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Considerations for the Development of Additively Manufactured (AM) Metallic Armor

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ABSTRACT

An examination of the current state-of-the-art in additive manufacturing (AM) of metallic armor products for ground vehicles was conducted. Primary barriers to the implementation of AM on ground systems are related to elevated cost compared to traditional fabrication techniques, a lack of public engineering data, and lack of specifications. Initial ballistic testing against 0.30-cal. armor-piercing (AP)M2 and 0.30-cal. fragment-simulating projectile (FSP) threats was conducted on a range of test coupons made from Inconel 718 and Ti-6Al-4V (Grade 23) extra-low-interstitial (ELI) materials made by direct metal laser melting (DMLM), wire-laser directed-energy deposition (WL-DED), and wire arc additive manufacturing (WAAM). Initial attempts at evaluating lot-to-lot variation, machine-to-machine variation, process-to-process variation, and the effect of as-printed surface roughness on ballistic protection were made to direct future research and development. Given the elevated cost and complexity of these products, a series of recommendations for further development are made to speed implementation of AM for ground system armor. Collaboration between original equipment manufacturers (OEMs) and Combat Capabilities Development Center (CCDC) laboratories is advocated.

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1. INTRODUCTION

Homogeneous metals dominate armor systems on all historical and modern combat vehicles. This makes the continued development of metallic armor concepts important to ground combat vehicles as threats continue to advance. The first use of iron-based armor in the New World was in 1862 during the famous battle between the Monitor and the Merrimac (CSS Virginia). [1] As technology progressed and threats evolved, the development of dedicated wrought and cast steel armor products for ground vehicles was utilized heavily through World War II. [2] In the 1950s, the need for lightweight ground systems became critical to the implementation of rapid airdrop in a series of world-wide conflicts resulting in the development and usage of a range of advanced, non-ferrous armor materials. [3] [4] Despite substantial advances in composite and ceramic armor technologies, manufacturing practices and material selection for ground systems have changed little since the 1960s and 1970s due to the continued cost effectiveness, reliability, and ready availability of metallic armors.

In recent years, a number of key technological improvements, including additive manufacturing (AM), have demonstrated the potential to improve the performance, cost efficiency, and production life cycle of manufactured products across myriad industries. These technologies have the potential to overcome a number of the challenges associated with incumbent manufacturing and design approaches.

The following sections will review the current state-of-the-art in metallic armor technology in ground vehicles and AM, followed by a review of the potential benefits of AM for armor fabrication. In addition, current barriers to the implementation of this technology on ground-vehicle platforms will be identified. Finally, suggestions for research to speed the implementation of this technology will be outlined.

The purpose of this project is to conduct a series of preliminary assessments to determine what factors in the development of AM armor products for ground systems merit further investigation. This information can be used to focus product development tasks and reduce the barriers to the implementation of AM armor products.

1.1. Ground Systems Armor Technology

Currently, metallic armor is manufactured by the forming, welding, and machining of wrought, extruded, cast, or forged materials. Examples of cast, forged, and extruded armor products can be found on a wide range of combat vehicles. [4] [5] [6] Armor plate is utilized extensively for the fabrication of vehicle structures, doors, and flat-panel applique parts. [7] [8]

The performance of these armor products has been studied, and detailed performance specifications published, for a range of metals including aluminum, steel, and titanium. [9] [10] [11] [12] Currently, few publications have addressed the potential for the use of metallic AM in armor technology. [13] [14] Current findings suggest that AM components are capable of exhibiting mechanical and ballistic behavior that is similar to conventionally manufactured parts of the same chemistry, properties, and microstructure. In order to achieve this performance, a unique set of processing parameters and heat treatments are required for AM products when compared to wrought, cast, or forged products. [15] [16]

1.2. Additive Manufacturing in Defense

Use of AM in military applications is most often found in weight-sensitive industries, most notably within aviation and aerospace. [17] [18] Benefits of AM for these industries is largely based on weight and part reduction, which is equated to a cost savings. As part of a 2006 study of complex components in aviation, it was demonstrated that the combination of weight consciousness and the need for extreme reliability resulted in AM being readily justifiable when the final component has a "buy-to-fly"[1] ratio of 12:1 or greater. [19] However, ground systems often increase in weight and do not place substantial value on lightness of weight as compared to aviation. [20] Extensive work has been conducted in recent years to more accurately assess the benefits of reducing the weight of ground-vehicle components that may add value to further development of AM in this industry. [21] Other potential benefits of AM include enhanced performance and reduction of logistics burden (reduction of part counts and simplification of the supply chain). The benefits of the reduced logistics burden have been recognized by both the United States Army and the United States Marine Corps (USMC) as a topic of importance to future operations. [22] [23]

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[1] "Buy-to-fly" refers to the ratio between the volume of material procured to the volume of material incorporated into the final part. The difference in the two states is typically due to machining complex structures from a solid, procured billet.

1.3. Codes & Standards

Currently, a range of commercial codes and standards are being developed for AM by organizations including the ISO, AWS, ASTM, and SAE. [24] These standards are being developed by a committee of machine manufacturers, service bureaus, end-item owners, users, and regulatory agencies who assess the current “state-of-the-art” based on available data and establish reasonable standards and quality-control metrics.

Conventional armor products are specified by Military Standard (MIL-STD) and contain a range of ballistic limit requirements to benchmark minimum performance. However, AM products do not currently fall under any of these MIL-STDs and, as such, are subject only to typical commercial controls. Original Equipment Manufacturers (OEMs) in the ground-vehicle industry have conducted investigations of AM, but material and manufacturing data are not available in the public domain to inform codes and standards. [25] This paucity in engineering data requires armor designers to develop and define quality and performance requirements on a case-by-case basis. This requires substantial time and monetary investment. This lack of standardization in AM armor products serves both as a barrier to product development and to its adoption on production platforms.

1.4. Potential for Additive Armor

AM has the potential to benefit ground systems in at least two critical ways. First, improved performance and manufacturability due to greater design freedom. Second, reduction of cost and lead time due to the elimination of tooling as a casting and forging replacement.

The primary barriers to implementation of armor produced by AM are the high cost of development due to lack of engineering data available in the public domain and the lack of codes and standards. These factors result in high developmental costs and no streamlined path to acceptance of new products.

2. Methods

All hardness testing was conducted in accordance with ASTM E18, Rockwell Hardness Scale C. All tensile testing was conducted in accordance with ASTM E8/E8M. Sample geometry was limited to plate-type armor (0.5 in.) listed in Figure 1 of the specification or cylindrical samples (0.350 in. in diameter) listed in Figure 8 of the specification. Ballistic limit testing was conducted in accordance with MIL-DTL-662 except as noted herein. Test projectiles were the 0.30-cal. armor-piercing (AP)M2 and 0.30-cal. fragment-simulating projectile (FSP) (MIL-DTL-46593). In addition, testing for density using a water-displacement-based method was conducted in accordance with ASTM B962 except without oil impregnation in order to more closely determine the “dry” density of the samples.

All components were procured based on commercial specification requirements provided by the vendor. Detailed requirements for feedstock, processing parameters, and heat treatment were not specified to replicate a typical procurement activity.

2.1. Inconel 718

Inconel 718 was printed by direct metal laser melting (DMLM) on two different machines with two different processes and were evaluated against AP and FSP threats. Microstructure and build quality[2] were compared to assess variation among builds. In addition, limited assessments were conducted on the ballistic performance of this material with and without back-face machining.

A summary of the sample configurations that were tested and their designations is provided in Table 1.

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[2] Build quality refers to the presence of defects generated during the build cycle (ISO/ASTM 52900). “Poor” build quality would refer to a printed material with porosity, cracks, delaminations, lack of fusion, or other defects. “Good” build quality would be the absence, or reduction, of defects in the material.

Table 1. Sample Conditions for Inconel 718.

Material	Process	Lot[3]	Surface	Condition
Inconel 718[4]	Machine 1[5]	Lot 1	As-Built (1/4")	A
		Lot 2	As-Built (1/4")	A
	Machine 2[5]	Lot 1	As-Built (1/4")	D
			Machined (Two-Side, 3/16")	D
		Lot 2	As-Built (1/4")	D
			Machined (One-Side, 3/16")	D
			Machined (Two-Side, 3/16")	D

In the body of the text, samples printed on "Machine 1" will be designated "M1" and samples printed on "Machine 2" will be designated "M2". Similarly, individual production lots (Lot 1, Lot 2) will be designated as L1 or L2.

2.2. Ti-6Al-4V

Ti-6Al-4V extra-low-interstitial (ELI) samples were printed by WAAM and LW-DED. Materials were fabricated and annealed in accordance with AMS 4999. The ballistic limits of the samples were evaluated to determine whether the performance of the material varied with deposition process given use of similar consumables, heat treatment, resulting structure, and mechanical properties.

3. Results

All data presented in this section were generated at BAE Systems' facilities. Any exceptions to test standards and acceptance criteria will be made here prior to further discussion of the data in Section 4.

3.1. Inconel 718 Results

In order to assess the potential effect of machine-to-machine and lot-to-lot variability in the ballistic properties of AM materials, samples were evaluated for profilometry, density, and hardness testing as shown in Table 2.

Table 2. Select properties of DMLM Inconel 718 samples.

Lot	Hardness (HRC)[6]	Roughness (µin Ra)[6]	Density (lb/in.^{3})
M1L1	38.4	294 – 304	.298
M1L2	38.6	390 – 400	.298
M2L1	44.2	300 – 310	.298
M2L2	44.0	-	.298

Evaluation of M1L1 samples in the as-polished condition revealed minor indications of spherical and rounded porosity in the bulk material. The good fusion of powder particles contributed to good surface finish with only minor indications of incomplete fusion at the surface, as shown in Figure 1 and Figure 2.

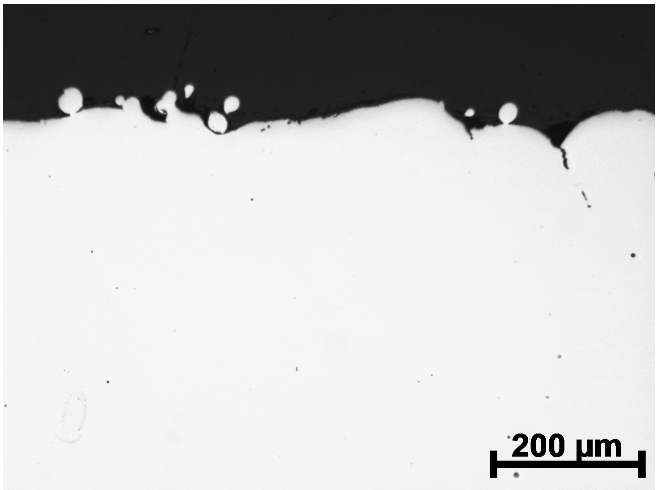

Figure 1. As-polished image of M1L1 cross-section at surface (Inconel 718, DMLM, 100X).

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[3] "Lot" refers to an individual build cycle (ISO/ASTM 52900). Parts with multiple lots were built in separately but heat-treated together.

[4] Samples in accordance with ASTM F3055.

[5] Samples printed on two different machines by two different vendors. Machine type and vendor will not be identified here.

[6] Average of five trials.

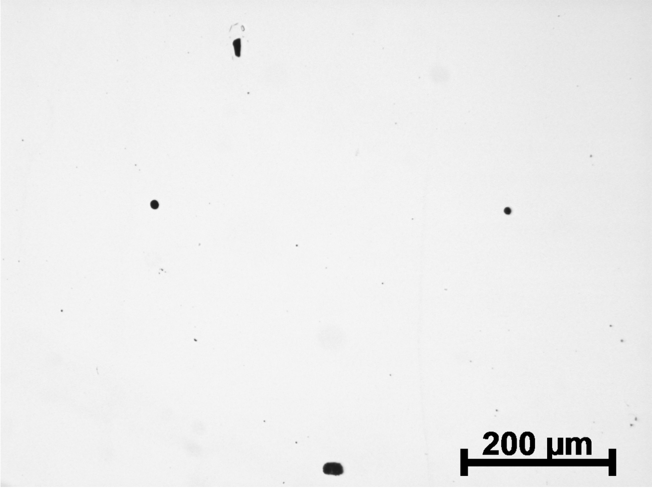

Figure 2. As-polished image of M1L1 cross-section in bulk (Inconel 718, DMLM, 100X).

M1L2 samples exhibited an increased frequency of voids with sharp or irregular geometries. These defects included similar spherical porosity as in M1L1 but also showed indications of incomplete powder fusion in the bulk as shown in Figure 3 and Figure 4.

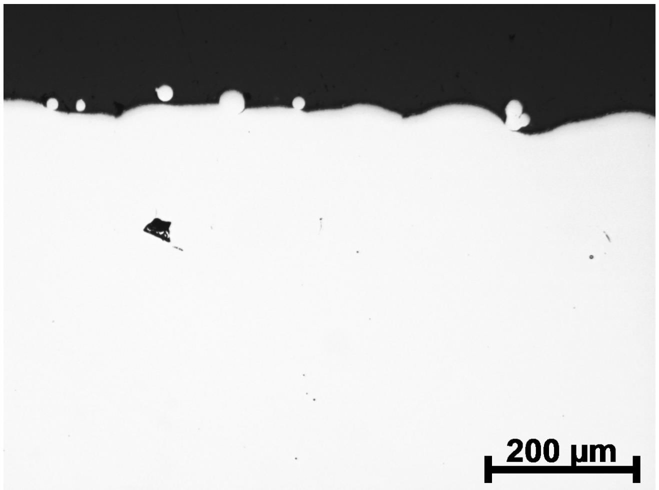

Figure 3. As-polished image of M1L2 cross-section at surface (Inconel 718, DMLM, 100X).

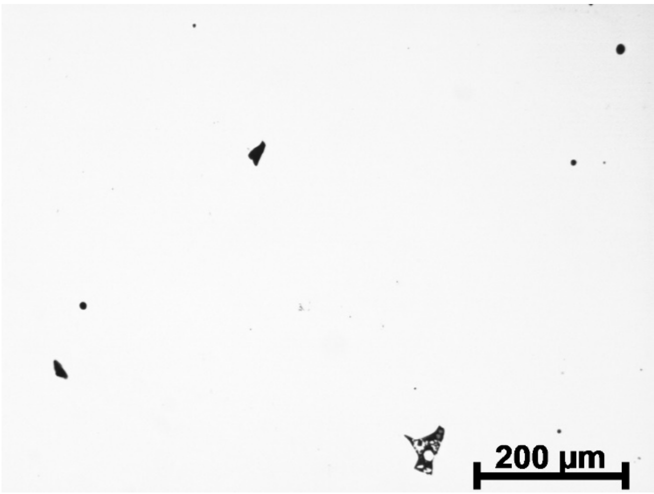

Figure 4. As-polished image of M1L2 cross-section in bulk (Inconel 718, DMLM, 100X).

The same powder, processing parameters, and machine were used for both lots. During the M1L2 build, however, the machine experienced a stoppage. The stoppage was addressed, and printing continued. The micrographs in Figures 3 and 4 were taken near the approximate location of the interruption; however, no substantial differences in build were observed by Quality inspection. Variations in build-quality between the two sample lots were not found to effect the measured density or hardness response of the two parts. Given the minor difference in build quality, additional tensile testing was conducted using 0.350-in.-diameter cylindrical bars (ASTM E8/E8M) and that data is summarized in Table 3.

Table 3. Average tensile properties of sample lots produced on Machine 1 (M1).

Sample	YS (ksi)	UTS (ksi)	Elong. (%)
M1L1	127.2	165.2	18.1
M1L2	131.5	170.0	19.4

Variation in quasi-static material properties was minor despite the inclusion of irregular porosity and lack of fusion with sharp geometry in localized areas. Ballistic limit evaluations (V_{50}) showed that ballistics were similarly insensitive to the lot-to-lot variation found between M1L1 and M1L2 when subjected to the 0.30-cal. APM2. The results are shown in Figure 5.

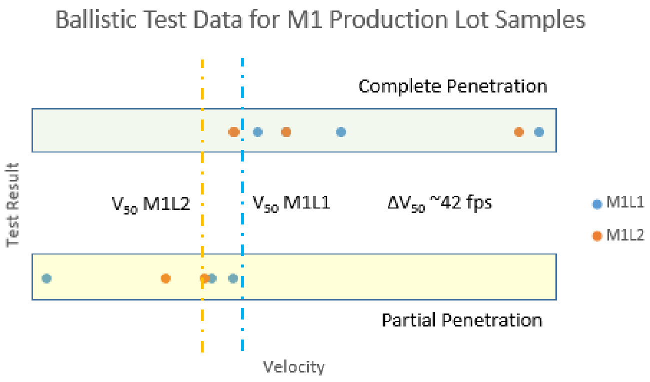

Figure 5. Comparison of ballistic limit against 0.30-cal.APM2 for Lot 1 and Lot 2 samples (Inconel 718, DMLM).

Variation in the lot-to-lot ballistic limits for material manufactured on the same machine, with identical parameters, feed stocks, and heat treatment were found to be < 50 fps. ASTM F3055 and corresponding heat-treatment requirements in AMS 2774 have minimum values established for tensile properties and hardness along with codified heat treatment scheduled which can be referenced in those documents. Both samples (M1L1, M1L2) were thermally processed in the same batch. Micrographs were etched with a solution of inverted glyceregia to examine the final microstructure of each sample and to determine whether there were any microstructural defects or variation between the two samples. These micrographs are shown in Figure 6 and 7.

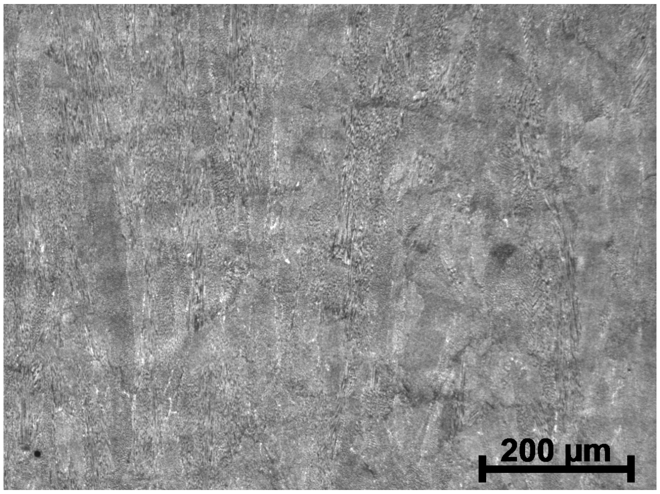

Figure 6. Etched image of transverse cross-section of M1L1 (Inconel 718, DMLM, 100X).

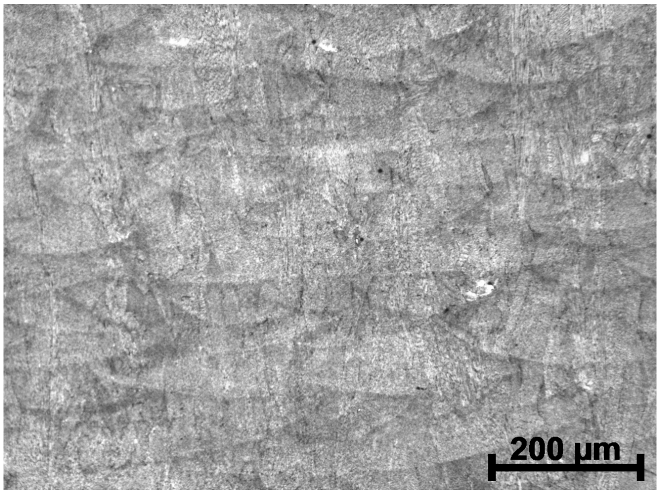

Figure 7. Etched image of transverse cross-section of M1L2 (Inconel 718, DMLM, 100X).

No appreciable differences were found in the microstructure of the two different sample lots.

Evaluation of M2L1 samples in the as-polished condition found a substantial lack of fusion or grain-to-grain bonding as shown in Figure 8 and Figure 9.

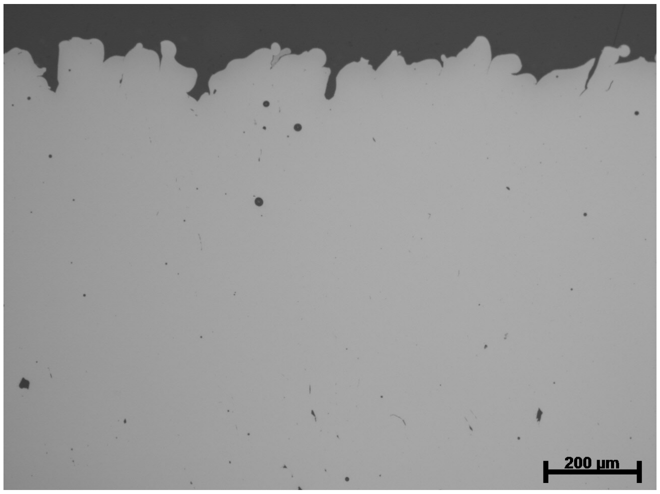

Figure 8. As-polished image of M2L1 cross-section at surface (Inconel 718, DMLM, 100X).

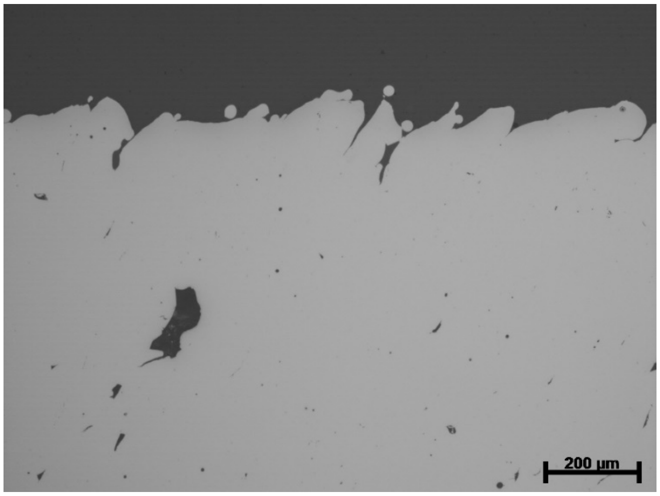

Figure 9. As-polished image of M2L2 cross-section at surface (Inconel 718, DMLM, 100X).

Defects found in both M2L1 and M2L2 production coupons included rounded gas porosity and a sharp lack of fusion defects. No characterization of feedstock or processing parameters was conducted; therefore, materials were accepted based on adherence to ASTM F3055 in order to assess the procurability of these materials using commercial standards.

As with M1 samples, etched images were taken of all M2 production samples and are shown in Figure 10 and Figure 11.

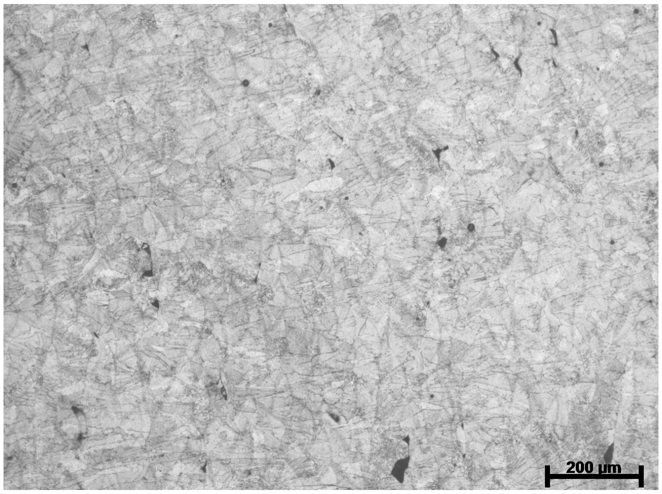

Figure 10. Etched image of transverse cross-section of M2L1 (Inconel 718, DMLM, 100X).

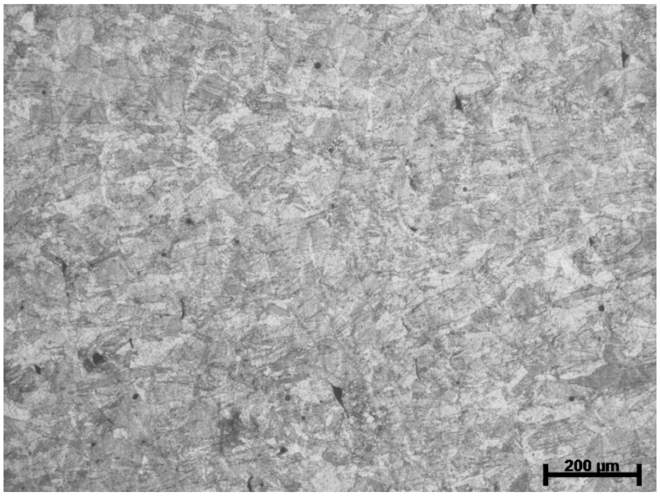

Figure 11. Etched image of transverse cross-section of M2L2 (Inconel 718, DMLM, 100X).

Overall, the bead profile generated during deposition for the M2 samples is finer than that of the M1 samples. Their approximate aspect ratio (height to width) appears to be similar, but the reduced bead profile evident after heat treatment suggests that lower laser power may have been used in the fabrication of the M2 coupons. The ballistic limit for the 0.30-cal. APM2 was determined for the M2L1 samples and compared with M1 samples, as shown in Figure 12.

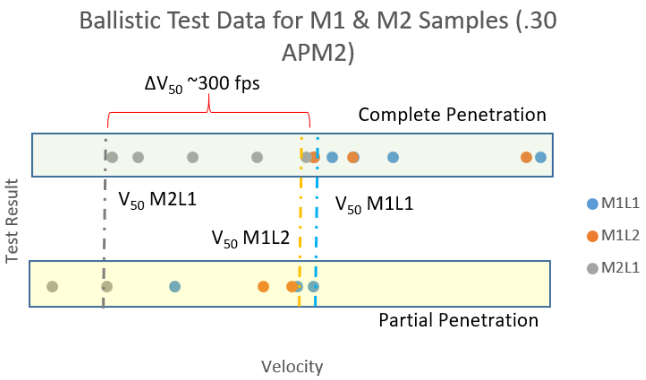

Figure 12. Comparison of ballistic limits for M1 and M2 samples (0.30-cal.APM2).

In general, all M2 samples had a ballistic limit ~300 fps lower than M1 samples. Post-test examination found that, M2 samples demonstrated a substantial increase in tendency to spall on the back-face as shown in Figure 13 and Figure 14.

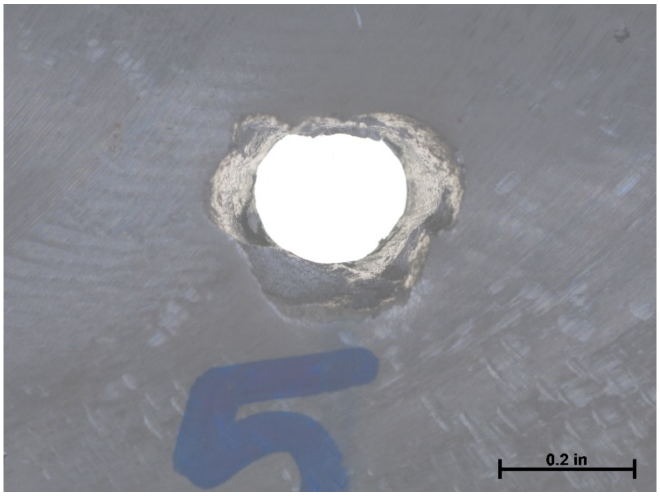

Figure 13. Image of back-side spall event when subjected to 0.30-cal. APM2 for M2L1 samples.

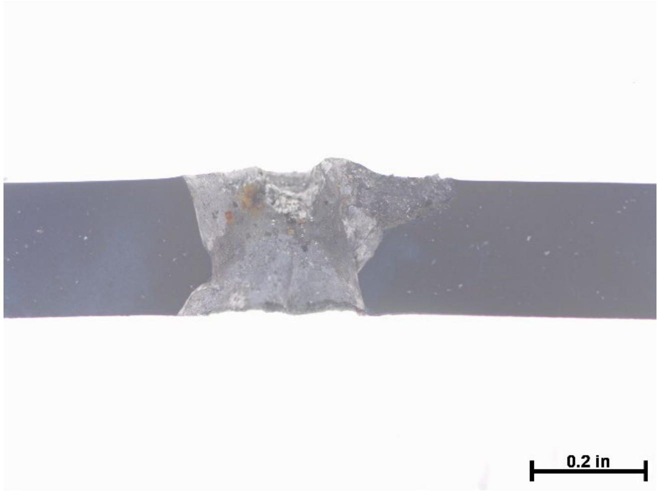

Figure 14. Image of cross-section of complete penetration for 0.30-cal. APM2 for M2L1 samples. (Top) strike-face, (bottom) exit.

It was noted that the spall behavior was inconsistent. Some impacts generated spall only from the region surrounding the exit hole. Often, the projectile was stopped, but the fragmentation caused perforation of the witness plate. After cross-sectioning of the impact location, it was observed that the material failed in a brittle mode and that the cracks propagated through near lack-of-fusion defects, as shown in Figure 15.

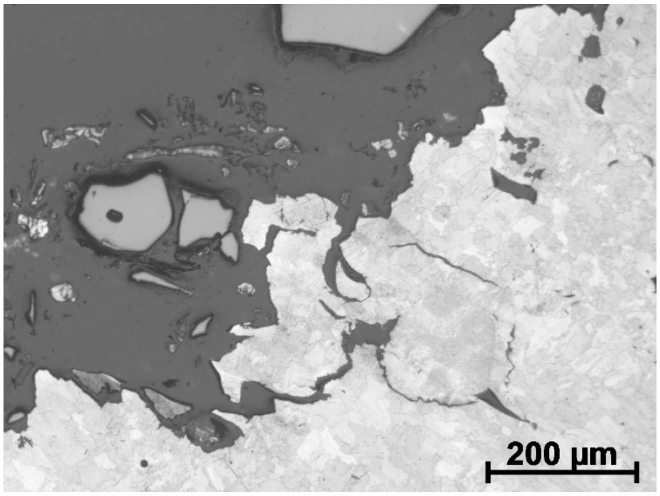

Figure 15. Image at impact site of 0.30-cal. APM2 on M2L1 samples (Inconel 718, DMLM, 100X).

In order to assess the effect of surface roughness on ballistic performance of these materials, coupons were machined to approximately 3/16-in. final thickness. The first sample set was machined from one side (strike face only) and the second sample set was machined on both-sides. The resulting ballistic limit data is shown in Figure 16.

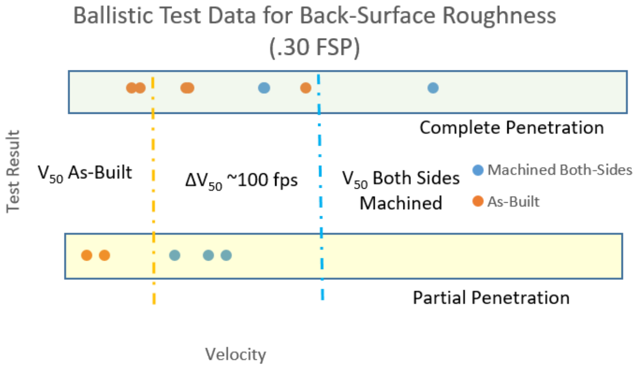

Figure 16. Ballistic limit results for M2 samples evaluated for effect of back-face surface roughness.

A difference of approximately 100 fps was noted between samples that were machined and samples that were not machined on the rear face when subjected to the 0.30-cal. FSP threat at the same thickness. The 0.30-cal. FSP threat was selected to assess the effect of back-surface roughness on ballistic limit, as that was determined to be the worst-case threat for this condition. As with samples tested against the 0.30-cal. APM2 threat, impacted locations produced substantial spall as shown in Figure 17 and Figure 18.

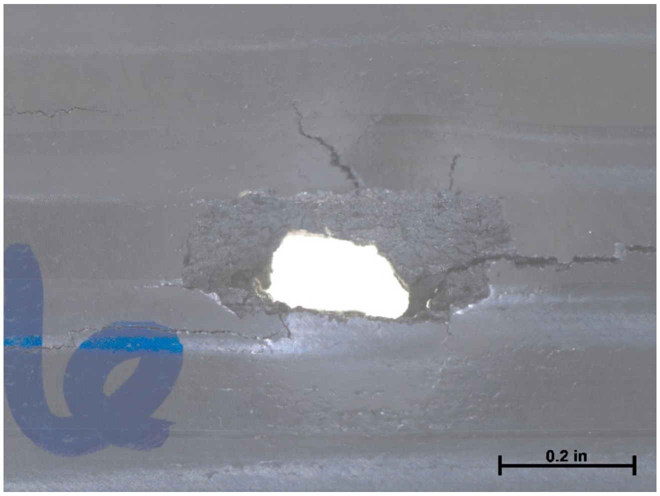

Figure 17. Image of back-side spall event when subjected to 0.30-cal. FSP for M2L1 (machined both sides).

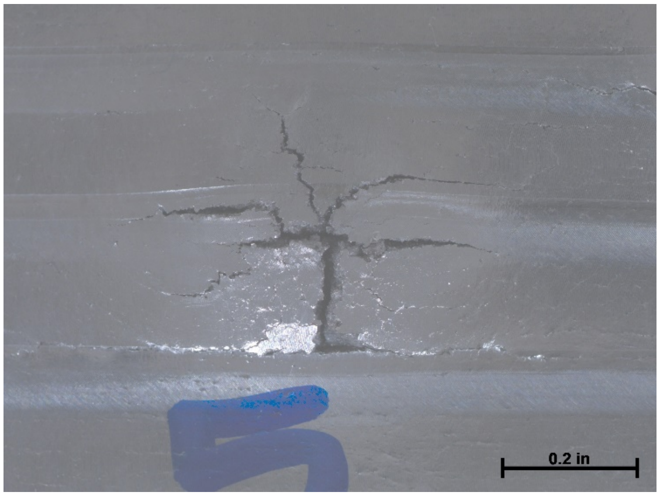

Figure 18. Image of back-side of 0.30-cal. FSP impact on M2L1 (no spall).

Secondary cracking was noted at the impact site at both the front and back sides of the 0.30-cal. FSP strikes. Some impacts resulted in local spall in certain areas, while others did not. The residual failures on the back surfaces of the impact regions varied substantially.

3.2. Ti-6Al-4V Results

In order to assess the ballistic characteristics of an alloy with an existing military specification for armor performance (MIL-DTL-46077) and known commercial use in ground systems, a series of Ti-6Al-4V armor products were compared to existing, commercial AM offerings built using WL-DED and WAAM.

Samples were analyzed by direct-reading Atomic Emissions Spectroscopy (AEDS) and it was found that all samples met the requirements for chemistry in accordance with MIL-DTL-46077, as shown in Table 4.

Table 4. Chemical analysis of various Ti-6Al-4V products made conventionally and made using AM.

Sample	Al[7]	V[7]	Fe[7]	Other[8]
Plate	6.5	4.1	0.17	0.05
Forging	6.3	3.9	0.20	0.04
WL-DED	6.3	4.0	0.11	0.03
WAAM	5.9	3.8	0.17	0.04

In addition, tensile testing was conducted on a flat bar coupon configuration per Figure 1 of ASTM E8/E8/M and the results are reported in Table 5. Data here are reported as an average between transverse and longitudinal test samples.

Table 5. Select tensile properties of Ti-6Al-4V samples.

Sample[9]	σ_y (ksi)	σ_{uts} (ksi)	Elong. (%)
Requirement[10]	110	120	10
Plate	132	144	17
Forging	132	142	18
WL-DED[11]	117	130	17
WAAM[12]	111	129	12

Although both AM products were lower strength than the equivalent plate and forged product, all coupons exceeded the minimum mechanical property requirements of MIL-DTL-46077. Both sets of AM materials were purchased with the goal of meeting the minimum tensile requirements of MIL-DTL-46077. Discussion with the vendors confirmed that their established processes for providing material for aviation applications met those requirements. As such, the material conditions described herein are representative of existing, materials and processes in use in other defense and commercial applications. Build progression and processing parameters were not controlled or tracked as part of this effort in order to simulate open procurement.

As-polished cross-sections of all samples were taken in order to assess any differences in the microstructure. Plate and forging products were found to be free of any notable manufacturing defects including cracks, laps, seams, or delaminations. Representative micrographs of the WL-DED and WAAM samples are shown in Figure 19 and Figure 20.

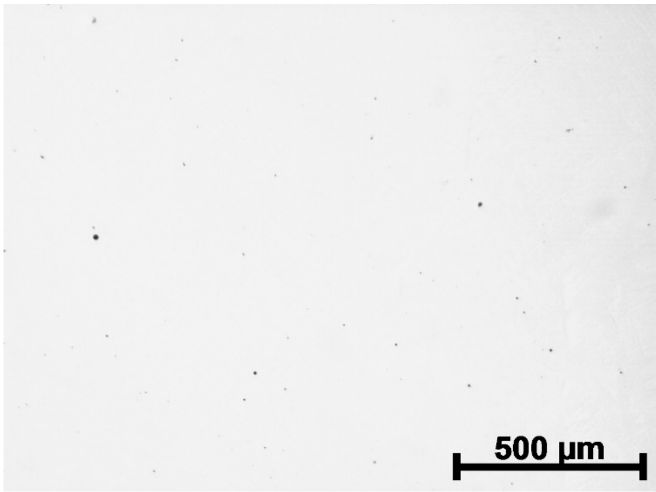

Figure 19. As-polished longitudinal cross-section of WL-DED Ti-6Al-4V (100X).

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[7] Allowable limits for Al are 5.50 – 6.50 and 3.50 – 4.50 for V. Allowable limit for Fe is 0.25 max.

[8] "Other" includes all other elements including Cu, Mo, Nb, Ni, and Si – it is limited to 0.10 each (max) and 0.40 total (max). C, O, N, and H are reported as "maximum allowable" limits in MIL-DTL-46077 – all samples reported below the maximum allowable limits.

[9] Tensile data are reported as an average of four samples for all conditions in the transverse and longitudinal directions per the requirements in MIL-DTL-46077. For AM bars, this meant that tensile bars were machined from the XY plane.

[10] Requirements are property minimums in accordance with Class 1, MIL-DTL-46077 material.

[11] Printed and then annealed in accordance with AMS 4999.

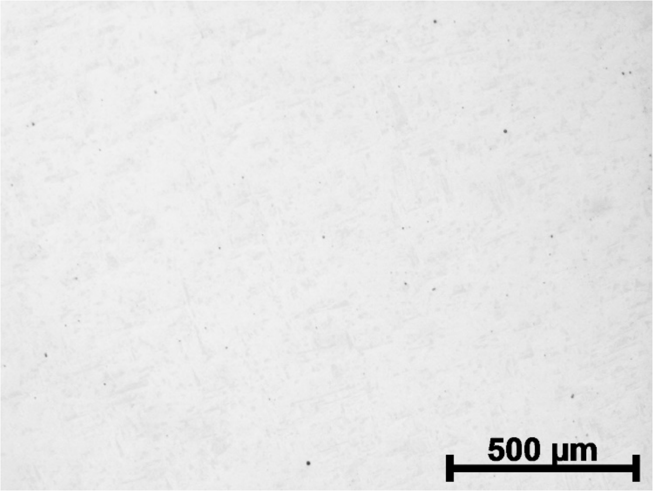

Figure 20. As-polished longitudinal cross-section of WAAM Ti-6Al-4V (100X).

Minor indications of gas porosity were found in both samples in the longitudinal and transverse directions. No indications of cracks, lack of fusion, or linear defects were found. Ballistic limit testing was conducted on samples from each AM process and the results are shown in Figure 21.

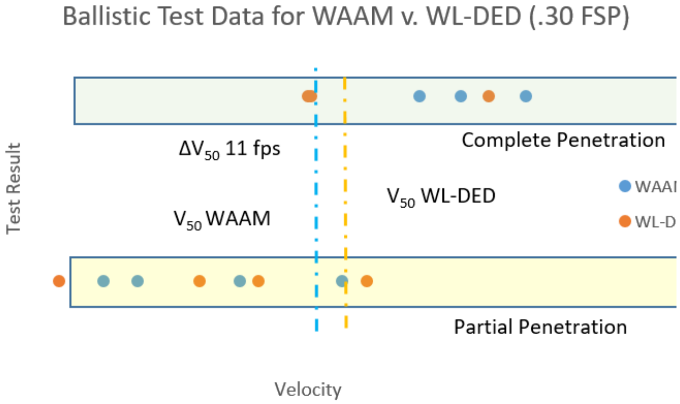

Figure 21. Ballistic limit comparison of WL-DED and WAAM samples made from Ti-6Al-4V ELI .

Comparison of the two processes found no appreciable difference in ballistic limit or failure mode. For the two samples, the difference in ballistic limit was 11 fps. However, data collected found that AM Ti-6Al-4V performed poorly in comparison to wrought and forged armor product and did not meet specification minimums.

Samples were etched with Kroll's reagent and evaluated to assess any contributions that the microstructure and heat treatment may have had on ballistic performance of these materials. The results are shown in Figure 22 and Figure 23.

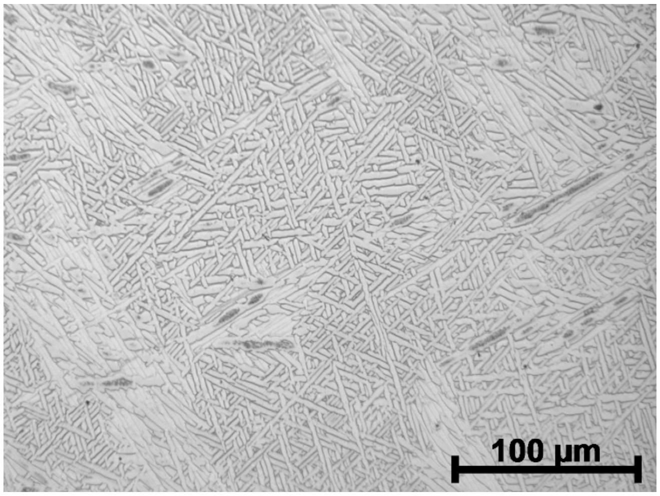

Figure 22. Etched longitudinal cross-section of WL-DED Ti-6Al-4V (250X).

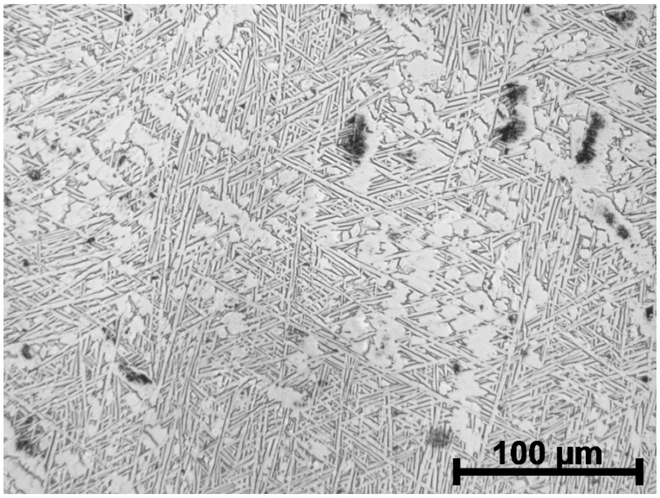

Figure 23. Etched longitudinal cross-section of WAAM Ti-6Al-4V (250X).

Etched microstructure was similar between the two processes. Both showed indications of alpha Widmanstätten structures within prior-beta grain boundaries, typical of AM Ti-6Al-4V. Variations in the microstructure between the two samples was minor, although marginally larger prior beta grain boundaries and some additional alpha-phase coarsening were observed in the WAAM samples.

4. Discussion

As mentioned previously, the data presented here are preliminary and represent the current state of research to assess the following: lot-to-lot variability, machine-to-machine variability, process-to-process variability, and potential effects of back-face (as-printed) surface condition on ballistic properties. Items determined to have significant effects on ballistic performance of the materials should be considered for future study.

4.1. Machine-to-Machine Variability

The data indicate that there is potential for differences in performance from machine to machine based on variations in build quality as previously defined. The data presented here do not allow for a direct comparison among identical products from different machines. Due to procurement limitations at the time, these products were developed with different heat treatment and mechanical property requirements.

What is evident, however, is that the specification of materials fabricated by AM must be more thoroughly explored for armor applications. Commercial applications may not provide sufficient quality controls to produce a consistent armor product without requirements for minimum required ballistic performance.

Determining whether process parameters and components can be transferred from machine to machine without re-qualification will be important to the implementation of these technologies on ground systems. Inability to do so will generate substantial non-recurring costs and restrict the available supply chain for additive parts.

4.2. Lot-to-Lot Variability

Preliminary testing of Inconel 718 materials suggests that, for an AM machine with proven process control among prints and feedstocks combined with well-defined process parameters and defined heat treatment, lot-to-lot variation in ballistic properties is minimal. What variability is present is likely to fall within acceptable performance parameters for armor systems. As a result, it is justifiable to encourage ballistic testing as a component of first-article testing and allow secondary metrics of performance to indicate the health of the system for subsequent builds. To do otherwise would be cost prohibitive and substantially reduce the flexibility with which AM could be utilized within the Army and the USMC. Further, sample lot M1L2 demonstrated that even when a print fails and must be re-started, it is possible to achieve good ballistic performance even if small defects are generated.

4.3. Effects of As-Printed Surface Finish

Based on the testing conducted in this evaluation, it was found that surface roughness or surface finish is likely to have an impact on the ballistic protection of the printed product. Investigation of appropriate “knock down” factors are likely needed in the design and qualification of armor products made with AM where the as-built surface finish is to be used.

The micrographs developed during this testing demonstrate that lack of fusion defects at the surface of a build can result in stress concentrations. These defects are a common occurrence and are well-cataloged in the literature. The introduction of these stress concentrations may either reduce the apparent cross-section of material through which a penetrator interacts, or result in the preferential failure mode transitioning to a less-energy-efficient mode than would otherwise occur.

Further investigations are needed to assess the exact mechanisms by which the back-face surface finish in AM results in decreased ballistic performance. The exact effect likely varies between different modalities and, as such, may require characterization for a range of processes.

4.4. Process-to-Process Variation

In surveying Ti-6Al-4V ELI coupons made with AM by WL-DED and WAAM processes, no appreciable variation in mechanical properties or ballistic properties was found. Ready comparison can be made between these two data points, as heat treat and material chemistry was similar, despite the fact that completely different deposition processes were used and feedstock requirements were not the same.

This result demonstrates that despite previous concerns with machine-to-machine variability, the manufacturing of AM armor does not need to be constrained to a limited set of modalities for any metallurgical reason. Rather, selection of an AM process may be dictated based on the need to balance cost, print size, and design complexity; provided the final process selected is well controlled.

4.5. Considerations for Implementation of AM Armor for Ground Systems

This preliminary work has demonstrated that there are a substantial number of unknowns inherent in the production of armor products by AM. As a result, any OEM that seeks to implement this technology on-vehicle is likely to face a substantial cost barrier to implementation. For those organizations that make this investment, the resulting information will undoubtedly be considered proprietary and serve as a barrier for other competitors to enter the market.

In order for additive products to gain acceptance and be implemented on ground vehicles, the following barriers likely need to be overcome or mitigated:

- Lack of engineering design data.
- Lack of defined qualification process for armor products.
- Lack of public codes and standards.

The above factors result in a large number of unknowns when designing AM armor systems, some of which have been examined in this study. The high cost of additive feedstock makes extensive developmental efforts cost-prohibitive for individuals to continuously re-create data for each new concept. [26] In addition, cost justifications and quality-control approaches that may be acceptable for aviation and aerospace applications may not be viable for ground-vehicle systems. In instances where research is funded by an OEM, the resulting data (which is costly to obtain) becomes guarded intellectual property, which discourages competition and slows the proliferation of this technology. Information available for conventionally manufactured armor is helpful to mitigate some of the development work that is required, but it is not sufficient to understand the behavior of AM materials used in similar applications.

The cost to design, qualify, and transition an AM armor product to production can be substantially reduced if a body of public information was made available and development supported by Government agencies. Rather than pursuing material development and product development separately, a joint effort between Government agencies and OEMs is preferable. The inclusion of material-development tasks within the scope of product-development programs allows OEMs to inform the direction of research to ensure smooth adoption of new technologies while maintaining public accessibility of material data that is generated. In this way, Army and USMC laboratories can ensure the implementation of new AM armor products (which are proprietary to the OEM), while still producing a body of public work that reduces barriers to future implementation.

5. Conclusions

A range of material samples were procured in common AM materials (Inconel 718 and Ti-6Al-4V ELI), made to commercial specification requirements, and subjected to a range of mechanical and ballistic testing. The following, preliminary conclusions merit additional consideration for future work:

- Preliminary work indicates that lot-to-lot variation in ballistic performance is negligible for well-controlled processes.
- Minor variations in build quality may be allowable for AM armor, but production evaluation methods must be defined.
- Machine-to-machine variability may be an important factor in the qualification of AM armor products.
- Different AM modalities are capable of producing satisfactory armor materials, provided that they are properly characterized and controlled.
- The established metallurgy of existing armor materials are an informative starting point for future AM product development, but should not be taken as directly translatable to AM armor even in instances where alloy composition and heat treatment is identical.
- As-built surface roughness demonstrated the potential to affect the ballistic limit of an AM armor product against the 0.30-cal. FSP threat.

This report seeks to establish the starting considerations for future work in AM armor systems as is relevant to ground-vehicle systems. The barriers to implementation of AM armor on ground-vehicle systems are as follows:

- Lack of effective codes and standards.
- Lack of a body of engineering design data for common AM materials of interest for armor.
- Lack of defined technical data package requirements for AM parts (model-based definitions or drawing-based definitions).

This report makes the following recommendations to speed the implementation of this technology on ground-vehicle systems:

- Conduct additional studies to confirm the results in this preliminary work for a defined material system to validate their accuracy.
- A general approach for the characterization and qualification of AM armor products should be established to include potential relevant variables that effect armor performance.
- Given the extreme cost of AM products, ground-vehicle system OEMs and CCDC laboratories should collaborate on targeted development of alloys of interest early on in the material-development cycle.
- Multi-entity procurement and characterization activities may be necessary to effectively survey AM armor products to ensure that established codes and standards are effectively procurable.

The results of this series of experiments have shown that a large body of work is still needed to codify typical and minimum performance values for AM armor products and that if AM is to be adopted on an appreciable scale for ground-vehicle systems, publically available research data is required.

6. References

[1] D. R. Kunkel, ""I Will Rise Again": The Life and Legacy of the U.S.S. Monitor," *Armstrong Undergraduate Journal of History,* vol. 8, no. 1, pp. 55-63, 2018.

[2] S. C. H. L. D. S. I.G. Crough, "Armour Steels," in *The Science of Armour Materials*, I. Crouch, Ed., Cambridge, Woodhead Publishing, 2017, pp. 24-27.

[3] R. Ogorkiewicz and J. Willis, "The historical development of alumihum armour for fighting vehicles," in *The military uses of aluminum*, Brimingham, Alcan Booth Sheet Limited, 1973, pp. 39-43.

[4] J. Brewer, "Design consideration on the use of aluminum in AFVs," in *The military uses of aluminum*, Birmingham, Alcan Booth Sheet Limited, 1973, pp. 45-50.

[5] J. Hernandez, "A Comparative Analysis of Options fo Preserving the Tank Industrial Base," Naval Postgraduate School, Monterey, 1993.

[6] J. R. Pickens, "Low-Cost Titanium for Ships and Tanks," Concurrent Technology Corporation, Johnstown, 2004.

[7] C. H. Kelvin Yap, "The Impact of Armor on the Design, Utilization and Survivability of Ground Vehicles: The History of Armor Development and Use," Naval Postgraduate School, Monterey, 2012.

[8] P. Hazell, Armour: Materials, Theory and Design, Boca Raton: CRC Press, 2016.

[9] M. Bolotsky, "Historical Review of the Correlation of Ballistic and Metallurgical Characteristics of Domestic Armor at Waterford Arsenal," Defense Technology Information Center, Watertown, 1945.

[10] S. Cimpoeru, "The Mechanical Metallurgy of Armour Steels," Defense Technology Information Center, 2016.

[11] J. Hess, "Study in Welding High Strength Aluminum Alloys and Study of Effect of Alloy Compositions and Temper as Well as Ingot Quality and Plate Quality on the Weldability, Mechanical, and Ballistic Properties of Medium and High Strength Aluminum Base Armor," Kaiser Aluminum, 1961.

[12] J. L. Sliney, "Status and Potential of Titanium Armor," in *Proceedings on the Metallurgical Advisory Committee on Rolled Armor held at the U.S. Army Materials Research Agency, Watertown, MA 21720 Jan 1964*, Watertown, 1964.

[13] Oak Ridge National Laboratory, "Functionally and Geometrically Ordered Ti Armor," Oak Ridge National Laboratory, Oak Ridge.

[14] M. Kristoffersen, M. Costas, T. Koenis, V. Brotan, C. O. Paulsen and T. Borvik, "On the ballistic perforation resistance of additive manufactured AlSi10Mg aluminum plates," *International Journal of Impact Engineering,* vol. 137, 2020.

[15] W. M. Tucho, P. Cuvillier, A. Sjolyst-Kverneland and V. Hansen, "Microstructure and hardness studies of Inconel 718 manufactured by selective laser melting before and after solution heat treatment," *Materials Science & Engineering A,* vol. 689, pp. 220-232, 2017.

[16] E. Chlebus, K. Gruber, B. Kuznicka, J. Kurzac and T. Kurzynowski, "Effect of heat treatment on microstructure and mechanical properties of Inconel 718 processed by selective laser melting," *Materials Science & Engineering A,* vol. 639, pp. 647-655, 2015.

[17] K. Ozsoy, B. Duman and D. Ickale Gultekin, "Metal Part Production with Additive Manufacturing for Aerospace and Defense Industry," *International Journal of Technological Sciences,* vol. 11, no. 3, pp. 201-210, 2019.

[18] A. Gisario, M. Kazarian, F. Martina and M. Mehrpouya, "Metal Additive Manufacturing in the Commerical Aviation Industry: A review," *Journal of Manufacturing Systems,* vol. 53, pp. 124-149, 2019.

[19] J. Allen, "An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts," in *Cost Effective Manufacture via Net-Shape Processing*, Neuilly-sur-Seine, 2006.

[20] Committee on Benchmarking the Technology and Application of Lightweighting; National Research Council, "Application of Lightweighting Technology to Military Vehicles, Vessels, and Aircraft," National Academies Press, Washington, 2012.

[21] R. Gerth and R. Howell, "What is a Ton of Weight Worth? A Discussion of Military Ground Systems Weight Considerations," SAE International, 2017.

[22] J. Drushal, "Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030," U.S. Army War College Fellowship, Philidelphia, 2013.

[23] R. W. Appleton, "Additive Manufacturing Overview for the United States Marine Corps," RW Appleton & Company, Inc., 2014.

[24] D. L. Bourell, J. J. Beaman and T. Wohlers, "History of Additive Manufacturing," in *ASM Handbook Additive Manufacturing Processes*, vol. 24, Materials Park, ASM International, 2020, pp. 11-18.

[25] J. Deters, "3D-printing impacts on systems engineering in defense industry," in *Additive Manufacturing Handbook: Product Development for the Defense Industry*, Boca Raton, CRC Press, 2017, pp. 49-56.

[26] D. S. Thomas and S. W. Gilbert, "Cost and Cost Effectiveness of Additive Manufacturing A Literature Review and Discussion," National Institute of Standards and Technology, 2014.

[27] I. Crouch, "The future of armour materials," in *The Science of Armour Materials*, Cambridge, Woodhead Publishing, 2017, pp. 675-692.