ARTICLE IN PRESS
SMM-11342; No of Pages 6
Scripta Materialia xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Scripta Materialia
journal homepage: www.elsevier.com/locate/scriptamat

Viewpoint Article

Design for additive manufacturing with site-specific properties in metals and alloys

S. Tammas-Williams *, I. Todd

Department of Materials Science and Engineering, University of Sheffield, Sheffield, S1 3JD, UK

ARTICLE INFO

Article history:
Received 7 September 2016
Received in revised form 19 October 2016
Accepted 22 October 2016
Available online xxxx

Keywords:
Additive manufacture
Functionally graded materials
Material properties

ABSTRACT

Intelligent application of materials with site-specific properties will undoubtedly allow more efficient components and use of resources. Despite such materials being ubiquitous in nature, human engineering structures typically rely upon monolithic alloys with discrete properties. Additive manufacturing, where material is introduced and bonded to components sequentially, is by its very nature a good match for the manufacture of components with changes in property built-in. Here, some of the recent progress in additive manufacturing of material with spatially varied properties is reviewed alongside some of the challenges facing and opportunities arising from the technology.

1. Introduction

The general advantages of additive manufacturing (AM) have been extolled by numerous authors [1–4]. However, one area where the advantages are still being explored, and are not as widely recognised, is using AM to generate materials with site-specific properties (MSP). By changing the material properties with position one can produce a more efficient engineering structure than would be possible with homogenous properties alone. Alternatively, without the use of MSP, engineers may be left with a choice to either use an advanced, and likely expensive, material for whole AM components when only a small section actually requires these properties, or redesign a less efficient structure. Examples of where it is desirable, or even necessary, for material properties to change with location can be found in both advanced engineering components and more common objects. Properties are typically altered by changing the composition, phases or microstructure with location.

While using AM to generate MSP is a relatively new opportunity, MSP have been used in advanced engineering structures for a number of years. In fact, depending on how strictly one wishes to define the concept of MSP, their development can be traced back millennia. One early, but still widely practised, method of manufacturing MSP is carburising, whereby the diffusion of carbon atoms is used to alter the carbon content and hardness of metallic materials. Ancient Egyptian axes, dating back approximately three thousand years, were carburised to produce a more than six-fold increase in the hardness of the material surface in comparison to the centre [5]. Similar to a modern kitchen knife, the hard but brittle cutting tip would remain sharper for longer, while the tougher internal material prevented fracture of the tool. Of course, in the years intervening between the manufacture of the axes and kitchen knives, huge steps forward in terms of manufacturing and properties of MSP have been made.

Travelling back even further in time, and turning our attention to the natural world, we find that MSP are the norm, and have been so for millions of years. Evidence suggests that fish 96 million years ago had scales which varied gradually in hardness with distance from the scale surface. Under biting attack from a rival or predator, the hard outer coating helped prevent penetration of the scale, while the softer material beneath dissipated the energy [6]. Natural structures almost invariably contain smooth variations in material properties to make best use of the raw material available. It is the authors' belief that this is where the future of using AM to generate MSP lies. Rather than discrete changes between material properties, by gradually changing material properties from location to location a number of benefits can be derived. To summarise:

- Improved bonding between dissimilar materials [7].
- Mechanical stress concentrations can be reduced, increasing component life [8–10].
- Reduction in thermal stress caused by different expansion coefficients [11,12].
- Removal of the distinct boundary in material properties can reduce the crack growth rate through different materials [13].

Such materials are commonly referred to as functionally graded. A metal-ceramic composite, developed in Japan in the 1980s, is considered a major step forward in the application of functionally, and compositionally, graded material [14]. A rocket casing material was required to withstand a maximum temperature of 2000 K and gradient of 1000 K over 10 mm, without developing high thermal stresses. It was only by

* Corresponding author.
E-mail address: s.tammas-williams@sheffield.ac.uk (S. Tammas-Williams).

http://dx.doi.org/10.1016/j.scriptamat.2016.10.030
1359-6462/

Please cite this article as: S. Tammas-Williams, I. Todd, Design for additive manufacturing with site-specific properties in metals and alloys, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.10.030

gradual change of material properties could a suitable component be manufactured. In addition to aerospace, other potential applications of MSP are found in biomaterials, defence, energy conversion and many other fields [15,16].

The gradient of the property change is of great importance in determining the overall behaviour of MSP. Possible gradients between distinct material properties/compositions are shown schematically in Fig. 1 and examples of each will be highlighted later. The most obvious transition between two compositions is the discrete version shown in Fig. 1a, comparable to a dissimilar metal weld. However, such a boundary is rarely achievable in practice, due to factors such as mixing of alloys in a melt pool, and may lead to undesirable effects; for example, DuPont reviews the issues associated with dissimilar ferrite to austenitic welds [17]. A gradual transition from one alloy, element or phase, to another shown in Fig. 1b is often favourable. The actual gradient following manufacture will be dependent on the thickness of deposited material layer, melt depth and the control with which the composition can be controlled. Alternatively, the material composition can switch between two or more different compositions at different locations as shown in Fig. 1c. On other occasions it may be desirable or even necessary to have more than two compositions (Fig. 1d). This could be utilised to exploit the different properties or avoid formation of unfavourable phases caused by the mixture of alloys B and C. Finally, with a great enough differential in melting temperatures, a metal matrix composite can be formed with a change in the density of insoluble powder particles in the matrix (Fig. 1e).

The advantages of MSP have led to them being regarded by some as the pinnacle of the modern material hierarchy [18]. Others have suggested that the current 'holes' in maps (stiffness/yield strength against density) of available materials may be filled by use of materials which combine two phases of differing properties. For example, Ashby [19] showed that in a sandwich panel, with a low density core and stiff outer sheets, can effectively fill requirements for high specific strength/stiffness materials. Similarly, lattice structures, where the absence of material could be considered the second phase, can provide relatively high mechanical properties for the low density region they occupy; one potential use is as the core of a sandwich panel. It should be noted that with such materials the geometric arrangement of the two phases is of critical importance in determining the overall material property [19,20], and thus careful consideration must be given to both the tolerances in the design and accuracy of manufacture of such structures to ensure they meet the requirements.

In addition to the issue regarding tolerances alluded to above, there are a number of other challenges facing MSP before they can be widely adopted into industrial use, not least the higher costs associated with their manufacture, either by AM or other methods. This paper will highlight some these challenges and, where possible, potential routes to overcome them. First though, some of the recent progress in producing MSP by AM is summarised in order to provide context to the challenges that are faced by the technology.

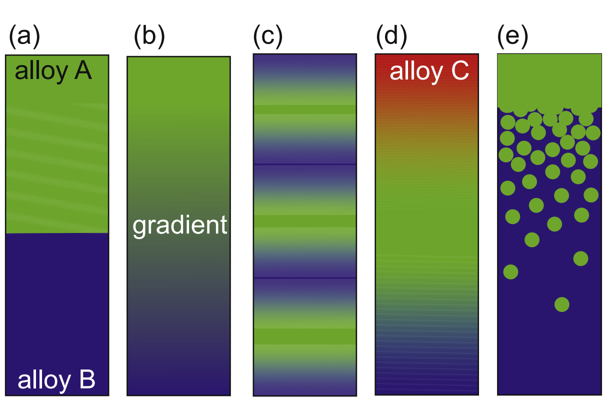

Fig. 1. Schematic diagram of potential material composition/property transitions. Redrawn from the examples provided by ref. [23].

2. Additive manufacturing of material with site-specific properties

While AM is the focus of the discussion presented here, it is important to realise that it is only a subset of possible methods for manufacturing MSP. The multitude of possible different manufacturing techniques are discussed elsewhere [5,21,22]. However, the very nature of AM, where material is added layer by layer, means that, in principle, any AM technique could be used to develop a graded structure with properties that vary with location. If all that is required to generate the desired site-specific properties is a change to the heat input strategy, then any AM technique may be as equally useful in their production. On the other hand, if compositional changes are required then some AM processes are inherently more favourable for MSP manufacture. Systems where the feedstock is locally introduced are more easily adaptable for the manufacture of MSP with varying composition, henceforth denoted MVC. For example, the multiple powder feeders arranged around the laser in the direct laser deposition (DLD) system allow a huge number of combinations of both composition and its gradient by dynamic control of the feedstock [23].

A variant of DLD, the laser engineered net shaping (LENS™) process, has been used in an attempt to vary the material composition in the ways illustrated schematically in Fig. 1a & b [24]. By attempting to generate a discrete boundary between two alloys (Fig. 1a), one potential issue with MSP has been highlighted. Despite a discrete change in powder feedstock, the transition between the two chemistries was blurred due to the re-melting of previous layers. Transport of material in the melt pool from the fraction of the re-melted layer into the newly deposited layer meant that it took three layers before the chemistry had completely changed. It is clear therefore that the chemistry of the feedstock does not necessarily correspond exactly to the final spatial distribution of chemistry within components. Thus, when designing components there must be a tolerance in the allowable chemical distribution.

Further considerations of the chemistry must be made if AM is used to generate alloys in-situ. Again the LENS™ process provides an example, this time consisting of two builds, one mixing powders of elemental titanium with niobium and another titanium with chromium [25]. The positive enthalpy of mixing the Ti-10 at.%Nb slowed the solidification and resulted in a poorly mixed, inhomogeneous alloy, whereas the negative enthalpy of mixing the Ti-10 at.%Cr resulted in better mixing and faster solidification. Thus demonstrating another factor that must be accounted for when AM is applied to MVC.

The LENS™ process has also been used to exploit an often overlooked use of MVC [26]. By altering the flow rate from two powder hoppers during a build the composition was smoothly altered from pure titanium to titanium with 25 wt.% vanadium. What makes this work distinct from the other examples mentioned is that, rather than trying to use changes in material property to produce a more efficient engineering component, the intention was to gain understanding of the effect of alloying elements on phase transformations and microstructural evolution in $\alpha + \beta$ titanium alloys.

Unfortunately, not all compositions can be so easily transitioned between. Hofmann et al. [27] suggested that phase diagrams should be examined to find which phases are likely to appear at the interface between alloys. A multi-component phase diagram can give clues as to whether any unfavourable phases will be generated during manufacture. They showed that Ti-6Al-4V could be successfully transitioned to pure vanadium without the formation of brittle phases. In contrast, attempts to build components varying from titanium to Invar or stainless steel failed due to the material cracking during AM. Yet another factor to consider when designing MSP is exemplified.

Please cite this article as: S. Tammas-Williams, I. Todd, Design for additive manufacturing with site-specific properties in metals and alloys, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.10.030