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Optics and photonics — Test methods for surface imperfections of optical elements —

Part 2: Machine vision

Optique et photonique — Méthodes d'essai applicables aux imperfections de surface des éléments optiques —

Partie 2: Visionique

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 172, *Optics and Photonics*, Subcommittee SC 1, *Fundamental standards*.

A list of all parts in the ISO 14997 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document was developed to account for the increased use of machine vision for surface quality inspections. The visual assessment of grades of surface imperfections of optical elements and systems is described in ISO 10110-7, and ISO 14997-1[1)]. The latter gives methods to obtain subjective results using the human eye, reference comparison standards, and in some cases optical magnification tools.

Utilizing machine vision opens the door for the objective evaluation of imperfections as well as electronic data storage of detailed and precise test reports along with statistical data handling. It offers an opportunity for better repeatability of the characterisation of surfaces and a potential method of arbitration in supplier / customer discussions about surface imperfections.

Inspection results of optics obtained by manual inspection and from already existing machine vision systems have shown good correlation. Minor deviations arise, but are largely due to the differences of subjective and objective evaluation.

Of particular concern can be long scratches such as sleeks. Such imperfections often are more visible when tilting and rotating the sample to the optimum position which, in machine vision devices, is often accomplished by covering an amount of incident illumination angles, which are limited due to practical reasons.

1) ISO 14997-1 is at the time of publication of this document published as ISO 14997:2017. The change in numbering of the International Standard is intended at the next revision of ISO 14997.

Optics and photonics — Test methods for surface imperfections of optical elements —

Part 2: **Machine vision**

1 Scope

This document provides guidance for the use of machine vision to objectively assess grades of surface imperfections as defined on a drawing using ISO 10110-7 with equivalent results as those obtained by applying the inspector-based methods described in ISO 14997-1.

This document also gives guidelines on how to setup a machine vision device regarding fidelity, repeatability and reproducibility, based on the dark field detection principles of ISO 14997-1.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10110-7, *Optics and photonics — Preparation of drawings for optical elements and systems — Part 7: Surface imperfections*

ISO 14997-1, *Optics and photonics - Test methods for surface imperfections of optical elements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10110-7 and ISO 14997-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
machine vision
application of computer vision to machine, robot, process or quality control

Note 1 to entry: This definition is also applicable for use in optical elements and components.

[SOURCE: ISO 2382:2015, 2123788, modified — Notes to entry omitted and new Note 1 to entry added.]

3.2
machine vision grading
application of a machine vision system and a computer algorithm to determine the grades of imperfections

Note 1 to entry: Machine vision grading reports the grade of a particular scratch or dig, which has usually been presented to the machine vision system by an operator.

3.3
machine vision inspection
application of automation hardware and software with a machine vision system to determine if a component or surface passes or fails a given surface imperfection specification

Note 1 to entry: In machine vision inspection, the machine vision grading is performed on all the detected imperfections on the surface to evaluate the surface against all of its requirements, i.e. maximum imperfection grade, accumulation of all imperfections and concentrations of imperfections.

3.4
sleek
polishing (hairline) scratch without visible conchoidal fracturing of the edges

[SOURCE: ISO 9802:1996, 3.6.2.1.4]

4 Symbols

Please see symbols of ISO 14997-1:2017, Clause 4 and the following:

IMV_D dimensional inspection using machine vision

IMV_V visibility inspection using machine vision

5 Considerations for machine vision systems applied to surface imperfection inspection of optics

5.1 Evaluation limits

ISO 14997-1 specifies the required evaluation limits for manual visual inspection, taking into account the human evaluation method and the limits of normal visual resolution. In machine vision assessment of imperfections, a typical inspection device consists of a camera, magnification optics, an illumination system and a computer-based evaluation algorithm. One key difference between machine vision and visual inspection is that visual inspectors are advised by ISO 14997-1 to filter irrelevant defects by adapting the illumination. Machine vision systems can use the same illumination independent of the surface specification and filter irrelevant defects when processing the data with a suitable algorithm.

NOTE Some calculations can be deceptively difficult for a system performing machine vision inspection. For example, the concentration requirements of ISO 10110-7:2017 4.2.4 and 4.3.3 require an extensive decision algorithm to evaluate all the possible combinations of imperfections that are present to determine if a concentration has occurred.

5.2 Sample preparation

According to ISO 14997-1 a test sample needs to be cleaned well enough to allow inspection to the required level. Adhered particles tend to be indistinguishable from digs and pits in the glass and therefore need to be counted as imperfections as well (see ISO 10110-7). If the operator is uncertain about the cleanliness of the sample, it is often best to re-clean the sample after inspection and test it again.

5.3 Illumination configuration

The test method is often a dark field configuration, to be sensitive to scattered light. It can be either a reflective light configuration or a transmitted light configuration. Best contrast is often achieved in dark field, close to the specular reflection. It is important to make sure the illumination conditions are sufficient for the testing system to be sensitive enough to observe all relevant imperfections as described in ISO 10110-7 and ISO 14997-1, including adhered particles.

Most of the imperfections have a well distributed angle dependency for scattered light. In many cases, long imperfections like scratches and sleeks will have a directional bias to the peak scattering direction; typically, in a rotation of 90° with respect to the long axis of the scratch. Moreover, they can produce a small cone of light with a small opening angle. Visual inspectors will tilt and rotate the sample until they reach best visibility and continue with the evaluation. In machine vision, this approach can be impractical and time consuming. In most machine vision inspection systems, a single camera is observing the element under only one angle, e.g. parallel to the optical axis or orthogonal to the surface. The lack of different camera viewing angles can be compensated partly by using an illumination system that covers a large angular spectrum.

Best results are usually achieved when the illumination system covers a wide range of azimuth (around the test piece) and polar (between the plane of the test piece and the system optical axis) angles. This can be achieved, for example, by using a passively illuminated dome or a direct ring or dome-like illumination with individual sources (typically LEDs) that are packed closely together. Illumination uniformity is important, both in azimuthal and polar angles. Best illumination is continuous or close to continuous in azimuthal range. Larger gaps in the azimuthal range increase the probability that scratches and sleeks are not continuously visible in the images. The range of polar angles is often maximized, within the practical constraints of a darkfield configuration and the application. For most imperfections, most light is scattered by only small angles, so that scattered light intensity is highest close to the direction of specular reflection. Larger polar angles tend to add to background illumination, but only a small fraction of the light ends up being scattered into the camera. Manufacturers of machine vision systems used in surface imperfection inspection can assist the user in determining the functionality of the system in their specific application by specifying the azimuthal and angular ranges covered by their device.

NOTE For curved elements, the ideal polar angle for illumination will vary across the surface, as it depends on the slope of the surface.

6 Dimensional inspection using machine vision (IMV_D)

NOTE For visual dimensional inspection (IV_D, IS_D and IM_D), see ISO 14997-1.

6.1 Dimensional resolution and accuracy considerations

For dimensional grade assessment of optical surface imperfections, the task of the inspection is to classify imperfections into grades according to the Renard R5 series described in ISO 3, e.g. 0,1; 0,063; 0,04; 0,025; 0,016; 0,01, etc. For (long) scratches, where these have been specified in the drawing, the grade number corresponds to the width of the scratch. General (and coating) imperfections such as digs are classified according to the square root of their area. The task of the inspection is to differentiate between imperfections of grade 0,25*A* and 0,16*A*, where *A* is the specified grade number, because of the accumulation and concentration rules for general and coating imperfections. ISO 10110-7:2017, 4.2.3, states that imperfections of "grade number of 0,16*A* or smaller shall not be counted", while larger imperfections are accumulated to compute the effective imperfection area. Long scratches are ignored if their grade is 0,25*A* or less.

The machine vision system for dimensional inspection typically uses a high-resolution image and image processing algorithms to determine the width and/or area of imperfections. The imperfections are then assigned grade numbers from the Renard R5 series.

The resolution of the machine vision system is dependent on

— the optical resolution of the magnification optics,

— the pixel pitch of the camera sensor, and

— the algorithm used to process the image data.

NOTE 1 The design of the illumination system could influence the resolution, e.g. when the aperture of a bright field light source is smaller than the aperture of the imaging lens.

ISO 10110-7:2017, 4.2.3 states that “A larger number of surface imperfections (including coating imperfections) with a smaller grade number is permitted, if the sum of their areas does not exceed the maximum total area.” It goes on to say “When determining the number of permissible surface imperfections or localized imperfections in optical assemblies, those with a grade number of 0,16*A* or smaller shall not be counted". Consequently, to evaluate the surface for the accumulation and concentration requirements the resolution of the system needs to be at least 0,16*A*, where *A* is the specified grade number.

NOTE 2 This is a much stronger expectation than asking that imperfections can be detected down to grade 0,16*A*. Typical machine vision systems with good signal-to-noise ratios can detect isolated objects well below their resolution.

The machine vision grading for each imperfection is subject to both random (statistical) and systematic errors. Key quantities are the system’s fidelity (proximity of results to the true value) and precision (repeatability and reproducibility) for determining the correct grade of an imperfection. However, the effect of fidelity and precision of an imperfection’s width/area *measurement* on its *classification* into a specific grade depends upon how close the given imperfection’s actual width/area is with respect to the limiting values of the grade size range. If the actual width or square root of the area is exactly equal to a grade number, the classification will be correct only 50 % of the time, assuming a Gaussian distribution of measurement results.

Under the assumption that the measurement results of the machine vision system for a given imperfection follow a Gaussian probability distribution, the probability of assigning the correct grade *A* to the imperfection can be approximated as

$$p \approx 1 - 0{,}8 \times \sigma / (A - 0{,}63A)$$

where

σ	is the standard deviation of the Gaussian distribution, i.e. the precision of the system, and
$(A - 0{,}63A)$	is the size of the interval of grade number *A* (see Annex A for a derivation).

EXAMPLE The probability of misclassifying an imperfection with grade number *A* with a machine vision system with a precision equal to 0,1*A* is approximately 22 %.

6.2 Brightness and sensitivity

ISO 14997-1 prescribes an illumination brightness that is required to be used with visual inspection. For machine vision grading, the detection limit will not only depend on the brightness of illumination, but also on the characteristics of the camera (gain and dark noise floor) and the image processing algorithms that are employed.

If the illumination is too bright, light scattered by larger and/or highly scattering imperfections will saturate the image sensor; if the illumination is too weak, smaller and/or weakly scattering imperfections do not stand out from the noise floor. The illumination needs to be as bright as necessary to make the smallest relevant defects stand out from the noise floor. If larger imperfections tend to saturate under these conditions, it is important that a careful calibration of the system is performed across the full relevant width and area range, so that very bright large imperfections do not appear enlarged to the processing algorithms.

6.3 Verifying dimensional inspection system performance

To verify that a machine vision system is able to properly classify imperfections, it is necessary to verify the system using certified artefacts. Visual inspectors typically use chrome-on-glass reference plates with objects of different shapes and grade numbers. Under ideal dark field conditions, a reflective surface cannot be distinguished from a transparent surface. Since only the edges of artefacts that are chrome on glass will be visible in the system, this can be problematic for system verification.

Ideally, a set of artefacts spans the whole range of relevant imperfections. These artefacts could be a collection of damaged parts on which imperfection grades have been determined with a calibrated microscope or other suitable method. There exist also techniques that allow the artificial production of reference artefacts that scatter light and are visible under dark field conditions; e.g., focused ion beam milling. In some applications, traceability of the reference artefacts to known size standards is important.

To verify that the machine vision system is working properly the repeatability, reproducibility and fidelity can be evaluated.

7 Visibility inspection using machine vision (IMV_V)

NOTE For visual inspection (IV_V and IS_V), see ISO 14997-1.

7.1 Visibility evaluation limit

For visibility grade assessment of optical surface imperfections, the inspection needs to differentiate between the visibility or brightness of imperfections under specific lighting conditions. A machine vision system used for imperfection grading or machine vision inspection needs to at least be able to detect imperfections that are visible to a human observer under the lighting conditions described in ISO 14997-1. The computer-based evaluation algorithm can then disregard imperfections which would not normally be visible to the human observer, and determine the relative visibility of an imperfection on an optical surface.

7.1.1 System resolution considerations

Typically, the machine vision algorithm together with the system differentiates the visibility of imperfections by comparing the brightness or visibility of an imperfection to a stored library of brightnesses or visibilities for a “comparison standard”, or a series of imperfection artefacts of varying grades. The optical system and the camera need to be able to resolve half the scratch or dig visibility of the imperfection to be evaluated. In performing machine vision grading, it is best if the system and algorithm can determine the brightness or visibility of an imperfection at least a factor of two less visible than the smallest grade in the comparison set. Most sets use scratches of grades 80, 60, 40, 20, and 10 and digs of grades 50, 40, 20, 10 and 5. Usually these dig grades correspond to the apparent diameter of the artefacts in units of 10’s of micrometres. Therefore, the system and its algorithm needs to be able to resolve scratches half as bright as a #10 scratch and half the diameter of the #5 dig, or 5 × 10 × ½ = 25 micrometres. The key quantities are the system’s fidelity, repeatability and reproducibility discussed in Clause 8.

NOTE Since there is no single comparison standard with defined scattering, all evaluations are traced to a specific standard to be able to compare results.

7.2 Illumination configuration

The illumination system can resemble the illumination configuration stated in ISO 14997-1; this includes colour (white light over the visible band) and in terms of angular spectrum to the extent possible. The exact configuration can vary as different technical methods are possible to allow optimal handling and detection.

Visual inspectors will tilt and rotate the sample until they reach best visibility and continue with the evaluation. In machine vision, this approach can be impractical and time consuming. Therefore, an alternative strategy is to cover a wide range of polar angles of illumination relative to the direction of detection, as in a dome-like or ring-like illumination configuration.

NOTE 1 Sleeks tend to be overestimated in visibility using visual inspection as they can be tilted and rotated to appear very bright. As a result, standard practice is to ignore sleeks in a scratch and dig visibility inspection.

NOTE 2 Standard coating imperfections will be visible using this method. Local chemical or physical deviations within one or more layers of a dielectric coating which e.g. have local points of higher reflectance would not be detected, because of the smooth optical surface, not producing stray light.

NOTE 3 Imperfections like orange peel, greyness and solvent remains are treated as any other imperfection. Sometimes, these types of imperfections can only be seen under special lighting conditions.

7.3 Brightness and grades

A machine vision system applied to surface inspection of optics is capable of achieving comparable results obtained from visual inspection. Analysing the reflective light setup of the viewing station from ISO 14997-1:2017, A.3 one finds an illuminance of 1 000 lx to 2 800 lx, however this needs to be used in combination with a human observer as opposed to a camera or other detector. In order to determine the effectiveness of the illumination in a reflective light machine vision system, a careful signal to noise analysis can be conducted to verify that the system will be able to reliably determine the grades of the smallest digs and most faint scratches.

NOTE As a computer-controlled machine is very rigid, it tends to also evaluate very dark imperfections barely coming above the detection threshold. This might lead to a subjectively perceived oversensitivity of the system. A compensation algorithm can be applied to yield results which can be duplicated using the methods described in ISO 14997-1.

Surface features which are not visible/detectable using the methods described in ISO 14997-1 are considered to have such weak influence on system performance that they are considered negligible. They typically do not contribute to the evaluation of surface quality.

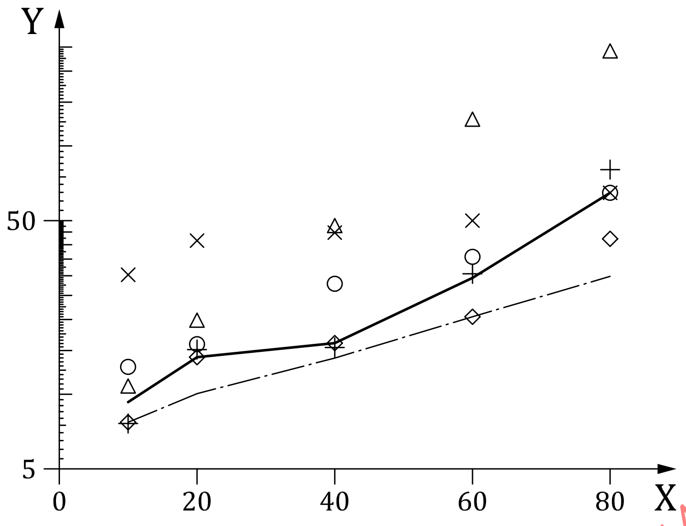
7.4 Verifying visibility system performance

To verify that a machine vision system is able to properly classify scratches and digs on components, it is necessary to verify the system using certified artefacts. In the old US MIL system described in MIL-PRF-13830B, or the system described in ANSI/OEOSC OP1.002 visibility, the comparison artefact was understood to be a US Army issued comparison standard made and tested to US Army drawing C7641866, and certified by the Army to be traceable to the original limit masters that are retained at Picatinny Arsenal. For the ISO 10110-7 implementation, however, any comparison standard can be referenced on the drawing. Specifically, ISO 10110-7:2017, 4.3.1.5 states "Since there are significant differences between different types of comparison standards, the make and model of the brightness comparison standard to be used shall be given in a note.". Such a comparison standard will likely be certified against some brightness or visibility reference retained by the manufacturer, or will perhaps be traceable to the US Army standard.

The machine vision system, therefore, can be verified by using the same comparison standard called out on the drawing, or some other traceable and certified artefact set. Such sets typically have at least three scratch-like artefacts and three dig-like artefacts, with known scratch grades and dig grades respectively, with grades that are representative of the range of brightness and size grades that will be employed in the evaluation. If the brightness and diameter of the artefacts are known, then the system can be calibrated to yield the correct values for the artefacts being used as the reference.

Note that the scratch brightness or visibility can vary significantly depending on the make and model of the scratch comparison artefact set being used. See for example, the average brightness in arbitrary units shown in Figure 1. Here, the brightness is given on a log scale, and some of the more common scratch and dig references are shown compared to the limit values for the US Army comparison reference sets. Reported values are for a specific sample of comparison set in each case; cited measurement error is ±1 count or 5 %, whichever is greater. For this reason, ISO 10110-7 requires that the make and model of the scratch and dig comparison set be referenced on the drawing.

To verify that the machine vision system is working properly the repeatability, reproducibility and fidelity can be evaluated.



Key

×	comparison set type 1	+	comparison set type 2
○	comparison set type 3	◇	comparison set type 4
△	comparison set type 5		
———	reference comparison set 1	—·—	reference comparison set 2

NOTE The solid and dashed lines are the limit values for the US Army comparison reference sets.

Figure 1 — Typical brightness values for a range of scratch comparison sets. Figure adapted from Reference [17]

8 Repeatability, reproducibility and fidelity in the context of optics imperfections

NOTE 1 The surface imperfection evaluation involves a binning process. The scratch and dig visibility or size is compared to a set of artefacts of a known grade, and designated to be one or the other grades as a result. Such a comparison has the benefit of speed when doing a visual inspection as compared to a more careful measurement of the specific properties of the imperfection. But a consequence of this binning system is that the repeatability, reproducibility and fidelity of a measurement system will vary depending on how close a given scratch or dig is to the nearest grade artefact. This phenomenon is described in more detail in Annex A. Therefore, it is important that the artefacts to be used in the evaluation of the performance of a machine vision system be chosen carefully, so as to best quantify possible errors. An artefact that is close to a specific grade will highlight the variation in result, while an artefact mid-way between two grades can mask measurement errors.

NOTE 2 An alternative method of evaluating imperfections using some specific measurand that can be quantified in SI units can be realised with machine vision. For example, it is possible to test the performance of the machine vision system in determining the value/measurand that is used to ‘lookup’ the grade. This applies to both visibility and dimensional testing parameters/measurands. Such an approach would allow a more conventional application of metrology standards, such as those described in ISO/IEC Guide 99 “International vocabulary of metrology”, (VIM), the ISO/IEC Guide 98 “Uncertainty in measurement” series, (GUM), and other standard metrology practices such as Gauge Repeatability and Reproducibility, or Gauge R&R. This is however not subject of this document at present.

8.1 Evaluation repeatability

The simplest of the performance metrics for a machine vision system to evaluate is repeatability. Repeatability in this context is the ability of the machine vision system to yield the same grade for a given comparison artefact to within its allowed evaluation error. In order to properly evaluate the performance of the system the repeatability can be verified with a scratch whose brightness or width is towards the middle of the range of scratches to be evaluated, and a dig whose diameter is towards the middle of the range of digs to be evaluated.

Machine vision systems are often specified with a required level of repeatability as a percent of attempted evaluations. The number of evaluations to be performed needs to be consistent with the specified repeatability. For example, a system which evaluated an artefact 20 times, in a short duration and with a single operator and which yields the same result all 20 times could be said to have greater than 95 % repeatability.

8.2 Reproducibility

The next parameter to be considered is reproducibility. For our purposes this is considered to be the ability to produce the same grade evaluation for multiple scratches and digs, under differing conditions. Parts are loaded and unloaded between evaluations. Different part orientations can be used, as well as different system operators if possible. Reproducibility is the ability to yield the same grade for a given comparison artefact to within its allowed evaluation error. In order to properly evaluate the performance of the system over a range of grades, the reproducibility can be verified with a range of artefacts that span the whole range of interest.

Machine vision systems are often specified with a required level of reproducibility as a percent of attempted evaluations. The number of evaluations to be performed needs to be consistent with the specified reproducibility. For example, reproducibility could be tested using four artefacts of the same grade that are evaluated 10 times each, repeated in two different orientations and by two different operators for a total of 160 evaluations. If the system produces the same grade in 144 of the 160 evaluations made, it could be said to have a reproducibility of 90 %.

8.3 Fidelity

The surface imperfection classification method described in ISO 10110-7 and ISO 14997-1 is based on the concept of visual comparison inspection with a human observer. This basis is the ultimate metric for the fidelity of a machine vision system employed to inspect optics based on their appearance or on their dimensions. When the machine vision system is realized correctly it can produce the same results on a certified artefact set as a trained inspector using the methods described in ISO 14997-1. When evaluating fidelity, the repeatability and reproducibility of the reference method is also taken into account, with the system yielding the same answer on average as the reference method, within some standard deviation determined by the reproducibility of the reference method.