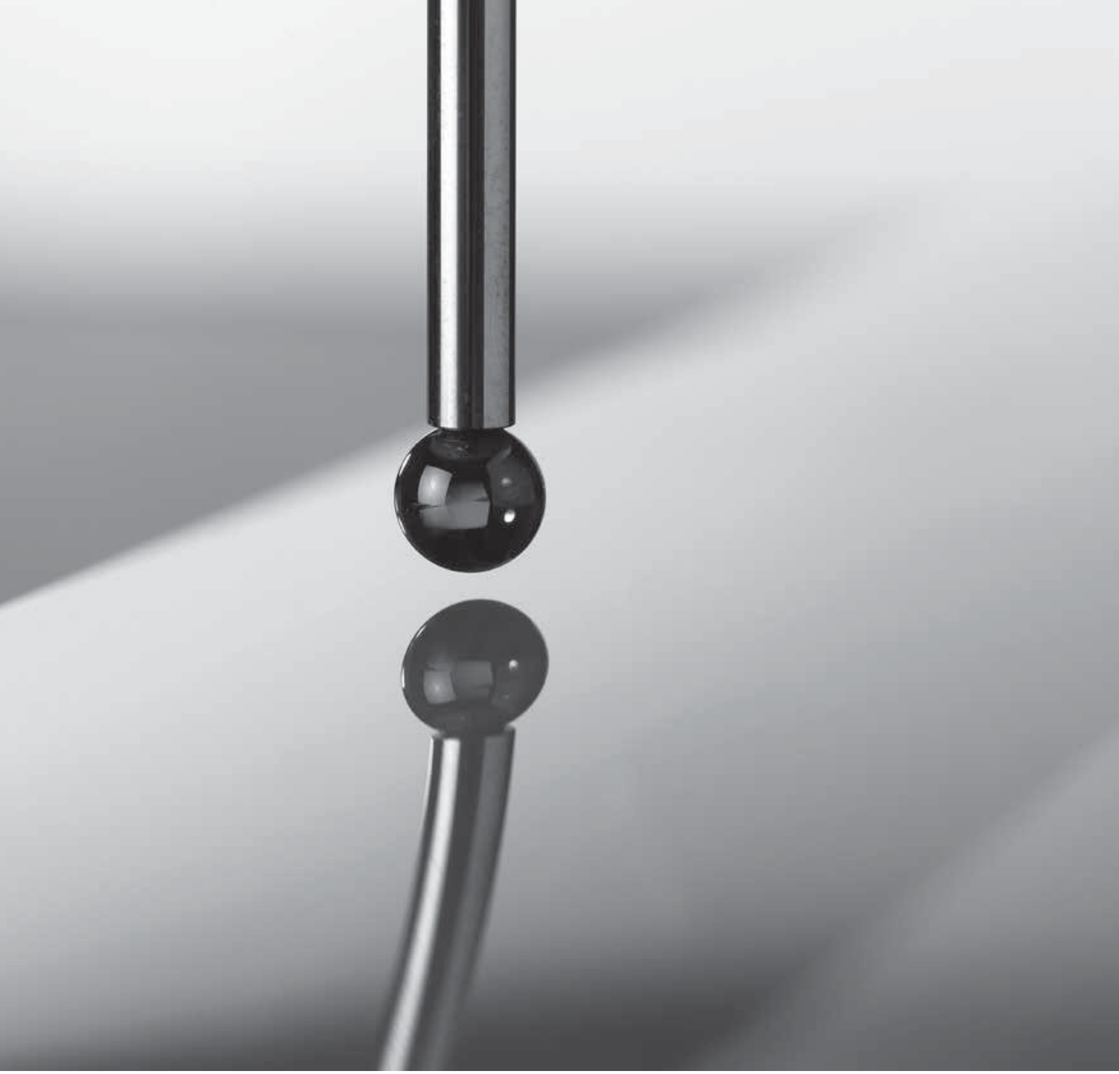


Mirrors for Synchrotron Radiation

Technical Information


// PRECISION
MADE BY ZEISS

Making your research even more brilliant.

Synchrotron X-ray mirrors

Introduction

Artist view of a 3rd generation synchrotron. The figure is courtesy of Synchrotron Soleil.

Today, synchrotron radiation is an established powerful tool for many kinds of research in basic sciences and industry. The increasing interest in this type of light source is demonstrated by a soaring number of large synchrotron radiation laboratories worldwide. New generations of synchrotron sources with enhanced performance, such as Free Electron Lasers (FEL), open new possibilities for fundamental and applied research.

Sources with higher brilliance and superior beam performance put increasingly stringent demands on beamline optics. Extremely high heat load density requires sophisticated cooling and reflection geometries. Recently Si became the material of choice for front end optics for its high heat conductivity, low degradation and accessible quality. Zerodur® and fused silica are still frequently used for downstream optical elements where beam exposure is not an issue. Typical requirements are slope errors significantly below 1" for aspheric elements and below 0.1" for flats or spheres. Roughness down to the Angstrom level helps to keep every photon in your experiment. Coherency considerations demand even harder specifications for the height errors in the order of 1 nm rms over optics as long as 1 m or even longer.

Today, our decades of experience make us one of the leading optics manufacturers in the world. Dedication to mirror fabrication and in particular to synchrotron optics are the focus of our commitment. Continuous advances in fabrication processes, metrology and coating offer our customers state of the art products for superior synchrotron beamline performance. You will later find more details about mirror fabrication at Carl Zeiss SMT GmbH.

Reflecting X-ray Optics
Geometrical Considerations

Reflective mirrors are most commonly used in synchrotron radiation optics. Due to the typically extremely small grazing angles required for X-ray wavelengths, the length-to-width ratio is usually between 4:1 and 20:1 and is therefore very different from the geometry of conventional optics. In addition, the tangential and sagittal radii differ by a factor of 10^2 to 10^5.

In most cases the task of the optics is to focus light from one point to another, or to focus a parallel or divergent beam to a well defined point. This can generally be achieved by using conic sections, e.g.

- ellipsoidal or
- paraboloidal

mirror surfaces, respectively. Depending on the desired imaging quality, substitution of the conic sections by more fundamental geometries such as

- spherical
- cylindrical, toroidal
- toroidal with meridional elliptical curvature

may be desirable.

These fundamental geometries approximate to a certain extent ellipsoidal or parabolic mirrors. In the case of cylindrical (and also flat) mirrors active supporting systems are often used for in-situ changing of radius of curvature, thus optimizing the focusing conditions within different experimental situations. Table 2.1 gives typical surface geometries supplied by ZEISS for various optical applications. As a rule of thumb, fabrication efforts increase from top to down with complexity.

Reflecting X-ray Optics
Geometrical Considerations

Class	Geometry		Variations
Base geometries		Flat	
		Sphere	
		Cylinder	
		Toroid	
ConicSections		Paraboloid	Plane parabola Parabolic cylinder
		Ellipsoid	Plane ellipse Elliptical cylinder
		Hyperboloid	
combined		e.g. Wolter	
freeform		freeform	

Table 2.1: Range of typical surface geometries manufacturable at Carl Zeiss SMT GmbH.

Optical Surface Errors

To characterize the quality of an optical component, the following categories of specifications are generally used:

- Tolerance of geometry parameters according to the experimental requirements and in particular to the possibility of adjusting these parameters in compliance with the assembly.

- Surface figure error: This term describes the maximum (pv: peak-to-valley) or average (rms: root mean square) deviation of the actual form from the ideal surface. Since the quality of the focus with grazing incidence optics is primarily determined by the slope distribution on the surface, it is more common to use the rms slope error as a specification for global form accuracy.

- The focus spot size containing 68% of intensity can be directly calculated from this specification.

- Microroughness: The scattering properties of the optical surface result mostly from its microroughness. The key value characterizing the microroughness is the rms value. The total scattering S is approximately correlated to the roughness by the relation.

$S = 1 - \exp(-4\pi/\lambda \sin\theta\, \sigma)^2$, where:

λ… wavelength of light

θ… angle of incidence

σ… rms roughness

Mirror Substrate Material

The material selection for synchrotron mirrors is mainly determined by the following criteria:

- good optical machinability
- long-term stability
- resistance to high heat load
- UHV compatibility

For components which are only used in low intensity systems, fused silica or Zerodur is generally chosen. Zerodur is a material with near-zero CTE (coefficient of thermal expansion) at room temperature. Both materials have good machinability concerning grinding, lapping and polishing, the essential optical manufacturing methods.

If high heat load has to be applied to the mirrors, the bulk material needs to have better heat conductivity than the materials mentioned before. In this case, metal mirrors are used if the heat load is not too high. The materials used in these applications are mostly aluminum or copper (GlidCop) with a thin (i.e. 100 µm) electroless Ni-coating. These metal mirrors are more difficult to handle during polishing, and according to stress phenomena the resulting accuracies are lower in general. Well-suited for very high heat loads are mirrors made from monocrystalline silicon. This material can even withstand undulator beam power densities. For applications with extremely high heat loads the components can be actively cooled either internally or by external elements (e.g. side cooling). Table 4.1 shows a selection of commonly used substrate materials for synchrotron mirrors. All listed materials are regulary manufactured at Carl Zeiss SMT GmbH. Contact us to discover our full capability.

Material	Pros	Cons	Application area
Fused Silica Zerodur ULE	Low CTE Good machinability Economically priced substrate material		For components which are only used in low intensity systems
Silicon	High power resistant Low degradation under high exposure	Needs more extensive machining	High heat load application
GlidCop or Cu with NiP layer	High thermal acceptance Sophisticated cooling designs realizable		Special cooling applications
Al with NiP layer	Popular replication substrate	Deformation under heat load	Easy and economical machinability
SiC with polishing layer	Low CTE	Laborious substrate manufacturing	Superior material stability

Table 4.1: Range of typical substrate materials manufacturable at Carl Zeiss SMT GmbH. Other substrate materials on special request.

Manufacturing Techniques

As a consequence of the unique properties of synchrotron beams, the geometry of most synchrotron radiation optics is very different from conventional optical components. Low vertical beam divergence leads to rectangular geometries with large length-to-width ratios. This in turn establishes the need for specially designed manufacturing techniques. The objective of these techniques is the

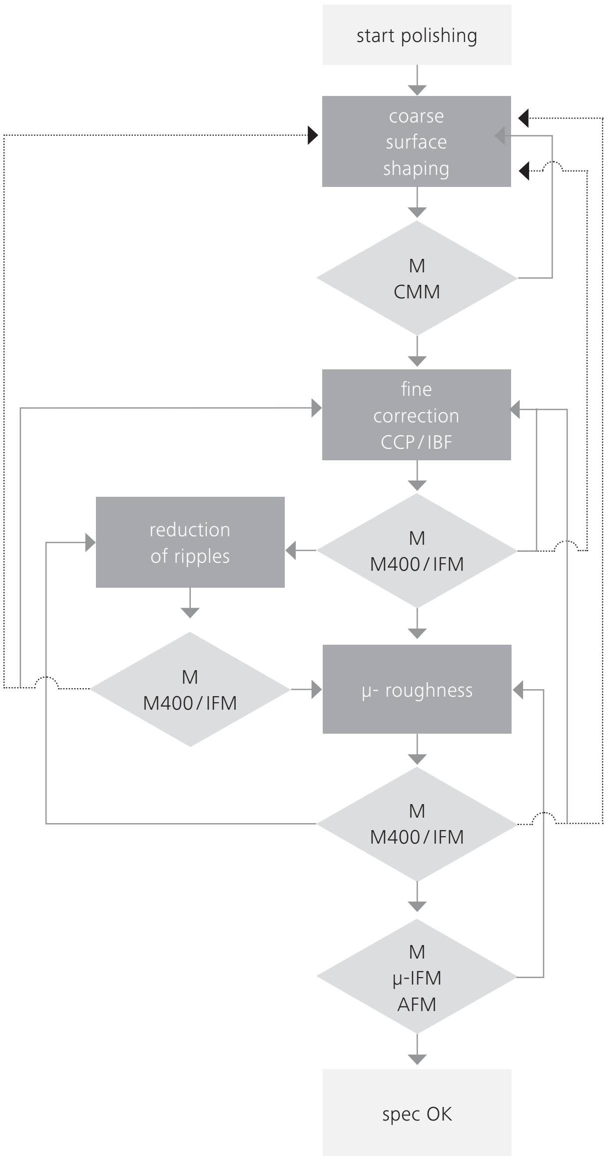
- shaping of the substrate and adjustment of the optical surface or optical axes relative to the substrate
- generation of the optical surface shape with the desired accuracy
- achievement of the desired microroughness and
- handling of the requested substrate material.

The direct manufacturing process generally includes the following steps:

- grinding approaches for premanufacturing of substrates and optical surface geometry
- etching for reducing stress and subsurface damage
- lapping for performing good thermal contact at the side faces and for optimizing the optical surface for subsequent steps
- polishing for the complete removal of subsurface damage and
- figuring for the correction of residual surface errors and finally
- smoothing for achieving the required microroughness.

Usually the entire process consists of loops of the individual manufacturing steps with intermediate metrology stages. The loops are continued until the surface attains the desired specification level. For figuring, metrology is usually integrated into a feedback loop. Thus, very close interaction between metrology and figuring is necessary.

Depending on the type of mirror geometry and on the required accuracy, the figuring of residual errors has to be performed by suitable tools. A summary of fabrication tools is available from ZEISS. Find out about the wide selection of tools for the manufacturing of the optical component for your special needs.



Graph 5.1: Typical process flow of optical components from the start of polishing to achievement of specifications. Note the close interaction of figuring and metrology.

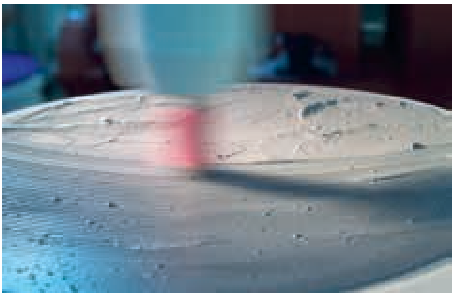
IBF – Ion Beam Figuring (see chapter 6)
CCP – computer controlled fine correction (6)
CMM – 3D Profilometry (7)
IFM – Interferometry (7)
M400 – 3D Profilometry (7)
µ-IFM – Microinterferometry (7)
AFM – AFM analysis (7)

Polishing and Figuring

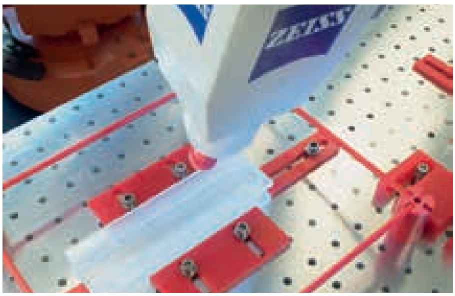
Subsequently the processes mentioned in chapter 5 will be illustrated in more detail. Process steps consist of conventional polishing, computer controlled fine-correction, ion beam figuring and diamond turning.

Conventional polishing
with large tools, adapting the geometry of the substrate. This technique is applicable on plane and spherical surfaces down to < 0.1 arcsec (rms), and for cylindrical and toroidal surfaces down to about 0.2 – 0.5 arcsec (rms). For other surface shapes like paraboloids, ellipsoids etc. the residual figure deviation can only be reduced to a value comparable to the asphericity. For higher form accuracy, ZEISS has developed special metrology and correction processes.

Computer controlled fine-correction processes
(CCP: Computer Controlled Polishing) Using these processes, form accuracies down to the order of 0.2 – 0.5 arcsec (rms) can be achieved, even on strongly deformed aspheres. The residual errors are detected by the high-resolution, M400 coordinate measuring machine or by interferometry (Interferometers: ZEISS D100 and ZYGO GPI). This surface data is used to generate control data for the polishing process. Subsequently this process can remove localized form deviations on the surface according to the accuracy of the metrology. The final achieved figure error heavily depends on the curvature and variation of curvature.

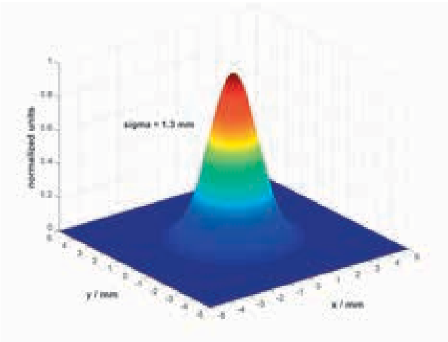


Computer controlled lapping (CCL) is the highly ablative process step for coarse figuring.



Computer controlled fine correction is the final process step for figure and roughness.

Gaussian IBF work function



Gaussian type removal function typical of CCP or IBF.

Ion Beam Figuring (IBF)
is an established powerful tool for high-end figuring of optical surfaces. Developments at ZEISS lead to accuracies below 0.02 arcsec (rms) or 0.1 µrad (rms) for other geometries. The achieved results are ultimately limited by the accuracy of the measurement technique.

Diamond turning
If metal mirrors have to be machined, the surface generation can also be performed by CNC diamond turning machines developed at ZEISS or also by diamond flycutting method.

Metrology, Testing and Analysis

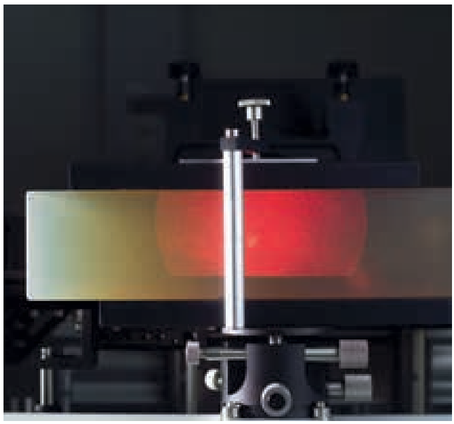
ZEISS offers metrology devices to cover the entire spatial error range from several nm to above 1 m: Full aperture interferometry is best suited for plane and spherical surfaces with dimensions below 12”. Thus, stitching interferometry and 3D profilometry are used when it comes to large or complex surfaces with high aspherical departure. For this purpose, ZEISS offers the 3D ultrahigh-resolution, M400 coordinate measuring machine. This device is able to measure surfaces up to 550 mm with a resolution < 10 nm where aspheric departure from base geometries is almost unlimited (see example 1).

Interferometric metrology devices are not strictly limited to plane or spherical surfaces. Cylindrical or weak freeform aspheres can be well measured by interferometric setups. Measurements with a plane stitching interferometer in the sub-nm level have been successfully demonstrated (example 2). Metrology is completed by µ-interferometers and AFMs, covering the entire PSD from the nm to the m range.

See the devices listed below for an overview of metrology at ZEISS dedicated to the synchrotron mirror fabrication:

Interferometry
This technique is best suited for plane and spherical surfaces. Aspherical surfaces can be tested if a component-specific null lens is used. This lens compensates for the wavefront aberrations resulting from the aspheric deformation. The measuring accuracy for the ZEISS D100 direct measuring interferometer is in the order < l/100 (l = 633 nm) with resolution < 1 nm.

Several settings for magnification and aperture allow optimum lateral resolution. Devices up to 24” aperture are available. For larger mirrors, grazing modes allow measuring of the clear aperture without significant loss of precision.



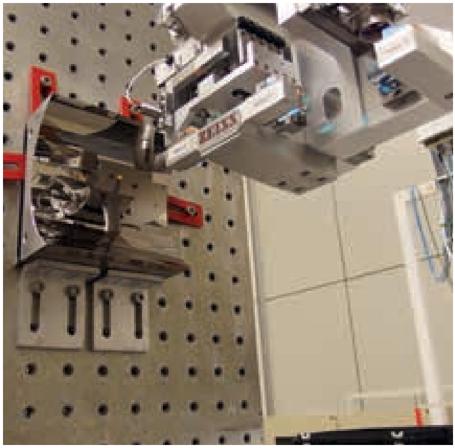
A wide selection of devices and dedicated mountings for the interferometry access of a wide selection of geometries.

3D Profilometry (CMM)

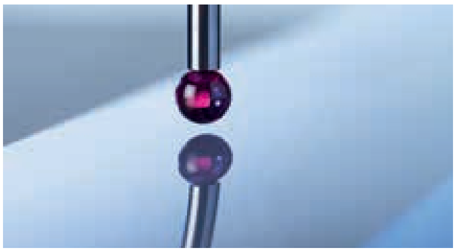
The figure errors of complex surfaces can be completely evaluated by means of the M400 3D ultrahigh-resolution coordinate measuring machine, developed at ZEISS. This device is able to measure surfaces up to 550 x 380 mm^2 with a resolution < 10 nm. Stitching approaches also allow qualification of larger mirrors. Surfaces with an angular spectrum of about ± 40° for both axes can be measured within one fixed set-up.

The measurement data from either M400 or D100 can then be directly used as input for a computer controlled fine-polishing process or for ion beam figuring methods described above.

In addition, for workpieces up to 1.2 m commercial coordinate measuring machines from the ZEISS Industrial Metrology business group are in operation (UPMC 850 Carat). The vertical resolution of these devices is generally 200 nm. Within the framework of the manufacturing process these measuring machines also allow highly accurate absolute adjusting or centering of optical surfaces in relation to the substrate with absolute accuracies below 1 micron. For mirrors larger than 1200 mm stitching methods are used for the qualification and iterative processes.

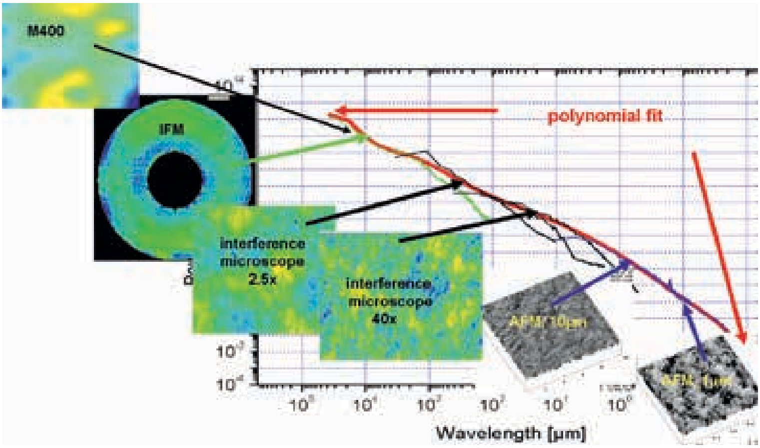


Metrology volume of the high precision M400 coordinate measurement machine.



3D profilometry reveals the full picture: The figure of the optical surface with respect to the entire substrate geometry.

Metrology, Testing and Analysis



PSD analysis with different measurement techniques: Interferometer, microinterferometer with different magnifications and atomic force microscopy with different scan sizes.

Microinterferometry
Qualification of mid spatial frequency roughness (MSFR) or mid spatial frequency figure errors (MSFF) is performed by microinterferometry.

For these microroughness errors a non-contact optical device (e.g. ZYGO, NewView 700) is used. Height resolution of the commercial device is below 0.1 nm. Objectives with magnifications of 2.5x, 10x and 50x magnification are in use. This corresponds to spatial sampling wavelengths between 0.6 µm and 5.8 mm

AFM analysis
Determination of high spatial frequency roughness (HSFR) is accessible by means of atomic force microscopy (AFM). HSFR is an essential surface characteristic for normal incidence X-ray optics and, depending on energy, also for grazing incidence optics. In particular, low HSFR requirements come into play when the optical surface is coated with multilayers. At Carl Zeiss SMT GmbH a Nanosurf AFM with special designed holder is in operation. This system performs spatial sampling between a few nanometers and nine microns. Depth resolution is below 0.1 nm.

Mirror in AFM action.

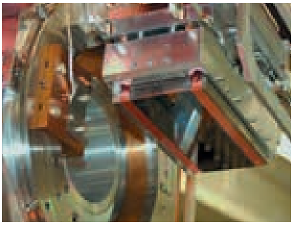
Mid-spatial frequency roughness (MSFR) detected with microinterferometry (ZYGO NewView 700).

Analyzing and qualification

Together, these measurement techniques give a complete description of an optical surface. Starting at surface wavelengths in the order of a few nanometers, all types of surface errors can be determined up to the full size of the optical element.

As a very powerful mathematical tool, PSD analysis (Power Spectral Density) is used at ZEISS for qualifying the complete surface over all spatial sampling frequencies. Fourier decompositions of all measurements from the different types of metrology are performed and the corresponding power spectra are overlapped in a double logarithmic interpretation. The sloping properties of such spectra give information about the surface behavior. Arbitrary wavelength intervals can be cut out of the spectra and according to Parseval's theorem the corresponding rms figure or roughness value can be integrated. By analogy, the rms slope error can be calculated for specific frequency ranges by means of a slope-PSD. Only by these means is it possible to remove figure deviations during the manufacturing process and at the same time optimize all kinds of surface roughness and finally provide a complete description of the finished component to the customer.

Coating



The picture is courtesy of GKSS, Incoatec and Prof. Stampanoni / SLS and shows a 2 stripe coated mirror with a Ru / C and W / Si multilayer coating mounted in the monochromator of the TOMCAT beamline at the SLS.

The design of an optical coating has to be adapted to the intended field of application of each customer and is thus an integral part of the complete mirror fabrication. Essentially, the coating is determined by the photon energy and the grazing angle or angular spectrum. Synergies of the different ZEISS coating laboratories and the experience of ZEISS scientists provide a broad spectrum of customer designed coatings. In addition, special coatings can be realized by our external partners. Table 8.1 shows the most commonly used coating materials. In some cases (e.g. Ru) a thin binding layer (e.g. 5nm Cr) is necessary for reducing stress and also for maintaining the microroughness performance.

Standard Materials

Metallic coating	Au	Pt	Rh	Ni	Mo
	Pd	Al	$AlMgF_2$	Ru	
Others	C	Si	SiO_2		
Binding layers	Cr	Hf			

Table 8.1: Commonly used coating materials.
All other coating materials on special request.

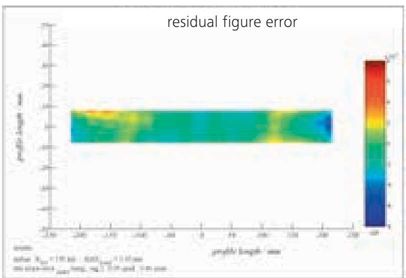
Examples

Example 1: Tangential cylinder

- low residual slope errors
- low figure roughness (height error)
- tight radius specification
- full roughness specification (MSRF + HSFR)

Features	Specification / Manufacture
Material	Si <100 >
Dimensions	450 x 30 x 50 mm^3
Clear aperture	385 x 5 mm^2 zone 1 430 x 15 mm^2 zone 2

Properties	Specification	Results
Geometry	cylinder radius: 150 km < R < 195 km	R = 170 km
Slope error	tangential: zone 1: 0.25 µrad rms zone 2: 0.63 µrad rms sagittal: zone 1+2: 2.0 µrad rms	0.09 µrad rms 0.09 µrad rms 0.41 – 0.46 µrad rms
Height error	zone 1: < 2.0 nm rms zone 2: < 5.0 nm rms	0.98 nm rms 1.35 nm rms
Surface roughness	MSFR: 5.2 – 1000 µm ≤ 0.25 nm rms HSFR: 0.02 – 2 µm ≤ 0.4 nm rms	0.12 – 0.13 nm rms 0.12 – 0.32 nm rms



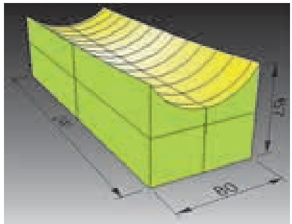
Results

- Excellent tangential slope errors below 0.1 µrad for zones 1 and 2
- Height error below 1 nm rms for zone 1
- Roughness results superior to specifications

Examples

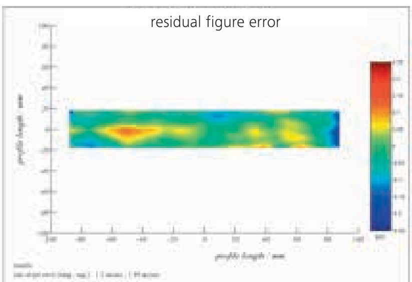
Example 2: Paraboloid

- strongly aspherical shape (local curvature)
- sagittal pitch > 3 mm on only 40 mm base variation.
- very small sagittal radius (50-60 mm)
- sagittal radius variation > 25 % within clear aperture length of 190 mm.
- low sagittal slope error (1.89 ")



Features	Specification / Manufacture
Material	ZERODUR®
Dimensions	> 190 x 30 x 50 mm^3
Clear aperture	> 150 x 20 mm^2
Coating	50 nm standard coating

Properties	Specification	Results
Parabola parameters	Vertex: R ~ 4.0 ± 0.05 mm off-axis: Xm ~ 400 ± 1 mm	as specified
Slope error	meridional: 5.0 arcsec (rms) sagittal: 1.5 arcsec (rms)	1.20 arcsec (rms) 1.89 arcsec (rms)
Surface roughness	≤ 0.5 nm rms	0.41 – 0.51 nm rms



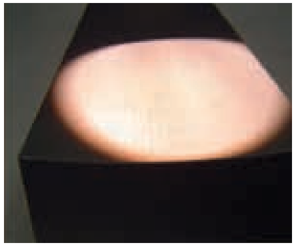
Results

- Geometry has been successfully fabricated
- Meridional slope error and roughness fully comply with specification
- Very challenging sagittal slope error of 1.5 arcsec has been missed by 25%

Example 3: Calibration spheres

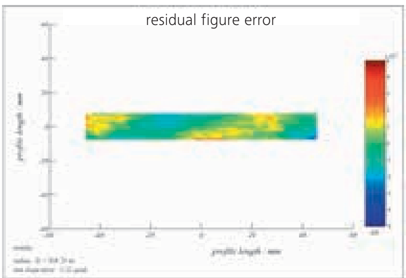
Set of 4 spheres with

- tight radius specifications (370 m ± 2%)
  - corresponds to 95 nm pitch over substrate length of 120 mm.
- challenging slope errors (< 0.5 µrad)
- high identicalness for radii ± 0.5 m
  - corresponds to only ± 6.5 nm pitch variation over substrate length of 120 mm



Features	Specification / Manufacture
Material	ULE (premium grade)
Dimensions	100 x 20 x 20 mm^3
Clear aperture	90 x 15 mm^2
Coating	-

Properties	Specification	Results
Geometry	spherical radius: R = 370 m ± 2 % all substrates are to have the same radius: ±0.5 m	R_{mean} = 368.21 m R_1 = 368.68 m R_2 = 368.20 m R_3 = 368.21 m R_4 = 367.74 m
Slope error (rms)	tang. slope error: < 0.5 µrad (rms)	G_1: 0.26 µrad (rms) G_2: 0.22 µrad (rms) G_3: 0.25 µrad (rms) G_4: 0.42 µrad (rms)
Surface roughness (rms)	MSFR: ≤ 1.0 nm, 10 µm < λ ≤ mm	0.27 – 0.33 nm, 20x 0.18 – 0.21 nm, 2.5x



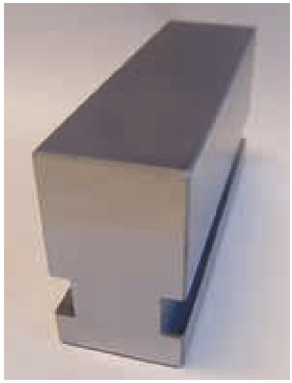
Results

- Radius precision within 0.94 m. This corresponds to a pitch identicalness of 10 nm.
- All slope errors comply with specifications. Average slope 0.29 µrad almost twice in specification.
- Roughness results about 0.25 nm on average

Examples

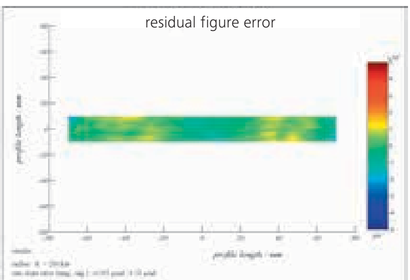
Example 4: Grating Blanks

- extremely low residual slope errors
- low roughness specification (MSFR)



Features	Specification / Manufacture
Material	Si <100>
Dimensions	120 x 30 x 23 mm^3
Clear aperture	110 x 15 mm^2
Coating	-

Properties	Specification	Results
Geometry	Plane with: Tangential radius > 30 km Sagittal radius > 3 km	Tangential radius >200 km Sagittal radius > 200 km
Slope error	Tangential: < 0.1 µrad (rms) Sagittal: < 0.4 µrad (rms)	Tangential: 0.095 µrad (rms) Sagittal: 0.13 µrad (rms)
Surface roughness	MSFR: < 0.2 nm (rms)	MSFR: 0.13 nm (rms)



Results

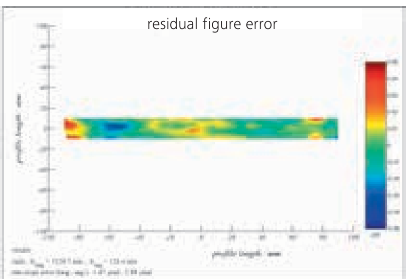
- No high frequency errors left within the clear aperture
- Below 1 nm PV height error

Example 5: Toroidal Mirror

- Low slope errors
- Tight radius specification
- Very high gradients due to small radii

Features	Specification / Manufacture
Material	Fused Silica HOQ310
Dimensions	200 x 30 x 30 mm^3
Clear aperture	180 x 25 mm^2
Coating	30 nm Au

Properties	Specification	Results
Geometry	Toroidal Parameters: Tang. radius = 5119 ± 25 mm Sag. radius = 125 ± 0.625 mm	Tang. radius = 5128.7 mm Sag. radius = 124.4 mm
Slope error	Tang.: < 1.5 µrad (rms) Sag.: < 3.0 µrad (rms)	Tang.: 1.47 µrad (rms) Sag.: 2.88 µrad (rms)
Surface roughness	MSFR: < 0.5 nm (rms) (50x) HSFR: < 0.5 nm (rms) (1µm AFM)	MSFR: < 0.34 nm (rms) HSFR: < 0.1 nm (rms)



Results

- Geometry successfully manufactured
- Tight radius specification has been met

Examples

Carl Zeiss SMT GmbH is a reliable partner for the manufacturing of synchrotron mirrors. We have implemented powerful metrology and manufacturing techniques for the upcoming generation of highest-quality optical components for synchrotron radiation and other X-ray applications. Form accuracies below 0.3 arcsec (1.4 µrad) (rms) have been achieved on highly deformed aspherical components, and surface qualities below 0.02 arcsec (0.1 µrad) (rms) are provided for flat mirrors. Mirrors up to 1200 mm in length can be produced in a wide variety of materials ranging from the glass ceramic Zerodur, to monocrystalline silicon.

Any exploration of the limitations for optical tolerances always needs the full picture of all optical parameters and tolerances. Consideration of material choice, dimensions and mechanical requirements leads to a serious discussion about achievable quality.

We stay tuned for future requirements: The advent of a new plane stitching interferometer enabled the fabrication and metrology of surfaces with figure errors below 1 nm rms and 0.01 arcsec (rms) slopes respectively.

In special cases customer requirements may be targeted through collaborations in order to overcome technical barriers. We are always open for your ideas and suggestions. Please let us know about your projects and special challenges.

If the desired component is not included in our production range listed above, please don’t hesitate to contact us.
We will be glad to find a tailored solution to your technical challenge.

Appendix

Abridgement of metrology

Optical parameters	Type of measurement	Device	Resolution	Spatial sampling area
Geometry / surface quality	Surface scanning using an opto-mechanical probe head	ZEISS M400 precision coordinate measuring device	< 10 nm	1 mm < λ < 560 mm
Geometry / surface quality	Surface scanning using an opto-mechanical probe head	ZEISS UPMC 850 S-ACC Carat precision coordinate measuring device	< 200 nm	0.2 mm < λ < 1200 mm
Surface quality	Interferometry	ZEISS D100 direct measuring Interferometer	< 1 nm	0.2 mm < λ < 1200 mm
Surface quality	Interferometry	ZYGO 6“ with cylinder CGH, stitching stage	< 1 nm	0.2 mm < λ < 1000 mm
MSFR	Microinterferometry	ZYGO NewView 700, 1000x1000 px, (magnification 2.5x)	< 0.1 nm	12 µm < λ < 5800 µm
MSFR	Microinterferometry	ZYGO NewView 700, 1000x1000 px, (magnification 10x)	< 0.1 nm	2.8 µm < λ < 1400 µm
MSFR	Microinterferometry	ZYGO NewView 700, 1000x1000 px, (magnification 50x)	< 0.1 nm	0.6 µm < λ < 290 µm
HSFR	Atomic force microscopy	Nanosurf Nanite S200 AFM	< 0.1 nm	4 nm < λ < 8 µm
HSFR	Atomic force microscopy	Digital Instruments, DI nanoscope D3100M	< 0.1 nm	4 nm < λ < 10 µm

Appendix

Abridgement: Tolerances of optical parameters

Geometries	Roughness (rms)	Slope error (rms)
Geometry / surface quality	< 0.1 nm	< 0.02 arcsec (< 400 mm) < 0.05 arcsec (400 mm < length < 700 mm) < 0.10 arcsec (> 700 mm)
Spheres	< 0.1 nm	< 0.05”, if measurable by interferometry < 0.1” else (also depending on dimensions and curvature)
Cylinders / toroids	< 0.2 nm	< 0.1“… 0.3“, depending on geometry
Elliptical / parabolic / hyperbolic cylinders	< 0.2 nm (SiO2, Zerodur), < 0.3 nm (Si)	< 0.1“…1“, depending on geometry
Other aspheres	< 0.5 nm (< 0.2 nm depending on asphericity)	< 0.1“…1“, depending on geometry

References to Carl Zeiss SMT GmbH for Synchrotron Optics

Flat
Dr. Friedmar Senf, BESSY GmbH, Berlin, Germany
Mr. Uwe Flechsig, Paul Scherrer Institut Swiss-Light-Source, Villingen PSI, Switzerland
Dr. Riccardo Signorato, Bruker AXS, Gladbach, Germany
Dr. Daniele Cocco, LCLS, Stanford, USA
Mr. Peter Stefan and Dr. Michael Rowen, SSRL / SLAC Stanford Linear Accelerator Center, Stanford, USA
Dr. Phil Heimann and Dr. Tony Warwick, Lawrence Berkeley National Laboratory, Berkeley, USA
Dr. Marco Zangrando, ELETTRA, Trieste, Italy

Large Mirrors
Dr. Friedmar Senf, BESSY GmbH, Berlin, Germany
Dr. Guenther Goerigk, FZ Jülich GmbH Institut für Festkörperforschung, Jülich, Germany
Dr. Kai Tiedtke, DESY GmbH, Hamburg, Germany
Dr. Fank Scholze, PTB Physikalisch-Technische Bundesanstalt, Berlin, Germany

High Curvature
Mr. Uwe Flechsig, Paul Scherrer Institut Swiss-Light-Source, Villingen PSI, Switzerland
Dr. Ray Barrett, ESRF Poly Scientifique Louis Néel, Grenoble Cedex, France
Dr. Phil Heimann and Dr. Tony Warwick, Lawrence Berkeley National Laboratory, Berkeley, USA
Dr. Kai Tiedtke, DESY GmbH, Hamburg, Germany
Dr. Friedmar Senf, BESSY GmbH, Berlin, Germany
Dr. Ruben Reininger, APS, Argonne, USA

Aspherical
Dr. Friedmar Senf, BESSY GmbH, Berlin, Germany
Dr. Jens Biegert, ICFO, Castelldefels, Spain
Mr. Frank Hertlein, INCOATEC GmbH, Geesthacht, Germany
Dr. Luca Poletto, CNR-INFM, Padova, Italy
Dr. Kai Tiedtke, DESY GmbH, Hamburg, Germany
Mr. Kyo Takahashi, ACCESS International Resources Ltd., Yokohama, Japan
Dr. Haruhiko Ohashi, JASRI, Sayo-Gun, Japan

Other
Dr. Peter Predehl, Max Planck Institut für Extraterrestrische Physik, Garching, Germany
Mr. Frank Hertlein, INCOATEC GmbH, Geesthacht, Germany
Dr. Ray Barrett, ESRF Poly Scientifique Louis Néel, Grenoble Cedex, France
Dr. Kai Tiedtke, DESY GmbH, Hamburg, Germany
Dr. Stefan Moeller, SSRL / SLAC Stanford Linear Accelerator Center, Stanford, USA
Mr. Frank Siewert, BESSY GmbH, Berlin, Germany
Dr. Simon Alcock, Diamond Light Source Ltd., Didcot, UK

EN_11_021_0001I Printed in Germany DDD-CZ-I/2016 UTo

Carl Zeiss SMT GmbH
ZEISS Gruppe
Rudolf-Eber-Straße 2
73447 Oberkochen
Germany

Phone: +49 (0) 7364 20-4300
Fax: +49 (0) 7364 20-2109
Email: info.smt@zeiss.com
www.zeiss.com/smt