# Scientific, technological and economic issues in metal printing and their solutions

3D printing is now widely used in aerospace, healthcare, energy, automotive and other industries. Metal printing, in particular, is the fastest growing sector, yet its development presents scientific, technological and economic challenges that must be understood and addressed.

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In the past few decades, 3D printing, also known as additive manufacturing (AM), has evolved from the rapid fabrication of functional prototypes to the manufacturing of various metallic components that cannot be easily and economically produced by other means[1–4]. Starting with a digital drawing, metals are deposited layer by layer to form a three-dimensional (3D) component. Stainless steels, aluminium, titanium and nickel alloys are printed using mainly powder bed fusion (PBF) and direct energy deposition (DED) techniques[1–4]. The feedstock is typically in the form of metal powder or wire which is melted by a laser beam, electron beam or an electric arc[1,2]. A component consisting of multiple alloys can also be produced by varying compositions in different layers[1].

Metal printing is now widely used in aerospace, consumer products, healthcare, energy, automotive, marine and other industries[5–9], as shown in Fig. 1a. The process has short lead times with the ability of using the same equipment to produce different products[2]. Customized parts and other important components can be produced on demand, such as patient-specific medical implants and a metallic impeller for the safe operation of a nuclear power plant[2]. The technology exhibits favourable return on investment for part-count reduction by consolidating multiple components into one and sustainment of legacy products where supply chains no longer exist[5,10].

With viability in diverse industries, the ability to print unique components and the potential to overcome deficiencies of current manufacturing processes, 3D metal printing is the fastest growing sector of AM today[11]. Figure 1b shows the accelerated sale of metal-printing machines in recent years[11] and evidence of increased population of users. It is also apparent from the available data on patents granted in past five years in Fig. 1c. The total number of global patents of metal printing is now comparable to that

of the other widely used manufacturing processes, suggesting a continued growth of 3D printing in the foreseeable future.

Like all growing technologies, metal printing has its fair share of challenges. The current 3D-printed product volumes are small in comparison with those from relatively more mature and common manufacturing methods[12]. It requires further improvements in productivity, quality control and repeatability[4]. Figure 1d summarizes the outcomes from associated academic and industrial activities to solve the fundamental or technological problems in 3D printing. It shows that scientific papers originated mostly from universities and national labs, whereas most patents were owned by corporations. The papers are often of a fundamental nature, largely devoid of economic and technological analysis and often too abstract for practical applications, while industrial innovations mostly remain unpublished to safeguard profits. The gap between the requirements of the 3D-printing industry and the ongoing research and development[4] needs to be addressed, with better understanding of the critical scientific, technological and economic issues (as illustrated in Fig. 2a) in order to find potential solutions.

## Scientific challenges

Scientific challenges stem from the diverse processing conditions and complex thermal cycles in metal 3D printing, as well as their unknown effects on the evolution of various microstructural features and defects that influence properties and performance of components.

**Processing–microstructure–property–performance relations.** The relationship between processing, microstructure, properties and performance of many commercial alloys is currently being investigated for 3D printing[1], yet the progress is slow due to the variations of the printing processes, the large number of

processing parameters, and the significant diversity in the structure, properties and performance of metallic components[12]. It may be noted that it took many decades of sustained research and development to create a process–microstructure–property knowledge base for the welding of major alloys[13]. A similar intensive effort would be necessary over the coming decades to fulfil this need for AM.

**Microstructure control.** Rapid cooling rates and spatially variable temperature gradients contribute to the complexity of microstructures in 3D-printed materials compared with cast or wrought materials[1]. Printed metals often exhibit high dislocation densities, segregation of elements, fine solidification structures and elongated grains[1]. Understanding and controlling the evolution of printed microstructures would ultimately allow the tailoring of component microstructure[1,2] to achieve combinations of properties not attainable by traditional processing, such as having both high strength and good ductility[14].

**Defect evolution and its impact on properties.** Defects in printed components originate from atomic to macro scales[1,15], and largely affect the mechanical properties of components[15,16]. For example, lack of fusion defects are known to adversely affect tensile properties[16]. High residual stresses may result in warping, buckling and delamination of components[10] and are also detrimental to fatigue properties[1]. Surface irregularities may act as the source of stress concentration that may result in premature failure of components[1]. The mechanisms of nucleation and growth of defects under the complicated thermal cycles of metal printing are nevertheless not well understood and require in-depth investigations. The role that different defects play in crystal plasticity, fracture and fatigue also remains to be fully explored[1]. Moreover, improved understanding of various hot cracking
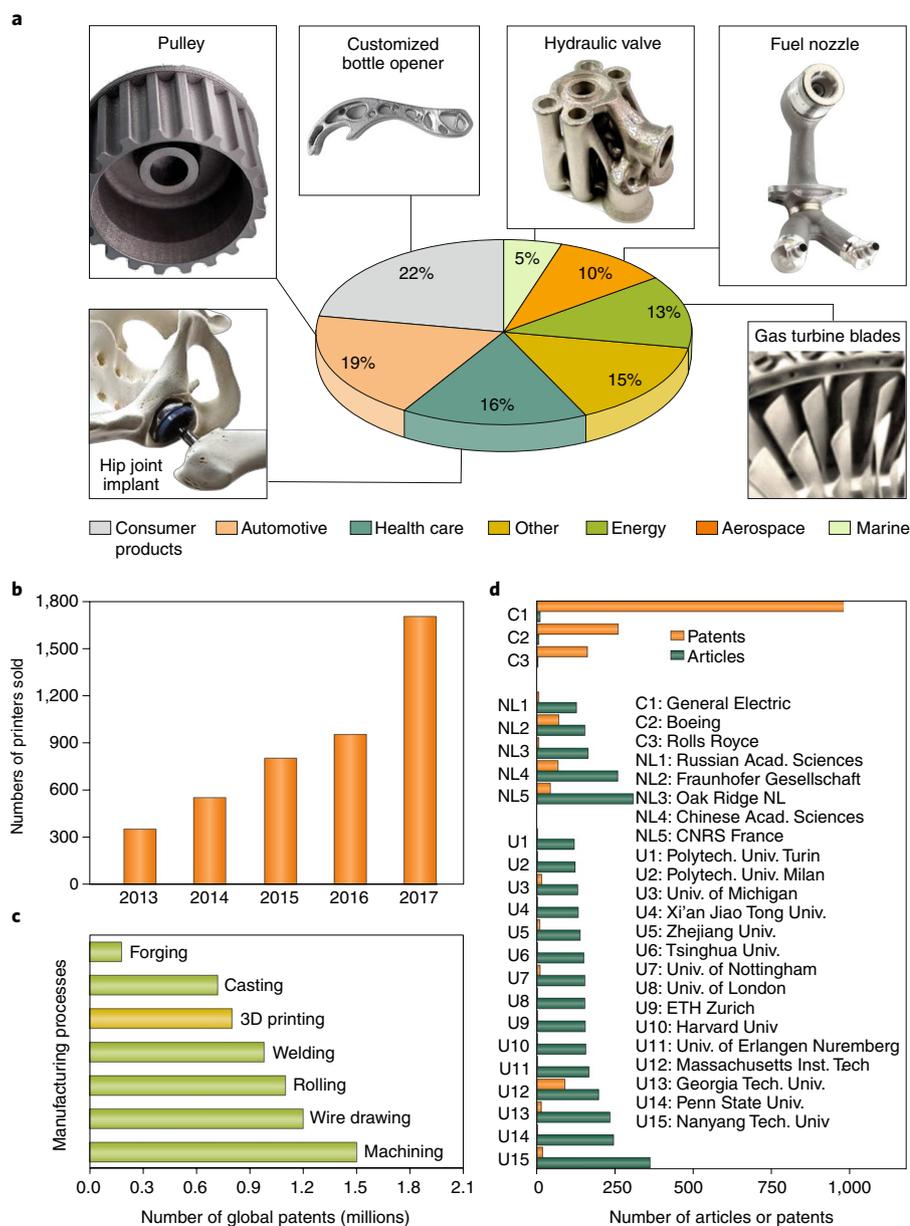
**Fig. 1 | Current status of metal printing. a**, Applications of metal printing in various industries[1] and the distribution of revenues[7] from the printed parts among various industries. **b**, Numbers of metal printers sold globally from 2013 to 2017[11]. **c**, Numbers of patents published in past five years on different manufacturing techniques (data are collected from Google Patents on 14 February 2019). **d**, Numbers of scientific articles and patents on 3D printing published in 2014 to 2018 from universities, national labs and industries worldwide. 15 universities and five national labs worldwide are selected based on their numbers of published literature on 3D printing. A maximum of five organizations are selected from a particular country. Data are collected from Web of Science (core collection) and Google Patents on 24 April 2019 using keywords 'additive manufacturing' or '3D printing'. Credit: SciePro/Science Photo Library (hip joint implant); GE Aviation (fuel nozzle). Adapted from ref. [8], Springer Nature Ltd (hydraulic valve); and ref. [9], Springer Nature Ltd (gas turbine blades)

phenomena[1] due to combined effects of microstructure, stresses and temperature is essential.

**Features of solidification structure.** For a given alloy, the solidification morphology and the resulting mechanical properties are affected by the ratio of the local temperature gradient, $G$, and the solidification growth rate, $R$, which can vary significantly depending on the printing techniques and the process parameters[12]. For example, Fig. 2b

presents strikingly different solidification structures[12] for stainless steel, resulting from the variations of these factors in different printing processes. The cooling rates during solidification that control the scale of solidification structures depend on the alloy, AM technique and process conditions such as heat input. Figure 2c shows five orders of magnitude variations in cooling rate with heat input[12]. The diversity in spatial and temporal variations of $G$ and $R$ and repeated thermal cycles present an unusual challenge for understanding the evolution of the solidification structure of printed metals.

**Evolution of grain structure, topology and texture.** Columnar grains that often form in printed components may significantly degrade mechanical properties[1,17]. Basic understanding of the evolution of grain structure and topology during AM is just beginning, and so is the mechanistic understanding of breakdown of columnar grains using grain refiners[17] and control of heat flow directions[1]. The anisotropic nature of textured microstructures has been observed in PBF-laser (PBF-L) of stainless steel and an aluminium alloy[18]. However, the influence of this anisotropy on product performance is not well understood and more work needs to be done in this area. Anisotropy in microstructure may present substantial risks to product performance under complex loading[1].

## Technological challenges
Besides the aforementioned scientific issues, the widespread adoption of metal AM in industry is also facing technological challenges.

**Qualification and certification.** Part qualification is currently done by trial-and-error testing[12]. This brute-force approach hinders rapid and precise qualification[2]. The process of building, sectioning, testing and characterizing components is time consuming, laborious and expensive[12]. Compared with well-established manufacturing technologies (such as casting, machining and welding), the high cost and slow qualification confine metal printing mainly to only niche markets where the challenges of high cost and slow qualification are not major considerations[12].

**Geometric limitations and complexities.** Each printing machine has limitations of product size, geometrical features and feedstock materials that affect the building of components[1]. Product size in the PBF process is restricted by the dimensions of the powder bed[10], while high-deposition-rate processes, such as wire-based gas
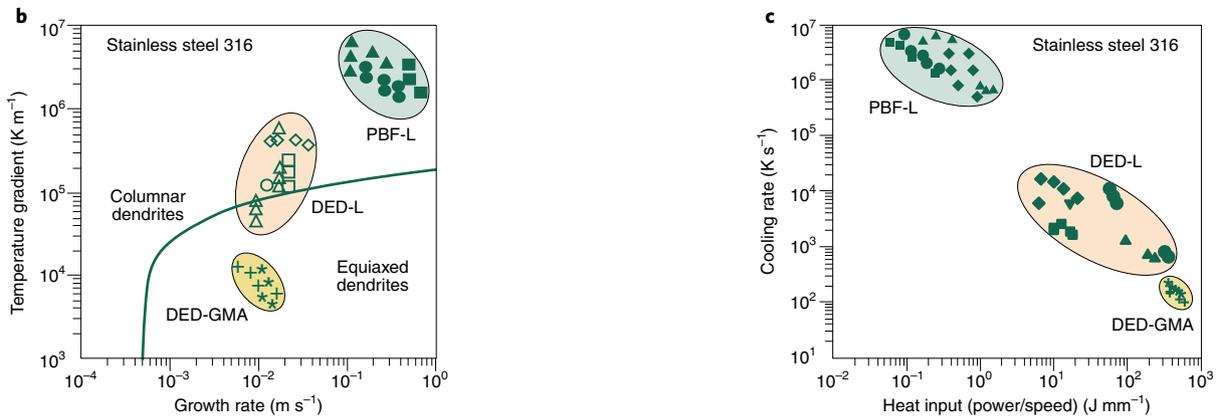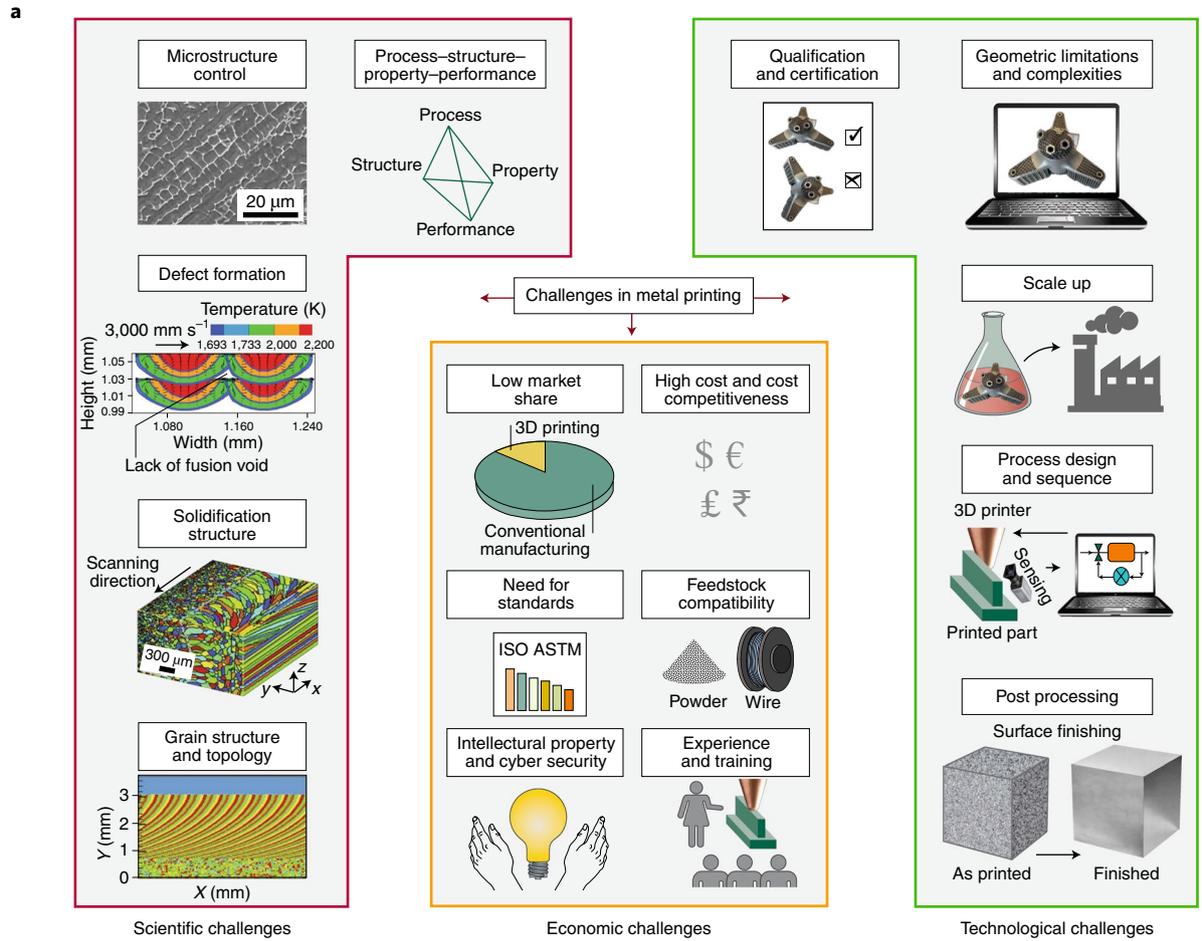
**Fig. 2 | Challenges in metal printing. a**, The main scientific (outlined in red), technological (green) and economic (orange) challenges in metal printing. **b**, Diversity of the two main causative factors of grain structure in 3D-printed components, temperature gradient and solidification growth rate, indicates the difficulty faced in controlling microstructures. Reported values[12] of these parameters for two printing techniques, DED-laser (DED-L) and PBF-laser (PBF-L), illustrate the wide range of these variables for printing stainless steel components. **c**, Variations in cooling rates during solidification[12] for stainless steel components for a wide range of heat input. GMA, gas metal arc. Adapted from ref. [12], Elsevier.

metal arc or plasma arc DED, don't have this restriction and can create large structures[5,10]. Such wire-based methods have economic advantages with less costly capital investment, multiple suppliers for certified weldable wire feedstock, and less

wire cost per unit volume than powder[1]. However, they have limitations on the feature resolution and surface finish[1], which may require extensive efforts for further improvement[2]. Moreover, design of the parts with complex geometries for

printing may require support structures that include additional material usage and post processing[19]. Complex geometries such as those with internal features and lattice structures also pose a unique challenge on non-destructive evaluation of printed
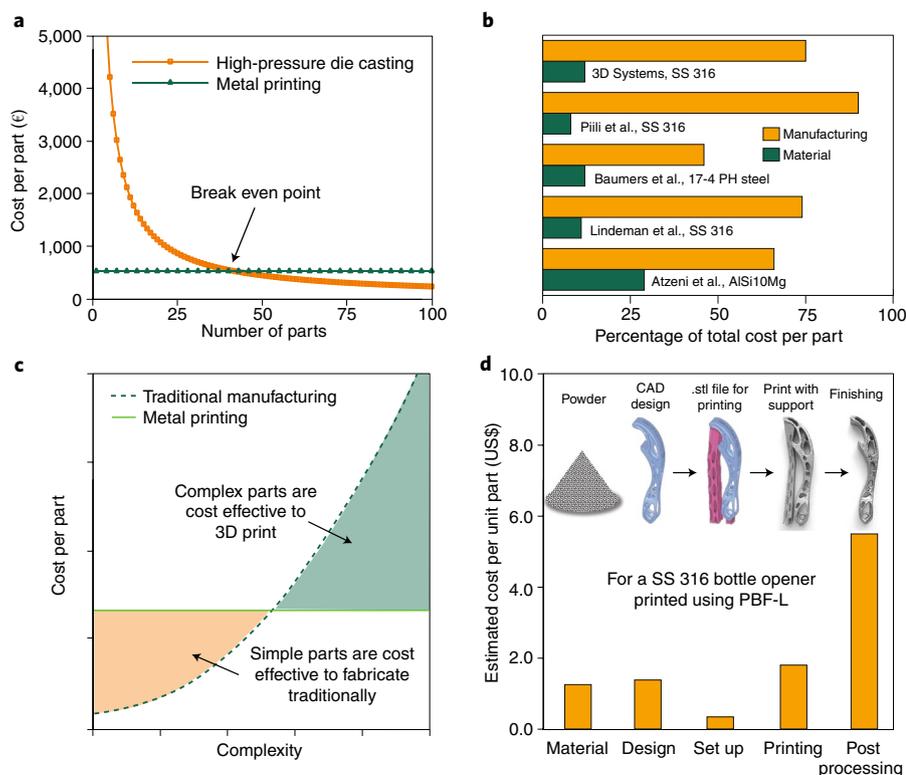
**Fig. 3 | Cost competitiveness of metal printing. a**, Cost of a landing gear part made of AlSi10Mg alloy by PBF-L is compared with that made by high pressure die casting[28]. **b**, Manufacturing and material costs as percentages of total cost per part printed using PBF-L. Data taken from the literature[26,28–30] as well as the shop floor data collected at 3D Systems. **c**, Qualitative representation[31] of the cost and part complexity relation for metal printing and traditional manufacturing. **d**, Cost of different stages of metal printing. The data are for the printing of stainless steel 316 bottle openers. Adapted from ref. [31], Elsevier (**c**). Bottle opener images in **d** courtesy of J. J. Blecher of 3D Systems.

products[10]. Therefore, the part design for metal printing involves consideration of the desired geometry, product attributes, manufacturability and costs[19].

**Scale-up.** Scale-up of building strategies from small coupons to large and complex components is a challenging task[4] because of machine-dependent part size and geometry limitations. In addition, size-dependent process parameter adjustment, scanning strategies and support structures depend on the specific printing equipment and part design[10]. Other scale-up limitations are that of manufacturing throughput and batch size, relating to both process speed and productivity. The thermomechanical complexities of 3D printing present risks to generate distortion, residual stresses and cracking that are not always apparent in simple coupons often utilized in mechanical testing[2].

**Process design and printing sequence.** Specifications of the orientation of the solid model within the build volume, creation of

the support structure, selection of process variables for each specific component and scanning pattern are currently not based on any rigorous principles[10]. For example, the geometry of a component often requires optimization to reduce additional material usage for the support structure[20]. Although artificial intelligence-based techniques are emerging[21], geometry optimization is achieved by trial and error in most cases. Different vendors use different preprogrammed methodologies, scanning patterns, building sequences, software and methods to support the process and product design that cannot be controlled by users[2]. Part attributes can be detected in situ during printing[2] and may deviate from its designed specifications. Process monitoring and control are continuously being improved to ensure product accuracy[2,10].

**Post processing.** Removal of support structure and base plate, and post processing such as surface cleaning, hot isostatic pressing, machining, coating and heat treatment add cost[22]. Currently, the need

for post processing depends on the AM process, alloy system and the part design[2,10]. For example, parts produced by DED-gas metal arc (GMA) often require machining to improve surface finish and dimensional tolerance[1]. Printed materials can respond differently to thermal and chemical post-processing treatments when compared to cast or wrought products[2]. Study of welding and joining of printed metallic components is just at the initial stage.

**Safety and health hazards.** Special care should be exercised both for handling the powder feedstock and for operating printing machines. The powder feedstock can be a potential source of fire or explosion[23]. One of the most hazardous substances is the condensate that results from the evaporation of liquid metal and condensation as high-surface-area fine particles in the filter, making the replacement of filters the most dangerous part of printer operation[23]. Formation of spatters resulting from the use of high-power-density heat sources also contributes to the deposition of fine metal particles within the chamber[1]. Heat sources such as the laser, electron beam or electric arc can be dangerous due to high energy density. Operators should use proper eye protection against laser radiation. Appropriate precaution has to be taken to handle, process and recycle large volumes of fine AM powders. Ultrafine alloy powder feedstock can affect the eyes and respiratory system and may cause diseases such as asthma[23]. For DED processes using wire as feedstock, the health hazards are similar to those already known in the welding field. For instance, an apparently innocuous alloy such as stainless steel contains nickel and chromium, both of which are known carcinogens[24]. Welding fumes and particulate matter are known to cause immune system dysfunction and upper and lower respiratory tract infections among welders[25].

### Economic challenges
Apart from the scientific and technological issues, the barriers for manufacturing current and future AM products will be based on economic considerations.

**Cost competitiveness.** The cost of metal printing affected by product volume and complexity will allow an evaluation of the conditions where AM is favoured over conventional manufacturing[22]. In traditional manufacturing, such as casting or machining, costs are incurred for raw material, equipment, tooling, set-up, part complexity and the volume of the order[22,26]. Unit cost is high due to the initial

**Table 1 | Different solutions for scientific, technological and economic challenges**

| | | Solutions | | | | | |
|---|---|---|---|---|---|---|---|
| | | Printability database | Mechanistic models | Digital twin | Digital tools | New policies | Research collaboration |
| Scientific challenges | Processing–microstructure–properties–performance | ✓ | | | | | ✓ |
| | Microstructure control | | ✓ | ✓ | | | ✓ |
| | Defect formation | ✓ | ✓ | ✓ | | | ✓ |
| | Solidification structure | ✓ | ✓ | ✓ | | | ✓ |
| | Grain structure and topology | ✓ | ✓ | ✓ | | | ✓ |
| Technological challenges | Qualification and certification | | ✓ | ✓ | ✓ | ✓ | |
| | Geometric limitations and complexities | | | | ✓ | | ✓ |
| | Scale up | | | | ✓ | ✓ | ✓ |
| | Process design and printing sequence | | ✓ | ✓ | ✓ | | ✓ |
| | Post processing | ✓ | | | | | ✓ |
| | Safety and health hazards | | | | | ✓ | |
| Economic challenges | Low market share | | | | | ✓ | |
| | High cost and cost competitiveness | | | | | ✓ | |
| | Need for standards | ✓ | | ✓ | | ✓ | |
| | Feedstock compatibility | ✓ | | | | ✓ | ✓ |
| | Intellectual property and cyber security | | | | ✓ | ✓ | |
| | Experience and training | | | | ✓ | | ✓ |

investment of the equipment and set-up if only a few parts are made, but reduces as the product volume increases with distributing the high set-up cost among products[26,27]. Since AM does not require any extra set-up and tooling costs for new parts, cost per part does not change significantly with product volume[27]. This trend is observed in Fig. 3a, which compares the costs of manufacturing a landing gear part made of AlSi10Mg alloy by PBF-L and by high-pressure die casting[28]. The economic viability of AM does not depend on a minimum order size. Cost of a printed part is mainly contributed by metal-printing equipment, feedstock material, manufacturing and indirect costs[26,27]. The material and manufacturing costs of various components made by PBF-L are compared in Fig. 3b based on literature data[26,28–30]. It shows that for a wide variety of engineering alloys, the feedstock material for metal printing is not the dominant contributor to cost compared with machine time and, in many cases, post processing.

AM really shines for printing complex parts eliminating special tooling in many cases, while conventional manufacturing usually requires assembly of smaller parts. Figure 3c qualitatively shows the impact of complexity on cost for AM and traditional manufacturing[31]. However, in some cases, the complexity of a part can increase both the material and manufacturing costs, as illustrated in Fig. 3d for the printing of a stainless steel 316 bottle opener by PBF-L. The complex design of the bottle opener requires a support structure of overhangs that need to be removed by hammering and grinding of the chipped surface after printing. Both the extra material needed for the support structure and the time required for the post processing add to the cost. The adaptation of novel designs where cast or wrought product geometries are not feasible can justify higher cost[32]. Enhancing system performance, reducing part count or product weight where possible may also offset product cost[2].

**Low market share of metal printing.**
The market value of 3D-printed products rose to US$7.3 billion, but only accounts for 0.06% of the global manufacturing economy[11]. Facility upgrade, high capital and operational costs of the equipment, the costs of feedstock, the safety practice and training, beyond those typical in conventional manufacturing, often limit the adoption of 3D printing by small to medium businesses[22]. The current status of market penetration and growth of AM follows the growth of a developing technology in its usual course of advancement[11].

**Need for standards.** The standards for qualifying printed metallic components are under development[12] by many well-established organizations such as the International Standards Organization (ISO), American Society for Testing and Materials (ASTM) and Society of Automobile Engineers (SAE). The responsibility for voluntary compliance with the standard will also rest with different organizations depending on the specific industrial sector. For example, in the United States, the Federal Aviation Administration is responsible for certification in the aerospace industry, whereas the Food and Drug Administration regulates the biomedical industry. The standards are developing slowly primarily because of the challenge of producing defect-free, structurally sound and repeatable parts in a large multi-parameter operating window[12]. The manufacturers of printing machines, feedstock suppliers and users will have a major role in adapting and using the standards that are being developed[2,3].

**Feedstock compatibility.** Currently only a few commercial alloys can be reliably fabricated by 3D printing[17]. Many of other alloys that are potentially printable either have not been tested or are not available yet as feedstock for printing[12]. New alloys may need to be created specifically for a given printing process[19]. Manufacturing of the components with compositional grading, precious metals and metals with very high melting points is challenging due to the lack of available feedstock material[2]. In addition, adaptation of a new material for 3D printing often requires a strong business case to pay for testing and qualifying the product[22].

**Intellectual property and cyber security.** The intellectual property landscape is rapidly changing as foundation patents expire, allowing more companies to enter the printing market. However, follow-up patents for methods and sub-systems such as the powder-spreading mechanism can still make machines unique and a component defined by a solid model may not match the one made on another system[32]. In addition, the rapid evolution of the digital design and production tools[32] presents new risks to data and cyber security.

**Lack of experience and training.** The emerging nature of the metal-printing industry has greatly benefited from, and capitalized on, advanced computer control technology that minimizes the traditional role of welding engineers, operators and metallurgists in the process[1,10]. The benefit to the metal printing industry is that turnkey machines have attracted an entirely new source of labour into the manufacturing field. However, a downside to this trend is that much of this new talent is not educated in the fundamentals of welding and/or metallurgy[4]. The lack of this knowledge leads to significantly increased trial and error development time and reduced reliability of fabricated components. Education and training often suffers from shortages of experienced metal-printing personnel that can provide a historical perspective of practice and relevant training in designing parts for optimum performance.

## Potential solutions

There is no straightforward and rapid solution to the issues outlined here, yet there are several helpful ways to address them, as shown in Table 1.

**Creating a printability database.** Widely used in the practice of welding, the weldability database[1] helps to predict the appropriate combinations of major alloys

and welding processes, and indicates if welding is recommended, difficult or not feasible under normal conditions. Similarly, printability rates the ability of a feedstock material to be successfully converted to components by a given AM process[1,15], which depends on both the alloy and the process conditions[1,15]. This ranking provides the relative outcomes of the quality of printed products. It considers both the susceptibilities to common printing defects such as lack of fusion, compositional change, residual stresses and distortion, as well as metallurgical and mechanical properties[15]. Currently, there is no generally available printability database[1,15]. Developing such a database will facilitate the selection of an appropriate printing process–alloy combination that can be helpful to reduce and, in some cases, avoid common defects in metal printing without extensive trial and error testing.

**Developing and utilizing mechanistic models.** Since microstructure, solidification structure, grain texture, topological features and defects of the printed components vary widely depending on the alloy compositions, printing techniques and process parameters, predictions of these characteristics using verifiable mechanistic models before printing are helpful for their control[1]. The mechanistic models calculate important parameters such as temperature fields, build geometry, cooling rates, residual stresses and distortion[1]. These models can be made bidirectional so that they can compute a set of process variables that are required for achieving desired metallurgical or mechanical characteristics of the product[12]. For example, the model can compute the heat input that is needed to obtain certain cooling rate for achieving a desired microstructure. Innovation in advanced computational algorithms and codes and high-performance computing are necessary to execute these models for improving both the process and the product[12].

**Implementing a digital twin.** A digital twin may consist of mechanistic, control and statistical models of the printing process, as well as machine learning and big data, which can control microstructure and properties and accelerate the process from design to manufacturing[12,33]. Within the digital twin of 3D printing, a sensing and control model can interface with multiple sensors[12]. A well-tested mechanistic model can provide important metallurgical variables[1]. The statistical model can minimize errors in the results obtained from mechanistic and control models by

learning from the previous data. While the utility of the digital twin approach is now widely accepted[12,33], the construction and testing of a digital twin of metal printing is just beginning.

**Utilization of emerging digital tools.** The metal printing technology operates at the cross roads of materials, machines, computing and data[1]. Advanced digital tools can augment human intelligence based on experience to provide optimization of process variables and product attributes[34]. When connected with innovative sensors, they may allow a cyber-physical system that would detect defects and initiate corrective actions during printing without human intervention[12]. Better integration of cloud computing, cyber-physical systems, artificial intelligence and Internet of things will improve both the processing and qualification of components through defect mitigation, continuous quality improvements and information technology-based manufacturing[12].

**Policies for standardization.** New policies[3] are needed for product and process standardization, training of the work force and knowledge sharing. The business model of intellectual property protection of undisclosed parameter sets is likely to be overturned by the standardization needs and demands of printing industry to the original equipment manufacturer (OEM) vendors[22]. New policies will have to address both this change as well as scaling up the applications from the laboratory scale to real-world applications. Moreover, in addition to policies needed for the certification and training of the work force, their successful implementation to solve some of the existing issues in metal printing will depend on the voluntary adaptation of these policies by OEM vendors and users[3].

**Precompetitive research collaboration.** Precompetitive research collaboration among universities, national labs and companies can develop processing–microstructure–property relations to expand the applications of the 3D printing of more alloys. Promising ideas for expediting and scaling up 3D printing that originate in universities and national labs through testing of small coupons can be further explored for fabricating real components in industries. Sharing of information on a need-to-know basis will partially alleviate the strict intellectual property barriers without any threat to profits[32]. Collaboration among different organizations may foster sharing of

knowledge that will be beneficial to train a large technical workforce[35] in both the theory and practice of 3D printing.

The solutions of the scientific, technological and commercial challenges outlined here will further expand the benefits of 3D printing in different aspects. The maturity of metallurgical science and technology, the rapid advancements in computer hardware and software, and the creativity of the workforce in the high-tech sector are synergistic factors for addressing these problems. ❑

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## References

1. DebRoy, T. et al. *Prog. Mater. Sci.* **92**, 112–224 (2018).
2. Milewski, J. O. *Additive Manufacturing of Metals* (Springer, 2017).
3. Roca, J. B., Vaishnav, P., Fuchs, E. R. H. & Morgan, M. G. *Nat. Mater.* **15**, 815–818 (2016).
4. Huang, Y., Leu, M. C., Mazumder, J. & Donmez, A. *J. Manuf. Sci. Eng.* **137**, 014001 (2015).
5. Frazier, W. E. *J. Mater. Eng. Perform.* **23**, 1917–1928 (2014).
6. Pollock, T. M. *Nat. Mater.* **15**, 809–815 (2016).
7. Verhoef, L. A., Budde, B. W., Chockalingam, C., Nodar, B. G. & van Wijk, J. M. *Energy Policy* **112**, 349–360 (2018).
8. Duda, T. & Venkat Raghavan, L. *AI Soc.* **33**, 241–252 (2018).
9. Murr, L. E. *Metallogr. Microstr. Anal.* **7**, 103–132 (2018).
10. Gu, D. D., Meiners, W., Wissenbach, K. & Poprawe, R. *Int. Mater. Rev.* **57**, 133–164 (2012).
11. Wohlers, T. T. et al. *Wohlers Report 2018* (Wohlers Associates, 2018).
12. Mukherjee, T. & DebRoy, T. *Appl. Mater. Today* **14**, 59–65 (March, 2019).
13. David, S. A. & DebRoy, T. *Science* **257**, 497–502 (1992).
14. Liu, L. et al. *Mater. Today* **21**, 354–361 (2018).
15. Mukherjee, T., Zuback, J. S., De, A. & DebRoy, T. *Sci. Rep.* **6**, 19717 (2016).
16. Thijs, L. et al. *Acta Mater.* **58**, 3303–3312 (2010).
17. Martin, J. H. et al. *Nature* **549**, 365–369 (2017).
18. Hitzler, L., Merkel, M., Hall, W. & Öchsner, A. *Adv. Eng. Mater.* **20**, 1700658 (2018).
19. Thompson, M. K. et al. *CIRP Ann.* **65**, 737–760 (2016).
20. Lefky, C. S., Zucker, B., Nassar, A. R., Simpson, T. W. & Hildreth, O. J. *Acta Mater.* **153**, 1–7 (2018).
21. Scime, L. & Beuth, J. *Addit. Manuf.* **25**, 151–165 (2019).
22. Berman, B. *Bus. Horiz.* **55**, 155–162 (2012).
23. Bours, J., Adzima, B., Gladwin, S., Cabral, J. & Mau, S. *J. Ind. Ecol.* **21**, S25–S36 (2017).
24. Stanislawska, M. et al. *Microchem. J.* **135**, 1–9 (2017).
25. Zeidler-Erdely, P. C., Erdely, A. & Antonini, J. M. *J. Immunotoxicol.* **9**, 411–425 (2012).
26. Baumers, M., Dickens, P., Tuck, C. & Hague, R. *Technol. Forecast. Social Change.* **102**, 193–201 (2016).
27. Hopkinson, N. & Dickens, P. *Proc. Inst. Mech. Eng. C* **217**, 31–39 (2003).
28. Atzeni, E. & Salmi, A. *Int. J. Adv. Manufact. Technol.* **62**, 1147–1155 (2012).
29. Piili, H., Happonen, A., Väistö, T. & Venkataramanan, V. *Phys. Procedia* **78**, 388–396 (2015).
30. Lindemann, C., Jahnke, U., Moi, M. & Koch, R. in *Proc. 24th Annual Int. Solid Freeform Fabrication Symp* (Laboratory for Freeform Fabrication, 2013).
31. Pinkerton, A. J. *Opt. Laser Technol.* **78**, 25–32 (2016).
32. Gao, W. et al. *Comput. Aided Des.* **69**, 65–89 (2015).
33. Qi, Q. & Tao, F. *IEEE Access* **6**, 3585–3593 (2018).
34. LeCun, Y., Bengio, Y. & Hinton, G. *Nature* **521**, 436–444 (2015).
35. Hagedoorn, J., Link, A. N. & Vonortas, N. S. *Res. Policy* **29**, 567–586 (2000).