Guest Editorial

Additive manufacturing

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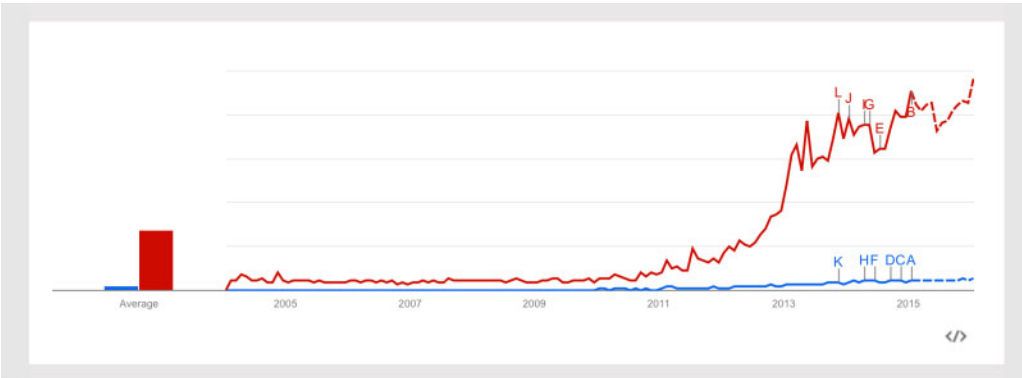
There has been rapidly growing interest in additive manufacturing (AM) across the world in recent years, as the capabilities of this set of technologies have been recognised and developed. The announcement of an initiative by the President of the USA to start an institute focused on AM,[1] as part of the National Network Manufacturing Innovation Institute, resulted in a significant increase in the search terms 'additive manufacturing' and the popular media's preferred term '3D printing' (see Fig. 1).

The ability to produce complex parts at reduced cost, including designs not able to be produced by traditional manufacturing, has enabled low volume production and customised products to become economically viable in many situations. This has led to reductions in lead times for product development and allows manufacture at source. An additive approach has also been seen to reduce assembly time and to offer the potential for improved sustainability through efficient use of materials. These advantages have already impacted a wide range of high value industries including aerospace, automotive and healthcare.

This leads to an obvious question: why has this technology not been more widely adopted across a manufacturing economy that is worth US$5.7 trillion?[2] The current lack in diversity of materials able to be processed using AM techniques, coupled with an incomplete understanding of how materials are affected by processing and the properties of the produced parts, is preventing these technologies being used in situations where considerable benefits could otherwise be achieved. There is a pressing need for more comprehensive verification, validation and qualification of parts made by this technology.

The need for trial and error experimental optimisation negates the economical benefit of AM going from CAD to part in one step. In addition, the lack of robust *in situ* process control or validation of material microstructure and resulting mechanical properties in AM parts limits their use to niche non-structural applications. Furthermore, there is a lack of sophisticated CAD models which can consider optimisation of topology (e.g. geometry), processing routes (e.g. scan paths) and resulting scatter in material properties (e.g. fatigue). This special issue of *MST* provides a snapshot of the ongoing research and development across many institutes to address these challenges, as well as the unique opportunities offered by AM processes.

Topology optimisation, design of AM parts: As a result of the fact that AM technologies can realise physical components with complex geometry from CAD easily, AM of topology optimised engineered structures has gained traction. EADS engineers demonstrated this concept by designing and manufacturing an Airbus A320 nacelle hinge bracket[3] having a form that can be manufactured only by AM technologies. Often, the objective function of the optimisation is to satisfy load bearing through changes in geometry. However, in this issue, Kim and co-workers[4] provide the next step in topology optimisation that includes geometry and materials. The topology optimisation algorithms work with commercial finite element methods, which in turn require constitutive properties of materials along different directions. Conventional finite element methods use experimentally measured anisotropic properties of AM parts, without an in-depth understanding of load partitioning. In this issue, Rezayat *et al.*[5] evaluate the role of load transfer between contours and rasters in AM parts made by a single layer fused deposition modelling method. In future, such evaluations have to be



1 Google trend data demonstrate rapid increase in popularity of terms related to 3D printing (red (upper) line) and additive manufacturing (blue (lower) line)

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repeated for all AM components with due consideration of multimaterials (metallic, polymer and ceramics), non-linear and temporal stress–strain behaviour (plastic deformation and creep), as well as fatigue crack growth. Along the same lines, Munguia and Dalgarno[6] address the fatigue behaviour of Nylon 12 parts fabricated by laser sintering. With emerging large scale AM processes,[7] such computational evaluations will require high performance computational (HPC) infrastructure.

Role of computational modelling of AM: The role of computational models to predict heat and mass transfer associated microstructural evolution, as well as plastic deformation leading to residual stress and distortion, in welding is well known.[8] The philosophy of using computational models is embodied in the new worldwide materials initiative known as integrated computational materials engineering (ICME).[9] It is noteworthy that even though it is possible to leverage the existing ICME tools for AM technologies, there are no published integrated tools for all the existing AM technologies. However, pioneering work is being performed across the world to address this challenge, one process at a time. In this special issue, Gockel *et al.*[10] have used simple two-dimensional (2D) finite element models to describe the processing map (function of process power and velocity) in electron beam wire AM. This model is able to predict the desired melt pool depth as well as grain size during AM of Ti–6Al–4V samples. Such processing maps can be used to reduce the scope of trial and error experimentation. The above 2D heat transfer models have limitations in describing the complex solidification grain structure due to the role of convective liquid motion. For example, Kempen *et al.*[11] use experimental process optimisation for single tracks that considers wetting and fluid flow issues to achieve builds with less porosity and acceptable microstructure and properties. The above optimisation cannot be achieved by models considering only heat transfer. To address the above limitation, Manvatkar *et al.*[12] have used detailed three-dimensional (3D) models capable of solving conservations of mass, momentum and energy conservation, as well as material addition. Based on these calculations, they have calculated liquid flow velocities in the range of 0.4–0.6 m s^{-1}, as well as temporally varying temperature gradient (G, dT/dx) and liquid/solid interface velocities (R, dx/dt). The spatial variation of temperature, G and R, will have a large impact on solidification grain structure. The role of G and R on solidification grain structure is also discussed in the papers by Dehoff *et al.*[13,14] in this issue. Extension of the above heat and mass transfer models to powder bed fusion techniques often faces challenge with respect to number of melt beads and their lengths in a unit volume of AM build due to the small size (100–200 μm) of the molten pool. In this issue, Zeng *et al.*[15] outline an innovative dynamic meshing routine to address this challenge. Finally, King *et al.*[16] outline the need for multiscale modelling within HPC to capture the physical processes that occur in the size scale of powder interfaces (<1 μm), melt pool ($\sim$100 μm) and part geometry ($\sim$ mm), including melting, solidification, residual stress and distortion. Data mining methodologies to extract optimum processing conditions from experimental and modelling data are also outlined in this contribution.

Microstructure evolution during AM and mechanical properties: As mentioned above, all the fusion based metal AM processes lead to unique combination of G (thermal gradient) and R (liquid/solid interface velocity) during processing. The welding literature suggests that by changing G and R, it is possible to attain columnar grain growth or equiaxed grain solidification.[17] Unlike casting and welding, electron beam melting and direct metal laser sintering (DMLS) powder bed fusion processes are capable of controlling G and R spatially within a few hundreds of micrometres by manipulating the energy delivery and scan paths. Dehoff *et al.*[13,14] have used this idea to manipulate the crystallographic texture during AM of Inconel 718 alloy builds. The above demonstration provides a unique pathway for the future design of metallic AM parts. For example, it is well known that fatigue crack growth in single crystal nickel based alloys is very sensitive to the orientation of the crystals with reference to loading axis.[18] It is quite conceivable that, using the methodology outlined by Dehoff *et al.*,[13] it will be possible to optimise the crystal orientation within a component to achieve site specific properties. Along similar lines, Kempen *et al.*[11] observed the spatial variations in the microstructure in a laser powder bed process, concluding that the properties of the AM part are equivalent to or better than the properties achieved by high pressure die casting. The alloys (Al–10.5Si–0.5Mg wt-%) used in these processes are close to the eutectic composition and often not age hardenable. However, the authors report a substantial increase in hardness (136–152 HV) after aging at 175°C for 6 h. This leads to a fundamental question: will the use of rapid liquid/solid interface velocity during DMLS lead to non-equilibrium solute trapping?[19] Further in depth analyses by atom probe and high resolution transmission electron microscopy will be necessary to confirm precipitation during aging.

Manufacturing of hybrid materials with unique properties: AM technologies can accelerate the manufacture of hybrid materials that combine metal, polymer, ceramic, glass and elastomers in different forms and functions.[20] In this issue, Bhat and Bourell[21] report the manufacturing of a hybrid (Cu–SiC) metal matrix composite material by laser sintering and electrodeposition. Interestingly, they found that this manufacturing process led to a material with low coefficient of friction as well as high hardness.

On the evidence of the 11 papers commissioned for this issue, the editors are optimistic that with due diligence and by leveraging the fundamental principles of materials science developed over the last century, AM technologies will usher in on-demand and mass customised hybrid components at low cost and for high value added applications, thereby competing with traditional manufacturing in an increasing range of applications.

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