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FeMnAl Technical Review Meeting 2020

by Krista R Limmer, Daniel M Field, and Katherine M Sebeck

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FeMnAl Technical Review Meeting 2020

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14. ABSTRACT
The second FeMnAl technical review meeting was held virtually 23–24 June 2020 as two half-day meetings bringing together the academic and industrial community working with the US Army on low-density armor steel development to more rapidly advance the material maturation. This report contains the meeting agenda, abstracts, discussion summary, and attendance roster. Appendixes containing a list of publications and presentations related to this effort and copies of the briefings presented during the meeting are also included.

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1. Introduction

The 2020 FeMnAl Technical Review meeting was held virtually 23–24 June. The meeting was hosted by the Lightweight Innovations for Tomorrow (LIFT) consortium on the Microsoft Teams platform. The objective of the meeting was to bring together the domestic academic, industrial, and defense communities working on the development of low-density armor steel to more rapidly advance the material maturation. FeMnAl, a ferrous (Fe) alloy containing large amounts of manganese (Mn) and aluminum (Al), has been evaluated domestically as a cast and wrought armor material with 10–15% lower density than traditional armor steels since the mid-2000s.[1] The current development and maturation efforts began in 2016 and have grown to include many different organizations working on various aspects of the material development and maturation process. Most of the current research projects have been funded through Department of Defense (DOD) programs and technically coordinated by the US Army Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center (GVSC) and CCDC Army Research Laboratory (ARL). The Steel Founder's Society of America (SFSA) has also coordinated projects under grants from the Defense Logistics Agency.

This second FeMnAl technical review meeting built upon the success of the first meeting, held at LIFT in January 2019, to bring together the researchers, program directors, and end users to evaluate the progress made in the past year and identify the immediate needs moving forward in FeMnAl development and maturation. The meeting was divided into two half-day sessions. The first day focused on the material development aspects, including composition variation, heat treatment optimization, advanced microscopy, and casting applications. The second day focused on the maturation aspects, including performance of industrially produced plate and secondary processing operations of machining and welding. Each technical briefing was 20 min including questions. The meeting agenda is shown in Table 1.

Table 1 2020 FeMnAl review meeting agenda; times in Eastern Daylight Time

23 June 2020			
Time	**Title**	**Speaker**	**Organization**
0900	The Current Status of FeMnAl Maturation	Katherine Sebeck	CCDC GVSC
0920	The effects of composition on age-hardening and notch toughness in FeMnAl castings	Laura Bartlett	Missouri University of Science & Technology
0940	Composition effects on the aging kinetics of wrought FeMnAl	Daniel Field	CCDC ARL
1000	Effects of composition on performance of wrought FeMnAl	Katherine Sebeck	GVSC
1020	*Break*		
1040	Advanced characterization study of carbide evolution in Fe-Mn-Al-C steel	Marcus Young	University of North Texas
1100	Microstructural characterization of age-hardened FeMnAlC steels	Dean Pierce	Oak Ridge National Laboratory (ORNL)
1120	Ni-containing Fe-Mn-Al-C alloys for high strength applications	Michael Piston	Missouri University of Science and Technology
1140	*Break*		
1200	Examination of chemical analysis methods for FeMnAl	John Griffin	University of Alabama–Birmingham (UAB)
1220	Casting FeMnAl track shoes	Diana David	SFSA
1240	*Discussion*		
24 June 2020			
0900	Comparison of properties and performance for industrially produced FeMnAl	Krista Limmer	ARL
0920	Machining and weldability of FeMnAl steels	Randy Dull	EWI
0940	Variation in microstructure and properties in fusion welds of low-density Fe-Mn-Al-C steels	Rishi Kant	Lehigh University
1000	*Break*		
1020	Assessing FeMnAl for combat vehicles	Craig Niese	General Dynamics Land Systems (GDLS)
1040	Weldability of wrought FeMnAl steels	Zhili Feng	ORNL
1100	*Break*		
1120	Evaluation of solidification cracking susceptibility of FeMnAl using the cast-pin-tear test	Antonio Ramirez	The Ohio State University (OSU)
1140	Hot ductility behavior of FeMnAl	Daniel Bechetti	Naval Surface Warfare Center (NSWC), Carderock Division
1200	*Conclusion*		

The virtual format for the meeting this year was required due to the travel restrictions in place from the COVID-19 pandemic. Although in-person interactions were not possible, the discussions that took place in the meeting "chat" throughout the meeting, as well as in the open discussion period at the end of the first day, provided adequate interaction for attendees to remain engaged and contribute throughout the meeting. While the discussions, both large

group and sidebar, were not able to be as long or free-flowing as an in-person meeting allows, the meeting was still successful in bringing the community together for development and maturation updates.

There were 52 participants across both days of the meeting representing 19 different government, academic, and industrial organizations. A list of the meeting participants and their affiliations is provided in Table 2.

Table 2 2020 FeMnAl review meeting participant list

Last name	First name	Affiliation
Allard	Lawrence	ORNL
Bartlett	Laura	Missouri University of Science and Technology
Bechetti	Daniel	NSWC, Carderock Division
Challa	Venkata	ArcelorMittal
Chizek	Philip	LIFT
Czech	Peter	LIFT
Dai	Tao	ORNL
David	Diana	SFSA
Doherty	Kevin	ARL
Dull	Randy	EWI
Feng	Zhili	ORNL
Field	Dan	ARL
Filar	Charles (Chip)	GVSC
Fisher	Charles	NSWC, Carderock Division
Foley	Michael	GVSC
Foley	Robin	UAB
Giorjao	Rafael	OSU
Griffin	John	UAB
Handayani	Dika	California State Polytechnic University, Pomona
Herman	William	GDLS
Horwath	Edward	ARL
Kant	Rishi	Lehigh University
Karaman	Ibrahim	Texas A&M University
King	Dion	ATI Metals
Kross	John	ArcelorMittal
Kyle	Doug	ORNL
Limmer	Krista	ARL
Marshall	Lewis	GVSC
Martinez	Andy	ATI Metals
Moore	Ryan	SFSA
Nicol	Ryan	US Army Program Executive Office–Ground Combat Systems

Table 2 2020 FeMnAl review meeting participant list (continued)

Last name	First name	Affiliation
Niese	Craig	GDLS
Okhuysen	Victor	California State Polytechnic University, Pomona
OMalley	Ronald	Missouri University of Science and Technology
Patrick	Robert	ATI Metals
Picak	Sezar	Texas A&M University
Pierce	Dean	ORNL
Piston	Michael	Missouri University of Science and Technology
Poplawsky	Jonathan	ORNL
Poweleit	David	SFSA
Ramirez	Antonio	OSU
Rori	Hadrian	LIFT
Sanders	Tom	GVSC
Sebeck	Katherine	GVSC
Steele	Joe	LIFT
Stewart	Colin	NSWC, Carderock Division
Thompson	Peter	Ellwood Quality Steels
Vaughan	Matthew	Texas A&M University
Vieau	Katie	GVSC
Wagner	Daniel	GVSC
Wagner	Nicole	California State Polytechnic University, Pomona
Young	Marcus	University of North Texas

2. Briefing Abstracts

An abstract for each of the 16 briefings presented at the meeting is included here in chronological order as outlined in Table 1. Each briefing slide deck is included as a separate appendix as denoted after each abstract.

2.1 Day 1: 23 June 2020

2.1.1 The Current Status of FeMnAl Maturation

Katherine Sebeck

GVSC

The overall state of FeMnAl development will be discussed at a high level. An overview of the various different collaborative and ongoing efforts will be given, as well as discussion regarding upcoming efforts and recent results. The outcome of various industrial efforts to date will presented, discussing major lessons learned.

This briefing is included as Appendix A.

2.1.2 The Effects of Composition on Age-Hardening and Notch Toughness in FeMnAl Castings

Laura Bartlett[1], Thomas Wall[1], Hollis Long[1], Michael Piston[1], Krista Limmer[2], Daniel Field[2], and Katherine Sebeck[3]

[1] *Missouri University of Science and Technology*
[2] *ARL*
[3] *GVSC*

A series of Fe-Mn-Al-C castings were produced and evaluated to determine the effect of Mn, Al, and C on the microstructure and mechanical properties of an austenitic FeMnAl steel. The microstructure, aging response at 530 °C, and Charpy V-notch toughness were evaluated as a function of composition. Results showed that increasing C had the greatest contribution to increasing the age-hardening kinetics. Notch toughness in the solution-treated condition was a strong function of increasing C-to-Al ratio. Increasing Al and decreasing Mn and C stabilized ferrite that produced brittle fracture and reduced notch toughness in both solution-treated and aged steels. In the aged condition, an Fe-29Mn-8Al-0.9Si-0.82C-0.42Mo steel was found to have the best combination of notch toughness with greater than 50 J (–40 °C) at a hardness of 300 Brinell hardness number.

This briefing is included in Appendix B.

2.1.3 Composition Effects on the Aging Kinetics of Wrought FeMnAl

Daniel Field[1], Krista Limmer[1], Laura Bartlett[2], and Katherine Sebeck[3]

[1] *ARL*
[2] *Missouri University of Science and Technology*
[3] *GVSC*

A series of Fe-Mn-Al-C alloys were evaluated to determine the effect of composition variation on resulting properties. Whereas past studies have examined the sensitivity of mechanical properties to changing a single element in the composition in these alloys, this study evaluated covariance of the major elements: Mn, Al, and C. In this study a series of wrought plates were produced by two vendors according to a two-factor design of experiments that were all expected to be age-hardenable through precipitation of κ-carbide. Aging kinetics and mechanical properties will be discussed in terms of microstructure. Complimentary CALPHAD modeling results and challenges in accurate composition evaluation will also be discussed.

This briefing is included in Appendix C.

2.1.4 Effects of Composition on Performance of Wrought FeMnAl

Katherine Sebeck[1], Ian Toppler[1], Katherine Vieau[1], Daniel Field[2] and Krista Limmer[2]

[1] *GVSC*
[2] *ARL*

FeMnAl steels were initially proposed as a drop-in replacement for rolled homogenous armor (RHA) steels, with similar performance at a lower density. Maturation efforts were originally initiated using a composition optimized for castability of P900 armor rather than for wrought plate. A series of Fe-Mn-Al-C alloys were evaluated to determine the effect of composition on both traditional mechanical properties and armor performance in the wrought form. Mechanical properties and high-level ballistic performance will be discussed in terms of composition and plate manufacturing. Material from a two-factor design of experiments will be compared with industrially produced material.

This briefing is included in Appendix D.

2.1.5 Advanced Characterization Study of Carbide Evolution in Fe-Mn-Al-C Steel

Nathan A Ley[1], Marcus L Young[1], B Chad Hornbuckle[2], Daniel M Field[2], and Krista R Limmer[2]

[1] *University of North Texas*
[2] *ARL*

Continued research on advanced high-strength steels is an important step in reducing weight and fuel consumption of modern vehicles. Fe-Mn-Al-C steels, which have increased concentrations of both Al and Mn, are currently under development to achieve these goals. Typically, these steels are strengthened by age-hardening to form nano-sized κ-carbide precipitates, $(Fe,Mn)_3AlC$. The addition of Al also helps to reduce the overall density of the steel. In this study the evolution of κ-carbide precipitates, as well as a few other phases, was investigated using scanning electron microscopy (SEM), transmission election microscopy, and synchrotron radiation X-ray diffraction. Mechanical properties were examined using Rockwell hardness and Charpy impact testing. Results are compared with CALPHAD predictions. The results from this study illuminate the effect of various heat treatments on the size, distribution, and volume fraction of the κ-carbide precipitates in Fe-Mn-Al-C steels.

This briefing is included in Appendix E.

2.1.6 Microstructural Characterization of Age-Hardened FeMnAlC Steels

D T Pierce[1], L Allard[1], J Poplawsky[1], K More[1], D Leonard[1], D Field[2], K Limmer[2], and K Sebeck[3]

[1] *ORNL*
[2] *ARL*
[3] *GVSC*

Low-density age-hardenable austenitic steels based on the FeMnAlC system exhibit promising combinations of strength and reduced density for structural components, but mechanical properties such as impact toughness can sometimes vary significantly depending on processing, chemical composition, and/or microstructural differences. In this work scanning transmission electron microscopy and atom probe tomography were used to characterize the microstructure of several FeMnAlC steels, including precipitate type, size, and distribution as well as grain boundary segregation. Kappa carbide was the dominant precipitate identified, while other types of precipitates were not observed in significant quantities. The grain boundaries of the aged specimens were found to be enriched in Mn, C, silicon (Si), molybdenum (Mo), and boron (B), and depleted in Fe and Al. The findings of the microstructural investigations and their potential impact on mechanical properties, including toughness, are discussed.

This briefing is included in Appendix F.

2.1.7 Ni-containing Fe-Mn-Al-C alloys for high strength applications

Laura Bartlett[1], Michael Piston[1], Ron O'Malley[1], Krista Limmer[2], and Daniel Field[2]

[1] *Missouri University of Science and Technology*
[2] *ARL*

Additions of nickel (Ni) to high-Mn, high-Al, low-density steels have been shown to greatly increase strength by forming hard intermetallic B2 precipitates within the austenite matrix. In this study, the effects of Ni-additions between 5 and 8 wt% were investigated as a function of thermomechanical processing in a base Fe-20Mn-9Al-0.9C-wt% steel. Increasing Ni content produced a higher density and a finer distribution of nano-sized B2 within the austenitic matrix after hot-rolling and subsequent precipitation. The size and morphology of the precipitates were modified using variations on the thermomechanical processing and annealing temperatures. The ductility and toughness are shown to be strongly dependent on the precipitate size and morphology.

This briefing is included in Appendix G.

2.1.8 Examination of Chemical Analysis Methods for FeMnAl

David Poweleit[1], Diana David[1], Palmer Lynch[1], and John Griffin[2]

[1] *SFSA*
[2] *UAB*

FeMnAl has been a difficult alloy to get a reliable composition measurement from due the lack of appropriate standards to accommodate the relatively high levels of key alloying elements. There is currently no standard practice for measuring the composition, and this study aims to determine the factors that are contributing to the variations in measurements by examining variations in technique and method. To examine the repeatability and reproducibility of chemistry analysis of FeMnAl, 10 laboratories participated in a round-robin study. Three samples were sent around to the participating labs where chemistry of these samples was measured using seven different methods, including Optical Emissions Spectrometry and Inductively Coupled Plasma.

This briefing is included in Appendix H.

2.1.9 Casting FeMnAl Track Shoes

David Poweleit[1], Diana David[1], Rod Grozdanich[2,] Richard Hardin[3], Christoph Beckermann[3], Laura Bartlett[4], Robin Foley[5] and John Griffin[5]

[1] *SFSA*
[2] *Spokane Industries*
[3] *University of Iowa*
[4] *Missouri University of Science and Technology*
[5] *UAB*

Investment castings are commonly considered to have fewer issues with inclusions (reoxidation). On one hand this seems counterintuitive given that the pouring and gating for a typical investment casting involves metal rapidly being poured down a long, large sprue (tree) and then oftentimes filling the mold cavity with additional "waterfalls". Thus, it would seem that the increased opportunity for interaction between the molten steel and air would promote the formation of inclusions. That said, typical investment castings do offer some opportunities. Wall sections are generally thin and quick to solidify, which would limit time for inclusions to agglomerate and float up. In addition, the ceramic shell of an investment casting is sintered and provides an inert atmosphere unlike sand castings, where mold–metal reaction must be managed. Inclusions have a deleterious effect on FeMnAl properties. A cast FeMnAl track shoe serves as a good opportunity to investigate properties and capability.

This briefing is included in Appendix I.

2.2 Day 2: 24 June 2020

2.2.1 Comparison of Properties and Performance for Industrially Produced FeMnAl

Krista Limmer[1], Daniel Field[1], and Katherine Sebeck[2]

[1] *ARL*
[2] *GVSC*

Four industrial (≤40 T) heats of FeMnAl have been processed to produce plate material. Chemistry, processing, casting quality, and heat treatment synergistically interacted to produce ever-increasing quality plate in both casting-to-plate-conversion rate and performance. The effect of chemistry variation, thermomechanical processing, and heat treatment will be discussed in generalities and their effect on plate quality, Charpy v-notch impact properties and microstructure will be identified. Higher rolling temperatures, lower solution-treatment temperatures and shorter aging times were shown to provide the highest quantity of viable plate for testing and produced the best impact properties. The properties and performance of the most recent heat will be discussed in more detail.

This briefing is included in Appendix J.

2.2.2 Machining and Weldability of FeMnAl Steels

Randy Dull

EWI

EWI evaluated the welding of FeMnAl plate. Gas metal arc welds (GMAWs) on FeMnAl were made with good mechanical properties using a variety of electrode types, including austenitic stainless steel and high-chrome, high-Mn electrodes. Base-metal mechanical properties had a strong influence on weld and heat affected zone (HAZ) mechanical properties, with low toughness in the base metal an issue on a few welds. The weld HAZ was generally not the limiting factor in performance.

EWI also evaluated using standard techniques, consumables, and conditions for cutting and machining developed for austenitic stainless steel as a baseline for comparison for their use on FeMnAl. Waterjet cutting can be effectively used on FeMnAl but with slower cutting speeds than on 304SS. Carbide-tipped blades can be used to cut FeMnAl with a band saw. Coated carbide tooling can be successfully used on FeMnAl with appropriate feeds and speeds

This briefing is included in Appendix K.

2.2.3 Variation in Microstructure and Properties in Fusion Welds of Low-Density Fe-Mn-Al-C Steels

Rishi Kant and John DuPont

Lehigh University

Fe-Mn-Al-C alloys are a promising lightweight substitute for the currently used low-alloy steels in thick-plate applications. The addition of lighter elements like Al and C lower the density of the alloy while also forming kappa carbides for higher strength. However, when welded, these precipitates can dissolve or coarsen in the HAZ of the weld. In this talk, the variation in microstructure and mechanical properties across the HAZ of Fe-30Mn-8.5Al-1C steel will be discussed. The mechanical tests (hardness, impact toughness, and tensile) are conducted on Gleeble simulated HAZ specimens. The effect of HAZ peak temperature, weld heat input, starting base metal heat treatment, and post-weld heat treatment on the mechanical properties will be discussed. The evolution of tensile properties across the gas tungsten arc welds fabricated using 316L and 17-4PH filler wires will also be discussed.

This briefing is included in Appendix L.

2.2.4 Assessing FeMnAl for Combat Vehicles

Craig Niese

GDLS

GDLS has a vested interest in continually evaluating methods to design and fabricate lighter-weight vehicles. Vehicle weight is critical for many aspects of how the vehicle is designed and how the vehicle can be used for its various missions. FeMnAl is attractive due to its potential of having traditional armor steel performance but at a lower weight density. GDLS has been evaluating the weldability and overall manufacturability of the material, and this presentation will provide an update where GDLS currently is with its evaluations, and outline what aspects is critical for GDLS to transition FeMnAl to production.

This briefing is included in Appendix M.

2.2.5 Weldability of Wrought FeMnAl Steels

Zhili Feng, Tao Dai, and Doug Kyle

ORNL

Developed for the application in armor vehicle or tank construction, wrought FeMnAl steels have the properties of high strength and lower density than the steels

with similar strength. This presentation will present the recent progress at Oak Ridge National Laboratory on the weldability of two heats of wrought FeMnAl steels, which is part of the Army FeMnAl steel development program. It was found that the two different heats exhibited rather significant differences in weldability, especially in high-temperature HAZ cracking tendency. The effect of different welding consumables, shielding gases, and welding processes will be presented and compared. Mechanical properties and microstructure features in the weld and HAZ of the two heats will be discussed as well.

This briefing is included in Appendix N.

2.2.6 Evaluation of Solidification Cracking Susceptibility of FeMnAl Using the Cast-Pin-Tear Test

Antonio J Ramirez[1], Rafael A R Giorjao[1], Katherine Sebeck[2], and Katherine Vieau[2]

[1] *OSU*
[2] *GSVC*

The US Army has engaged in comprehensive research for alternatives to current armor steel that is both tough and lightweight. A new steel based on the Fe-Mn-Al ternary system can provide an important overall reduction in weight without compromising its armor functionality. To date, only exploratory and limited research has been conducted on joining methods of FeMnAl plates, and very limited work has been performed on the metallurgical weldability of this system. In the present study, the OSU Welding Engineering team will further expand on their work on the evaluation and quantification of the solidification cracking susceptibility of several experimental heats of cast and hot-rolled FeMnAl alloys. Solidification cracking testing was conducted using the Cast-Pin-Tear Testing to evaluate, quantify and compare the studied alloys susceptibility to this cracking phenomenon. Solidification cracking was evaluated and observed in several pins' lengths, confirmed by the fractography using SEM. The composition differences between the tested alloys did not produce major effects on the solidification cracking susceptibility. In addition, the alloys susceptibility was also addressed using CALPHAD modeling and the new criteria developed by OSU to quantify metallic materials' solidification cracking susceptibility.

This briefing is included in Appendix O.

2.2.7 Hot Ductility Behavior of FeMnAl

Daniel H Bechetti and Matthew F Sinfield

NSWC, Carderock Division

Austenitic alloys have a well-documented history of base metal heat affected zone (BMHAZ) weldability challenges, many of which are influenced by the presence and stability of precipitates in the microstructure. In this work two FeMnAl BMHAZ weldability metrics, liquation cracking susceptibility and ductility dip cracking (DDC) susceptibility, were evaluated using the Gleeble hot ductility test. FeMnAl (Fe-0.9C-29.7Mn-9Al-0.9Si-0.7Mo-0.01S wt%) specimens were heated at several different rates under the application of a constant load to establish the alloy's nil strength temperature. The on-heating and on-cooling ductility responses at temperatures from 400 to 1200 °C were then determined. The material was found to have a relatively narrow ductility recovery temperature range, which implies moderate resistance to liquation cracking, and a large and deep intermediate temperature ductility trough, which is consistent with high DDC susceptibility. Recommendations for microstructural investigations, welding procedure, and filler metal development are provided based on the experimental results.

This briefing is included in Appendix P.

3. Discussion

As FeMnAl reaches maturation, the next step to implementation into defense assets is the development of materials qualification and materials use specifications. ARL is the custodian of most Army-relevant materials specifications, including MIL-DTL-12560K, *Armor Plate, Steel, Wrought, Homogenous (for use in Combat-Vehicles and for Ammunition Testing)*[2] commonly referred to as RHA. GVSC is the custodian of most Army-relevant materials manufacturing specifications, including MIL-STD-3040, *Arc Welding of Armor Grade Steel*.[3] Implementation of FeMnAl as a drop-in replacement for RHA applications would be simplest, from an end-user perspective, if it was added to the existing MIL-DTL-12560 specification. The current language in MIL-DTL-12560 could be modified to allow the addition of a new "low-density" class of RHA (i.e., Class V). Due to our collective experiences with material quality control and not insignificant differences in secondary processing (e.g., machining and welding), the creation of a new materials specification would be more appropriate for the proper handling and implementation of FeMnAl.

The first day of the meeting concentrated on the physical metallurgy of FeMnAl. Composition and toughness optimization have been ongoing questions for FeMnAl.

The composition round-robin indicated that most methods of measuring composition are adequate provided the appropriate reference standards are used, although the composition tolerance and determination methods will need to be evaluated further for appropriate inclusion into the material specification documentation. One of the primary toughness concerns has been the severe effect of phosphorous (P) on toughness in FeMnAl castings.[4] The laboratory and industrial heats of wrought FeMnAl produced to date have had P levels below 0.010 wt%, at which level there is not expected to be a significant concern. Accurate measurements into the parts-per-million range that would be required for validating lower P levels are not practical for implementation. Cerium (Ce) additions have been used to getter P in some laboratory scale castings; however, caution should be used implementing this into a heat, as any residual Ce will form Ce-sulfides that are detrimental to toughness and ballistic performance. The laboratory-scale composition study demonstrated no significant change in ballistic performance with composition changes—only on the aging kinetics to achieve the target hardness and the resulting toughness. Compositions that stabilized ferrite also generally had lower impact toughness. Heat-treatment optimization studies have shown that solution-treating at the lowest possible temperature to prevent grain growth, while aging at the hottest possible temperature, yields the maximum toughness for a given hardness target.

The second day of the meeting focused on work in welding and machining of wrought FeMnAl necessary for integration. A variety of commercial weld wires have been successful in GMAW. Some liquation cracking was observed in the first industrial heat of material, but the changes made to improve the toughness of the base material for the second industrial heat led to improvements in the welded plate as well. The microstructure of FeMnAl is found to be moderately susceptible to solidification cracking and may require care when welding, similar to stainless steels. Machining practices for a number of common operations have shown FeMnAl performance similar to that of 304 stainless steel. Discussion focused on sharing the techniques various groups have developed to date, including appropriate use of cutting depth, feed rate, and rotation speed, to the extent that cutting fluid was not required if these parameters were properly tuned.

Due to a number of programmatic changes, as well as the limited success in defeating specific threats, the urgency regarding FeMnAl maturation has slowed. The focus is shifting to thorough documentation and fundamental understanding, enabling future designs to leverage this unique alloy system. Opportunities remain for partial substitution on legacy platforms to be explored. Weight reduction of complex systems is a challenging problem, and FeMnAl remains a unique potential solution for when performance, space, and weight requirements are in conflict.

Since the recent FeMnAl development and maturation efforts were kicked off in 2016, a significant body of work has been published by DOD researchers and external collaborators, from journal articles and technical reports to conference presentations to patent applications. Figure 1 shows the annual distribution of presentations and publications, and a complete list of the citations is given in Appendix Q.

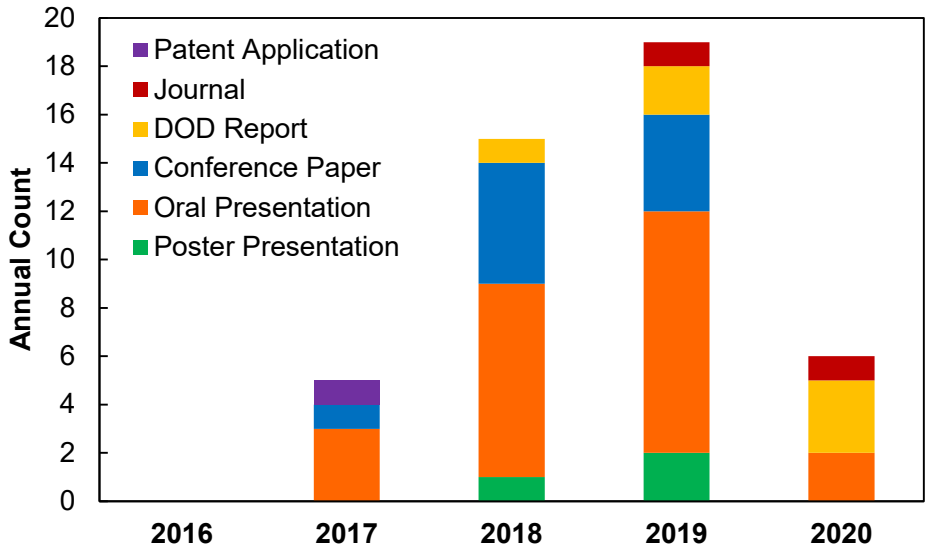


Fig. 1 Dissemination of FeMnAl-related research results since 2016 as papers, reports, patents, and conference presentations (not including presentations at the 2019 and 2020 FeMnAl Technical Review Meetings)

4. References

1. Howell RA. Microstructural influence on dynamic properties of age hardenable femnal alloys. Rolla (MO): Missouri University of Science and Technology; 2009.
2. MIL-DTL-12560K (MR). Armor plate, steel, wrought, homogeneous (for use in combat-vehicles and for ammunition testing. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2013 Dec 7.
3. MIL-STD-3040. Arc welding of armor grade steel. Warren (MI): Army Ground Vehcle Systems Center (US); 2016 June 29.
4. Bartlett L. On the effect of silicon and phosphorus during the precipitation of K-carbide in Fe-Mn-Al-C alloys. Rolla (MO): Missouri University of Science and Technology; 2013.

Appendix A. The Current Status of FeMnAl Maturation

This appendix appears as a PDF attached to the report.

Appendix B. The Effects of Composition on Age-Hardening and Notch Toughness in FeMnAl Castings

This appendix appears as a PDF attached to the report.

Appendix C. Composition Effects on the Aging Kinetics of Wrought FeMnAl

This appendix appears as a PDF attached to the report.

Appendix D. Effects of Composition on Performance of Wrought FeMnAl

This appendix appears as a PDF attached to the report.

Appendix E. Advanced Characterization Study of Carbide Evolution in Fe-Mn-Al-C Steel

This appendix appears as a PDF attached to the report.

Appendix F. Microstructural Characterization of Age-Hardened FeMnAlC Steels

This appendix appears as a PDF attached to the report.

Appendix G. Ni-Containing Fe-Mn-Al-C Alloys for High-Strength Applications

This appendix appears as a PDF attached to the report.

Appendix H. Examination of Chemical Analysis Methods for FeMnAl

This appendix appears as a PDF attached to the report.

Appendix I. Casting FeMnAl Track Shoes

This appendix appears as a PDF attached to the report.

Appendix J. Comparison of Properties and Performance for Industrially Produced FeMnAl

This appendix appears as a PDF attached to the report.

Appendix K. Machining and Weldability of FeMnAl Steels

This appendix appears as a PDF attached to the report.

Appendix L. Variation in Microstructure and Properties in Fusion Welds of Low-Density Fe-Mn-Al-C Steels

This appendix appears as a PDF attached to the report.

Appendix M. Assessing FeMnAl for Combat Vehicles

This appendix appears as a PDF attached to the report.

Appendix N. Weldability of Wrought FeMnAl Steels

This appendix appears as a PDF attached to the report.

Appendix O. Evaluation of Solidification Cracking Susceptibility of FeMnAl Using the Cast-Pin-Tear Test

This appendix appears as a PDF attached to the report.

Appendix P. Hot Ductility Behavior of FeMnAl

This appendix appears as a PDF attached to the report.

Appendix Q. Publications and Presentations To-Date Related to the US Department of Defense Development and Maturation of FeMnAl

Q.1 Patents

Howell RA, Cheeseman BA, Montgomery JS, Shirley AD, Sebeck KM, Limmer KR. High aluminum containing manganese steel and methods of preparing and using the same. United States patent application 15/685,180; filed 2017 Aug 24.

Q.2 Peer-Reviewed Journal Publications

Field DM, Limmer KR, Hornbuckle BC. On the grain growth kinetics of a low density steel. Metals. 2019;9(9):2075.

Green WH, Cheeseman BA, Field D, Limmer KR. Very low-intensity throughput X-ray computed tomography of a cast FeMnAl steel alloy. Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems 3. 2020;4.

Q.3 Conference Proceedings and Extended Abstracts

Howell RA, Gerth R. Fe-Mn-Al-C alloy steels – a new armor class. Warrendale (PA): SAE International; 2017. SAE Technical Paper No.: 2017-01-1703.

Evans W, Ramirez AJ, Sebeck K. Investigation of hot cracking phenomena in light-weight armor steel based on the FeMnAl-C alloy system. Proceedings of the NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2018 Aug; Novi, MI.

Limmer K, Field D, Cheeseman B, Montgomery J, Sebeck K, Howell R. Accelerated heat treatment of high Mn TRIPLEX steels for armor applications. Journal of Iron & Steel Technology; 2018 Oct.

Limmer K, Field D, Cheeseman B, Howell R. Effects of micro-alloying and processing history on Fe-Mn-Al-C steel. Supplemental Proceedings of AIME Materials Science & Technology; 2018 Oct; Columbus, OH.

Pierce D, Sebeck K, Limmer K, Field D, Muralidharan G, Muth T, Frederick DA, Feng Z. Hot deformation behavior of a low-density austenitic steel. Supplemental Proceedings of AIME Materials Science & Technology; 2018 Oct; Columbus, OH.

Sebeck K, Toppler I, Rogers M, Limmer K, Cheeseman B, Howell R, Herman W. High Mn, high Al steels for thick plate armor applications. Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium; 2018 Aug; Novi, MI.

Field DM, Limmer KR. Effect of solution treatment on grain size and toughness of lightweight Fe-Mn-Al-C steel. Journal of Iron and Steel Technology. 2019 Oct.

Green W, Cheeseman B, Field D, Limmer K. Quantitative analysis of porosity and voids in cast Fe-Mn-Al steel alloy material via X-ray computed tomography. Proceedings of the 46th Review of Progress in Quantitative Nondestructive Evaluation; 2019 July; Portland, OR.

Sebeck K, Toppler I, Limmer K, Field D, Wagner D, Gafner A. Compositional sensitivity of high Mn, high Al steels. Proceedings of the NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2019 Aug; Novi, MI.

Walter TR, Moy P, Sano T, Limmer K. Characterization of dynamic deformation and failure of novel light weight steel alloy. In: Dynamic behavior of materials. Cham (Switzerland): Springer; 2019. Vol. 1. p. 351–353.

Q.4 Oral Presentations

Howell RA, Gerth R. Fe-Mn-Al-C alloy steels–a new armor class. Warrendale (PA): SAE International; 2017 Mar 3. SAE Technical Paper No.: 2017-01-1703.

Sebeck K, Limmer K, Howell R, Gerth R. Characterizing high Mn steel for thick plate applications. Presented at Materials Science and Technology; 2017 Oct; Pittsburgh, PA.

Sebeck K, Howell R, Limmer K, Cheeseman B. High-Mn high-Al steel for thick plate applications. Presented at the Defense Manufacturing Conference; 2017 Dec; Tampa, FL.

Evans W, Ramirez AJ, Sebeck K. Investigation of hot cracking phenomena in light-weight armor steel based on the FeMnAl-C alloy system. Presented at the NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2018 Aug; Novi, MI.

Limmer K, Field D, Cheeseman B, Montgomery J, Sebeck K, Howell R. Accelerated heat treatment of high Mn TRIPLEX steels for armor applications. Presented at AISTech; 2018 May; Philadelphia, PA.

Limmer K, Field D, Cheeseman B, Howell R. Effects of micro-alloying and processing history on Fe-Mn-Al-C steel. Presented at Materials Science and Technology; 2018 Oct; Columbus, OH.

Pierce D, Sebeck K, Limmer K, Muralidharan G, Muth T, Frederick D, Feng Z. Hot deformation behavior of a low-density austenitic steel. Presented at AISTech; 2018 May; Philadelphia, PA.

Pierce D, Sebeck K, Limmer K, Field D, Muralidharan G, Muth T, Frederick DA, Feng Z. Hot deformation behavior of a low-density austenitic steel. Presented at Materials Science and Technology; 2018 Oct; Columbus, OH.

Piston M. Microstructural evolution and age hardening behavior of a lightweight ultrahigh strength Fe-16Mn-10Al-0.9C-5Ni steel. Presented at Materials Science and Technology; 2018 Oct; Columbus, OH.

Sebeck K, Toppler I, Rogers M, Limmer K, Cheeseman B, Howell R, Herman W. High Mn, High Al steels for thick plate armor applications. Presented at the NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2018 Aug; Novi, MI.

Sebeck K, Howell R, Tzelepis D, Foley M. Thermomechanical processing of high-Mn, high-Al steels for thick plate applications. Presented at the Mineral, Metals and Materials Society Annual Meeting and Exhibition; 2018 Mar; Phoenix, AZ.

Evans W, Giorjao R, Ramirez AJ, Sebeck K. Evaluation of solidification cracking resistance of light-weight armor steel based on the FeMnAl system. Presented at the 2019 DOD Steel Summit; 2019 Nov; Aberdeen Proving Ground, MD.

Field DM, Limmer KR. Effect of solution treatment on grain size and toughness of lightweight Fe-Mn-Al-C steel. Presented at AISTech; 2019 May; Pittsburgh, PA.

Green W, Cheeseman B, Field D, Limmer K. Quantitative analysis of porosity and voids in cast Fe-Mn-Al steel alloy material via X-ray computed tomography. Presented at the 46th Annual Review of Progress in Quantitative Nondestructive Evaluation; 2019 July; Portland, OR.

Ley N, Young M, Hornbuckle B, Field D, Limmer K. Synchrotron radiation X-ray diffraction studies of carbide evolution in Fe-Mn-Al-C steel. Presented at Materials Science and Technology; 2019 Sep; Portland, OR.

Limmer KR, Field DM, Cheeseman BA, Sebeck KM. New armor steel specifications – FeMnAl case study. Presented at the 2019 DOD Steel Summit; 2019 Nov; Aberdeen Proving Ground, MD.

Limmer K, Field D, Bartlett L, Sebeck K. Composition-dependent precipitation kinetics in Fe-Mn-Al-C alloys. Presented at Materials Science and Technology; 2019 Sep; Portland, OR.

Bartlett L, Piston M, Limmer K, Field D. Age hardening in lightweight FeMnAl steels with nickel additions. Presented at Materials Science and Technology; 2019 Sep; Portland, OR.

Sebeck K, Toppler I, Limmer K, Field D, Wagner D, Gafner A. Compositional sensitivity of high Mn, high Al steels. Presented at the NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2019 Aug; Novi, MI.

Sebeck K, Toppler I, Tzelepis D, Limmer K, Field D, Rogers M. Characterization of FeMnAl steel structure-processing-properties relationships. Presented at The Mineral, Metals & Materials Society Annual Meeting and Exhibition; 2019 Mar; Phoenix, AZ.

Walter TR, Moy P, Sano T, Limmer K. Characterization of dynamic deformation and failure of novel light weight steel alloy. Presented at Annual Conference and Exposition on Experimental and Applied Mechanics; 2019 Jun. Reno, NV.

Limmer K, Field D, Sebeck K, Bartlett L. Effect of composition on properties of age-hardenable Fe-Mn-Al-C alloys. Presented at The Mineral, Metals & Materials Society Annual Meeting and Exhibition; 2020 Feb; San Diego, CA.

Bartlett L, Piston M, O'Malley R, Limmer K, Field D. Understanding the effect of nickel on the microstructure of low density FeMnAl steels. Presented at The Mineral, Metals & Materials Society Annual Meeting and Exhibition; 2020 Feb; San Diego, CA.

Q.5 Posters

Limmer KR, Labukas JP. Corrosion performance of a low-density armor steel. Presented at the Gordon Research Conference – Aqueous Corrosion; 2018 July; New London, NH.

Evans W, Giorjao R, Ramirez AJ, Sebeck K. Hot cracking phenomena in light-weight armor steel based on the FeMnAl-C alloy system. Presented at the 2019 DefenseTechConnect & Smart Cities Connect Conference; 2019 June.

Piston M. Microstructure and mechanical properties of lightweight Fe-Mn-Al-Ni steels for armor applications. Presented at the 2019 DOD Steel Summit; 2019 Nov; Aberdeen Proving Ground, MD.

Q.6 DOD Technical Reports

Green WH, Cheeseman BA, Field DM, Limmer KR. Advanced X-ray computed tomography of voids and porosity in as cast FeMnAl steel alloy material. Army Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2020 June. Report No.: ARL-TR-8975.

Limmer KR, Field DM, Kudzal AG, Sebeck KM, Payton EJ, Draper MC. Report of the 2019 Department of Defense steel summit. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2020 Apr. Report No.: ARL-SR-0427.

Limmer KR, Sebeck KM. FeMnAl technical review meeting 2019. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2019 Feb. Report No.: ARL-SR-0414.

Limmer KR, Ligda JP, Cheeseman BA. First industrial trial production of a low-density austenitic wrought steel plate. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2019 Dec. Report No.: ARL-TR-8873.

Considine TA, Labukas JP, Farrell AA, Demaree JD, Pope DA, Kelley JV, Braswell TE, Escarsega JA, Limmer KR. Evaluation of FeMnAl corrosion and coatings performance: phase 1. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2020 Jan. Report No.: ARL-TR-8894.

Horwath EJ, Limmer KR, Cheeseman BA. Lightweight FeMnAl armor steel: material development and ballistic performance. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2018 Aug. Report No.: ARL-TR-8459.

List of Symbols, Abbreviations, and Acronyms

Al	aluminum
ARL	Army Research Laboratory
B	boron
BMHAZ	base metal heat-affected zone
C	carbon
CCDC	US Army Combat Capabilities Development Command
Ce	cerium
DDC	ductility dip testing
DOD	US Department of Defense
Fe	iron
GDLS	General Dynamics Land Systems
GMAW	gas metal arc welding
GVSC	Ground Vehicle Systems Center
HAZ	heat-affected zone
LIFT	Lightweight Innovations for Tomorrow
Mn	manganese
Mo	molybdenum
Ni	nickel
NSWC	Naval Surface Warfare Center
ORNL	Oak Ridge National Laboratory
OSU	Ohio State University
P	phosphorus
RHA	rolled homogeneous armor
SEM	scanning electron microscopy
SFSA	Steel Founders' Society of America

Si	silicon
UAB	University of Alabama–Birmingham

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