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Impact of 3D printed lightweight structures on the surface quality of diamond turned aluminum mirrors

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Abstract

This scientific work aims to experimentally compare the effect of lightweight structures on optical surfaces of 3D printed aluminum rounds. Therefore, a variety of different additive manufactured lightweight structures are compared to a conventionally milled one. Maintaining surface specifications whilst reducing mass on mirror systems is elementary for the functionality and efficiency of dynamic optical applications. For stiff materials like glass or ceramics, adding lightweight structures doesn´t carry much of a risk of form deviations on the optical surface caused by the underlying structures. However, on mirrors made from aluminum the underlying lightweight structures would be visible on the optical surface when measured. Additive Manufacturing technologies like Laser Powder Bed Fusion (L-PBF) offer new possibilities in the design of lightweight structures by creating finely linked and densely arranged support structures that otherwise couldn´t be created. In combination with a finishing process like diamond turning, lightweight mirrors without form distortions on the optical surface could be created. The study investigates the visibility of underlying lightweight structures on surfaces machined to mirror quality using ultraprecision diamond turning. Interferometry is utilized to measure surface deviations and provide insights into the visibility characteristics of the underlying structures. Two aluminum rounds are manufactured using the same L-PBF process and material. One of the rounds is a solid block of 3D printed aluminum where a honeycomb lightweight structure is applied through milling. The second round is already printed with differently shaped lightweight structures. Through this study, we aim to gain a deeper understanding of the influence, additive manufactured lightweight structures have on optical surfaces. Contributing to the advancement of manufacturing techniques in the field of 3D printed optical components. Establishing additive manufacturing methods for optical structures could also enable further optimizations in terms of long-time form accuracy and increased thermal stability, if consistently applicated.

Additive manufacturing, laser power bed fusion, diamond turning, monocrystalline diamond, light structures, optical surfaces, form error, 3D printing, aluminum mirrors, optical applications, optical manufacturing, image distortion, complex geometries, dynamic optics

1. Introduction

The adherence to surface specifications while simultaneously reducing the mass of optical components is crucial for the functionality and efficiency of dynamic optical applications. Especially in the case of aluminum mirrors, underlying lightweight structures are typically measurable on the optical surface after processing and negatively affect the subsequent process chain or application.

Additive Manufacturing technologies, such as the Laser-Powder Bed Fusion process (L-PBF), offer new design possibilities for lightweight components. Previous studies have already investigated the potential of 3D-printed, topology-optimized aluminum mirrors. Typically, structures specifically adapted for the application are calculated using FEM (finite element method) simulations. [1], [2], [3]

This study focuses on delicate lattice and cell structures, whose versatility fully exploits the advantages of Additive Manufacturing without the need for elaborate simulations or customized designs. Generic and finely interconnected structures should also provide the possibility to uniformly support optical surfaces. The key advantage of this approach is that significant mass reductions could be achieved simply and quickly. Another objective of this study is to investigate, through experiments, how an aluminum-iron-zirconium alloy behaves as an optical base material when these generic structures are used for lightweight applications.

2. Theoretical Framework

Laser Powder Bed Fusion (L-PBF) is an Additive Manufacturing process that enables the fabrication of complex structures through the layer-by-layer melting of metal powder. The process begins with the application of a thin layer of powder on a build platform. A laser beam selectively melts the powder according to the CAD data, fusing it together to form the desired geometry. After melting, a new layer of powder is applied, and the process is repeated until the component is fully constructed. The L-PBF technology allows to produce structures that would be challenging or even impossible to achieve with conventional manufacturing methods. The freedom in geometry enables the development of complex internal structures, lattice structures, and optimized shapes that reduce weight while simultaneously increasing strength.

Ultraprecision diamond turning is a machining finishing process using a geometrically defined tool, typically made from monocrystalline diamonds. Due to the small cutting-edge radius of the diamond tool ($r < 50$ nm) and high machine accuracies, optical surfaces can be directly produced in ductile materials such as aluminum or nickel. According to empirical values, the supporting structures on a surface processed in this manner are measurable with an interferometer. Even with such small cutting-edge radii and low cutting depths (< 10 µm), a portion of the material is deformed due to the pressure of the cutting edge on the workpiece.

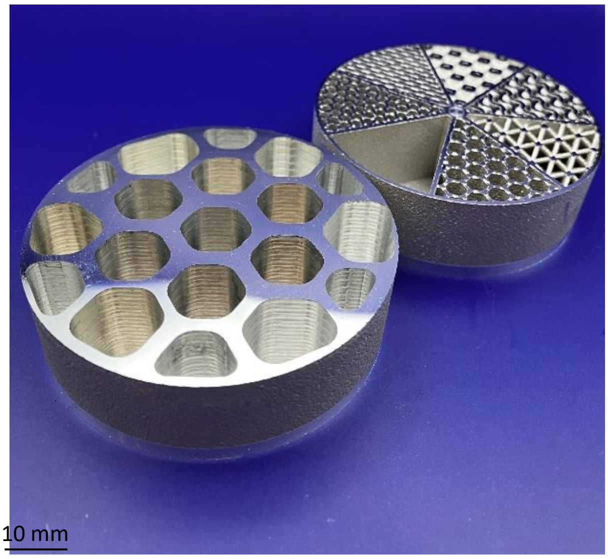

Figure 1: AM-round (right) and C-round (left), laying on the later optical side, both sides processed diamond turned; Manufactured using L-PBF, C-round subsequently milled, D60 mm

3. Methodology

Two identically manufactured aluminum rounds (D = 60 mm, h = 20 mm) are used as the starting material for the test. In the C-round printed as solid material, an exemplary honeycomb structure is introduced by milling, whereas the AM-round already receives different lightweight structures during the printing process (see Figure 1).

The AM-round is divided into seven circular segments. A different structure is generated for each segment. This allows for the investigation of differences between the lightweight structures. One of the circular segments was deliberately created without a support structure to act as a reference and to proof the importance of support structures. It is assumed that the different lightweight structures will influence each other. Therefore, after evaluating the individual segments, another round is to be manufactured, which will exclusively feature the structure identified as the most promising. This will then be compared with the milled C-round.

To determine the best type of support structure, the interferometric shape measurement of the AM-round is divided into seven circular segments. The evaluation of the individual circular sections is carried out both qualitatively and quantitatively. The evaluation metric used, in addition to the PV value (Peak-to-Valley), is the RMS (Root-Mean-Square) of the shape measurement.

For process preparation and to ensure the later comparability of both rounds, the upper and contact surfaces are prepared using diamond turning. The surface thickness of both rounds is turned to the same thickness.

Usually for components without a lightweight structure, the workpiece can be clamped using a vacuum chuck without significant risk of distortion. Since unsupported surfaces are particularly affected by the vacuum in the clamped state, both rounds are initially bonded to adapter plates in a stress-relieved manner. Machining trials are conducted with both clamping variants.

Table 1: Processing parameters for preliminary and finishing operations ($R_{th,kin}$ = theoretical surface roughness)

n [min^-1]	$r_ε$ [mm]	a_p [mm]	$R_{th,kin}$ [nm]
1000	1.4	0.015	20
1000	1.4	0.001	1

4. Results

After UP-turning, the machining of the aluminum alloy results in reflective surfaces, as expected. The microscopic image of the rounds (Figure 2) shows that the surface exhibits defects such as pores and micro-scratches. Measurements of surface roughness using white light interferometry indicate that repeatable Sa values of approximately 4 nm (measurement field 0.34 mm x 0.38 mm) can be achieved across all tests.

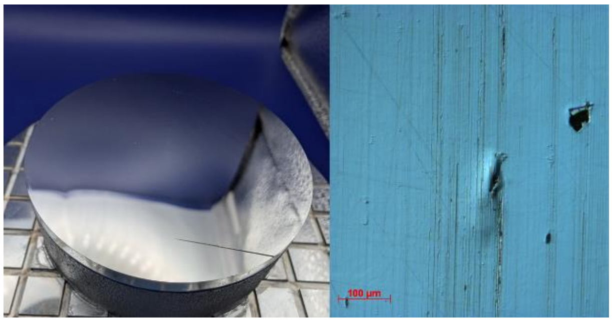

Figure 2: diamond turned aluminum rounds (left), microscope image of pores and surface defects (right)

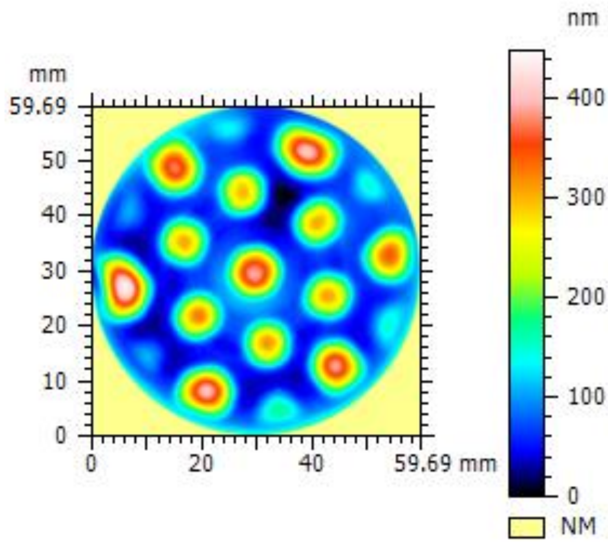

Figure 3: C-round, interferometer (λ = 632.85 nm), diamond turned, vacuum-clamped, surface thickness = 0.9 mm, 4th order removed

Error! Reference source not found. and Figure **4** show the rounds after the diamond turning process. The underlying lightweight structures are clearly visible on the surfaces of both rounds. For the C-round, a form deviation with a PV of 448.3 nm and an RMS of 85.95 nm was measured.

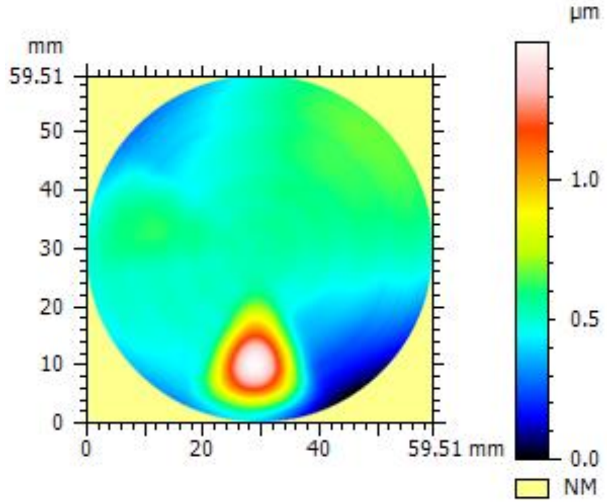

Figure 4: AM-round, interferometer (λ = 632.85 nm), diamond turned, vacuum-clamped, surface thickness = 0.9 mm, 4th order removed

The shape measurement of the AM-round resulted in a PV of 2.480 µm and an RMS of 260 nm. Both rounds were clamped with vacuum and diamond turned. The surface thickness is 0.9 mm.

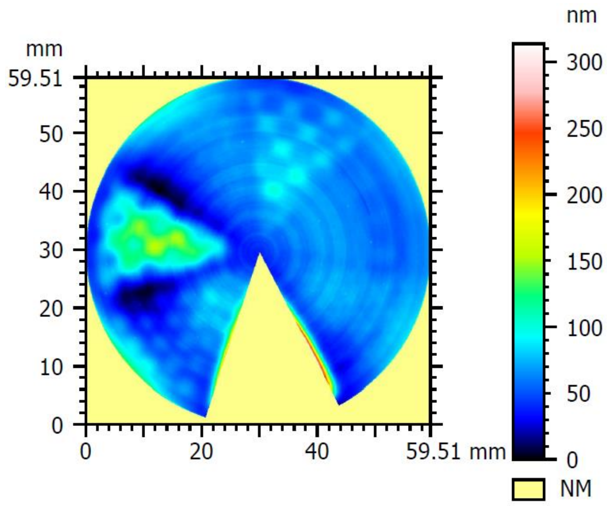

Figure 5: AM-round masked, interferometer (λ = 632.85 nm), diamond-turned, vacuum-clamped, surface thickness = 0.9 mm; masked circular section, 4th order removed

For the AM-round, a PV value of 190 nm and RMS of 22 nm could be measured by excluding the circular segment without support structure (

Figure **5**). For comparison, a shape deviation of approximately 250 to 150 nm PV was measured for both rounds when bonded to adapter plates. As shown as example in Figure 6 the lightweight structures are nearly unmeasurable on the optical surface. Further test results are summarized in Table 2. For further evaluation of the results, the unsupported segment is always excluded in the AM-round, as this segment possesses only low stiffness and would overshadow the other segments by the large shape deviation.

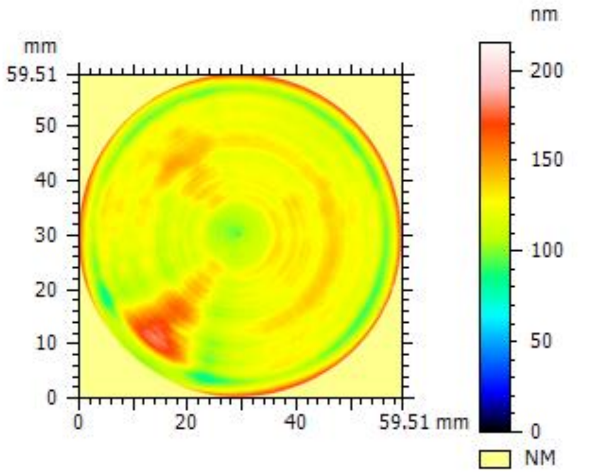

Figure 6: AM-round, interferometer (λ = 632.85 nm), diamond turned, bonded to adapter plate, surface thickness = 0.9 mm, 4th order removed

Table 2: Experimental results with varying surface thicknesses, bonded and vacuum clamped

Experiment	PV [nm]	RMS [nm]
AM-round ST1.3 vacuum	258,1	22,46
C-round ST1.3 vacuum	188,4	34,53
AM-round ST1.3 bonded	87,74	7,99
C-round ST1.3 bonded	77,75	13,02
AM-round ST0.9 vacuum	314	24,01
C-round ST0.9 vacuum	448,3	125,00
AM-round ST0.9 bonded	142,3	11,85
C-round ST0.9- bonded	146,5	17,26

From the analysis of the surface segments with different support structures, the best circular segment across all test conditions results in an average of 83 nm PV and 9.9 nm RMS

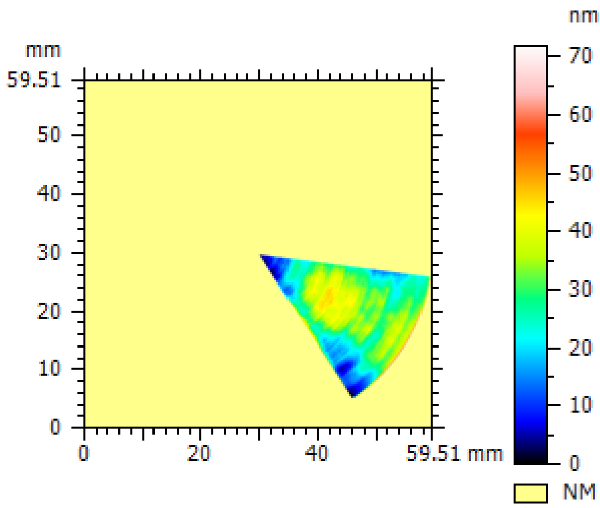

Figure 7: AM-round, interferometer (λ = 632.85 nm), UP diamond-turned, vacuum-clamped, surface thickness = 0.9 mm, 4th order removed; best circular section selected, gyroid structure

In the context of the analysis of the measurement data, only shape errors up to the 4th order are subtracted. This ensures that long-wavelength shape errors, caused by the clamping, do not influence the evaluation. The relevant deformations due to the lightweight structures become visibly more clearly.

5. Discussion

Results so far demonstrate the potentials and challenges of combining L-PBF and diamond turning in the production of optical aluminum components. Additive Manufacturing technologies offer unique possibilities that can be utilized in the fabrication of highly precise and complex structures. As the results show, these possibilities can be accessed using standard software-generated support structures. The finely meshed gyroid structure shown in Figure 7 was most promising in this study. This structure features three-dimensionally arranged material struts, which is why high stiffness is to be expected in multiple load directions. This significantly enhances the suitability for highly dynamic systems. Other tested three-dimensional structures, such as an octahedral structure, as well as additional 2.5D structures, performed worse.

Fundamentally, newest alloys that are particularly suitable for additive manufacturing processes also present novel challenges. Especially concerning the quality of the surfaces, the choice of material must be adapted to the later application. For example, it can be assumed that the zirconium particles contained in the alloy used will be torn out from the softer aluminum matrix by the diamond cutting edge. This leads to pores and micro-scratches on the surface (Figure 2). Without additional coating, it is not expected that the produced surface with a surface roughness of 4 nm RMS can be used unrestrictedly as an optical surface. However, for optical applications in the infrared wavelength range, usage could potentially be possible. It can be assumed that the examination of the form behavior is possible despite the currently existing micro-roughness.

For small surface thicknesses, the measured shape deviation for the AM-round, without considering the unsupported segment, shows a lower shape deviation (**Table** 2). The shape deviation of the unsupported segment of the AM-round illustrates the significant impact of appropriate surface support.

However, it must be mentioned that the current results of the AM-round do not represent the optimal condition for the diamond turning process. The different lightweight structures within the AM-round create significant variances in stiffness and weight distribution. The resulting vibrations affect the processing outcome. As the outcome of this study shows that the 3D-printed aluminum alloy cannot be used unconditionally for all optical applications without additional coating. Typically, optical aluminum components are chemically coated with for example high-phosphorus nickel to create the substrate for the later optical surface. It is assumed that the results obtained here regarding dimensional accuracy can be transferred to parts coated with high-phosphorous nickel.

6. Conclusion and Outlook

The results of the study investigating the influence of lightweight structures on the optical surface of 3D-printed aluminum mirrors demonstrated the potential of these technologies for producing complex and highly precise aluminum components. Additive Manufacturing enables the integration of lightweight structures that contribute to increased shape accuracy.

The aim of this study was to examine the impact of lattice and cell structures on optical surfaces. The focus was primarily on standard structures that can be generated automatically by appropriate software solutions even without elaborate pre-simulations. These offer the decisive advantage of achieving mass reductions simply and efficiently. The results presented here illustrate that the choice of lightweight structures, and their arrangement, significantly influences the stiffness and thus the machining quality. The AM-round, with suitable lightweight structures, exhibits less shape deviation than the C-round. This underscores the importance of careful planning and selection, especially with software-generated standard structures.

Further optimization potential lies in the detailed design and optimization of the structure parameters themselves. Variables such as structure density and wall thickness are influential factors regarding the expected stiffness and weight savings.

Challenges, such as superficial defects and therefore induced higher-frequency defects caused by zirconium as an alloy component, limit the usability of surfaces for optically visible light. Depending on the application, use in the infrared wavelength range is possible. For future applications, it is crucial to optimize material selection and support structure planning to fully exploit the advantages of additive manufacturing. The findings from this study suggest that targeted adjustments in the process chain can further improve the functionality and quality of the manufactured components.

The next steps include a verification test with a round fully supported by the finely meshed gyroid structure. The absolute weight savings will also be introduced as a quality indicator for further experiments. In addition to optimizing lightweight structures, it is also necessary to examine how the results correlate with a high-phosphorus nickel coated surface and even other alloys as base substrate.

These and other optimizations are intended to culminate in a process for the simple and reliable lightweighting of optical components, which delivers (near) ideal shape and surface values depending for the application.

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