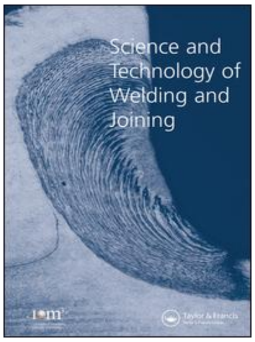

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Harnessing the scientific synergy of welding and additive manufacturing

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ABSTRACT
Additive manufacturing (AM) of metallic materials and welding share many similarities in their physical processes and the way the microstructure and properties of the products evolve. This synergy can be a powerful driver for the scientific and technological advancements of both these important technologies for the benefit of all people. *Science and Technology of Welding and Joining* provides a forum for the exchange of emerging scientific and technological advancements in AM. This special issue of the journal highlights the current research in the AM processes, and the microstructure and properties of metallic components. Furthermore, it identifies some of the current challenges and opportunities for the future.

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Introduction

The main variants of additive manufacturing (AM) or 3D printing for metallic materials share many common features with welding. The similarities have been discussed in detail in a recent review [1], but it is useful to recall them briefly for the discussion here. They include the following: (a) Both use moving heat sources which can be a laser, electron beam, an electric arc or a plasma source. (b) Melting and solidification are important in both processes. (c) Some fusion welding processes use multiple passes to fabricate a joint which is somewhat like the layer-by-layer printing of parts. (d) Phase transformations and the evolution of microstructure and properties during heating and cooling take place in both processes. (f) Defects such as porosity, loss of volatile alloying elements, cracking, and residual stresses and distortion affect the properties and serviceability of parts in both processes. Since many of the personnel now involved in 3D printing have backgrounds in welding, *Science and Technology of Welding and Joining (STWJ)* provides an appropriate forum for the synergistic growth of both technologies. In addition, the history of welding research spanning over almost a century may be helpful to charter a path for the scientific and technological progress in AM. The expertise and the experience of our readers, authors, Editorial Board members and the reach of *STWJ* to the materials research community can be useful for this purpose.

The papers in this special issue cover several variants of AM. They are classified generally based on the types of heat source and the feedstock material used [2]. Directed energy deposition (DED) is a process in which the heat source melts either a stream of powders or a wire using a laser beam (DED-L), an electron beam (DED-EB) or an electric arc (WAAM). In Powder bed fusion (PBF), the heat source selectively melts a powder bed using either a laser or an electron beam. The laser-assisted PBF is also referred as selective laser melting (SLM).

In order to appreciate the diversity of the AM processes covered in this special issue, we examine the variations of the heat inputs in different processes. Why focus on the heat input? One of the enduring lessons from welding research is the important role of heat input in the evolution of microstructure and properties of welds. The ratio of heat source power and welding speed is a measure of heat input per unit length of welds. This parameter is an important indicator of cooling rate which affects both the extent of phase transformations and the scale of microstructures. Figure 1(a) shows that different variants of AM use more than 50-fold variations of power and more than 1000-fold variations of scanning speed [3]. The impact of using these wide ranges of scanning speeds and powers results in a remarkable four orders of magnitude variations in the reported values of heat input [3] as shown in Figure 1(b). This magnitude of variation of heat input is exceptionally large compared to welding. The impact of this immense diversity of heat input is illustrated in Figure 1(b) where the cooling rate is plotted as a function of heat input and shows that the reported rates vary by about three orders of magnitude (about 50,000 times). In short, the parameter space of AM is unusually

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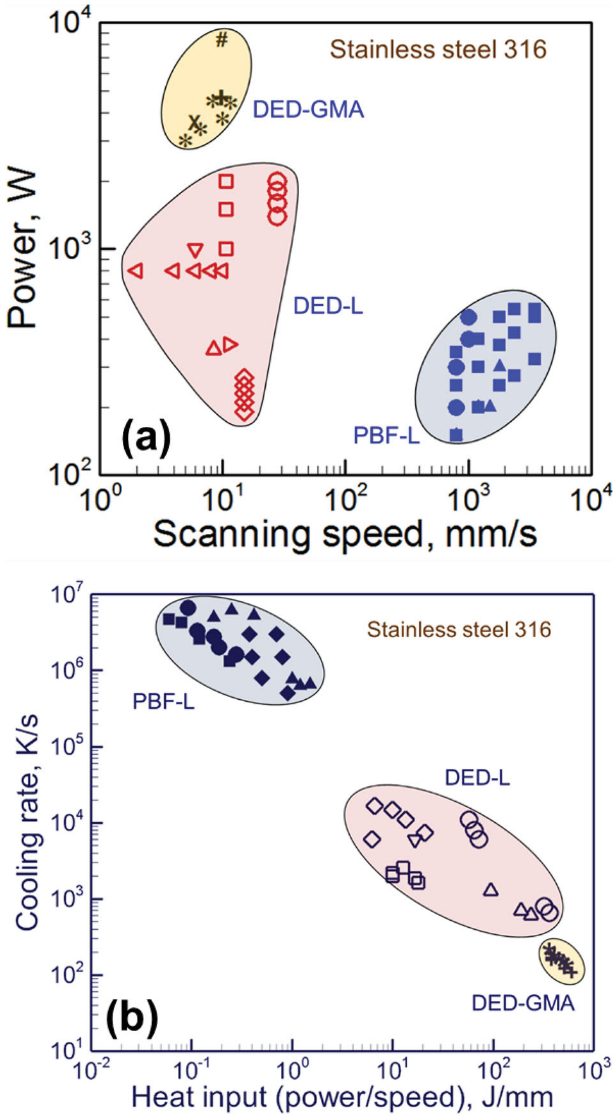

Figure 1. (a) Variations of the reported values of power and scanning speed reported in the literature. (b) Cooling rates and heat inputs reported in the literature [2].

large. Heat inputs in welding do vary significantly from gas-metal-arc welding to laser and electron beam welding. For example, the electron beam and laser beam welding typically use much lower heat input than the arc welding processes. However, the extent of variations pales compared with the AM processes and the diversity in microstructure owing to process parameter variation in welding is not as profound as that in AM. This raises questions about the ease of controlling microstructure and properties. Although investigations have started to examine the relationship between the processing, microstructure, properties and serviceability of many commercial alloys in AM, the wide range of process variables indicates that the progress in this area will take sustained research over a prolonged time period.

Although the current experience in AM has been limited to a handful of alloys, it is fair to say that developing processing conditions to attain a target microstructure is not a straightforward task for welding. Models for the prediction of microstructural features of steels have been well-tested over many decades [4–6]. However, there are two issues that need careful attention to use modelling for the possible tailoring of microstructures. First, the available models for the prediction of microstructures are forward models that require welding conditions to be specified as input to predict microstructures. In contrast, what is desirable is the ability to calculate AM process variables to achieve a desired microstructure. Such inverse modelling has been performed in welding to achieve a particular fusion zone geometry [7,8]. However, because of the diversity of microstructures that can be attained for a commercial alloy, inverse modelling of AM is scarce. Second, AM is more complicated than welding because of the larger number of wide-ranging variables. AM processes depend on the type of heat source, scanning speed, hatch spacing, layer thickness, pre- and post-heating conditions, and the shielding gas. For example, the role of scanning pattern on microstructure development is well recognised for some alloys. Figure 2 shows the effects of unidirectional and bi-directional scanning patterns on the directions of primary dendrites growth [9]. Both the computed and the experimentally determined growth directions show that the heat flow direction was closely aligned to the growth directions. The solidification texture in the bi-directional scanning particularly indicated the importance of scanning pattern. It is important to emphasise here that scanning pattern alone cannot, in most cases, control solidification texture because of the misalignment between the solidification growth direction and the dominant heat flow direction and other complexities of metallic systems. More work is needed to better understand the solidification behaviour in AM [10–11].

This special issue on AM/3D printing contains 14 original research articles and one review article. Editors of *STWJ* invited active researchers working on AM, particularly with backgrounds in welding and joining to contribute manuscripts to this special issue. In addition, an invitation was extended to the readers of *STWJ* to contribute to this issue. The manuscripts received were peer reviewed in the usual manner. The editors appreciate the contributions of all the authors and welcome commentaries and other contributions for the future issues of the journal.

Papers in this special issue

Process

Metallic materials, exposed to focused energy beams during AM, need to be protected against possible oxidation and contamination from the environment in the deposition chamber. Inert shielding gases are used for this purpose. Elmer and Gibbs [12] investigated

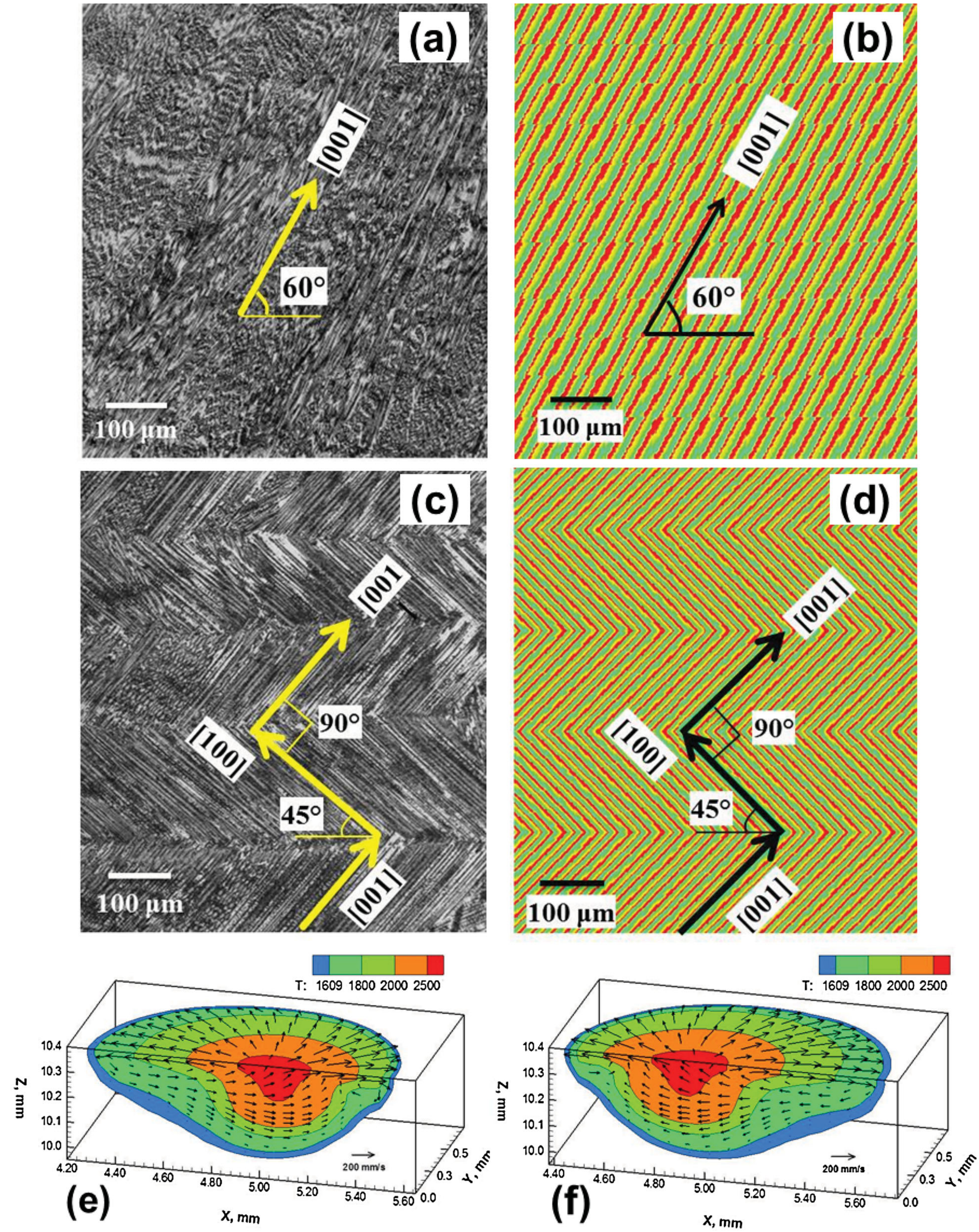

Figure 2. Primary dendrite growth directions [9] in unidirectional and bi-directional laser scanning patterns for DED-L of Inconel 718. (a) experimental result for unidirectional scanning, (b) computed dendrite growth direction for unidirectional scanning, (c) experimental result for bi-directional scanning, (d) computed results for bi-directional scanning. Typical fusion zone temperature and velocity fields for scanning (e) from left to right and (f) from right to left.

the effects of atmospheric contamination on WAAM of stainless steel (SS) 308L, Ti–6Al–4V, and pure Ta components which have different affinities for oxygen and nitrogen. Oxygen levels were adjusted from 210,000 ppm to 1 ppm in nitrogen in the building chamber. They found that all three alloys could be deposited with compositions similar to the starting wire under moderate purging. However, the parts deposited in air demonstrated significant oxygen and/or nitrogen levels which were deemed unacceptable for most applications.

Their results provided recommended purge box atmospheres for the three alloys SS308L, Ti–6Al–4V, and Ta [12].

The liquid metal flow within the molten pool significantly affects convective heat transfer and the overall geometry of the molten pool. Zhang et al. [13] explored the hybrid additive/subtractive (milling) manufacturing of Al5Si aluminium alloy component. They found that after the surface of the previously deposited track was milled to remove the crown, the liquid metal flow pattern changed resulting in improvements of the geometrical accuracy of the deposited thin walls and the surface roughness.

Kuo et al. [14] discussed the fabrication of the AISI 4130 steel sheets with soft Ni interlayers using ultrasonic AM which is a solid-state manufacturing technique. The localised plastic deformation in the Ni-interlayer significantly reduced the voids between the hard steel sheets. Post-process heat treatment was used to dissolve nickel into steel matrix, with evidence that about 10 μm Ni from the interlayer diffused into the steel. The shear strength improved after post-process hot isostatic pressing compared with the as-processed 4130 steel sheets.

Khan and De [15] reported a method to expedite heat transfer calculations for selective laser melting using a finite element method. Since the spatial variation of temperature and other variables were most pronounced close to the laser heat source, a set of fine grids that moved with the heat source was used. The grids were coarser further away from the beam. The computed temperatures were in good agreement with those calculating using fine mesh and the experimental data.

Metal transfer from the filler wire to the molten pool during wire-fed DED-L affects the stability of the process and the resultant dimensional accuracy of the deposit. Hu et al. [16] investigated the fluid flow pattern during filler wire fed DED-L using a three-dimensional heat transfer and fluid flow model. They showed that the liquid bridge was stable when the dimensionless slenderness number was in the range of 3.2–4.6.

Mukherjee and DebRoy [17] used mechanistic models to examine susceptibility of stainless steel 316 to common defects such as residual stresses and distortion, composition change and lack of fusion defects for several variants of AM processes. Components built by DED-GMA were most susceptible to residual stresses and distortion but was least likely to have lack of fusion defects because of high heat input. PBF-L caused significant loss of volatile alloying elements from the tiny liquid pools and as a result, the deposits were most vulnerable to composition change.

The effectiveness of hybrid cold spray solid state coating processes aided by laser, shot peening and friction stir processing was reviewed by Li et al. [18]. Special attention was paid to overcome the common problems of inadequate ductility when cold spray technique was used alone. Opportunities for further research were also identified.

Structure

Models of solidification segregation and dendrite structure in AM parts often consider only a few alloying elements for simplicity. Faria et al. [19] demonstrated a methodology to predict the spatial variations of chemical composition due to micro-segregation for PBF-L of Inconel 718. They used a modified Scheil model and computed the compositional maps in a dendrite cell. By comparing the computed and experimental results, they established the applicability of the model for multi-component systems.

Currently, only a handful of commercial alloys are printed by AM and the examination of microstructure and properties of commercial alloys are just beginning. Wang et al. [20] examined the microstructure, hardness and tensile strength of ultra-high strength 30CrMnSiNi2A steel components produced by powder-fed DED-L. The results showed the spatial variations of microstructure and properties. They suggested a need for a post processing heat treatment for this alloy.

Properties

The heat-treatable titanium alloy Ti5553 (Ti–5Al–5Mo–5V–3Cr) maintains a near-beta microstructure that is both ductile and strong in components built by SLM. Carlton el al. [21] explored the heat treatability of these components up to temperatures approaching the β-transus. They found that the strength increased while maintaining ductility at high temperatures (700–800°C), but embrittlement occurred at intermediate temperatures (400–600°C). It was thought that the embrittlement was due to changes in volume fraction and morphology of the α-phase and/or the presence of ω-phase.

Cai et al. [22] examined the microstructures and mechanical properties of 2219 Al parts produced by DED-GTA. The size and distribution of both eutectics and particles changed significantly after the heat treatment and the Vickers hardness of the component increased by 97% due to the significant precipitation strengthening by the heat treatment.

Distortion is a common difficulty in AM. Wu et al. [23] showed that interpass cooling with CO_2 gas significantly reduced distortion of Ti–6Al–4V parts built by WAAM. The improvement was thought to be caused by the enhanced dissipation of heat and the consequent reduction of heat accumulation within the deposition. The maximum reductions of 81% in longitudinal distortion and 69% in transverse distortion for the wall structures were realised.

Functionally graded components

Functionally graded components are desirable for service conditions that require different local properties within the same structure. DED with powder or wire feedstocks is a promising AM approach to produce graded structures because of the flexibility it offers in controlling the chemical compositions during the deposition process. Marinelli et al. [24] showed that wire based WAAM could be used to deposit two functionally graded structures, tantalum to molybdenum and molybdenum to tungsten. Both composition and hardness showed linear gradients.

Zhang et al. [25]investigated the joining of SS316L and IN625 using powder-fed DED-L with/without the intermediate layers. They found that the microstructure varied gradually on gradient samples. The hardness values gradually changed over the gradient zone. The yield strength of graded samples was close to that of IN625 while the ultimate tensile strength was approaching to that of SS316L because the sample fractured inside SS316L.

Wang et al. [26] examined the deposition of WC reinforced Ni-based composite coatings with Y_2O_3 addition on Ti–6Al–4V titanium substrate by laser cladding. They found that the metallurgical bonding between the coatings and the substrate was good. The primary phases were γ-Ni, TiC, TiB_2, Ni_3B, $M_{23}C_6$ and WC. Most of the WC was dissolved during the laser cladding process. The micro-hardness of the composites coatings was about three times that of the titanium substrate and the wear resistance of the composites coating was also superior to that of the substrate.

Concluding remarks

Can we print any metallic component we wish? Although printing of metals is a rapidly growing industry, we now print only a handful of the available 5500 commercial alloys. Many of these alloys are not generally available in powder or wire forms needed for AM. In addition, like all new technologies, AM needs to overcome many scientific, technological and commercial problems to be able to significantly increase its market penetration. The valuable papers in this special issue provide a glimpse of the current problems and issues in AM.

The striking diversity of heat input and the occurrence of common defects such as the lack of fusion, loss of alloying elements through vaporisation and residual stresses and distortion, indicate a need for sustained research and development for effective use of AM. The progress in understanding fusion welding in the last several decades provides an indication of the intense level of activity needed in AM to better understand the process, microstructure and properties and mitigate the common defects in the printed components.

Although the rich knowledge bases of metallurgy and welding are immensely helpful for the research and development in AM, there are compelling reasons why the path for the progress of AM will deviate significantly from those followed in metallurgy and welding. In the long and rich history of welding and metallurgy spanning well over a century, the applications of computational technology to metallurgy and welding have been relatively recent, spanning only the last four decades or so. These uses were mostly for numerical simulations, image processing and statistical data analysis and only a minor portion of the research in metallurgy and welding was concerned with the use of digital tools for discovery, continuous quality improvement or process or product improvements based on data science. In contrast, AM from its inception has depended critically on the software and hardware capabilities of computational technology. As a result, AM can take advantage of the accelerating rate of progress of the tools of the digital age that were largely unavailable for the development of metallurgy and welding.

Numerical simulations, digital twins and machine learning can be immensely helpful for the progress in AM. In fact, some of the tasks that have been accomplished solely by the time-tested physical experiments and characterisation in welding are impractical for AM. Consider, for example, the widely used weldability database which helps to avoid common failures in welding. A similar printability database can help the AM community to avoid common defects and reduce the number of trial and error experiments to obtain sound components. Is it possible to create a similar database for printability based on experiments alone? Considering the high cost of AM machines and feedstock materials it would be expensive to create the specimens needed for testing. In addition, components are printed one thin layer at a time and often these layers are thinner than a human hair. As a result, AM is a relatively slow process. The time consuming and expensive nature of AM mandates a new paradigm rather than the brute force manner of building and testing. A combination of both experiments and simulations can greatly reduce the trial and error testing and will allow creation of a printability database for the benefit of all.

The synergy of welding and AM benefits both communities. Some of the well-recognised joining problems are being solved by AM. Considering the welding of dissimilar welds of ferritic and austenitic alloys, the abrupt changes in composition, microstructure and properties compromise serviceability of these joints. In particular, the degradation of the creep resistance due to loss of carbon from the ferritic steels limits lives of such dissimilar welds in nuclear industry. Substitution of such welds by a compositionally graded joints made by AM is a potentially attractive solution. [27].

In summary, AM has significant similarities with welding and the synergy is beneficial to the growth of both technologies. However, like all emerging processes, AM has its share of unique scientific and technological issues that will require sustained research and development. The papers in this issue provide a glimpse of these problems. The Editors welcome further submissions of technical papers, critical assessments and reviews on AM to *STWJ*.

Disclosure statement

No potential conflict of interest was reported by the authors.

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