PROBABILISTIC MODELING OF SELECTIVE LASER MELTING USING THE BAYESIAN EAGAR-TSAI MODEL

A STAKEHOLDER FOCUSED ACCOUNT OF THE DEVELOPMENT OF ADDITIVE MANUFACTURING

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By
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Additive manufacturing technologies (AM technologies) are a class of manufacturing methods in which products are built up by depositing and fusing raw material in successive passes, or *additively*. In particular, metal-based AM technologies like Selective Laser Melting (SLM) successively fuse layers of metal powder using a scanning laser. (Tian et al., 2020) In contrast, many traditional manufacturing methods are *subtractive* methods. That is, these methods start with solid raw material and form the product by cutting into the desired shape. (Le et al., 2017). Although AM technologies have existed since the 1980s (Wohlers & Gornet, 2016), there has been an increased interest in the technology recently due to the potential advantages that AM offers over traditional techniques. For example, at appropriate scales, AM is more resource-efficient than traditional methods. These advantages may allow for greater economic gains. Of note is the ability to reduce time to market, and also the ability to increase supply flexibility via on-demand manufacturing. (Debnath et al., 2022)

However, the adoption of AM has been slowed by technical challenges. Specifically, there is a need to develop standardized methods for production to control variation in quality. A lack of standardization makes it difficult to produce consistent results, but the creation of a standard requires a large number of specimens (5000-100,000) to be tested, incurring a significant cost (Frazier, 2014). This difficulty is partly due to the fact that AM processes are determined by a large number of processing parameters. For SLM, these parameters include laser power, laser speed, powder thickness, laser beam diameter, and more (Oliveira et al., 2020). So, systematic experimentation requires exhaustively testing a large combination of processing parameters. To accelerate standardization, quality control methods that can link processing parameters and product quality are needed. These models can guide experimentation by focusing on parameters likely to achieve good results. Thus, my technical project focuses on developing a physics-informed statistical model capable of estimating quality from processing parameters.

There are also organizational and social challenges in employing AM systems. The literature on societal impacts of AM presents a wide variation of scenarios regarding its future, such as a transition from centralized to distributed manufacturing (Ben-Ner & Siemsen, 2017) and the incorporation of on-demand manufacturing with consumer information to achieve higher levels of product personalization (Jiang et al., 2017). This variation broadly seems to indicate uncertainty about outcomes of adopting AM. Simultaneously, the promise of design flexibility and cost savings from AM technology has attracted interest from a wide variety of stakeholders, each with differing motivations for investing in AM. These stakeholders include, but are not limited to, aerospace manufacturers, biomedical companies, the US government, and auto manufacturers (Chang, 2016). A holistic understanding of the stakeholder landscape of AM could inform future directions and thus be of great utility to many decision makers in the AM world, such as policy makers looking to explore regulation of AM, and managers seeking to understand the economic impact of AM on their business. Thus, in the STS portion of this work, I aim to provide a stakeholder-focused account of the development of additive manufacturing, with a goal of understanding how the involved stakeholders shape the role and perception of additive manufacturing.

Technical Topic

The technical project in this work focuses on the AM process known as Selective Laser Melting (SLM). SLM fabricates parts in an iterative process. First, the machine spreads a layer of metal powder onto the base plate. Then, the metal powder is fused together with a scanning laser, melting the powder layer into the desired shape. Another layer of metal powder is spread over the fused layer by a wiper blade and melted again by the laser, adding another layer of fused metal (Trevisan et al., 2017) (Figure 1).

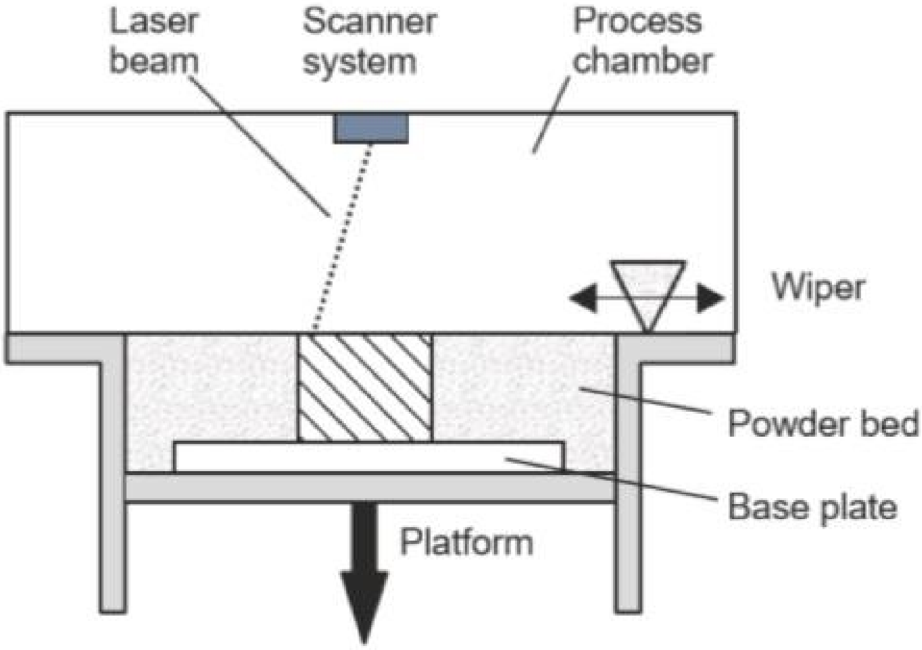

Figure 1. A schematic of the SLM process. (Montero et al., 2019)

SLM manufactured parts can contain defects arising from different physical phenomena. The defects of interest are *porosities* - gaps in the final product - which reduce its strength. It is especially necessary to control defects in safety critical applications where failure could be catastrophic (Blakey-Milner et al., 2021). Porosity formation has been linked to *melt pools*. (King et al., 2014) As the laser strikes the powder, a pool of liquid metal forms underneath the beam. The shape of this pool depends on the processing parameters, primarily laser power and speed. Categories of melt pool are established based on their associated defect:

1) *Keyholing* melt pools: indicate an excess of laser energy, resulting in pores formed from vaporized metal.

2) *Lack-of-fusion* melt pools: indicate incomplete melting of metal powder, resulting in unmelted powder in the final product.

3) *Conduction* melt pools: indicate appropriate absorption of laser energy and sufficient melting.

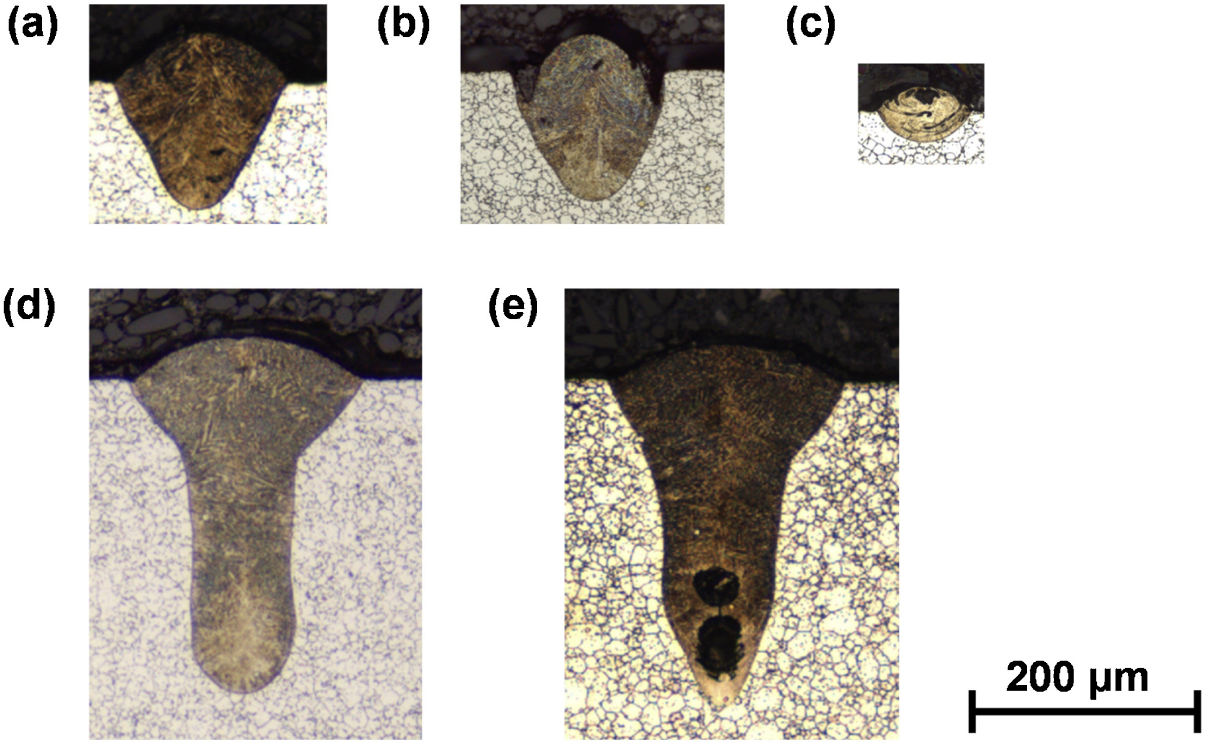

Figure 2. Representative melt pool shapes. (a) corresponds to a conduction melt pool. (b) and (c) correspond to lack-of-fusion melt pools. (d) and (e) correspond to keyhole melt pools. (Scime & Beuth, 2019)

Criteria for classifying melt pools into these categories have been developed from experiments (Scime & Beuth, 2019). However, the same principle can also be applied to simulations. Thus, computational models that link processing parameters to melt pool dimensions provide a way of predicting settings likely to result in good quality products prior to experiment. Our model is *physics-based* - incorporating physical principles from the SLM process, and also *statistical* –

incorporating information and uncertainty from experiment. It is based on Bayesian calibration and the Eagar-Tsai model (ET Model) (Whalen et al., 2021). The Eagar-Tsai model is a computationally efficient lower-fidelity physics based model capable of predicting melt-pool geometries. Due to its lower fidelity, it may not agree well with experimental result. Thus, we fit the ET Model to experimental data using Bayesian calibration methods, which are a class of statistical model-fitting methods capable of providing uncertainty quantification in forward prediction (Kennedy & O'Hagan, 2001). The computational model will then be used to develop a *printmap*, which indicates regions of processing space are suitable for manufacturing. (Figure 3)

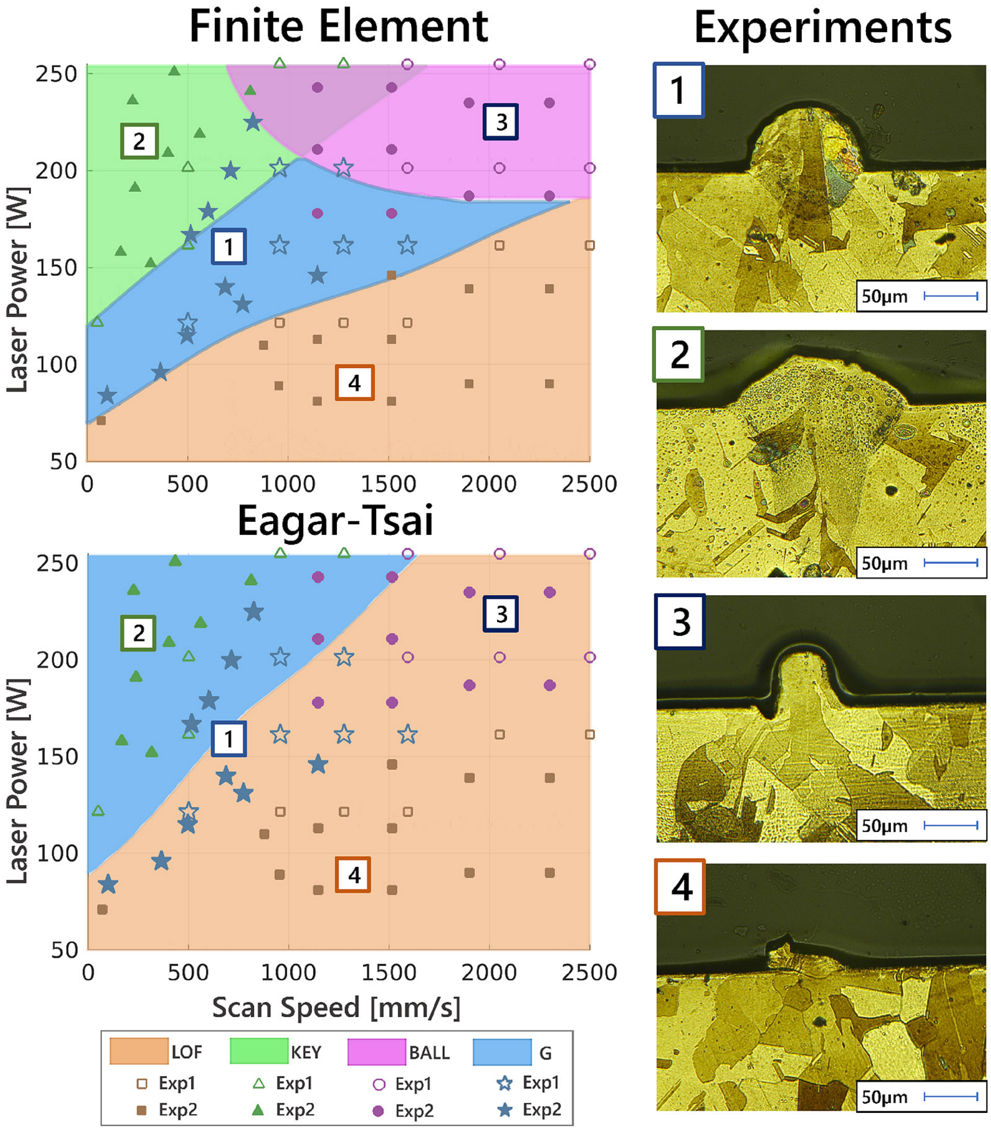

Figure 3. A printmap. The x-axis is laser speed, and the y-axis is laser power. The blue regions correspond to conduction (no defect). Other regions are marked according to their likely melting mode, e.g keyhole or lack-of-fusion (Johnson et al., 2019).

The technical topic reflects a broader recent trend in industry and academia of using data-driven modeling techniques in AM processes. This can be connected to “Industry 4.0,” a neologism referring to the increasing usage of “smart” manufacturing.

The AM Stakeholder Landscape: Opportunities and Challenges

Short term benefits from employing AM translate to concrete economic benefits like the ability to evade lengthy supply chain processes. AM technologies have been projected to have far-ranging impacts in diverse areas, ranging from global organization management structure and intellectual property law. In particular, AM is predicted to drive a reversal of globalization trends, marking a shift from centralized manufacturing to distributed manufacturing (Ben-Ner & Siemsen, 2017). The nature of additive manufacturing as a digital manufacturing technique has raised concerns about the capability to protect designs, as digital designs could be copied and distributed over the internet (Jiang et al., 2017). There is the broader expectation of AM as a key piece in "Industry 4.0." Representing an expectation of future development, Industry 4.0 will be characterized by a revolution in manufacturing practices driven by "smart" technologies, resulting in modular manufacturing systems capable of realizing high throughput and extensive customization, informed by multi-modal streams of data from consumers and manufacturing equipment. These developments are motivated by trends in IT and software development, including increased personalization and shorter development periods (Lasi et al., 2014)**.** In accounts of Industry 4.0, AM is often cited as a critical technology, being one of the few technologies in the framework readily bridging the gap from digital to physical (Butt, 2020). Most studies on the social aspects of AM have largely been empirical studies utilizing survey data. For example, in (Jiang et al., 2017), the authors conducted a survey study of experts in AM in order to derive likely scenarios for its future development by 2030. Thus far, comprehensive stakeholder-centric accounts of the development of AM were not readily found in the literature, besides (Naghshineh et al., 2021), which provided an extensive enumeration of possible social impacts of AM found by literature survey, linking the social impacts to categories of stakeholders. However, general terms to describe the categories were used to describe the stakeholders, e.g "Local community" and "Society." In terms of analyzing notions like Industry 4.0, a more granular description of stakeholders will be necessary.

To develop a comprehensive account of AM's development, I will utilize Pinch and Bjiker's theory of the social construction of technology (Pinch & Bijker, 2008). SCOT is intended to explain the development, adoption, and eventual stabilization of a technology in social terms. This framework is suited towards analyzing the case of AM due to its nonlinear nature and its ability to assess the relationship between social norms surrounding a technological artifact and different stakeholder groups. In this framework, *social groups* (or 'stakeholders') are the actors involved with a technology or *artifact*, all sharing some common attribute or membership in a particular group. Each social group faces *problems* which may or may not be amenable to technological *solution.* SCOT defines a notion of "interpretive flexibility" and "closure." As a technology emerges, its essential qualities may not yet be considered fixed as different social groups, and thus there may be a lack of consensus on the appropriate usage of the artifact, or *interpretive flexibility*. As consensus is built, the identity of the technology stabilizes and *closure* is achieved.

I expect that SCOT will allow me to explore (i) *who* is using AM (social groups/stakeholders), (ii) *why and how* they are using AM (problem/solution), and (iii) what that means for the *identity of AM* (flexibility/closure). This analysis will result in an improved understanding of the key stakeholders driving the current development and usage of AM, with an eye towards understanding how the relations and dynamics in this dimension can inform future use cases and development trajectories for AM. In particular, for the case of Industry 4.0, it will be instructive to consider *who* is pushing for this notion in order to understand whether it is likely to become an integral part of what AM will be, or whether it is just a vaguely defined term referring to a disjointed collection of expectations about the future of manufacturing. Although it will likely be difficult to comment on closure of AM technologies at the current time, an assessment of its interpretive flexibility may also prove fruitful in understanding at least the current identity of AM as an inherently flexible technology.

Research question and methods

How are the stakeholders involved in the usage, promotion, and development of additive manufacturing technologies shaping the identity and acceptable uses of the technology?

The question is aimed to directly guide the relationship between stakeholder and artifact that will be the core of this SCOT based analysis. Practically, if a stakeholder is discovered to be influential in shaping the identity of AM, that stakeholder's vision for the technology will likely affect future use cases.

To answer this question, an initial survey of the research literature of the social impact of additive manufacturing will be conducted to identify and enumerate categories of stakeholders present in the literature. Major themes of problem and solution related to these stakeholders will also be identified in order to apply the SCOT framework. This literature survey will involve bibliometric analysis by tagging papers according to the stakeholder groups mentioned and the associated problems. To gain a more representative picture of the entire stakeholder landscape, the survey will also attempt to employ reports from industry and government, e.g (Wellener et al., 2020) and (White House, 2022). Visualizations (e.g influence diagrams) will be created to depict the stakeholder relations in an intuitive and graphical manner.

Ultimately, the information gathered from the stakeholder analysis is intended to be used to assess the plausibility of claims regarding AM's development trajectory. Thus, during the literature survey, projections on the future of AM will be collected from the literature and tabulated. Broad classes of claims will be aggregated together, and the evidence in support of those claims evaluated in light of the information from the stakeholder analysis. Altogether, major themes from both the stakeholder analysis and evaluation of projections will be synthesized to comment on the broad direction of AM's current identity and likely future directions.

Additional perspective on the research topic can be obtained by consulting with experts in the field. Prof. Cindy Chang in the Department of Engineering Systems and Environment at UVA is an expert in smart manufacturing systems and data driven analysis. Prof. Ji Ma in the Department of Materials Science and Engineering is an expert in metal-based additive manufacturing methods. An interview would aid in identifying critical organizational and technical challenges that stakeholders employing AM currently face. Their opinion would also aid in evaluating the likelihood of future scenarios for AM. It will also be informative to get their opinion about the most likely future identity for AM as another form of evidence for the analysis.

Conclusion

Interest in additive manufacturing has surged in recent years due to the possibility of the technology to realize a host of economic and social benefits. However, technical and social obstacles currently inhibit the full realization of its potential. On the technical side, comprehensive and standardized processes for controlling quality variation in AM processes have not yet been fully realized. This poses a major challenge in applying AM to safety critical applications where mechanical failure could be catastrophic. On the social and organizational side, comprehensive accounts of the stakeholder landscape in AM are not yet readily available in the research literature in due to the emerging nature of the technology. In this sense, both aspects of this work will focus on delivering useful insights for decision-makers in AM with the ultimate goal of making informed and judicious decisions about how to realize the best social outcome from AM. The technical solution is intended to guide machine operators and quality assurance engineers towards processes that fabricate defect-free parts in order to realize these benefits of AM, while the STS portion of this work will focus on providing an account of the stakeholder landscape of AM.

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