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Additive Manufacturing via Surface Engineering

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Additive manufacturing (AM) is ideal for making prototypes during the early development phases of a product, thereby significantly reducing the time required for product development and market launch. The strengths of AM lie in those areas where conventional manufacturing reaches its limitations. The technology is of interest where a new approach to design and manufacturing is required so as to come up with solutions. It enables a design-driven manufacturing process—where design determines production and not the other way around. Furthermore, AM allows for highly complex structures which can still be extremely light and stable. It provides a high degree of design freedom, the optimization and integration of functional features, the manufacture of small batch sizes at reasonable unit costs and a high degree of product customization even in serial production. Although the AM technology is over 30 years old, it is only in the past few years that it has captured the attention of industry and made inroads into numerous application-oriented sectors. Especially, recent advances in complex motion systems integrated with various sensors for accuracy and remote operation along with possibilities of in situ synthesis of advanced material systems have opened the door for a concept of surface engineering via additive manufacturing (SEAM). SEAM simultaneously facilitates site-specific in situ synthesis of a material system and its fabrication into a desired shape on the substrate. Thus, SEAM, unlike traditional AM, provides tremendous savings in materials and process/fabrication time, thereby rendering it the most efficient and economical technique, especially for complex geometries and strategic materials.

Narendra Dahotre, Benjamin Boesl, and Hitesh Vora the *JOM* advisors for the Surface Engineering Committee of the Materials Processing & Manufacturing Division, and guest editors for the Surface Engineering via Additive Manufacturing topic in this issue

As the fields of applications for AM/SEAM expand every day, they are primarily driven by the application-oriented advanced manufacturing system-based approach. The developments in system-based AM/SEAM are mostly focused on aspects such as machine design and performance; processes and techniques; process control and sensing including cyber-enabled AM; design; validation, verification and quantification of AM parts; infrastructure of AM; supply chain impact of AM; sustainability issues in AM; product lifecycle design; testing and adaptation; rapid tooling; etc. However, substantially limited emphasis has been provided on basic understanding related to development, characterization, and performance of materials during AM/SEAM. Furthermore, modeling and simulation of AM/SEAM processes in view of materials are severely lacking. Without further concentrated efforts in these areas, the exciting technology of AM/SEAM would produce the components of dimensional complexity and accuracy but with inferior mechanical, chemical, and functional properties.

In light of this, this set of papers under the topic of SEAM deals with fundamentals of materials processing during SEAM. The physical processes occurring during SEAM are recognized, and their effects on the compositional and microstructural evolution within the material and the resultant mechanical, chemical, and functional properties are evaluated and explained. These aspects related to materials are presented through modeling and optimization efforts supplemented by experimental/practical observations. In addition, a discussion about various types of AM/SEAM processes and their effects and limitations in fabrication and resultant component properties are provided.

In the first paper on VC cladding on a steel substrate using a laser-based SEAM technique, Zhang and Kovacevic employed the Taguchi-based grey relational method to optimize the laser cladding parameters for clad height, carbide fraction, and carbide dissolution in the clad composite surface layer for desired hardness. The microstructural analysis of the composite surface layer indicated the presence of martensite, retained austenite, VC, $M_{23}C_7$, and M_7C_3 phases which provided higher average hardness in the composite surface layer compared to the substrate steel. The work indicated that the hybrid Taguchi experimental design with grey relational analysis was an effective method to optimize the processing parameters for the process with multiple responses. In the second paper, the same group (Ding and Kovacevic) adopted traditional 3D printing using robotized laser-based AM for printing 431L HC stainless steel structures of two geometries corresponding to enlarged positive and negative Poisson's ratios. The mechanical structures for the desired mechanical properties were designed and simulated using a multiphysics finite element model and then fabricated using robotized laser-based 3D printing and tensile-tested to verify the simulations, thus proving the validity and suitability of the robotized laser-based metal additive manufacturing technique.

The paper by Book and Sangid describes the novel approach of using mechanical processing in situ with the AM to control the microstructure, defects, and surface roughness in AM materials. As AM processes are based on the successive application of material layers to form a 3D part, the mechanical surface treatments such as sliding severe plastic deformation (SPD) and fine particle shot peening (FPSP) were applied to change the specific characteristics of each layer of the direct metal laser-sintered (DMLS) AlSi10 Mg material. The in situ application of these mechanical surface treatments during the AM process established the potential for tailoring the internal material characteristics for improved performance with a possibility of lowering the number of post-processing steps required after the build.

Amanov and Pyun in their paper established the possibility of improving adhesive failure and wear loss in a plasma-sprayed Al_2O_3 coating on an H13 steel substrate by pre-plasma spraying surface preparation. Although they were inconclusive about friction coefficient, their study indicated that surface preparation by sanding followed by ultrasonic nanocrystalline surface modification provided the possibility for improving the adhesion of plasma-sprayed Al_2O_3 coating on an H13 steel substrate. It is assumed that continued efforts by them will provide an understanding of the physical phenomena behind the improved adhesion and wear performance.

The economic viability and environmentally cleaner methodology of the micro-plasma transferred arc (μPTA) process for additively remanufacturing of dies and molds in near-millimeter ranges has been established in the work by Jhavar, Paul, and Jain. The paper presents their efforts on μPTA process optimization for single bead geometry which was further extended to the fabrication of a stacked multi-bead thin wall using AISI P20 tool steel material. The optimization efforts were based on the correlation between the process parameters (plasma power density, material feed rate, and interaction time) and the bead parameters (shape, size, and material dilution). They also emphasized the viability of the μPTA process by comparing it with other SEAM processes on the basis of various criteria.

The papers by Ocelik et al. and Vora et al. emphasize the versatility of SEAM, not only to fabricate desired physical shape but also in the synthesis of novel and advanced materials systems and tailoring microstructure/phases. Ocelik et al. attempted to form high entropy alloy (HEA) coatings with a direct laser deposition from the mixture of elemental powders for AlCoCrFeNi and AlCrFeNiTa compositions. The effects of laser surface processing parameters on the microstructure and hardness of the HEA coating were evaluated. It was concluded that, although several material and processing parameters are influential, the solidification rate is the most important factor in generation and distribution of HEA phases in the coating. Thus, due to the sensitivity of formation of the HEA phase on a multitude of parameters, the synthesis of an HEA coating using laser-based SEAD techniques remains a challenging approach. Vora et al. have explored laser-assisted additive manufacturing of a W coating on an aluminum substrate. In their paper, unlike conventional coating techniques, they have successfully demonstrated the synthesis of a composite coating with the formation of transition metal intermetallic phases via extending the solid solubility of the W transition metal in an aluminum substrate using laser-based SEAM. They also demonstrated that laser-based SEAM can be controlled to achieve the thermodynamic and kinetic conditions necessary for desirable physical, microstructural, and compositional attributes within the surface coating. Their work involved the development of a multiphysics finite element model to predict the temperature profile, cooling rate, melt depth, dilution of W in the Al matrix, and the corresponding microhardness in the coating, and the interface between the coating and the base material.

Thus, this set of papers under the topic of SEAM covers a range of aspects such as techniques, post-process analysis/characterization, process control and optimization for material properties, and the synthesis of advanced material systems. Integration of these aspects is essential and likely to rapidly advance AM/SEAM technology to its maturation and infiltration into many practical applications.

The following papers being published under the topic of Surface Engineering via Additive Manufacturing provide excellent details and research on the subject. To download any of the papers, follow the url http://link.springer.com/journal/11837/68/7/page/1 to the table of contents page for the July 2016 issue (vol. 68, no. 7).

- "Multiresponse Optimization of Laser Cladding Steel + VC Using Grey Relational Analysis in the Taguchi Method" by Zhe Zhang and Radovan Kovacevic
- "Feasibility Study on 3-D Printing of Metallic Structural Materials Using Robotized Laser-Based Metal Additive Manufacturing" by Yaoyu Ding and Radovan Kovacevic
- "Evaluation of Select Surface Processing Techniques for In Situ Application During the Additive Manufacturing Build Process" by Todd A. Book and Michael D. Sangid
- "Wear and Adhesive Failure of Al_2O_3 Powder Coating Sprayed onto AISI H13 Tool Steel Substrate" by Auezhan Amanov and Young-Sik Pyun
- "Micro-Plasma Transferred Arc Additive Manufacturing for Die and Mold Surface Remanufacturing" by Suyog Jhavar, Christ Praklash Paul, and Neelesh Kumar Jain
- "Additive Manufacturing of High-Entropy Alloys by Laser Processing" by V. Ocelík, N. Janssen, S.N. Smith, and J.Th.M. De Hosson
- "Laser Assisted Additively Manufactured Transition Metal Coating on Aluminum" by Hitesh D. Vora, Ravi Shanker Rajamure, Anurag Roy, S.G. Srinivasan, G. Sundararajan, Rajarshi Banerjee, and Narendra B. Dahotre