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Ultra-precision machining of additively manufactured lightweight freeform precision mirrors

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Abstract
Components of today seek to coalesce multiple functions into singular elements with the increase in fabrication complexity. However, it is imperative that these parts are designed not only to perform their desired function, but to also include overall considerations in the entire fabrication process chain to ensure the successful realization of the component. Leveraging on the freedom of design expression in additively manufactured elements, components of today also require the need precision finishing to achieve their final shape. As such, the conglomeration of these process considerations from functional design, printing, fixturing and post-processing can no longer be done independently. The fabrication of lightweight freeform precision mirrors well demonstrates these considerations holistically. These freeform mirrors not only need to reflect light well with the nanometric finishing required of them, but also required to be lightweight to save on the overall impact of these optical assemblies, which are critical in applications with payload sensitivities.

SLM, 3D Printing, Ultra-precision, Diamond

1. Introduction

The advent of additive manufacturing processes has enabled the physical manifestation of our imagination by removing the need for traditional manufacturing constraints during fabrication. Along with their increased accessibility to both the physical technology and digital libraries, component fabrication can be easily picked up by hobbyist and students alike [1]. With these skills, a new manufacturing workforce paradigm with additive manufacturing will be created in the future.

However, as additive manufacturing is being adopted into more mainstream precision engineering components, there remains a need for shift in manufacturing design considerations to realize and employ these components into complex systems of the future. This is especially important to decrease the time-to-market of the component with reduction in the number of design iterations before the first prototype. Additionally, with increasing importance placed in manufacturing sustainability, a lower iteration count will also result in a reduction in wastages due to rapid prototyping and energy consumed in the design stage. This decreases the overall embodied carbon footprint of the component just within the design stage.

As such, it is paramount to understand and embody the design considerations along the process flow of these components. As shown in Figure 1, 3D printed engineering components usually go through 5 main processes before the components are functionalized. Starting with the design stage, these components are required to not only serve their purpose but should also be designed with great consideration to the limitations and needs of the manufacturing processes.

The material selection follows the design process, where a decision on the type of materials used and the corresponding processes are decided. Here, the feedstock parameters and the base material can also be considered, significantly affecting the types of processes available for the operation.

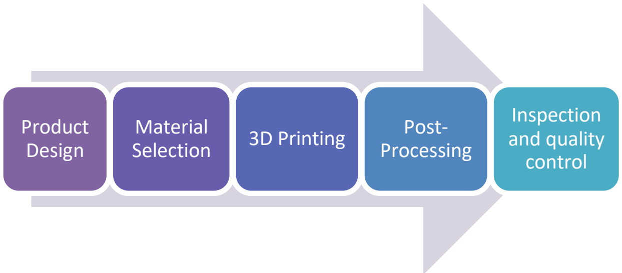

Figure 1. End-to-end solutions for additively manufactured components

This is followed by the 3D printing component where the design is actualised before post-processing the printed product for functionalization. Post-processing steps may include processes such as CNC machining, coatings, or other finishing steps to allow the AM printed components achieve net-shape. These processes end with inspection and quality control to ensure that the components are made to the designed specifications and purpose.

Using an ultra-lightweight mirror as a demonstrator for this study, an example of the various design considerations is described in this paper. To fabricate these mirrors, ultra-precision machining is required to achieve the high geometrical accuracy and surface finishing required, requiring special attention to how the functional surface can be generated. These considerations enable the end-to-end manufacturing processes, as described in Figure 1, to realize such high precision functional components which cannot be done with either additive or subtractive manufacturing alone. As such, this paper hopes to provide a holistic view into the design considerations required where 3D printing process are used in the line of fabrication.

2. Design for Manufacturing

While 3D printing process expand the flexibility of possible physical designs, multiple other considerations are required to be accounted for a component to be successfully fabricated and perform as desired. These considerations may not be presented in a sequential form as listed in this paper but should be embodied directly into the design of any component that requires both additive and subtractive processes. These thought processes would thus allow for quicker time-to-market of the components, while also reducing the time and material wastage due to the need for multiple redundant rapid prototyping iterations to achieve the first successful prototype. The 4 main considerations are the design for function, design for additive manufacturing, design for subtractive manufacturing, and design for inspection, as observed in Figure 2. Each of these considerations will be elaborated further in the following sections.

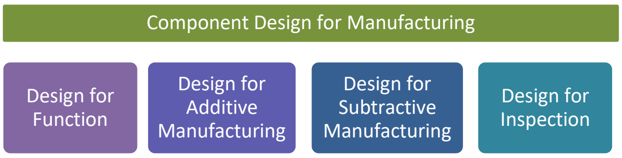

Figure 2. Various elements of component design for manufacturing.

2.1. Design for Function

Design for function usually supersedes the other design considerations, always creating the component to serve its intended purpose. For this demonstrator, the main function is to direct collated infrared light into a photodetector. The entire device is to be made as compact and lightweight as possible for weight sensitive applications, allowing for more weight to be attributed to other more critical functions and components.

This weight saving can be performed in two main ways. The first way is to combine the functions of various components into one, reducing the amount of space required of the device, while also further reducing the overall weight due to the reduction of components. This requires a freeform mirror shape that replaces the conventional lens and planar mirror setup [2]. This can be observed in the Figure 3, where the function of the mirror surface can be described as follows:

$$z = \frac{x^2 + y^2}{a} + b \quad (1)$$

Where the constants a and b represent the curvature acuteness and the vertical shift in the parabola, respectively. To verify that the surface performs as intended, simulations using ray tracing is performed. This is done using ZEMAX to ensure that the collimated spot is at the desired focal distance in space, with respect to the mirror position, as observed in Figure 4.

Using an input of 10,000 rays and irradiance of 1 watt, the simulated peak irradiance of the lens at the detector location reached 2212.7 watts/ cm^2 with 9989 hits on the detector. With adequate signal intensity and a spot size measuring approximately 1 mm by 1.5 mm, the requirements for the optical function of the lens were achieved.

For the second functional objective on light weighting, besides reducing the total number of components in the device, mass reduction can be done on the non-critical sections of the body of the mirror. This leaves the functional surface alone, along with the walls of any fixturing points that will be discussed later. Thus, the main bulk of the material is subjected to weight reduction via latticing. This creates a network of repeated units throughout the body, creating a structural framework that removes non-essential volume of the component, reducing the overall weight without compromising on the integrity of the structure. This can be seen in Figure 5, where various lattice structures are used for light weighting purposes.

There are also other component functions of which can be considered in the design phase, which are not included within this demonstrator. These design considerations can be classified under an umbrella of Design for excellence (DfX), where designs are made to achieve functional objectives, which includes and are and not limited to the component functions of assembly and disassembly, end-of-life processes, circularity, logistics, safety, corrosion, ergonomics, simplicity, cost, etc [3,4]

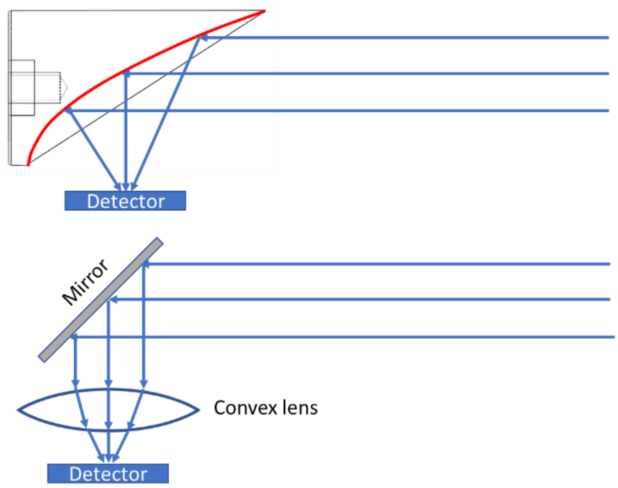

Figure 3. (Top) Single component that combines both reflection and focusing into a single component. (Bottom) Conventional mirror and lens setup for the same function.

2.2. Design for Additive manufacturing

Additively manufactured components moving into mainstream manufacturing lines have disrupted the paradigm of conventional design for manufacturing considerations by introducing more design dimensions into the mix. These features leverage on the use of AM-enabled processes but would require full embodiment of the technology to take complete advantage of such capabilities.

In the light weighting of these mirrors, additive manufacturing has enabled the use of 3D lattice structures, which have eluded traditional component designers using conventional production techniques. These cellular structures have brought about many other benefits besides removing unwanted bulk [5,6]. Due to the modularity of the cellular design, each cell can be morphed differently to be optimized for various functions and applications, such as for isotropic and anisotropic behaviours.

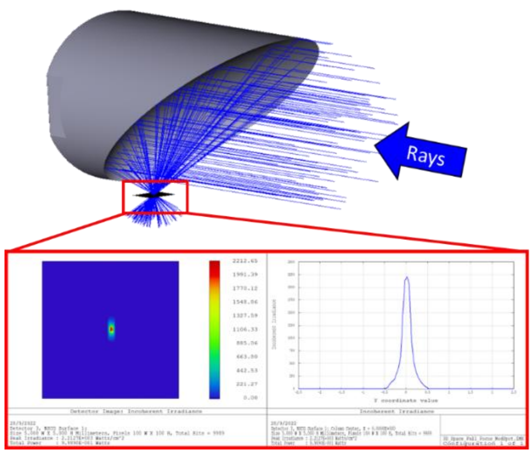

Figure 4. Optical simulation of the newly designed component. The position of the detector shows the spot size and focus intensity of the reflected rays through the ray trace simulation.

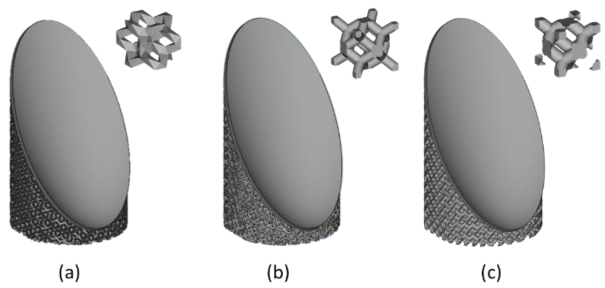

Figure 5. Various lattice structures were used to replace the bulk of the material to further reduce the weight of the component. (a) Thick Diode lattice. (b) Thick Rhombic Lattice (c) Thick Diamond Lattice.

While problems such as non-uniform neighbouring cell-to-cell structural connections persist [5], for this demonstrator, the lattice structures used are non-topologically optimized. The main function they serve is for light weighting and are thus the unit cell is uniformly distributed throughout the non-functional mass of the component. For this mirror, Selective Laser Melting (SLM) is used to create a near-net shape form. This layer-by-layer powder bed fabrication technique uses a laser source to discriminatory melt thin areas of which the component's model intersects with the layer slice. Here, powder-bed process design considerations take dominance to influence the final design.

Repeatability issues of powder-based processes have been observed due to the distribution of the powder sizes, resulting in variability in fabrication results. Final build porosity and maximum layer thickness depend on parameters such as powder size distribution, packing density, feature size, and material, due to the penetration of the lasing source [7,8].

Other build properties such as the intricate resolution finesse of the SLM machine also rely on the lasing source properties. These include and are not limited to the spot size, lasing source, lasing power, scanning speed and strategy [8]. Furthermore, the high surface of these lattice structures quickly dissipate heat, which may prove challenging for the SLM process to generate if the melt pool cannot be created at the point of interest [9].

In this demonstration, three main lattices were shortlisted, as shown in Figure 5. Each lattice possesses different weight, surface area and mechanical characteristics, as shown in Table 1. While ideally this non-functional mass can be totally removed, these structures provide invaluable thermo and mechanical characteristics to the component in extreme operating environments. This act as additional structural support, with the increase in surface area allows for additional heat exchange.

Table 1 Surface are and weight reduction of component using the various lattice structures.

Type / **Property**	Thick Diode	Thick Rhombic	Thick Diamond
Surface area (mm^2)	32210.981	29214.266	22053.112
Weight reduction (%)	61.7%	57.3%	57.5%

Out of the three options, the thick rhombic design was selected for the final design. While the thick diode option has better weight reduction and a larger surface area, the minimum feature size of the structure has proven to be difficult to print based on experience, with some structure defects shown in Figure . Comparing the thick rhombic and thick diamond designs, the weight savings are nearly the same, thus taking the design with a larger surface area as a criterion. For this study, the lattice was tessellated using a 3 mm unit cube.

Other AM design considerations include and are not limited to overhang limit, support design and removal, standard reference models, consolidation of parts, etc.

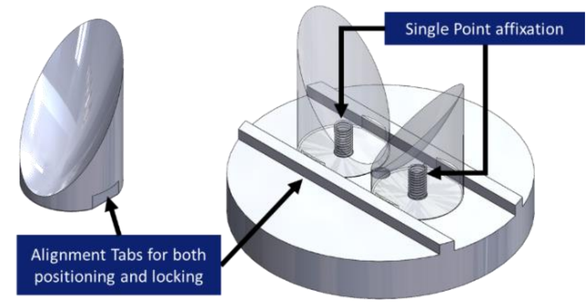

Figure 6. Fixturing of lightweight mirrors for high rpm UPM

2.3. Design for Subtractive manufacturing

Given the freedom of design that AM technologies enable in fabrication, not all components can be directly used as printed. This must be considered during the design phase as post-processing may be required to bring the product to net shape and functionality. Here, design simplicities are usually embodied into the part to ensure ease of setup and reduction in overall operations required to carry out the necessary subtractive process. Other considerations include and are not limited to fixturing, tool interference, physical limitations, feature accessibility, tolerances, quantity, etc.

For this demonstrator part, the functional surface of the component requires for it to not only be geometrically accurate, but also reflective to perform as designed. While a metallic or highly reflective polymeric coatings can be done to provide the mirror-like function, such coatings may only be done on a geometrically accurate surface. Hence, ultra-precision machining serves not only as a subtractive manufacturing process, but also as a finishing step directly produce mirror-like surface finishing due to the use of highly precise diamond tools.

Fixture design and how to accurately mount the component in the machine is thus important, along with an understanding of the various operations required. In this demonstrator, the workpieces are mounted onto the fixture using threaded bolts. With a single point of affixation, alignment tabs are required on the workpiece to not only provide a surface reference, but also to prevent rotation of the component during the machining phase. These are reflected on the fixture as tracks, with sufficient spacing in between them for the workpiece to snugly fit. These setup considerations can be observed in Figure 6.

2.4. Design for Inspection

Uncertainty in measurement is as reliable as the instruments that are used. While complex and intricate designs can now be fabricated using 3D printing, it is important that these features can be measured and verified to show adherence to the intended designed. While there is also the availability of non-destructive measurement techniques, the frequency and time required to inspect the component quickly can add up to the cost. Thus, it is paramount that the appropriate measurement tools are selected early in the design phase and have accessibility to the key characteristics that are to be measured, noting the total embodied cost. Along with the appropriate datums and tolerances, this measurement accessibility should be considered within the component design.

For the freeform lens within this study, the main functional surface that requires measurement is the reflective surface. This mainly includes the surface finish and the form of the lens, which can be easily determined using a stylus profilometer. The design of the lens exposes it for machining and is thus also assessable for the stylus to contact. While a fixture can also be designed for rapid inspection of similar lenses, it is not covered in this study.

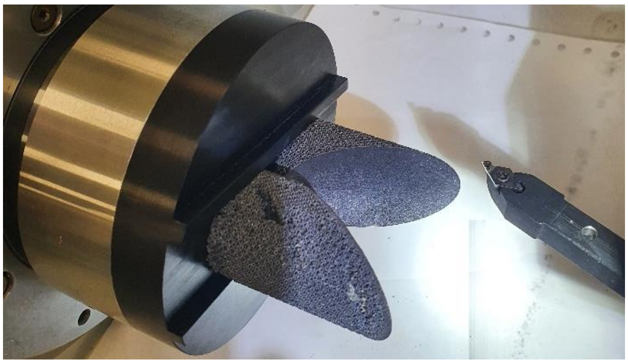

Figure 7. Experimental setup for ultra-precision diamond turning of the functional optical surface.

3. Experimental Setup

On the software front, the bulk of the component's CAD model was firstly created on Solidworks. This model included all the design considerations required for the end-to-end process to achieve the lightweight mirror. After which, the model was sent to Magics by Materialize to selectively keep certain surfaces at a particular thickness. These functional surfaces are namely the mirror surface and the walls that reinforces the threaded hole. The rest of the bulk was replaced by a uniform lattice structure for light weighting. Following this, the model was converted into STL format, ready to be uploaded for printing.

The SLM machine used is the EOS m290 system, with a scanning speed of 1300 mm/s. It possesses a build volume of 250 by 250 by 325 mm and uses a Yb laser and a F-Theta lens for high-speed precision scanning of up to 7.0 m/s. The power used for this setup was 370 W with a focus diameter of 100 µm. The printing material selected for this component was AlSi10Mg. This material was selected as it not only possesses a good strength-to-weight ratio, but it is also a well-established SLM printable material. It is also a non-ferrous material, making it ideal for diamond turning. The powder size distribution for this setup was around 15 to 63 µm, with a layer thickness of 30 µm.

For the post processing, the workpiece and the fixture were placed in an ultraprecision machine tool, the Toshiba ULG-100C (H3), as seen in Figure 7. A single crystal diamond tool of 0.2 mm nose radius with a 15° front clearance and a 0° rake was used as a tool, set with a rotation of 20°. This rotation and the front clearance of the tool both ensured that there was no interference between the tool shank and the workpiece surface during the machining process. Using MATLAB, the tool path of the machine tool is generated, along with the compensation of the tool nose radius to ensure conformity to the geometry of the surface. The rpm used for machining is 1000 rpm with a 1 mm/min feed for finishing.

4. Results and discussion

The additively printed lightweight high aspect ratio lenses were successfully fabricated using SLM, as shown in Figure 8, and finished using ultra-precision machining, as shown in Figure 9. Using a stylus profilometer, the surface roughness of the lens was measured with an Ra of 22.5 nm. This deviation from the typical quality of UPM products can be attributed to lack of lubricant used during the cutting process. Dispersion of lubricants facilitate in the chip flow in the cutting region, allowing for a more consistent relative shear angle of the chip. Also, due to silicon content present within the material, the lubricants can also help in evacuating these particles from the cutting region, avoiding scratching of the optical surface.

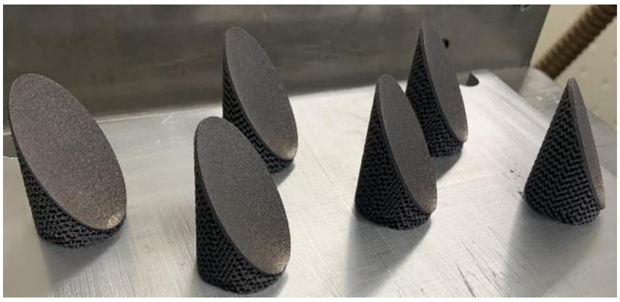

Figure 8. Batch printing of lattice structures for the freeform mirror base using SLM.

Figure 9. The ultraprecision lightweight freeform mirror

While this sample maybe simple in terms of the number of processes required, the time to produce the part was significantly reduced due to the considerations of the various requirements to manufacture the lens from the design phase. This approach avoids unproductive occupation of the machine and operators, allowing for more productive overall job queues, especially with the world rapidly moving towards hyper-personalization with high-mix low-volume production. This disparity in lead time is observed more obviously where product designers lack the knowledge in fabrication capability, requiring designs to bounce between the many stakeholders (i.e. the designers, shopfloor, management, customers, etc).

5. Conclusion

In this study, the design for end-to-end production is conceptualized with the successful production of high aspect ratio freeform lightweight lenses. While additive manufacturing has allowed for a lot of design freedom, many engineering products still require subtractive and post-processing steps to reach net-shape. Emphasizing on the importance of the design phase, features of a component must be considered in totality. This reduces the lead time, material, and energy wastage. The need for repetition can also be reduced, which can be quite substantial between customers and fabrication service providers. As such, for smooth fabrication of additive manufactured products, end-to-end knowledge is key. This includes the functional objective shape and the process route limitations, influencing the final design together to ensure that the successful fabrication to these components.

References

[1] Trust T and Maloy R W 2017 *Comput. Sch.* **34** 253-66
[2] Gimenez-Benitez P, Miñano J C, Blen J, Arroyo R M, Chaves J, Dross O, Hernandez M, Falicoff W 2004 Opt. Eng. **43** 1489–1502
[3] Bralla J G 1999 *Design for Manufacturability Handbook.* 2nd ed.
[4] Beitz W, Pahl G, Grote K 1996 *Mrs Bulletin* **71**
[5] Wang Y, Zhang L, Daynes S, Zhang H, Feih S, Wang M Y 2018 *Mater. Des.* **142** 114-23
[6] Daynes S, Feih S, Lu W F, Wei J 2017 *Mater. Des.* **127** 215-23
[7] Dowling L, Kennedy J, O'Shaughnessy S, Trimble D 2020 *Mater. Des.* **186** 108346
[8] Balasubramanian N, Hu Z, Song X, Zhai W, Wei J 2019 *Engineering* **5** 702-20
[9] Reza Yavari M, Cole K D, Rao P 2019 *Procedia Manuf.* **33** 375-82