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Additive Manufacturing Modeling and Simulation

A Literature Review for Electron Beam Free Form Fabrication

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April 2014

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Abstract

Additive manufacturing is coming into industrial use and has several desirable attributes. Control of the deposition remains a complex challenge, and so this literature review was initiated to capture current modeling efforts in the field of additive manufacturing. This paper summarizes about 10 years of modeling and simulation related to both welding and additive manufacturing. The goals were to learn who is doing what in modeling and simulation, to summarize various approaches taken to create models, and to identify research gaps. Later sections in the report summarize implications for closed-loop-control of the process, implications for local research efforts, and implications for local modeling efforts.

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Nomenclature

2-D	two-dimensional
3-D	three-dimensional
AM	additive manufacturing
ANN	artificial neural network
ASME	American Society of Mechanical Engineers
CA	cellular automata
CLC	closed loop control
DOE	design of experiments
EB	electron beam
EBF ³	electron beam free form fabrication
FE	finite element (model)
FV	finite volume (model)
GA	genetic algorithm
GGF	greedy geometric feedback
GTAW	gas tungsten arc welding
ICME	integrated computation materials engineering
ILC	iterative learning control
LB	lattice Boltzmann
LENS	laser engineered net shaping
M&S	modeling and simulation
PSO	particle swarm optimization
SFF	solid freeform fabrication

SECTION 1 OVERVIEW

Additive manufacturing (AM) is coming into industrial use and has several desirable attributes. For example, it may be possible to control microstructural features through variations in additive processing parameters (ref. 1). If microstructure can be controlled then AM could contribute to a goal of the integrated computational materials engineering (ICME) community. ICME has a goal to deliver designer materials based on performance requirements (ref. 2). In addition to providing designer materials, additive manufacturing will also enable unique part design by removing some manufacturing process constraints (ref. 3). While other challenges such as certification must be overcome for everyday use, this paper will focus on what is currently being done to understand the deposition process through modeling and simulation (M&S). The published literature on laser-based additive manufacturing appears more extensive than electron beam-based wire deposition. Gu et al. provide an overview of laser-based powder additive manufacturing methods and review physical aspects and microstructural and mechanical properties (ref. 4).

Through the literature search, this paper will:

- identify key player in the AM modeling field
- summarize approaches being taken to model and/or simulate the deposition process
- pinpoint research gaps in M&S for AM

Modeling and simulation of AM enables the design and implementation of process control methods. Therefore, paper selection also includes efforts on AM process control to provide insight into what other research or M&S effort is needed to improve process control.

Further, the intent was to limit the literature review to AM papers and limit how much welding literature was reviewed. AM can be thought of as the consecutive placement of weld beads on top of previous beads to build a component layer by layer. As such, AM and welding share common physics related attributes. The welding literature contains a wealth of information on molten pool dynamics, energy insertion, microstructure development, and residual stress information that cannot be ignored and is thus included in this review.

Topics are organized according to the flow of energy in the additive process: energy insertion, molten pool dynamics, microstructure evolution, residual stress and distortion, and material property prediction. Following that are summaries of literature that deal with deposition modeling and deposition control. The final section summarizes the implications this search may have on electron beam free form fabrication (EBF³) efforts towards closed-loop-control (CLC), EBF³ process research, and EBF³ modeling efforts.

SECTION 2 ENERGY INSERTION

Most of the literature in energy insertion has to do with laser energy sources. Observed phenomenon with laser and electron beam energy inputs include keyhole energy physics, vaporization losses, and energy loss to vapor clouds.

T. Zhang, Zheng, and Zhao (2013) showed that using two different energy source models can result in two different thermal distributions in the substrate. One model of the energy beam more accurately describes the physics and timing of the real system (pulsed timing with a parabolic heat distribution) while the other model was typically used to model heat input in various studies (a static Gaussian distribution). Experiments were conducted to confirm that the pulsed model more accurately predicts thermal distribution. The energy source must be modeled accurately since thermal distributions determine residual stress fields and microstructure evolution, (ref. 5).

Shen and Chou (2012) showed that larger electron beam diameters resulted in lower molten pool temperatures for the same energy input. This affects cooling rates and therefore the resulting microstructure (ref. 6).

Peng et al. (2011) described a complete system for characterizing an electron beam, which included an equation for relating measured voltage to beam density. It also related the geometry of the beam distribution to accelerating voltage, beam current, travel speed, and focus. The three-dimensional (3-D) shape of the beam, if altered by faulty cathode geometry, could yield an asymmetric weld bead (ref. 7).

A group of papers that describe Faraday cup design and application are summarized in chronological order to help show the progression through time. Elmer and Teruya (2001) described an enhanced Faraday cup design (ref. 8). Palmer and Elmer (2007a) showed a nearly 20 percent difference in two electron beam welders with similar beam parameter settings (ref. 9). Palmer et al. (2007b) described a procedure for transferring electron beam welding parameters between different machines which produced similar welds on both machines with small error after calibration (ref. 10). Palmer (2008) tracked 90 welds over 18 months while beam parameter variations were controlled to within ± 2.2 percent. The study cited that this variation easily fell within the 5 percent tolerance specified by the American Society of Mechanical Engineers' (ASME). This study also included detailed data showing variation in operator determined sharp-focus settings (ref. 11).

Safdar, Li, and Sheikh (2007) studied laser beam geometry and energy density and distribution from four different beam geometries. The variations were shown to affect temperature distribution, heating/cooling rates, and fluid flow. A series of finite volume simulations agreed with experimental results. The simulations revealed beam geometry effects related to conductivity and Marangoni flow (ref. 12).

Nath et al. (2002) presented a laser welding study that showed how coupling efficiency changes with energy transfer mode in austenitic stainless steel. In conduction mode 15 percent of the lasers energy was transferred into the material. In keyhole mode 65 percent of the lasers energy

was transferred. This paper also cites changes in microstructure based on travel speed with higher travel speed resulting in solidification cracking (ref. 13).

Wei and Chow's (1992) research reported variations in fusion zone geometries with different focal locations, spot sizes, and convergence angles in electron beam processing. The study described a 3-D steady-state model of the energy beam, molten pool cavity, and energy absorption. The model was supported by experimental data showing that energy flux is governed by focal spot location, energy distribution at the focal spot, and convergence angle (ref. 14).

Table 1. Faraday cup and beam energy distribution.

Year	First Author	Ref.	Title	Affiliation
2013	Zhang	[5]	A dynamic welding heat source model in pulsed current gas tungsten arc welding.	China
2012	Shen	[6]	Thermal modeling of electron beam additive manufacturing process – powder sintering effects.	USA
2011	Peng	[7]	Beam quality test technology and devices of electron beam welding.	China
2008	Palmer	[11]	Improving process control in electron beam welding using the enhanced modified Faraday cup.	USA
2007	Safdar	[12]	Numerical analysis of the effects of non-conventional laser beam geometries during laser melting of metallic materials.	UK
2007b	Palmer	[10]	Transferring electron beam welding parameters using the enhanced modified Faraday cup.	USA
2007a	Palmer	[9]	Characterization of electron beams at different focus settings and work distances in multiple welders using the enhanced modified Faraday cup.	USA
2002	Nath	[13]	Laser power coupling efficiency in conduction and keyhole welding of austenitic steel.	India
2001	Elmer	[8]	An enhanced Faraday cup for rapid determination of power density distribution in electron beams.	USA
1992	Wei	[14]	Beam focusing characteristics and alloying element effects on high-intensity electron beam welding.	Taiwan

SECTION 3 MOLTEN POOL

This section includes electron beam and laser welding papers. Other heat sources are considered only if there is something of relevance to the molten pool dynamics that might need to be considered.

3.1 Molten Pool Physics Based Models

The first of four papers by Wei, Liu, and Lin (2012a, ref. 15) thoroughly cover fundamental physical principles related to molten pool dynamics. All of these papers may offer insight to modeling molten characteristics such as temperature distribution and geometry without 3-D finite element simulation. The authors made use of Prandtl and Marangoni numbers and scale analysis. See also Wei, Lin, Liu, and Ting (2012b, ref. 16), Wei, Lin, Liu, and DebRoy (2012c, ref. 17), and Wei and Liu (2012d, ref. 18).

Fan and Liou (2012) provided a technical overview of the equations needed to model the physics of a molten pool. The two-dimensional (2-D) simulation, parameterized for Ti-6Al-4V, was able to show free surface movement based on surface tension and wetting forces (ref. 19).

Daneshkahi, Najafi, and Torabian's (2012) study was based on laser keyhole welding and shows equations for modeling a 3-D volumetric heat source. The introduction section summarized other keyhole model heat source techniques that might be of interest. The described 3-D model was validated and agreed well with experimental data (ref. 20).

W. Zhang et al. (2012) conducted a welding study where backside bead width was predicted from molten pool width, length, and convexity in gas tungsten arc welding (GTAW). Five parameters were considered, but these three were shown to be the most effective in a least squares algorithm. The variance of the optimal model was small compared to the precision required for a feedback control system (ref. 21).

Manvatkar et al. (2011) used Abaqus (formerly ABAQUS) to create a 3-D heat flow model of SS 316 laser engineered net shaping (LENS™) deposition. A custom subroutine used 0.20 mm cube volumes to estimate molten pool growth and geometry as powder was added. The geometry was not predicted by using the physics relationships of surface tension and wetting forces. Computed temperature profiles were used to estimate yield strength with the Hall-Petch coefficients (ref. 22).

Rai, Palmer, et al. (2009a) described a numerical 3-D heat transfer model for an electron beam welder in keyhole mode. The model computed molten pool fluid flow and its effect on weld bead geometry. The paper covered experimental verification and provided many references on model creation (ref. 23).

Rai, Burgardt, et al. (2009b) calculated the keyhole shape in electron beam welding based on an energy balance model. Molten pool fluid flow and heat transfer were computed for keyhole welding (ref. 24).

Rai, Kelly, et al. (2008) described calculations of keyhole geometry based on material properties and a 3–D finite element model for heat flow (ref. 25).

Rai, Roy, and DebRoy (2007) described a model similar to Rai, Kelly, et al. (2008) but compared the different thermal conductivities of SS 304L and Al 5754. The model predicted different molten pool geometries of the high and low Peclet number systems. The Peclet number is the ratio of convective to conductive heat transfer (ref. 26).

Table 2. Molten pool physics.

Year	First Author	Ref.	Title	Affiliation
2012a	Wei	[15]	Scaling weld or melt pool shape induced by thermocapillary convection.	Taiwan
2012b	Wei	[16]	Transient thermocapillary convection in a molten or weld pool.	Taiwan
2012c	Wei	[17]	Scaling weld or melt pool shape affected by thermocapillary convection with high Prandtl numbers.	Taiwan
2012d	Wei	[18]	Scaling thermocapillary weld pool shape and transport variables in metals.	Taiwan
2012	Fan	[19]	Numerical modeling of the additive manufacturing (AM) processes of titanium alloy.	USA
2012	Daneshkhah	[20]	Numerical simulation of weld pool shape during laser beam welding.	Iran
2012	Zhang	[21]	Characterization of three-dimensional weld pool surface in GTAW.	USA
2011	Manvatkar	[22]	Estimation of melt pool dimensions, thermal cycle, and hardness distribution in the laser-engineered net shaping process of austenitic stainless steel.	India
2009a	Rai	[23]	Heat transfer and fluid flow during electron beam welding of 304L stainless steel alloy.	USA
2009b	Rai	[24]	Heat transfer and fluid flow during electron beam welding of 21Cr-6Ni-9Mn steel and Ti-6Al-4V alloy.	USA
2008	Rai	[25]	A convective heat-transfer model for partial and full penetration keyhole mode laser welding of a structural steel.	USA
2007	Rai	[26]	A computationally efficient model of convective heat transfer and solidification characteristics during keyhole mode laser welding.	USA

3.2 Molten Pool Process Maps

Vasinonta, Beuth, and Griffith (2007) constructed process maps to predict molten pool geometry for thin-walled laser powder AM structures (ref. 27). The findings assert that “melt pool length

was a strong function of laser power and velocity, and was a weak function of preheat temperature” (ref. 27, p. 107).

Vasinonta, Beuth, and Griffith (2001a) showed process map models that assume temperature independent material properties. This paper showed details about process map development, experimental verification, and example calculations (ref. 28).

Vasinonta, Beuth, and Ong (2001b) used process maps for molten pool geometry prediction and compared results from thin-walled and bulk deposits. Results showed that more heat input is needed for the bulk deposits to maintain a constant molten pool size (ref. 29).

Vasinonta, Beuthm and Griffith (2000) laid the groundwork for process map research that was used in subsequent papers detailed above (ref. 30).

Table 3. Molten pool process maps.

Year	First Author	Ref.	Title	Affiliation
2007	Vasinonta	[27]	Process maps for predicting residual stress and melt pool size in the laser-based fabrication of thin-walled structures.	USA
2001a	Vasinonta	[28]	A process map for consistent build conditions in the solid freeform fabrication of thin-walled structures.	USA
2001b	Vasinonta	[29]	Melt pool size control in thin-walled and bulky parts via process maps.	USA
2000	Vasinonta	[30]	Process maps for controlling residual stress and melt pool size in laser-based SFF processes.	USA

SECTION 4 MICROSTRUCTURE EVOLUTION

This section on microstructure evolution and the next on residual stress are somewhat related. Papers in both sections relate the process to the microstructure. Due to the volume of papers that focus on residual stress, that topic is given its own section.

Jingwei Zhang et al. (2013) used a 2-D cellular automata (CA) approach for simulating microstructure evolution in SS 316. This model will eventually be expanded to 3-D and validated with experimental data from a laser/powder based AM system. (ref. 31).

Eshraghi, Felicelli, and Jelinek (2012a) used combined lattice Boltzmann (LB) and CA methods to simulate solute-driven dendrite growth. This combination is easily parallelized and exhibits good parallel scalability compared to finite element and finite volume approaches. These attributes are necessary for increasing the scale of computation to macroscopic levels and, while adding the ability to handle several types of grain evolution, include fluid flow and temperature calculations (ref. 32). Eshraghi and Felicelli (2012b) revealed a lattice Boltzmann model for heat conduction and phase change (ref. 33).

Barrales-Mora, Gottstein, and Shvindlerman (2012) simulated “the effect of finite triple junction mobility on the growth rate of 2-D polycrystals” (ref. 34, p. 546).

Amoorezaei, Gurerrich, and Provatas (2012) demonstrated “computationally and experimentally that a material’s surface tension anisotropy can compete with anisotropies present in processing conditions during solidification...” (ref. 35, p.657).

Brandl et al. (2011) showed microstructural characteristics of Ti-6Al-4V single bead deposits in relation to deposition parameters. The article is based on laser wire deposition and includes tables of data, micrographs, and an extensive bibliography. This paper does not contain any discussion in regard to modeling but provides a fair amount of experimental data and discussion of interest to a deposition modeler (ref. 36).

Groeber (2010) presented two approaches for representing microstructure, explicit and statistical. Developing an accurate and sufficient representation microstructure is necessary for computational studies that hope to compute material properties from microstructure (ref. 37).

Barrales-Mora, Gottstein, and Shvindlerman (2008) simulated normal grain growth from single grains to polycrystals. The simulation used a 3-D vertex model that agreed well with various analytical approaches. Simulation results were compared to previous models (ref. 38).

Rai, Kelly, et al. (2008) presented a 3-D laser keyhole model parameterized with A131 structural steel properties for experimental verification. “The solidification microstructure tends to become more dendritic with increase in laser power, and coarser with increase in heat input per unit length. The microstructure also varies with location due to spatial variation of the cooling rate” (ref. 25, p. 107). See also Rai, Roy, and DebRoy (2007, ref. 26).

Bontha et al. (2006) used a 2-D Rosenthal solution for a moving heat source to develop process maps for predicting microstructure. Process parameters for LENS™ Ti-6Al-4V deposition on a

thin wall are mapped to microstructure. This work shows that laser power and velocity change cooling rates by several orders of magnitude (ref. 39).

Demirel et al. (2003) simulated evolved microstructure at the scale of individual grains in aluminum foil. In the study, computed microstructure evolution using curvature-driven grain boundary motion and anisotropic interface properties showed better agreement with experimental results than when isotropic properties are used (ref. 40).

Yang et al. (2000) showed a 3–D monte carlo simulation of grain growth in a titanium weld bead that demonstrated good agreement with experimental data. The paper noted that earlier 2–D simulations did not show good agreement with experimental data. This suggests that grain growth prediction must consider all three dimensions (ref. 41).

Table 4. Microstructure evolution.

Year	First Author	Ref.	Title	Affiliation
2013	Zhang	[31]	Probabilistic simulation of solidification microstructure evolution during laser-based metal deposition.	USA
2012a	Eshraghi	[32]	Three dimensional simulation of solutal dendrite growth using lattice Boltzmann and cellular automata methods.	USA
2012b	Eshraghi	[33]	An implicit lattice Boltzmann model for heat conduction with phase change.	USA
2012	Barrales-Mora	[34]	Effect of a finite boundary junction mobility on the growth rate of grains in two-dimensional polycrystals.	Germany
2012	Amoorezaei	[35]	Orientation selection in solidification patterning.	Canada
2011	Brandl	[36]	Deposition of Ti-6Al-4V using laser and wire, part 1: Microstructural properties of single beads.	Germany
2010	Groeber	[37]	Digital representation of materials grain structure.	USA
2008	Barrales-Mora	[38]	Three-dimensional grain growth: Analytical approaches and computer simulations.	Germany, Russia
2008	Rai	[25]	A convective heat-transfer model for partial and full penetration keyhole mode laser welding of a structural steel.	USA
2007	Rai	[26]	A computationally efficient model of convective heat transfer and solidification characteristics during keyhole mode laser welding.	USA
2006	Bontha	[39]	Thermal process maps for predicting solidification microstructures in laser fabrication of thin-wall structures.	USA
2003	Demirel	[40]	Bridging simulations and experiments in microstructure evolution.	USA
2000	Yang	[41]	Three dimensional monte carlo simulation of grain growth during GTA welding of titanium.	USA

SECTION 5 RESIDUAL STRESS

Lindgren, Lundbäck, and Fisk (2013) stated that strong nonlinearities and large deformations are difficult to model. Residual stress and deformations are very dependent on material behavior. This is a very recent finite element (FE) model applied to manufacturing simulations (ref. 42).

Ding et al. (2011) summarized a finite element model for an additive manufacturing process. A FE model is used as input to a 3-D mechanical model that computed residual stress and distortion. The model output was compared to experimental results and data from an ENGIN-X neutron diffraction strain scan (ref. 43).

De and DebRoy (2011) presented an editorial on welding induced residual stress with an extensive bibliography of 120 papers related to residual stress and residual stress modeling (ref. 44).

Tian et al. (2008) simulated the temperature field and mechanical aspects in electron beam (EB) welding of a large (1 meter) aluminum part with 8 meters of weld. The simulation included a 3-D model of keyhole physics. This was a systematic study of process parameters to minimize distortion to the welded structure. Pre-deformation affected the final distortion but was not as much of an influence as process parameters (ref. 45).

Vasinonta, Beuth, and Griffith (2007) showed process maps for thermal gradients and that heat input and travel velocity selection can cause a 20 percent change in residual stress in SS304. “The biggest payoff in reducing residual stresses comes from uniform baseplate (and wall) preheating...” to 400 °C (ref. 27, p. 107).

Vasinonta (2000) wrote, “The maximum reduction of residual stress by preheating the part is approximately 40 percent and is achieved by preheating the part to 400 °C” (ref.30, p. 207). This paper lays the groundwork for the later papers.

Table 5. Residual stress.

Year	First Author	Ref	Title	Affiliation
2013	Lindgren	[42]	Thermo-mechanics and microstructure evolution in manufacturing simulations.	Sweden
2011	Ding	[43]	Thermo-mechanical analysis of wire and arc additive layer manufacturing processes on large multi-layer parts.	UK
2011	De	[44]	A perspective on residual stresses in welding	India, USA
2008	Tian	[45]	Finite element modeling of electron beam welding of a large Al alloy structure by parallel computations.	China, Canada
2007	Vasinonta	[27]	Process maps for predicting residual stress and melt pool size in the laser-based fabrication of thin-walled structures.	USA
2000	Vasinonta	[30]	Process maps for controlling residual stress and melt pool size in laser-based SFF processes	USA

SECTION 6 MECHANICAL PROPERTY PREDICTION

Roy et al. (2013) used a design of experiments (DOE) method to derive an empirical model relating welding process parameters to weld hardness, ultimate tensile load, and toughness. With the empirical model, a genetic algorithm was used to search for process parameters that meet desired combinations of mechanical properties (ref. 46).

Manvatkar et al. (2011) discussed a 3-D heat flow model, built in Abaqus, for predicting hardness in LENS™ processing. This model overpredicted hardness because of the underprediction of cell spacing. This model used Hall-Petch coefficients that are normally used for wrought and annealed grain structures which may have also contributed to an overprediction of the hardness (ref. 22).

Brandl et al. (2011) wrote part two of a two part series. The article showed that hardness measurements do not necessarily correlate with thermal history. There is some correlation between thermal history and bead dimensions. This paper does not contain any discussion concerning modeling but provides a fair amount of experimental data and discussion that might be considered by a deposition modeler (ref. 47).

Robertson et al. (2011), while not specifically discussing mechanical property prediction, summarized the state of the art in material characterization technologies. This paper is of interest as simulation validation would rely on these technologies (ref. 48).

Guo et al. (2009) showed recent developments in material properties modeling for castings. While not related directly to additive manufacturing, this paper may provide insight to the state of the art in materials property prediction in simulation (ref. 49).

Table 6. Mechanical property prediction.

Year	First Author	Ref	Title	Affiliation
2013	Roy	[46]	An approach for solving multi characteristics optimization of submerged arc welding parameters by using grey based genetic algorithm	India
2011	Manvatkar	[22]	Estimation of melt pool dimensions, thermal cycle, and hardness distribution in the laser-engineered net shaping process of austenitic stainless steel.	India
2011	Brandl	[47]	Deposition of Ti-6Al-4V using laser and wire, part II: Hardness and dimensions of single beads.	Germany
2011	Robertson	[48]	Towards an integrated materials characterization toolbox.	USA
2009	Guo	[49]	Materials properties for process simulation.	UK

SECTION 7 DEPOSITION MODELING

Tong et al. (2013) described an interesting approach to multiscale, multiphysics modeling. This paper summarizes an approach to fusion welding that considers all scales from molecular dynamics up through to the macro-scale thermal field. To accomplish this, the authors did not attempt to mix all scales into one large model as is typically done. Instead, each model was designed to work on its own with its own appropriately scaled mesh and solver. An upper level algorithm moved data from model-to-model as they step through time. This was no small effort. This paper has 20 authors from 10 different locations including Ireland, the UK, Urbana IL, Switzerland, the Netherlands, and Germany (ref. 50).

Lundbäck and Lindgren (2011) discussed a complete finite element model of multipass welding. The model was validated against experimental results to include thermal history and distortions due to residual stress. Thermal history data from the model showed good agreement with experimental data. Deformation calculations also showed good agreement. The model was *generic* in the sense that material is added by activating mesh elements. There was no explicit model of added wire or powder. The bibliography appears to capture previous work done in this type of FE-related AM modeling (ref. 51).

Fallah et al. (2011) gave an FE approach to laser powder deposition. This study modeled the real-time molten pool shape to predict molten pool and solidification geometries. This was done without a multiphysics-based model of the molten pool. Instead, a fine mesh of elements was activated based on a set of mass flow equations. The geometry prediction appears to be somewhat predetermined but has a higher resolution than just adding large rectangular elements as the energy beam passes (ref. 52).

Bag and De (2010) and Bag, De, and DebRoy (2009) showed a FE 3-D heat transfer and fluid flow model that was used to optimize GTAW welds. There are four parameters in the model that were uncertain: coupling efficiency, effective arc radius, effective thermal conductivity, and viscosity. To find values for these coefficients the model was integrated with a Genetic Algorithm (GA) that finds optimal values for these parameters by matching simulation output with experimental samples. Once the values were computed they were then used to parameterize welds with various requirements for final weld geometry (ref. 53 and 54).

Table 7. Deposition modeling.

Year	First Author	Ref	Title	Affiliation
2013	Tong	[50]	Multiscale, multiphysics numerical modeling of fusion welding with experimental characterization and validation.	USA, European
2011	Lundbäck	[51]	Modeling of metal deposition.	Sweden
2011	Fallah	[52]	Temporal development of melt-pool morphology and clad geometry in laser powder deposition.	Canada
2010	Bag	[53]	Probing reliability of transport phenomena based heat transfer and fluid flow analysis in autogeneous fusion welding process.	India
2009	Bag	[54]	A genetic algorithm assisted inverse convective heat transfer model for tailoring weld geometry	India, USA

SECTION 8 DEPOSITION CONTROL

W. Zhang and Y. Zhang (2012) monitored the weld pool of a GTAW system and the responses of a novice human welder. The human welder was sufficiently trained such that responses were not random. Part I (ref. 55) discussed the experimental setup and data collection. Part II (ref. 56) discussed the results. A system identification method was used with weld pool geometry (length, width, and convexity) as the input variables. The model was able to show that a manual welder makes control responses based on observations made 1.5 to 3 seconds earlier. Adjustments to the weld current were also based on previous adjustments made 1 second earlier. There was no discussion of using the model as a control system sans human, but it would seem to be the next logical step.

Heralić, Christiansson, and Lennartson (2012) demonstrated a machine learning algorithm applied to deposition control. While this paper was not about a numerical model derived for control, machine learning does imply some type of *model* that is able to predict or correct and, therefore, is included here. This system used a 3-D scanner to measure previous deposition heights and then controls wire feed rate, in feed forward fashion, to make height corrections in the next deposited layer (ref. 57).

Tang and Landers (2011) showed height control for laser powder deposition based iterative learning control (ILC) and particle swarm optimization (PSO). To develop height control, a process model was built and tested. PSO was used to estimate model parameters from measured temperature and track height profiles. ILC was then used to schedule powder flow rates for the next layer to obtain the desired height profile (ref. 58).

Cohen and Lipson (2011) proposed greedy geometric feedback (GGF) for closing the loop in controlling solid freeform fabrication (SFF). Typical CLC designs monitor and manipulate low level system parameters (feed rates and energy) but do not necessarily guarantee accurate final part geometry. The GGF method proposed by the authors manipulated deposition location (mass and location) to compensate for geometric inaccuracies. An SFF system was shown that implemented GGF, but results were only compared to open-loop deposition. GGF was better than open-loop, but no comparison was made to any other CLC design (ref. 59).

Chandrasekhar and Vasudevan (2010) described a method to optimize activated flux tungsten inert gas welding (A-TIG) process parameters to achieve desired weld geometry. In this study a genetic algorithm (GA) was used to tune an artificial neural network (ANN) from experimental data. This study was included here to illustrate the amount of experimental data required by this type of approach for a limited operational range and for each working alloy. For each alloy, 120 single bead deposits were made and 3 output parameters were measured; depth of penetration, bead height, and bead width (ref. 60).

Table 8. Deposition control.

Year	First Author	Ref	Title	Affiliation
2012a	Zhang	[55]	Modeling of human welder response to 3-D weld pool surface: Part I—Principles.	USA
2012b	Zhang	[56]	Modeling of human welder response to 3-D weld pool surface: Part II—Results and analysis.	USA
2012	Heralić	[57]	Height control of laser metal-wire deposition based on iterative learning control and 3-D scanning.	Sweden
2011	Tang	[58]	Layer-to-layer height control for laser metal deposition process.	USA
2011	Cohen	[59]	Geometric feedback control of discrete-deposition SFF systems.	USA
2010	Chandrasekhar	[60]	Intelligent modeling for optimization of A-TIG welding process	India

SECTION 9 EVALUATION OF THE LITERATURE POOL

The goals of this literature survey were to document the state of the art in modeling and simulation as applied to additive manufacturing and determine who is doing the work. About half of the papers in this survey are from Asia, Canada, and Europe. Papers from China appear to be more focused on welding technology while those from India are focused on fundamental work in optimization and control. European, Canadian, and USA papers cover all aspects of the additive manufacturing process.

9.1 Implications for CLC

Molten pool temperature alone is not a good indicator for CLC; there are many molten pool geometries with similar temperatures (ref. 58). From local experience, geometry alone may not be a good indicator for fine CLC control. Perhaps a mix of both is needed.

It is possible to maintain energy input while decreasing the temperature of the molten pool by increasing the area of the energy beam (ref. 6). There are several papers that suggest that beam shape, or energy distribution, should be considered in CLC design (refs. 5, 6, 7, 12, 13, 14). That is, the electron beam geometry should be held constant and calibrated with a Faraday cup or DOE experiments need to consider electron beam geometry.

Empirical approaches have been taken to control deposition processes and have proven effective. Experimental data was collected and used to develop either a set of empirical equations or the data was used to train a machine learning method. These approaches are effective but require large amounts of data and careful analysis. They may be useful for a bounded set of deposition parameter settings but would require a significant amount of data to handle a multitude of alloy systems and gradient deposits.

A great deal of effort has been spent on modeling fusion welding and deposition processes. For what has been learned, there has not been a breakthrough moment in terms of how to use what is known for effective control. Process control has been advanced through M&S for specific metals and specific process parameter regions of interest, but there is no unifying equation or other understanding that reveals mastery of the process.

9.2 Implications for Process Related Research

Repeatable builds with an electron beam may require a higher level of calibration and characterization of the heat source. Those in the field currently treat and model the energy source as a blunt and simple thing, which it is not. For modeling, is it possible to model the heat source and penetration and exploit energy insertion for better control of microstructure in parameter ranges that might otherwise be *bad*? Can *bad* parameter sets become favorable by changing the energy distribution? How might variations in focus and energy distribution at this level affect microstructure evolution?

The shape of the energy beam is important. Faraday cup calibration should be used to ensure consistent beam quality during an individual experiment and across multiple experiments where

comparisons can be drawn. This will be especially important as two or more electron beam systems are used to produce consistent and repeatable samples.

The current research literature appears limited to single factor experiments while the underlying physics are far more complicated. Multifactor experimental designs, such as DOE, would certainly enhance the literature pool.

For industrial applications and research efforts, consideration must be made for calibrating two different energy sources that may be tasked with building the same part. Any differences between energy sources must be minimized through calibration or through parameter settings in a CLC.

9.3 Implications for Modeling Efforts

The shape of the energy beam is important. One cannot assume that a simple double elliptical beam model, which is typically used, is adequate. Shape can affect the thermal field which in turn affects the molten pool depth, undercooling rates, microstructure, residual stress, and distortion.

The finite element and finite volume (FV) approaches have repeatedly been able to predict thermal fields and have been effective in predicting residual stress and distortion. Experiments comparing FE and FV modeling have consistently shown good agreement. However, care should be taken when choosing mesh density, solvers, and simulation time step size. While the FE and FV methods are effective, some level of validation should be exercised to increase confidence in what is being modeled.

To effectively model across multiple scales, from molecular to macroscopic, it may be more efficient to build and operate models appropriate to each scale level and then integrate them through data sharing. This will become easier to accomplish as the cost of computing infrastructure continues to decrease.

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14. ABSTRACT Additive manufacturing is coming into industrial use and has several desirable attributes. Control of the deposition remains a complex challenge, and so this literature review was initiated to capture current modeling efforts in the field of additive manufacturing. This paper summarizes about 10 years of modeling and simulation related to both welding and additive manufacturing. The goals were to learn who is doing what in modeling and simulation, to summarize various approaches taken to create models, and to identify research gaps. Later sections in the report summarize implications for closed-loop-control of the process, implications for local research efforts, and implications for local modeling efforts.					
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