Recent Trends in Mechanics: Future Synergy between Computational Mechanics and Advanced Additive Manufacturing

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INTRODUCTION: Several governments of industrialized countries have articulated strategies to revitalize their industries which have stressed the importance of advanced manufacturing and the development of related innovative research tools [AMP1]. These strategies have highlighted the role that additive manufacturing can play for developers of advanced next generation systems [AMP2]. Industries stand to make great gains by understanding and adopting the latest tools and processes in manufacturing. The dramatic increase in computational power for mathematical modeling and simulation opens the possibility that scientific computing can play a *significant role in the analysis* of many emerging complex manufacturing processes. However, for this goal to be realized, a central objective is to develop experimentally-validated, next-generation, computational tools which can allow engineers and scientists to rapidly develop and analyze new additive manufacturing processes, resulting in superior products, produced at lower overall operational costs. Of particular interest is the design and synthesis of novel surface-based materials which exhibit desired mechanical, thermal, electrical, magnetic and optical behavior. In many cases, these manufacturing processes may involve complex multi-step multi-physical stages that combine disparate techniques such as (additive) deposition of powdered material onto surfaces, targeted laser processing and (subtractive) ablation of the material in order to create structures that are impossible to construct using standard manufacturing methods.

Additive manufacturing is a wide-ranging field that includes powder deposition and three dimensional (3-D) printing, primarily building up a work piece by sequentially adding layers of material. Additive manufacturing has exploded on the scene due to the need for rapid new product creation, designed materials, faster production, and more complex part geometries. Evolving from rather novel and simple applications of hot melt polymers and selective laser sintering, additive manufacturing is now employed in a wide variety of industries for the creation of complex, multi-material products and components expected to operate in demanding environments. Additive processes are finding use in industry, for example aerospace, for prototypes, repair parts, tooling and parts for use in operating systems. An excellent example of this, currently in industry practice, is particle deposition followed by laser welding and milling – a hybrid process combining deposition and fusing of a powder material and a subtractive milling process. This offers interesting possibilities for creating repair parts in remote locations (such as on an orbiting space station or a distant combat zone) as well as distributed manufacturing of consumer products. A recent overview of the state of the art can be found Huang et al. [12]. There are a large variety of deposition techniques, and we refer the reader to the surveys of the state of the art found in Martin [18, 19]. The present report highlights some of the key issues in modeling these processes and discusses the potential synergy between emerging additive manufacturing processes and next-generation mechanics-based modeling and simulation techniques, as well as future research directions.

MULTISTAGE ADDITIVE PROCESSES: In order to illustrate the issues involving computational mechanics and additive manufacturing, in particular the multiphysical phenomena, as an example, we have selected a subclass of specific additive processes methods, namely *print-based manufacturing*, which entails powder deposition and subsequent surface processing. Over fifty percent of the raw materials handled in industry appear in powdered form during the various stages of processing. *These powdered materials form the foundation of current additive manufacturing processes.* One widely used approach is the deposition of particle-functionalized “ink” slurries (particles in a solvent) followed by laser processing. This has wide-ranging applicability to printed electronics on flexible foundational substrates, with end products such as flexible solar cells and smart electronics, for example. One important technological obstacle is to develop inexpensive, durable electronic material-units that reside on flexible platforms/substrates, which can be easily deployed onto large surface areas, manufactured using additive print-based technologies. This class of additive manufacturing involves dynamic deposition of appropriate powdered materials followed by laser processing in targeted regions to sinter or ablate the material.

Such additive processes have advantages over other methods, for example high purity of processed materials, relatively few steps in fabrication (thus avoiding impurities) and the production of near net-shape of the desired product, which can be utilized to produce products with complex shapes that cannot be easily made with other methods. However, robust simulation methodologies, embedded into design software, are not yet available, primarily because classical continuum-based methods, such as the Finite Element Methods are ill-suited to simulate systems which are inherently discontinuous, since they are comprised of discrete units (particles) and because many manufacturing processes of interest involve the evolution of discontinuous domains. However, there are emerging alternative computational methods that are being developed, based on Discrete Element methodologies which are ideal for simulation of many additive manufacturing processes. This class of approaches is advantageous in dealing with domains that fragment or congeal (such as those encountered in additive processes), compared to traditional continuum-based Finite Element methods, which have severe limitations in this regard.

DISCRETE ELEMENT METHODS: Discrete Element-based mechanics and numerical methods have become wide-spread in the natural sciences, industrial applications, engineering, biology, applied mathematics and many other areas. The term "particle mechanics/methods" has now come to encompass research, with interpretations as: (1) Particles representing a physical unit in granular media, particulate flows, plasmas, swarms, etc., (2) Particles representing material phases embedded in continua at the meso-, micro-and nano-scale and (3) Particles representing a discretization unit in numerical methods. *The use of such methods to simulate additive print-based manufacturing processes is in it's infancy, but potentially could have significant impact.*

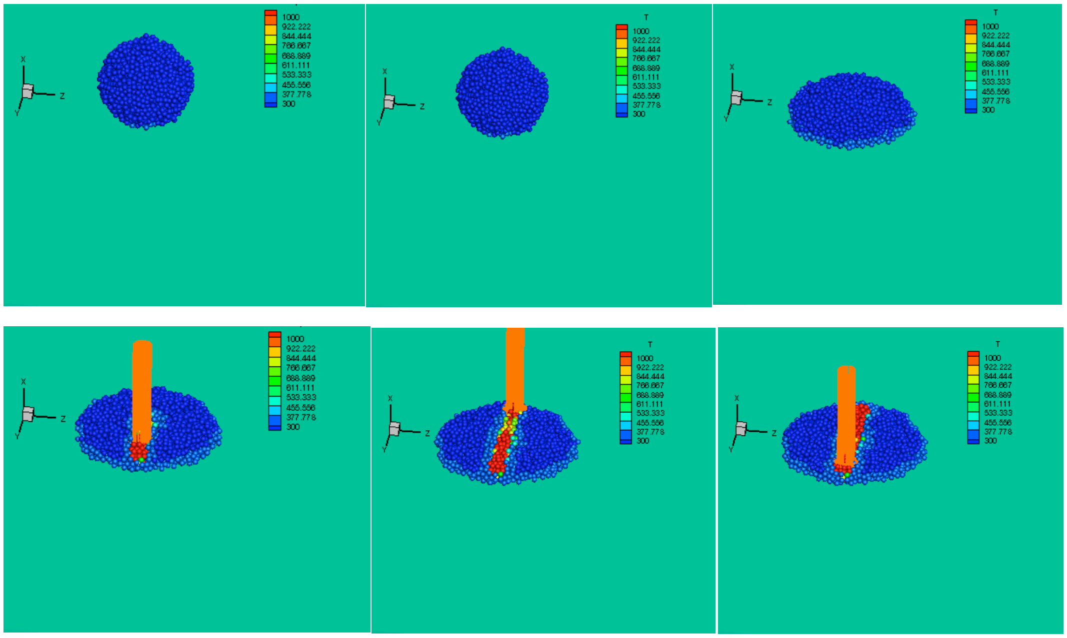

Figure 1. An example of a Discrete Element simulation of additive material deposition simulation of an ionized droplet of particulate material (sequence from left to right and top to bottom) followed by selective laser sintering (Zohdi [37]). The colors indicate the temperature.

Simulation of print based deposition-driven manufacturing applications, involving particle-based materials primarily requires the description of flowing particulate media involving intra-particle momentum exchange through thermo-mechanical contact, laser-induced heat transfer and materials softening and phase-transformation (Figure 1). Because of the precise nature of lasers, they are an attractive way to post-process (anneal, bond, ablate, etc.) powdered materials, in particular with pulsing, via continuous beam chopping or modulation of the voltage.

Carbon Dioxide (CO2) and Yttrium Aluminum Garnett (YAG) lasers are commonly used. The range of power of a typical industrial laser is approximately between 100-10000 Watts. Typically, the initial beam produced is in the form of collimated (parallel) rays that are 1-2 mm apart, which are then focused with a lens onto a small focal point (approximately 50 mm away) of no smaller than about 0.00001 m in diameter. One of the primary uses is selective laser sintering, which was pioneered by Householder [11] in 1979 and Deckard and Beamen [6] in the mid-1980's. A closely related method, Electron Beam Melting, fully melts the material and produces dense solids that are void free. In some cases, where melting and eventually ablation is involved, as the material changes phase from solid to liquid, its absorptivity increases, thus increasing the depth of the cut/hole. Because of the extremely tight profit margins and short turn-around times in manufacturing of new materials, there is an industrial need for numerical simulation of laser post-processing of particulate based-materials, in order to reduce time-consuming experiments.

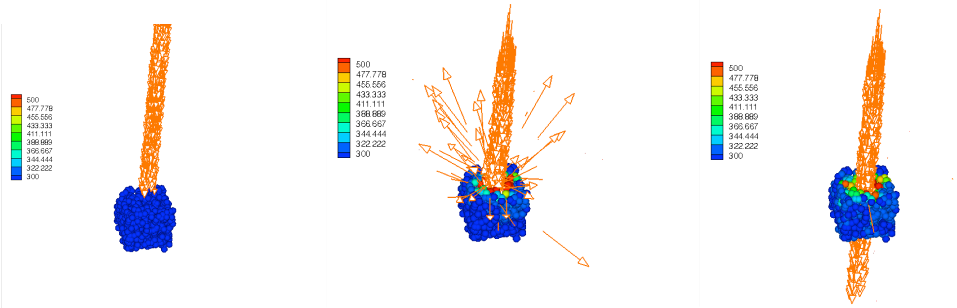

Figure 2. High intensity beams use to a "drill" a hole via ablation, in the sintered powder (Zohdi [35]). The colors indicate the temperature.

This is a strongly-coupled multiphysical system. For example , in Figure 2, by increasing the duration and intensity of the laser, one can drill holes through the sintered particulate material. One simulation approach, adopted by Zohdi [29-39], is to construct a submodel for each primary physical process mentioned and to use a staggering solution scheme whereby (at a given time increment): (1) each field equation is solved individually, "freezing" the other (coupled) fields in the system, allowing only the primary field to be active and (2) after the solution of each field equation, the primary field variable is updated, and the next field equation is treated in a similar manner. The process is applied recursively until the system converges to a solution. The extensive use of Discrete Element methods has historically been for describing the flow of granular media, fracture and fragmentation of materials under impact and blast loads and excavation and drilling problems in the oil/gas industry. For reviews see, for example, Duran [10], Pöschel and Schwager [22] and the works of Onate and collaborators: Onate et al. [20,21], Rojek et al. [24], Carbonell et al. [7] and Labra and Onate [16]. From a mechanics point of view, models for such processes bear resemblance to granular media models for the compaction of powders. For example, see Anand and Gu [3], Fleck [13], Gethin et al., [14], Gu et al. [15], Lewis et al. [17], Ransing et al. [23], and Zohdi [26, 27].

USES AS A DESIGN TOOL: The adoption of nascent computational methods, such as the Discrete Element family of methods, in integrated design and additive manufacturing has the potential to change prevailing unsustainable manufacturing trends. Computational model-based technologies can be invaluable in all phases of the life-cycle: design, verification, construction, validation, fault tolerance, maintenance and resilient operation and end of life considerations (Figure 3).

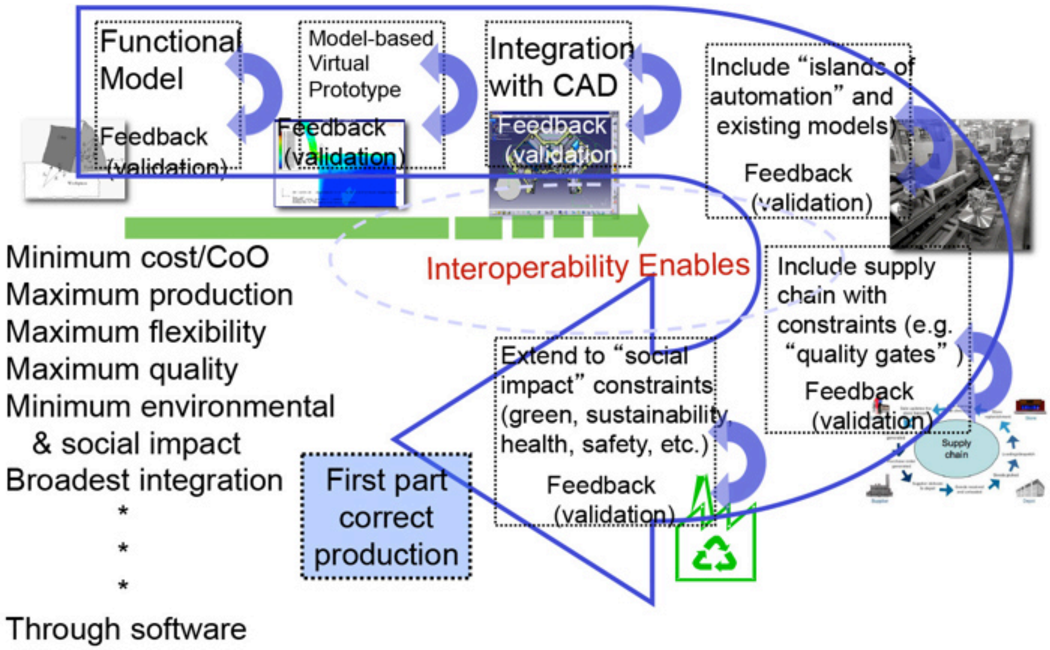

Figure 3. Manufacturing "pipeline" for model and component based methods in integrated design and manufacturing (Source: Dornfeld, LMAS Website)

Perhaps the most profound impact of model- and component-based technologies is that they enable a fully integrated treatment of design and manufacturing. This is to say that manufacturing considerations can be brought forward into the design process by characterizing designs from the point of view of manufacturability. Computational models which can characterize the capabilities of various manufacturing machines and processes. Less traditional processes like additive manufacturing can enable manufacturers to match design models with manufacturing processes and automatically update essential characteristics of design models from "as designed" to "as manufactured." The effectiveness of both product design and manufacturing is greatly increased by detailed models of components, manufacturing equipment and processes. This is consistent with a "levels of design to manufacturing" view (Dornfeld [8]). The recent emphasis on additive manufacturing and the use of large amounts of process or machine derived data at sufficient rates and content with machine learning techniques and analytics can offer both insight into the operation of processes and machines as well as provide useful data for enhancing or validating model and component-based technologies and can increase their efficiency (see Avila et al [5], Dornfeld et al [8], Vijayaraghavan and Dornfeld [26] and Vijayaraghavan et al [25]).

CHALLENGES AND CLOSING REMARKS: There are a number of research challenges, from the point of view of the end-user of such simulation tools which should be addressed by software developers for manufacturing, including (Dornfeld and Lee [9] and Dornfeld [10]):

- validated quality and integrity of the products designed using computational methods for critical applications which resolve thermally-induced defects, inclusions and lack of proper bonding and

- validated precision surface features including form and dimensions (for example, layer thicknesses and deposition angles), production rates and energy and material consumption issues.

From the point of view of purely computational mechanics challenges, the types of numerical methods needed to simulate such processes are still in their infancy. *One objective of future research should be the development of Discrete Element models and codes for high-fidelity Additive Manufacturing Processes, guided by careful experimentation,* which can be seamlessly coupled to continuum-based models, utilizing the best of discrete and continuum formulations, that can capture:

(a) *particle motion/dynamics* involving contact with substrates (which are often electrified),
(b) thermal and electrical current flow through the particles,
(c) thermal softening of the particles and (c) change of phase from a solid, to a liquid to a gas,
(d) laser energy propagation (such as optical reflection and absorption) through complex material microstructure, its conversion into heat and the subsequent conduction and phase transformations involving melting and vaporization and
(e) ejecta (debris) dynamics from laser ablation

Any realistic simulation of an advanced additive manufacturing process will involve many of the subprocesses mentioned above, leading to a strongly-coupled multiphysical system and, as mentioned earlier, adopting modular staggering methods, is probably the most robust approach (Zohdi [29-39]).

Many of the challenges facing additive manufacturing processes center around extending current capabilities to generate simple shapes to more sophisticated complex geometries (external and internal features) comprised of multi-materials with performance meeting or exceeding components, created using conventional processes and production at desired speeds and quantities. Despite the attractive features of additive manufacturing, it alone rarely produces the surface quality needed for structural integrity. Subtractive, intermediate, high-precision surface milling is usually needed to create components with acceptable toughness and fatigue life. It is imperative that additive and subtractive processes be combined, guided by simulation software for deposition and removal of material with attention paid to part quality, dimension and tolerances and surface finish. This must draw on a combination of existing and new numerical methods for additive manufacturing, multi-axis machines and computational modeling of process performance. A recent American Society of Precision Engineers (ASPE) conference at Berkeley *on Dimensional Accuracy and Surface Finish in Additive Manufacturing (AM)* addressed a number of key concerns that will need to be addressed if AM is to realize its full potential for real components used in critical systems. These include issues related to: *(a) dimensional control needed for AM to be used in precision applications, (b) design for manufacturing including design rules for additive manufacturing and the impact of dimensional errors on structures designed using optimization methodologies, (c) standards including certifying AM equipment capabilities and artifacts for assessing machine performance, (d) using AM-fabricated components in precision assemblies and component-to-component relationships, stack-up tolerances, friction, robotic grip-ability and (e) metrology and quality of external surfaces and internal features including materials validation.* Some of these issues can be addressed by hybridizing AM with appropriate other processes – ranging from precision machining to Electrical Discharge Machining (EDM) to industrial-scale polishing methods such as Chemical-Mechanical Planarization (CMP). Industry has been quick to react to the advances in technology. For example, one of the largest machine manufacturers in the world, DMG Mori has just introduced a 5-axis CNC machine tool with an array of conventional milling and drilling tools (subtractive processes), in addition to a laser powder fusion head (additive processes) that can be mounted in the machine tool spindle in place of cutting tools (subtractive processes) to offer a “build and machine” option.

There are a number of issues in the additive manufacturing “process family” that are not well-understood. If systematic approaches can be developed meeting industry standards, this is a game-changer. This needs to draw upon the expertise of researchers in a number of disciplines in engineering:

(1) Computational science, (2) Precision manufacturing, (3) Materials science, (4) Solid and fluid mechanics, (4) Computer Aided Design (CAD), geometric part representation, Computer Aided Manufacturing (CAM) and tool path generation (5) Multi-degree of freedom precision machines, robotics and control theory, (6) Heat transfer and (7) Tribology.

The pace of product development is accelerating with increasing use of advanced design and manufacturing technologies based on computer aided design tools, digital representation of complex part shapes and features, multi-degree of freedom machine tools and robot manipulators, precision manufacturing processes, hybrid processes and systems and automation. Digital (or knowledge-driven) manufacturing allow highly efficient and productive, information intensive, and reconfigurable fabrication that minimizes the time needed to move from the “as designed” to the “as manufactured” state. The tools and techniques provided by knowledge-driven manufacturing coupled with increased automation and more sophisticated production lines have made it more economical to manufacture high quality goods in relatively high wage countries. Industries stand to make great gains by understanding and adopting the latest tools and processes in manufacturing. One mission is to provide young researchers with the skills to innovate and improve margins through the combined use of cutting edge, advanced manufacturing, modeling and simulation techniques. From an educational point of view, the development of a modern advanced manufacturing curriculum, with a strong mechanics foundation, which can meet the needs of students across multiple departments, is critical. If successful, students will gain a critical understanding of the issues currently at the forefront of advanced manufacturing technologies and, in particular, the ability to model and simulate such processes with high fidelity. It is our hope that this will be a positive influence in coordinating additive manufacturing and mechanics-based research and to insure that additive manufacturing lives up to its potential as a viable advanced manufacturing technology. For more detailed information on the topics outlined in this article write to T. I. Zohdi at zohdi@berkeley.edu of D. A. Dornfeld at dornfeld@berkeley.edu or visit

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