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Policy needed for additive manufacturing

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The successful adoption of metallic additive manufacturing in aviation will require investment in basic scientific understanding of the process, defining of standards and adaptive regulation.

Policymakers in the United States and elsewhere have recognized that a broad and competitive manufacturing sector is crucial to a robust economy and that to remain competitive a nation must invent and master new ways of making things[1]. However, progressing technologies from the laboratory to commercial success poses considerable challenges. If the technology is radically new, this transition can be so risky and require such a large investment that only very large private firms can attempt it. To help advance new manufacturing technologies across this 'valley of death', the executive branch of the US government has funded seven National Network of Manufacturing Innovation (NNMI) Institutes and intends to fund at least another two[2]. One such new technology, and the focus of activity for the first NNMI Institute, America Makes, is metallic additive manufacturing (MAM). MAM provides a vivid illustration of the tensions policymakers must resolve in simultaneously supporting the commercialization of early-stage innovations of strategic national interest, while fulfilling the government's duty to ensure human health and safety.

MAM technologies make it possible to build a part, layer by layer, from either a powder or wire feedstock (Fig. 1). A laser or electron beam, or plasma arc, is typically used to selectively melt together the feedstock (according to a computer-generated design file), permitting the part to be built up by successive rastering of the beam, and topping up of the feedstock[3]. This process offers several advantages over traditional methods, including the ability to produce hollow and lightweight parts, parts with geometries that cannot be produced conventionally, and the ability to perform repairs in the field. A particular advantage of MAM compared with traditional metal-based processing is that very small batches of parts could be produced in a short time with less financial investment (as compared with casting, where expensive dies must be fabricated), making it ideal for low volume or one-off parts and rapid prototyping. These advantages make MAM attractive in a wide range of industries, including biomedical engineering, transportation and defence.

An application of particular interest for MAM is civil and military aerospace[4], which is central to national economic and military competitiveness. For example, in the United States the civil aviation industry accounts for the largest share by annual value of exports of manufactured goods[5]. However, aviation demands extraordinarily high standards of safety, which are currently difficult for MAM to achieve. This is because fabrication processes at the technological frontier have not been standardized and rely heavily on the careful calibration of individual machines and extensive testing of finished parts, making it expensive to guarantee the mechanical integrity of each component. Broad adoption of MAM will thus require regulation that is proactive in giving industry practical guidance and in safeguarding public safety when the technology is immature, but that also adapts as models are developed to establish relationships between process inputs and outputs for a variety of customized geometries and materials. A difficult balance between multiple factors thus exists, as demonstrated by criticisms of what some would argue are arbitrarily selected and erratically applied safety factors for titanium castings in aviation[6].

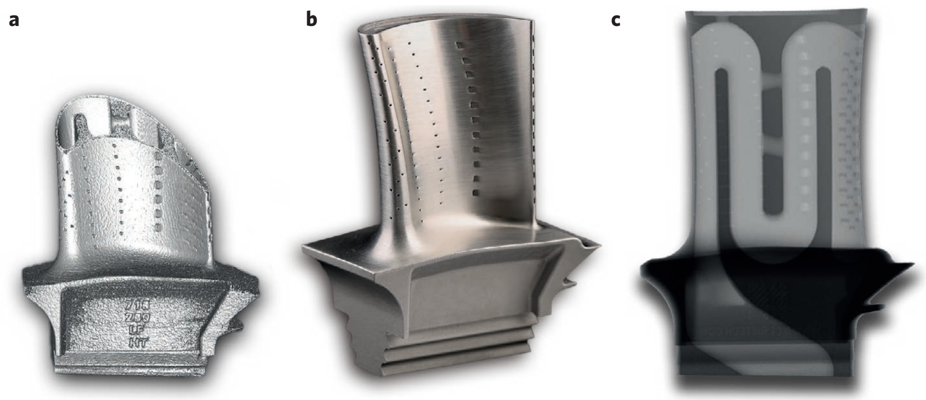

Figure 1 | Ni-based superalloy (Inconel 718) turbine blades for jet engines produced by direct laser metal sintering, a form of metallic additive manufacturing (MAM). **a**, The as-built turbine blade demonstrates an important limitation of MAM: a rough surface finish introduces possible sites for the initiation of cracks during service. **b**, Finishing of the surface is therefore necessary, as can be seen in the final part. Panel **a** also shows a cross-sectional cut through the blade, showing internal air cooling channels. **c**, A neutron radiograph showing these channels, which help to maintain the mechanical integrity of the blade at high operating temperatures. The ability to build internal structures into a component is hard to achieve by conventional metal processing. Figure courtesy of Oak Ridge National Laboratory, managed for the United States Department of Energy by UT-Battelle; reproduced with permission from ASM International (March 2013 cover and ref. 24).

Regulating an immature technology

That MAM technology is in the earliest phases of development poses two distinct, yet closely intertwined, problems. First, there is, as yet, insufficient ability to accurately and consistently predict the mechanical properties of a particular design, produced using a particular feedstock, on a particular machine[7]. Thus if a new, nominally identical machine is acquired to make an existing MAM-produced part, extensive testing and validation is required because, given the current state of the technology, obtaining an identical part to that fabricated on a different machine cannot be taken as certain. Second, Federal Aviation Administration (FAA) standards for material design require that manufacturers demonstrate that they can reliably produce a part that is extremely unlikely to fail[8]. For other technologies, the FAA has worked with industry to translate this performance standard into more explicit design guidelines[9]. This has not yet happened for MAM.

Overcoming this first challenge requires advancing understanding of the basic science. For MAM's full potential to be realized, basic materials processing knowledge must improve and investment must be made in reducing the variability in microstructure, surface finish and geometric tolerances (all of which affect mechanical performance), which is currently inherent to MAM. One way to achieve this is for closed-loop control processes to be developed: the material could be monitored *in situ*, and the manufacturing process adjusted to correct aberrations. While all the parameters that affect the microstructure of parts are not known, the research community and manufacturers are at the earliest stages of developing the ability to monitor a few of the parameters that are known to be important. For example, one electron beam melting machine offers a camera-based system to monitor the part as it is built[10]. Another gauges the temperature of the pool of molten metal (which determines the part's eventual microstructure) created by the laser beam striking the powder bed by sensing its brightness. It then compares this stream of data to that gathered from parts that have been built successfully in the past, and uses this history to alert operators when defects are likely to arise[10].

Data about the pivotal relationship between processing conditions and microstructure are being generated at considerable expense by some corporations working at the frontier of integrating MAM into their products. However, these firms closely guard their data and have little incentive to share them with each other, or with the wider community of suppliers to the aerospace industry, as their early adoption is explicitly with the intent of developing competitive advantage. If the data could be shared, the public good — through an improved regulatory framework and more rapid adoption across industry with associated fuel savings and environmental benefits — could be much greater than the private benefit to these firms[11]. Thus, the acquisition of fundamental knowledge and eventual pace of uptake by aviation, and a number of other industries, of MAM technology could be greatly enhanced. A classic approach that may help in this instance is for governments to provide basic technical and institutional infrastructure, such as material databases, for these data to be collated and curated. For example, NASA (National Aeronautics and Space Administration) Aeronautics helped to fund the collection and publication of much of the basic data on composite material properties such as the static and dynamic (that is, fatigue) strength of composite materials in different operating conditions[11]. These datasets eventually contributed to commercial products such as the Boeing 787 Dreamliner and the Airbus A350 XWB. In the case of MAM, the government might not only provide funding. It may also act as a steward to ensure that access to such a repository is managed fairly, and that it serves the broader goal of enabling the development of a new technology, in which the government has made significant investment given its potential to enhance national economic and military competitiveness. Serving as a steward would require a focused and well-resourced effort that builds on the work currently being done under the auspice of America Makes. Current resources, however, may not be enough for this institute to fulfil such a role. America Makes is set to receive up to US$50 million in federal funding, with an additional US$39 million from corporate members and the states of Ohio, Pennsylvania and West Virginia[10] to help accelerate the adoption of additive manufacturing. Between 1986 and 2015, the National Science Foundation "has expended more than $200 million on additive manufacturing research and related activities"[12]. In contrast, during critical development periods, the federal government may have annually been investing in composite materials an amount equivalent to the total it has invested in additive manufacturing so far. RAND Corporation[13], a think-tank, estimates that the federal government in 1987 was spending an equivalent of US$240 million (2014 dollar rates) per year on advanced composites. At that point, the technology was far more mature than MAM is today, in terms of being application-ready: advanced composites funding by the US Air Force alone peaked at US$160 million (2014 dollar rates) per year in 1964–1965[13]. Excluding manufacturing and structural or flight testing, US$1 billion from federal research and development funds was spent on composites in the quarter of a century between the mid-1960s and 1990[13].

Including those activities, federal spending on advanced composites amounted to several billion dollars. These snapshots suggest that large early-stage funding was probably critical to setting composites on the path to wide adoption. While an estimate of total federal spending in MAM is not readily available, it is unlikely that the US federal research and development spending is anywhere near the amount invested in the development and adoption of composites. This lack of investment is probably a major constraint on the development of MAM.

Overcoming the second challenge — translating the FAA's general performance standard into specific guidelines for part fabrication and testing by MAM — requires not only the expansion of basic knowledge (the previous challenge), but also a consensus on manufacturing and testing standards. Standard-setting bodies have not yet specified what parameters of the production process must be controlled (and to what degree) for safety-critical aircraft components. Testing organizations have also not prescribed, or developed, non-destructive tests that can economically verify that additively manufactured metallic components do indeed possess the claimed properties[14]. It therefore falls to standards developed by other, independent, bodies (ASTM, the American Society of Mechanical Engineers (ASME), the International Organization for Standardization (ISO) and so on) to translate that goal into specific requirements and guidelines. For example, a standard may list a series of parameters that must be controlled within specified tolerances to ensure that successive parts of the same design made on the same machine have identical properties. Standard-setting bodies must take into account the special needs of the aviation industry, and produce a standard that is sufficiently exacting. If an appropriate independent standard does not emerge, history suggests[15] that the practices of the financially dominant firm will become the *de facto* standard, regardless of technical merit. Another possible outcome is that no widely accepted standard emerges. In that case, each firm would pursue its own way of doing things, resulting in a fragmented ecosystem that stunts growth of the technology.

Cross-country lessons for MAM

The introduction of a new technology like MAM creates major technical and institutional challenges, even for highly developed countries such as the United States, which have an established industrial base and a priority of maintaining military superiority. Countries that have a less developed manufacturing base, and less prominent military priorities, would be well advised to develop technical know-how in additive manufacturing by applying it in industries where the inherent barriers to entry are lower. Japan is an example of a country that built a manufacturing base in new materials technologies (for example, composites and ceramics) in comparatively low-risk industries (sports goods and automobiles)[16]. As a consequence of this accumulated expertise, Japanese industries have been extraordinarily successful in leveraging this manufacturing base to make themselves indispensable to the US civil aviation sector[17].

China is approaching additive manufacturing in a focused and coordinated manner[10]. While it is inevitable that Chinese manufacturers will 'learn by flying', it can be argued that accumulating a large number of flight hours is, by itself, not enough to develop the understanding and maturity required to create products or equipment that are reliable. For example, the de Havilland Comet jet aircraft was flown for tens of thousands of cumulative hours with square windows and punch riveting before stress concentrations led to metal fatigue failure, resulting in several instances of the fuselage breaking up mid-flight. These disasters, caused by a lack of understanding of the relevant failure mechanisms alongside manufacturing flaws, set the British aircraft industry back by years.

While European manufacturers dominate the production of MAM fabrication equipment, the United States leads in terms of MAM application in designs and products. Just over 40% of all industrial additive manufacturing systems are installed in the United States[10], while Germany, Japan and China each have 9% of the total installed systems. Overall, Europe accounts for 28%. Given that the technology is not mature enough for part design and manufacturing to be decoupled from equipment design and calibration, to maintain and enhance their competitiveness in MAM, countries will probably need to develop expertise in those aspects of the technology (equipment or application) in which that country's industry is not currently skilled.

Three US policy recommendations

First, to catalyse the growth of MAM, the US Congress should provide significantly larger, sustained funding to improve understanding of the materials and processes involved in additive manufacturing. Given the global environmental and national economic and security benefits of MAM, this knowledge should be viewed as a public good (that is, a good whose production generates larger gains for society than a self-interested producer could capture) and managed by a public body: NASA's Aeronautics Research Mission Directorate could oversee its creation and ensure broad, fair access while ensuring that information that is critical to national security is protected.

As described in the preceding discussion, MAM machines are being equipped with the ability to monitor production in increasing detail. The data that these monitoring systems capture should be shared (if necessary, under agreements with a time-restricted confidentiality clause) with materials scientists who can analyse them to build better models of the physical processes involved (heat transfer to the feedstock, microstructure development and so on). These models could, in turn, be utilized to better control the production process. Researchers must additionally address the technical challenge of capturing, structuring and processing vast quantities of data in real time. The Materials Genome Initiative in the United States aims to promote the sharing of data and the enabling tools[18]; however, it is currently focused on data that emerge from federally funded projects, and does not include all of the necessary stakeholders. The government should undertake the institutional work necessary to forge extensive collaboration and data sharing with key stakeholders across industry, government labs and academia.

Second, strategies should be developed to allow US industry to 'learn by doing' without compromising safety, in the same way that was vital to the advance of composite materials. For example, Boeing's ecoDemonstrator Program adds new technologies to one of three aircraft in order to test their performance in actual flight, with the aim of improving environmental performance. These aircraft are taken out of commercial service, but are of a type that is currently in commercial use. Boeing's approach makes it possible to not only test safety, but to prove and quantify the advantages of nascent technologies and help make the case for their adoption. More programmes of a similar nature, including at least some in which the resulting knowledge and data are put in the public domain, would help accelerate this critical in-flight learning. Technological and regulatory barriers are lower, and risks smaller, in general aviation (for example, recreational and business aircraft) than in commercial aviation, which includes all scheduled services (that is, airlines)[19]. This makes general aviation an attractive platform for gaining experience in a new technology. The government and the civil aviation industry should explore ways to encourage general aviation to play this role in metallic additive manufacturing, as it did for composite materials.

Third, while early regulatory approaches must inevitably reflect the technology's immaturity, regulators should be careful to avoid lock-in. Provisions must be made so that rules can adapt to become less onerous as knowledge of MAM improves and microstructure becomes more predictable across a range of custom MAM materials and geometries. For example, rules should be accompanied by a 'sunset provision', requiring that the regulatory strategy be substantially rethought at regular time intervals until the technology is deemed mature.

Government's catalytic role

The challenges associated with generating the basic and applied knowledge to confidently utilize additive manufacturing in aviation, where both the risks and the opportunities are great, are daunting. The United States clearly has the research and development and industrial capacity to surmount these challenges. However, the benefits to individual private firms may not be large enough to stimulate the necessary level of investment. The uptake of MAM thus requires the government to play a catalytic role, as it has successfully done for many other technologies, including advanced composites in aviation, and nanotechnology in general[20].

While US industry is pivotal to the global supply chain for aviation, nearly a third of the components of Boeing 787 aircraft are procured from elsewhere in the world[21,22]. Similarly, nearly 42% by value of Airbus's 'aircraft-related procurement' is from the United States[23]. Hence, if US aerospace firms successfully push the technological frontier by embracing additive manufacturing, they will create a powerful incentive for their partners and competitors to move towards that frontier also. Adopting policies that are supportive of additive manufacturing may prove important not only to maintaining US competitive advantage in the aviation industry, but also to ensuring that a promising technology reaches the potential that it holds to influence global manufacturing in a number of industries. ❐

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