A Novel Approach Towards Standardizing Surface Quality Inspection

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ABSTRACT

Quality control of optical surfaces specified according to ISO 10110-7 and ISO 14997 today is mainly performed by visual inspection, despite the drawbacks common to all operator-dependent processes, such as a lack in reproducibility and accuracy. In this work we present a detailed validation study of the automated surface inspection system ARGOS, which is capable of classifying flats as well as curved optics. The study reveals that ARGOS detects imperfections as small as 1 µm, can accurately determine imperfection sizes larger than 4 µm, and has an average repeatability of around 1 µm.

Keywords: surface quality inspection, surface imperfections, scratch-dig, ISO 10110-7, ISO 14997, ARGOS

1. INTRODUCTION

Quality control is an indispensable step in the production of high quality optical components. One major component of either outgoing quality control after manufacturing or incoming quality control before assembly of individual components is checking for surface imperfections. Surface imperfections such as digs or scratches may impair the function of a component. In addition, they may also be undesirable for pure cosmetic reasons – customers may not be willing to accept visible imperfections on expensive components.

Scratch and dig quality control is typically carried out by trained inspectors who place the component under suitable illumination and carefully scan the samples for imperfections with the bare eye. Following the requirements of ISO 14997:2011[1], which defines how the classification of surfaces has to be carried out, the size of an imperfection is determined by comparing the imperfection with reference imperfections for all imperfections larger than 10 µm. For imperfections smaller than 10 µm, sizes cannot be distinguished with the naked eye and only the shading effect of imperfections can be compared to totally absorbing reference imperfections[♦].

While well-trained inspectors detect larger surface imperfections with remarkable speed and accuracy, the overall inspection process is subjective and results may depend on a variety of factors. Differences between companies, e.g. in training of the inspectors, illumination conditions, etc. are causing a lack of comparability of the results. Human factors, such as concentration, fatigue, mood, and motivation add another degree of perturbation and bias to the process leading to possibly lengthy customer complaints. These shortcomings of manual visual inspection can be overcome by using a calibrated instrument which gives reproducible and accurate results and is independent of environmental conditions or operator influence.

The quality of optical surfaces is specified according to ISO 10110-7[2], in which the surface imperfection sizes are described in terms of *grade numbers*. For a general surface imperfection, e.g. a dig, the grade number is the square root of the

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[♦] The current DIS Version of the ISO 14997 sets a larger limit to the visual inspection process. Imperfections with a diameter larger than 40 µm diameter or 25 µm width can be determined by visual inspection, smaller imperfections have to be analyzed under magnification.

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imperfection area. Only a discrete set of logarithmically spaced grade numbers is used, and the class of each surface imperfection is the one with the next larger grade number.

If a separate specification for long scratches exists, the grade number is the maximum width of the scratch. A typical specification for surface imperfection then follows the notation

5/ N x A, L N'xA',

in which 5/ is the code for surface imperfections, N is the allowed number of general surface imperfections with maximum grade number A, and N' is the allowed number of long scratches (longer than 2 mm) with maximum grade number A'. Additional specifications may be given for coating imperfections and edge chips.

An optical surface passes the inspection according to ISO 10110-7, if:

- No surface imperfection has a grade number larger than the specified maximum grade number
- The accumulated area of relevant surface imperfections (for scratches: the sum of the widths) is smaller than NxA^2 (for scratches: N'xA')
- There is no imperfection concentration, in which 20% or more of surface imperfections are concentrated in 5% of the test surface

Several attempts to implement a machine inspection approach have been undertaken, however, up to now and to the authors knowledge only two devices are commercially available (Savvy Inspector and ARGOS). The Savvy Inspector is a camera based setup in dark field configuration for the scratch-dig inspection according to the MIL norm[3]. It captures the stray light of imperfections and compares it to the brightness of a reference master captured under identical conditions, thereby eliminating the human influence on the evaluation. A second approach was realized by Turchette and Turner employing an automated microscope-based system to classify surfaces according to the ISO 10110-7[4]. While a microscope based setup offers high resolution, the field of view is usually limited to a few mm requiring multiple scans and image stitching to cover a usual 1 inch optic. This setup does not appear to be commercially available. Liu et al. followed a similar approach and developed a microscopic scattering imaging system based on a multi-beam fiber light dark field illumination, a motorized xy-stage, and an optical zoom microscope for the inspection of high power laser optics[5].

In this paper we present a novel machine inspection approach, which automatically detects imperfections and classifies them according to their ISO 10110-7 specification. This *ARGOS* system completely removes the operator influence on the classification and thereby generates a highly reproducible inspection process[*].

2. METHODS

ARGOS Setup

The ARGOS system follows a dark field imaging approach since it provides better imperfection visibility due to an enhanced signal-to-background-noise-ratio[6]. In dark field configuration the specular reflection of the light source at a perfect surface is prevented from entering the aperture of the imaging system, so that only light scattered at surface imperfections is captured.

In contrast to previously developed machine inspection systems, the ARGOS setup employs the combination of a line scan sensor and a rotation stage instead of a matrix camera sensor. This concept delivers the capability to inspect curved optics, provides high resolution, and facilitates the light management as detailed below.

Figure 1 shows ARGOS and the components of the setup. The line scan sensor (on top of the instrument) has 8192 pixels and is coupled with an imaging lens in a 2.5 times magnification configuration with an aperture of F 4 resulting in an effective pixel size of 2.85 µm/px. The samples held in a self-centering mount are placed onto a rotation stage and are

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[*] The system is commercially available from the DIOPTIC GmbH.

illuminated by a dome light source with high power LEDs providing a total illuminance of up to 2.5 million lux enabling exposure times of a few µs.

Figure 1. ARGOS inspection system

A special feature of ARGOS is the tiltable camera arm. The combination of a tilted camera and rotation stage enables scanning of curved surfaces as illustrated in Figure 2. Whereas flat samples can be scanned directly from above (Figure 2a), the limited depth of field of the high resolution camera prohibits the application of the same process to curved optics. By tilting the camera and rotating the sample, the sensor can be aligned to the average slope of the sample, parallel to the virtual connection between apex and edge of the sample. This clearly decreases the depth of field necessary to capture the whole surface (Figure 2b).

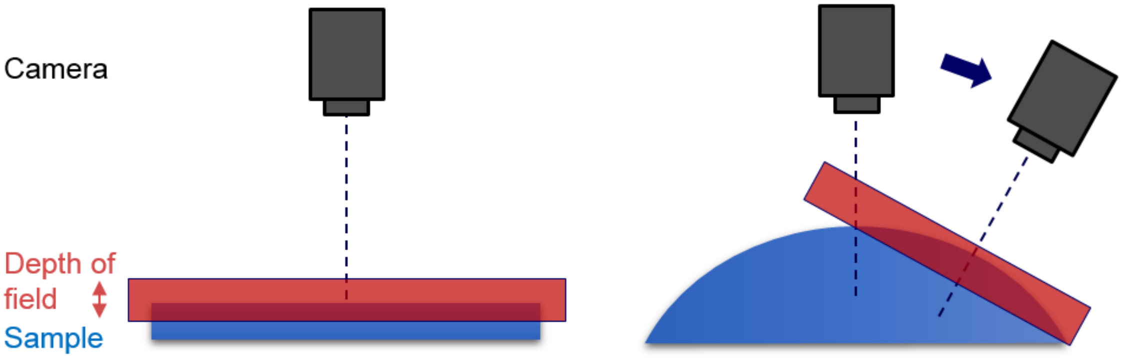


Figure 2. Illustration of the sensor tilting. A flat optical surface (left) can be scanned from above. The red shaded area indicates the depth of field. By tilting the camera, the depth of field is adapted to the shape of a curved sample (right).

Image acquisition and processing

The image acquisition process is shown in Figure 3. During a measurement, the sample is rotated once by the rotation stage with a velocity of 180 degrees/s, equivalent to a duration of 2 s for one measurement. Approximately 50000 line scans are captured synchronized to the position of the stage. The resulting raw image (in polar coordinates, radial position axis to the right, angular position axis towards the bottom) is shown in step two of Figure 3 is subsequently transformed into Cartesian coordinates generating an image of 16000 pixels squared. This enormous image resolution of 256 megapixels is another advantage over matrix sensors, whose typical resolutions are at least one order of magnitude smaller.

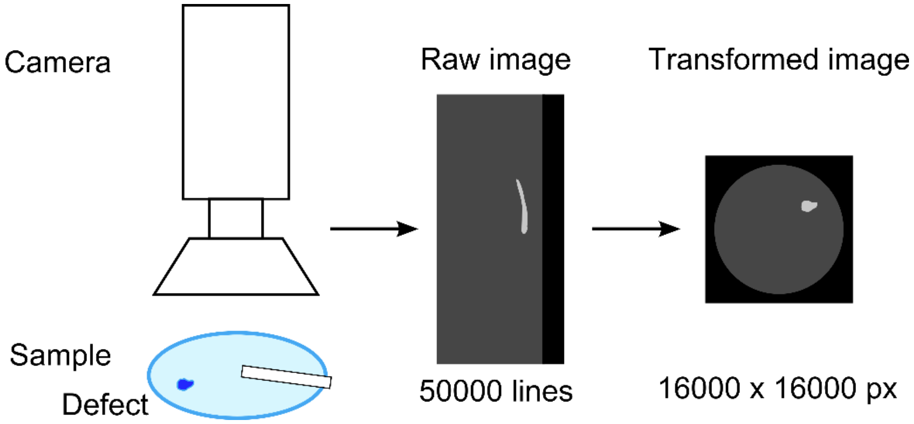


Figure 3. Image acquisition. During rotation of the sample, the line scan sensor constantly captures images. The resulting raw image consists of approx. 50000 lines and is subsequently transformed into Cartesian coordinates forming a 256 megapixel image.

Surface imperfections are detected after a series of processing steps, as illustrated in Figure 4. First, the image is filtered to suppress unwanted background signals (Figure 4 b). In the following segmentation step, surface imperfections are separated from the background, resulting in a binary image (Figure 4 c). This binary image is analyzed and visible imperfections are classified according to the specification of the sample. For documentation, inverted images with enhanced visibility of the imperfections and showing the detected imperfection contours are generated (Figure 4 d).

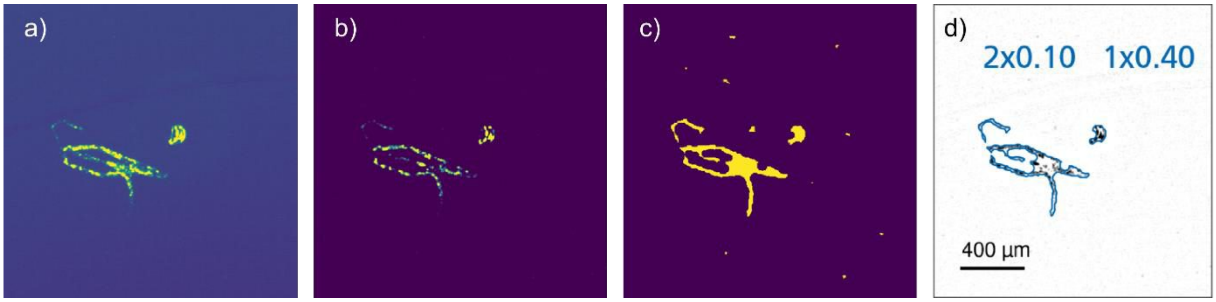


Figure 4. Image processing steps with ARGOS. a) Raw image after transformation to Cartesian coordinates. b) Filtered image. c) Binarized image. d) Inverted image with imperfection contours and grade numbers.

Reference targets

Commercially available reference targets are not suited for the calibration and validation of a dark field surface imperfection measuring system. Reference plates suggested in ISO 14997:2011 have chrome on glass lines and dots, imitating the “absorption” effect of surface imperfections when viewed in transmission. For dark field measurements, a reference that imitates the scattering behavior of imperfections is required. Such reference samples are available for specifications according to MIL-PRF-13830B. According to MIL-PRF-13830B, scratches are classified into certain scratch number classes based on their visibility, not based on their dimensions, making the specifications (and reference targets) incompatible with the requirements of ISO 10110-7/14997.

Therefore, a custom target was designed and produced using focused ion beam milling. A set of reference imperfections of circular shape with grade numbers between 0.001 to 0.063 mm and rectangular imperfections with a length of 0.100 mm and grades between 0.001 and 0.063 mm were milled into a glass substrate with a depth of 1 µm. For the imperfections larger than grade 0.004 mm a random rough surface was added to the trough of the imperfections. The random surface was generated by filtering a random (white noise) distribution with a Gaussian mask. The simulated imperfections were then milled into a standard 1” diameter glass lens. The circular imperfections were chosen to be reference imperfections for digs, and the rectangles represent scratches. Since for a scratch the figure of merit is the width, the lengths of the rectangles was limited to 0.1 mm to reduce the milling time.

3. RESULTS

In order to assess the capabilities of the ARGOS system, several checks and measurements were carried out in a detailed validation study. The following sections give an overview of the system’s depth of field, repeatability, accuracy, the visibility of small imperfections, and a measurement example of a curved lens.

Depth of field

The depths of field of the ARGOS has direct influence on the smallest radii of curvature that can be classified in a single scan. To determine the depth of field for different feature scales, reference imperfections were repeatedly measured, each time varying the focus position. The captured images were analyzed with the ARGOS software to extract the grade numbers. The results for reference digs with grade numbers between 0.0016 and 0.063 are shown in Figure 5. The grade numbers were not rounded to the next larger ISO grade for this analysis

The determined size for the smallest reference dig (grade 0.0016) does not seem to depend on focus position, while for all other imperfections, the determined size increases with increasing distance from the focal plane. Two factors contribute to the measurement of the size: As the distance from the focal plane increases, the blurring of the imperfections increases. The objects thus appear larger. On the other hand, the brightness of the objects decreases with increasing blurring. As a threshold is used in the ARGOS software to binarize the image before determination of the object size, a decreasing object brightness may cause outer object pixels to fall below the threshold, thus decreasing the determined object size.

For the smallest dig (0.0016), both the increasing and the decreasing effect balance each other. As the object is shifted away from the focal plane, the brightness of the image decreases, until the segmentation threshold is not reached anymore for any object pixel. This is why the line ends at -160 µm and +140 µm. For larger defocus, the imperfection is not detected anymore by the ARGOS software. All larger imperfections are visible throughout the range presented here, and the decrease of brightness seems negligible. The apparent size of the objects increases further away from the focal plane, due to blurring of the images. The effect decreases with increasing object size, the relative error is below 5% at +-100 µm for grades 0.063 and larger.

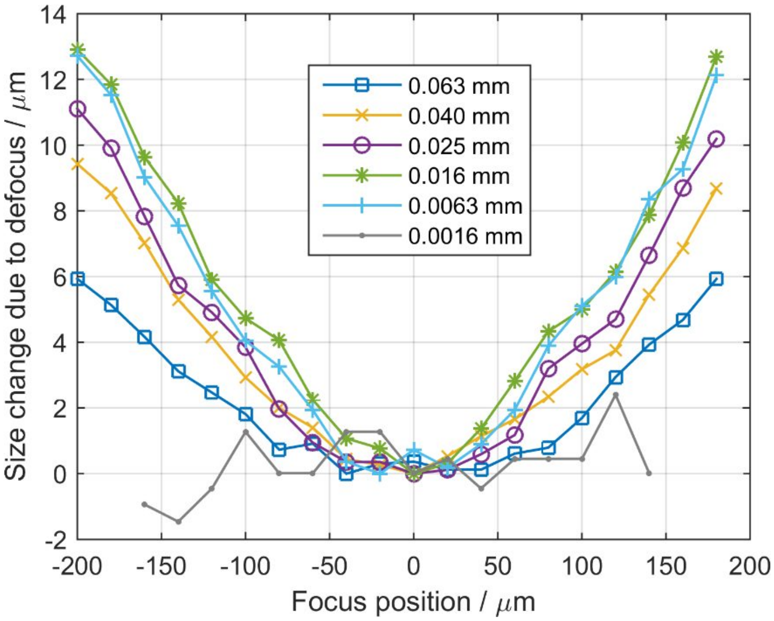


Figure 5. Depth of field of the ARGOS system. The different symbols represent reference imperfections between 0.0016 to 0.063 mm.

The depth of field of the imaging system is of interest for two reasons. One is measuring curved optics, which will be described in detail below. The other relates to the question of how large the influence of the operator is on the inspection result. If a flat sample is not properly focused, imperfection sizes are generally overestimated. Figure 6 shows the border of the reference sample for different focus positions, with the sample shifted 0, 40, 80, and 120 µm from the focal plane (right to left). The right-most image clearly appears best focused, showing that an operator will certainly get within +-40 µm of the best focus position. In this range, the maximum error due to defocus is negligible for larger grade numbers and below 5% even for small grades down to 0.025. Thus, the inspection result will not depend significantly on the focus position selected by the operator.

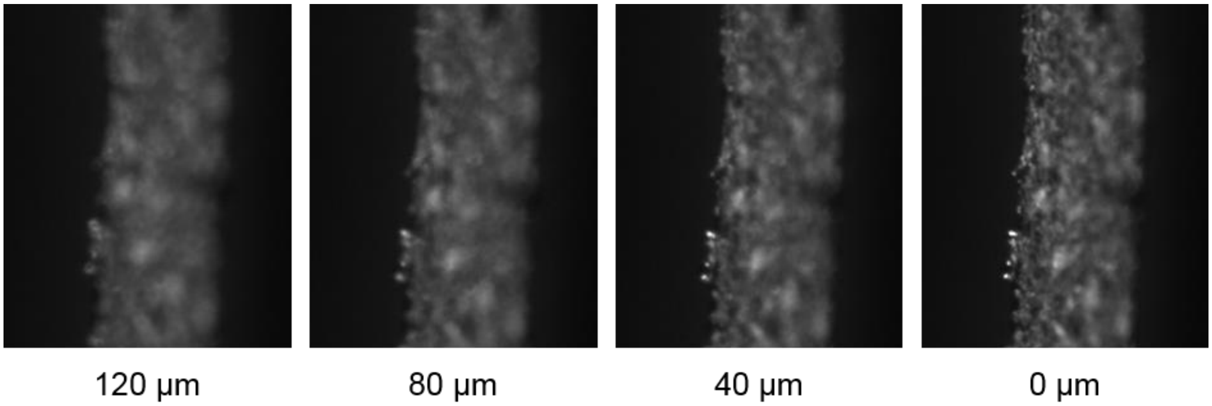


Figure 6. Effect of defocus on the sharpness of the lens border. The number indicates the distance from the focal plane.

Inspection of curved optics

The machine inspection of curved optics is challenging because the physically given trade-off between magnification, depth of field, and field of view limits the feasibility of such systems. As was shown above, typical values for the depth of field in high magnification and high resolution systems are hundreds of micrometers. As most curved optics have sagittal depths that are much larger, inspection of a curved optic with high magnification usually implies scanning the sample while refocusing the camera depending on the position on the sample. The ARGOS system follows a different approach. As described in section 2, the combination of a tilted sensor and a rotation stage allows to adjust the focal plane of the imaging system to the average slope of the curved sample. This allows to get the maximum sagittal depth out of a limited depth of field, so that the whole surface of a curved optical component can be scanned with one revolution of the stage. Figure 7 shows an example of a spherical plano-convex lens with a focal length of f = 150 mm and a diameter of 1’’. The lens has been prepared with a fingerprint to generate a reference structure. The top panel displays a small image of the lens marking the area of interest, which is shown enlarged in the middle panel and bottom panel. The focus was set to the border of the lens and images were acquired with two different tilt angles of the camera. The middle panel was captured with a tilt angle of 0° for reference, the bottom panel shows the same areas of interest captured with the 4° tilted camera setup.

The images clearly demonstrate that when the lens border is in focus, the sharpness of the image captured with 0° tilt angle decreases strongly to the center of the lens (middle panel). This is not surprising, as the lens has a sagittal depth of 1.1 mm, which is much larger than the depth of field of the camera. In contrast, the measurement with the tilted camera appears in focus across the whole surface. To get a similar result without tilting the camera, at least four images with different positions of the focal plane have to be fused. Using a tilted camera for the inspection is both fast and less prone to errors than using a series of images acquired with a vertical camera.

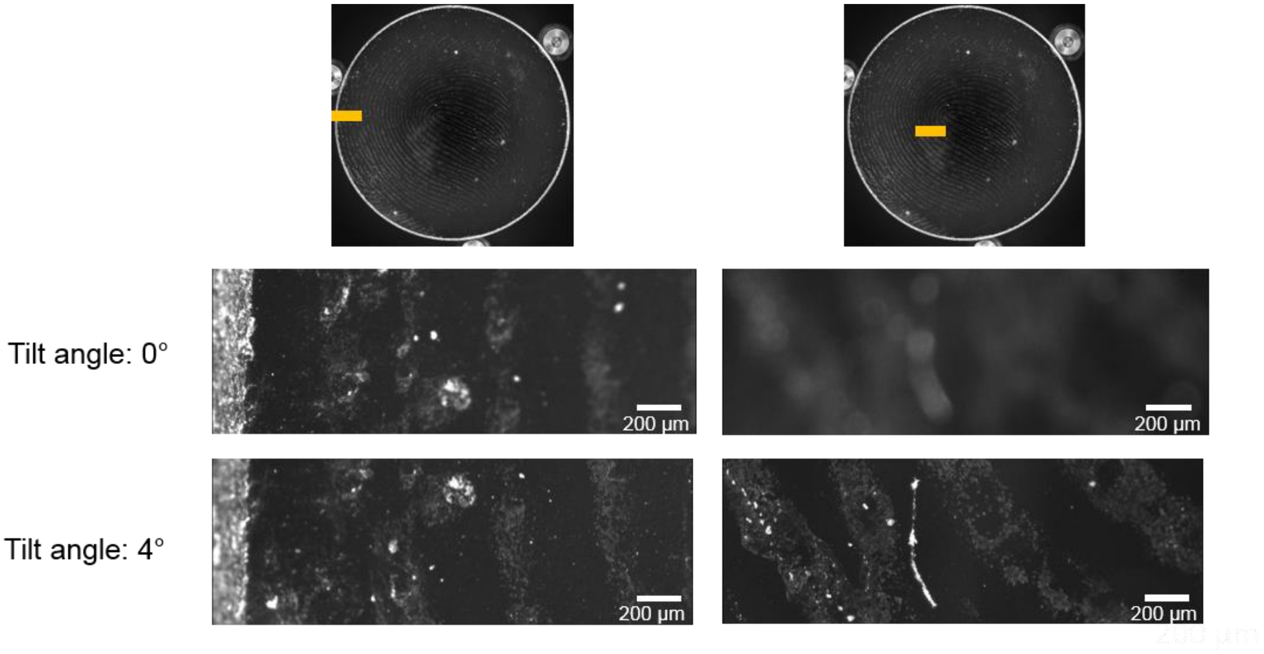


Figure 7. Measurement of f = 150 mm 1’’ plano-convex lens prepared with a fingerprint. Top panel: Miniature image of the lens. The yellow box indicates the area of interest (AOI) shown below. Middle panel: 100% zoom of the AOI captured with 0° tilt angle. Bottom panel: 100% zoom of the AOI captured with 4° tilt angle.

Measurement system analysis

An automated inspection process for the classification of optics has to be precise and repeatable. A measurement system analysis was conducted with ARGOS to determine its capabilities. In a series of measurements, the focused ion beam (FIB) reference target was inspected 30 times. To mimic real inspection conditions, the sample was removed from ARGOS between measurements. The grade numbers for the imperfections were determined with the calibrated ARGOS software, for the "dig" like circular imperfections, the grade number was taken as the square root of the area; the grade number for the "scratch" like rectangular imperfections is their width. The grade numbers were not rounded to the next larger ISO grade for this analysis.

Figure 8 shows the determined grade numbers plotted against the reference grade numbers. The error bars are the standard deviations calculated for each imperfection for the 30 repetitions. Note that the measured grades for all digs smaller than 2.5 µm are set to a fixed value of 2.5 µm by the software. Imperfections as small as 1 µm are visible to the software, but grade numbers below 2.5 µm cannot be accurately quantified, as can be seen from their standard deviations. Table 1 lists the standard deviation for each reference imperfection. For a lens surface tightly specified with 5/1x0.040, the standard deviation is only around 1 % of the grade number, enabling very precise classification. Throughout the whole reference imperfection grade range, the average repeatability is around 1 µm for digs as well as scratches.

ARGOS further provides detailed test reports for the documentation of the inspection. Figure 9 shows an excerpt of an exemplary test report of an optical surface specified with 5/2x0.160;L1x0.010. An overview image displays the position of the imperfections on the sample (left), and the table on the right side of Figure 9 provides details about the grade numbers, imperfection types, and exact positions of the largest imperfections. For the largest two imperfections detail images with the defect contours and a scale bar are given. The table in the bottom of Figure 9 summarizes the classification and lists the results for imperfection concentration, largest dig grade, effective area, and largest scratch width and effective scratch width, if specified. Since in this example the two largest imperfections are in specification, as are the effective area and the width, and no imperfection concentration was detected, the sample passed the inspection. The test report further includes additional information to identify the sample (e.g. operator, drawing number, specification).

This analysis shows that automated inspections systems with dark field illumination are capable of measuring imperfection grades sufficiently accurate to comply with the requirements of ISO 14997. As classification results of these systems are not operator-dependent and reproducible, and the systems are calibrated with a reference target and provide full documentation of the results, they open the door to new quality standards in the inspection process which cannot be guaranteed by operator-dependent visual inspection.

Table 1 Repeatability of ARGOS

Reference grade / µm	1	1.6	2.5	4	6	10	16	25	40	63
Std. for scratches / µm	0.7	0.8	0.7	0.6	0.5	0.5	0.5	0.9	0.4	0.5
Std. for digs / µm	1.1	1.1	1.3	1.1	0.9	0.8	0.9	0.7	0.5	0.4

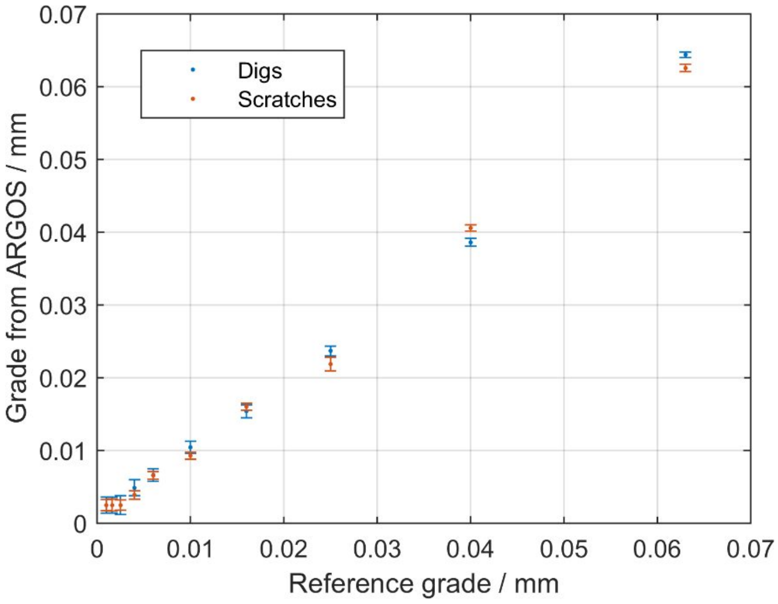
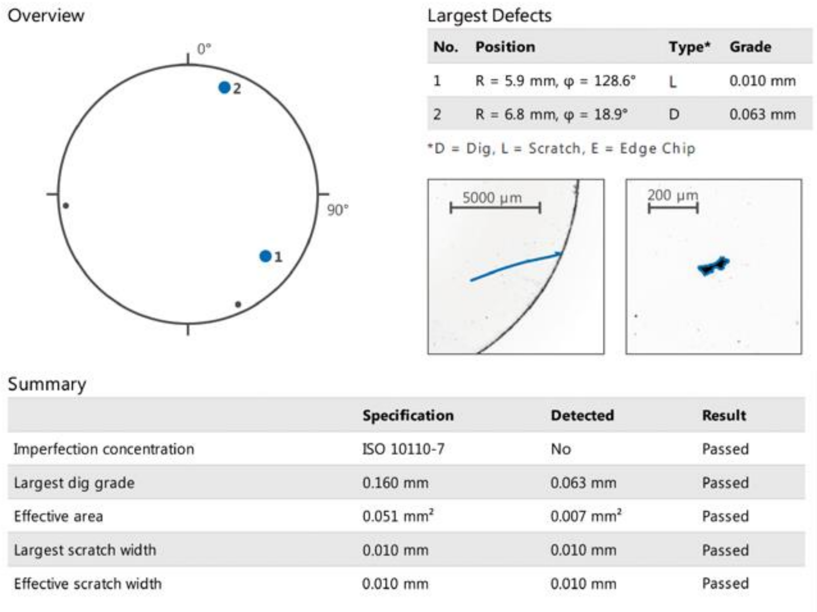


Figure 8 Accuracy and repeatability of the classification with ARGOS. The blue points represent dig-like imperfections and red points are scratch-like imperfections. The error bars are the standard deviations for 30 measurement repetitions.



Overview

Largest Defects

No.	Position	Type*	Grade
1	R = 5.9 mm, φ = 128.6°	L	0.010 mm
2	R = 6.8 mm, φ = 18.9°	D	0.063 mm

*D = Dig, L = Scratch, E = Edge Chip

Summary

	Specification	Detected	Result
Imperfection concentration	ISO 10110-7	No	Passed
Largest dig grade	0.160 mm	0.063 mm	Passed
Effective area	0.051 mm²	0.007 mm²	Passed
Largest scratch width	0.010 mm	0.010 mm	Passed
Effective scratch width	0.010 mm	0.010 mm	Passed

Figure 9. Excerpt of an exemplary test report of an optical surface specified with 5/2x0.160; L1x0.010.

4. CONCLUSION

We presented an automated and standardized approach towards surface inspection of optical surfaces. The advantages of a dark field setup with a combination of a line scan sensor and a rotation stage in the inspection of curved surfaces were demonstrated. The presented ARGOS instrument features an imperfection visibility starting at a grade number of 1 µm, the capability to distinguish between imperfections starting at 4 µm, an average repeatability better than 1 µm across all classes, and the ability to inspect flat as well as curved optics. It provides all features necessary to implement an accurate and repeatable surface inspection process. The automated imperfection analysis eliminates the operator influence in the classification process, and an automatically generated test report provides detailed documentation of the surface quality.

5. ACKNOWLEDGEMENTS

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