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UTILIZING DESIGN FOR METAL ADDITIVE MANUFACTURING AND TOPOLOGY OPTIMIZATION TO IMPROVE PRODUCT DESIGNS

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ABSTRACT
Metal additive manufacturing has transformed the product design process by enabling the fabrication of components with complex geometries that cannot be manufactured using conventional methods. Initial designs can be further enhanced by employing topology optimization software and Design for Metal Additive Manufacturing (DFMAM) guidelines. In this study, a commercially available bicycle spider-crank was optimized for three-dimensional (3D) metal manufacturing. The 3D surface geometry of the original spider-crank was acquired using a white light scanner and used to generate a 3D solid model of the part. Boundary conditions were obtained from cycling loads found in published literature and applied to an ANSYS Finite Element Analysis (FEA) model. The FEA model was analyzed to determine the von Mises stress throughout the part. ANSYS Topology Optimization software was applied to the model. The software uses an iterative process to remove low stress material and recalculate stress within the part until no more material can be removed without exceeding a target maximum stress value. Following topology optimization, DFMAM principles were applied to enable the part to be 3D printed. Results from the FEA showed the DFMAM optimized design to be 41.5% lighter than the original design. The maximum stress increased from 41.2% of the material yield strength to 61.5% in the DFMAM optimized design, which exceeded the target optimization value of 50% yield strength. Analysis results were verified experimentally. The original design and DFMAM optimized design were printed using an EOS M 290 metal additive manufacturing machine. Parts were separated from the support structure and tested on a universal testing machine. A custom testing apparatus was designed and built to conduct the testing. Testing was performed at 15 degrees intervals throughout the range of motion. Strain gages attached to the arm of the crank were used to obtain stress values at specific locations and dial indicators were used to measure the deflection of the crank arm under load. Experimental results closely matched results obtained from the FEA, validating the model. With the model validated at specific locations, it was assumed that the stress calculated by the FEA at the critical points were also accurate. The results showed the topology optimization software to be an effective and useful tool for optimizing the design of 3D metal printed parts. However, topology optimization alone was not enough to finalize a design prior to printing. The application of DFMAM principles were needed to ensure that the overhanging structures would not collapse during printing. Because the determination of what constitutes an overhang is determined by the part orientation when printed, some modification will generally be required prior to printing. In conclusion, using a bicycle spider-crank as an example, this research has shown that the use of topology optimization software and Design for Metal Additive Manufacturing principles is able to reduce the weight of a 3D metal printed part while simultaneously achieving a maximum stress near a target value.

1 INTRODUCTION
Metal additive manufacturing can be used to create complex and novel geometries that cannot be manufactured using traditional subtractive machining processes. Unlike milling and turning that remove material, additive metal manufacturing builds the metallic structure layer by layer [1]. In this process fine powder is spread over a flat and level surface. A computer controlled (CNC) laser sinters the metal in specific location to form a solid structure using a process called direct metal laser sintering [2]. Because the metal is built in layers, complex internal geometry can be produced that is impossible to produce using subtractive technology due to the inability of tool access [3].

This technology has created new opportunities for component design, but new design methodologies are needed to leverage the capabilities of metal additive manufacturing. A requirement to producing high quality parts at minimal cost is the application of design for manufacturing (DFM) principles. DFM principles are currently being developed for 3D metal printing and those that exist are focused around the ability to manufacture components as designed. The application of Design for Metal Additive Manufacturing (DFMAM) guidelines increases the likelihood that the part will be build successful, avoiding manufacturing problems such as structure collapse, part damage during powder deposition, and difficulty removing the part from the build plate [4]. Design for Manufacturing also includes merging neighboring parts if they can be fabricated out of the same material, if they do not need to move relative to each other, or if they do not need to be removed to enable access to another part [5].

Another opportunity that results from designing component for DMLS is the utilization of topology optimization [6]. In traditional subtractive machining, part cost is minimized by reducing the amount of material removed from the part. This is because removing material takes time, so each cutting operation adds to the labor cost of the component. There is a tradeoff between part cost and weight. In contrast, the cost of a part produced using additive manufacturing is roughly proportional to the amount of material in the part. Decreasing the amount of material decreased manufacturing time, material used, and part weight. This makes metal additive manufacturing highly attractive for some applications. Topology optimization software can be utilized to reduce material in a component and optimize the design for metal additive manufacturing [7].

This research illustrates the process used to optimize a part design for metal additive manufacturing. Topology optimization software was used to remove unnecessary material from the part design and DFMAM principles were applied to enable the part to be 3D metal printed successfully. The design was evaluated theoretically using finite element analysis and experimentally verified by physically testing 3D printed parts.

2 ORIGINAL DESIGN

A commercially available bicycle crank arm was selected for evaluation of the design optimization method (Figure 1).

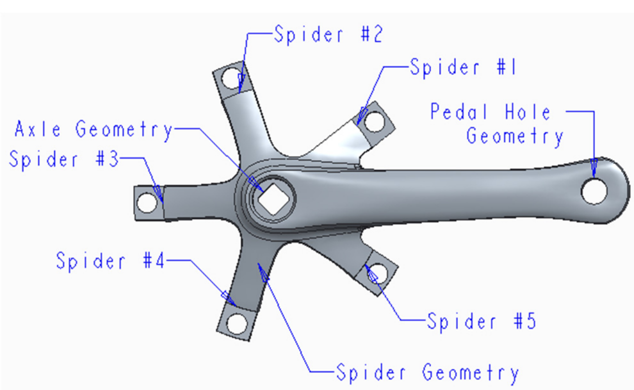

Figure 1: Bicycle crank arm

Three-dimensional geometry of the part was acquired using a ATOS II white light scanner (GOM, Brunswick, Germany). No surface preparation was needed because the crank arm was painted black. GeoMagic software (Morrisville, NC) was utilized to stitch together the surfaces to create a 3D solid model of the part.

Pedal forces were obtained from published literature. Hull and Stone measured the pedal forces of experienced cyclists [8] and their data was digitally captured using Image J software (Madison, WI). Results were replotted using a new reference frame with zero degrees defined as horizontal (Figure 2).

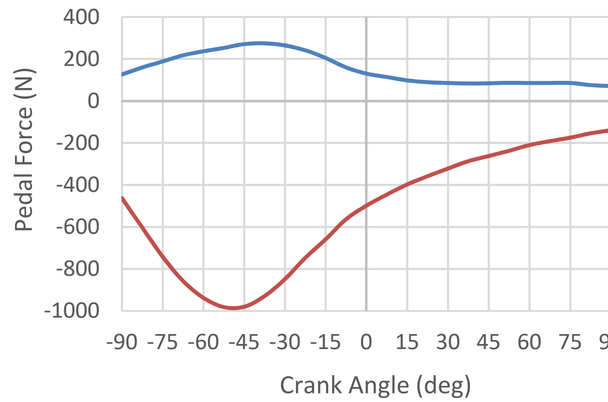

Figure 2: Pedal force toward the front of the bicycle (blue) and vertically upward (red).

3 FINITE ELEMENT MODEL

The 3D model of the bicycle crank was imported into ANSYS 19.1 finite element analysis software (Canonsburg, PA). Automatic meshing was performed (Figure 3) and boundary conditions were applied to the model. Forces and moments were calculated by taking into account crank arm and pedal geometry and the resultant forces vectors applied during cycling at 15-degree increments.

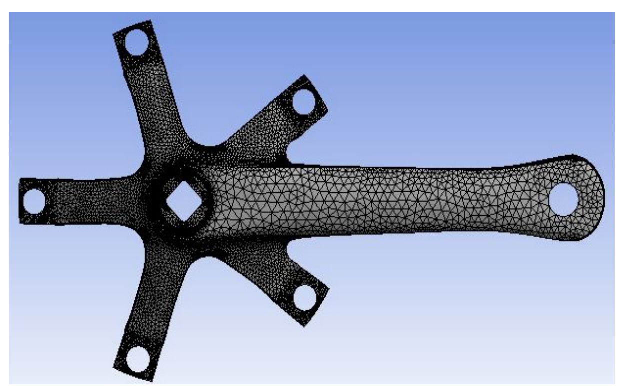

Figure 3: Finite Element Model

These data were used to calculate the von Mises stress, and the deflection of each element within the part. This formed the baseline for comparison with the optimized design. Next, ANSYS 19.1 Topology Optimization software (Canonsburg, PA) was used. The software automatically removes material from the part in elements that are calculated to have low stress. This effectively shifts the stress to the remaining element, so the stress in the new design is then calculated. The process is repeated, iteratively removing material and recalculating stress until a preset design value is attained. In this research, the target stress level was set to 50% of the yield strength of the material and the optimization was performed at the crank angle of -45°. This is the angle where the force applied to the pedal is maximum. In order to retain geometry at the attachment points of the crank arm, exclusion regions were defined prior to topology optimization (Figure 4). This optimized topology is shown in Figure 5.

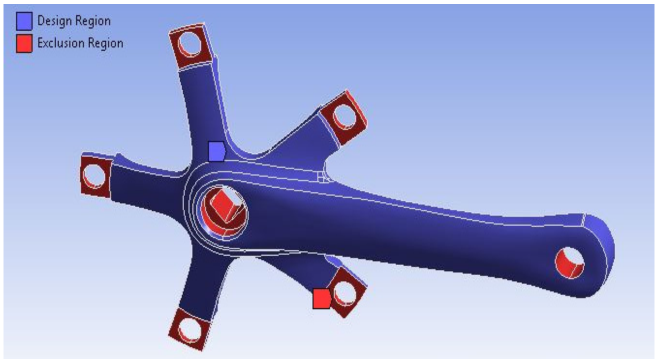

Figure 4: Location of exclusion regions. These are areas to be avoided during the topology optimization process.

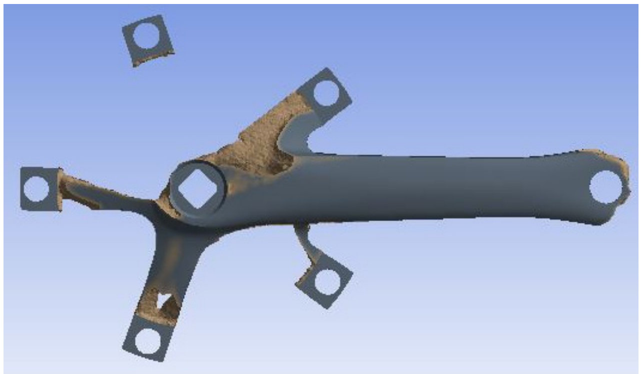

Figure 5: Optimized Topology

Since the focus of the research was to understand the potential of topology optimization, effort was not expended to improve the appearance of the design or to apply other design improvement techniques. Although not easily visible in figure 5, an internal cavity was formed within the body of the crank arm during the topology optimization process (Figure 6). Structurally, this design meets the maximum stress criteria, but it is not printable using the DMLS process because it creates an unsupported overhang. DFMAM principles were used to improve the design of the cavity prior to manufacturing. Material was added inside the cavity so that the ceiling was no flatter that 45 degrees (Figure 7). This was done to make the cavity self-supporting, eliminating the need to build supporting structures on the interior of the cavity. An additional concern is the very small volume of material connecting spider leg #5. The thickness of the leg was increased to strengthen the connection. Spider leg #2 was found to be unnecessary, so the geometry at the attachment point to the sprocket was removed as well. After completing design optimization, finite element analysis was performed to calculate von Mises stress and the deflection of each element within the part.

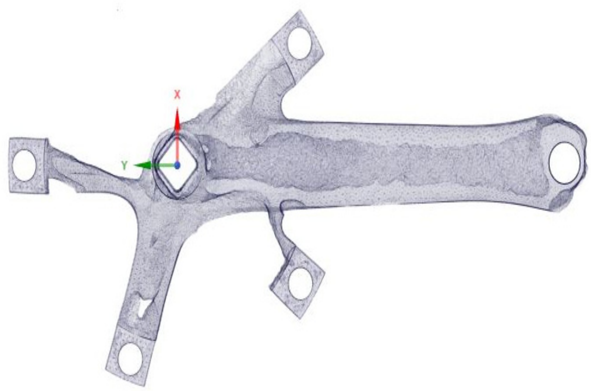

Figure 6: View of internal cavity within the optimized geometry

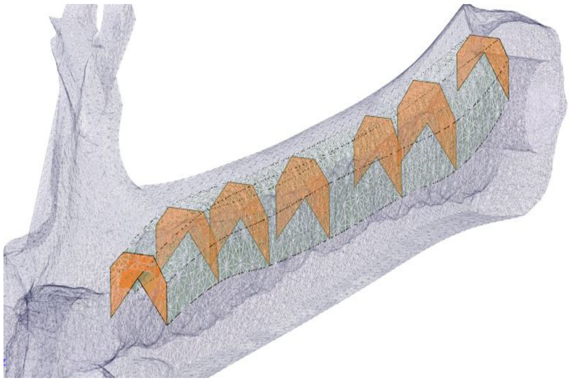

Figure 7: Design for Metal Additive Manufacturing principles were applied to make the internal cavity self-supporting

4 EXPERIMENTAL SETUP

The original design and the optimized design were printed on an EOS M 290 metal additive manufacturing machine (EOS, Krailling, Germany) using 316L stainless steel. It was important when comparing the two designs to produce both the original design and the optimized design using the same material and the same manufacturing process. Figure 8 shows the original design after printing before separation from the build plate and removal of the supporting structures.

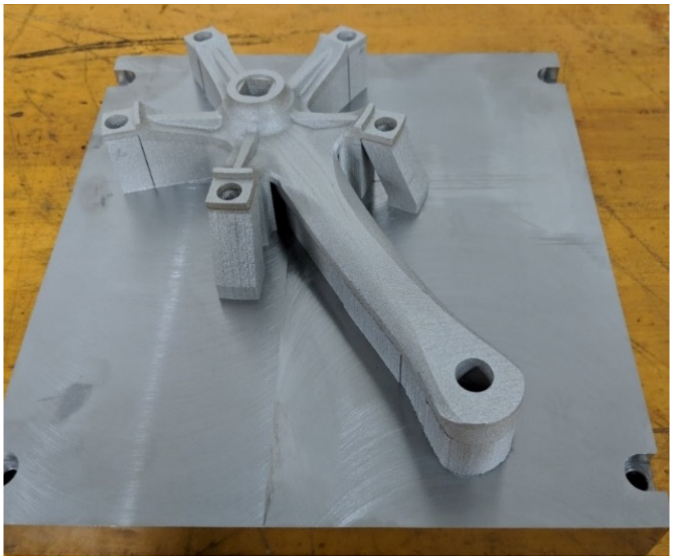

Figure 8: Parts were printed using an EOS 290, 3D metal printer

Specimens were cut from the build plate using a band saw and the remaining support structure was broken away and the surface filed to remove adhering support material. Front and rear images of the original design and the optimized design are shown in Figure 9. After the part was removed, the test specimen was prepared by attaching strain gages to the crank arm.

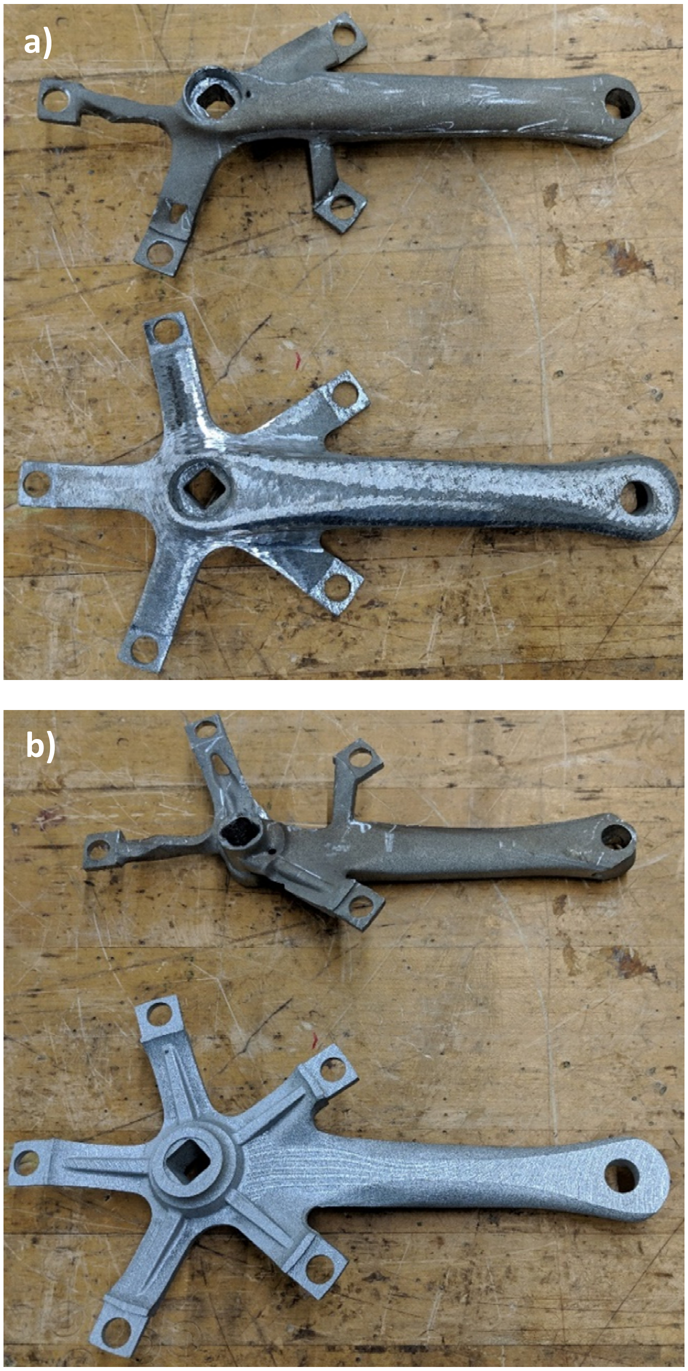

Figure 9: Front(a) and rear (b) view of the original design and the optimized design

A test fixture was designed using 3D CAD modeling to mount the bicycle crank arm in a universal testing machine (Figure 10). The device needed to be adjustable to allow the crank arm to be rotated for testing at different crank angles and slid horizontally so that it could be aligned with the loading axis of the testing machine. The test fixture was laser cut from steel plate, welded, and painted.

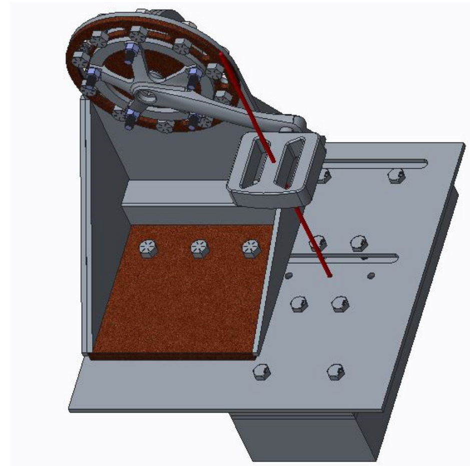

Figure 10: 3D CAD model of test apparatus

The test fixture was bolted to an Instron 5967 universal testing machine (Instron, Norwood, MA) to create a rigid attachment during testing. The specimen was mounted, the test angle set, and the fixture adjusted to align the center of the pedal with the axis of the testing machine (Figure 11). The original design and the optimized design were tested at 15-degree intervals. Loads were applied slowly at a rate of 1 mm per minute until the force equaled the magnitude of the previously calculated resultant force vector at the specified angle. When the maximum force was attained, the strain gage value was recorded. In addition, the deflection of the end of the crank arm near the pedal mount was measured with dial indicators. These were positioned to measure vertical and horizontal displacement at the end of the crank arm. They were zeroed prior to force being applied and the displacement at maximum force was recorded for each test angle and for each design.

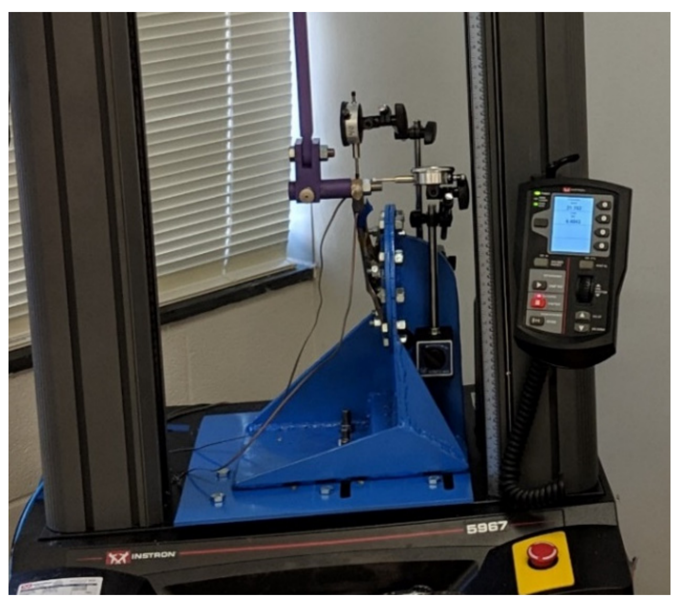

Figure 11: Each design was tested on an Instron 5967 universal testing machine at 15 degree15-degree increments

5 RESULTS

The resultant force vector was maximum at an angle of -45 degrees. The stress at this loading condition is shown in the finite element analysis below (Figure 12). The maximum stress was 215 MPa and located at the web between spider leg #1 and the main body of the crank arm. This value was 43% of the yield strength of the material (500 MPa) and 86% of the stress threshold (250 MPa) used during the topology optimization.

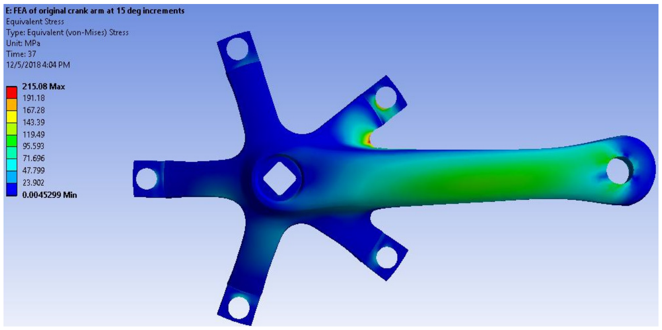

Figure 12: Stress in original design from FEA

Finite element analysis of the optimized design showed the maximum stress to be 237 MPa (Figure 13). This value was 47% of the yield strength of the material (500 MPa) and 95% of the stress threshold (250 MPa) used during the topology optimization. Note that the optimized design also includes the design modifications necessary to achieve design for manufacturability. This small amount of added material is the reason that the optimized design did not exactly match the target value of the stress threshold.

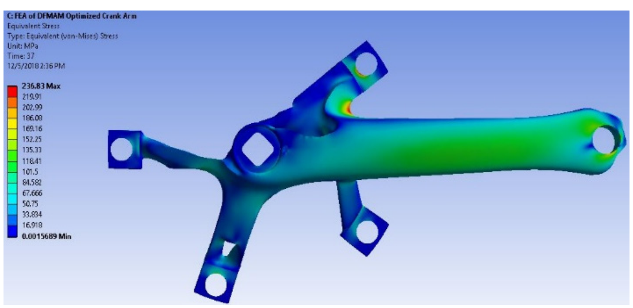

Figure 13: Stress in optimized design from FEA

Analysis of the weight was performed theoretically by calculating the weight from data in the computer models and experimentally by weighing the manufactured parts (Table 1). Theoretical and experimental results differed by less than one percent. The results showed that topology optimization and DFMAM could produce a manufacturable design that was more that 41% lighter than the original design.

Table 1: Analysis of part weight

Weight Analysis						
	Theoretical Results			Experimental Results		
	Volume (mm^3)	Calculated Weight (kg)	Weight Savings Compared to Original Printed Crank Arm (%)	Measured Weight (kg)	Weight Savings Compared to Original Printed Crank Arm (%)	% Difference Between Theoretical Weight and Actual Weight
Original Printed Crank Arm	109110	0.862	N/A	0.859	N/A	-0.33%
Optimized Crank Arm	63836	0.504	-41.5%	0.500	-41.8%	-0.83%

* Calculated Weight = *Density* × *Volume*

Although the optimization was only performed at one crank angle (-45°), the performance of the design was evaluated between -90° and 90° (Figure 14). While the original design had a peak stress at -45°, the angle of the maximum resultant force vector, this was not the case for the optimized design. As the angle deviated from the optimization value, the stress increased reaching a maximum value at 0° with a magnitude slightly over 300 MPa. This value is considerably higher than the target optimization value of 250 MPa. The reason for this deviation is likely due to a shift in stress within the part as the direction of the applied force changed. Even though the force magnitude was lower, the change in direction would require other areas of the part to resist the forces. Material in these areas may have been removed during the topology optimization process because they were unnecessary when the load was applied at a different direction.

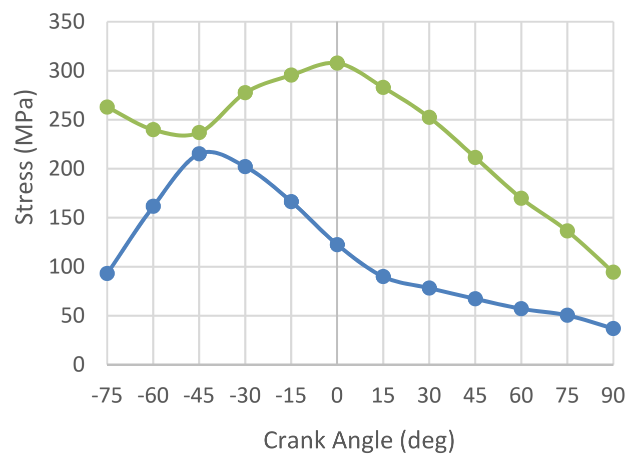

Figure 14: Comparison of maximum stress at different crank angles for the original design (blue) and the optimized design (green)

Analysis of the deflection show a minimal reduction in stiffness caused by the topology optimization (Figure 15). The impact of optimizing the design using only one angle seems to be adequate for this parameter.

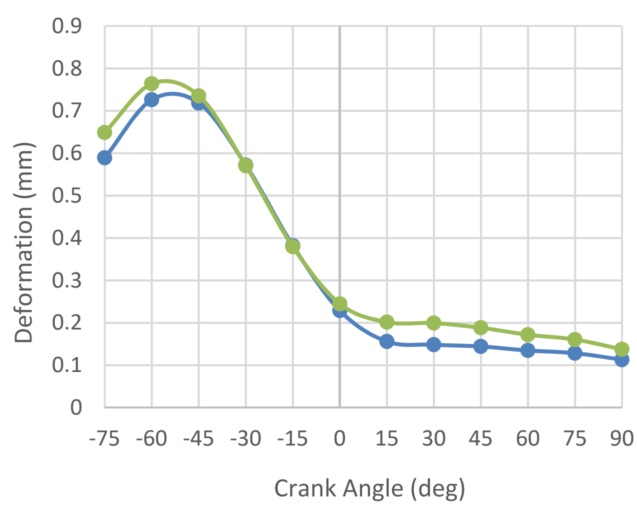

Figure 15: Comparison of deformation at different crank angles for the original design (blue) and the optimized design (green)

6 CONCLUSIONS

The results showed that topology optimization software to be an effective and useful tool for optimizing the design of 3D metal printed parts. However, topology optimization alone was not enough to finalize a design prior to printing. The application of DFMAM principles were needed to ensure that the overhanging structures would not collapse during printing. Because the determination of what constitutes an overhang is determined by the part orientation when printed, some modification will generally be required prior to printing, so the process cannot be completely automated.

Topology optimization was performed at the angle of the maximum resultant force vector. This approach was sufficient to achieve weight reductions without compromising deflection, but it was less than ideal for achieving a targeted maximum stress within the part. The topology optimization process seems to be sensitive to the direction of force application. These results show that it is necessary to optimize the topology accounting for all the force vector directions even when the magnitude of these forces are lower than the maximum value.

In conclusion, applying topology optimization and design for metal additive manufacturing principles to a bicycle crank arm was able to reduce the weight of a 3D metal printed part by 41% while simultaneously achieving a maximum deflection close to the original design and maintaining maximum stress near a target value.

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