Media Cybernetics Applications Note

Development of an Automated Optical Inspection System for Determining Percent Area Coverage for Spacecraft Contamination Control

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Abstract

This paper describes the use of an automated optical inspection system used to determine the percent area coverage of particle matter on surfaces for determination of surface cleanliness, in accordance with IEST-STDCC1246 (formerly MIL-STD-1246). The system consists of an optical microscope, motor-driven X-Y stage, digital camera, and image analysis software. It can be used to scan surfaces for particles with selected features; an example will be given of a scan of glass beads on Gel-Pak® surfaces. Gel-Paks are used to tape-lift spacecraft structure prior to shipment to a propulsion system supplier who prohibits glass beads from entering its facility.

Introduction

Contamination of spacecraft optical and thermal control surfaces by particulate matter is a constant concern during design, integration and launch operations. Traditional methods of assessing surface particle contamination consist of tape-lift and manual particle counting using optical microscopy per ASTM E1216, with classification of surface cleanliness in accordance with IEST-STD-CC1246 (formerly MIL-STD-1246). In order for a contamination control engineer to determine the allowable time that critical instrument apertures can be open to cleanroom environments, airborne dust settling rates must be obtained by counting and sizing dust particles on fall-out plates. Polished silicon wafers[1] and Gel-Pak® surfaces have been found to work well for this purpose.

These techniques all rely upon the use of optical microscopy to count and size particles, a labor intensive and time consuming task, but a task perfectly suited to automated optical inspection (AOI). Fields employing AOI and related image analysis include electronic manufacturing[2], biological sciences[3], remote sensing[4], surveillance[5], and security[6].

System Description

The system is shown below and consists of the following (Figure 1.):

Microscope:	Leica model DMRX with 2.5X, 5X, and 10X objectives
Digital camera:	Diagnostic Instruments Insight
Stage controller:	Ludl Electronics model MAC5000
Hand controller:	Ludl Electronics model 73000362
X-Y stage:	Ludl Electronics model 9801-NE
Illumination source:	Schott ACE I Fostec
Fiber optic cable:	Schott Fostec with dual guides
Illumination lens:	Schott Fostec 1-inch by 1/8-inch slit
Reticle:	Leica model 10310345 ruled calibration standard
Personal Computer:	Flat screen display running Windows 2000 with at least one GB RAM
Software:	ImagePro-Plus v. 4.5.0.19 Scope_Pro v. 4.0 (Media Cybernetics)

Figure 1- System Configuration and Description

Calibration Standards

Calibration standards consist of a Leica glass reticle (ruled in 0.1 mm increments and used to verify linear measurement accuracy) and Adtek chrome on a glass photo-mask (to verify the accuracy of percent area calculations). The photo-mask has four one square inch areas; each with evenly spaced 10µm x 10µm dots and the following percent area coverage: 0.01%, 0.1%, 1.0%, and 5%. This photo-mask was made using standard photolithography methods employing sub-micron accuracy. The standards are pictured in Figure 2. The Diagnostics Instruments Insight camera used for the analysis produces an image size of 1600 pixels by 1200 pixels. The three objectives produce frames with the following pixel sizes and frame characteristics (Table 1):

Figure 2- Adtek Photo-Mask and Leica Glass Reticle

Objective	Pixel Size	Frame size
2.5x	2.95-µm x 2.95-µm	4726-µm x 3545-µm
5x	1.47-µm x 1.46-µm	2349-µm x 1756-µm
10x	0.73-µm x 0.73-µm	1166-µm x 871-µm

Table 1- Pixel Information for Diagnostics Instruments Insight Camera

Gel Pak® Enables AOI

Some technologies enable others to progress. This is certainly the case with Gel-Pak trays, which are used in the application to facilitate imaging with the AOI system. Gel-Pak trays were originally developed for the transport of semiconductor die, where they are currently still in widespread use[7]. The removable tray consists of a molded black dissipative plastic square pedestal coated with a uniform tacky silicone pressure-sensitive adhesive (PSA). Tackiness of the PSA ranges from very mild to very aggressive, depending upon user requirements. Figure 3 shows Gel-Pak trays in their closeable carrying cases. The left-hand Gel-Pak was used to tape-lift a flight structure for percent area coverage determination. The right-hand Gel-Pak contains 5-mil glass beads used for roundness determination, as part of a glass bead inspection of honeycomb structural panels prior to shipment to propulsion system supplier facility.

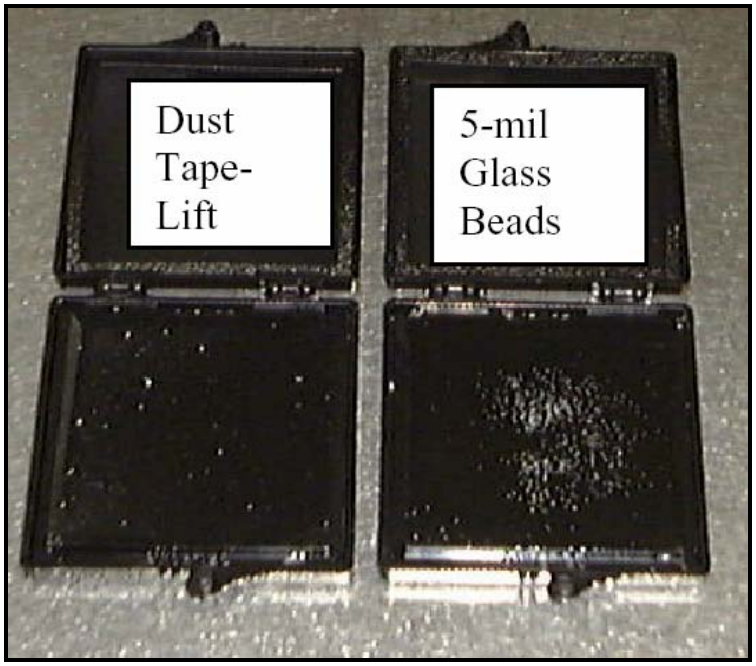


Figure 3- Gel-Pak Trays

Unpublished testing by the author indicates that the Gel-Pak adhesive begins to lose weight at about 60°C ; up to about 80°C the weight loss is entirely isopropyl alcohol (IPA). Testing at the Applied Physics Laboratory (APL) has shown that a monolayer of siloxane is left on surfaces that come into contact with Gel-Pak trays but this slight residue is easily removed with common cleaning solvents such as IPA, hexane, and chloroform. Further testing at APL has shown that paint films applied to Gel-Pak tested surfaces have excellent adhesion in thermal vacuum testing over the temperature range of liquid nitrogen to 100ºC. Typical Gel-Pak thicknesses, as measured on a computer controlled coordinate measuring machine, had these statistics for the thickness of the tacky film fixed to a granite base:

Min:	0.0722
Max:	0.0834
Range:	0112
Average:	0.0775
Std. Dev.:	0.0021
# of Points:	411

Image Processing

Under dark-field illumination particles on wafer or Gel-Pak surfaces look like stars in the night sky. Figure 4 shows dust fixed to a Gel-Pak substrate. The image is used as an example of percent area coverage determination, however, the entire Gel-Pak tray could be scanned using the 2.5x objective. As indicated in Table 1, the resolution at this magnification is about 3-microns under ideal illumination. At higher magnifications the flatness deviation of the Gel-Pak surface (typically ~0.112-inches) reduces the area that remains in focus during scanning. At 2.5x the entire 2-inch by 2-inch surface is scanned by Image-Pro's Scope-Pro module in about 154 frames. This plug-in allows highly repeatable frame tiling to occur and for a composite tiled image to be created. At 5x the number of frames to cover the Gel-Pak becomes 625, however experience has shown that a ten-frame by ten-frame scan is about the maximum that remains in focus. At 10x the number of frames to cover a Gel-Pak is 2541. The in-focus scan size at 10x is usually 3-frames x 3-frames. These limitations on scan area will soon be removed when an auto-focus (z-stage) control is added to the AOI system.

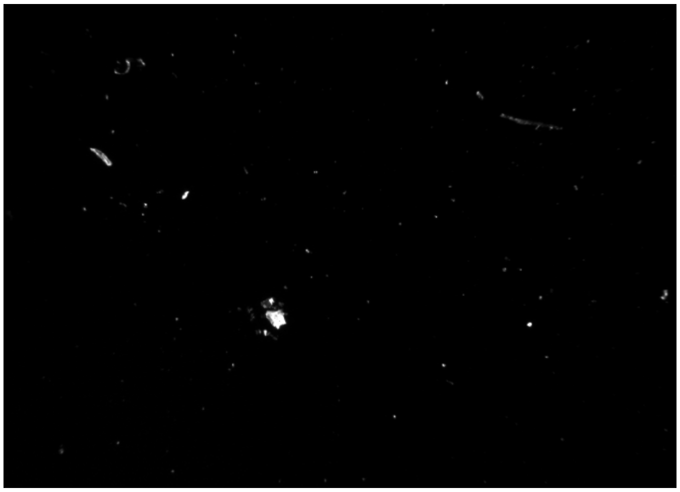
The flatness of 4-inch diameter silicon wafers is such that the entire wafer remains in focus at 10x with the present system. It is customary to scan a 2-inch by 2-inch area of each wafer at 10x, producing an image of 2541 frames or 4.9 giga-pixels. With a pixel depth of 8-bits this is a 39Gbit image. The PC used with this system has a clock speed of 2.53GHz which yields an image speed of 14.7 frames per minute.

Example 1- Percent Area Coverage

Figure 5 shows thresholded areas from the captured image. Image-Pro Plus® software allows many analysis tasks to be performed on the captured image[1]. In this example a single frame is analyzed for percent area coverage by selecting the **Area** property on the **Count/Measure** screen, performing the count and then dividing sum of area (in square microns) by total scan area. In this example:

149979.59 μm2 (4726.7μm x 3545.1μm) x 100 = 0.895%

[1] Such as background correction, restricted dilation, threshold adjustment, fast Fourier transform, filtering, mathematical operations, and segmentation.



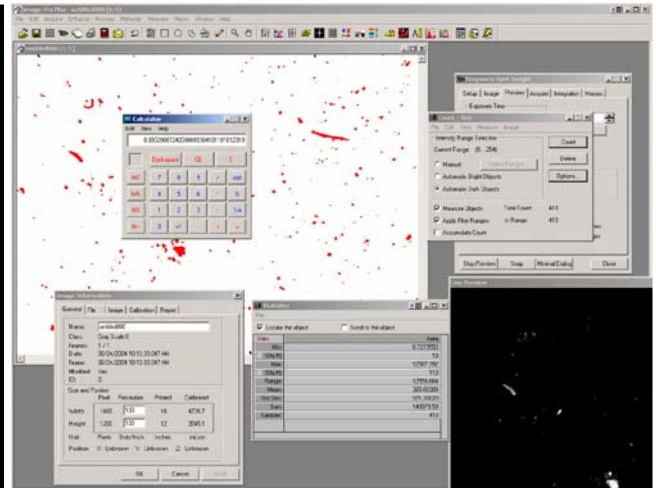


Figure 4 (Left)- Gel-Pak tray with fixed particles. Darkfield illumination, 2.5x magnification.
Figure 5 (Right)- Thresholded areas (red) indicating particulate matter. The original image appears toward the lower right of the workspace.

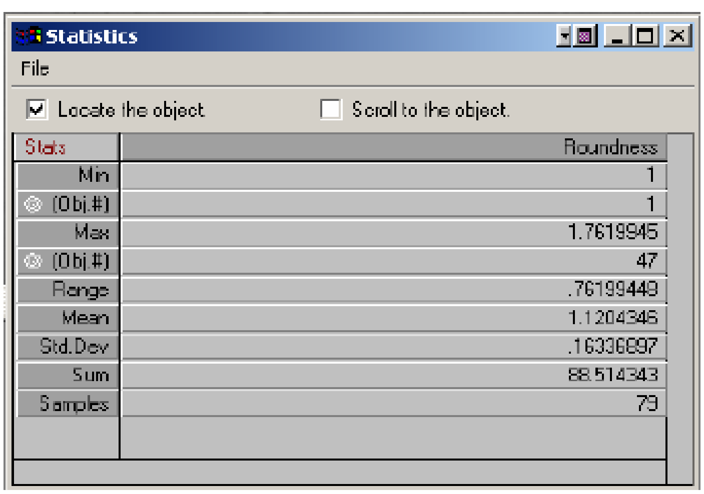
Example 2- Glass Bead Inspection

Three APL spacecraft have their propulsion systems manufactured and installed at a facility that has a prohibition on glass microspheres due to their propensity to migrate into assembly areas and cause latch valve leaks. These spacecraft are for the New Horizons mission to Pluto and the Kuiper Belt (website: http://pluto.jhuapl.edu/) and the STEREO mission (website: http://stereo.jhuapl.edu/). A convenient method of sampling a large amount of surface area is to use a single Gel-Pak to touch about one hundred different 2-inch by 2-inch areas (about 2.8 square feet). In this manner relatively few Gel-Paks can represent most of the spacecraft structural area; these Gel-Pak samples can be scanned in a few minutes. In this particular case the criteria was to screen for 5-mil glass micro-sphere. In order to obtain an idea of the relevant properties of 5-mil glass beads a sample was obtained from the composites laboratory at APL by sprinkling onto a Gel-Pak, as shown on the right-hand sample in Figure 3. The most useful initial filter criteria were area, size, and roundness. After several trials roundness was found to be the most useful screen. Roundness is defined as:

$$P^2=(4\prod A)$$

Where P = perimeter and A = area

Roundness statistics for 5-mil glass beads are shown in the following example:



Statistics

File

☑ Locate the object ☐ Scroll to the object.

Stats	Roundness
Min	1
(Obj.#)	1
Max	1.7619945
(Obj.#)	47
Range	.76199449
Mean	1.1204346
Std.Dev	.16336897
Sum	88.514343
Samples	79

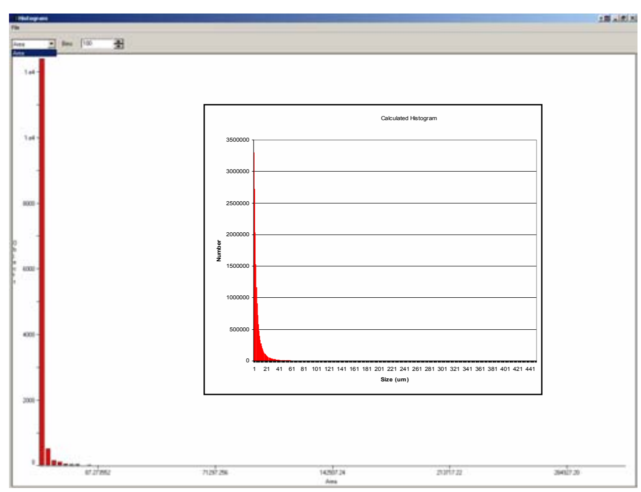


Table 2- Roundness Distribution/Statistical Summary from Image-Pro Plus. The histogram display on the right shows an example of roundness value distribution for a range of thresholded particles (larger view) as well as estimated values calculated using IEST-STD-CC1246 (inset). The data suggest the distribution is log-normal, verifying the use of the IEST-STD-CC1246 standard.

Discussion

Automated optical inspection (AOI) is the fusion of traditional optical microscopy with digital imaging and digital image analysis software. As applied in the contamination control laboratory, AOI technology speeds determination of particle counting for tape-lift and fall-out determination and increases accuracy. The ability to sort objects also allows statistical treatment of images for the detection of round objects, i.e. searching for glass micro-spheres. Gel-Pak trays enable particle counting by tape-lift and fall-out to be performed easily and quickly.

The image analysis software used on the AOI system of the Contamination Control group within the Space Department at the Applied Physics Laboratory of Johns Hopkins University (APL/JHU) is Image-Pro Plus from Media Cybernetics, Inc.

Image analysis software on the AOI system described in this paper allows up to fifty two morphological filters to be applied to an image as well as over a dozen mathematical operations; thus making IPP a powerful tool for research and production. Examples of how this capability has been used at APL include:

- Determination of spacecraft surface cleanliness in accordance with IEST-STD-CC1246D (formerly MILSTD-1246)
- Correlation of predicted and actual particle fall-out rates based upon intermittent airborne particle counting per ISO 14644-1 (formerly FED-STD-209)
- Determination of biological object origin on fall-out samples for possible remediation of air handling equipment
- Particle generation potential from chromate conversion coating after exposure to various thermal vacuum conditions
- Determination of particle release due to actuation of separation systems and other spacecraft mechanisms
- Spot-checking of facility and equipment cleanliness
- Sampling spacecraft structure for glass beads prior to shipment to propulsion system supplier's facility
- Implementing an easily replaced fall-out monitor within payload fairings during launch operations

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