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Rules, Precursors and Parameterization Methodologies for Topology Optimized Structural Designs Realized Through Additive Manufacturing

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Additive manufacturing, more commonly known as 3D printing is a rapidly developing, thoroughly novel means of producing complex, previously difficult to manufacture components. Slowly divorcing itself from previously held preconceptions of rapid prototyping and now capable of producing comparable structures from materials such as titanium and high strength nickel alloys, it is a means of manufacturing structures deemed too complex for existing fabrication techniques. Whilst free of conventional constraints, the unique intricacies of the manufacturing process can lead to the creation of factors, detrimental to production success. The research detailed within this paper demonstrates through example, how the orientation of a part prior to build can be optimized in order to significantly mitigate these effects and to maximize build economics. Furthermore the research details a new method for the combined assessment and tailored structural topology optimization of parts intended for production by specific additive manufacturing technologies.

Nomenclature

AM = Additive Manufacturing
BE = Build Economics
DMLS = Direct Metal Laser Sintering
DR = Design Rules
EBM = Electron Beam Melting
GD = Geometric Distortion
RS = Residual Stress
SLM = Selective Laser Melting
SR = Surface Roughness
STO = Structural Topology Optimization

I. Introduction

Additive manufacturing (AM) [1] is perhaps *the* most import developing technology for industrial consumers of high value, lightweight components such as commercial aerospace [2]. Capable of producing highly complex geometric profiles with almost unparalleled efficiency and accuracy, the processes which together make up AM,

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promise to revolutionize the manufacturing industry. The ability of powder bed (PB) AM to realize designs with almost no conventional manufacturing constraints, has led, almost inevitably, to the combining of AM with almost freeform Structural Topology Optimization (STO) as a means to capitalize on the benefits of both technologies.

Whilst it is broadly correct to state that the use of AM can eliminate a swathe of conventional manufacturing constraints from the design process; the use of these novel industrial technologies introduces additional complexities which must first identified, and then accounted for in any applied design process. Design rules (DR) for AM are a highly complex and contentious issue, requiring intimate knowledge of myriad aspects relating to the design and manufacture process, for multiple, often disparate AM technologies [3] The work performed as part of this investigation addresses numerous technical considerations including, but not limited to: end user design requirements/rules; the operational physics of the AM processes; the metallurgical properties ascribed to AM techniques; and the effect of geometric profiles and build orientation on as built metallurgical properties. Primarily, a series of non-topologically Optimized component geometries are evaluated in response to the identified technical considerations; a formulated multi-objective optimization problem is then used to minimize the adverse AM effects through orientation modification, customized support structure and variation of process parameters. A secondary analysis with a view towards the use of STO is then undertaken; using the outputs (build orientation and proposed supporting structure) of the primary analysis as design inputs, alongside initial customer design requirements and constraints, a strategy for detailed Parameterization of the STO input is created. The outputs of the STO are then re-analyzed and compared to the design inputs from the stage one analysis in order to determine their effectiveness. Together, the work demonstrates a substantial step forward in amalgamation of STO and AM by tailoring the application of both approaches to their inherent strengths, through understanding of their greatest limitations.

A. Scope and Limitations

In order to manage the scope of the investigation, this research focused only on those AM techniques which demonstrate the highest levels of technical maturity, therefore having the most relevance to the aerospace sector. Whilst there are currently hundreds of different AM platform providers, with many more non-commercial machines established at universities and research laboratories, the vast majority can be broadly categorized into three distinct classes; PB, Directed Energy Deposition and Wire-fed [4].

Currently only PB AM techniques demonstrate suitable levels of process maturity, and as such, only these techniques will be included in the scope of the topic. Furthermore, whilst several platform vendors exist for metallic AM, the vast majority are broadly similar [5] and have analogous technical limitations. Therefore, the two dominant techniques in the field are the intended research focus. EOS Direct Metal Laser Sintering (DMLS) [6] is the most commonly used platform for laser based PB AM, Conversely, Electron Beam Melting (EBM) [7] is the dominant form of electron beam based PBAM technology. Together, and as of this date, these two technologies represent the largest adoptions of AM platforms in the aerospace industry, thereby justifying their inclusion within the project scope.

B. Technical Limitations of Shortlisted AM Processes

Within the bounds of the technical considerations for the investigation, a number of factors are present which can, if unaddressed, seriously inhibit the ability of AM to successfully produce parts which are deemed fit for purpose; Material Properties are one such area. Though generally considered as good, with properties similar to, or in some cases exceeding, metallic properties for castings, AM material properties do suffer significantly in one key area…fatigue performance. There are several known [8] and even more theorized [9] reasons for this exhibited deficiency in additive manufactured parts, with a large percentage ascribing blame to surface finish. However, there is also data which suggests that porosity [10] and material microstructure [11] can elicit similar knockdown factors. In addition, there is emergent research [12] which suggests that certain geometric features in AM slices can have significant effects on microstructure and therefore fatigue performance. Identification and parametric inclusion of those geometric features with design rules for AM is a key area for a combined approach to design Optimization.

If one considers a software-only-approach on a platform which is locked for production, one in which laser properties, powder metallurgy and process changes cannot be altered, one must adapt the design of a part, in order that it best suits the known deficiencies of the process in order to achieve the best results. Of the known factors affecting PB AM produced parts, perhaps the most debilitating are related to surface roughness (SR), geometric distortion (GD) and build economics (BE). The most obvious of these flaws to any outside observer would be the substantial roughness found on the surface of most (though this varies between materials and processes) additively manufactured metallic parts. It is common attribute of AM and is formed as an artifice of using a layer-wise method of construction through a highly focused energy source. SR is arguably caused and exacerbated by a number of factors [13]; principally, the major contributors to increased SR are related to energy overspill [14] layer thickness, powder particle size [15], energy properties [16] and highly overhung angled surfaces [17]. Most of the factors listed above fall outside the scope of this investigation as they are part of the platform parameters. However, SR problems encountered due to overhanging surfaces can be reduced through careful build orientation.

C. Surface Roughness and Overhanging Surfaces

Angled or overhanging surfaces (surfaces which are varyingly angled with respect to the XY plane) represent a multifold problem for all AM production techniques due to the manner in which AM production works; principally, each layer of an AM build represents a geometrically complex, microscopically thin plate; at the edges of these plates a contour profile is drawn which is largely perpendicular to the plate surface. As such, any overhanging surface will (when examined closely) resemble a step function. Figure 1 shows the appearance of this step function and its effect on surface roughness with decreasing angles of the build. Furthermore, also demonstrates the significant compounding effect of larger layer sizes and angle surfaces upon SR.

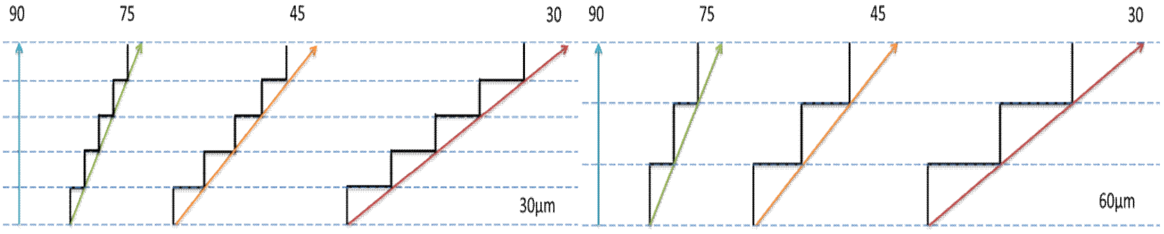

Figure 1. – Effect of surface overhang and layer thickness upon surface roughness

Though somewhat dependent upon layer-thickness/build-angle and process type, it is common in PBAM techniques to support (during build) overhanging/angled faces in order to prevent geometric distortion. These required support structures can cause significant increases in SR as shown in Figure 2 The combination of an increase in required supporting structures for AM builds [18] The use of support structure and levels of variation in relation to their application are well documented [19] however research into their effects on SR and methods to reduce it are less well researched.

Figure 2. - Effect of support structure type on part surface roughness

D. Geometric Distortion in Powder Bed Additive Manufacturing

Initially, both PB AM processes (DMLS and EBM) appear broadly similar in their approach to AM, however, the similarities are only superficial. Whilst both platforms use a CAD input along with a feedstock comprised of layered, atomized metallic powder, the manner in which the required input energy is applied, differs vastly between the two. DMLS is a cold process (~25) conducted within an Argon filled chamber, with all input energy accurately applied directly to the part slices via either a 200w or 400w CO2 based laser. Conversely, EBM is a hot process (~700) and is conducted within a vacuum, this time with preheating performed in-between each applied layer using a defocussed EB, prior to refocusing the beam energy for the primary melt. The temperature difference between the processes creates significant differences in material microstructure [14] but more importantly, is a contributing factor in the formation of significant residual stress (RS) factors within the colder DMLS process. The effects of this stress formation within DMLS processes can vary significantly and are highly geometry specific [20] In mild cases, the appearance of witness lines can be attributed to RS effects [21] and in more extreme cases they can cause a complete build crash. Minimization of RS factors and effects in DMLS processes are a key area of research for the industrialization of the DMLS processes. Minimization of these stresses and their subsequent distortions is of particular importance for the DMLS process.

In both SR and RS, the use of, along with the minimization/mitigation of the effects of supporting structures during the build are critical, and are often not convergent for any particular strategy. More simply, in order to counteract the effects of distortion (due to RS) and increase the likelihood of a successful build (thereby minimizing cost), additional support structure is used to anchor the part to the build-plate. Conversely, the addition of support structure not only increases surface area for processing, but also part roughness and the requirement for post processing of the part afterwards, all of which thereby increase part cost, waste and time. A method of minimizing the required supports due to either projected surface overhang or predicted residual stress is required.

E. Build Economics

Build economics are affected by myriad different factors, and quite process specific. However, there are a number of commonalities to both processes which can, and should be included into any Optimization strategy. The first and most obvious is that related to build completion, any strategy which increases the risk of a build failure should be discouraged as machine time and powder are particularly expensive. Factors which can incur the risk of build failure relate to both geometric distortion and total scan area and are somewhat interrelated. A second factor relates to build time, usually exemplified by maximum (Z) height of the part. These factors can be controlled the constraint and penalization functions during the Optimization.

II. Problem Formulation

In order to fully define the optimization requirements, categorization of identified detrimental factors and potential design variables in selected AM processes was first required. Following this, factors which could influence the technical limitations of AM techniques and be varied in a discrete manner were sought. Several potential candidates known to have effects in multiple domains were identified, these included beam properties, hatching strategy and orientation. However, it was determined that whilst all identified criteria all had (arguably) large effects, most fell outside the scope of this investigation due the dependence upon machine hardware/software parameters rather than design for manufacture assessment and Optimization. Ultimately, it was deemed important to mitigate the AM limitations in the primary design and nesting phases, with nesting an orientation being accomplished in the primary phase of Optimization.

Due to its inherent interrelation with all three AM limitations, the principal variable in the primary Optimization study is thusly related to preliminary build orientation; As a start point, and for each investigated structure, an empirically determined build orientation is initially defined and subsequently analyzed for its effectiveness in terms of SR, RS and BE. For each structure analyzed, the range of variation from its defined origin in the primary study relates to its rotation about either the X and/or Y axes in the range +/- 15° from the Z axis. This gives a total range of 30 degrees in either axis of rotation, and a total number of possible designs close to 1000 possibilities.

F. Metamodelling for Simulation Reduction

Due to the complexity of the slicing program the time required for a comprehensive investigation and comparison of each design point is both computationally expensive and infeasible should the process be used for subsequent structural analyses. A more computationally efficient and expedient method was required. Metamodeling techniques are designed to provide just such a solution and have receiving wide employment in engineering design in order to improve the efficiency of optimization in design systems which are based on computationally expensive simulation. Based on the number of projected DOE points and the likely variability in the derived functions due to the vast complexities of changeable input geometry, a moderately large sample size of 120 points was determined to be adequate enough to allow suitable complexity whilst substantially reducing complexity. A customized Latin Hypercube design was selected as the optimal method for domain sampling based on established data (REF) makes an , a series of sample points are used to create a metamodel upon which the preliminary Optimization study is performed. Whilst both low SR and low RS are requirements of the Optimization, they are, at this juncture reformulated into constraint functions with maximal values applied to each function. In this way, the minimization of surface overhangs can be formulated as the primary objective function for the problem.

With design variables and sampling methodology established, formulation of the remaining factors for the Optimization could proceed. Problematically and as previously established, there are three (potentially competing) different objectives for the any Optimization study in which one attempts to address the problems concerning the use of design to address AM related build issues; maximize build economics (Max BE), minimize residual stress (Min RS) and maximize quality whilst minimizing required support structure (Min SR). In essence there are 3 objective functions.

There exists a number of methods by which one can Optimize for multiple objective functions; firstly one can include multiple objective functions within the optimization problem, applying weighting functions/multipliers in order to bias/stabilize the optimization output [22] Problematically, this further increases the computational load which has been previously reduced and is an unattractive position in an already computationally demanding simulation. Alternatively, objectives can be reformulated into constraint functions based on minimum requirements and applied separately to the operational domain. This approach was selected for use in the investigation. In this instance the primary objective function is the minimization of SR. Constraints are then placed on build time and ascribed cost, based on the outputs of a devised costing model for both processes. Finally, residual stress is applied as a further constraint function using outputs of the slice analysis to identify and penalize factors known to cause increases in stress formation during layer on construction.

G. Optimization Summary

To summarize, the primary Optimization variable is related to orientation variation allowing rotation of +/-15 deg about both the x and y axes. These variables are obtained using sampling techniques to create a metamodel upon which the Optimization is solved. Constraints are placed on the maximum percentage of overhanging surfaces with significant penalization applied to those surfaces at angles less than 65 deg from the build plate which would subsequently require support. Build economics are constrained within 10% of the original maximum Z height of the primary design, with XY surface coverage similarly constrained. Stress formation is constrained using slice-file analysis to predict and penalize likely stress raisers in the design. The objective of the Optimization is the minimization of surface roughness for as-built parts based on surface overhang.

III. Geometry Cases

Though trialed on several geometric cases, the vast majority of derivative data is commercially sensitive and as such cannot be released to the public; however a single abstracted, but representative sample is shown (Figure 3) within these pages in order to more accurately convey the narrative of the work undertaken.

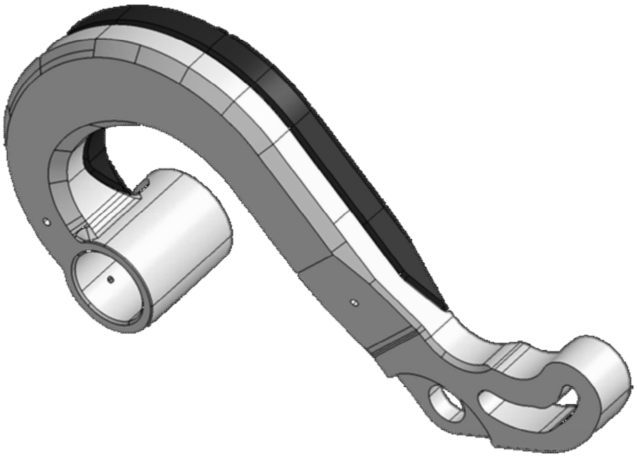

Figure 3. - Geometric case study for Optimization analysis

IV. Preliminary Analysis

Using existing processes and techniques, each component was analyzed by an experienced technician and placed in the perceived best orientation for minimization of residual stress and maximization of quality at the expense of economics. A custom made STL slicer was then used to bisect the components parallel to the platform build plate at an interval of 100microns. Each layer is then analyzed and its mass properties and surface angles in relation to the build platform are calculated. Allowing up to a +/-15 degree rotation about both the X and Y axes, the various combinations of rotations define the design variables for the primary optimization. Using a gradient based Optimizer, minimization of angular structures below 65 and in excess of 130 degrees, the amount of required support structure is reduced and the maximization of reduced SR is attained.

V. Preliminary Analysis Results and Comparison

The results of the preliminary analysis graphically demonstrate the effectiveness of engineering judgment on the choice of build orientation. Figure 4 shows a comparison between effective and poor build orientations, giving an indication of areas of predicted increases in surface roughness.

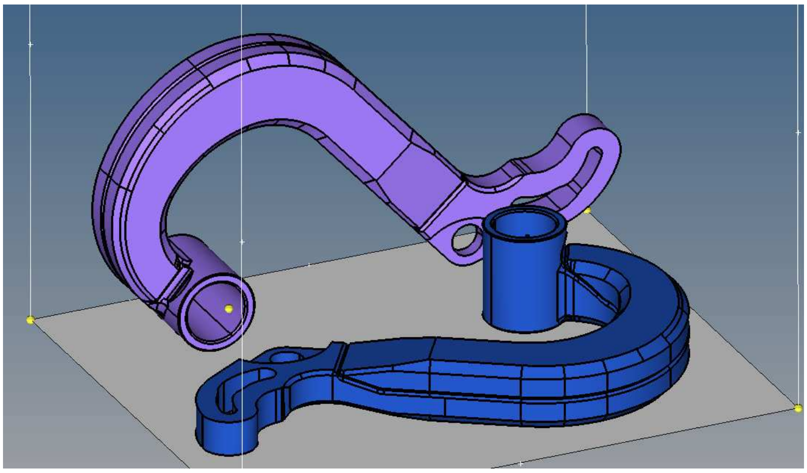

Figure 4. - Demonstration of optimal (purple) and problematic (blue) build orientations for DMLS processes

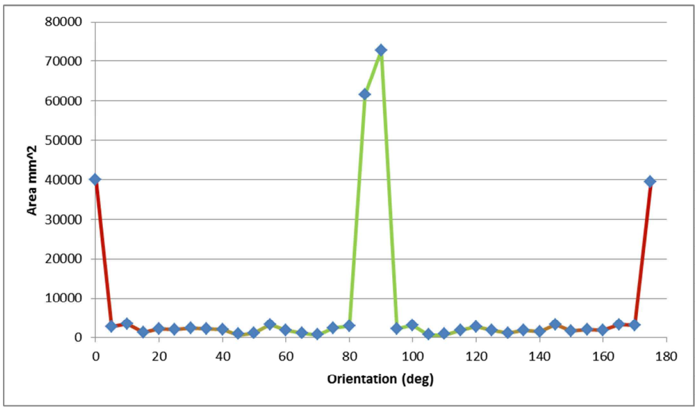

Figure 5. – Chart showing the number of overhanging surfaces for un-Optimized orientation setup

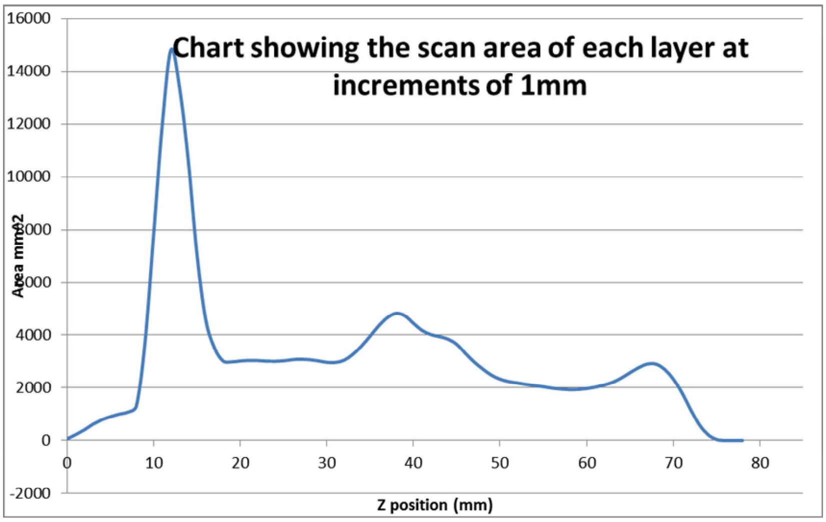

Figure 6. – Chart depicting the changes in area for layer-wise construction of components

VI. Primary Optimization Results

The results of the primary Optimization phase graphically demonstrate Figure 7 the effectiveness of design assessment prior to a final build setup and manufacture. Through small variations in build orientation which were unobserved by an experienced operator significant reductions in both SR and RS are seen in the resulting slice file analysis.

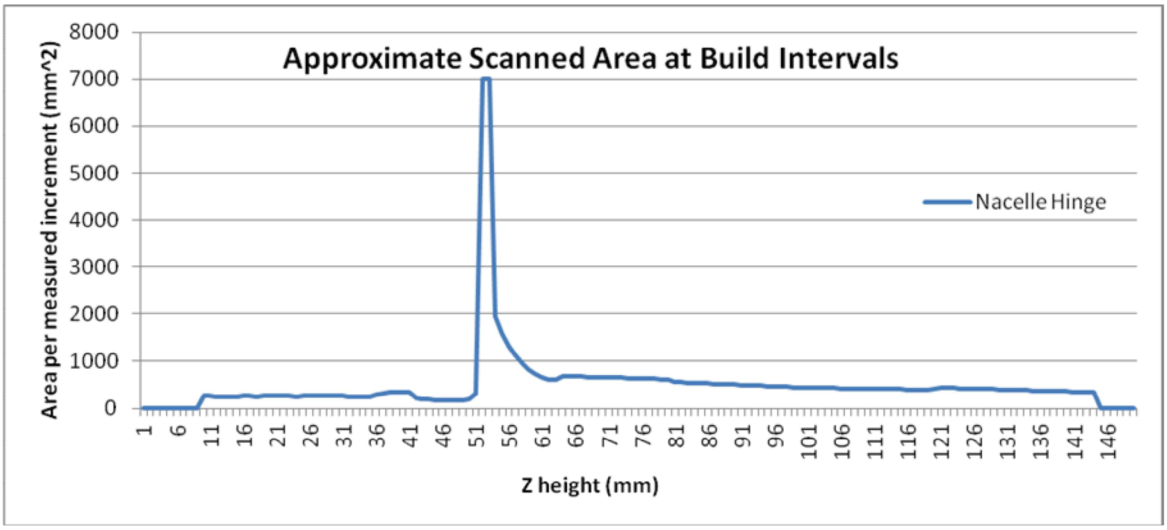

Figure 7. – A direct comparison of preliminary part setup and the newly derived optimal build orientation

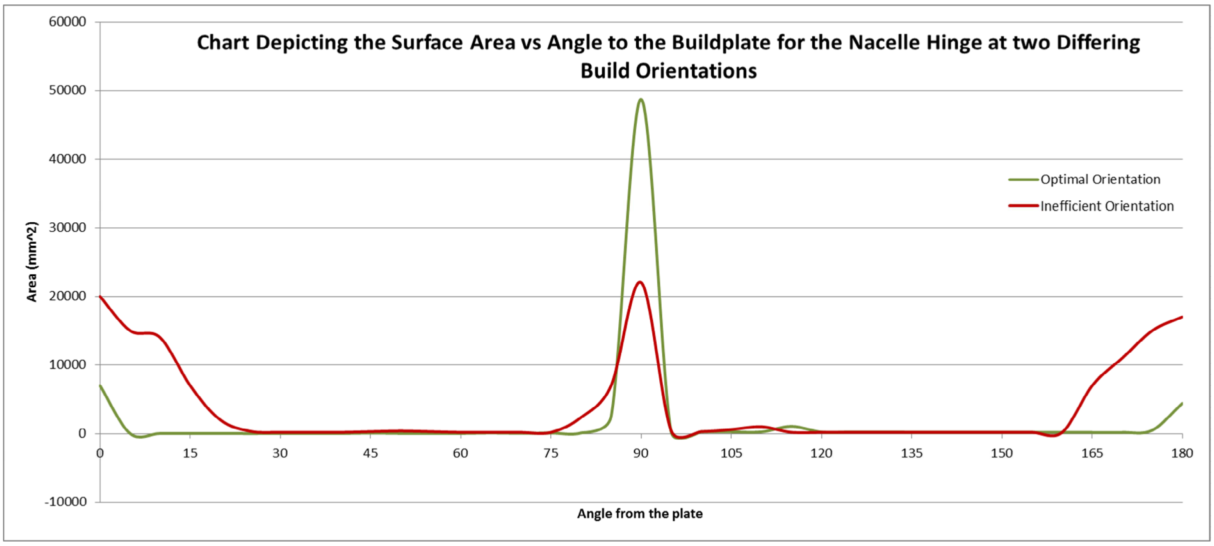

Figure 8. - Comparison of overhanging surfaces on optimum build setup vs. preliminary assessment setup

An analysis of the raw data which makes up Figure 8 demonstrates a potential reduction in surface overhang of almost 11% and a subsequent reduction in required support of some 17% leading to a further reduction in SR.

It can also be seen in Figure 9 that the predicted mass changes during construction have substantially smaller and less positive gradients, which research suggest should allow for substantive reductions in residual stress when produce using the DMLS or other Selective Laser Melting (SLM) based Am platforms.

Figure 9. - A comparison of layer-wise mass changes between preliminary and optimal build orientation

The results inevitably show that even when setup by an experienced operator, a substantial refinement in build orientation can be provided through careful use of simulation, modelling and Optimization. Furthermore, the effectiveness of the Optimizer on component geometry and orientation setup are significantly more pronounced on structures with complex geometry which requires careful support strategies in order to build effectively. This would be especially true in the case of a topology Optimized structure possessing of the complex truss type features which typify topology Optimized structural designs.

VII. Continuing Work – Secondary Optimization

The penultimate stage of this research focuses upon methods intended to integrate the use of the preliminary Optimization stage into the initial Parameterization for combined topology Optimized structural design. Through use of a multi-stage Optimization in which the primary Optimization phase demonstrated within this paper is used in conjunction with a conventional freeform structural topology Optimization in order to provide the inputs for the combined approach.

This secondary analysis is intended to tailor the use of STO for the selected additive manufacturing processes through use of the outputs from the primary analysis (optimum build orientation and bespoke support strategy) as design Parameterization inputs for structural topology optimization. Using conventional methods, a compliance based optimization problem is then formed around the original topology for each of the analyzed components. Additional parameterization is applied in two phases, the first uses specifically developed automated techniques [23] in order to define constraint attachments [24] non-design space and optimization parameters in an expedient manner. The second phase uses the determined optimal build orientation along with parameters for self-supporting structures bespoke for each am process.

VIII. Secondary Optimization Results

A three tranche comparison of the compliance optimization was performed during this stage, the first tranche approach is a relatively freeform optimization featuring conventional/manually applied constraints and optimization techniques, the second tranche uses the advanced automated Parameterization techniques [25] in order to more heavily constrain the Optimized de technique was devised in order to aid design extraction through heavy use of Parameterization and at the expense of computational efficiency. The final tranche builds upon the techniques of its predecessors to further tailor the STO output to AM production techniques. Using Boolean functions and sliced mass properties connected via B-splines, the Optimized structural output from tranche 2 is used to introduce heavily penalized domain sectors, designed to constrain the optimization process into structural pathways which are conducive to unsupported AM production. Figure 10 demonstrates the dramatic difference in the outputs of structural optimization when additional constraints for the AM production technique are applied to the initial parameterization.

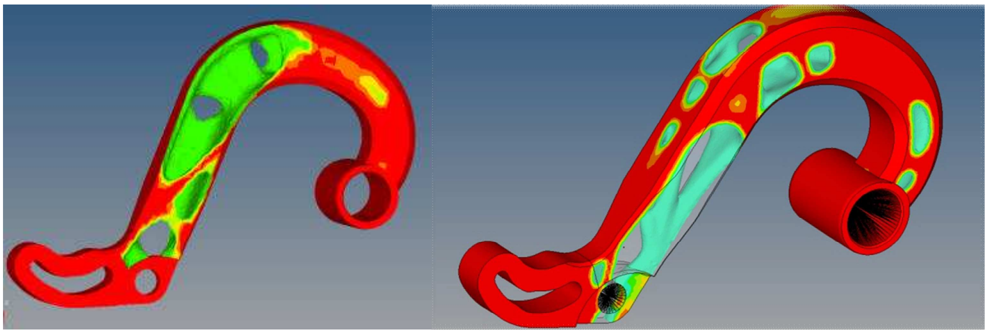

Figure 10. - A comparison of unconstrained (left) vs constrained (right) topology Optimization tailored for EBM AM

IX. Conclusions

Whilst still incomplete, the research demonstrated thus far as part of this investigation represents one, if not *the* first holistic approach intended to combine the most critical aspects of design for manufacture and structural design tailored for multiple AM processes. The work completed as part of the primary Optimization phase demonstrates the need for significant pre-build assessment of most structural components intended for production via AM. By including carefully Parameterized Optimization as precursor to build setup, the likelihood of incurred geometric distortion caused by a build-up of residual stress is substantially reduced, and in-turn, dramatically reduces the likelihood of an expensive build failure. Such improvements in AM build cost and performance are achieved at a price, albeit a small on; by including additional constraints within the structural domain intended to force the structural design toward one which suits an AM process, the range of feasible designs within that domain decrease. The result is that the percentage mass reduction is generally lower than would be achieved without the additional constraints. Again this is a largely geometry driven concern, and does not affect all designs, though it must be acknowledged.

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