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Advanced Manufacturing – A Transformative Enabling Capability for Fusion

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Issues of concern for fusion plasma facing components (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 all gas-cooled PFCs are 4) achieving high efficiency heat transfer to the coolant, and 5) mitigating tritium retention and permeation into the coolant. Additive Manufacturing (AM) has the potential to create novel and complex engineered material structures. Controlled porosity micro-fibers and/or nano-particles that can collect He and transmutation products, limit tritium, and graded compositions and transitions in materials are all features can be important in developing PFC solutions. The capability to generate robust coatings is also of interest. This capability may be particularly valuable in development paths. Major concerns for using AM to manufacture refractory parts are the power required and residual stresses arising in fabrication. A related issue for LENS-type AM systems is the required combination of lasers to continue heating of deposited material (to reduce stresses) and deposit material at a reasonable built rate while providing adequate surface finish and resolution for meso-scale features. Direct Writing may offer capabilities better suited to PFCs.

Keywords: plasma facing components, first wall, divertor, tungsten, additive manufacturing, 3-D printing, direct writing

1. Introduction to Advanced Manufacturing

Additive manufacturing (AM) AM processes fall in two general categories. 3-D Printing makes 3-D parts directly from CAD models in layer-by-layer "builds" by melting with a laser or electron beam (e-beam) or deposition as with a plasma torch. Of interest here are thick parts rather than thin layers. Direct Write uses a thick slurry (ink) to build a rheologically stable but fragile "green" preform that can be machined easily and cured later to gain its finished properties. The term can also be a catch-all category for other processes such as robocasting of an "ink" stream from a nozzle and processes that use plasmas to induce self-assembly of nano-structures. Various AM processes create precursor structures that are treated or cured of have open volume filled with another material.

An earlier paper [1] proposed a new vision for fusion Plasma facing components (PFCs) but did not include Direct writing which, as noted later, may have the greatest potential for refractory PFCs. A recent overview of Direct Write [2] has extensive references.

Refs [2-8] give good high level overviews with differing perspectives. Ref [5] has the perspective of research management. The topics include examples of many sizes of projects, types of investment needed, and appropriate organizations to complete the work. Refs [9-28] have more detail on processes and modeling, the science underlying the materials and processes; several of these describe work on high temperature alloys and related issues, e.g., power required and residual stresses.

We use a broader term here Advanced Manufacturing (AM+) to include AM, Direct Write, spark sintering and other processes. Also included are multi-process steps such as subtractive manufacturing (machining) and infiltration with liquids or chemical vapor deposition. AM technology in general, especially Direct Writing, is in its infancy with regard to predicting the structure-property relationships of the builds. This capability is important as one considers how to develop a research path that would first indicate promise for using AM+ to make fusion sub-components, and mature in later phases.

ITER has made us aware of the extremely detailed understanding in the sciences and engineering, and the large sustained effort required to design and build a D/T machine. For the next D/T device, we will have what experience the US can retain from ITER plus post-ITER-design information in both physics and technology now and in future. A useful US interim target is FNSF or Fusion Nuclear Science Facility. (The Chinese Fusion Engineering Test Reactor or CFERT has a more mature design.) These are future D/T devices that can test fusion nuclear systems with high availability and most of the challenges of the first fusion reactor. AM+, and other transformative technologies, will shape how we make such devices.

2. Application of AM+ and Future Development

We will undoubtedly use AM+ in fusion. It will become increasingly established simply due to its economics and will permeate energy industries and nearly all others. Its broad applicability is transforming manufacturing all over

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the world and enabling new products and is being applied to many high-value components. The trend is evident in aerospace, electronics, bioengineering and medicine. AM is of interest in nearly all major research institutions. Let us briefly examine visions of past fusion reactor designs and of some future technology development.

The US, with extensive foreign participation, led the world in design studies until about a decade ago. The US study of fusion research needs, ReNeW [29], notes this legacy of a still widely-used body of information on issues in nuclear fusion technology and plasma-surface interactions or PSI. Now, however, pieces are missing or outdated.

We need new studies with clever confinement solutions, e.g., recent work by the team at the MIT's Plasma Fusion Science Center [30], 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 engineering, such as how we integrate subsystems and clever ways to build them.

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. In other cases, another dynamic can occur. As trials proceed, process innovations produce discoveries that lead in new directions. So, serendipity plays a role.

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. This may be an area of great potential collaboration in fusion. However, the approach to sharing information is also fraught with potential issues noted in Section 3.

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

Inside a fusion vessel, heat from captured neutrons makes all parts heat sinks. AM+ could simplify manufacturing and enable designs with complex cooling paths that improve performance. Most in-vessel parts are likely applications.

The focus in this paper is on plasma facing components (PFCs), which are a special case because they receive ~20% of the fusion power from the plasma and must survive under intense heat and particle loads. Features that may be useful and can be easily provided using AM+ 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 in the region of material close to the plasma-facing surface. This the might increase recombination and recycling of D/T or mitigate crack growth into the deeper structure. The latter is of particular concern for tungsten-based PFCs.

Solid breeders are typically ceramics with relatively poor thermal conductivity arranged in pebble beds. AM+ offers the possibility to make open porous structures that could offer much improved performance and eliminate issues such as compaction in a pebble beds. Also, a radially-graded structure would be possible to adjust the breeder fraction and cooling to the gradients in nuclear heating and tritium production. With a pebble bed, this would require additional structure to make separate zones.

Youchison has worked in developing open porous structures and has modeled the details of the flow and heat transfer. [31] He has also worked with US companies in fabricating such open celled structures with ceramics.

Table 1: AM+ processes for several fusion applications

	DPT Refractory Composite	Tungsten-steel composite FGM	Tungsten parts for:
Method	Binder jet	Ultrasonic welding	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	DOE labs and industry have significant facilities and personnel resources. Significant leverage expected.	US industry has appropriate facilities.	DOE 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.

Other applications are manifolds and shielding where continuous serpentine cooling passages could replace designs with straight main and cross channels based on the approach of gun-drilling and plugging for fabrication.

3. Conclusions Regarding a Path Forward

As part of the community input to the previously mentioned study on fusion burning plasmas being carried out by the US National Academy of Science, we have recommended AM+ as an important transformative enabling capability for fusion technology. We have urged that this capability be engaged soon in the development of fusion.

We propose that more specific initiatives can be derived from the basic elements below.

1. Engage AM+ talent for the fusion program. Use this expertise to:
   a) Identify some R&D pathways for fusion-specific AM+ applications;
   b) Quantify the benefits for these applications;
   c) 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 of cooling technology.
3. Establish a dialogue with international collaborators. For the US, useful topics cold 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).

Worldwide the activity in Additive Manufacturing is widespread. However, industry, laboratories and other organizations have processes for which they need to protect the intellectual property. This is likely to be an issue of concern in sharing of information in international collaborations. Moreover, in some countries including the US, concerns about the use of AM in developing parts for military applications will be an additional concern. These issues will likely be general concerns for each country but with differing ramifications that depend on the processes for development of commerce and for development of fusion. The main purpose of this paper is to prompt discussion of this topic among the leaders in fusion.

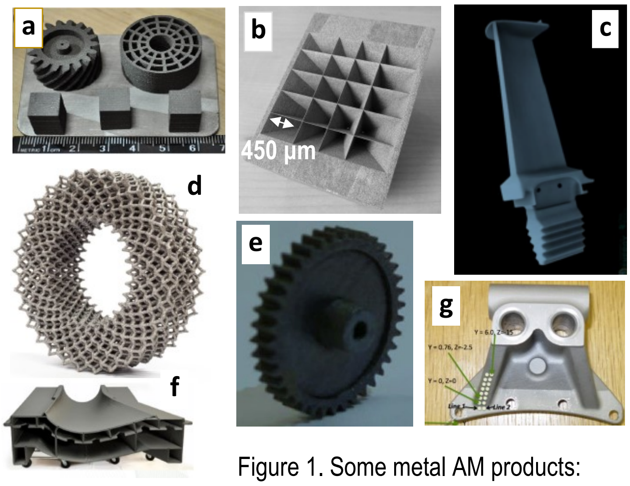

Figure 1. Some metal AM products:

a) TiC-Ferritic-Martensitic steel composite preforms, binder jet AM
b) Multi-pinhole collimator, selective laser melting of tungsten powder
c) Titanium turbine blade e-beam AM
d) Wind turbine blade
e) Inconel 718 engine mount, direct metal laser sintering (DMSL)
f) complex shape, tungsten, e-beam AM
g) tungsten gear, e-beam AM

4. References

[1] Nygren RE, DL Youchison, BD Wirth, LL Snead, A new vision of plasma facing components, *Fus. Eng. & Des.* (2016) Apr 18

[2] Lewis JA, Direct Ink Writing of 3D Functional Materials, *Adv. Funct. Mater.* **16** (2006) p2193–2204

[3] The Printed World: Three-dimensional printing from digital designs, 10 Feb 2011. www.economist.com/node/18114221

[4] LaMonica M, Additive Manufacturing, *MIT Technology Review,* 23 April 2013.

[5] Wong KV, Hernandez A, A Review of Additive Manufacturing, *International Scholarly Research Network*, ISRN Mechanical Engineering 2012, ID 208760, 10p, doi:10.5402/2012/208760

[6] Baykara T, Özbek, Ceranoglu AN, A generic transformation of advanced materials technologies: Towards more integrated multi-materials systems via customized R&D and Innovation*, J. High Tech. Management Res.* **26** (2015) 77–87

[7] Babu SS, L Love, R Dehoff, W Peter, TR Watkins, S Pannala, Additive manufacturing of materials: Opportunities and challenges, MRS Bulletin 2015 p1154-61.

[8] Additive manufacturing: A Game Changer for the Manufacturing Industry, Roland Berger Strategy Consultants, Munich, FRG, Nov. 2013, access 6/2015 www.rolandberger.com/media/pdf/Roland_Berger_Additive_Manufacturing 20131129.pdf,

[9] Lipson H, M Kurman, *Fabricated: The New World of 3D Printing,* Wiley, New York, 2013

[10] Gibson I, DW Rosen, B Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing,* Springer, New York, 2nd ed., 2015

[11] Griffith ML et al., Understanding Thermal Behavior in the LENS process, *Mat. & Design* **20** (1999) p107-113

[12] Keicher DM et al., Using the Laser Engineered Net Shaping (LENS) Process to Produce Complex Components from a CAD Solid Model, *SPIE* **2993** (1997) p91

[13] Sames WJ, List FA, Pannala S, Dehoff RR, Babu SS, The metallurgy and processing science of metal additive manufacturing, *Int. Mater. Rev.* **61**/5 (2016) p315-360 http://www.tandfonline.com/loi/yimr20

[14] Herdereck E, Additive Manufacturing of Metals, *Mat. Sci. & Tech.* (2011) *Oct 16-20*

[15] Rape A, S Chanthapan, J Singh, A Kulkarni, Engineered Chemistry of Cu-W Composites Sintered by Field-Assisted Sintering Technology for Heat Sink Applications, *J. Mater. Sci*. **46** (2011) p94-100

[16] Dehoff RR et al., Site specific control of crystallographic grain orientation through electron beam additive manufacturing, *Materials Science and Technology* **31.8** (2015) p931-938.

[17] Nie B, L Yang, H Huang, S Bai, P Wan, L Liu, Femtosecond Laser Additive Manufacturing of Iron and Tungsten Parts, *Applied Physics A, Mat. Sci. & Processing* [DOE 1-.1007/s00339-015-9070-y] March 3, 2015.

[18] Zhang DH, QZ Cai, JH Liu, L Zhang, RD Liu, Select laser melting of W–Ni–Fe powders: simulation and experimental study, *Int. J. Adv. Manuf. Tech.* **51** (2010) p649-58

[19] Watkins TR et al., Residual Stresses in an Additively Manufactured Inconel 718 Engine Mount, *Int. J. Mach. Tool Manuf*. (2015)

[20] Cakmak E et al., Microstructural and micromechanical characterization of IN718 theta shaped specimens built with electron beam melting, *Acta Materialia* **108** (2016) p161-175

[21] Prabhakar P, WJ Sames, R Smith, R Deho, SS. Babu, Computational Modeling of Residual Stress Formation during the Electron Beam Melting Process for Inconel 718, *Add. Manuf.* **17** (2015)

[22] Tomus D, PA Rometsch, M. Heilmaier, X Wu, Effects of minor alloying elements on crack-formation characteristics of Hastelloy-X manufactured by selective laser melting, *Add. Manuf.* **16** (2017) p65-72

[23] Dunbar AJ, ER Denlinger, MF Gouge, TW Simpson, P Michaleris, a comparative study of builds using laser power bed fusion technology, *Add. Manuf.* **15** (2017) p57-65

[24] Nycz A, AI Adediran, MW Noakes, LJ Love, Large Scale Metal Additive Techniques Review. Oak Ridge National Laboratory, Oak Ridge, TN (United States). Manufacturing Demonstration Facility (MDF); 2016 Jan 1

[25] Dehoff RR, Hummelt E, Solovyeva L. Feasibility and Testing of Additive Manufactured Components. Oak Ridge National Laboratory, Oak Ridge, TN, Manufacturing Demonstration Facility (MDF); 2016 Sep 1.

[26] Sudbrack CK, Kirka MM, Dehoff RR, Carter RW, Semiatin SL, Gabb TP. NASA/ORNL/AFRL Project Work on EBM LSHR: Additive Manufacturing of High-Temperature Gamma-Prime Strengthened Ni-Based Superalloys 2016

[27] Ohriner EK, RDehoff R, LL Snead, Electron-beam Additive Manufacturing of Tungsten Materials for Fusion, Fusion Reactor Materials Program, June 30, 2013. DOE/ER-0313/54. (2013) p114-116

[28] Raplee J, A Plotkowski, MM Kirka, R Dinwiddie, A Okello, RR Dehoff, SS Babu, Thermographic Microstructure Monitoring in Electron Beam Additive Manufacturing *Scientific Reports* (2017) Mar 3;7:43554

[29] Hazeltine R, Research Needs for Magnetic Fusion, National Academy of Sciences (2009) http://burningplasma.org/ReNeW

[30] Whyte DG, J Minervini, B LaBombard, E Marmar, M Greenwald, Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path *J. Fusion Energy* **35** (2016) p41-53

[31] Youchison DL, Garde JM, Thermo-Mechanical Evaluation of High-Temperature Refractory Foams Used in Thermal Management Systems**,** *Trans. Fus. Sci Technol. (2012)* **61**, 322