attended, a majority (80%) had attended at least one in-person summit before the pandemic.

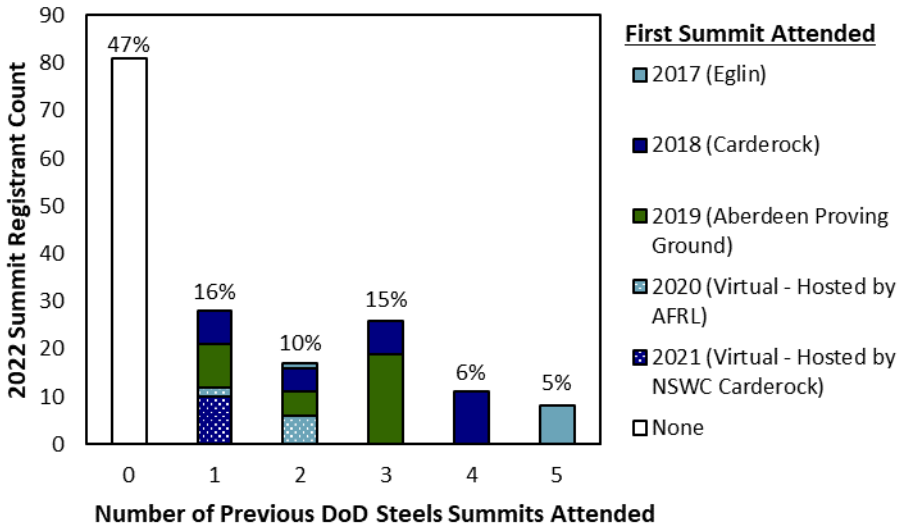


Fig. 2 Number of DoD Steels Summits previously attended by 2022 registrants. Also indicated is which summit was first attended by the registrants.

2. Technical Content Overview

Authors, affiliations, titles, and abstracts for each of the special speakers, panel discussion, technical briefings, and poster presentations are included in this section based on type of presentation. A short summary of the panel discussion is also included. Technical briefings are listed in chronological order, and posters are presented in alphabetical order by title. Presenting authors are indicated in italicized text. Proceedings and posters that have been cleared for public release in print form have been included as separate appendixes as denoted at the end of each abstract. Abstracts have not been edited and appear as submitted by the corresponding authors.

2.1 Special Speakers

2.1.1 Keynote Speaker

Relevance of Steel in a Modern Threat Environment

COL Ryan Howell, PhD

US Army Program Manager Main Battle Tank Systems

Keywords: Steel, Metal, MDO, Threat, Capability

Army ground combat modernization is no longer a classic metals centric endeavor. Capability is defined by software, sensors, AI, automated and robotic enabled capabilities. That presents opportunities for steel and materials as well as risks to

investment. As we are all witnessing from the RU-UKR war, offensive capability in a Multi-domain Operation (MDO) still requires copious amounts of heavy metal, armor capability, and steel enabled lethality to offensively remove an aggressor from the battlefield. As the US Army modernizes for future conflict, steel remains the backbone of the force and therefore the steels we use must modernize commensurate with the capabilities needed to fight on the modern battlefield now and into the future.

2.1.2 Invited Speakers

Steel Research Needs and Trends in the USAF Weapons Portfolio

Rachel Abrahams (USAF Agile Weapons Lead EN/SME)

US Air Force Life Cycle Management Center

Introducing HAMMER-ERC

Glenn Daehn

The Ohio State University

Keywords: Hybrid Autonomous Manufacturing, Forging, Supply Chain, Local Properties

Our new NSF Engineering Research Center (HAMMER) Hybrid Autonomous Manufacturing Moving from Evolution to Revolution will complement the efforts of the DoD steels community. We have secured a long-term grant and hope to provide high-quality agile-manufacturing solutions in service of the US economy and security efforts. The core of the approach is related to numerically controlled deformation to serve a number of use cases. Issues of quality, trust, automated build and qualification, including model-based certification and the research agenda required to create value with this new technology will be emphasized. See some details of our center at http://hammer.osu.edu.

2.2 Panel Discussion

A summary of the panel discussion “The Steel Industry of Today and Tomorrow” along with the participants is provided here. This is not intended to be a transcript of the dialogue, rather an overview of the topics discussed.

Abstract: After decades of globalization and public policy have eroded the domestic manufacturing ecosystem, what manufacturing technology will sustain or even enable leapfrog capability to support the warfighter. The focus will be on

technology and a next generation workforce to suit the technical nature of the audience.

Panelists:

- Jim Myers (MetalTek)
- Mike Maxeiner (Arcosa)
- Raymond Monroe (Steel Founders Society of America, Steel Performance Initiative)

Moderator: David Poweleit (Steel Founders Society of America)

The panel led off by considering the biggest challenges facing their industry, offering thoughts including personnel and the challenge of working with the DoD acquisition environment. Challenges for personnel included not only recruiting people to metallurgy but also keeping them invested and engaged throughout business developmental cycles. The panelists commented that it is easy to recruit from far away for short term, but it is often difficult for people to permanently relocate if not from that region. With increasing facility automation, recruiting personnel with advanced technological skills and interests is also becoming increasingly important. The DoD acquisition environment also poses a significant challenge because of the combination of low quantity, low cost, and high performance. One panelist also commented that the qualification standards should be reviewed and revised such that only relevant testing is being done to reduce unnecessary burden on suppliers. The panelists further commented on the things they need: earlier engagement during materiel development, continued tool development, and specification revision. The panel also discussed briefly how to recruit people into metallurgy and emphasized showing off the cool aspects and demonstrations, and promoting hands-on projects such as Cast in Steel and senior design projects.

2.3 Oral Technical Briefings

2.3.1 Session A: Structure-Processing-Property Relationships

Intercritical Annealing of HY Steel to Improve Impact Toughness

John D. Galuardi, Kip O. Findley, and Emmanuel De Moor

Colorado School of Mines

Keywords: Intercritical Annealing, Impact Toughness, Retained Austenite, Austenite Stability, Casting Products

Intercritical annealing/tempering treatments (IA/T) have been historically used to improve low-temperature impact toughness in Ni-bearing steels, and have been applied to the High Yield (HY) system to improve impact toughness in large section size castings. IA/T treatments are believed to improve impact toughness by stabilizing retained austenite (RA) leading to transformation-induced plasticity. IA treatments ranging from 1380-1435 °F and T treatments from 1140-1265 °F have been applied to cast HY-80 material representing a 5" section size. Mechanical testing found yield strengths between 58-100 ksi with Charpy impact energies measured at -100 °F ranging between 28-108 ft-lbs. The impact toughness properties are independent of the measured RA volume fraction. Dilatometry indicates the ratio of stable austenite to ferrite during IA may affect yield properties. Lower IA temperatures extend the range of T temperatures that achieve acceptable mechanical properties below the minimum T temperature outline by NAVSEA requirements.

Proceedings included as Appendix A.

Effects of Direct Resistance Heating on Recrystallization in Cold-Worked Steels

Dawn Van Iderstine, Shiraz Mujahid, YubRaj Paudel, and Hongjoo Rhee

Center for Advanced Vehicular Systems, Mississippi State University

Keywords: Steel production, recrystallization, grain growth, thermomechanical simulation, electron wind effect

The electron wind effect, where an electric current interacts with microstructural features such as dislocations, has been cited as a potential catalyst of solid-state transformations in metals. While literature focuses primarily on high-density currents (≥1000 A/mm2), recent studies suggest that the phenomenon can occur at lower current densities, such as those used by thermomechanical simulators. Owing to precise thermal control, these simulators are seeing increased use in developing novel microstructures for advanced high-strength steels. However, industrial-scale recreation of such microstructures through convective/radiative means requires analysis of heating method effects on microstructure evolution. This study compares the response of cold-worked steels to heating in a conventional furnace and in a Gleeble 3500 thermomechanical simulator, focusing on the rate and extent of recrystallization and subsequent grain growth. Mechanisms for resultant microstructural discrepancies are examined in the context of prior work on the topic.

Proceedings included as Appendix B.

HSLA-100 for Thick-Section Forgings

Joshua J. Mueller[1], Virginia K. Euser[1], Joshem Gibson[1], Nick Ferry[2], and Mark Royer[2]

[1] Los Alamos National Laboratory
[2] Lehigh Heavy Forge Corporation

Keywords: Low-Temperature Toughness, Forgings, Charpy V-Notch, Hardenability, Retained Austenite

HSLA-100 is a naval steel that was developed to exhibit exceptional combinations of strength and toughness while maintaining good weldability without post-weld heat treatment. Originally developed as a plate steel grade, there is interest in adapting HSLA-100 to thick-section forgings. The work presented here investigates the amenability of HSLA-100 to forgings, and highlights successes and challenges associated with production of high-strength, high-toughness forgings relative to plate. Mechanical property results, including uniaxial tensile and Charpy V-notch, for various heat treatments are presented. Variation in mechanical properties in thick-section forgings are discussed and tied to through-thickness changes in microstructural evolution. Finally, potential alloy modifications are introduced that intend to remedy challenges associated with adapting HSLA-100 to thick-section forgings. Experimental trials suggest that HSLA-100 forgings can meet marginally reduced strength-toughness targets with the original HSLA-100 composition; however, with judicious alloy modifications, thick-section forgings may achieve properties comparable to plate.

Proceedings included as Appendix C.

2.3.2 Session B: Data Science and Modeling

Machine Intuitive Design of Army Steels - MIDAS

Krista R. Limmer, Heather A. Murdoch, Benjamin A. Szajewski, Daniel M. Field, Berend C. Rinderspacher, Daniel Schreiber, Levi D. McClenny, and Mulugeta A. Haile

DEVCOM Army Research Laboratory

Keywords: alloy design, machine learning, CALPHAD, property prediction, high throughput

The goal of this study is to understand the degree of material composition and processing history required to reliably predict properties and performance in a machine learning enabled framework for developing materials that can be applied

in Army applications. Our hypothesis is that the composition and processing variables are insufficient to inform a robust machine learning model, and the addition of synthetic microstructures developed through high-throughput CALPHAD methods will provide the additional information required to inform the models and make a more robust framework that is generalizable to other systems. We present a preliminary integrated machine learning and alloy design workflow based on low alloy steel hardness response during tempering. The framework links composition – processing – properties through a series of models of varying fidelity. Model uncertainty and databasing challenges will also be discussed.

Proceedings included as Appendix D.

Incorporation of Partitioning Effects During Martensitic Phase Transformation in Phase Field Modeling of Steels

YubRaj Paudel, Shiraz Mujahid, Haitham El Kadiri, and Hongjoo Rhee

Mississippi State University

Keywords: Partitioning, Phase Field Modeling, Martensitic Phase Transformation

This work presents efforts to incorporate partitioning effects in thermo-mechanical Phase Field (PF) simulation of austenite to martensite phase transformation in steels. A Ginzburg-Landau equation is coupled with mechanical equilibrium, heat conduction, and diffusion equations to incorporate the effect of carbon partitioning under various thermal and mechanical boundary conditions. The simulations were performed on single crystal and polycrystal domains with a multivariant embryo as an initial condition to motivate initial convergence in the absence of nucleation criteria. The simulation was able to predict variation in microstructure due to coupled partitioning effects. The robust phase-field model of martensitic phase transformation with partitioning effects allows for microstructure prediction under various heat treatment schedules.

Proceedings included as Appendix E.

2.3.3 Session C: Physical Metallurgy of Ultra-High Strength Steels

Effect of Thermomechanical Processing and Heat Treatment on Mechanical Properties and Fracture Behavior of a Cr-Ni-Mo-V Ultra-High-Strength Steel

Viraj Ashok Athavale[1], Kingsley T. Amatanweze[1], Soumava Chakraborty[1], Mario F. Buchely[1], Laura N. Bartlett[1], Ronald J. O'Malley[1], Daniel M. Field[2], Krista R. Limmer[2], Katherine M. Sebeck[3]

[1] Missouri University of Science and Technology

[2] DEVCOM Army Research Laboratory
[3] DEVCOM Ground Vehicle Systems Center

Keywords: casting, partially rolled, tensile ductility, toughness, cleanliness

Quenched and stage I tempered ultra-high-strength steels, UHSS, have widespread potential use for a variety of military castings as well as for rolled high hard armor. A study was conducted to understand the effect of heat treatment and thermomechanical processing on *Cr-Ni-Mo-V* ultra-high-strength steel castings and partially rolled plates. The results were compared with the properties of the commercially produced product. All materials were given a standard heat treatment of stage-I tempering to obtain martensitic microstructure and tempered to a target hardness of 50 HRC. The tensile properties and Charpy V-notch toughness was evaluated at room temperature and at -40 °C. Although ultimate tensile strength and yield strengths between the cast and partially rolled steels remain comparable at 240 ksi and 182 ksi respectively, partially rolled materials showed a three-fold improvement in tensile ductility over cast material. The hot-rolled *Cr-Ni-Mo-V* steel showed excellent notch toughness of 40 J. Fractography and microstructural characterization elucidated the influence of the production route on porosity, cleanliness, and ultimately the improvement in mechanical properties.

Proceedings included as Appendix F.

High-Fidelity, Through-Thickness Measurements of Residual Strain in Bent Armor Steel Plates

Marriner H. Merrill[1], Tony Wang[2,3], Gary Cola[4], Alex Thiel[5], Kelly E. Nygren[6], J. Y. Peter Ko[6] and Chris Budrow[7]

[1] U.S. Naval Research Laboratory
[2] Prior: U.S. Naval Air Systems Command, Naval Air Warfare Center, Aircraft Division
[3] Navistar Advanced Technology Center
[4] Flash Steelworks, Inc.
[5] Oshkosh Corporation
[6] Materials Solutions Network at CHESS, Cornell High Energy Synchrotron Source, Cornell University
[7] Budrow Consulting, LLC

Keywords: Synchrotron, Residual Stress, Armor Steel, Bending, Forming

Armor steels are often bent and formed during vehicle manufacturing, potentially leading to high residual stresses that could make the material more susceptible to cracking. Different forming methods and armor materials are hypothesized to have

higher or lower amounts of residual strain after bending. We obtained high-fidelity thru-thickness measurements of residual strains in bent armor plates through testing at the Materials Solutions Network at CHESS (MSN-C) with synchrotron X-Rays. Measurements included strains in X, Y, Z, and XY axes, where X is the primary bending strain, and Y is the through-thickness strain. The bent armor samples were from two different sources, and hardness included 500, 550, and 600 Brinell hardness, corresponding to MIL-DTL-46100, -46186, and -32332. In this paper, we report only analysis of the primary bending strains. However, the other strains were also significant. We have seen delayed cracks develop perpendicular to the bend line, which are likely related to these stresses. The complete dataset of all measured strains and the accompanying stress tensors are available as an Appendix.

Proceedings included as Appendix G.

Application of Rapid Tempering to High Hardness Armor Steels

Lawrence Cho[1], Garrison M. Hommer[1], Kapil B. Bhagavathula[1], Leslie Lamberson[1], Daniel M. Field[2], Krista R. Limmer[2], Kip O. Findley[1], and John G. Speer[1]

[1] Colorado School of Mines
[2] DEVCOM Army Research Laboratory

Keywords: High hardness armor steels, rapid tempering, quenching and tempering, toughness, tempered martensite embrittlement

Recent studies have shown that rapid higher temperature tempering can mitigate tempered martensite embrittlement and improve strength-toughness combinations compared to conventionally quenched and tempered martensitic microstructures. The objective of this study is to apply rapid tempering to high hardness armor steels and demonstrate enhanced impact toughness and dynamic fracture performance at high hardness levels, associated with the MIL-DTL-46100E specification. The Hollomon-Jaffe tempering parameter was used to determine tempering temperatures that would provide an approximately equivalent degree of tempering for given conventional (1800 s) and rapid tempering times (1 s). Rapid thermal processing was simulated using a Gleeble 3500 thermomechanical simulator, and the results were compared to conventional furnace tempering. Toughening and embrittlement mechanisms associated with rapid and conventional tempering are discussed along with microstructural and fractographic analyses.

Proceedings included as Appendix H.

2.3.4 Session D: Additive Manufacturing of Ultra-High Strength Steels

Prediction of Prior Austenite Grain Size and Morphology as a Function of Processing Parameters in AF9628 Steel Processed via Directed Energy Deposition

Stephen Cluff, Clara Mock, and Brandon McWilliams

DEVCOM Army Research Laboratory

Keywords: Steel, Microstructure, Modeling, Austenite, Additive

The ability to control local microstructure in high-strength steel via AM is of direct interest to the Army. Such control over steel microstructure provides a means to homogenize mechanical properties across varied part geometries, and to implement designed heterogeneities. The localized application of heat that occurs during AM enables such control, as heat is the primary driver for the formation of both microstructure and mechanical properties. One steel of interest is AF9628, which has shown microstructural sensitivity to AM processing parameters. The control of this steel's final microstructure via AM is mediated by the prior austenite microstructure. The current work presents a model that captures the evolution of the parent austenite grain structure in this material during DED processing using a Potts/Monte Carlo method implemented in the SPPARKS software. This model is used to predict austenite grain size and morphology as a function of processing parameters and can be used as a design tool for the control of austenite and subsequent final microstructure.

Proceedings included as Appendix I.

Laser Powder Bed Fusion and Directed Energy Deposition Printability Frameworks to Fabricate Ultrahigh Strength Martensitic and Austenitic Steels

Ibrahim Karaman[1], R. Seede, M.W. Vaughan[1], A. Whitt[1], M. Elverud[1], J. Ye[1], S. Gibbons[2], P. Flater[2], B. Gaskey[2], R. Arroyave[1], and A. Elwany[1]

[1] Texas A&M University
[2] Air Force Research Laboratory

Keywords: Additive manufacturing, framework, laser powder bed fusion, directed energy deposition, advanced high strength steels

Currently, the printing process is poorly standardized, so it can often be challenging to print new materials with properties comparable to that of wrought alloy counterparts, with the various AM technologies available. For this reason, this talk

presents the printability frameworks developed at Texas A&M University that, when applied, can solve these problems, by successfully printing steel parts to near full (>99%) density via various AM technologies, e.g. laser powder bed fusion (L-PBF) and directed energy deposition (DED). Here, different advanced high strength steels (AHSSs) such as martensitic AF9628 and austenitic FeMnAl were printed successfully by both L-PBF and DED to near full (>99%) density by applying these frameworks. Overall, ultimate tensile strengths well in excess of 1 GPa and excellent ductility (>10% for AF9628 and >30% for FeMnAl) were realized, results that validate the framework and show its applicability for advancing the AM of other DoD metal systems.

Limited distribution proceedings not included in this report.

Process-Feature-Microstructure Property Relationships for AF9628 Directed Energy Deposition Additive Manufactured Steel Components

Nikolas Vega Michalak[1], Boian T. Alexandrov[1], Dennis D. Harwig[1,2]

[1] The Ohio State University
[2] EWI

Keywords: Steels, additive, manufacturing, welding, AF9628

A computational design of experiment (CDoE) platform for process-feature-microstructure-property optimization is being developed for additive manufacturing (AM) of AF96 steel components. A key component of this platform are quantitative process-property-microstructure relationships for a range of DED deposit sizes, heat inputs and interpass temperature build conditions.

This paper presents continuous cooling transformation (CCT) diagrams developed for the conditions of GMA- and PL-DED deposits with a focus on the coarse-grained, fine grained, and intercritical heat affected zones (HAZ) of AF96 steel. In general, AF96 steel develops fully martensitic microstructure in a wide range of cooling rates from above the A_{C3} temperature, while multiple reheats below the A_{C1} temperature generate significant tempering effect.

The developed CCT diagrams represent the process-microstructure relationships for AF96 DED processes. The feature-microstructure-properties relationships will be developed by tensile and Charpy impact testing of samples with simulated AM microstructures and of AF9628 AM builds produced by WA- and PL-DED.

Proceedings included as Appendix J.

2.3.5 Session E: Degradation and Performance

Corrosion Fatigue of Shaft Steels in Seawater Environment

Attilio Arcari[1], Ryan McCoy[2], Aron Rubinoff[2], Derek Horton[1], Edward Lemieux[1]

[1] Naval Research Laboratory
[2] Excet Inc

Keywords: corrosion fatigue, natural seawater, low alloy steel, damage initiation, exposure time

Steel forgings are often used as propulsion shafts which are subjected primarily to bending, torque, and thrust loads. Given the corrosion susceptibility of steel exposed to a seawater environment, corrosion fatigue life is an important design consideration for shafting materials. We show that while corrosion damage initiates within the first few hours exposure, there is a significant effect of long-term environmental exposure on fatigue life beyond corrosion damage accumulation. The fatigue life of two classes of MIL-STD-23284A steel were tested at three different test frequencies in rotating bending, during open circuit exposure in natural seawater at the U.S. Naval Research Laboratory located in Key West, Florida. A statistically significant difference in fatigue life was found as a function of testing frequency. Fatigue damage initiation, evolution, and progression are discussed, based on fractographic images and corrosion rate measurements.

Limited distribution proceedings not included in this report.

Effect of Microstructure on Hydrogen Diffusion of Ultra High Strength Steel

Gregory Kubacki and Yoel Emun

University of Alabama

Keywords: ultra-high strength steel, environmental degradation, hydrogen embrittlement

Martensitic, ultra-high strength steels (UHSS) offer excellent strength-to-weight ratio and impact resistance for vehicle components. However, UHSS are known to be susceptible to hydrogen-assisted cracking in environments with excessive hydrogen evolution or during high temperature joining processes. Here, we investigate the hydrogen absorption and transport characteristics of a variety of materials meeting a single specification to develop predictive knowledge on the relationship between microstructure and hydrogen-assisted cracking susceptibility. Electrochemical techniques were used to assess hydrogen diffusivity and the strength and distribution of trapping sites. These results will be correlated to

microstructure. Hydrogen uptake is found to correlate with the fraction of precipitated or retained austenite as well as increased charge passed for iron oxidation during high-rate potential sweeps, which may suggest hydrogen-enhanced decohesion is a contributing factor to failure. Further investigation is underway into the presence, location, and chemistry of nanoprecipitates that may affect the diffusion rate and trap strength.

Proceedings included as Appendix K.

Damping Measurement from Charpy Impact Test

Jin Hyeong Yoo and Nicholas J. Jones

Naval Surface Warfare Center – Carderock Division

Keywords: Charpy impact test (CVN), metallic damping capacity estimation, force oscillation, logarithmic decrement, material toughness

The Charpy impact test (CVN) was invented in 1900, and it is one of the most common tests used to evaluate the relative toughness of a material. One possible parameter to be measured from the CVN is damping capacity. Damping capacity is a measure of a material's ability to dissipate elastic strain energy during mechanical vibration. The damping capacity of a material may also be a good measure of a material toughness or resistance to crack initiation. While traditional CVN tests measure impact toughness, measurement of the damping performance during fracture gives a detailed picture of the mechanistic and real-time absorption of the energy during an impact or blast event. This technique requires no changes to specimen blanks, machining criteria, or additional specimens, but shows great promise for improving the correlation of conformance criteria to material performance and may provide significantly more correlations to useful toughness metrics.

Proceedings included as Appendix L.

2.3.6 Session F: Ballistic Performance

Development of Ballistic Cast Steel Appliques using Additively-Manufactured Cores

William Gooch[1,2], Hathibelagal M. Roshan[3], and Michael Wabiszewski[3]

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[3] Maynard Steel Castings Company

Keywords: Steel, castings, appliques, AM cores, aluminum, MIL-A-11356F

Over the last 20 years, lightweight monolithic aluminum appliques have provided increased ballistic protection to steel-based tactical trucks and light combat vehicles. These removable appliques were first machined from low-cost 6061 wrought plate with later development of higher-cost, higher-density aluminum alloys allowing increased ballistic performance but requiring additional engineering design trade-offs between thickness, areal weight, and cost.

Maynard Steel has patented a casting process producing three-dimensional, non-homogeneous cast steel appliques that replace aluminum on an equal thickness and/or areal weight basis. The cross-sections of less-costly heat-treatable steel alloys are cast using patented AM sand cores. Comparative ballistic testing with 6000/7000 series monolithic alloys will be provided. The intent is to replace higher-cost aluminum appliques with lower-cost cast steel equivalents at equal performance, thickness and areal weight.

Proceedings included as Appendix M.

Ballistic Performance of Additively Manufactured 17-4 PH Stainless Steel

William Slocumb, Brandon Holm, and Vic Kelsey

BAE Systems (CMS)

Keywords: .30 APM2, .50 FSP, 17-4 PH, H1025, additive manufacturing, AM, wire arc additive manufacturing, directed energy deposition, WAAM, DED, microstructure, mechanical properties

Armored fighting vehicles make extensive use of alloy steel armor in wrought, cast, and forged product forms. As a result of increasing system performance requirements and lack of agility and availability in more complex casting processes, additive manufacturing (AM) has become desirable for increasingly production agility and developing novel armor geometries for use on ground vehicles. To address this need, three distinct directed energy deposition (DED) processes were used to fabricated 17-4 PH (Type 630) stainless steel samples in Condition H1025 to subject to ballistic testing against the .30 APM2 and .50 FSP projectiles. Processes surveyed were wire arc additive manufacturing, wire-laser DED, and laser powder-blown DED. These were compared against commercial wrought 17-4 PH (Condition H1025) with a baseline target performance of meeting the MIL-DTL-12560 minimums. In general, all AM production methods did not meet specification requirements but performance was similar regardless of which process was used. Chemical, mechanical, and microstructural data were collected for both AM and wrought samples.

Proceedings not included in this report due to copyright restrictions.

2.4 Poster Session

Additive Manufacturing of Ferrium C64 for Aerospace Gear Applications

Diana David and Thomas Kozmel

QuesTek Innovations LLC

Keywords: Additive Manufacturing, gears, Ferrium C64, steel, aerospace

Additive manufacturing (AM), by allowing for net-shape fabrication of highly complex geometries without molds or machining, offers the potential to reduce material usage and fabrication time. AM presents the unique opportunity to manufacture single components quickly and also provides the potential to examine the effects of individual design alterations on overall system performance. QuesTek has utilized its proven integrated computational materials engineering (ICME) methodology to adapt Ferrium C64 for additive manufacturing, and demonstrated success in AM-processing from procurement of powder through final test part fabrication. This production route is demonstrating the ability to fabricate a near-net shaped part at a significantly reduced lead time, making it especially useful for rapid prototyping of new components.

Poster included in Appendix Q.

CANCELLED - Aermet360 Material Properties at Production Scale

Calvin Lim[1], Jason Wood[2], Colleen Tomasello[3], Kate Adkinson[3], Kyle Santangelo[1], and Aisha Haynes[1]

[1] DEVCOM Armaments Center
[2] Southern Research
[3] Carpenter Technology

Keywords: Aermet, 360, High Temperature, High Toughness, High G

The US DoD uses steel thanks to its strength, formability and most of all its relative abundance in almost everything and is always seeking to make products stronger and lighter. It is hard to replace steel so the most fruitful way is to advance and push the limits of steel. Aermet 360 is the latest of these efforts and was initially produced in smaller quantities. The Army worked with Carpenter Technology to develop the steel further in a larger production environment to ensure its properties would be retained in the most adverse and extreme environments. Several large billets were commissioned and various heat treat methods were investigated.

Testing was performed with multiple labs including Southern Research Institute (KRATOS) to provide an independent assessment of the material properties. The data shows that the Aermet achieved 364.9 ksi maximum stress and 31.12 Msi for Elastic Modulus at room temperature and retained 21% of the maximum stress at 1300 °F along with 47% stiffness. With this higher toughness and ability to retain its properties, this can mean saving weight, or pushing the performance envelope of its current portfolio with a relatively simple transition plan.

Agile Expedient Manufacturing Using Scrap Steels

Marc Pepi[1], Brandon McWilliams[1], Danielle Cote[2], Christopher Massar[2], Christopher Eonta[3], Andrew LaTour[3], Matthew Charles[3]

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Keywords: Advanced Manufacturing, Recycled Steel, Cold Spray, Laser Powder Bed Fusion, Operational Readiness

ARL and its research partners have been developing new capabilities for processing scrap and indigenous materials into usable feedstock for traditional, or advanced manufacturing at the point-of-need with optimized material properties. The motivation for this research thrust is to develop a "grave-to-cradle" concept of utilizing materials at the point-of-need to fabricate parts or repair weapon system components to improve Warfighter operational readiness, overcome traditional supply chain/long-lead time issues and reduce the logistics tail of getting spare parts to the battlefield. A key component of this work is the Greyhound Mobile Foundry (developed by the MolyWorks Corporation, and refined and optimized through Army SBIR funding), which is capable of gas atomizing scrap and/or virgin material into AM-Grade metallic powder of various size distributions. Scrap steels that were utilized as part of this study include AISI 4340, 316 stainless steel, FeMnAl, and Rolled Homogeneous Armor (RHA). The powders created from these scrap steels were characterized, and subjected to additive manufacturing (AM) processes, including cold gas dynamic spray (cold spray) and/or laser powder bed fusion (LPBF). The results of these AM processes showed the potential of this system to gas atomize metal scrap at the point of need for further AM processing.

An Evaluation of Advanced EBSD Methods for Phase Detection in Martensitic Steels

David Rowenhorst and Richard Fonda

US Naval Research Laboratory

Keywords: Microstructure, EBSD, martensite, austenite

Electron backscattered diffraction (EBSD) mapping has become a powerful tool for the evaluation of alloy microstructures due to its ability to clearly differentiate between phases and crystallographic orientations, and thereby providing clear descriptors of grain size and morphologies. However, due to the high amount of plastic strain present in some alloys, such as martensitic steels, the EBSD signal can be weak and difficult get reliable indexing. Because even small amounts of retained austenite can strongly influence the properties of a steel, this study evaluates the ability of two different pattern processing and indexing methods, Dictionary Indexing and Non-Local means Pattern Reindexing (NLPAR), to improve the indexing success in a martensitic steel with a minority of retained austenite. We will show that both methods improve the indexing success rate by at an order of magnitude, and can accurately differentiate between the BCC-indexed martensite and the FCC austenite.

ARL Designed High-Strength Steel Feedstock for Powder Bed Fusion Additive Manufacturing

Frank Kellogg[1,2], Daniel Field[2], Matthew Vaughn[2,3], Alex Butler[3], Josh Taggart-Scarff[1,2], and Brandon McWilliams[2]

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[2] DEVCOM Army Research Laboratory
[3] Oak Ridge Associated Universities

Keywords: Powder Feedstock, Additive Manufacturing, High-Strength Steel, Charpy Impact Testing

Due to the amount of time, effort, and cost of material development, once a steel alloy reaches the common market, there is little to no room to make changes to its composition. However, with additive manufacturing (AM) opening the possibility of making parts with properties tailor made for specific applications, a one size fits all approach to alloy chemistry does not work as well. Small production volumes and small volumes of material usage makes AM an ideal method for screening multiple compositions of the same alloy. In this study, different compositions of a high strength steel were designed via thermodynamic modelling for either 1) lower cost powder feedstock, 2) enhanced processing via laser powder bed fusion (LPBF) AM, or 3) improved strain hardening. These newly designed alloys were then manufactured and produced in small batches, processed via PBF AM, and compared to established AM high strength steel samples by tensile and Charpy impact testing.

Poster included in Appendix Q.

Cast in Steel 2023

Raymond Monroe

Steel Founders Society of America

Keywords: casting, steel, student competition

Cast in Steel is a sponsored competition for University teams to cast an item that has been made traditionally as a forging. This year teams have been challenged to produce an African Spear point. The entries are awarded for authenticity, best casting, their technical report and video documenting the project and most importantly; competing in a Forged in Fire type competition. Ben Abbott from the show is one of the judges every year. Past winners will be shown including the bowie knife 2019, Thor's hammer 2020 and Celtic leaf sword, 2022. We are being supported this year by DoD OSD IBAS as a part of their engagement in workforce development. We welcome DoD experts to work with us and help the student teams succeed, potentially doing a webinar for the teams on the design or material choices.

CANCELLED - Design & Microstructural Evolution of Fe-Rich Multi-Principal Element Alloys for Protective Structures

James Frishkoff, Madeline Rivera, Nathan Brown, Kester Clarke, and Amy Clarke

Colorado School of Mines

Keywords: Multi-principal element alloys, metastability, dual phase, alloy design

Multi-principal element alloys (MPEAs) are promising for demanding mechanical, thermal, corrosion and wear environments. Improved understandings of microstructural evolution with processing and deformation are prerequisite for the adoption of MPEAs in structural applications. Recrystallization, grain growth and precipitation kinetics are of particular relevance. In order to study these behaviors, a family of non-equiatomic, Fe-rich and Co-free precipitation-hardening MPEAs was designed through a multifactor screening approach. A design of experiment for thermomechanical processing and precipitation heat treatments is presented. Recrystallization, grain growth and precipitation kinetics are discussed and compared to existing ferrous alloy products.

Development of Ballistic Cast Steel Appliques using Additively-Manufactured Cores

Hathibelagal M Roshan[1], Michael Wabiszewski[1], and William Gooch[2,3]

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Keywords: Steel Castings, Additive Manufacturing, Sand cores, Appliques, Ballistics

In 2017 Maynard Steel Casting Company patented a lightweight steel manufacturing process that combines traditional casting technology, additively manufactured precision cores and heat treatment to create cost-effective, high stiffness structural/ballistic panels. Additively manufactured cores enable production of unique internal structures that enhance structural stiffness and blast/ballistic performance while greatly reducing areal density. W A Gooch Consulting Inc has worked with Maynard Steel since November 2019 to develop military applications of their technology. This technology offers direct cost savings and reduces dependence on high cost materials or processes. It enables to produce structures with improved ballistic and blast resistant properties. 2" thick light weight steel panels with the same areal density as aluminum appliques were manufactured and V50 ballistic performance was determined. This technology will allow the current army vehicles to be re-fitted with steel add-on armor appliques having similar ballistic and blast resistance performance compared to current aluminum appliques.

Poster included in Appendix Q.

Dynamic Mechanical Characterization of AF9628 Steel

Andrew Roginski, Cody Kirk, and Weinong Chen

Purdue University

Keywords: Dynamic loading, Kolsky bar, ballistics, synchrotron, steel alloy

AF9628 (Patent 0369362, 2016) is a steel alloy developed for improved ballistic performance. However, the thermo-mechanical response to high-rate loading, the effects of microstructures, and variability of the dynamic properties of the steel have not been well understood. In the realm of ballistics, understanding the bridge between microstructure features/composition and the failure modes at intermediate to high strain rates is critical for research and safety measures. Currently, dynamic tension tests at the Advanced Photon Source (APS) at Argonne National Laboratory have been performed to evaluate the dynamic properties of AF9628 at a spectrum of strain rates ranging from 500 to 2500 1/s. Techniques including Kolsky bar, X-ray diffraction, thermal imaging, and phase-contrast imaging (PCI) have been implemented to evaluate the mechanical response and microstructure evolution in-situ.

Poster included in Appendix Q.

Dynamic Recrystallization Behavior of Ni-containing Lightweight Fe-Mn-Al Steels

Rogerio Cardoso[1], Mike Piston[1], Mario Buchely[1], Laura Bartlett[1], Ron O'Malley[1], Krista Limmer[2], Daniel Field[2], and Katherine Sebeck[3]

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Keywords: Lightweight steel, Recrystallization kinetics, thermomechanical testing, precipitation hardening

Lightweight ultra-high-strength steels, UHSS, have the potential to lower the density of RHA and HHA armor steels by as much as 15%. These steels can be hardened by a combination of NiAl precipitation after hot rolling and subsequent kappa carbide precipitation. Understanding the effect of thermomechanical processing on recrystallization kinetics and subsequent NiAl precipitation is important to control the final microstructure and mechanical properties. Controlled microalloy additions of Nb are also promising to control grain size during hot rolling. In the current study, a Fe-21Mn-9Al-7Ni-0.9C-1.0Mo steel with and without Nb additions was subjected to single-hit tests in the temperature range of 850 to 1200 ºC using a quenching deformation dilatometer with the goal of determining the effect of Nb on the recrystallization kinetics of austenite.

Poster included in Appendix Q.

The Effect of Adding Minor Alloying Elements on Mechanical Properties and the Effect of Carbon Content on Embrittlement and Recovery Mechanisms in High Yield Strength (HY) Steels

Aphrodite Strifas[1,2], Matthew Frichtl[1,2], Matthew Draper[2], and Sreeramamurthy Ankem[1]

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Keywords: Microstructure, Grain size, Micro-alloying addition, Temper Embrittlement

The present work reports on prior austenite grain size refinement due to a micro-alloying addition to a baseline HY-80 composition and that effect on mechanical properties, including tensile and Charpy impact properties. In addition, the present

work also reports on the effect of different levels of carbon equivalent on embrittlement and recovery mechanisms in HY-80 steels. The explanation for the mechanisms of temper embrittlement includes the stress and strain distributions as determined by finite element modeling regarding continuous carbide precipitation along the grain boundaries. The details of the investigation will be presented.

Acknowledgement: This research is partly sponsored by the DLA-Troop Support, Philadelphia, PA, and the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, VA.

Effect of Section Size on AF9628 Mechanical Properties and Microstructure

Michael Rupinen Jr, Amy Clarke, and John Speer

Colorado School of Mines

Keywords: section-size, strength, toughness, cooling-rate, microstructure

AF9628 steel is a highly hardenable steel with a favorable balance of yield strength and impact toughness. While the high hardenability allows for the manufacture of large components, the effect of section size on the microstructure and properties throughout a component is not fully understood. Large sections may experience significant differences in cooling rate during quenching leading to significant autotempering and autopartitioning. Understanding how cooling rate and alloying affect properties in large sections is critical in continuing to develop strong/tough steels. A model has been developed to predict the relative effect of autotempering and tensile and Charpy specimens quenched in various media to simulate fast and slow quenching conditions were tested to observe differences in microstructure and properties. Significant differences in the microstructural evolution and mechanical properties (especially Charpy impact energy) following quenching and tempering were observed.

Electron Beam Welding AerMet 360

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Keywords: AerMet, Weld, EB, FeUH, Toughness

NiCoCr Martensitic Steels Alloys provide the highest combination of strength and toughness in the Ultra-High Strength Steel Alloy Class (FeUH) of materials. These alloys are designed to provide materials solutions to mission critical challenges. For

example, AerMet Alloys have been developed into a family of alloys which provide Ultimate Tensile Strength capabilities ranging from 280 KSI to over 360 KSI while preserving the highest level of toughness reflected in Elongation %, Reduction of Area %, Charpy V-Notch Impact Strength, and Fracture Toughness. AerMet 100 has been used extensively in DOD, Aerospace, and Automotive Racing applications and while AerMet 100's mechanical strength capabilities make it very attractive from a performance perspective, it also possesses other desirable characteristics that make it conducive to the demands of these challenging applications. These characteristics include tolerant hot workability, castability, Additive Manufacturing (AM) characteristics, repeatable and predicable heat treat characteristics, and weldability. In a December 1993 paper published in Foundry Management & Technology by Paul Novotny (Carpenter Technology Corp.), it was demonstrated that Cast + HIP'ed + Heat Treated properties were almost equivalent to those of cast wrought properties. (1) In a 1999 paper published by Sandia National Laboratories, the welds of AerMet 100 were demonstrated to have almost the same mechanical strength and ductility of the base metal. (2)

The work presented in this paper explores the Electron Beam Welded (EBW) characteristics of AerMet 360 which is currently the highest strength member of the AerMet series of Ultra-High Strength Steel Alloys. The work demonstrates that the EB weld properties closely match the base metal properties. The resulting microstructure depicting the as welded condition and welded + post weld heat treatment condition is presented in support of the observed mechanical property performance.

Proceedings included as Appendix N.

Poster included in Appendix Q.

Enhanced Performance in Steels Through Intense Shear Deformation Processing: Potential for Solid State Additive Manufacturing

Rajiv S. Mishra[1], Brandon McWilliams[2], and Kyu C. Cho[2]

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Keywords: Steels, Intense shear deformation, Microstructure, Strength, Ductility

Steels have a very high degree of microstructural flexibility for a given composition, which happens through controlled phase transformation. Last twenty years have seen development of steels for exceptionally high structural performance. The microstructural tailoring in these alloys is mostly done through heat treatment optimization. Friction stir processing involves intense shear

deformation at high temperatures. Steels processed through this technique show synergistic improvement in strength-ductility combination. Examples of enhanced performance in P92 steel, AF9628 steel and Eglin steel will be given to highlight the fundamentals as well as the potential for using friction stir additive manufacturing. The microstructural variants responsible for enhanced properties will be discussed.

Enhanced Thermal Stability of Retained Austenite in a HighNi Martensitic Steel via a Thermomechanical Treatment

Chia-Pao Lee[1], Amir R. Farkoosh[1], Paul Lambert[2], and David N. Seidman[1]

[1] Northwestern University
[2] Naval Surface Warfare Center - Carderock Division

Keywords: High-Ni steels, phase transformation, crystallographic defects, electron backscatter diffraction, atom probe tomography

A standard quench-lamellarization-tempering (QLT) treatment of 10 wt.% Ni steels result in a fine dispersion of retained austenite in a martensitic matrix, which is critical to their excellent ballistic resistance attributed to the transformation-induced plasticity (TRIP) effect. We have demonstrated that an additional cold rolling step (~10 - 70% plastic deformation step, "D") between the Q- and L-steps (denoted as a QDLT treatment) can significantly increase the volume fraction of the retained austenite. Herein, we further study the underlying mechanisms that lead to a higher volume fraction as well as the enhanced thermal stability of the retained austenite in QDLT-treated steel utilizing atom probe tomography (APT), in-situ x-ray diffraction (XRD), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD).

Poster included in Appendix Q.

Evaluation of FeMnAl for Corrosion Protection & Coating Performance

Lindsey Blohm, Krista Limmer, and Joe Labukas

DEVCOM Army Research Laboratory

Keywords: FeMnAl, RHA, corrosion, coating, adhesion

FeMnAl, a ferrous alloy containing large amounts of manganese (Mn) and aluminum (Al) is under consideration for use in Army systems and is subsequently being investigated for corrosion performance. FeMnAl has the potential to be utilized as an alternative for Rolled Homogeneous Armor (RHA). An electrochemical investigation of 12 alternate FeMnAl compositions was performed

in 0.1 M H_2SO_4 electrolyte, showing only minor changes in the corrosion potential. Mass loss was also performed in ASTM B117, showing FeMnAl alloys to be comparable in corrosion performance to RHA. Work has also been performed to evaluate FeMnAl's coating performance following pretreatment and coating application. This work includes four pretreatments with MIL-DTL-53022 in ASTM B117, GMW 14872, and ongoing outdoor exposures top coated with MIL-DTL-53039 at Cape Canaveral Space Force Station.

Evaluation of Martensite Transformation Temperatures using Magnetometry

Nicholas J. Jones, Paul K. Lambert, Jin-Hyeong Yoo, Suok-Min Na, and Charles R. Fisher

Naval Surface Warfare Center - Carderock Division

Keywords: phase transformations, martensite, austenite, magnetism, thermodynamics

Martensite start and finish temperatures are two critical parameters needed to define the processing variables for steels. Magnetization measurements have been used herein as a method to determine these structural phase transformation temperatures. Eight compositions of steel having published martensite start temperatures ranging from -130 °C to +30 °C were synthesized via vacuum arc melting. After a high-temperature homogenization heat treatment, samples were extracted and room-temperature magnetic hysteresis loops were measured before and after a temperature cycle to cryogenic temperatures under constant applied field. Samples showed pronounced increases in magnetization as temperature decreased due to the martensitic transformation, and eventually magnetization plateaued below the sample's martensite finish temperature. In addition to the measured martensite start and finish temperatures and general characterization of the samples, the choice of applied magnetic field strength will be discussed, to ensure that the transformation is being appropriately characterized.

H&M Blacknitride+® QPQ Nitrocarburizing A-21 Stainless Steel

Humberto Raposo[1], Robert Buck, Ph.D.[1] Shade McMillen[2], Patrick D. Quinn[2]

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[2] H&M Blacknitride+ ™

Keywords: A-21, Nitriding, Stainless, Steel, QPQ

A-21 Stainless Steel is a novel alloy originally designed to maintain exceptional corrosion resistance after carburizing whereby it develops a robust hard and wear resistant 60 HRC case in combination with a tough and ductile core. In this

condition, it has displayed the ability to pass 200 hour salt spray corrosion testing per ASTM B117. This is a unique accomplishment in itself. A-21 Stainless has also shown the ability to develop a deep 0.003" 70 HRC nitride case with excellent corrosion resistance using the H&M Blacknitride+ QPQ salt bath nitro-carburinzing process. The depth of this case can be modified by controlling the time and temperature through the carbo-nitriding process. The results of the salt bath nitriding process and associated microstructures are presented in this poster.

The benefits of A-21 Stainless can be broadly applied by either using the alloy in the Quench and Tempered condition, the carburized condition, or the nitro-caburized condition. The surface hardness can be manipulated by carburizing or nitro-carburizing to achieve properties suitable for the intended application. In all conditions, the alloy develops exceptional corrosion resistance.

Proceedings included as Appendix O.

Poster included in Appendix Q.

High Hardness Additively Manufactured Steels in Fuel Lubricated Sliding Interfaces

Nikhil Murthy[1], Monica Ferrera[1], Caleb McCoy [2], Kelly Jacques [2], Miranda McCraw[2], Vanessa Montoya[1], Jonathan Ligda[1], Diana Berman[2], and Stephen Berkebile[1]

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Keywords: Wear, Engine, Fuel, Additive Manufacturing, Tribology

Additive manufacturing (A.M.) can offer many advantages to the next generation of direct injection fuel delivery systems such as potential weight savings and ease of manufacturing of small integrate components. However, scuffing and wear are persistent issues in these systems, especially in the presence of low lubricity fuel. In this study, we attempt to address these fuel lubricity concerns by evaluating three A.M. engineered high hardness steels. Two sets of experiments were used to compare the performance of the A.M. steel candidates to a baseline AISI 52100 steel under three low lubricity fuels: F-24 jet fuel, decane, and ethanol. The first experiment determined the friction and wear under a constant load and the second experiment evaluated resistance to scuffing under an increasing load. Additionally, post-test evaluation of the wear tracks was conducted to determine the effects of topography and surface chemistry.

ICME Design and Characterization of Nano-Precipitate Strengthened Austenitic Steel

Colin Stewart[1], Edwin Antillon[1], Richard Fonda[1], Keith Knipling[1], Patrick Callahan[1], and Paul Lambert[2]

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Keywords: ICME, Medium-Mn, Atom Probe Tomography, Precipitation, First Principles

Integrated computational materials engineering (ICME) tools have been used to discover a promising family of Mn-stabilized fully Austenitic steels, Fe–17.7Mn–10.0Ni–5.0Al–4.7Cr–4.0Cu–1.0V–0.48C (wt.%). These steels can achieve hardness values over 560 HV (estimated σ_y ~200 ksi) by forming three nano-scale phases upon ageing: (i) insoluble Cu; (ii) β-NiAl; and (iii) VC. Depending on the composition and ageing treatment, these precipitates will form with a variety of morphologies, size distributions, and spatial arrangements. Such factors can influence the yield strength and affect the overall material cost. This poster will discuss the characterization of precipitate evolution using atom probe tomography (APT) and microhardness, and how the experimental microstructures may be predicted with ICME tools. Modeling the yield strength by combining microstructural data with molecular dynamics and theoretical models will then be discussed, in the context of further ICME alloy development.

In situ Neutron Diffraction Observations of Steel Deformation Mechanisms

Daniel Magagnosc, Krista Limmer, Jeffrey Lloyd, and Daniel Field

DEVCOM Army Research Laboratory

Keywords: Neutron Diffraction, Stacking fault energy, mechanical properties, twinning, TRIP

Advanced high strength steels employ a variety of deformation mechanisms, such as dislocation slip, twinning induced plasticity (TWIP), and transformation induced plasticity (TRIP), to achieve improved strength and ductility. The active deformation mechanism is predicted in part by the stacking fault energy (SFE) and austenite-to-martensite driving force. In situ neutron diffraction during tensile loading is used to investigate the deformation mechanisms in medium-Mn steels. Three examples, corresponding to dislocation slip, TWIP, and TRIP mechanisms, are presented to elucidate the role of temperature and stress on each mechanism. The deformation characteristics are observed through lattice strain measurements

and full diffraction pattern fitting. In a duplex steel, a temperature dependent composite strengthening mechanism is found. Next, in TWIP the temperature and stress dependence of the SFE is revealed. Finally, the transition from phase transformations to twinning at elevated temperatures is examined in a TRIP steel.

Influence of Annealing on Microstructure and Mechanical Properties of Additively Manufactured 316L

Matthew Schreiber, Charles Smith, Olivia Denonno, Kip Findley, John Speer, Jonah Klemm-Toole, Zhenzhen Yu, Amy Clarke, Craig Brice, and Joy Gockel

Colorado School of Mines

Keywords: 316L, PBF-LB, LPBF, DED-Arc, WA-AM, AM, annealing, mechanical properties

In this presentation, the annealing response of 316L manufactured with both laser powder bed fusion (PBF-LB) and wire-arc additive manufacturing (DED-Arc) is discussed in the context of microstructural evolution and mechanical properties. Because AM comprises several technologies that differ in heat source, feedstock, and scan strategy, among other build variables, the final products can exhibit a range of thermal histories. These unique thermal histories can subsequently influence as-built properties and annealing response of AM materials, most notably those manufactured with different AM deposition processes. Characterization methods including optical microscopy, electron backscattered diffraction (EBSD), and tensile testing are utilized to better understand how deposition history affects the extent of annealing. Comprehensive characterization results are presented to provide insight into the necessary post-build processing required to achieve desired properties for AM materials.

Influence of Composition on the Weldability and Tensile Properties of Cast Monel Alloys

Christopher Farnin and John DuPont

Lehigh University

Keywords: Monel, Weldability, Mechanical Properties, Solidification, Segregation

Monel alloys are used extensively in marine environments due to the combination of good mechanical properties and excellent resistance to corrosion. Silicon alloying leads to high strength via Ni-Si precipitation, however the formation of intermetallics during solidification leads to poor ductility and weldability. Despite widespread use, there is a significant lack of understanding on the influence of composition on the weldability and mechanical properties of cast Monel alloys. In

this work, a matrix of alloys with systematic variations in composition was characterized through several techniques such as EPMA, varestraint testing, and tensile testing to determine the effects on solute segregation, weldability, and tensile properties. Initial results showed that higher Si contents led to increased precipitation and hardness, while higher Cu, Mn and Nb additions stabilized intermetallic phases expected to be detrimental to solidification temperature range and tensile properties.

Poster included in Appendix Q.

Laser Powder Bed Fusion of Aermet 100

Elias Jelis and Matthew Feurer

DEVCOM Armaments Center

Keywords: Steel, Additive Manufacturing, Aermet, Laser, powder

Aermet 100 is high alloy steel with high strength (280 ksi min.) and high fracture toughness (100 ksi-in$^{.5}$ min). It is good candidate for laser powder bed fusion because it is weldable and can tolerate large flaws. Laser powder bed fusion parameters were developed (LPBF) for Aermet 100 to reach full density (>99.5%). Heat treatment in vacuum is necessary to reach the desired tensile (290 ksi) and yield strength (245 ksi). Laser diffraction of procured powder showed non-spherical powder in particle sizes outside of the specification set for this effort. This is considered the cause for large amounts of spatter and insufficient melting of powder. Large defects were present on the fracture surface tensile test specimens and in the microstructure. The defects correlated with a reduction in ductility in the tensile specimens when in the heat treated condition. It was concluded that better control of the powder size and morphology is required to improve the material and mechanical properties.

Laser Powder Bed Fusion of Ultra-High Strength Steel from Gas Atomized Alloy Powders

Thinh Huynh and Yongho Sohn

University of Central Florida

Keywords: laser powder bed fusion, gas atomization, AF9628, phase transformations, microstructure

High strength steel, AF-9628 alloy was gas atomized to produce powder feedstock for additive manufacturing by laser powder bed fusion (LPBF). Charge alloys were inductively melted with Argon shrouding at a superheating temperature of 1800 °C, and subsequently gas atomized using Argon gas at a pressure of 2 MPa. The as-

atomized powders were characterized for microstructure, composition, phase constituents, particle morphology, size distribution, and flowability. Phase transformations and microstructural development during rapid solidification of gas atomization were analyzed. LPBF optimization was then performed as a function of power and scan speed. The as-fabricated LPBF specimens consisted of martensite and traces of supersaturated austenite. Changes in the as-built microstructure and phase constituents were documented as a function of laser scan speed. Tensile properties and hardness were examined to assess the mechanical behavior as functions of various heat treatments along with correlated microstructural development.

Microstructure and Mechanical Properties of a Multipurpose High-Strength High-Toughness Martensitic Steel Produced via Selective Laser Melting

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Keywords: Selective laser melting, high-Ni steels, Transformation induced plasticity, Retained austenite, Atom-probe tomography

In recent years, several steel design activities have been initiated to develop alternatives to the high yield (HY) and high strength low alloy (HSLA) steels with improved mechanical properties, producibility, and weldability. Born out of these research efforts is a novel multipurpose low-carbon 10 wt.% Ni martensitic steel, which exhibits high strengths, high toughnesses, and excellent ballistic resistance at ambient and cryogenic temperatures. In this study, we have utilized laser powder bed fusion to additively manufacture a variant of this steel. Excellent mechanical properties: a tensile yield strength of 1150 MPa and 22% elongation were achieved, demonstrating superior mechanical properties to those of conventional counterparts. We utilize synchrotron X-ray diffraction, electron backscatter diffraction (EBSD), and local-electrode atom-probe tomography (LEAP) to study the microstructural features of this AM steel over hierarchical length scales.

Poster included in Appendix Q.

Modeling Magnetic Field Influence on Iron Alloy Phase Transformations

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Keywords: martensite, magnetization, field assisted processing, ICME

In order to take full advantage of magnetic field as a processing parameter it is necessary to be able to predict the change of material behavior (such as phase transformation temperatures) as a function of applied magnetic field, processing temperature, and composition. Such methodology will aid in determining which materials/alloys will be most responsive to applied magnetic field. Here we focus on Fe-X and Fe-X-C alloys (where X= Co, Ni, Mn, etc.) and their austenite/ferrite and martensitic transformations. We have also collated the necessary magnetic properties of these alloys, namely magnetic moment and Curie temperature as a function of alloy content. The application of alternate magnetization models (Kuz'min, Arrott) to the typically used Weiss Molecular Field Theory allows for the improved prediction of magnetic field assisted phase transformations in addition to a larger compositional and temperature range than previously studied.

Modeling of the Transient and Varying Thermophysical Properties of Nickel Aluminum Bronze

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[3] University of Northern Iowa

Keywords: Modeling, Thermophysical, Transient, Properties, NAB

A novel transient one-dimensional energy equation is presented here to determine the thermal conductivity and latent heat of fusion of nickel aluminum bronze (NAB) poured initially at 1340 K. Because of its superior stability and robustness in numerical modeling, fully implicit scheme was used in solving the transient one-dimensional heat conduction equation of NAB. Three different finite control volume integration equations were developed to model NAB transient thermophysical properties as a pure liquid, a liquid-solid mixture, and a pure solid. The changes in density and specific heat during phase transition were modeled using the rule of mixtures to incorporate the contributions of various metallic alloying elements of NAB at specific temperatures. The fraction of liquid and solid curve was determined at the center of the computational domain of the discretized form of a one-dimensional transient energy equation. The latent heat of fusion was obtained at 198.8 kJ/kg, which agreed with published literature. The values of NAB thermal conductivity between 1300 to 1340 K were determined at 132.8 and 18.8 W/m-K, respectively during phase transition.

Proceedings included as Appendix P.

Poster included in Appendix Q.

Prediction and Experimental Validation of Solidification for the Study of Hot Tearing in a Cr-Mo-Ni Steel

Katelyn Kiser[1], Ron O'Malley[1], Laura Bartlett[1], Simon Lekakh[1], Mario Buchely[1], Viraj. A Athavale[1], Soumava Chakraborty[1], Krista Limmer[2], Katherine Sebeck[3], and Daniel Field[2]

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Keywords: solidification, hot tearing, continuous casting, high temperature laser confocal microscopy, thermodynamic modeling

An investigation into the differences between simulated and experimental solidification results for Cr-Mo-Ni steels for the purposes of increasing accuracy during the controlled deformation test (CDT). The CDT was designed to replicate hot tearing conditions during continuous casting in order to assess an alloy's sensitivity to hot tearing. Scheil and Equilibrium solidification results are compared to a two-point Fourier analysis derived from experimental results from a controlled deformation test. In addition, simulated results and experimental results are also compared to solidification studies in a high-temperature laser confocal microscope which allowed for in situ identification of phase transformation temperatures.

Poster included in Appendix Q.

Q&P Processing of Plate Steels for Dynamic and Toughness Applications

Miranda Bell[1], John Speer[1], Kip Findley[1], Krista Limmer[2], and Daniel Field[2]

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Keywords: Q&P, Plate Steels, Toughness, Dynamic Performance,

There has been significant research effort into the development of advanced high-strength steels (AHSSs) for non-defense applications such as automotive structures. These steel concepts may be of interest for DOD applications, and one such effort involves the utilization of the quench and partition (Q&P) heat treatment, a method that aids in the partitioning of carbon from martensite into austenite to stabilize retained austenite (RA). The objective is to utilize the TRIP effect associated with RA to enhance mechanical properties in low-alloy steels. Current Q&P development has focused on thin sheet steels; therefore, research into Q&P

processed plate steels is needed. This poster will highlight current work to develop Q&P plate microstructures with improved combinations of hardness and Charpy impact toughness when compared to current quench and tempered plate steels.

Solid-state Additive Manufacturing of High-Strength Steels via Additive Friction Stir Deposition

Nikhil Gotawala, Ryan B. Gottwald, Donald J Erb, Reece Pressier, and Hang Z. Yu

Virginia Tech

Keywords: solid-state, additive manufacturing, friction stir, high strength steel, martensite

Using fusion-based approaches like wire arc additive manufacturing or selective laser melting, additive manufacturing often leads to porosity, undesired microstructures, and high residual stresses in high-strength steels. Qualifying the printed steel parts for DoD applications requires rational design of the feedstock, careful control of the process condition, and extensive post-processing efforts. Here, we explore pathways to additive manufacturing of high-strength steels without melting and solidification. Specifically, we leverages the friction stir principle and material feeding to enable location-specific printing of 4xxx and USAF-96 high-strength steels. Known as additive friction stir deposition, the feed material undergoes severe plastic deformation at elevated temperatures, resulting in forging-like microstructures and mechanical properties. We demonstrate the printing by instrumenting a desktop CNC machine, which leads to fully-dense steels in the as-printed state with excellent interface quality. Such a miniaturized set-up not only improves the spatial resolution but also offers a sustainable solution for W-Re tooling.

Poster included in Appendix Q.

Stainless Steel and Aluminum Alloy Development for Highly Consistent and Isotropic Properties in Laser Powder Bed Fusion

Benjamin Rafferty[1], Jeremy Iten[1], Aaron Stebner[2], Sridhar Seetharaman[3], Branden Kappes4, Akansha Singh[5], Dyuti Sarker[2], and Soumya Mohan[2]

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[3] Arizona State University
[4] KMMD
[5] Colorado School of Mines

Keywords: Stainless Steel, Laser Powder Bed Fusion, Alloy Development, Additive Manufacturing, integrated computational materials engineering

To increase additive manufacturing (AM) robustness and reliability, there is a need for metal feedstocks that produce more isotropic and highly consistent properties. Current laser powder bed fusion (LPBF) feedstocks show variation in microstructure and mechanical properties based on build direction. By combining integrated computational materials engineering (ICME) with an inoculant-based approach, we experimentally validated a more isotropic 300 series stainless steel and an extraordinarily consistent high-strength 5000 series aluminum metal matrix composite. The 300 series stainless steel showed UTS measurements consistency across X-Y and Z direction of 96% compared to 90% for 316L. The 5000 series aluminum MMC showed >99% equivalent UTS across X-Y and Z directions and showed no change in YS or UTS from the as-built condition after a 2-hour stress relief at 300 °C. The 5000 series aluminum MMC demonstrated a yield strength 3 times that of wrought 5083-O with 7% elongation.

Synthesis and Sliding Behavior of Bearing Steel-based Composites

Stephen Berkebile[1], Caleb Matzke[2], Emily Dahlke[2], Abdulrahman Aldossary[2], Nikhil Murthy[1], and Surojit Gupta[2]

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[2] University of North Dakota

Keywords: bearing steel, composite, synthesis, microstructure, wear

There is a need for high performance materials for triboactive applications. We demonstrate that MAX phases – layered, hexagonal carbides – increased the hardness and improved tribological properties in 100Cr6 steel composites. We determined the microstructure and hardness of 100Cr6 Steel - MAX phase composites (100Cr6 steel – 5 vol% Cr_2AlC) and their effect on the wear and coefficient of friction when lubricated by fuels of varying chemistries (Ethanol, F-24) compared to dry sliding. The steel composites were densified in an unpressurized furnace using argon atmosphere at 1400 ºC for 30 minutes. Steel composites were also heat treated in a small box furnace heated to 840 ºC for 23 minutes in air and then quenched in deionized water. Nital-etched surfaces were captured using optical and scanning electron microscopy, which revealed unique structure formations. Detailed tribological studies will be presented for these compositions.

CANCELLED - Variant Segmentation of Prior Austenite Grains via Graph Cut

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[2] Air Force Research Laboratory
[3] University of Cincinnati

Keywords: Graph cut, computational, segmentation, reconstruction

Reconstruction of prior austenite grains from a nearly or fully transformed Martensitic structure is a challenging process that has seen progress in recent years by multiple methods. Similarly challenging though is mapping regions of the structure to the correct martensite variant they formed from. Doing so can lead to insights into the structure/property relationship of martensitic steels. Of specific interest is investigating which subgrain boundaries (packet, block, and/or variant) predominantly control different microstructural responses, such as fatigue, shock response, and corrosion properties.

This work uses graph cut theory and entropy minimization to assign variant maps in an automated and rapid fashion to Electron Backscatter Diffraction Maps of an AF96 martensitic steel.

Appendix A. Intercritical Annealing of HY Steel to Improve Impact Toughness

This appendix appears as a PDF attached to the report.

Appendix B. Effects of Direct Resistance Heating on Recrystallization in Cold-Worked Steels

This appendix appears as a PDF attached to the report.

Appendix C. HSLA-100 for Thick-Section Forgings

This appendix appears as a PDF attached to the report.

Appendix D. Machine Intuitive Design of Army Steels - MIDAS

This appendix appears as a PDF attached to the report.

Appendix E. Incorporation of Partitioning Effects During Martensitic Phase Transformation in Phase Field Modeling of Steels

This appendix appears as a PDF attached to the report.

Appendix F. Effect of Thermomechanical Processing and Heat Treatment on Mechanical Properties and Fracture Behavior of a Cr-Ni-Mo-V Ultra-High-Strength Steel

This appendix appears as a PDF attached to the report.

Appendix G. High-Fidelity, Through-Thickness Measurements of Residual Strain in Bent Armor Steel Plates

This appendix appears as a PDF attached to the report.

Appendix H. Application of Rapid Tempering to High Hardness Armor Steels

This appendix appears as a PDF attached to the report.

Appendix I. Prediction of Prior Austenite Grain Size and Morphology as a Function of Processing Parameters in AF9628 Steel Processed via Directed Energy Deposition

This appendix appears as a PDF attached to the report.

Appendix J. Process-Feature-Microstructure Property Relationships for AF9628 Directed Energy Deposition Additive Manufactured Steel Components

This appendix appears as a PDF attached to the report.

Appendix K. Effect of Microstructure on Hydrogen Diffusion of Ultra High Strength Steel

This appendix appears as a PDF attached to the report.

Appendix L. Damping Measurement from Charpy Impact Test

This appendix appears as a PDF attached to the report.

Appendix M. Development of Ballistic Cast Steel Appliques using Additively-Manufactured Cores

This appendix appears as a PDF attached to the report.

Appendix N. Electron Beam Welding AerMet 360

This appendix appears as a PDF attached to the report.

Appendix O. Nitriding A-21 Stainless Steel

This appendix appears as a PDF attached to the report.

Appendix P. Modeling of the Transient and Varying Thermophysical Properties of Nickel Aluminum Bronze

This appendix appears as a PDF attached to the report.

Appendix Q. Posters

This appendix appears as a PDF attached to the report.

List of Symbols, Abbreviations, and Acronyms

AFRL	Air Force Research Laboratory
AHSS	advanced high-strength steels
Al	aluminum
AM	additive manufacturing
AP	armor piercing
APT	atom probe tomography
ARL	Army Research Laboratory
bcc	body-centered cubic
C	carbon
CALPHAD	calculation of phase diagrams
CCT	continuous cooling transformation
CDoE	computational design of experiments
CDT	controlled deformation test
CHESS	Cornell High-Energy Synchrotron Source
Co	cobalt
Cr	chromium
CVN	Charpy V-notch impact
DED	directed energy deposition
DEVCOM	US Army Combat Capabilities Development Command
DoD	Department of Defense
EBSD	electron backscatter diffraction
EBW	electron beam weld
ERC	engineering research center
fcc	face-centered cubic
Fe	iron
FSP	fragment simulation projectile
HAMMER	Hybrid Autonomous Manufacturing Moving from Evolution to Revolution
GVSC	Ground Combat Systems Center

HAZ	heat-affected zone
HHA	high-hardness armor
HSLA	high-strength low-alloy
IA/T	intercritical anneal/temper
IBAS	industrial base analysis and sustainment
ICME	integrated computational materials engineering
LEAP	local-electrode atom probe tomography
LPBF	laser powder bed fusion
MDO	Multi-domain Operations
Mn	manganese
Mo	molybdenum
MPEA	multi-principal element alloy
NAB	nickel aluminum bronze
Ni	nickel
NLPAR	Non-Local means Pattern Reindexing
OGA	other government agencies
OSD	Office of Secretary of Defense
PCI	phase-contrast imaging
PF	phase field
Q&P	quench and partition
QDLT	quench, deform, lamellarize, and temper
QLT	quench, lamellarize, and temper
RA	retained austenite
RHA	rolled homogeneous armor
SBIR	Small Business Innovation Research
SFE	stacking fault energy
TRIP	transformation-induced plasticity
TWIP	twinning induced plasticity
UHSS	ultra-high-strength steel
WAAM	wire arc additive manufacturing

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