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Machining of SuperTest® ZD Machinable Glass-Ceramic

Processing of SUPERTEST ZD®

SUPERTEST ZD® is a zero expansion glass ceramic with extraordinary properties. SUPERTEST ZD® parts are applied in precision mechanics where geometrical dimensions and shapes are required to be extremely stable during temperature changes.

Optical mirrors, scales, gauges, distance holders, traverses, laser gyro bodies are some examples for broadband applications. Melting and machining methods are fully developed to match dimensions of a few millimeters up to several meters.

SUPERTEST ZD® can be machined by grinding processes, lapping and traditional polishing. The following technical information describes the machining methods employed by the manufacturer and gives hints on design rules for SUPERTEST ZD® parts.

1. Description of the material

SUPERTEST ZD® is a inorganic, nonporous glass ceramic [1]. The production process corresponds in the first stages to that of an optical glass. In a subsequent temper process, the so-called ceramization, microcrystallites grow in the glass until they reach a size of typically 0,05 µm and a weight ratio of about 70%.

The crystallites exhibit a negative coefficient of thermal expansion. By means of the precisely controlled ceramization process one achieves that this negative thermal expansion of the microcrystallites and the positive one of the remaining glass compensate each other. Hence the net thermal expansion of the glass ceramic SUPERTEST ZD® ends up to be close to zero.

The material SUPERTEST ZD® is transparent and clear. SUPERTEST ZD® in contrast to crystals is isotropic, there are no preferred directions within the material.
Hot forming of SUPERTEST ZD® is not possible. At temperatures >600℃ SUPERTEST Z D® will change
its material properties irreversibly.

With respect to its bending strength and its machining properties it behaves like a glass. SUPERTEST ZD® parts can be designed according to the guide-lines for the design of glass or ceramic parts. In contrast to pure ceramics, SUPERTEST ZD® has the advantage that the surfaces generated are pore free allowing the production of a smooth optical surface polished to the highest standard.

2. Machining of SUPERTEST ZD®

The machining of SUPERTEST ZD® is done using the same machines and processes as those used for the precision machining of optical glass.

For fabrication of SUPERTEST ZD® parts with simple non circular geometries and low tolerance requirements in the mm range cut-grinding is employed (see chapter 2.1). More complicated shapes with tolerances in the tenth and hundredths of a mm range are generated using CNC

(**C**omputer **N**umerical **C**ontrol) grinding processes (see chapter 2.2 and 2.2.1).

The final surface condition of SUPERTEST ZD® depends on the finishing process. Surface finishing with CNC-machines is made using 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 (see chapter 2.2.2).

Other grinding processes use loose SiC (silicon carbide) grains. Such processes are usually referred to as lapping processes. Also cutting SUPERTEST ZD® can be done in such a way that loose SiC grains are rinsed into the gap of the cut while a steel wire is drawn through it.

2.1 Cut-grinding of SUPERTEST ZD®

Cut-grinding (sawing) is mainly employed for non circular parts with low tolerance requirements. The sawing tool is either a wire immersed in liquid with loose SiC grains or a steel disc of high strength with diamond grinding segments at its periphery.

The wire saw cutting machines allow economical cutting of SUPERTEST ZD® parts up to a dimension of 4 m in diameter with achievable geometrical tolerances from ±10 mm up to ±1 mm depending on the size of the part. The tolerance is influenced by the fact that the wire is not perfectly straight especially at the edges of the part to be cut. The surfaces after this cutting are therefore not flatness optimized and exhibit a mean roughness (Ra) of about <8 µm.

CNC saws are specially suited for mass production and dimensional precision. Figure 1 shows a schematic picture of a large CNC portal cut-grinding machine. The maximum part dimension which could be cut is 3500 x 2000 x 600 mm. The edge of the cut-grinding disc consists of a sintered metallic carrier with diamond grains embedded. With cutting discs smaller than 1200 mm diameter, high cutting speeds and manufacturing of geometrical tolerances of ±1 mm and better are possible. The maximum sized cut-grinding disc is 1700 mm in diameter. The surface quality in terms of flatness and roughness is better compared to the wire saw cutting.

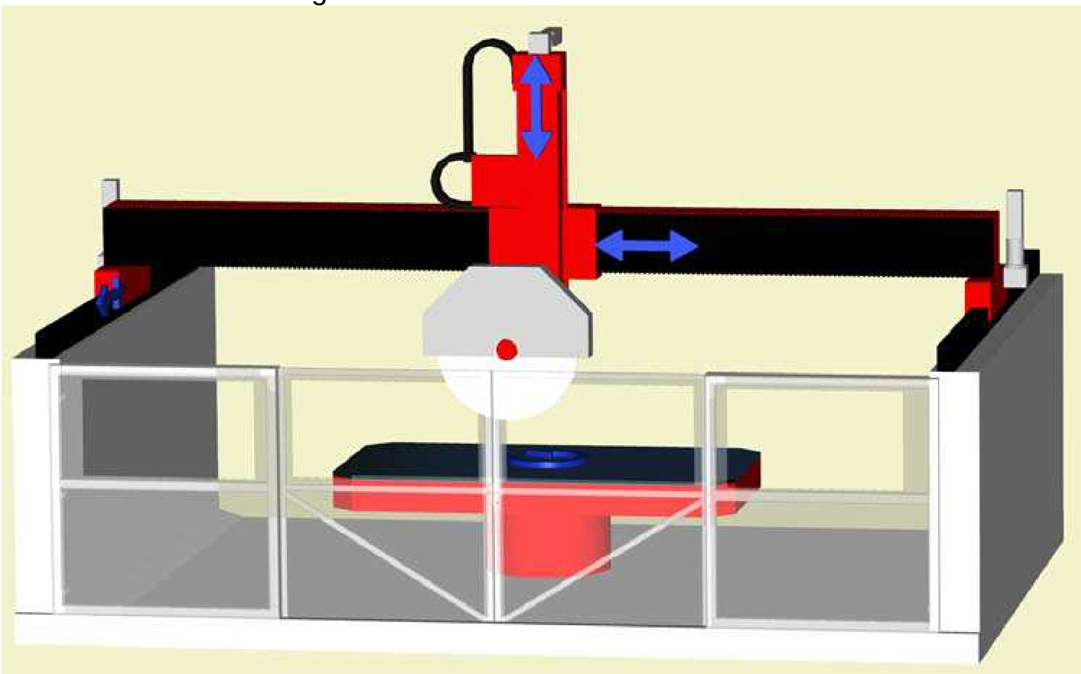


Figure 1: Schematic representation of a large portal cut-grinding machine used by the manufacturer.

2.2 CNC-grinding of SUPERTEST ZD®

At SCHOTT 3- to 5-axis CNC grinding machines of different sizes and design are used for the precision machining of SUPERTEST ZD®. The CNC grinding machines allow the precise fabrication of workpieces up to a maximum diameter of 4 m. The following table 1 shows an overview of the achievable maximum sizes depending on the type of machine at the manufacturer.

Maximum workpiece size	Rectangular shape L x W x H [mm]	Round shape Dia. x H [mm]
5 axis CNC-grinding	2000 x 2000 x 1200	2000 x 1200
3 axis CNC-grinding	4000 x 5000 x 1150	4500 x 1150

Table 1: Achievable maximum sizes using 3 to 5 axis grinding machines at the manufacturer.

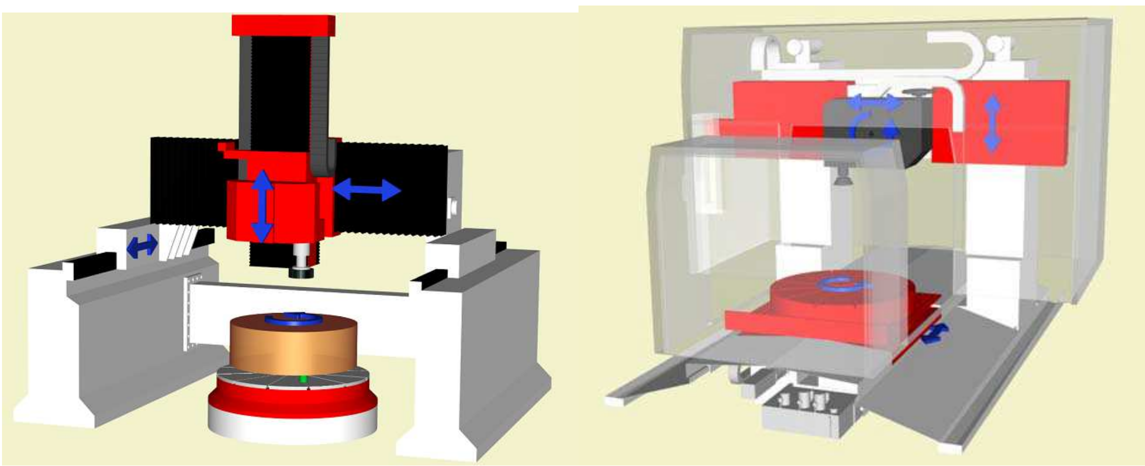


Figure 2: Schematic representation of a 3-axis (left) and 5-axis (right) grinding machine

Figure 2 shows a schematic representation of 3-axis and 5-axis grinding machines employed at the manufacturer. The blue arrows indicate the different degrees of freedom of each machine type. For the fabrication of workpieces up to a diameter of 4 m the open 3-axis portal CNC machining type is used. The 5-axis grinding machine shown in the right picture is used for the mass production of parts up to 2 m in diameter.

Diamond tools are used for the machining of SUPERTEST ZD®. Depending on the process either sintered or galvanic bonded tools are used. Typical tool types used are disc- or cup-wheels, profile grinding wheels, shaft grinders, blind hole drills, core drill. Diamond grain sizes are between D64 and D251 (please refer to chapter 2.2.2). On special request also finer diamond grain is possible. The main focus thereby lies on the economic grinding of large volumes of material with high accuracies as indicated in the following table 2.

The dimensional tolerances of the ISO 2768 (class v, c, m, and f) and the form and position tolerances listed in ISO 2768 (class L, K and H) can be fulfilled. On special request and depending on the geometry even tighter tolerances are possible. Table 2 indicates possible tighter tolerances. They depend on geometry and size of the parts and can not be combined freely. For special products even tighter tolerances have been realized.

	Dimensions < 2000 mm		Dimensions ≤ 4000 mm	
	Standard tolerances [mm] *	Tighter tolerances [mm] **	Standard tolerances [mm] *	Tighter tolerances [mm] **
Length, width, height	± 0.3	± 0.1	± 0.4	± 0.2
Diameter	± 0.3	± 0.1	± 0.4	± 0.2
Angle tolerances	± 5'	± 1'	± 5'	± 1'
Flatness*** ⏥	0.1-0.2	0.05	0.2	0.1
Cylindricity*** ⌭	0.1	0.05	0.2	0.1
Profile*** ⌓	0.2	0.1	0.4	0.2
Parallelism*** //	0.1-0.2	0.05	0.2	0.1
Position*** ⌖	0.1	0.05	0.2	0.1
Concentricity*** ◎	0.1	0.05	0.2	0.1
Run-out*** ↗	0.1	0.05	0.2	0.1

* in general all tolerances defined in ISO 2768 can be fulfilled
** improved tolerances depend on the size and geometry of the part. They can not be combined freely.
*** according ISO 1101

Table 2: CNC grinding tolerances for dimension and shape

For the production of astronomical telescope blanks the profile tolerance of the ground mirror surface is one of the most important properties. The profile tolerance zone describes the width of the tolerance zone centered around the ideal surface profile, and is therefore related to the maximum allowed radial deviation of single measured data-points from the ideal surface profile.

The achievable profile tolerance depends on the outer diameter of the blank and on the radius of the functional surface. By improvement of the processes we have achieved a profile tolerance of 0.05 mm on 1.5 m diameter blanks with a concave surface radius of < 5 m.

The 42 delivered 1.8 m hexagonal blanks of the GRANTECAN Telescope project with a surface radius of ~33 m exhibit a mean profile tolerance over all blanks of < 0.1 mm. Figure 3 shows the achieved distribution of the profile values for the concave and convex surface of the blanks.

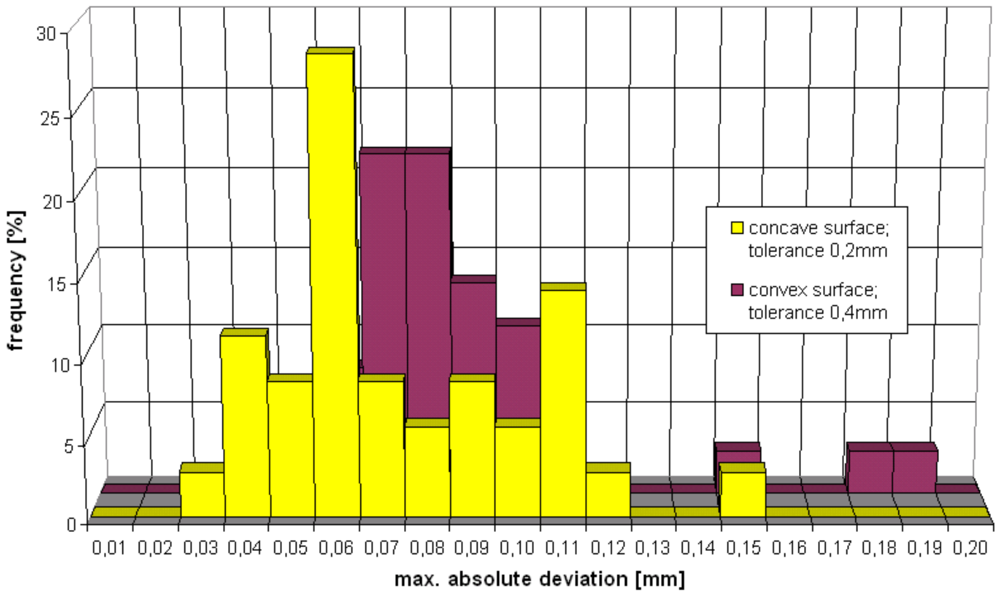


Figure 3: Profile tolerance of radial surfaces as achieved during the GTC project. [1]

2.2.1 Grinding lightweight structures

Lightweight structures in SUPERTEST ZD® 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 SUPERTEST ZD® blank or even more complex structures like undercut holes with nearly freeform geometries. Using only grinding processes a mass reduction of up to 70% is achievable. The final mass reduction strongly depends on the design. Figure 4 shows an example for simple lightweight structures with standard geometry holes.

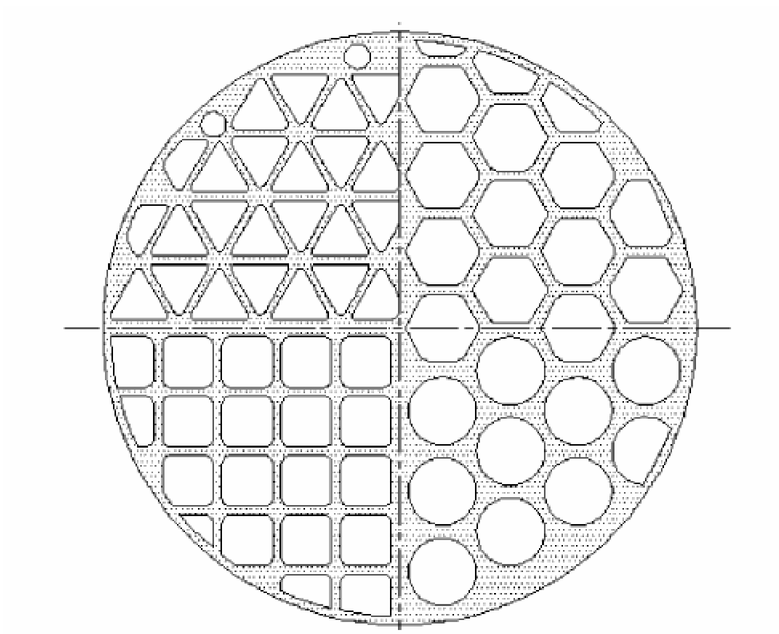
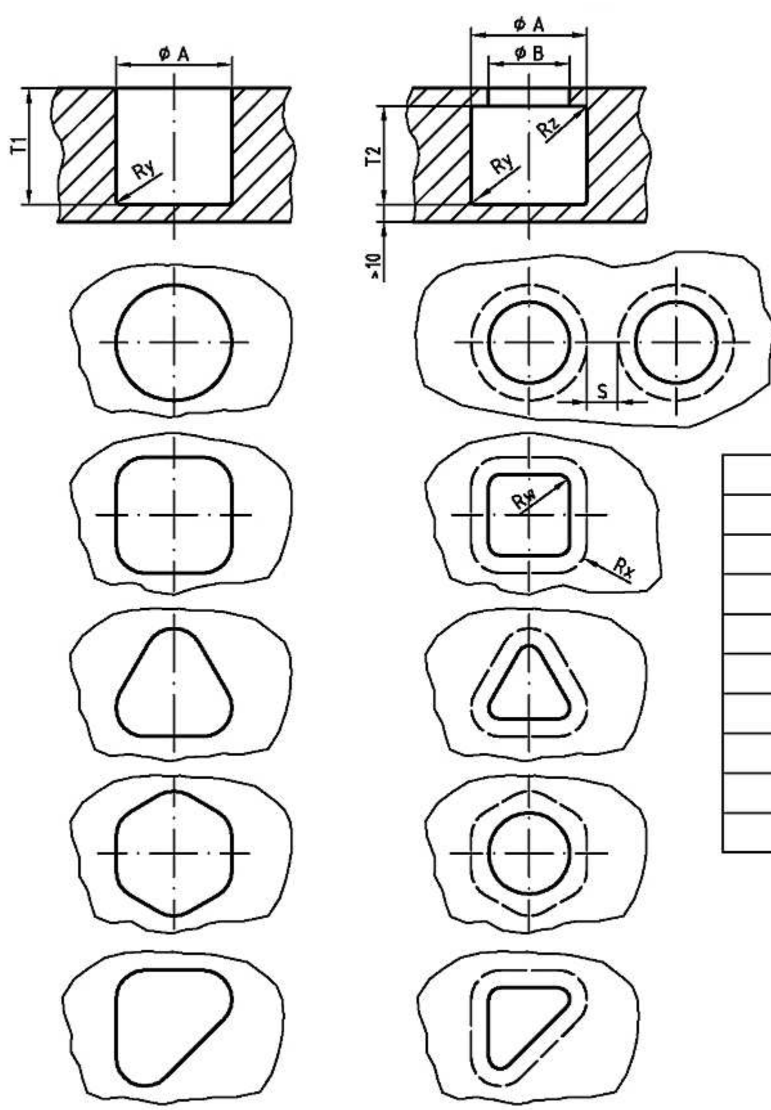


Figure 4: Simple lightweight structures with standard hole geometry

In general the design for the lightweight structure is provided by the customer. Nevertheless The manufacturer has finite element calculation facilities in house and can provide consultation. Figure 5 shows some common lightweight structure elements and the typical achievable dimensional ranges. The drawings on the left show traditional hole geometries. The so called “under cut hole design” shown on the right of figure 5, is generated by using special grinding tools and leads to a higher stability of the blank.

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 tools diameter the corners cannot be sharp edged but only rounded in the ranges given for Rw, Rx, Ry, and Rz in figure 5. The drawing also indicates the typical faceplate thickness of 10 mm. More detailed information on lightweight structures can be found in [2].



	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.

2.2.2 Surface condition of ground glass surfaces

The grinding tools mostly consist of a metal carrier with bonded single diamond grains of a definite size distribution.

The cutting ability of the tool results from the geometrical rear position of the bonding with respect to the abrasive grains at the extreme edge zone. This provides space sufficient to take away the glass waste, and for rinsing with the cooling agent. The sharpness of the tools is characterized by the protruding grain edges and the geometry of the edges. Wear of the bonding and the grains breaking off lead to a sharpening effect of the grinding wheel.

As already mentioned in chapter 2.2 we typically use grinding tools with grain sizes of the range D251 to D64. Table 3 shows an overview of the typical grain sizes associated with the designation according to DIN 848 and FEPA Std. 42-D-1984.

	Designation	Mean size [µm]	Max. size [µm]	ASTM equiv.
Bonded diamond grains acc. DIN 848	D251	231	250	60/70
	D151	138	150	100/120
	D107	98	106	140/170
	D64	58	63	230/270
Loose silicon-carbide grains acc. FEPA Std. 42-D-1984	SiC 100	116	149	--
	SiC 230	53	84	--
	SiC 320	29	49	--
	SiC 600	9	19	--

Table 3: Grain sizes of grinding tools

The achievable surface roughness does not only depend on the mean grain size of the tool but also on the grinding process itself. For rough grinding and cutting typical mean surface roughness values of Ra < 3.5 µm are obtained. For fine grinding based on process and tool a roughness Ra < 1 µm can be realized.

3. Microstructure and general aspects of glass strength

The strength of glass and glass-ceramics is not a material property like the Young's modulus e.g. It is dependent on

- The microstructure of the surface which is tension stressed by the load applied,
- The area of the surface exposed to tensile stress,
- The rate of stress increase and
- The environmental media.

A piece of glass breaks when two conditions coincide. The first is the presence of tensile stress at the surface and the second is the presence of a flaw in the region of the tensile stress.

The milling and grinding of glass introduces microcracks to the surfaces. Empirically one found with SUPERTEST ZD® that the microcrack or subsurface damage depth is similar to the maximum grain size of the sieve fraction. As a rule narrow grain size distributions lead to comparatively narrow strength distributions for ground surfaces. Decreasing grains sizes result in less deep microcracks and in higher characteristic strength values consequently. Nevertheless fracture toughness comparisons between D64 and D151 fabricated surfaces have shown that this holds only for fracture probabilities higher than 10%, due to the fact that the Weibul distribution becomes wider for the smaller grain size leading to an overlap of different grain size fracture distributions at low fracture probabilities [4].

For practical purposes the result means that the higher effort, time and cost related to processing with the finer grain D64 is not necessary from the strength improvement point of view. D151 surfaces will provide similar performance.

In [4] it was also shown that etching of ground surfaces does significantly improve the characteristic strength of the glass by eliminating the microcracks. The characteristic strength becomes nearly independent of the former grain size, whereas the strength probability distribution widens (the Weibull slope is smaller).

Polished surfaces have theoretically the highest strengths, even if the Weibull slope and achievable maximum strength of a polished surface are at least similar to that of the ground and etched surface. However, this is valid only if the microcracks introduced by the preceding machining processes have been eliminated. This is achieved by subsequent grinding with decreasing grain sizes each grinding process taking off a material layer at least three to four times as thick as the maximum microcrack depth of the preceding process.

The old conservative bending strength values for long-term applications of optical glass and SUPERTEST ZD® are 8 MPa and 10 MPa respectively. Newer evaluations have already shown that these values underestimate the real bending/design strength of the material. It was shown for example that a homogeneous isotropic load of 41 MPa (2 MPa/s) on a 1 m^2 SUPERTEST ZD® surface (without any pre-damage), ground with bound diamond grain tool D151, leads to a failure probability of less then 0.001 (0,1%) 95 % confidence level range. This is a stress amount that is 4 times higher than the conservative rule indicates at a moderate surface treatment. More information can be found in [3] and [4].

4. Design of SUPERTEST ZD® parts

As a rule single parts or parts for small series will be cut out of existing blanks and machined subsequently. For large series it is more economic to produce near net-shape preforms to reduce the cutting expense by minimizing the material surplus. We have experience in casting rectangular, triangular, disc and hexagonal shaped parts. The near net-shape approach is only valid for simple geometries and not for complicated lightweight structures.

Simple geometrical shapes like plane faces, circular edge faces or circular bore holes can be fabricated in the most economic way. By applying CNC-grinding machines complex shapes like free form surfaces can be processed as long as they can be described by a mathematical function.

Even if most of the tolerances given in the ISO 2768 can be fulfilled with SUPERTEST ZD®, the construction of SUPERTEST ZD® parts can not directly compared to the construction of a metal part. There are several general hints for the design of SUPERTEST ZD® parts resulting from its strength properties.

The main design target should be to minimize tensile loads concentration areas in the design. Therefore notches and sharp internal edges should be avoided by assigning largest possible transition radii (e.g. ~R2 according ISO 2768 at bottom edges and even larger radii at inner quadratic structures as shown in figure 6).

Edges in general should furnished with small chamfers. Preferably obtuse angles should be assigned to external profiles.

If application forces have to be taken into account in the design they should be area-like. Point like and line-like force distributions should be avoided because they might lead to fracture or chips depending on the height of the load.

For flat parts the minimum distance of bore holes from the edges should be at least half its thickness.

Generally the feed rates are lower than those for the corresponding machining processes of metal parts. Therefore assigning voids for saving material in a SUPERTEST ZD® component does not lead to cost reduction since the material would have to be cut out.

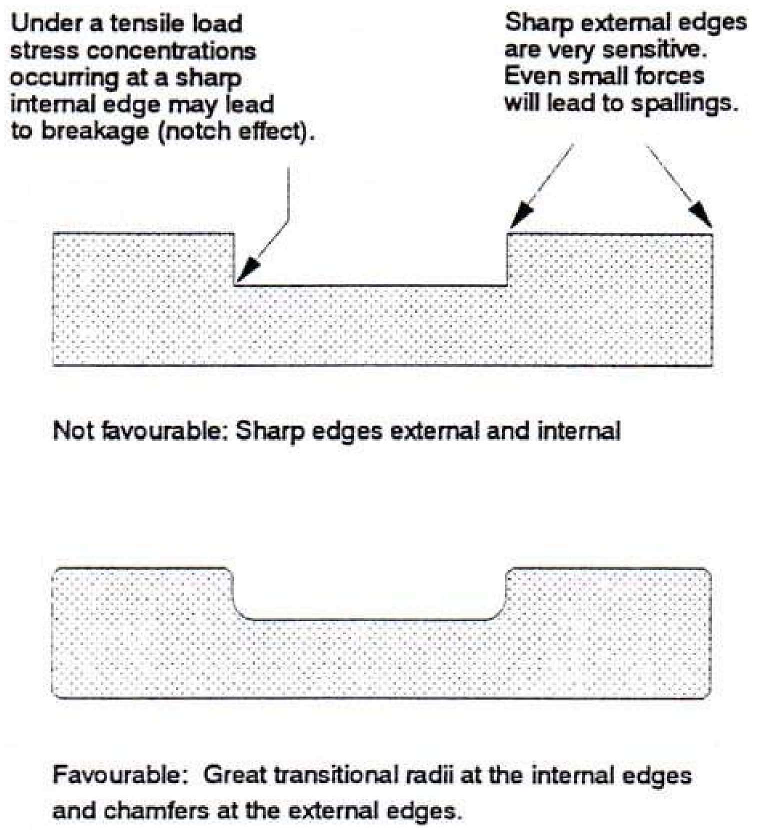


Figure 6: Favorable edge design of SUPERTEST ZD® parts.

5. Bonding of SUPERTEST ZD®

There are either mechanical methods or chemical methods to bond SUPERTEST ZD® to SUPERTEST ZD® parts or to other materials.

If SUPERTEST ZD® should be bonded to a different type of material, it is necessary to take into account the impact of the different thermal expansion coefficients of the participants. Large thermal expansion differences may lead to mechanical stress during temperature changes influencing the integrity of the bond.

Traditional mechanical bonds by generating threads in the material and using screws to bond different parts are not possible with SUPERTEST ZD® in this straight forward manner. Due to the fact that SUPERTEST ZD® is a brittle material, it is not recommended to generate screw threads directly in the material. This is not a matter of processing capability by grinding technology, but it’s a matter of strength of the thread under a given torque, that is usually not high enough for commercial bonds.

In general SUPERTEST ZD® parts are mechanically connected to SUPERTEST ZD® parts or other materials by clamping using grommets and screws with nuts. Or by using threads glued into holes ground in the SUPERTEST ZD® part. This is done mainly at our customers workshop. The main risk using this technology is the different thermal expansion coefficient between the metal nut and the SUPERTEST ZD®. In the best case the nut should be made from a material that has a low thermal expansion coefficient.

Mechanical SUPERTEST ZD® to SUPERTEST ZD® bonds can be achieved by using special epoxy glues. Also in this case the thermal properties and the elastic behavior of the bond plays needs to be taken into account properly. The durability of the bond depends strongly on the mechanical forces (static, dynamic, load conditions) and surrounding conditions (atmosphere, pressure, temperature changes) during the application.

6. Measurement equipment

An efficient mass production of large SUPERTEST ZD® components needs automatic measurement methods. Therefore the manufacturer uses two coordinate measurement machines (CMMs) for a high accuracy verification of the specified geometry. Our largest CMM (Carl Zeiss, type PRISMO 10 HTG) has a measurement volume of 2400 x 1600 x 1000 mm and is able to measure with an accuracy in the range of ~3 µm within this volume (with an additional size depending factor). Figure 7 on the right shows a picture of the coordinate measurement machine. Another machine is used with a smaller measurement volume but with an accuracy down to 1 µm depending on the volume.

For the metrology of large SUPERTEST ZD® parts like mirror segments with a dimension > 1.6 m (e.g. the GRANTCAN project or 4 m mirror blanks) a laser tracker system (Leica LT 500) with an accuracy of ±10 µm/m distance can be used. The calibration of the Laser Tracker System is done by an internal calibration routine and reference standards made of SUPERTEST ZD®. Figure 7 left shows the measurement setup using the laser tracker system for the geometry measurement of the GTC mirror blanks.

Figure 7: Measurement of mirror blank segments with a laser tracker system (left), large CMM at manufacturer (right).

7. Literature

[1] Technical Information TIE-37: Thermal expansion of SUPERTEST ZD®
[2] Technical Information TIE-38: Lightweighting of SUPERTEST ZD®
[3] Peter Hartmann, Kurt Nattermann, et. all; Strength aspects for the design of SUPERTEST ZD® glass ceramic structures; Proc. SPIE Vol 6666 Optical Materials and Structures Technologies III; William A. Goodman, Joseph L. Robichaud, Ed.; 2007
[4] Peter Hartmann, Kurt Nattermann, et. All; SUPERTEST ZD® glass ceramics- strength data for the design of structures with high mechanical stresses; Proc. SPIE Advanced Optical and Mechanical Technologies in Telescope and Instrumentation; 2008