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Advanced manufacturing—A transformative enabling capability for fusion

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ABSTRACT

Additive Manufacturing (AM) can create novel and complex engineered material structures. Features such as controlled porosity, micro-fibers and/or nano-particles, transitions in materials and integral robust coatings can be important in developing solutions for fusion subcomponents. A realistic understanding of this capability would be particularly valuable in identifying development paths. Major concerns for using AM processes with lasers or electron beams that melt powder to make refractory parts are the power required and residual stresses arising in fabrication. A related issue is the required combination of lasers or e-beams to continue heating of deposited material (to reduce stresses) and to deposit new material at a reasonable built rate while providing adequate surface finish and resolution for meso-scale features. Some Direct Write processes that can make suitable preforms and be cured to an acceptable density may offer another approach for PFCs.

1. Introduction to advanced manufacturing

Additive Manufacturing (AM) makes parts from 3-D models typically in layer-by-layer "builds." Some 3-D Printing processes use lasers or electron beams (e-beams) to melt each layer deposited on the build platform. Direct Write processes, not included in an earlier paper [1], are less widely known. One approach in Direct Write deposits a thick slurry (ink) to build a fragile "green" preform that can be machined easily and cured later to gain its finished properties. We use a broader term here Advanced Manufacturing (AM+) to include AM, Direct Write, spark sintering, etc., multiple steps, subtractive manufacturing (machining) and infiltration with liquids or vapors.

The applications of interest here are thick parts that lie within a fusion chamber. We exclude AM processes that make thin layers only, as for electronics applications, although robust integral coatings, e.g., tungsten (W) on ferritic steel, may be of interest. Among the attractive features of AM+ for fusion applications are its flexibility to produce complex shapes, enclosed void space (e.g., coolant channels), novel materials and joint-less transitions from one material to another. Some areas of interest are (1) how novel structures can improve and simplify the way we would build fusion in-vessel components and (2) which approaches (e.g., fabrication of refractories without melting) may mitigate issues such as distortion, residual stresses and crack formation in large structures.

Refs [2–18] are high level overviews. Ref [5] describes many types of projects and the investment and organizations needed. Nickels's brief overview [13] includes a diagram of industrial scale AM processes and lists companies doing metal additive manufacturing as of 2016. Refs [14,15] describes Direct Write technologies, and Ref [10] notes the use of Direct Write with multiple inkjet heads for bio-applications. Refs [16–18] review 3D printing of hierarchical and novel materials, and Ref [18] compares the processes giving characteristics and figures of merit. A few additional references are provided as examples to give details on materials, processes, modeling, underlying science, work on high temperature alloys and related issues, e.g., power required and residual stresses [19–27].

2. Application of AM+ and future development

We will undoubtedly use AM+ in fusion. Its broad applicability is

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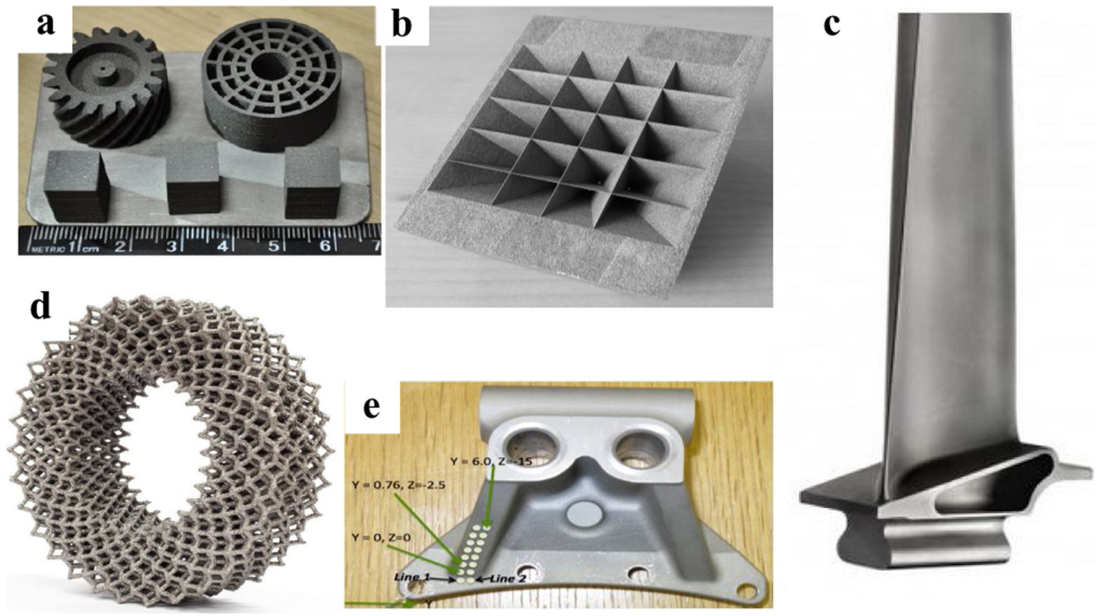

Fig. 1. Some AM metal products, *processes noted below.*
a. TiC-Ferritic-Martensitic Steel preforms, *binder jet* [28]
b. W Multi-pinhole collimator, *Selective Laser Melting* [29]
c. Ti turbine blade, *e-beam* [30]
d. W complex shape, *e-beam* [31]
e. Inc 718 engine mount, *Direct Metal Laser Sintering* [32]

transforming manufacturing worldwide and enabling new products [2–9], is becoming increasingly established due to its economics, and will permeate energy industries and nearly all others. The transformation is evident in aerospace, electronics, bioengineering and medicine.

AM is being applied to many high-value components in industry and is of interest in nearly all major research institutions. Fig. 1 shows AM parts with complex configurations. For example, General Electric is a major player. Their GE Aviation Business Avio Aero in Italy uses production equipment from the GE Additive Business Arcam in Sweden to make jet engines. Ref. [30] includes web links that show the production of the AM engine parts. Fig. 2 shows parts with internal cooling channels made for a fusion divertor application.

The capability to predict process-structure-property relationships of the builds is still in its infancy. This predictive capability is important as one considers how a successful research path for fusion would (a) initially confirm promising approaches for using AM+ to make fusion sub-components, and then (b) develop mature approaches in later phases.

2.1. Base for a path forward

Let us briefly examine visions of past fusion reactor designs and of some future technology development. Until about a decade ago, the US led the world in design studies, with extensive foreign participation. ReNeW [34] notes this legacy of still widely-used data on nuclear fusion technology and plasma-surface interactions. For a future D/T device, we will have what experience in physics and technology we retain from ITER and then after ITER. Useful interim targets are the US's FNSF or Fusion Nuclear Science Facility [35] and the Chinese Fusion Engineering Test Reactor or CFETR [36]; the latter has a more mature design. These are future D/T devices that can test fusion nuclear systems with high availability and have most of the challenges of the first fusion reactor. AM+ and other transformative technologies will shape how we make such devices.

2.2. AM+ applications for a D/T fusion chamber

Inside a fusion vessel, all parts capture neutrons and are heat sinks. Most have complex shapes and are likely applications for AM+ to simplify manufacturing and enable designs with complex cooling paths that improve performance.

Fusion plasma facing components (PFCs) are a special case. Overall, they receive ~20% of the fusion power and must survive under intense heat and particle loads from the plasma. Issues of concern for PFCs include 1) mitigating brittleness, 2) preempting deleterious effects from helium as the microstructure of tungsten-based materials evolve, and 3) neutron-induced transmutations in tungsten that lower its thermal conductivity and mechanical integrity. Other more general concerns for subcomponents in a fusion chamber are 4) achieving high efficiency heat transfer to the coolant, and 5) mitigating tritium retention and permeation into the coolant

Features that may be useful for PFCs and that AM+ can be easily provide include: controlled porosity, functionally graded materials and complex cooling channels. Enabling designs with a fine array of cooling jets for PFCs is one example. Another is controlled porosity or other nano-features (micro-fibers and/or nano-particles) in the region of material close to the plasma-facing surface. Such features might increase recombination and recycling of D/T or mitigate crack growth into the deeper structure (an identified concern for W-based PFCs). Features that can collect He and transmutation products and limit tritium trapping, as well as graded compositions and transitions in materials may be important in developing PFC solutions and their development paths.

In some fusion development paths, designs for a D/T device beyond ITER extrapolate from ITER's water-cooled stainless steel PFCs as the next logical step. In other paths, W is the plasma-facing material (PFM) in the divertor, the first wall is an advanced ferritic-martensitic steel, and both are cooled with helium.

In the tritium breeding blankets, most programs give solid breeders a higher priority for R&D than liquid breeders (e.g., Li or Li-Pb). Solid breeders are typically ceramics with relatively poor thermal

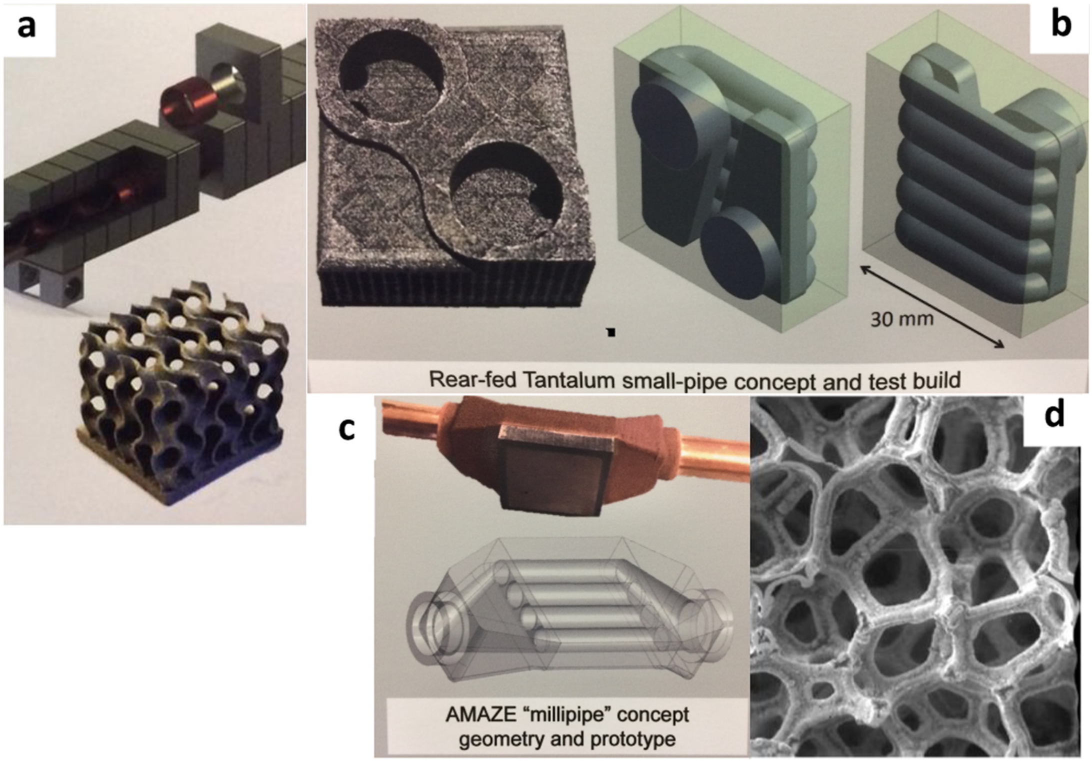

Fig. 2. (a–c) AM parts for fusion, Hancock et al. U-Sheffield & CCFE [33], d) Mo ligament structure formed in CVD.

conductivity arranged in pebble beds.

AM+ offers the possibility to make open porous structures that could offer much improved performance for tritium breeding blankets and eliminate issues such as compaction in pebble beds. Also, with a radially-graded structure, adjusting the breeder fraction and the cooling to the gradients in nuclear heating and tritium production would be possible. A standard pebble bed design would require additional structure to make separate zones.

Youchison has worked in developing open porous structures (Fig. 2d) and has modeled details of the flow and heat transfer. [37] He has also worked with US companies in fabricating such open celled structures with ceramics.

Manifolds and shielding are also potential AM+ applications. Serpentine cooling passages, called freeform geometries by Thompson et al. [18], could replace arrays of straight main and cross channels fabricated by gun-drilling and plugging. Fig. 2 has examples of structures relevant for fusion chamber parts.

Other fusion applications likely to benefit from the flexibility of approaches with AM+ are load pads, as for example with magnets and cryogenic systems. The load pads must remain robust under high mechanical loads while also providing thermal or electrical isolation or both. AM+ provides the advantage of easily formed materials transitions that couple layers that provide low thermal or electrical conductance with those that can be stiff and robust or designed with a specified compliance.

Another possible revision in how AM manufacturing might alter fusion designs is by re-envisioning large parts design to be collections of smaller unit cells. In-vessel components for fusion have odd shapes. Let us suppose such shapes can be aggregates of many similar unit cells with other special shaped cells added to complete the overall configuration needed. Potential benefits would be a more flexible design approach, a reduced volume of special shapes needed, and a reduction in the volume of the standing inventory of replacement parts.

2.3. Some concerns for AM+ in fusion

AM+'s flexibility and agile approaches enable materials systems and engineered architecture that cannot be made in other ways. AM+ may give better performance at lower cost for some fusion applications. However, AM is rife with mega-hype and overblown promises. Many would-be users view AM as a silver bullet to fix all. However, AM experts can easily determine where AM is useful.

Among the concerns with AM of refractory parts are the power required (high melting temperatures) and the residual stresses for the processes that require melting, e.g., with (laser-based) LENS-type AM systems and electron beam systems. A related issue is the number of simultaneously operating lasers or beams to do the following: a) continue heating the deposited material to reduce stresses, b) deposit material at a reasonable build rate, and c) provide adequate surface finish and adequate resolution for meso-scale features.

For a given AM process, control of the many variables to render a part of adequate quality with the features noted previously and do this reliably would require an extensive targeted R&D effort. Indeed, large investments in AM+ targeted for specific outcomes, as for aerospace, have produced new structures that are light, rigid, tough and manufactured quickly at low cost. Thompson et al. [18] reviews some of these factors quantitatively from the perspective of design for AM. Lee et al. [17] focuses on a comparison of methods for 3D printing of novel materials; and Singh's [38] perspective is materials issues.

3. Conclusions regarding a path forward

In the limited scope of this paper, we do not attempt to project how the needed R&D for fusion applications would be done, as this is premature. Rather we identify some elements to begin a useful study of the potential for AM applications in fusion. We emphasize again the need for a new vision of fusion. We need new studies with clever confinement solutions (e.g., Ref [39]) and up-to-date information to give us a better vision of fusion energy and the path for its development. A successful path will include attention to the practical aspects of fusion

Table 1
AM+ processes for several fusion applications.

Method	**DPT Tungsten Composite**[a] *Binder jet*	**Tungsten-steel composite FGM**[a] *Ultrasonic welding*	**Tungsten parts for HEMJ**[a] *Laser beam*
Estimated Current TRL	2	2–3	3
Advances required to achieve TRL6	Moderate investment to develop material and element or component. Fusion-relevant nuclear test facility.	Address welding feasibility (W to steel). Moderate investment to develop prototypic element. Nuclear test facility	Moderate investment to develop material and element or component. Nuclear test facility
Time to achieve goal for application	1 yr from TRL 2 to 3 2 yrs to TRL4 2 yrs to TRL5 Then nuclear test	1 yr from TRL 2 to 3 2 yrs to TRL4 2 yrs to TRL5 Then nuclear test	2 yrs to TRL3 to 4 2 yrs to TRL5 Then nuclear test
Available resources Leverage	US DOE labs and industry have significant facilities and personnel resources. Significant leverage expected.	US industry has appropriate facilities.	USDOE labs and industry have significant facilities and personnel resources. Significant leverage expected.
International and US status	Strong international activities in related area.	Key industrial partners in US industry.	Limited work in UK and US.

[a] DPT is ductile-phase toughened, FGM is functionally graded material, HEMJ is the helium cooled divertor with multiple jets.

engineering, such as how we integrate subsystems and clever ways to build them. The term “path forward” suggests a roadmap for AM in fusion. The authors believe this is premature for reasons stated later and offer the thoughts below on a path forward.

Since an earlier paper on AM in fusion [1], the US National Academy of Science (NAS) began a study on fusion burning plasmas. For this, the authors are recommending AM+ as an important transformative enabling capability for fusion and urging that this capability be engaged soon in the development of fusion. We propose that appropriate initiatives can be derived from the basic elements below.

1. Engage AM+ talent for the fusion program. Use this expertise to:

- Identify some R&D pathways for fusion-specific AM+ applications;

- Quantify the benefits for these applications;

- Continue the engagement to develop depth for fusion applications.

2. Identify R&D activities that produce interim products. For example, surrogate materials made with AM+ may be useful for benchmarking materials development and verifying CFD computations for cooling technology.

3. Establish a dialogue with international collaborators. For the US, useful topics could include US engagement in the development of fusion reactor concepts and access for experiments and testing in facilities outside the US (at labs, in industry and in fusion devices).

These elements overlap some with those in Singh’s recommendations [38], which come from a materials perspective that is much broader than fusion and include such elements as the development of industrial standards. Roca et al. provide an interesting perspective from the point of view of regulators and government decision-makers on metal additive manufacturing (MAM). [40] The review includes many international examples. More extensive remarks in Roca’s thesis [41] note the following in Section 3.1 Cross-country lessons for additive manufacturing and cite Ref. [42]: “China is approaching additive manufacturing in a focused and coordinated manner, … EU manufacturers dominate production of MAM fabrication equipment, the US leads in terms of MAMs application in designs and products … just over 40% of all industrial additive manufacturing systems are installed in the United States.”

Table 1 gives some examples of potential applications with materials of interest in fusion, subjective ratings of their Technical Readiness Levels (TRLs) and our assessments of US capability and that elsewhere. We offer this as an example and recommend that each country examine its own capabilities in AM+ and how these capabilities are being integrated into their program for fusion development.

Worldwide the activity in Additive Manufacturing is widespread. This may be an area of future collaborations in fusion. However, the approach to sharing information, and for creating a fusion AM roadmap, is also fraught with potential issues:

1) information is insufficient;
2) barriers for export control based for example on military applications pose constraints *(such barriers were the subject of private discussions by the lead author and EU researchers at the ISFNT13)*;
3) intellectual property rights likely restrict what information would be shared; and
4) institutions will likely not divulge strategic roadmaps.

Also, the scope of a general AM roadmap is huge, so such efforts typically pare the scope as was done in the America Makes roadmap [43]. Ref [44] comments on AM modeling. A recent book by Chua, Wong and Yeong [45] gives roadmaps for AM standards and measurement science. Qualification of high quality parts made with AM is increasingly perceived as a potential roadblock.

Each country or region may have similar general concerns but with differing ramifications that depend on the processes for development of commerce and for development of fusion, and hence, need a different roadmap. The main purpose of this paper is to prompt discussion among the leaders in fusion of how we (collectively) might proceed to uncover the potential of AM+ for fusion.

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