TIE-38: Lightweighting of ZERODUR®

0. Introduction

The thermal stability of mirrors in modern astronomical telescopes (either ground based or space) is not the only crucial issue in the design. With more and more increasing apertures of the mirrors the weight and stiffness of the components become an important issue. Therefore many mirror designs today exhibit a thin faceplate with a lightweight back structure resulting in an optimized weight per area ratio and stiffness.

In the past there have been several projects using ZERODUR® mirror blanks with a lightweight back structure. Table 1 gives an overview on some of these projects. In general lightweight mirror blanks are used as secondary or tertiary mirrors in the telescope (figure 1). The ratio of weight reduction is defined as the ratio of the weight after lightweighting process to the weight of a solid mirror blank with the same outer geometries. By mechanical processing weight reduction rations between 66% to 70% have been achieved. Weight reductions above 70% were achieved by additional acid etching.

Project	**Dimensions [mm]**	**Weight [kg]**	**Weight per Mirror Area [kg/m^2]**	**Weight Reduction Ratio [%]**
WIYN M3	776/1101 (elliptic)	59	88	66
ESO/VLT M3	880/1250 (elliptic)	108	125	66
WIYN M2	∅ 1200	115	102	70
Magellan M2	∅ 1376	187	126	70
MMT M2	∅ 1714	290	125	70
MSG-SEVIRI Scan	530/830 (elliptic)	16	45	73*
Gemini M2	∅ 1024	50	47	85*

Table 1: Ground based telescopes with a lightweight ZERODUR® mirror blank (*= after acid lightening).

The definition “weight reduction ratio” can be misleading especially if the mirror is very thin. In chapter 1 is explained that in general the mirror blank needs a minimum faceplate thickness to prevent print through effects in polishing. Therefore the achievable total lightweighting ratio might be lower than the figures above, if the total thickness of the mirror blank is thin compared to the faceplate thickness. We recommended to additionally use the weight per mirror area definition for specification purpose which will be more meaningful in such a situation.

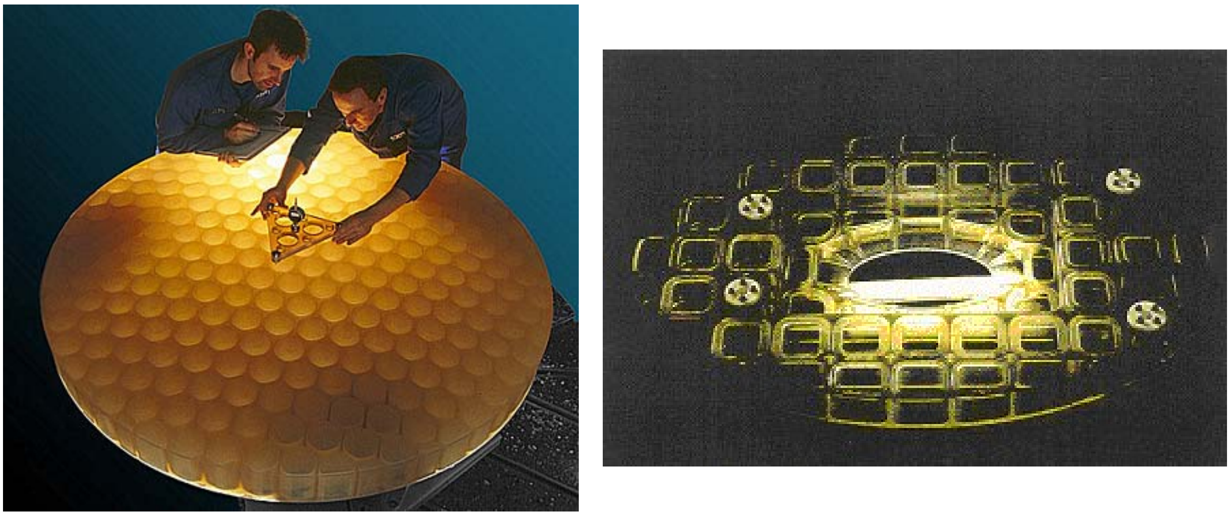


Figure 1: left side: Magellan M2 mirror blank, right side: SEVIRI Scan mirror

The examples in table 1 are all mirror blanks for ground based telescopes. In table 2 several space based telescope mirrors and their weight reductions are displayed. All mirrors are satellite mirrors except for the SOFIA mirror, which has been installed inside a Jumbo Jet.

Project	Dimensions [mm]	Weight reduction %	Launch
SPOT	735 x 85	70	1986
Meteosat	400 x 45	65	1978
Hipparcos Astrometry	600 x 70	70	1990
SOFIA	2705 x 350	75	2001

Table 2: Space based telescope mirrors

In the following chapters we will give an overview on the production methods of lightweight ZERODUR® mirror blanks at SCHOTT

1. Grinding lightweight structures

Lightweight structures in ZERODUR® are mainly generated by grinding holes out of the solid material using CNC grinding processes. These holes can exhibit either simple geometries like for example triangular, square or hexagonal blind holes in the back of a massive ZERODUR® blank or even more complex structures like undercut holes with nearly freeform geometries. Using pure grinding processes a mass reduction of up to 70% is achievable. The final mass reduction strongly depends on the design. Figure 2 shows an example for simple lightweight structures with standard geometry holes. Figure 3 gives some examples of more complex hole structures.

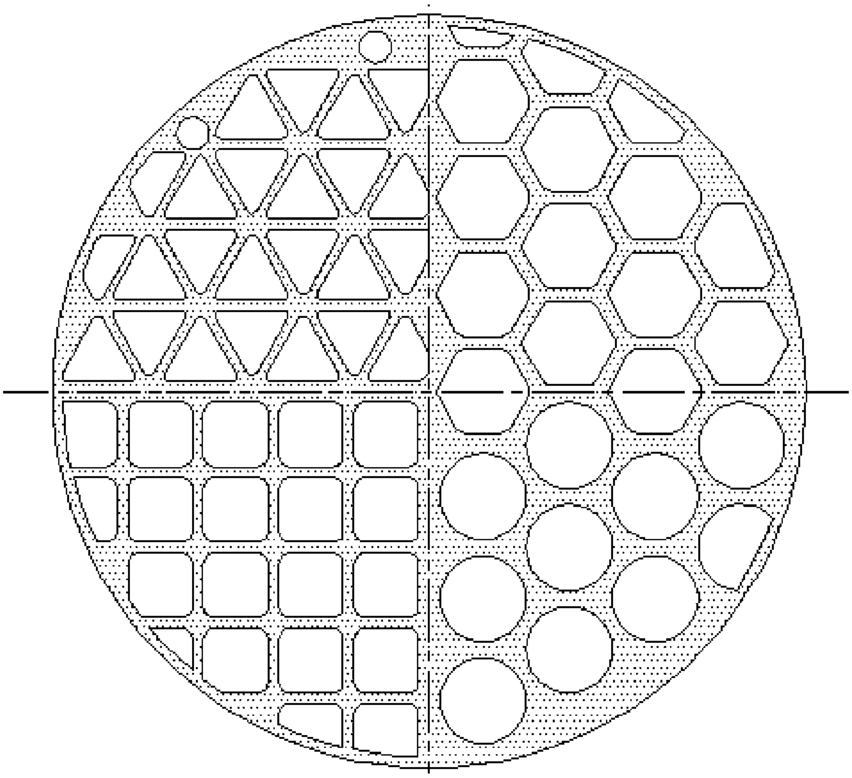


Figure 2: Simple lightweight structures with standard hole geometry

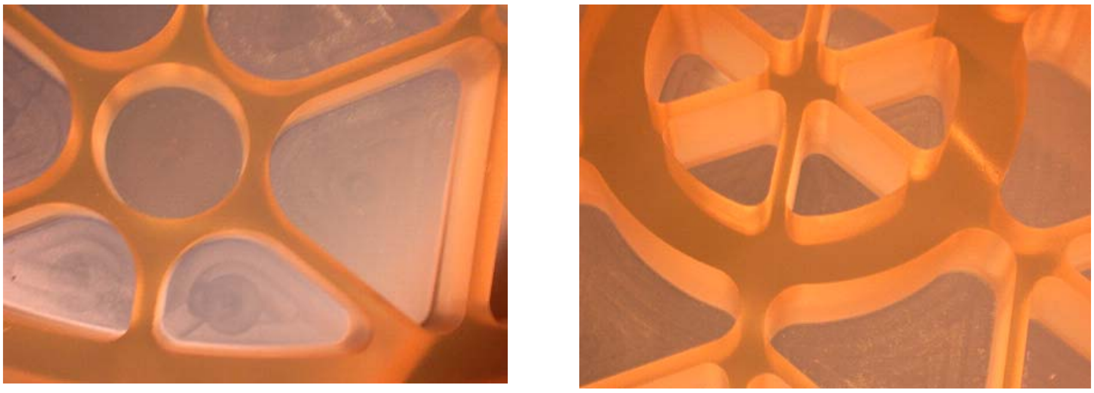


Figure 3: Example for a mixture of different hole structures.

The typical achievable minimum rib thickness between the holes can be a few mm, depending on the processing parameters and the geometry of the structure. The height of these ribs, however, is depending on the length and should be lower, the longer the ribs are. For a lightweighting structure with a structure height of 36 mm a rib thickness of 2.5 mm was achieved [4]. For grinding thinner ribs the risk of breakage increases.

The minimum thickness of the faceplate in general depends on the print through effect during polishing process [5]. The thinner the faceplate and the larger the holes, the higher the risk is that during polishing the faceplate deforms. The final faceplate thickness after grinding is typically in the range of 10 mm to 20 mm.

In general the design for the lightweight structure is provided by the customer. Nevertheless SCHOTT has finite element calculation facilities in house and can provide help.

To achieve additional stability often a so called “under cut hole design” is generated by using special grinding tools that can be seen in figure 4.

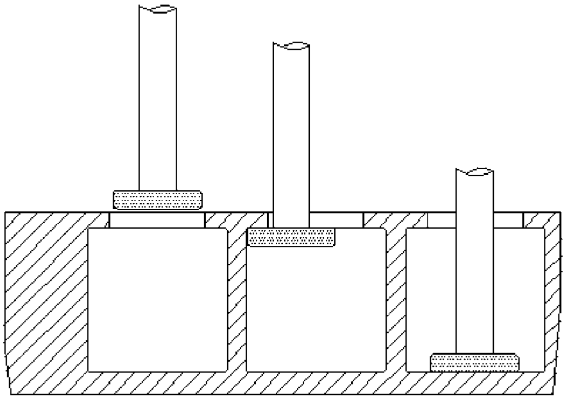
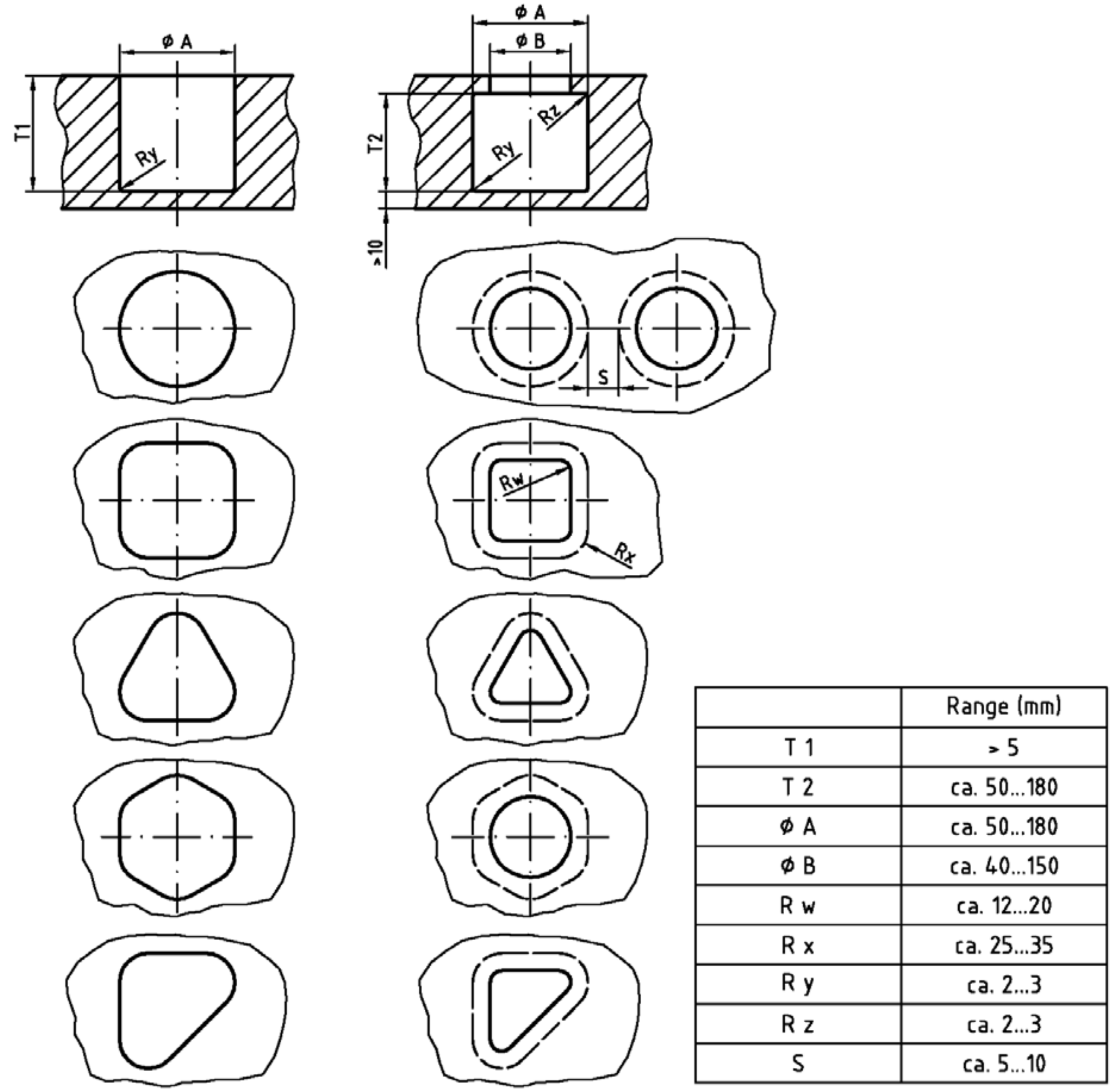


Figure 4: Schematic of the undercut hole processing tool.

Figure 5 shows some common lightweight structure elements and the typical achievable dimensional ranges. The size relation of the back plate opening (diameter B in figure 5) and the under cut hole dimension (diameter A and also depth T2) depends on the tool and shaft diameter relation. This relation depends on the stiffness of the tool. Owing to the tool diameter the corners cannot be sharp edged but only rounded in the ranges given for Rw, Rx, Ry, and Rz in figure 5.



	Range (mm)
T 1	> 5
T 2	ca. 50...180
ø A	ca. 50...180
ø B	ca. 40...150
R w	ca. 12...20
R x	ca. 25...35
R y	ca. 2...3
R z	ca. 2...3
S	ca. 5...10

Figure 5: Typical dimensional ranges of the lightweight structure elements.

2. Economic lightweighting

For a mass production of lightweight mirror segments for extremely large telescopes (ELTs) the production costs will be more important than the achievement of the highest weight reduction.

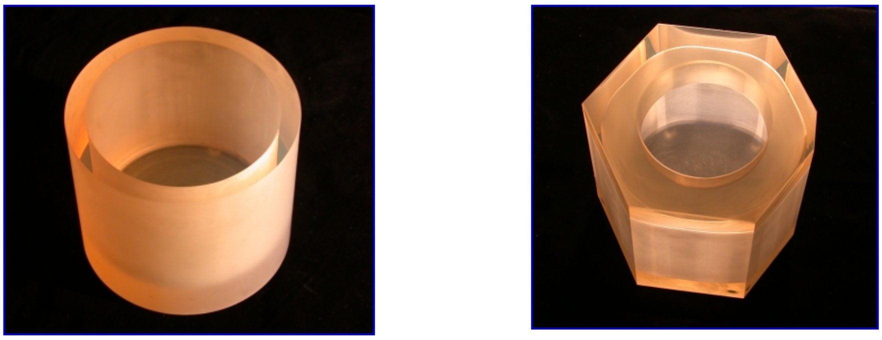


Figure 6: left side: standard circular hole, right side: blind hole

So we propose to use the following effective lightweighting process [1]: A weight reduction factor of about 50% can be achieved by grinding of circular holes (figure 6 left) in a high speed machining process. Blind holes are used instead of more complex undercut structures (figure 6 right).

The rib thickness between the holes and also the thickness of the front plate were increased to a certain extend to allow the highest machining speed. To verify this approach, SCHOTT performed a test production of such structures and thereby optimized the grinding process parameters and also the grinding tools. Figure 7 shows two sample designs of such a structure with 50% lightweighting.

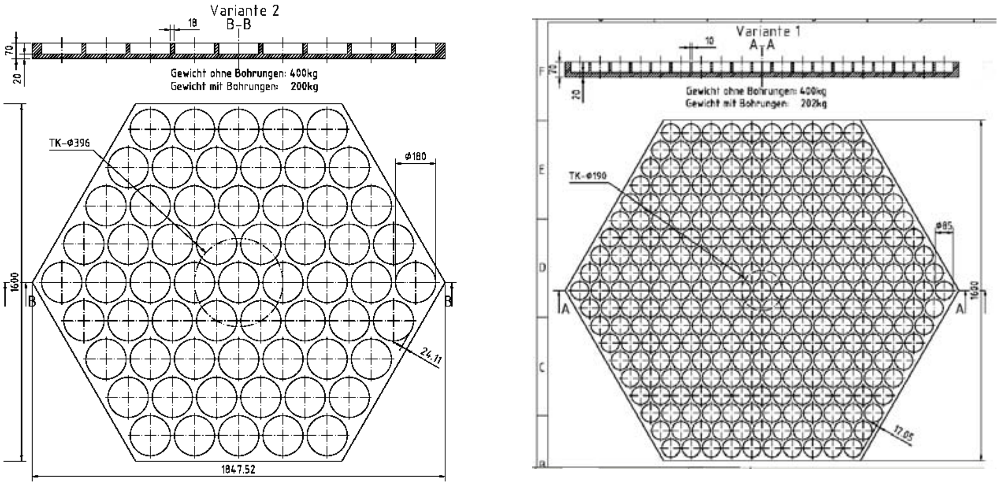


Figure 7: Two examples of economic lightweighting with 50% weight reduction [1].

3. Surface quality and acid etching

In general the grinding is performed by using CNC-machines with tools consisting of a metal carrier material with bonded diamond grains. The grains exhibit a special size distribution. The grain size distributions result from definite sieve fractions. They are standardized in DIN 848 (equivalent to ISO 6106). Grinding surfaces of brittle materials like glass and glass ceramics leads to microcracks. Empirically one found with ZERODUR® that the maximum microcrack or subsurface damage depth is similar to the maximum grain size of the sieve fraction. This is about 64 µm with a D64 tool. Since microcracks are not open their depths cannot be measured with surface roughness inspection devices as commonly used in mechanical workshops. Smaller subsurface damage depths may be achieved by using tools with finer grains. Usually one takes off a layer with a thickness corresponding to the fourfold maximum crack depth of the preceding grinding process.

Each grinding process changes the internal and surface stress distribution. Therefore mechanical stresses can be observed at the ribs and edges of the lightweight structure. Mechanical stress in turn results in stress birefringence, which can be visualized using crossed polarizers [2]. In the left picture of figure 8 the internal stress is visible as a bright area near the edges of the pockets. Since the stress is concentrated around the subsurface damage area at the surface the stress can be relieved either by a time consuming re-annealing step or by acid etching methods.

Figure 8: left: lightweight structure with internal stress visible between crossed polarizers. Right: the same structure as seen between crossed polarizers after acid etching.

For lightweight structures in general it is possible to individually etch the surfaces of the holes. The acid used penetrates the subsurface damage area. About 0.1 mm of material is removed during the etching process. Etching reduces the amount of microcracks and leads to a rounding of the microcrack tips. This reduces the stress concentration at the tips under tensile loads and hinders the crack to grow. Of course this etching process also influences the geometry of the mirror but only to a small extend. Nevertheless it is also possible to use the acid etching process for additional material removal.

4. Acid Lightening of ZERODUR®

As mentioned in chapter 1 the typical final minimum rib thickness using grinding processes is a few mm. A much smaller rib thickness can be achieved with a special subsequent acid etching method. Acid etching is a process without mechanical forces and therefore less critical for the integrity of thin-walled structures. The Gemini M2 mirror has been ground at SCHOTT to a rib thickness of 9 mm and was acid etched to a final weight reduction of 85%. The final rib thickness is about 4 mm. Figure 9 shows a picture of the finished and etched lightweight structure.

Figure 9: The Gemini M2 mirror blank acid etched to a final weight reduction of 85%.

Current developments at SCHOTT regarding the acid lightening were targeted to improve the homogeneity of the removal rate of the acids etching process. For very thin ribs in the range of 1 mm the homogeneous removal of material by acid etching is critical. A ground lightweighted prototype with an initial rib thickness of 8 mm has been etched down homogeneously to a final rib thickness of 0.9 mm. Starting from a structure with an initial rib thickness of 2.5 mm achieved by grinding a final rib thickness of only 0.65 mm and an extremely high lightweigthing ration was achieved (see figure 10) [4].

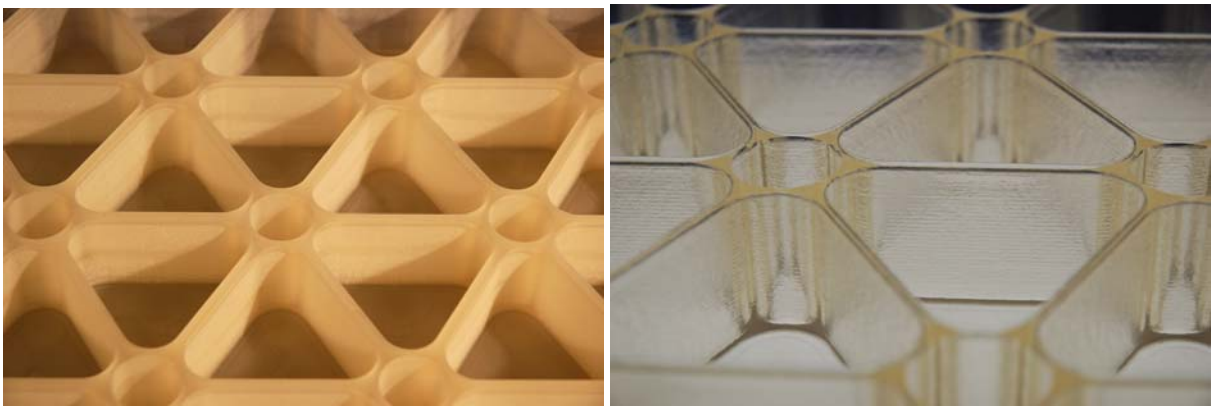


Figure 10: Etching from initial 2.5 mm rib thickness after grinding (left) to 0.65 mm (right) [4]

5. Industrial equipment

Telescopes are not the only applications with a use for lightweight structures in ZERODUR®. Also in industrial equipment lightweighting with complicated structures in ZERODUR® is an issue. Figure 11 shows some examples of ZERODUR® components with complicated structures. All these structures could be fabricated using CNC grinding processes.

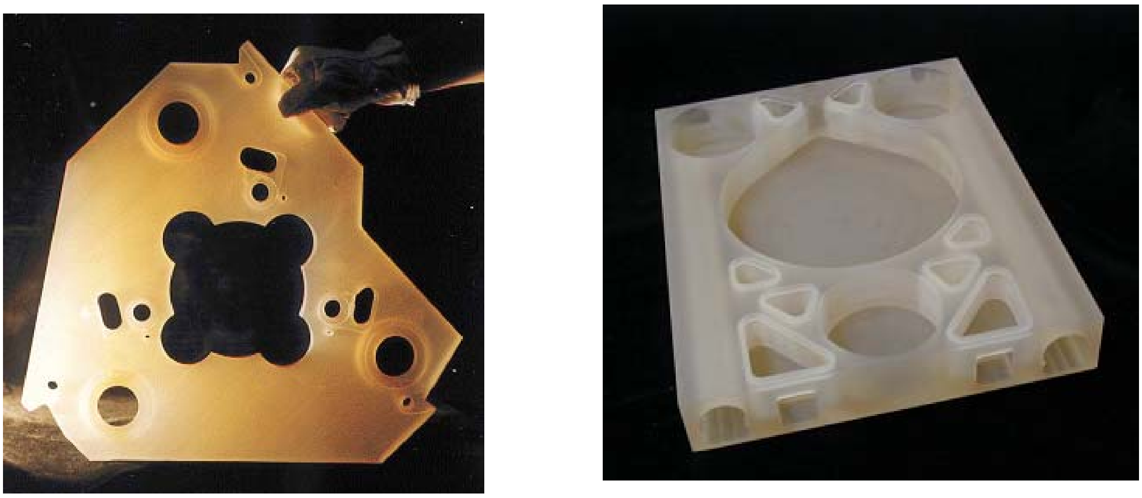


Figure 11: Lightweighting in industrial applications

6. Literature

[1] Thorsten Doehring, Peter Hartmann, Ralf Jedamzik, Armin Thomas; Status of ZERODUR® mirror blank production at SCHOTT; Proc. SPIE Vol. 5869, p. 5-13, Optical Manufacturing and Testing VI; H. Philip Stahl; Ed.; 2005
[2] SCHOTT Technical Information TIE-31: Mechanical and thermal properties of optical glass
[3] SCHOTT Technical Information TIE-37: CTE of ZERODUR®
[4] Thorsten Döhring, Armin Thomas, Ralf Jedamzik, Heiko Kohlmann, Peter Hartmann; Manufacturing of lightweighted ZERODUR® components at SCHOTT; Proc. SPIE Vo. 6666, Optical Materials and Structures Technologies III; William A. Goodman, Joseph L. Robichaud, Ed.; 2007
[5] Winfried Arens, Volker Schmidt; Fertigung leichtgewichtiger Spiegelträger mit geringer thermischer Ausdehnung; Photonik 6/2004

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