opportunities for materials discovery, and for innovations in design and manufacturing. In fulfilling those aspirations, advanced structural ceramics will undoubtedly play a crucial role. In most cases, straightforward replacement of metallic components within existing propulsion systems is unlikely to exploit the full potential of advanced ceramics. Thus, a ceramics-relevant redesign of the entire system is needed, where the whole-component performance and function(s) requirements within the system are understood and specified. Meeting those aggressive requirements will necessitate the design of components with hierarchical architectures, comprising constituent ceramics and their ensembles, while embracing and exploiting the increasing complexity at multiple length scales. Accelerated development of new constituent ceramics will be needed to achieve the required properties within the ensemble that cannot be met by existing materials. Processing and manufacturing of these components will remain a challenge, but it presents a fertile ground for innovation, and it needs to be an integral part of the effort. Considering the inordinate expense of extensive component-level testing under realistic engine conditions, reliable physics- and mechanisms-based models that describe the behaviour of the constituent ceramics, the ensembles and the component at multiple length/temporal scales will need to be developed. Sophisticated *ex situ*, *in situ* and *in operando* multiscale characterization, and representative multiscale testing of the constituent ceramics, the ensembles and the component will be needed to inform and to validate the models. However, there is no substitute for targeted component-level experimental demonstrations to familiarize systems designers in working with advanced structural ceramics, and to bring about a culture shift. This integrated design–modelling–experiment–manufacturing approach, spanning the ceramics–ensembles–component–system hierarchy, embraces the Integrated Computational Materials Engineering[34] and the Materials Genome Initiative[35] paradigms. Advanced structural ceramics are poised to shape the future of aerospace propulsion, but such paradigm and culture shifts will be needed to accelerate their development and take advantage of their full potential. ❐

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Alloy design for aircraft engines

Tresa M. Pollock

Metallic materials are fundamental to advanced aircraft engines. While perceived as mature, emerging computational, experimental and processing innovations are expanding the scope for discovery and implementation of new metallic materials for future generations of advanced propulsion systems.

As one of the major engineering achievements of the twentieth century, jet engines are among the most technologically complex engineering platforms that, from their inception, have been enabled by materials innovations[1]. Since 1980, commercial airline passenger traffic has grown by approximately 500%, with more than 3.5 billion passengers transported in 2015[2]. The engines on these passenger aircraft consumed US$180 billion in fuel and operated with remarkable reliability[2]. Over the next 20 years it is projected that more than 38,000 new aircraft will be produced[3]. In addition to

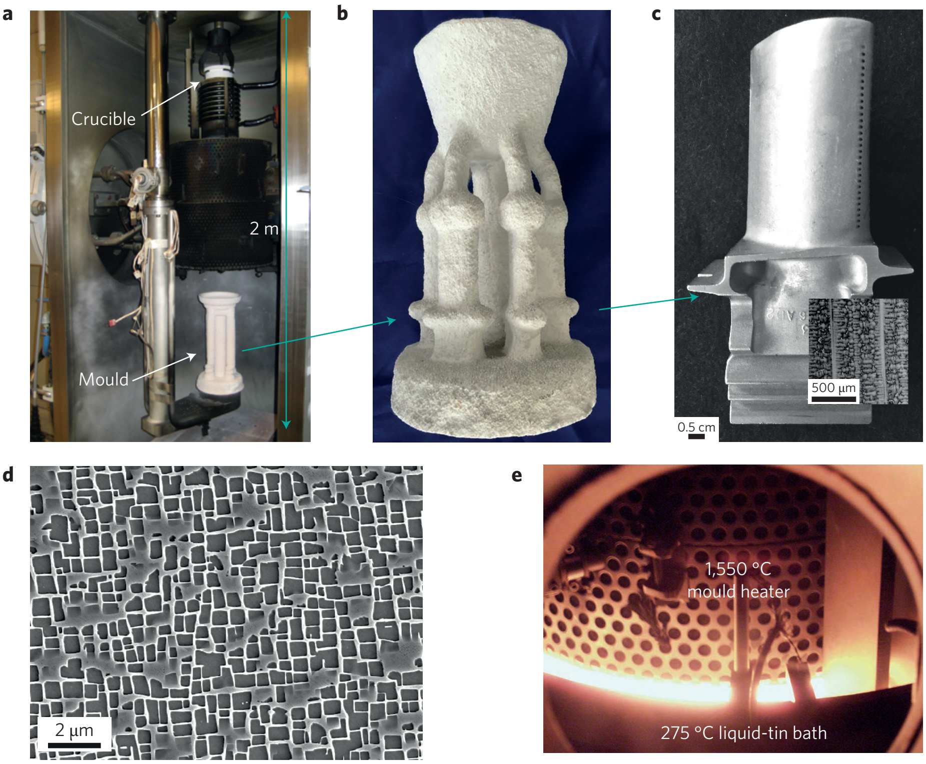

Figure 1 | Growth and microstructure of nickel-based single crystals. **a**–**c**, Bridgman furnaces (**a**) are used for single-crystal growth, such as for turbine blades (**c**) via an investment mould (**b**). The inset in panel **c** shows the typical dendritic microstructure at the millimetre scale, with strong segregation of refractory elements W and Re. **d**, On the micrometre scale, the single crystal is a two-phase mixture of solid-solution-strengthened face-centred cubic nickel (bright, continuous phase) and intermetallic $L1_2$ Ni_3Al (dark phase). **e**, A close-up view of the liquid-metal cooling process in a Bridgman furnace, where the investment mould is withdrawn from a 1,550 °C hot zone into a 275 °C liquid-tin bath to maximize thermal gradient and minimize segregation.

safety and reliability, fuel efficiency and low emissions are priorities for future propulsion systems. These requirements, in combination with the need to design and deploy new engines with shorter engineering lead times, motivate the production of new materials with higher melting points, higher strength, lower density and improved durability that can be rapidly developed with a high degree of confidence in their properties and performance.

Current materials

Current commercial aircraft engines typically range in weight from 2,000 to 8,500 kg (refs 4,5), with metallic materials comprising 85–95% of the weight of the engine[4]. Metals are dominant due to their unique combination of properties, including high strength and toughness, high resistance to degradation under thermomechanical cycling and good surface stability in the severe oxidizing and corrosive environments that are encountered during engine operation. The thermodynamic cycle dictates the gas temperature and pressure and, therefore, the associated suites of available materials for each section of the engine, starting from the fan at the front, through to the compressor, combustor and turbine[5]. For the fan, low-density materials with high toughness are a priority, motivating the production of titanium alloys and polymer matrix composites for blades, combined with some aluminium in outer, static structural components. With compression, the gas-stream temperatures rise through the compressor up to ~700 °C; this section is primarily comprised of titanium alloy blades and disks. In the combustor section, high-temperature nickel- and cobalt-based sheet alloys (with moderate strength to enable wrought processing) have been the main materials of construction. After combustion, gas temperatures are in the range of 1,400–1,500 °C as they enter the high-pressure turbine, where the rotating turbine blades experience the most severe combinations of stress and temperature in the engine. Turbine blades are remarkable aerothermal components, with thin-wall, multilayer geometries that enable complex internal cooling schemes[6]. They are currently comprised of single-crystal nickel-based superalloy substrates that are first coated with an oxidation-resistant intermetallic ‘bond coating’ and subsequently with a porous, low-conductivity yttria-stabilized zirconia top coat that serves as a thermal barrier. The blades are attached to turbine disks comprised of nickel-based alloys in polycrystalline form. Among the most safety-critical components in the engine, the disks are often fabricated from powders that are consolidated and shaped via extrusion and superplastic forging, to maximize strength and fatigue properties[5,7]. As work is extracted from the hot gases through the turbine, the temperatures fall again to moderate levels, below 800 °C. The rotating and static components in the later stages of the turbine section are dominated by polycrystalline cast nickel-based superalloys. The engine shafts, which must possess very high strength and fatigue resistance, are typically composed of either high-strength steels or nickel-based superalloys.

New opportunities

Aircraft engine design combines a broad set of scientific disciplines to optimize an overall system architecture for maximum product capabilities. New materials are typically only worth the risk if they provide a substantial system benefit or enable novel engine architectures. Within the design process there is always a driving force to increase the turbine-inlet temperature for increased efficiency and performance. Thus, higher-temperature materials and coatings for the high-pressure turbine section of the engine are often a major focus of research and development efforts. Historically this motivated one of the well-known materials science achievements, wherein processes for growth of single-crystal turbine blades of nickel-based alloys were developed[6]. The advent of single-crystal processing (Fig. 1a–c), enabled successive generations of nickel-based single-crystal alloys to be developed, with increasingly higher temperature capabilities[5,7]. The improvements in temperature capability were a result of experimentally intensive efforts aimed at tuning alloy compositions to optimize the volume fraction, composition and morphological shape and distribution of the Ni_3Al intermetallic strengthening phase, which is embedded in a highly concentrated Ni solid-solution matrix (Fig. 1d). The outcome is a collection of highly complex alloys, typically containing 8–10 major alloying elements[5,7]. For example, a third-generation alloy in service,

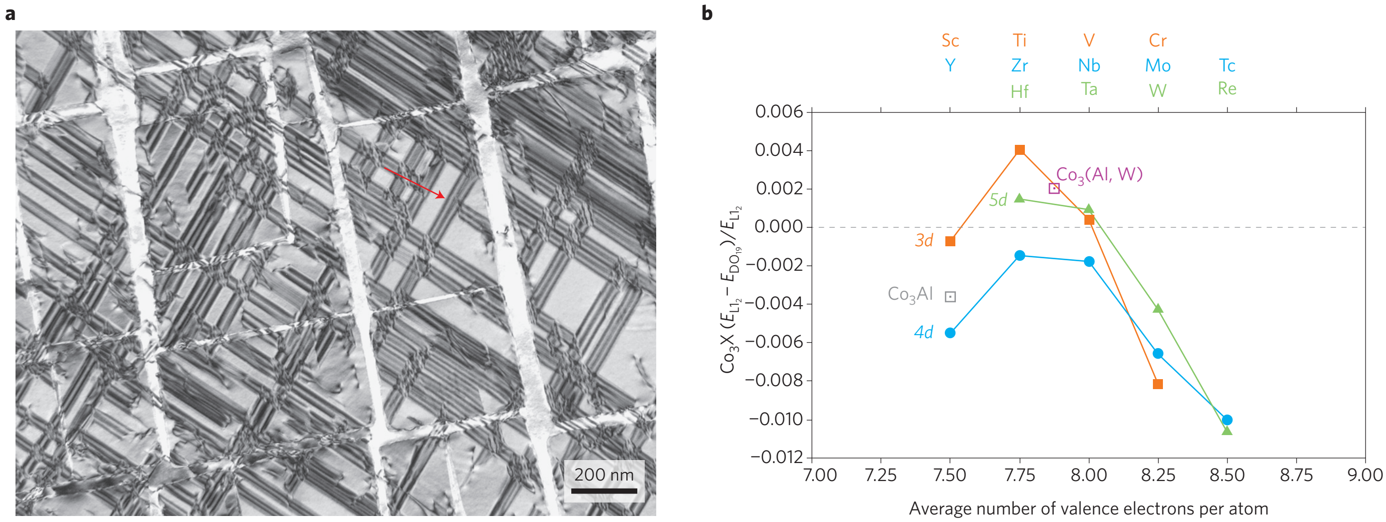

Figure 2 | New Co-based single-crystal alloys. **a**, A transmission electron micrograph of a two-phase Co–Al–W alloy containing Co_3(Al, W) precipitates embedded in a continuous face-centered cubic, solid-solution-strengthened Co matrix (bright continuous phase). Deformation at high temperature occurs by an unusual mode of precipitate shearing, creating faults in the intermetallic precipitates (indicated by the red arrow). **b**, Density functional theory calculations[17] have been employed to calculate the relative thermodynamic stability and fault energy (both proportional to the energetic term $(E_{L1_2} - E_{DO_{19}})/E_{L1_2}$) as a function of composition of the Co_3X phase, with the hypothesis that higher stability and higher fault energy will lead to high-temperature strength. Elements predicted to have a positive effect (Ta and Ti) do indeed provide the highest level of strengthening observed to date[17,18]. Note that Re additions would be detrimental. Part **b** reproduced with permission from ref. 17, Annual Reviews.

René N6, has a nominal composition of 57.5Ni, 12.5Co, 7.2Ta, 6.0W, 5.8Al, 5.4Re, 4.2Cr, 1.4Mo, 0.15Hf and 0.05C (wt%). A more complex alloy with an even higher temperature capability (not yet used commercially), TMS-238 (ref. 8), has a composition of 57.8Ni, 7.6Ta, 6.5Co, 6.4Re, 5.9Al, 5.0Ru, 5.0W, 4.6Cr, 1.1Mo and 0.1Hf (wt%). As the levels of potent refractory element strengtheners (Re, W, Ru) have risen and the size and geometric complexity of single-crystal components has increased, the propensity for the breakdown of solidification due to refractory-element-induced convective instabilities has motivated the development of new 'high-gradient' crystal-growth approaches[7]. Examples of high thermal gradient processes include the liquid-metal cooling approach (Fig. 1e), where the ceramic investment mould that contains the single crystals (Fig. 1b) is withdrawn into a cooling chamber where thermal gradients are enhanced by the presence of a circulating bath of liquid metal (either tin or aluminium) or, alternatively, inert gas[9,10].

The global abundance, supply risk and price of some of the constituent elements of these single crystals are of concern. This includes Ru, Re, Ta and W, which impart high-temperature strength and may comprise up to 20–25 wt% of the alloying constituents. For example, the current price of Re is US\$2,500 kg^{-1}, but in 2008 it rose to more than US\$10,000 kg^{-1} due to expanded use of Re in both aircraft engines as well as in new, high-efficiency power generation turbines. This motivated the development of low-Re and Re-free single-crystal compositions[11]. While new generations of materials for turbine airfoils often require 6–10 years to develop, the urgency of the Re supply problem motivated, for the first time, a rapid data-driven approach to the development of alloys, with minimal experiments and only two years to full qualification[11].

The introduction of materials that provide step-change improvements in capability, but possess overall properties that are substantially different from the materials they displace, has been an even greater challenge. These new materials, often by necessity produced with novel processing routes, typically require decades of development before they impact commercial engines. Intermetallic alloys based on the compound TiAl are an example of a new class of materials that overcame this challenge. With a density of 3.9 g cm^{-3}, alloys based on TiAl are ideal for replacing polycrystalline Ni-based alloys (≈8.5 g cm^{-3}) in the cooler, low-pressure turbine section. This compound was the subject of electron microscopy studies in the 1950s, alloying and property research in the 1970s, commercial alloy and process development in the 1980s and the first engine test in 1993. Entry into commercial service (GEnx on Boeing's 787 Dreamliner) finally occurred in 2012[11,12], with the introduction of two stages of TiAl blades resulting in a weight reduction of 400 lbs. The lengthy development path for this system[12] resulted from a variety of factors. First, the low and highly variable tensile ductility of these alloys, typically in the range of 1–2%, which required an entirely new engine design framework for these semi-brittle materials to be developed. Second, the complexity of the chemistry-dependent phase transformations and accompanying challenges with an experimentally driven optimization approach for a broad suite of mechanical and physical properties. Third, the need to develop processing, fabrication and engine assembly paths for a material that is highly reactive in the liquid state and relatively brittle at room temperature. Last, the added expense of the material with these traits, as well as the associated risk for its first commercial implementation. Given the many lessons learned[12], it is likely that future intermetallic compounds will have a lower barrier for entry into the engine.

The role of computation

At present, there is a convergence of factors that promise to dramatically reduce the time and cost of developing new classes of advanced structural materials[13]; these developments will undoubtedly have a positive impact on aircraft engine materials. First is the advent of materials databases, including (i) rich, highly populated experimental databases (as mentioned for the Ni-based single crystals above),

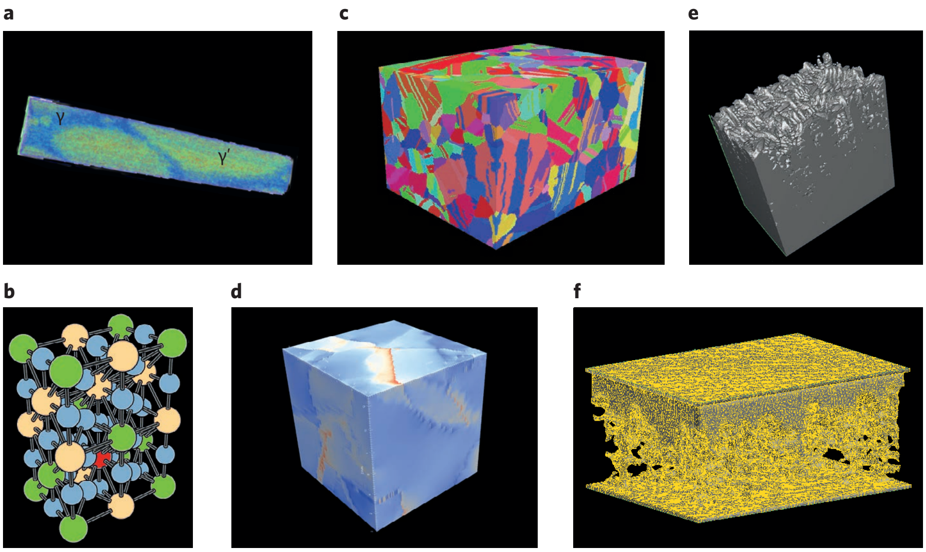

Figure 3 | Tomographic datasets and their corresponding use in modelling. **a**,**b**, An atom probe dataset (**a**), showing partitioning of elements between the γ and γ′ phases in a Ni-based alloy, resulting in an accurate simulation cell (**b**) for density functional theory calculations of fault energies as a function of precipitate chemistry. **c**,**d**, A mesoscale TriBeam 3D dataset (**c**) of the grain structure and orientation (indicated by colour) with annealing twins in a polycrystalline Ni-based turbine disk alloy (200 μm × 250 μm × 150 μm), with (**d**) being an analysis showing a stress hot spot (in 50 μm^3 subvolume) that is a likely fatigue initiation site. **e**,**f**, A robotic serial-sectioned single-crystal solid/liquid interface (2.3 × 2.3 × 1.5 mm; panel **e**), with a resulting meshed model (**f**) for fluid flow calculations of permeability. Parts **e**,**f**, reproduced with permission from ref. 23, Elsevier.

(ii) computational thermodynamic and kinetic databases for multicomponent systems and (iii) dynamically expanding databases being populated with materials properties via automated first-principles calculations. Examples include the well-known Calphad databases[13] and the more recent Materials Project database[14] which currently contains ~65,000 inorganic compounds, with band structures available for 43,650 of these compounds and elastic tensors for 2,270 compounds. This rapid expansion of knowledge regarding the barely explored higher-dimensional compositional space is leading to new materials discoveries. For example, ternary Co–Al–W and quaternary Co–Al–Nb–Mo cubic $L1_2$ intermetallics were discovered in 2006 (during a Calphad assessment) and in 2015, respectively[15,16]. This kicked off the development of a whole new class of high-temperature structural materials that potentially offer higher temperature capabilities relative to the Ni-based alloys[17,18]. For the new Co-based systems, emerging computational tools have further served to quickly focus searches on the most promising dimensions of multidimensional space. As elaborated on in Fig. 2, density functional calculations have been used to select major alloying additions that maximize the stability and volume fraction of the Co–Al–W intermetallic precipitates and to tune fault energies to maximize high-temperature mechanical properties. These calculations interestingly demonstrate that, unlike the Ni-based systems, rhenium will not provide significant strengthening. Compared with early-stage alloy exploration exercises for prior generations of Ni-based alloys, we estimate that the widespread availability of such computational tools could reduce the time for early-stage exploration by 3–5-fold for most metallic systems. More systematic mapping of higher-order compositional spaces is likely to reveal many more promising materials opportunities that can be explored with this expanding set of computational tools.

The rapid expansion of computational power has also enabled multiphysics simulations that enable prediction of transport, structure, defects and properties at the nano-, micro- and mesoscale[19]. This has enabled the simulation of a wide spectrum of relevant phenomena, including diffusion, solidification, hot working and superplastic forming operations, as well as the morphological evolution of phases and grain structure. However, plasticity remains a major challenge, as simulations of dislocation dynamics are still limited in their ability to predict 3D bulk plastic deformation phenomena, particularly in multiphase materials.

An overarching goal for engine manufacturers is the integration of the emerging predictive tools across length- and timescales to enable property prediction with the degree of confidence required for safety-critical materials in aircraft engines. Robust homogenization schemes and uncertainty quantification are key elements of an infrastructure for property prediction. Maintaining a strong feedback loop between experiment and theory/modelling is critical for the guidance of both the models and the critical experiments that provide the information needed to build models. This is the motivation of many current research efforts, which can loosely be categorized as Integrated Computational Materials (Science) and Engineering (ICME or ICMSE)[13,19].

Advanced characterization

The prediction of properties with a desired degree of confidence (often >95% for materials in aircraft engines) and in a location-specific manner within a component requires a statistically significant measure of microstructure, often in three dimensions. Tremendous advances in tomography now enable the acquisition of large-scale 3D data. This includes the atom probe at the atomic scale, focused ion beams at the nanoscale, lab-scale and synchrotron X-ray sources, and robotic-based and femtosecond laser-based serial sectioning[20–25]. Examples relevant to aircraft engine materials (Fig. 3) include an atom probe dataset and a femtosecond-laser Tri-Beam grain-scale dataset of a nickel-based turbine disk alloy, and a robotic serial-sectioned dataset of the dendritic structure at a single-crystal solidification front. Parallel first-principles, deformation and fluid flow models that take the tomographic data as input are also shown. As apparent in Fig. 3, the 3D data can be directly meshed for subsequent thermal, mechanical or fluid calculations, or alternatively used to generate statistical distributions of structural features to create virtual instantiations for further analysis. Such simulation protocols are rapidly evolving and promise significant advances in our ability to predict a spectrum of properties without the need for large-scale experimental characterization.

Many of the critical mechanical properties of the nickel alloys in the turbine section and the titanium alloys that comprise the major portion of the compressor are controlled by the plastic deformation at the scale of the microstructure. New digital image correlation techniques[26,27] that employ nanometre-scale markers and corrections for sample drift and lens distortions in the scanning electron microscope allow for *in situ* examination of the local deformation processes and their dependence on microstructure. Fig. 4 shows the influence of material structure on strain localization during monotonic and cyclic loading of nickel-based and titanium-based alloys that are deployed in safety-critical turbine disks in the turbine and compressor sections of the engine, respectively. Such information motivates the development of alternate material processing paths that change structure and induce more favourable plastic deformation modes. Capturing the details of these complex deformation patterns in constitutive models that can be embodied in finite element analyses remains a major challenge. Nevertheless, as the experimental, computational and big data tools continue to mature in their ability to pass information along the length scales and timescales, it is expected that entirely new classes of materials and processes for their manufacture will be deployed into engines at much faster rates and at a fraction of the cost[14].

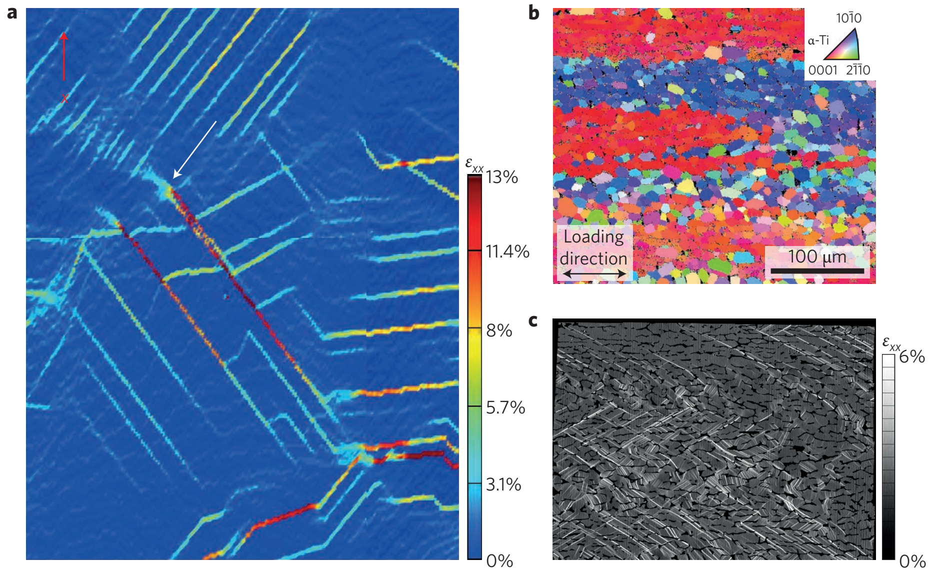

Figure 4 | Strain maps measured during *in situ* straining in a scanning electron microscope. **a**, In a nickel-based polycrystal (the same as shown in Fig. 3c), strains (ε_{xx} are strongly localized along twin boundaries (during 1% macroscopic straining of the sample). The white arrow also shows strain concentration as a slip band impinges on a grain boundary. The red arrow indicates loading direction (x). **b**,**c**, Ti–6Al–4V at a strain below the macroscopic yield point: localized strain processes are strongly influenced by grain texture (**b**) and deformation is very inhomogeneous (**c**). Part **a** reproduced with permission from ref. 27, Springer.

Emerging materials

The Ni-based single crystals that currently represent the highest-temperature materials in the safety-critical rotating components of the engine tolerate temperatures in operation of up to 1,100 °C, with occasional hot spots approaching 1,200 °C (refs 28–30). Remarkably, this approaches ~90% of the temperature where the onset of melting occurs. New ceramic thermal barrier coatings (TBCs) will allow for further increases in gas temperature. However, the substantial differences in the elastic and thermal properties of these ceramic coatings necessitate the development of interlayers, known as bond coatings, that mitigate the property changes between the metallic substrate and the ceramic top coat[30]. These bond coatings are typically a mix of metallic and intermetallic phases with high Al content, so that in addition to serving a mechanical role, they additionally provide protection against oxygen diffusion into the substrate via the formation of a protective Al_2O_3 layer. Currently these bond coatings suffer from insufficient high-temperature strength; new higher-strength bond coat compositions are currently under development[31].

Beyond highly engineered multilayers, new classes of substrate materials with higher melting temperatures are required. The new Co-based materials discussed above potentially provide a 100–150 °C benefit relative to Ni-based alloys, with the added advantage of an existing supplier infrastructure[17]. Materials with an even higher potential benefit regarding temperature include refractory alloys based on Mo and Nb, and ceramic matrix composites (CMCs). These higher-temperature materials all represent a greater challenge from the processing point of view. They also possess distinctively different combinations of mechanical and environmental properties, including limited low-temperature tensile ductility and a high propensity for oxidation. In this sense they can all benefit from prior design efforts for brittle titanium aluminides, multilayer design approaches and from advanced ICMSE tools currently under development.

Nb-based systems have been of interest due to their relatively low density (ρ = 8.56 g cm^{-3} for pure Nb) and the ability to synthesize *in situ* composites[28]. An example is an alloy of composition Nb, 19Ti, 4Hf, 13Cr, 2Al, 4B, 16Si (at%) which contains a mixture of a solid-solution-strengthened Nb, Nb_5Si_3 silicide and Cr_2Nb Laves phases. While the creep properties of these Nb–Si alloys exceed those of Ni-based single crystals, achieving a balanced set of properties, including oxidation and toughness, along the distinctively different processing paths required remains a challenge[28]. With respect to the molybdenum system, multiphase alloys based on the Mo–Si–B ternary offer the greatest promise[29,30]. These alloys contain a mixture of the high-temperature ternary intermetallic Mo_5SiB_2 (T2) phase, $MoSi_3$ (T1) and a solid-solution-strengthened body-centred cubic Mo phase. In current engines the Ni-based alloys typically contain aluminium, which is selectively oxidized to form a dense, protective Al_2O_3 layer at elevated temperatures. In the higher-temperature domains where Nb, Mo and CMC-based systems aim to operate, Si additions become more desirable, as the parabolic rate constant for oxidation is lower compared with Al above 1,300 °C (ref. 30). The three phase Mo-based alloys possess some degree of oxidation resistance due to the formation of an adherent borosilicate layer at elevated temperatures[30]. However, the high viscosity of both SiO_2 and the borosilicate that forms below 800 °C results in poor oxidation in the lower temperature range[29]. Promising borosilicide coatings applied by pack cementation have recently been developed[31]. Also, Mo–Si–B alloys containing Ti exhibit high-temperature creep properties (beyond second-generation nickel-based single crystals); these material variants synthesized by powder processing to obtain fine distributions of the constituent phases are stable at 1,300 °C (ref. 32). A powder processing approach avoids many of the problems of conventional casting by greatly reducing the segregation induced by the solidification path[32].

At the front of the engine, the fan, which may have a diameter in excess of 3 m with complex-shaped blades that approach 1.5 m in length, requires low-density, materials with high toughness that can

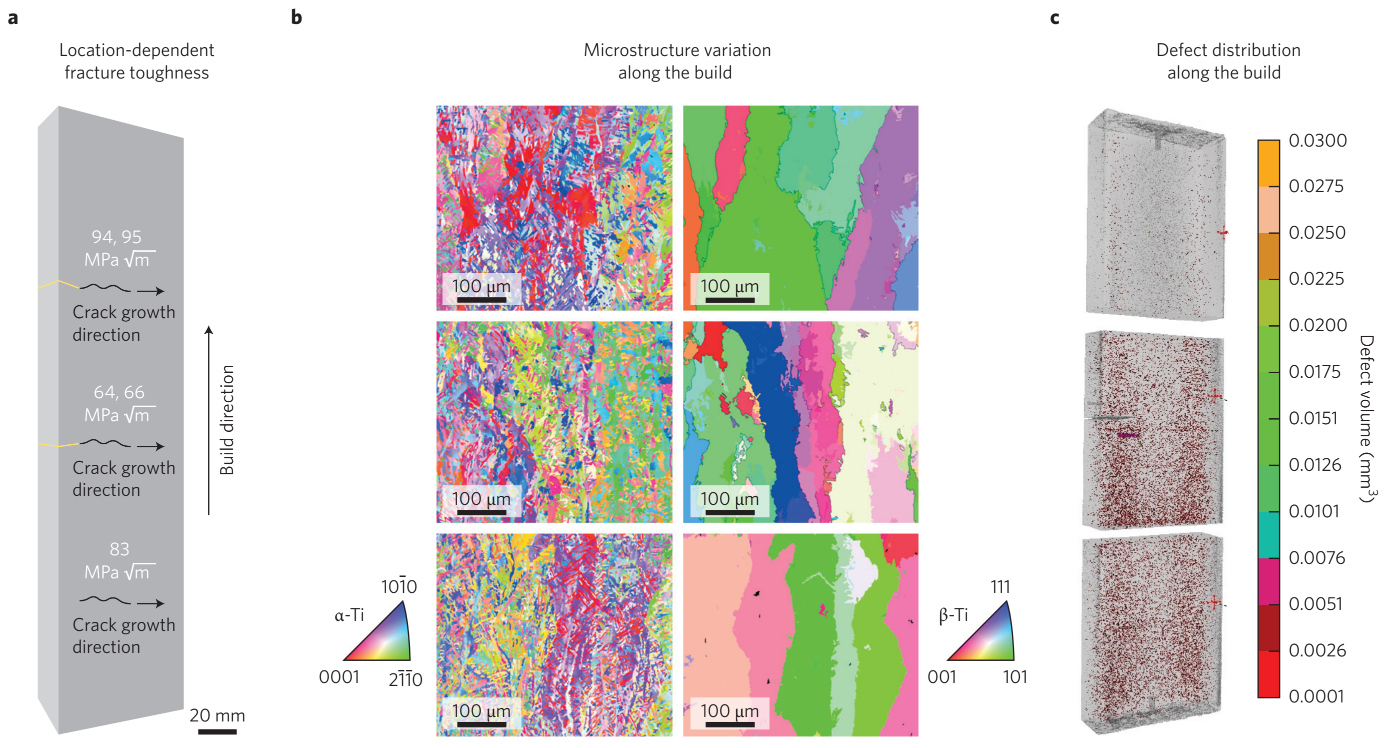

Figure 5 | Structure and defects in additively manufactured titanium. **a–c**, Variation in fracture toughness (in units of MPa √m) (**a**), grain structure and texture (**b**), and defect content (**c**) as a function of build height in as-built Ti–6Al–4V samples fabricated by an electron beam additive manufacturing process. Parts **a–c** reproduced with permission from ref. 37, Annual Reviews.

withstand impacts from foreign objects ingested on runways or in flight. For many years, fan blades have been manufactured with titanium alloys, evolving from solid blades to hollow blades produced through superplastic forming[33]. In recent years there has been significant innovation in the development of new materials and hybrid metal–composite structures that can tolerate the stringent requirement that these blades be contained within the body of the engine if they should suffer a catastrophic impact, for example, if a bird is ingested in the engine. Carbon-fibre epoxy resin composites have enabled significant reductions in weight and may be combined with titanium or new Al–Li alloys in a hybrid structure to improve durability[34].

Additive manufacturing

The advent of improved computational tools for mechanical, aero and thermal design of turbine components has resulted in greater geometric complexity of many engine components. The additional trend toward production of metallic materials in powder form increasingly motivates the development of additive manufacturing approaches. In the past two decades tremendous advances have been made in the development of laser- and electron-beam-based additive manufacturing (AM) systems for layered synthesis of metallic systems[35–37]. This includes a large suite of approaches that involve melting, including powder-bed processes such as electron beam melting, direct metal laser sintering and selective laser sintering; powder-feed processes such as laser engineered net shaping; and wire-feed deposition processes. These layer-by-layer manufacturing processes enable fabrication of geometrically complex components in near net shape form with rapid transfer of 3D designs to final components. For example, laser-printed fuel nozzles in new GE LEAP engines weigh 25% less and reduce the number of parts to be assembled from 18 to 1 (ref. 34). Due to strong material anisotropy[35–37] and an incomplete understanding of the defects that are associated with this suite of 3D printing approaches, all early applications are likely to be non-rotating structural components. Figure 5 shows an example of the significant variation in defects, structure and properties as a function of build distance in Ti–6Al–4V manufactured by an electron beam additive process[37]. Major challenges remain in demonstrating the integrity and predicting the properties of metallic components manufactured by these additive processes to the degree of confidence required for operation in the extreme environments of the aircraft engine. Advances in the ability to gather and analyse large sensor-based datasets and new non-destructive evaluation approaches are likely to be required to ensure integrity and reproducibility of structure and properties.

Outlook

Metallic materials, with their unique combinations of mechanical and thermophysical properties, are likely to remain as major constituents of aircraft engines and other related advanced energy-generation and propulsion systems, particularly in safety-critical rotating turbine and compressor components such as disks and blades. Emerging tools for discovery, design, characterization and property prediction will greatly enhance and accelerate the discovery and development process for new metallic and intermetallic systems. The severe environment of the turbine engine will increasingly motivate the development of multilayered, multimaterial designs for increased functionality. Processing innovations, exemplified by the early development of single-crystal growth processes for turbine blades and by the recent activities in additive manufacturing, will continue to positively impact these platforms. ❐

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Policy needed for additive manufacturing

Jaime Bonnín Roca, Parth Vaishnav, Erica R. H. Fuchs and M. Granger Morgan

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].