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One of the most widely used analytical methods of determining cleanliness for industrial cleaning is the collection and evaluation of residues that remain on parts after cleaning. Advancing technologies have brought us a variety of ways to measure not only the number and weight of residual particles, but also their size and shape, an increasingly important consideration in the evaluation of part cleanliness. Cleaning technicians must choose wisely and according to their specific applications, however, because evaluations of the same data using different techniques may give vastly differing results.

Why Measure Particle Geometry?

Over the years, as cleanliness standards have become more stringent and specific, particle composition, size, and geometry have become important considerations in the evaluation of part cleanliness. In a growing number of cases, size, geometry, or composition of a particle is of even greater concern than its other characteristics. This is especially true when parts are to be assembled into close tolerance devices, including internal combustion engines, transmissions, and braking systems with many mating and sliding surfaces and orifices. In these devices, a single particle of a particular type may result in a costly repair or possible loss of life.

Particles of different geometries can be generated depending on the operations a part sees during its manufacturing process. A casting may contain casting sand (crystals of silica), slag (metallic residue formed in the matrix of the casting sand), scale (carbonized flakes formed from mold releases or organic contaminants during the casting process), or machining chips. Chips will take on a variety of configurations depending on the machining operation or operations that formed them. Drilling will produce long spirals (soft metals) or "C" chips (harder metals). Boring will produce large "C" chips or slugs, while tapping will produce small "C" chips or thin spirals. Sawing will produce small irregular chips as wide as the cutting blade. Single-point machining will produce spirals or "C" chips. Honing, lapping, and polishing will generate very small particles (200 μ m or smaller) of irregular shapes. These particles will consist of abrasives, binders, metal being removed, and materials trapped in the matrix of the substrate.

Filtration systems rely on geometry to capture or prevent the passage of particles. Square, round, or irregularly shaped objects may get caught in a woven mesh or in a filter "mat" composed of randomly oriented fibers, depending on the dimensions of the openings in the filter. Conversely, long, thin, or spiral objects may pass or "work their way through" a mesh filter, so filter meshes or screens are particularly susceptible to long, slender particles. A mesh opening of 40 μm is actually a rectangle and, by simple trigonometry, can still allow a particle up to 56 μm in minimum dimension to pass through on the diagonal. The same mesh will effectively stop a cubed particle of 41 μm.

Depending on the orientation of the fibers in the mesh or mat material, the openings can also change. A filter mesh for an automotive fuel injector has openings of 35 μm, and the fibers are measured to be 30 μm in diameter. In the application, the mesh is curled into a small tube. In its undistorted condition, the openings are rectangular. However, the openings can become irregular due to distortion of the mesh as a result of bending. This allows particles of greater dimension to penetrate the mesh from different angles. The filter scenario is an appropriate parallel to many situations found in a variety of mechanical assemblies involving passageways and contaminating chips.

Practical examples can be seen in fuel or hydraulic circuits. Curly chips, although they may not plug a nozzle directly, may serve to hold back other chips and particles in a mass that will clog a passage. Long, thin chips may move through an orifice and cut an O-ring or plug an injector nozzle.

Weighing and Counting Solid Particles

Residues fall into one of two classifications: liquids, generally consisting of fingerprints, oil, grease, and other lubricants used in the manufacturing process, and solid particles of all descriptions. In many critical applications involving mechanical equipment, solid particles are the major concern, as they may interfere with proper operation of moving parts.

In analyzing cleanliness related to the presence of solid particles, the particles must first be collected and segregated. This is commonly accomplished by simple filtration. Samples of parts washed using the technique to be evaluated are rewashed using a more aggressive cleaning agent (normally a solvent) and enhanced mechanical means (flushing, hand brushing, and, in many cases, ultrasonics). The liquid used for rewashing is collected along with the contaminants it has removed. Particles are separated from the rewashing liquid and soluble contaminants by vacuum filtration through a fine filter. Once the particles are isolated on the filter, they are evaluated either gravimetrically by measuring their total weight or by other appropriate means, such as number, size, or makeup and characteristic shape.

The weight of the particles collected is determined by simply subtracting the weight of the filter patch before filtration of the rewashing liquid from the weight of the patch and particles after filtration. This technique is simple, repeatable, and requires a minimum of sophisticated equipment. Simple weight analysis is an adequate evaluation of cleanliness when the nature of the contaminant is well established, as is often the case with buffing and lapping compounds. Weight may also be an appropriate measure of overall solid contamination when particle size and configuration are not issues.

Another widely used analytical technique is simple particle counting, one method of which is to collect the particles on a filter media with a grid printed on it. A simple count of the number of particles seen in a given area as defined by the grid pattern establishes the particle count.

Alternatively, a transparent grid overlay placed directly on the filter or a calibrated grid generated by the microscope optics may be used to establish the boundaries of the area for counting.

Particle Measuring Methods

Traditional methods used to measure particle size involve an operator using a microscope with a graduated reticule scale or a crosshair reticule and a calibrated micrometer stage to measure the length, width, and other dimensions of particles. Visual observation, however, is tedious and may be subject to operator error. Automated methods of particle evaluation using computer vision and sophisticated software are rapidly replacing human operators. The parameters for particle characterization and measurement, however, remain basically the same as described below.

In the following particle measuring methods, the same collection of reference particles is evaluated using several different techniques. These particles are typical of those seen on ductile metal castings. Some are a result of the casting process itself, such as parting flash and sand residue, while others are generated by a variety of cutting operations including drilling, tapping, sawing, milling, turning, and broaching.

Simple Area

Historically, only the longest dimension of a particle was considered for evaluation. Now, however, it is more common to consider particles as two- and often three-dimensional objects. To determine the simple area of a particle, one mentally visualizes a rectangle around the particle and measures the length and width of the imagined rectangle (**Figure 1**). From these measurements, one can determine the rectangular area that would contain the particle, hence, the minimum dimensions of a rectangle that would allow the particle to pass. If machine clearances are sufficient to allow the particle to pass, it is of little concern. If not, the particle would be unacceptable. This measurement is also important in determining if the filtration in a given application is sufficient to remove this particle.

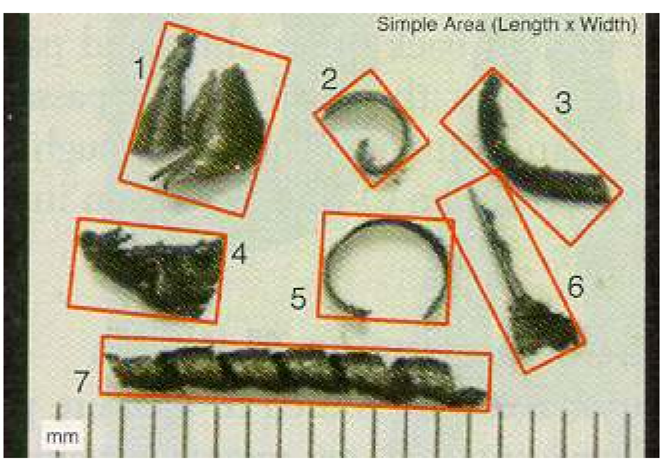

Figure 1. The simple area of a particle is determined by claculating the area of an imaginary rectangle around the particle.

A major shortcoming of this technique is that chips, particles, and fibers seldom present themselves as neat rectangles. Curves, spirals, and irregular shapes do not fill the total area of a rectangle and are therefore misrepresented using this technique; they may not be stopped by a given filter, even though their rectangular cross sections will not fit through a given opening.

Long Axis and Cross Section

Another method commonly used to measure particles is to determine the long axis and the widest cross section of the particle using the measurement techniques described above for the rectangle. The area of the particle is then calculated using these measurements, as seen in Figure 2. Again, some difficulties appear. On some particles, such as Particle 1 in the figure, the calculated area will not change from the area measured using the rectangle technique. On others, though, it will change slightly, as illustrated by Particle 4. For curved particles such as "C"-shaped chips and full loops like Particles 2, 3, and 5, this method more accurately determines the minimum opening through which particles of this shape will pass.

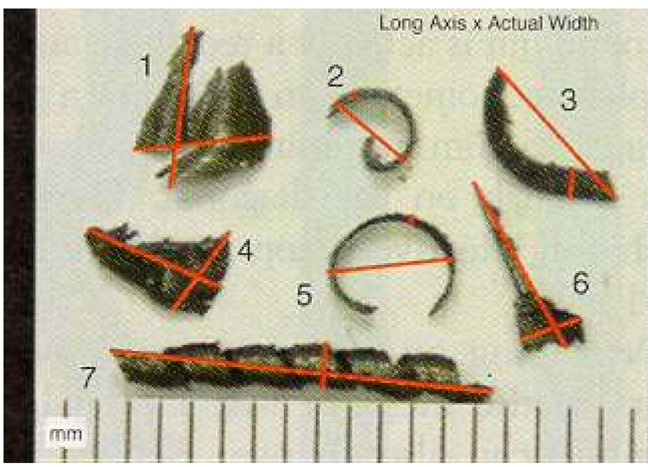

Figure 2. The long axis and cross section method of claculating the size of a particle is most useful for "C"-shaped chips and loops (Particles 2, 3, and 5).

Curvilinear Length and Longest Width

A method used to obtain a better picture of oddly shaped particles and those that are flexible, such as fibers, is to measure the curvilinear length (Figure 3). By using edge-tracking methods provided by measurement software or breaking the curved object into line segments, the total length of this type of particle can be measured. This is particularly useful in characterizing Particles 2, 3, and 5. Knowing the curvilinear length of a particle helps in the determination of the consequences in the worst-case condition should the particle assume its longest possible configuration by flexing.

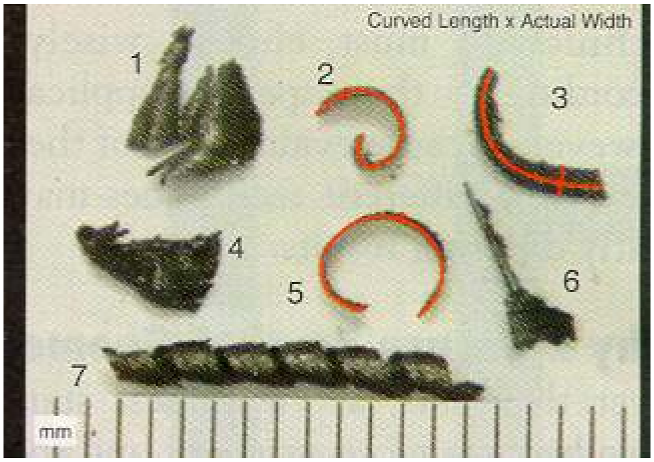

Figure 3. Software can be used to measure the curvilinear length of a particle, which accounts for the longest possible configuration in the event of flexing.

Circumscribed Area

A novel approach taken by some automotive manufacturers is illustrated in Figure 4. This "circumscribed area" technique involves taking the long axis of the particle and rotating it. The area is determined by using the formula for the area of a sphere ($\pi D^2 \div 4$). The theory is that the particle can cause interference anywhere within its circle of influence. Although similar to width by length measurement, this measure allows for interference in any possible particle orientation.

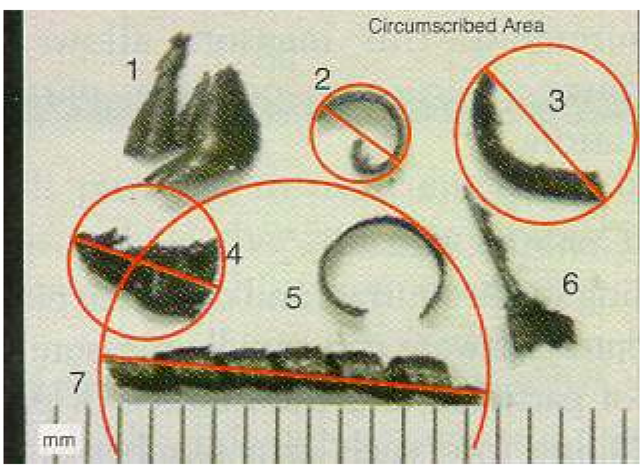

Figure 4. The circumscribed area is calculated by taking the long axis of a particle and forming a sphere, the area of which accounts for its circle of influence.

Pixel Contrast Area

By using shade contrast and counting pixels, computer software can rapidly measure the sizes of particles, and the number of particles falling into each of a number of size ranges (Figure 5). The major benefit of this measurement technique is that it is automated, thereby making the evaluation process faster, more accurate, and insensitive to operator interpretation. Some of the pitfalls of this technique are that it may not count bright or reflective areas on the image, or it may count shadows as areas. Tools provided to overcome these limitations include changing the contrast of the image or using histogram stretches.

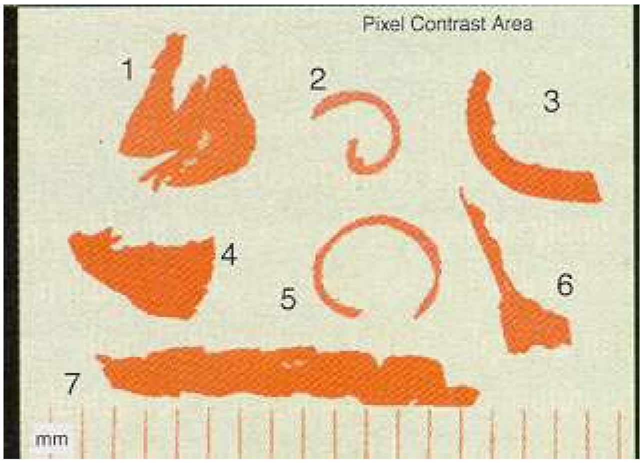

Figure 5. Computer software can use shade contrast and pixel count to quickly and accurately measure the size of a particle.

Differences in Data

The **Table** shows that each measurement technique can yield widely varying results on the above group of reference particles. Depending on the geometry of the particle, the simple length from a box around the object can be different from the long axis. Curvilinear length measurements will be significantly larger than simple or long axis measurements. Widths will also vary depending on where and how they are taken. For instance, Particle 3 is a curved chip. If a box is drawn around it (**Figure 1**), the simple length is 5.26 mm and the simple width is 2.54 mm, resulting in an area of 13.36 mm^2. The long axis and longest width yield 5.72 mm^2, the curved area 6.46 mm^2, rotational area 25.16 mm^2, and the pixel area 5.02 mm^2. Therefore, different methods will give larger and smaller values.

Table: Particle Measurement Values

Image #	Simple Length (mm)	Simple Width (mm)	Long Axis (mm)	Actual Width (mm)	Curved Length (mm)	Simple Area (mm^2)	Long Axis Area (mm^2)	Curved Area (mm^2)	Rotational Area (mm^2)	Pixel Area (mm^2)
1	5.11	4.40	5.11	4.40	5.11	22.48	22.48	22.48	20.51	10.54
2	3.01	2.79	2.93	0.40	7.12	8.40	1.17	2.85	6.74	2.64
3	5.26	2.54	5.66	1.01	6.40	13.36	5.72	6.46	25.16	5.02
4	4.72	2.98	4.70	2.82	4.73	14.07	13.25	13.34	17.35	7.81
5	4.11	3.33	4.11	0.50	9.46	13.69	2.06	4.73	13.27	1.94
6	5.97	2.15	5.97	2.15	5.97	12.84	12.84	12.84	27.99	3.84
7	12.30	1.91	12.30	1.47	12.30	23.49	18.08	18.08	118.82	11.20

Careful Specification

A thorough cleanliness specification process addresses not only the weight and size of particles allowed but also their geometry. Careful analysis of the mechanical system and the possible effect of chips of differing geometry is an important part of the determination of an appropriate cleanliness specification.

About the Author

Bill Rockwell is a laboratory manager for CAE Cleaning Technologies and has worked in the cleaning/coating/painting/plating industries since 1983. He has a degree in chemical engineering from Tri-State University in Angola, Ind. He can be reached at brockwell@caeclean.com.