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Overhanging Features and the SLM/DMLS Residual Stresses Problem: Review and Future Research Need

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Abstract: A useful and increasingly common additive manufacturing (AM) process is the selective laser melting (SLM) or direct metal laser sintering (DMLS) process. SLM/DMLS can produce full-density metal parts from difficult materials, but it tends to suffer from severe residual stresses introduced during processing. This limits the usefulness and applicability of the process, particularly in the fabrication of parts with delicate overhanging and protruding features. The purpose of this study was to examine the current insight and progress made toward understanding and eliminating the problem in overhanging and protruding structures. To accomplish this, a survey of literature was undertaken, focusing on process modeling (general, heat transfer, stress and distortion, and material models), direct process control (input and environmental control, hardware-in-the-loop monitoring, parameter optimization, and post-processing), experiment development (methods for evaluation, optical and mechanical process monitoring, imaging, and design-of-experiments), support structure optimization, and overhang feature design; approximately 142 published works were examined. The major findings of this study were that a small minority of the literature on SLM/DMLS deals explicitly with the overhanging stress problem, but some fundamental work has been done on the problem. Implications, needs, and potential future research directions are discussed in-depth in light of the present review.

Keywords: additive manufacturing; 3-D printing; metal additive manufacturing; selective laser melting; SLM; direct metal laser sintering; DMLS; metal powder processing

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1. Introduction

Additive manufacturing (AM) technologies, commonly known as *3-D printing* tools, are a family of manufacturing processes which produce solid geometries by “joining [raw] materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods” [1]. While most commonly used and established AM processes use plastics and photopolymers as the initial raw material, a number of AM processes which can process metals (usually in the form of fine powder) are emerging and being rapidly developed and perfected. The availability of such fabrication tools offers great promise to many sectors of manufacturing, especially the aerospace, medical, and automotive industries, in their ever-growing quest for lighter, stronger, tougher, more complex, and more cost-efficient metal parts.

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One of the most promising and flexible of these metal-printing processes is known as Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS). The process is known by both names, depending on geographical area of the user; in the early days of development, "SLM" was most commonly used in Europe and "DMLS" in the USA, but both names have been used synonymously as the technology has matured over the past decade or do. Compared to other metal-melting AM process, such as Electron Beam Melting (EBM), SLM/DMLS is very cost effective, works well with a wide variety of elemental metals and alloys, produces an excellent surface finish, provided excellent feature resolution, and is more industrially-safe [2-4]. Unfortunately, the SLM/DMLS process is dominated by one serious weakness, which is preventing its more wide-spread acceptance and use as a standard manufacturing process: the tendency of the process to build an unbalanced stress profile into the part between the layers during processing. This has become known as the *residual stresses problem* and has been the topic of research since the process was first introduced. The collection of both general and regional residual stresses into parts without a way for them to naturally dissipate (as they do in non-metal AM processes) can be major problem because this can initiate cracks, warpage, and delamination if the part is not properly designed or has delicate features, both during and after processing, and can reduce the fatigue strength of the part by a factor of 10 or more when compared to bulk formed parts [5-8].

These problems are especially apparent and challenging in parts that have overhanging or protruding features, as the stresses tend to build up more seriously in and near these features during printing [5, 9]; this can cause severe warping and damage to the features and cause the destruction of the entire part, sometimes before it is even finished printing. Temporary support structure can be used to prevent in-process failure but using these in SLM/DMLS can come with its own set of problems. With careful part design, use of special support structures for delicate features, and various rules-of-thumb developed over the years the process can be used successfully for specific applications; however, it would be far more useful and trustworthy, more cost-efficient, and more widely accepted if a general theory of design were available for the parts that will be created using SLM/DMLS.

2. The SLM/DMLS Residual Stresses Problem

According to the US patent for SLM/DMLS, the process is a variation of the powder bed fusion process in which a thin layer of "metallic powder free of binding and fluxing agents" is selectively "heated by [a] laser beam to melting temperature" in order to fuse it into a solid slice of material in the correct shape of the part. The laser beam energy "is chosen in such a way that the layer of metallic powder is fully molten throughout its layer thickness at the point of impact of [the] laser beam" and the laser beam is "guided across a specified area of the powder material layer.....in such a way that each run partially overlaps the preceding run" in order to form proper metallic bonds between scans (and between the current layer and previous layers) and therefore produce a homogeneous solid. The entire operation is run in a "protective gas environment" during the described procedures to prevent unwanted reactions and oxidations. Because the powdered material is "free of binding and fluxing agents" and because it is "heated to its melting temperature throughout the layer thickness," the resulting solid has mechanical properties similar to bulk-formed materials [10]. As each layer is selectively melted in this way, the build table in the printer drops down the distance of one layer

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thickness (20-100 μm) and a wiper deposits a fresh layer of new unmelted powder, starting the whole operation over again. This cycle continues until the part is complete [5-7, 11]. Traditionally, only metallic materials could be used with SLM, but some work has been done to extend the process to ceramics and metal/ceramic/polymer composites [12-14]. Figure 1 demonstrates the basic anatomy and process chain for SLM/DMLS.

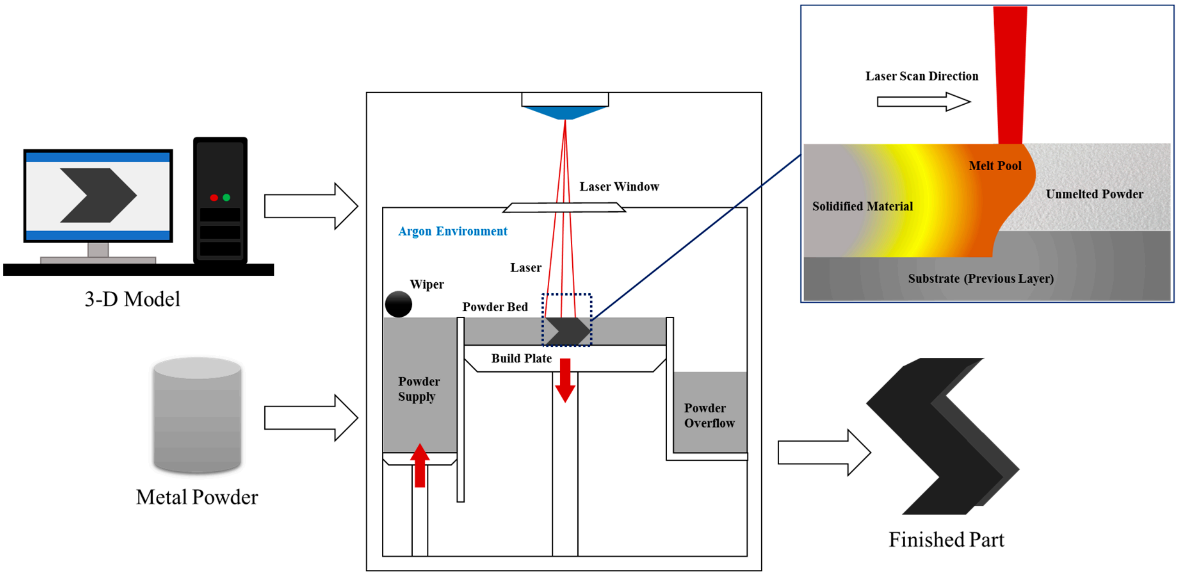

Figure 1. SLM/DMLS process mechanics

By definition, "residual stresses" are the stresses within a plastically or elastically deformed material that remain within the structure after the load that deformed it is removed [15]. In the SLM process, the major source of the residual stresses is the heat cycling as the laser scans across each layer, where previously solidified layers are re-melted and cooled several times at inconsistent levels of heat. When looking at the stress gradients in a particular single layer of the part during heating, the two most important regions are the top of the layer (exposed to the laser) and the interface between the layer and the previous layer (Figure 2).

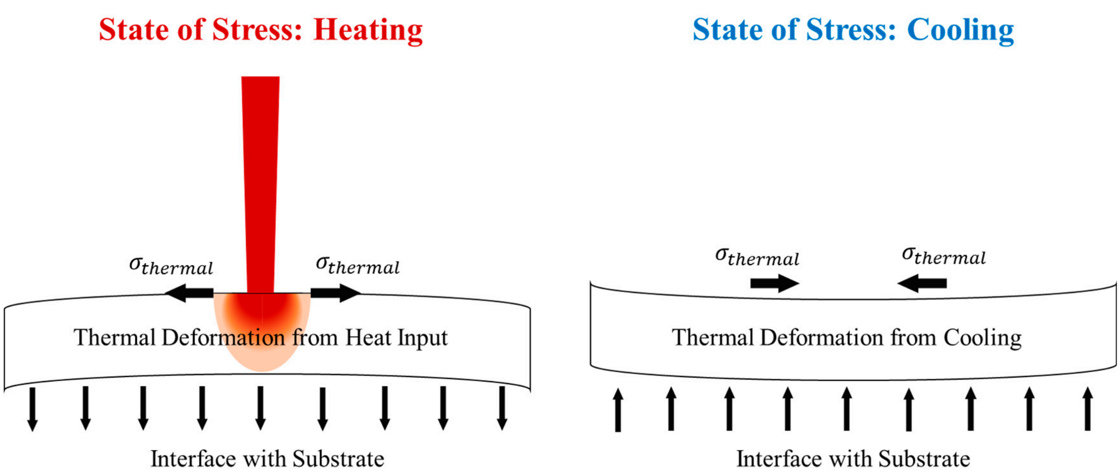

Figure 2. Stress gradients in single layers

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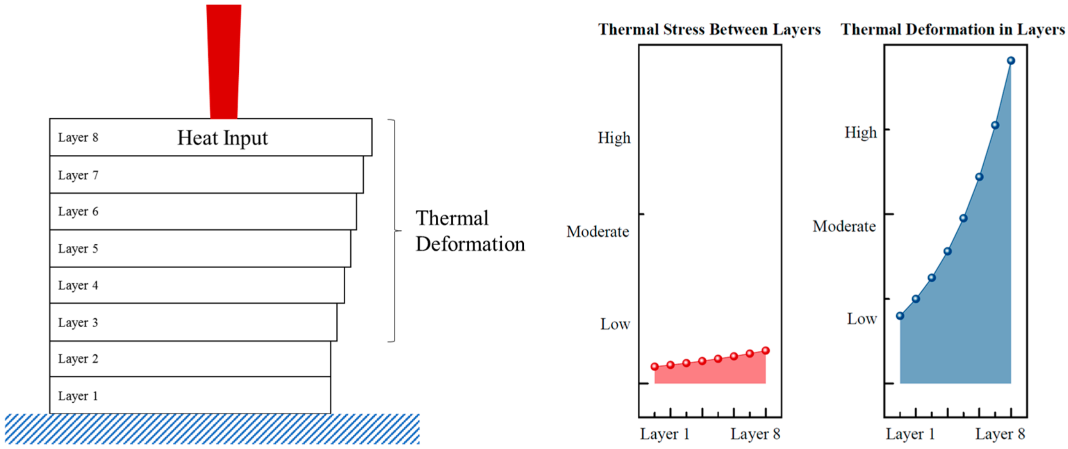
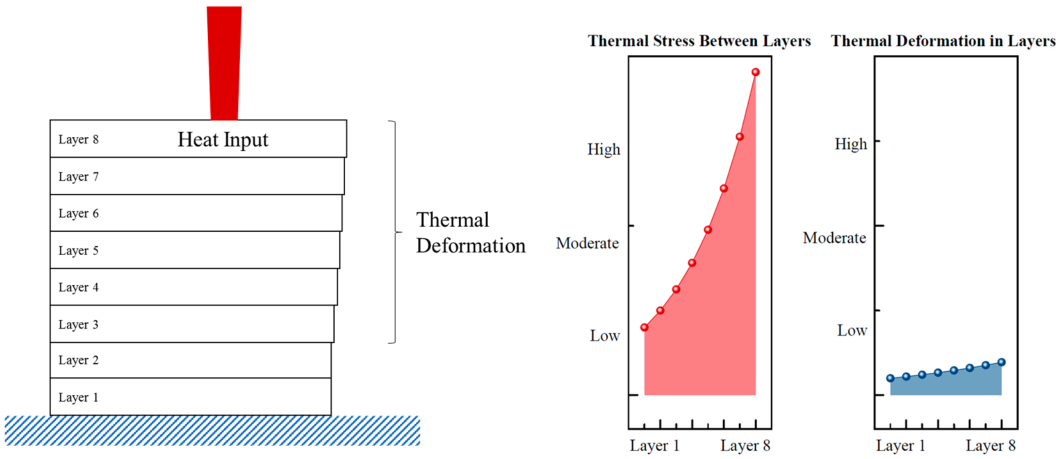
Due to thermal expansion, the top of the layer experiences a tensile stress, while the cooler interface has compressive stresses acting on it. If only one layer was to be printed, this would not be a problem, as the stresses would dissipate naturally once the material cooled. The problem manifests itself when the underlying layers restrict the thermal expansion and contraction of the layers immediately below the melt pool; this can occur several layers deep simultaneously, can happen multiple times to the same layer throughout the build, and the material does not necessarily need to be molten for it to happen. This can cause an elastic compressive strain within the layers, resulting in a stress gradient between the layers [8-9]. Figure 3 demonstrates this graphically. Where the layers are free to move (Figure 3a), the residual stress between the layers is low; it is not zero, however, since some friction will still exist between the layers. Where the layers are restricted from moving by fusion (Figure 3b), the stresses can build up quickly because they are not allowed to move freely and therefore can become warped as the subsequent layers are heated. Figure 4 shows an example finite-element (FEA) model of the thermal deformations during laser scanning; the material shown is six layers (50 μm) of 316 stainless steel, with a 200 W laser input and 24°C ambient temperature, with the base fixed to the build plate. This model is for concept demonstration only and not a new research tool; no new powder is added in this figure, this is simply the deformation of the material under laser load.



(a) Example 1: Free-sliding layers, fixed on build plate



(b) Example 2: Fused layers, fixed on build plate

Figure 3. Stress between layers

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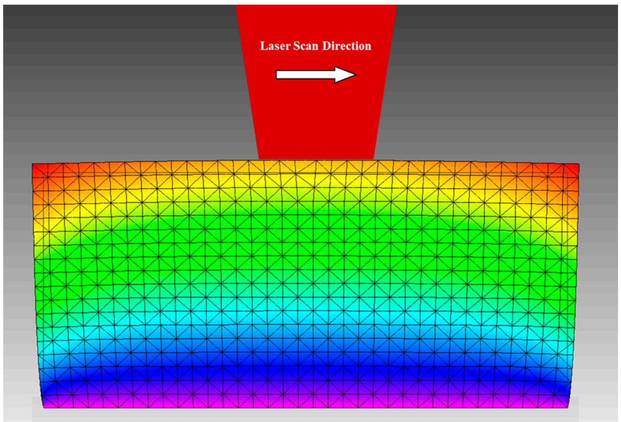

Figure 4. Stress between layers (FEA deformation example)

Several published studies explicitly described the specific mechanics of the stress formulation as described above, most notably in the works of Mercelis and Kruth [9] and Knowles *et al* [8]. Other studies which discussed this issue in depth were those by Roberts *et al* [16-17], Matsumoto *et al* [18], Gu *et al* [19], Guo and Leu [4], and Van Belle *et al* [20].

There are a number of ways to combat the residual stresses problem when printing very simple parts; most parts created by SLM are physically connected (welded) to the build plate at the base, helping to both support and tie down the layers until the part body is large enough to support the stresses; this is common knowledge in the world of metal powder manufacturing. Unfortunately, there is little experimentally-based information to be found concerning the effects of the residual stresses on the design of complex parts with overhanging or protruding features (Figure 5). Most of the studies typically discussed in literature searches discuss rule-of-thumb ways to physically prevent the stresses from destroying the parts during printing and are little concerned with trying to understand the mechanics of the stresses and how they directly affect the overhanging features. There was considerable discussion of this problem in the studies by Hussein *et al* [21-22], Matsumoto *et al* [18], Calingnano [23], Mohanty & Hattel [24], Zeng [25], Li *et al* [26], and Gan & Wong [27] but these addressed application-specific issues and did not discuss the problem at the level of feature and part design.

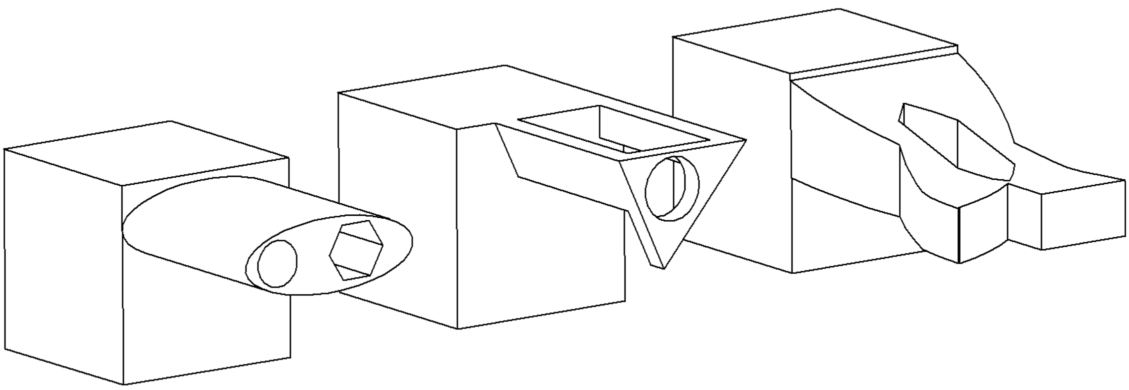

Figure 5. Examples of overhanding and protruding part features

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Some of the opinions commonly heard from practitioners are that the overhanging features are most severely affected by the stresses because they are not physically welded to the build plate during the printing and are thinner and less resistant to thermal shock. Depending on the specific geometry, stress concentrations between the features and the main parts also likely play a role in magnifying the effect. However, there is little rigorous treatment of this in the technical literature to verify if these opinions are indeed true for general cases. The current study hopes to discover more in-depth answers to these questions.

Up to now, the best solution has been to use strong support materials, in spite of some problems using both a powder bed and supports; concerns included the required extra post-processing, extra material use, increased cycle time, increased risk of damage to the part, damage to the finish of the part from support removal, and restrictions on the part design to accommodate the support structure are all issues when using support structures with SLM. Some studies that well discuss the pros and cons of support structures to prevent damage in SLM/DMLS were those performed by Hussein *et al* [21-22], Jhabvala *et al* [28], Matsumoto *et al* [18], Thomas and Bibb [29-30], Wang *et al* [31], Kruth *et al* [32], and Papadakis *et al* [33]. Data from several studies by Hussein *et al* [22], Kruth *et al* [32], Vora *et al* [34] and Patterson *et al* [35-36] suggested that the use of rigid support structures during SLM/DMLS for overhanging features may actually cause the residual stresses to be worse than if the overhang had no solid support during printing.

3. Survey of Previous Work

The main goal of this literature review was to identify studies and methods used or in development for SLM/DMLS to combat the negative effects of residual stresses within overhanging and protruding features. To accomplish this, a large number of fundamental sources were collected, sorted into categories, and reviewed; they will be discussed in depth in here and in Section 4. This review is not meant to be an annotated bibliography and does not claim to cover every single published work in any particular area. The review simply explores the topic in depth in order to define the problem and discover the kind of solutions that may be available to deal with it. With this information, future research directions can be identified and guided.

The residual stresses problem has been an obvious problem since the invention of the SLM process and has put a cap on its full and free utilization, so a number of researchers have worked to develop solutions to this problem since the early days of the technology in 1997-2001 [10,18]. Relevant previous work in this area can be categorized into five areas (Figure 6): (1) process modeling and simulation, (2) process control and post-processing methods, (3) experiment development, (4) support structure optimization, and (5) design and analysis of overhanging structures. While the great majority of the previous work does not directly address the overhanging structures problem, works that are clearly or potentially relevant to the topic are collected and reviewed in this chapter, with explicit treatments of the overhang structures addressed at the end of the review.

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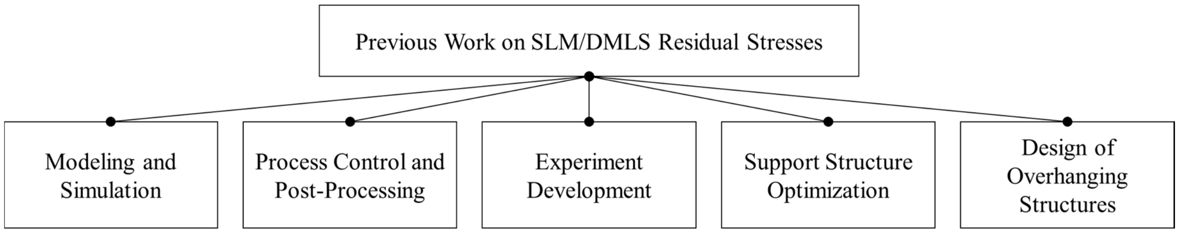

Figure 6. Previous work categories

3.1. Process Modeling and Simulation

As with any problem solution, a good model is needed for problem understanding before any useful work on the problem can be attempted. A number of models have been developed for the SLM/DMLS process, some general process models and many that model specific aspects of the process. These modeling studies can be sorted into several subcategories, as shown in Figure 7.

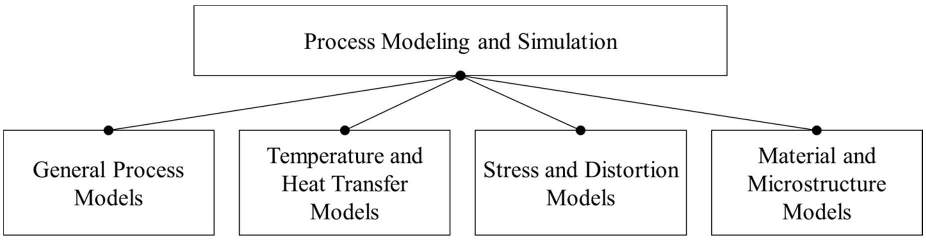

Figure 7. Process modeling and simulation categories

3.1.1. General SLM/DMLS Process Models

Two of the best known, trusted, and widely cited general SLM/DMLS process models were produced by Kruth *et al* [9, 37-38] at the University of Leuven (Belgium) and manufacturing scientists at Lawrence Livermore National Laboratories (LLNL) [39-43] in the United States. Both research teams developed comprehensive analytical thermo-mechanical models of the SLM/DMLS process, which are based on first principles, basic energy balances, phase changes, material properties, material states, and part geometries, among many other physical phenomena. Numerous experiments, both physical and numerical, were developed to develop and verify these models, which are considered to be the state-of-the art in the field. The limiting factor of these models is that they are highly proprietary and not usually available for use by outside research groups and practicing engineers.

Another research group based primarily in Germany, Papadakis *et al* [33], proposed a model reduction in order to simplify the creation and running of good finite element models of the thermal and mechanical effects in large parts made by SLM. The study shows that for large parts, the finite element model can be simplified without a significant loss of accuracy and usability. The model considers all of the most important process considerations, such as heat input, molten region geometry, material deposition, phase transformations, heat transfer modes and other effects. The model is well-verified experimentally and is becoming more widely used.

These state-of-the-art models can become very cumbersome to use for more general problems, so Markl & Korner [44] developed a numerical model on multiple length and time scales to model and

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describe various aspects of the process across numerous applications and parameter sets. Carefully designed experiments were used to tune and verify the numerical model in real time in order to provide a more comprehensive understanding of the underlying physics of the process. This marriage of simultaneous modeling and experimentation to understand SLM/DMLS provides a larger window and clarifies much of the mystery behind the process for product designers.

3.1.2. Temperature Distribution and Heat Transfer Models

Many excellent heat transfer models of the SLM/DMLS process have been developed; the earliest established models were primarily stress-based (see Section 3.1.3), which depended heavily on the heat transfer mechanisms within the material. Early research showed that the heat transfer was an unpredictable quantity in standard stress models, necessitating the development of complex heat transfer models. Many of the models deal with the temperature distribution and gradients within the material during processing using finite element analysis; the model, developed by Contuzzi *et al* [45] at the Polytechnic University of Bari in Italy, advanced a simple finite element analysis model to simulate the temperature distribution through the layers during the SLM process; stresses were not directly addressed in the model, but a stress model could easily be derived from the heat transfer model. The model also includes a method for directly modeling the phase change of the materials as the process is being run.

The models produced by Huang *et al* [46], Li *et al* [47], and Kundakcioglu *et al* [48] are similar in nature to [45], but are more theoretically-based, make fewer assumptions and heavily consider volume shrinkage and phase changes within the material. Coupled transient heat and mechanical analyses are used in these models. The study by Masoomi *et al* [49] combines the theory of several thermal models and gathers significant empirical and experimental data concerning the true heat profile. Roberts *et al* [16-17] used a novel finite element analysis method known as "element birth and death" to facilitate modeling the heat gradients and the heat transfer between layers. A numerical experiment was performed, in which the stresses in a single layer were studied in detail and a very complex FEA model was created of the heat transfer and stresses for a very small area.

Other, more specific, thermal models were developed by Gusarov *et al* [50], Li *et al* [51], Fu & Guo [52], Shifeng *et al* [53], and Heeling *et al* [54]. Gusarov *et al* modeled the heat transfer in the material, both conductive and radiative, assuming that the laser scan tracks were nonuniform and that the material temperature was unstable. Li *et al* varied the scan speed and modeled how this changed the heat profile within the material during processing, while Fu & Guo modeled the thermal history in the material as a function of layer buildup, which varied significantly with time. The mechanics of the melt pool, its boundaries. and its influence on the surrounding material was modeled by Shifeng *et al* and Heeling *et al* using finite element methods.

3.1.3. Stress and Distortion Models

The primary purpose of much SLM/DLMS research is the accurate and effective modeling of part distortion and deformation during processing in order to produce good quality finished parts. The earliest examples of a stress model for SLM/DMLS were developed by Matsumoto *et al* [18, 55] at Osaka University in Japan and first published in 2001-2002. Kruth *et al* at University of Leuven in

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Belgium have also worked extensively on this problem [9, 32, 37-39, 56-58] and over time developed one of the most well-respected general SLM/DMLS models in the world, as discussed previously. Other important stress and distortion models that have been developed can be classified into two categories: models of single layer processing and models of bulk (multiple layer) processing. Single layer models analyze the stress effects in just once layer of the part, while bulk models treat several layers or even an entire part at once. In general, the single layer models are more detailed but the bulk models give a more system-level view of the processing effects.

The most widely cited single layer stress models using finite element analysis are those developed by Hussein *et al* [21], Matsumoto *et al* [18], Contuzzi *et al* [45], Dai & Gu [59]. Wu *et al* [60] proposed a model that analyzed the stresses within a single layer of powder as it solidifies, unlike the others, which were based on stresses within the solid materials. A variety of bulk (multiple layer) models exist and can be divided into four groups: first principles and analytical models, computational FEA studies that are verified using simple beam deformation experiments, finite element models built in commercial software (such as ANSYS), and multiscale modeling to predict part distortion. First principles models, both simple and complex, were proposed by Patterson *et al* [35-36] and Fergani *et al* [61], all of which were demonstrated and verified using various numerical experiments and comparisons to published experimental data. Examples of computational studies that were verified using various simple part deformation experiments were those performed by Vrancken *et al* [62], Zinovieva *et al* [63], Liu *et al* [64], and Safronov *et al* [65]. Stress models built using ANSYS include those models developed by Zaeh & Branner [66] and Gu & He [67]. The studies by Li *et al* [68-69], Parry *et al* [70], and Vastola *et al* [71] were multiscale finite element models for fast and efficient prediction of part distortion, primarily intended to inform part designers and engineers.

3.1.4. Material and Microstructure Models

The presence of residual stresses within the material clearly influences the way that the material solidifies and forms the microstructure during cooling. Several studies have explored this in depth from several different perspectives, including microstructure evolution, the effects of some specific process parameters on the microstructure, evaluation of bonding issues related to surface roughness, and modeling small defects in the material structure during processing.

Some studies that examined microstructure evolution were those by Liu *et al* [72], Toda-Caraballo *et al* [73], Thijs *et al* [38], Chen *et al* [74], and Mertins *et al* [56, 75]. Liu *et al* and Thijs *et al* examined the residual stress evolution at the microstructure scale using Vickers hardness tests and concluded that the residual stresses within the microstructure were greatest in the overlapping regions between scan tracks, but was heavily dependent on scan speed and heat profile. Toda-Caraballo *et al* examined the influence of the residual stresses in the material on the recrystallization behavior in new solid material as the part was built. Chen *et al* examined and modeled the basic thermal behavior of the material during processing at the microstructure level. An examination of an out-of-equilibrium microstructure was examined by Mertins *et al*, finding that defects in the material were produced both by poor melting/cooling dynamics and a lack of complete melting of some powder during processing.

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Alyoshin *et al* [76] examined the microstructural problems when using SLM/DMLS to process materials with poor weldability and developed a method for finding and modeling microcracks in the material. Alloys with poor weldability typically have a low fatigue life, as the recrystallization of the material grains is poor. The researchers were able to increase the fatigue life, particularly in the plastic region, by relaxing the residual stresses using an argon-based treatment to better form the grains during processing.

3.2. Process Control and Post-Processing

Direct process control and post-processing are the most common and preferred methods of dealing with the residual stresses in practice. Several categories of solutions (Figure 8) have been developed, including process input control, environment control, in-situ monitoring and feedback control, process parameter optimization, and post processing.

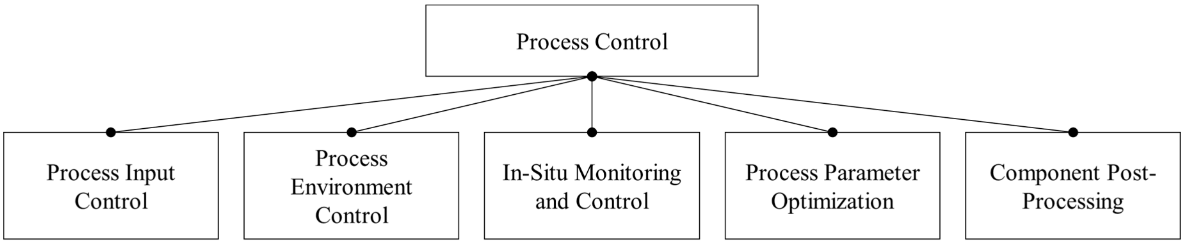

Figure 8. Process control and post-processing categories

3.2.1. Process Input Control

The basic goal of process input control is to parameterize and control the values of the input parameters, such as laser power, scan speed, and other factors in order to obtain the best possible processing results. While this is the most common technique, besides post-processing, to optimize parts, it depends mostly on the experience and intuition of the user and is usually not applicable to general problems using SLM/DMLS. While many case studies and part- and machine-specific solutions have been published, the best documented and most widely-cited solutions which analyze residual stresses were those by Kruth *et al* [32], Carter *et al* [77], Zhang *et al* [78], Abe *et al* [55], Bo *et al* [79], Shiomi *et al* [80], Yasa & Kruth [81], and Mumtaz and Hopkinson [82].

Kruth *et al* and Carter *et al* explored the effects on the thermal stresses of modifying the length and orientation of the laser scan vectors, performing pre- and post-scanning and island scanning, varying the layer thickness, heating the base plate, and heat treating the final parts. The results showed that all of these modifications to the process produced improved thermal stress values, particularly modification of the scan parameters and reducing the temperature gradient by preheating the build plate. Zhang *et al* looked at the effects of the laser parameters, powder setup, environmental conditions, and preheating on the quality of the final parts. Shiomi *et al* explored the influence of three major factors: heat treating the part after printing (improvement of 70%), heating the powder bed during printing (40% improvement), and re-scanning each layer before printing the next one (55% improvement). Abe *et al* and Bo *et al* suggested that the scan pattern of the laser can be designed so that the residual stresses can be “designed” and contoured to dissipate naturally or even provide material advantages for the part. Yasa and Kruth analyzed the value of scanning each layer more

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than once (re-melting) and found that this additional operation significantly reduced the residual stresses by "massaging" them out of the material. Mumtaz and Hopkinson found that using a pulsed laser in SLM resulted in better control over the structure and features, as the power output of the laser was easier to control.

Other useful studies which varied processing parameters to control residual stresses include those by Tolosa *et al* [83], Brandl *et al* [84], Edwards and Ramulu [85], Guan *et al* [86] Yadroitsev & Smurov [87], Yadroitsev *et al* [88], Cheng *et al* [89], Xia *et al* [90], Lu *et al* [91], and Yu *et al* [92]. Tolosa *et al*, Brandl *et al*, and Edwards & Ramulu varied the orientation of build samples to study the effects of the material anisotropy on the mechanical properties of parts. Build orientation was also studied by Guan *et al*, as well as various layer thicknesses, overlap rates, and hatch angles. Yadroitsev & Smurov studied the influence of surface roughness on bond strength between layers. Yadroitsev et al studies the combination of pre-heating the build plate and varying the scan speed. Various adjustments to the laser settings were studied by Cheng *et al*, Xia *et al*, and Lu *et al*. Yu *et al* examined the influence of various processing parameters on laser penetration depth and melting/re-melting densification during selective laser melting of difficult aluminum alloys.

3.2.2. Process Environment Control

In addition to parametrizing the basic input parameters for the process, modifying the chamber environment seems to have a positive effect on the residual stresses. These controls primarily consisted of chamber temperature control, using inert gases to prevent oxidation and reduce temperature gradients in the powder bed. Jia & Gu [93], Dai & Gu [59], and Dadbakhsh *et al* [94] looked at the effect of having oxygen in the environment during printing and ways to eliminate it. Dai & Gu and Dadbakhsh *et al* suggested running an inert gas through the powder bed during the process to prevent oxidation between the layers of the part and produce a more uniform temperature throughout. Ladewig *et al* [95] examined the use of the inert gas to deal with metal splatter and to flush out process by-products and trash. Buchbinder *et al* [96] and Mertens *et al* [75] examined the ways to effectively pre-heat the powder and build plate to reduce the likelihood of stresses.

3.2.3. In-Situ Monitoring and Control

SLM/DMLS is a notoriously difficult process to monitor and control during processing due to its complex nature and the need for a perfectly clean and oxygen-free environment to function properly. Methods for monitoring and controlling the process are clearly valuable and will increase the usefulness and breadth of experimentation with the process in the future. Two major systems for real-time process control have been proposed and are in development by Craeghs *et al* [97-100] and Devesse *et al* [101]. Both systems use a system of optical sensors to collect information about the progress of the part build and to send temperature data to a processor that can control and make modifications to the process parameters in real time. Both of these systems can help to control the process in real time and adjust the parameters as needed; general monitoring and testing technologies are discussed later in the section on experimental development.

3.2.4. Process Parameter Optimization

Most of the previous research on the influence of process parameters on the stresses and deformations in SLM/DMLS have been parametric studies, where effects from adjusting parameters were

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measured. A different type of parameter study that has been published is the optimization of parameters to gain the best possible solution before the processing begins. The major works in this area have been from Pacurar *et al* [102], Casalino *et al* [103], and Aboutaleb *et al* [104]. Pacurar *et al* developed a system for automatically generating process parameters based on models of the process, while Casalino *et al* use a statistical optimization technique, and Aboutaleb *et al* uses a knowledge-database approach which catalogs the results from previous studies and selects the best parameters based on these results.

3.2.5. Part Post-Processing

The most common way to deal with the residual stresses within SLM/DMLS parts is to post-process them after building. This solution is very simple, as it makes use of existing technologies and does not require special knowledge or modification to the SLM/DMLS process itself. However, post processing can add to the time required to produce the parts and dramatically increase the cost, while the post-processing itself may not fully remove the stresses and may expose them, destroying the part in the process. The normal forms of post-processing for SLM/DMLS are heat treatment and hot isostatic pressing (HIP) [105-115], but methods such as shot-peening have been successfully used as well [116].

3.3. *Experiment Development*

Experimental methods that can be applied to SLM/DMLS are very valuable, as the process is very difficult to monitor and control using traditional methods. Methods that have been developed or adapted for use with SLM/DMLS can be categorized as shown in Figure 9.

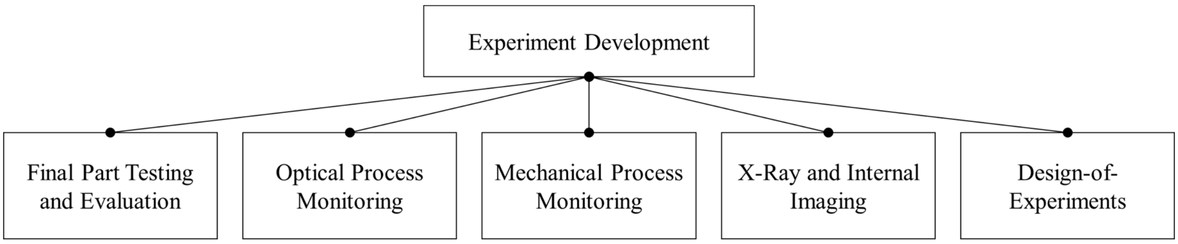

Figure 9. Experiment development categories

3.3.1. Final Parts Testing and Evaluation

Final parts testing and evaluation is very important, as any SLM/DMLS parts that are used commercially or in government or military use must be tested and certified for duty. A testing standard should be developed for this, but there is yet to be one available. Previous work has been done in developing part evaluation techniques, including ultrasonic testing [117] and various methods for tracking crack growth in the parts after processing [5,6].

3.3.2. Optical Process Monitoring

Since SLM/DMLS is so difficult to monitor and control using traditional methods, new methods are very useful. Optical methods are the easiest to use during experimentation, as they are usually non-disruptive to the process and can be applied externally without modifying the process or equipment. A number of excellent optimal monitoring systems have been developed, in particular those by

Craeghs *et al* [97-100], Kleszczynski *et al* [118], Clijsters *et al* [119], Chivel [120], Grasso *et al* [121], Hirsh *et al* [122], Kanko *et al* [123], and Lott *et al* [124]. Infrared thermography systems for SLM/DMSL have been developed by Rodriguez *et al* [125] and Smurov *et al* [126].

3.3.3. Mechanical Process Monitoring

While optical process monitoring is less disruptive, the major disadvantages are in calibrating the imaging devices and in monitoring non-surface phenomena. Some methods have been developed to deal with this problem by effectively using strain gauges on or near the parts to monitor the materials during processing, such as those by Knowles *et al* [8] and Casavola *et al* [127]. Others fix the parts to larger bodies which contain various sensors in order measure deformation in real time, represented by the methods developed by Yadroitsava & Yadroitsev [128], Dunbar *et al* [129], and Havermann *et al* [130].

3.3.4. X-Ray and Internal Imaging

Yadroitsava *et al* [131] developed an x-ray diffraction technique to study residual stresses within parts during and after processing, overcoming some of the challenges of the mechanical monitoring methods while providing the hands-off benefits of thermal monitoring.

3.3.5. Design-of-Experiments

To more effectively study process parameter effects on residual stresses and deformations during processing, designed experiments should be used. These are carefully formulated experimental approaches and tools that allow valid statistical analysis of data collected from experiments and reduce the number of experiments needed to draw defendable conclusions from processing data. While still under development, methods by Patterson *et al* [35-36] and Protasov *et al* [132] appear promising for future experimental design in SLM/DMLS.

3.4. Support Structure Optimization

Structural supports are typically needed in order to prevent the failure of unsupported overhanging features, as well as many other complex types of features. This, however, is a necessary nuisance that must be tolerated to utilize the design freedom of this AM process; the extra time required to cut, grind, or mill off the support structures, the extra material used (which is wasted), the longer print time, the damage to the surface finish when the structure is removed, the extra time required to design the part to accommodate the structure, and the design of the structure itself are some of the irritations that come with the using SLM to create parts with overhanging features. Thankfully, work has been done to simplify the job and reduce the impact of the support structures, while reaping the full benefit of using the structures. Many studies in this area exist, but only the fundamental papers who present new and novel methods (as opposed to case studies) are shown here. It should be noted that optimization of removable support materials and the design of overhanging features are separate topics of study, and therefore will be discussed separately in a later section of the paper.

Some of the most fundamental work in this area was done by Sundar *et al* [133], Jhabvala *et al* [28], Hussein *et al* [21-22], Maliaris *et al* [134], Strano *et al* [135]. Sundar *et al* found that printing the part on top of a wire mesh made removal from the build plate easier, facilitated the creation of delicate features and thin walls, reduced the time needed to cut off the support structure, and created a buffer to prevent damage to the part itself from the removal. Jhabvala *et al* built support structures using a pulsed laser, which has a number of advantages including support material that is not full density and is soft compared to the rest of the body but is strong enough to handle the stresses and heat transfer. This creates a structure that provides support, but is very easy to remove during post-processing. The laser itself was set to both full-power and pulse modes as needed, the full-power mode creating the part and the pulsed setting creating the support structure. Hussein *et al*, Maliaris *et al*, and Strano *et al* experimented with using delicate cellular lattice structures as supports; the advantages to this are material savings, easier removal from the part, and some time savings compared to methods using solid support structures. However, this takes extra time to design.

3.5. Overhanging Feature Design

When collecting sources for the other sections, several references to and discussions about designing overhanging structures in SLM were found. While the number of sources directly related to the overhang problem is far smaller than many of the other SLM/DMLS topics, progress is being made to address the problem. Additional searches were also performed in several journal databases and academic search engines and this uncovered a several relevant papers, in addition to studies that have already been discussed.

In work discussed earlier, four studies discussing various aspects of overhanging structures were Calignano [23], Mohanty & Hattel [24], and Patterson *et al* [35-36]. Calignano suggests avoiding overhanging structures in design as much as possible; however, when they are unavoidable, special support structures should be designed to have the minimum possible contact with the overhang. A detailed discussion about overhang design is presented as well, with several case studies showing great improvement in warping when following the design rules. Mohanty & Hattel looked at the influence of scan orientation on the quality of the overhang structures, with and without support, and conducted a detailed error and sensitivity analysis. Patterson *et al* suggested developing a factorial-based design-of-experiments (DOE) approach to stresses and deformation in 90-degree overhangs, both supported and unsupported. The studies by Patterson *et al* were unique because they considered the influence of geometric stress concentrations, as well as the normal part deformation under thermal load. A detailed numerical study and comparison to published experimental data showed that the stress concentration had a very large influence, as least as much as the laser power, on the stress and deformation. The DOE approach also allowed the calculation of parameter effects and interactions, allowing a multi-dimensional analysis of the problem. The simple thermal model used in these studies needs more development, refinement, and verification, but the results gathered match expected results from other studies.

Other works that addressed the concern of overhanging feature stresses in SLM/DMLS were those by Wang et al [136-138], Cloots et al [139], Fox et al [140], and Kruth et al [141]. The focus of the studies performed by Wang *et al* was the design of curved overhanging parts and parts set at small angles, so designed that they did not need significant support material. The primary analyses were done to determine the settings and design to accomplish the best possible surface finish for the parts. Cloots *et al* proposed a method like that of Calignano [23], except that structures were lattice networks instead of support points. The study also focused on the number of layers needed to provide a stable part overhang with the goal of minimizing the need for the supports altogether. A small case study was also done to show that the overhang design technique used by Cloots *et al* could be used to stack parts and provide more dense part packing on the build plate. Similar to the studies by Wang *et al*, Fox *et al* was interested in the surface finish of part overhangs and studied empirical relationships between process parameters, overhang angle, and surface roughness. The study by Kruth *et al* was a benchmarking study where a number of different geometries were built, including overhanging features, and the results compared between SLM/DMLS and other processes.

4. Discussion and Future Research Need

In this study, a deep and detailed literature review was done to collect previous works related to the effect of SLM/DMLS residual stresses on delicate overhanging and protruding features. Unfortunately, little work has been done to explicitly address this issue or to even understand and model it properly; most of the conclusions about overhanging featured were limited to numerical studies and part-specific design case studies. Clearly, much research effort is needed in this area in the future. In the process of examining the literature for works related to stresses in overhanging features, a large body of work related to the general residual stresses problem was collected. The work reviewed was divided into a set of 16 categories:

1. General SLM/DMLS process models
2. Heat transfer models
3. Stress and distortion models
4. Material and microstructure models
5. Direct process input control
6. Direct environment control
7. Hardware-in-the-loop monitoring
8. Process parameter optimization
9. Part post-processing
10. Part evaluation method development
11. Optical process monitoring
12. Mechanical process monitoring
13. Internal imaging method development
14. Design-of-experiments
15. Support structure optimization
16. Overhang feature design

Each of the first 15 categories have existing tools that can be applied to further work in the area of overhanging feature design in the future, such as modeling, process control, post-processing, part evaluation methods, design-of-experiments, and support structure optimization. However, none of these tool sets are complete in themselves and require additional refinement and development in the future to become more powerful, useful, and reliable. This review was very helping in uncovering some of the major gaps and needs for future research in this area. Some suggestions on future directions and projects are:

1. Process models clearly are useful in analyzing overhanging and other complex structures; however, great care much be taken to make sure they accurately model the material conditions in the presence of overhanging structures. Some aspects need further consideration in future research when used for overhanging and other complex features, particularly in the mechanical and heat responses of the overhanging features. These features may act like mechanical springs,

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deforming in a non-linear fashion, and could introduce extra vibrations into the material during processing and use. The overhanging features will also be subjected to different heat conditions than the rest of the part; the features will generally be thinner and subjected to much faster energy transfer from the laser (and therefore, much more severe stresses).

2. Something that was not encountered in any detail in the reviewed literature is the presence of regions of stress concentration in and near overhanging features. This, combined with unknown heat effects, puts into question the results from existing models with complex geometry, questions which should be analyzed and answered.
3. Most of the previous work in verifying the models was the completion of numerical and parametric studies; formal designed experiments should be used to further verify these models, as they are capable of analyzing both main effects from the input factors and the interactions between these factors. While they are more expensive than parametric studies and require detailed planning before research begins, the use of interaction analysis will aide in the quick identification and tracking of error factors in the models. This will allow a higher confidence over the needed analysis range, and therefore more trustworthy models.
4. Another major concern in using models for this manufacturing process is that the best and most trusted models for SLM/DMLS are proprietary or government lab-owned and not available for use and improvement by the SLM/DMLS community. This can stunt the growth of accurate general-use design models, which will be essential when developing formal design-for-manufacturability methods. Greater access and transparency with these models should be pursued in the future. At the least, those who own and develop the proprietary models should publish technical works guiding the formation of more public-use models.
5. To simplify the design process, a method should be developed to identify the "dominating" factors within the SLM/DMLS build plan for particular designs. Using this, the part can be redesigned or the decision can be made by the designer that some or all the "dominated" factors can be safely ignored (as is often done in engineering optimization problems [142]). This will create a much more efficient system, but care should be taken with this task to make sure that the ignored factors are indeed dominated and not just weak factors in the application range.
6. Alongside developing post-processing techniques, direct control of the process parameters is the usual first line of defense when dealing with residual stresses in SLM/DMLS, particularly in complex and overhanging part features. The ability to control the process parameters simplifies the processing of the complex geometries and allows custom, optimal parameters for particular applications. There are still limitations in this, however, which need to be addressed: In most cases, the custom process parameters are set by the user before the processing begins. *In-situ* monitoring and HWIL systems partially solve this problem, but still rely on the detection of some anomaly or defect in the part before process parameters are modified. Even if the form of the part can be saved, it is typically scrap and not trustworthy for its original purpose. Some sort of an anticipatory system is needed, perhaps based on a combination or the digital build path progress and preliminary scanning of the powder layer for potential defects. While this could make the process much slower, it could dramatically reduce failure rate; the slower build speed may also assist in the creation of overhanging features by reducing the magnitude of the thermal shock experienced by the feature during scanning.

7. An *in-situ* system for monitoring the quality of the fresh powder layer itself (prior to scanning each layer) could be an important advancement and could use existing technology. The process would need to be stopped for a scan between each layer, which could be a simple roughness measurement with a laser or could be an ultrasound or x-ray scan. The ultrasound scan might require disturbing the powder bed somewhat, but the settling effect could prevent air pockets and help the layers to be more uniform in thickness. The powder bed would be more tightly packed as well, reducing (but not eliminating) the need for support material for some overhang geometries.
8. A system could also be developed that controls laser power as a function of the material thickness at a particular scan location. An optimal minimum material thickness could be determined experimentally as a function of laser power. When the laser encounters thin sections of the geometry, the power will be reduced to avoid thermal shock to the material and provide a consistent amount of heat flux into the material.

Finally, in order for the part made using SLM/DMLS to be useful in the real world, there must be a system for testing, verifying, and certifying the parts. If no other major research needs described in this paper are attempted, the formation of technical testing and quality standards should be a priority for the SLM/DMLS community. Of all the potential projects described here, the development of these standards is the most urgent and critical; even initial and draft guidelines based on current knowledge are a starting place from which excellent documents can be developed.

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