Additive Manufacturing Technology Readiness Questions

Additive Manufacturing (AM) combines information technology, advanced sensors and deposition equipment to build 3D components. For metallic AM, two approaches are dominant, powder bed fusion (PBF) and direct energy deposition (DED). PBF has the advantage of fine detail and complex geometries but is limited in size and speed. DED is capable of producing large complex components but typically would need subtractive finishing to meet the surface finish and final dimensions. AM has been considered as a possible supplement or replacement for castings and forgings to allow for a more robust and flexible supply chain. AM is an exciting technology that holds the promise in many applications and environments to provide unique and innovative solutions to part creation. A request has been made for input on the potential of AM for large scale components in particular:

1. an assessment of the "technology readiness of AM as a whole" – both metal and non-metal AM – <u>in general and specifically for C&F needs</u>– for use in:
    a. the broader defense industrial base
    b. by depots and forces in garrison
    c. in expeditionary situations (forward deployed and afloat forces)
2. include concepts related to manufacturing readiness (including enabling capabilities like machine and process qualification, capitalization, provision of power, logistics for materials and machines, product inspection capabilities, data communications infrastructure and cybersecurity, workforce, etc.)
3. Provide recommendations to close technology and other gaps

As suppliers of metal castings and forgings for DoD requirements, this document will not assess non-metal AM and will seek to provide a background and framework to understand the use and limits and future opportunities for AM in complex and high-performance roles traditionally served by castings and forgings.

Casting and forging producers have relied on welding additive processes not only to join metal sections together but also to add metal to create features and meet quality and dimensional requirements. Arc welding for engineering components has been used for fabrication and additive since after World War I. AM DED is essentially automated welding to create the shape of the part. Because of this context, AM DED has the benefit of a rich understanding of the properties and processes used but also must grapple with the limitations and qualification hurdles well known from welding.

One useful framework for considering the suitability of the use of AM in DoD applications was developed, if I remember correctly, by the Marines. Their proposed structure for approval and use of AM was to create 3 categories of application and approval. The first was for applications where the risk of failure was trivial. These are applications where failure of an AM part might be costly or frustrating, but the failure would not compromise the mission or degrade unit performance. A second was for applications that were not life critical and not intended to become routine but were approved by the unit commander to facilitate the mission. In these circumstances, failure could be consequential, but the commander already bore the responsibility for the risks and performance of the mission. The most restrictive applications were when the failure of the AM component would result in risk to life and endanger others.

If the categories included in the request are framed in these modes:

1.a. - the broader defense industrial base: Applications of AM in the broader defense industrial base includes both the first, trivial- not necessarily unimportant where failure is not costly enough to prevent ordinary judgements as to making and using AM parts rather than wait for replacements or to fabricate, cast or forge new components. It also includes the third where the AM part is intended to replace a flight critical or sub-safe part and must meet all the requirements and qualifications of any new process and component in this type of application.

1.c. - in expeditionary situations (forward deployed and afloat forces): Applications in expeditionary situations would need guidance and leadership judgement for which criteria was applicable for each case. As deployed forces, the commander needs the ability to make informed and responsible judgements in the use of AM to meet his unit's needs and maintain and enhance their capabilities. The commander has the responsibility for the troops under command and for the performance of the mission.

1.b. - by depots and forces in garrison: Applications by depots and forces in garrison would be a mix of AM parts that were not critical but would facilitate the operation of the depots or applications like those in expeditionary situations where the commander would have some discretion as to the risks and benefits of using AM parts to enhance capability.

These categories depend heavily on the question 2, concerning manufacturing readiness , qualification, etc. It may be helpful to distinguish between the AM production of smaller complex parts using PBF and the production of large-scale components using DED.

The development and transition of smaller scale components from PBF production is being managed with the ordinary methods and procedures applicable to any new process or existing process modification. AM PBF is a mix of the issues of investment castings and powder metallurgy processing. Aerospace components are typically transitioned in system tests as individual components. Land and naval components can be qualified generically based on standard process and inspection requirements. AM as a newer process has been working the problem of uniformity of machines and feedstocks with variability of production part performance to become an acceptable alternative process to current production methods. For many materials, the transition is readily achieved. For example components made from 316L, a common PBF alloy, the low strength and high ductility and toughness makes the risk of failure low if the AM PBF component meets all the other criteria for the part.

It is useful to distinguish between metallic materials and their sensitivity to quality details on performance. Mechanical failures of metallic components are normally due to loads that exceed the capability of the materials. These failures can be categorized as ductile tearing, brittle cracking or fatigue. Metals that are high performance are often limited by their toughness, the resistance to cracking, rather than strength, the resistance to tearing.

AM components for aerospace applications, especially structural items are well advanced. Aerospace components are normally individually designed and qualified for their fitness for purpose. Each item needs to be tested and qualified by the PEO, PM and TWH for the application. These are not large-scale items typically and often the use of AM PBF techniques can make components large enough for service. One of the primary successes for aerospace is the use of AM to produce ceramic shells for casting complex items with detailed internal passages. This eliminates the challenge of polishing internal cooling passages after production. It also allows more tailored cooling to improve performance and reduce weight.

AM for casting and forging is one of the original commercial successes of AM. Castings in particular used AM from the beginning to produce pattens for prototypes or limited production. Printed patterns for investment casting was an early success for toolless production.

Ground vehicle applications are also moving forward and are larger scale than aerospace typically. Ordinary structural and functional components from traditional alloys should be readily able to be qualified and produced through AM techniques. Developments on process control, feedstock quality, machine reproducibility, part quality and inspection should be compatible with other manufacturing techniques. One big opportunity for all AM applications is hybrid processing. Many AM parts need machining to meet tolerances and surface finish needs. They may also need heat treatment to get the desired properties. Hot-Isostatic Pressure (HIP) processing or local forging may be needed to gain the maximum properties in critical sections and best performance.

For protection applications, AM facilitates hybrid or layered and functionally graded materials for components. Developing affordable and capable AM techniques remains a challenge but holds real promise.

One of the key areas where large scale AM has been promoted is within the ship building community to alleviate the supply chain concerns about casting and forging producers.

Large scale products made as castings and forgings have difficult mechanical properties to meet routinely with the HY grades necessary for ship construction. AM certainly offers promise to eventually contribute to these applications but a significant amount of work and development will be necessary that will take years to qualify these processes.

Large scale steel components made as castings and forgings have been developed through the industrial evolutionary process as equipment has gotten bigger, materials and processes better, combat experience and equipment failures have identified additional requirements and concerns for these items. Much of the understanding needed is well developed for fabrication applications. AM DED methods are essentially automated welding techniques to produce large scale components. Gantry or robotic systems driven by IT solid models allows rapid and accurate production of large-scale shapes. Smaller scale test material has been shown to meet some of the requirements and shows promise to be able to facilitate production and supply

There is a host of historical concerns and technical requirements in T9074-BD-GIB-010.0300 Rev 2 for the steel products and T9074-BC-GIB-010/0200 for the welding process that frame the issues that would need to be addressed. These same challenges are also present in any critical applications for large-scale AM. Some of the challenges that will need to be resolved include:

1. First Article Approval
2. Composition/Feedstock for production
3. Process development to meet property requirements for heavy sections
4. Process/part/property verification through final testing
5. Component soundness and quality
6. Hydrogen
7. Compliance

These requirements for existing production processes are laid out in T9074-BD-GIB-010.0300 Rev 2 and a similar structure for AM would be necessary.

Fabrication is done by the shipbuilders to using filler materials from T9074-BC-GIB-010/0200 and procedures from T9074-AD-GIB-010/1688, MIL-STD-1689 or other fabrication documents. Weld repairs are regulated in T9074-BD-GIB-010.0300 Rev 2 for plates- A3.6.1, B3.6.1, F3.8.2,3.8.3, shapes- H3.5.2 , and castings- D3.11. When allowed the depth, area, inspection and welding process is limited. They are forbidden for billets for forging 3.6, allowed only when approved for forgings C3.10, E3.9.1.2 or for bars G3.11. Weld repairs are a form of AM DED and is strictly regulated in shipbuilding. AM DED will need to address concerns and requirements for both the base material components and the special concerns associated with welding.

First Article Approval

Large scale castings and forgings require first article approval prior to production. It would be necessary to develop standard requirements for first article approval for AM large scale components. First article inspection is required for all products in T9074-BD-GIB-010.0300 Rev 2. This approval requires a proposal for a detailed qualification plan that must be approved for the manufacturing process and testing, (3.1). All material covered by the specification must be made by the same process used for the first article, (3.2). Each lot of material provided requires a certificate of compliance including the revision of the Process Control Plan used and the date of most recent first article approval or certification, (4.1.6). The largest section size, thickness, to be qualified must be used for the first article testing. Enough material is required to be supplied to allow for explosion testing if needed, (4.3.1). The melting, casting, forming, and heat treatment procedures are required for the Process Control Plan, (4.3.2.1). It is also required to identify the procedures and processes for removal and testing of tensile specimens from forging prolongations or cast test blocks.

It is not clear how to integrate AM large scale components into these requirements. For example, the lot for composition is an ingot, ladle, etc. What would the lot be for chemical composition for AM? For forgings (Appendix C), two forgings are required that represent the largest thickness and representative complexity to demonstrate compliance, (C.4.3.1.1). Testing includes a prolongation the size of the largest cross-section of the forging and it must remain attached until after heat treatment, (C.4.3.1.2.1). Twelve un-welded forged plates are required for explosion testing, (C.4.3.1.3).

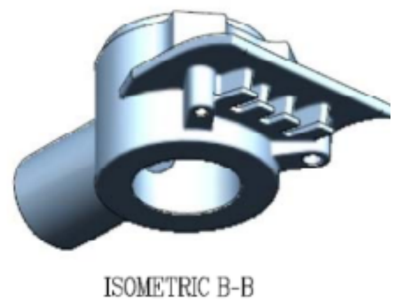

Figure 2 Example First Article for Qualifying Casting Producer for HY steels (Figure D-10)

Castings require similar requirements for first article qualification. All castings require either a prolongation or an attached test block for determining compliance. This material must be the size equivalent to the casting thickness or cross-section to be qualified. (D.4.1.2). To ensure that a casting of suitable complexity is selected, a sample first article casting design is included in the requirements, (Figure D-10).

Some of these qualification requirements are also of concern for other services. For Army armor in MIL-A-11356F, castings require first article testing and testing of the first production casting for other designs, (3.1). New suppliers for castings for MIL-A-11356F need to collaborate with Army officials to get approval for their procedure and process for qualification. These castings, like for the Navy, require a menu of non-destructive testing (NDT) to qualify the first article, first production casting and ordinary lots of production. Test bars need to be consistent with the thickness of the part and attached to the casting, (4.6.2.2). Weld procedures for casting production is also specified, (Appendix B-10.1).

It is not clear how these type of qualification requirements can be modified to accommodate qualifying AM for these critical roles with a first article test.

Composition and Feedstock

One of the characteristics of large-scale steel components made as forgings and castings is that the material is melted in traditional equipment and the processes of casting and forming are understood. Testing has evolved to ensure that the composition and properties are uniform enough and as expected to provide reliable service. Thick section components face increasing challenges to make the desired properties due to segregation and limits on heat treatment. AM DED to produce large scale steel components for critical service is a relatively new approach.

For AM DED processing, the production of the component uses a welding like method to add the metal to make the part. Current production methods use welding to fabricate and repair welding to add metal to plates, castings and with approval to forgings. These weld practices and required inspection and properties, including approved filler materials and pre-heat and subsequent heat treatments. These weld practices do not necessarily or regularly use compositions the same as the base metal and the weld properties may also be different. Some of the initial large scale AM DED trials have used the weld requirements to test the AM test blocks, but this is not the same as the requirements for large scale castings or forgings.

One challenge will be to get uniform filler material when large volumes are required. When the higher than HY-100 materials were being developed, millions of dollars were spent to qualify the material over a decade. The plate and other materials were shown to be adequate and the weld procedures suitable. When initial rate production was attempted, the weld fillers varied too much to get reproducible results. This was attributed to segregation in the ingot cast to draw out into the wire required. While current tests on small scale AM DED may show satisfactory results, it may be difficult to get large quantities of filler/feedstock alloy to make large scale AM parts with repeatable properties and quality. No existing supply of alloy wire tailored to AM DED part production exists. It is not clear either if alloy modifications may be required for AM DED large scale components to be repeatably produced for critical applications.

Process development to meet property requirements for heavy sections

The ability to transition large scale AM components into metallic components will be dependent on the type of material needed for performance. A useful way to characterize metals for their performance and requirements is to relate the resistance to cracking, fracture toughness (K1c), to the ability to resist tearing, strength (YS). The ratio of toughness to strength squared ((K1c/YS)^2) is a measure of how vulnerable the alloy is to cracking. This ratio is a length that is the size of the plastic zone. This length determines how big a defect can be tolerated without cracking and how thick a component can be before cracking is a concern. These properties for common alloys are shown in Figure 3. On this graph, the lines with inch markings designate the ratio of toughness and strength, ((K1c/YS)^2). For a typical example of a flaw in a section, the propensity of cracking is 2.5 times the ratio in Figure 3 and the smallest critical flaw is the ratio divided by 1.6.

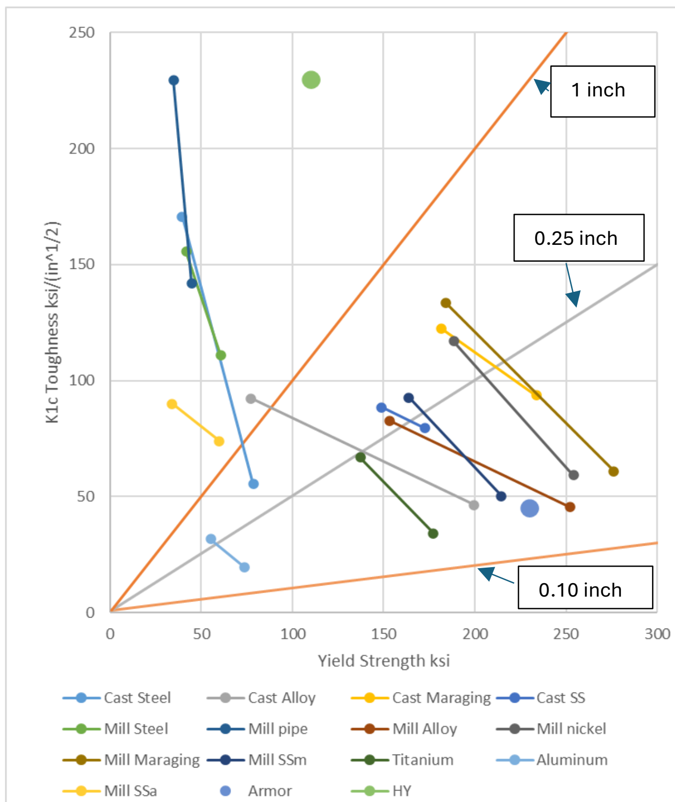

Figure 3 Common Metal alloys yield strength and fracture toughness

For common commercial grades of steels, cracking is not much a concern since the toughness and strength are evenly matched, close to a ratio of 1 inch. For higher performance where strength is the dominant need like in armor, the toughness is the limit for performance where the critical defect size determines the performance. Typical armor steel properties are shown in the big blue dot on the lower right. For other applications like naval vessels, toughness is the critical need and strength levels are limited to these high toughness alloys. This is shown for the naval HY grade by the green dot in the upper section of the graph.

Heavy sections poise more challenges because they begin with material that is cast in thicker sections giving larger areas and sizes of porosity and segregation, heat treatment is limited in heating and cooling rates by thermal conductivity, inspection through the section is more difficult to assure soundness, properties vary in all products but variation is more in thick sections, and thick sections with complex geometries have more constraint, making materials more prone to cracking rather than tearing. Forging and rolling reduces and allows re-crystallization that improve properties for these thick sections. Hot Iso-static Pressing (HIP) also improve properties by reducing segregation from the longer-term higher heat cycle than traditional heat treatment and reduces porosity. Steel products receive a final heat treatment especially in large scale components to get the required properties.

It can be seen that for the high-performance steels and other alloys, quality and toughness are fundamental limits. These limits are a material property and not application specific. Little is known about the toughness and durability of AM DED parts. Small scale parts made in PBF or alloys like martensitic stainless steels and AF96 show promise in meeting the strength requirements but are limited in ductility.

Common requirements for various product forms used for critical structures in ships are shown in Table 1. This shows the yield strength, and elongation required for these product forms. As can be seen, the properties are similar but vary depending on the product form. The place and testing of these alloys for qualification of a casting, forging or lot of mill product varies. For product forms the requirements often depend on section thickness, position and orientation. For castings, tests for large scale heavier sections are required from the center of the section, T/2 and from the interior and also deeper at T/4. For forgings and rolled mill shapes, requirements vary with orientation, longitudinal or transverse and thickness. In Table 1, a selection of the thickest sections was taken to allow comparisons to the large-scale products.

A limited range of less than 20 ksi for the strength is allowed throughout most products for HY-80 restricting the maximum to less than 100 ksi. The exceptions are shapes and welds. A tighter range of 15 ksi is required for some HY-100 products but many of the products are allowed a 20 ksi range. These are tight ranges, commercial standard which give a limited range limit the ultimate strength to a 25 ksi range. Welds are allowed to have the highest strengths.

Table 1 Comparison of Requirements for Tensile Properties of HY products and Welds

Product	Grade	Thickness	YS ksi	EL%	RA%
Plate	HY-80	> 0.75 inch	80-99.5	20	50
Bars	HY-80	Longitudinal	80-99.5	20	55
Shapes	HY-80	Longitudinal	80-110	20	60
Forging	HY-80	Longitudinal	80-99.5	20	55
Forging	HY-80	Transverse	80-99.5	18	50
Casting	HY-80	6 < T≤ 10 inch @ T/2	78-99.5	18	50
Casting	HY-80	T> 10 inch @ T/2	76-99.5	14	50
Welds	MIL-10018-M1	As Welded	82-110	20	
Welds	MIL-10718-M	As Welded	88-122	20	
Plate	HY-100	> 0.75 inch	100-120	18	45
Bars	HY-100	Longitudinal	100-115	18	50
Shapes	HY-100	Longitudinal	100-120	18	55
Forging	HY-100	Longitudinal	100-115	18	50
Forging	HY-100	Transverse	100-115	16	45
Casting	HY-100	6 < T≤ 10 inch @ T/2	98-120	15	50
Casting	HY-100	T> 10 inch @ T/2	93-120	12	45
Welds	MIL-12018-M2	As Welded	102-123	18	

For these grades, toughness is the primary concern. A similar comparison is given in Table 2. Listed are the minimum average Charpy V-Notch (CVN) test requirements along with the test temperature. Also given is the dynamic tear test (DT) that gives a more meaningful measure of toughness for these steels. In this case, the only factor to determine the level is product thickness, no orientation. In HY-80, plates from 6 to 8 inches and forgings over 8 inches require 30 ft-lb minimum when testing at -120^{0}F. Castings over 6 inches require 50 ft-lb at -100^{0}F and over 10 inches at the center 30 ft-lb at -100^{0}F. Welds have to lowest requirements of 35 ft-lb at -60^{0}F as welded and 20 ft-lb at -60^{0}F for stress relieved welds

As similar trend is seen in the requirements for HY-100 products. For plates of 6 to 8 inches and forgings over 8 inches, the minimum CVN required is 35 ft-lb at -120^{0}F. For castings over 6 inches, the CVN minimum is 50 ft-lb at -100^{0}F and for over 10 inches 30 ft-lb at -100^{0}F. The one weld material in the standard requires 45 ft-lb at -60^{0}F.

Current weld standard CVN requirements for HY alloys are below the large-scale product form requirements for castings and forgings. All products are required to report a DT test

Table 2 Comparison of Requirements for Toughness of HY Products and Welds

to evaluate the toughness of the material supplied. For HY-100 products with a minimum requirement, the requirements run from 450 to 500 ft-lb tested at -40^{0}F while the welds are tested at -20^{0}F and required to have a minimum of 400 ft-lb.

Product	Grade	Thickness	CVN min ft-lb/Temp °F	CVN min ft-lb/Temp °F	DT min ft-lb/Temp °F
Plate	HY-80	6 to 8 inch	60 @ 0	30 @ -120	450 @ -40
Bar	HY-80	Longitudinal	70 @ 0	50 @ -120	N/A
Shapes	HY-80	over 2 inch	80 @ 0	60 @ -120	N/A
Forging	HY-80	0.50 to 8 inch	60 @ 0	50 @ -120	450 @ -40
Forging	HY-80	over 8 inch	60 @ 0	30 @ -120	400 @ -40
Casting	HY-80	6 < T≤ 10 inch @ T/2	70 @ 0	50 @ -100	Reported
Casting	HY-80	T> 10 inch @ T/2	50 @ 0	30 @ -100	Reported
Welds	MIL-10018-M1	As Welded	60 @ 0	35 @ -60	300 @ -20
Welds	MIL-10718-M	As Welded	60 @ 0	35 @ -60	300 @ -20
Welds	MIL-10018-M1	stress relieved	50 @ 0	20 @ -60	
Welds	MIL-10718-M	stress relieved	50 @ 0	20 @ -60	
Plate	HY-100	4 to 6 inch	60 @ 0	35 @ -120	500 @ -40
Bars	HY-100	Longitudinal	70 @ 0	50 @ -120	N/A
Shapes	HY-100	over 2 inch	80 @ 0	60 @ -120	N/A
Forging	HY-100	0.5 to 6 inch	60 @ 0	50 @ -120	500 @ -40
Forging	HY-100	over 6 inch	60 @ 0	35 @ -120	450 @ -40
Casting	HY-100	6 < T≤ 10 inch @ T/2	70 @ 0	50 @ -100	Reported
Casting	HY-100	T> 10 inch @ T/2	50 @ 0	30 @ -100	Reported
Welds	120S		60 @ 0	45 @ -60	400 @ -20

There are weld procedures and filler materials qualified for HY-80 and HY-100, but for higher strength grades like armor, undermatched weld fillers are common. This does not often limit performance as long as the ultimate strength of the weld exceeds the yield strength of the base material. The constraint of the weld joint limits deformation and the load on the weld is mitigated by the base material yielding prior to the weld experiencing failure.

The limits embedded in the welding requirements for armor and HY navy steels makes it unclear as to how AM DED for large scale components can be qualified and routinely tested. Will testing require three or more orientations? How will test blocks produced by AM DED be made, processed with the part, tested? Will AM DED large scale components be made in the same material alloy grades? How will AM affect the properties, variability, local quality, reliability?

Are AM DED large scale components to be heat treated? How will this process be managed and controlled?

These questions are being actively investigated and are likely to be resolved but this will take time, cost money, and require demonstrations of capability.

Process/part/property verification through final testing

A major cost and requirement for large scale mission critical components is verification through inspection and final testing. Steel casting producers are required to make test blocks to experience the full range of process steps to verify that the final component has the expected properties. Rigorous NDT inspection is needed to ensure performance. Forging producers design into their product, prolongations to be used to qualify the properties of the part. They also have difficult and exacting NDT requirements. The testing, acceptance standards and reliability of these components is due to the evolutionary process of designing ever larger and higher performance equipment with the advancing technology of the manufacturing process. Many of the requirements pay tribute to early failures.

AM DED for large scale components is different. Unlike the current products that begin as a cast ingot or casting that is processed to get the final component and has a single heat/ladle of steel that can be qualified as a material, AM DED is making the material and has a fundamentally different character, not starting as a single casting but produced as layers of molten pools that fuse with the underlying and adjacent beads. This has the advantage of a fine solidification microstructure that has no macro-segregation or quality details larger than the molten pool. Will heavy section AM test coupons be made? What orientations, locations and properties will be tested? What part mechanical testing will verify that properties are met? What properties for these components will be required?

Component soundness and quality

AM DED does not make a unitary part but constructs it additively. How does the purchaser look inside the material and ensure soundness and quality? Welding quality is done partially through inspection of the weld appearance but relies heavily on standard procedures and operator qualification. The process control for AM DED is similar to the procedure qualification for welds (PQR) and the weld procedure specification (WPS). These process control documents have a range of process parameter that require new qualification is exceeded. How will AM DED process parameters be specified? What is the action when the process varies from the specification during production? For critical welds, ultrasonic testing may be required to ensure a sound weld and fusion. Inspection needs to ensure that the sound material is fused together using not radiography but ultrasonics. How does the responsible purchaser and builder ensure that the AM part supplied will serve? What NDT methods and standard will be used to ensure product quality?

Hydrogen

High performance steels are sensitive to hydrogen pick up that reduces the capability of the steel. For most applications, care is taken in melting and welding to ensure that the properties meet the requirements. Armor steels are sensitive to hydrogen cracking in the base material and welds. For HY materials, a hydrogen soak is used to reduce hydrogen to low levels to ensure reliable service. For plates over 3 inches, a post hot rolling soak is specified, (A.3.5.1, B.3.5.1). Castings require a long hydrogen diffusion anneal, (D.3.7 g). Low hydrogen procedures are required when welding HY materials. Post-weld heat treatments may require a heat soak to prevent cracking in welds. The control and mitigation of hydrogen damage and limits on alloy performance needs to be addressed by AM DED for large scale equipment. While in development facilities, careful control and premium material can be used to ensure control, how will large scale AM DED facilities operate to control hydrogen? As a weld like process, how will the process be managed to ensure low hydrogen conditions during production? How will low hydrogen contents for performance be assured? In castings, the T/2 tensile tests, especially the reduction in area, is used to screen for hydrogen contamination.

Compliance

The most significant complaint and challenge for casting and forging suppliers to meet the DoD requirements in a timely and responsive way is the inability for the supplier to get the order with the proper lead time, the challenge of approvals from the OEM and DOD for routine first article, first production run, NDT qualification, weld approvals, etc. It is hard to see how this challenge will be mitigated or reduced by a new tier of suppliers who are less familiar with the products and procedures.

Closing Gaps

AM for large scale components is being attempted with demonstration projects. This approach seems suitable to determine what performance and production challenges are present in the AM process. It would seem prudent to begin to address all of the qualifications required by alternative methods of production. Some of the fundamental questions that are open:

1. Feedstock- If the quality, availability and performance compatible parts with current methods?
2. Material properties- What is the strength, toughness, ductility for heavy sections and in different orientations on large scale AM builds using quantity feedstocks?
3. Process qualification- Can the process be qualified for parts with first articles to demonstrate the ability to meet material properties in heavy sections? What first production item tests will be needed? What product variations from requirements will be allowed?

4. Process control- What measures of process control will be required and how will they be measured and documents? What options are there for variations from the control ranges?
5. Part qualification- What tests and test material will be required for part qualification? What re-tests or added re-processing like re-heat treat will be permitted?
6. Fabrication Compatibility- Will these parts respond similarly to traditional items in welding into larger structures and maintain the needed performance?
7. Inspection- What NDT and other inspection tools will be required? What will the inspection specification levels be required for parts made with AM?
8. Legacy issues- The specifications and requirements for castings and forgings are dated and burdensome without providing direct assurance of reliable performance. Revising or adding options to the requirements would be a major step to improve the supply of needed components.

There is undoubtedly a large effort beyond what is published or widely known addressing these issues. The effort to begin by qualifying selected large scale AM DED parts for targeted applications seems a reasonable way to explore what further issues need addressed and how to answer these questions.

Conclusions

Additive Manufacturing for large scale components will find a niche that will provide high value to DoD. Some products currently produced by casting and forging suppliers will be better procured from AM. The challenge though is that many of these components will remain with the traditional processes due to their reliability and efficient service. The casting and forging industry has confronted and resolved the challenges that have led to the current designs and production methods. While innovation and change is essential to success, they are not limited to AM but reside as well in casting and forging.

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[i] AMPOWER Insights, Vol 12., “Additive Manufacturing- Part Cost and Pricing, August 2023