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Clean Manufacturing Tutorial:
"Abrasion Basics for Contamination Control"
To minimize particles, understand abrasion

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Everyday experience shows that particles are generated by abrasion. Chalk dust, pencil "lead" powder, particles due to the wear of bearings—all are familiar. Despite how commonplace wear seems to be, however, the subject is actually quite complicated and still under active investigation. Abrasion — the wearing away of one solid surface by another — is a common source of contaminating particulate matter in clean manufacturing. Abrasion-generated particles can be transported by gas, liquid, or solid-solid contact and result in significant damage to products.

The literature of tribology (the study of lubrication, friction, and wear) indicates that the volume of material produced by abrasion is proportional to the normal force and the relative distance traveled, with the proportionality constant itself dependent on the materials (which may change as the abrasion continues), the environment, and, sometimes, the speed.[1] Environmental factors such as temperature and humidity complicate and may also contribute to the process.

Figure 1 shows two surfaces sliding with respect to each other at velocity U. The force normal to the area of contact between the two is L, and the apparent area of contact is A. The volume rate of particle generation is therefore[1]:

$$dV/dt = k\,L\,(dx/dt) / H$$

where

k = dimensionless constant

L = load, force units

dx/dt = velocity, distance per unit time

H = hardness, pressure units, force per unit area

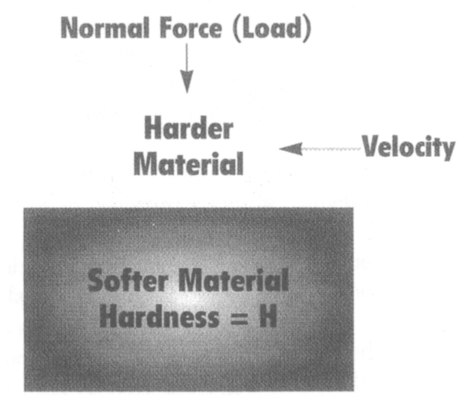

Figure 1. Basic components of a system undergoing abrasion.

The dimensionless constant k has values from near 0.1 (e.g., zinc on zinc) to much less than 1 ppm (e.g., polyethythene on tool steel[1]). There is a significant role of adhesion involved in abrasion, so relative hardness is only one of the factors influencing wear. A softer material can somewhat abrade a harder material, and two identical materials will wear each other. One striking aspect of this equation is that the apparent area of contact does not appear. For the same force, wear is not decreased by spreading the force over a larger area.

The explanation for this is that the microscopic contact involves only a small fraction of the area, and the material deforms until the local pressure no longer exceeds its yield stress, so that the contact area increases to match the load.

If the wear particles are emitted to and mixed with a gas or liquid stream, then the concentration in the stream will be, at dynamic equilibrium, the ratio of the generation rate (G, as number, mass, or volume of particles per unit time) to the fluid volume flow rate (Q, volume per unit time), which for

$G = dV/dt$ becomes
$c = G/Q = k\ L\ (dx/dt)/H\ Q$

Thus, the concentration can be reduced by lowering generation or raising the dilution flow. If the particles are left behind on the surface, then their area concentration will tend toward the ratio of the generation rate to the rate of new apparent area of contact

$c' = G/(dA/dt)$, which becomes
$c' = [k\ L\ (dx/dt) / H] / [W\ dx/dt] = k\ L/W\ H$

so that spreading the load in a direction perpendicular to the motion does not lessen the generation rate but does lower the concentration left behind.

What Is Wear?

Rabinowicz[1] listed the following types of wear: abrasive, adhesive, corrosive, and surface fatigue.

Abrasive wear is like the plowing of a field and the removal of some of the material disturbed by the plow. The “plows” may be asperities on the surfaces or particles generated by previous wear. Softer materials are particularly susceptible to this kind of wear.

Adhesive wear occurs when parts of one surface are strongly attracted to parts of another surface, to the point where these parts adhere and a new boundary is formed elsewhere, transferring the materials from one surface to another. Very similar surfaces are particularly susceptible to this kind of wear.

Abrasive and adhesive wear are quite common. To lessen such wear, Rabinowicz[1] recommended:

- Use hard materials.
- Use materials that do not adhere well to each other, such as a metal and a non-metal.
- Lubricate where feasible.

To this list, one might well add a fourth point:

- Remove wear debris as rapidly as possible to prevent it from accelerating wear.

Corrosion, the chemical transformation of a surface, is another cause of generation of particles by surfaces. (The rusting of iron is a familiar example.) Corrosion is generally accelerated by moisture and by the presence of ionic contaminants (e.g., NaCl).

Except in extremely dry environments, water molecules are absorbed on virtually all surfaces. As the relative humidity[*] increases, the surfaces become more nearly covered with a layer of water molecules. Various salts are hygroscopic (attracting water) and change from crystals to droplets at characteristic humidities. Sodium chloride, for example, changes at 75% RH at room temperature. Scratches and tiny spaces between particles and surfaces also hold water molecules preferentially and can be wet at humidities well below 100% RH. The products of

[*] RH = moisture concentration in air divided by moisture concentration at saturation. See “Water, the Deadly Intruder,” A^2C^2, March 1998

corrosion may well, like rust, be less strong than the original material, leading to greater wear during abrasion.

Surface fatigue occurs when surfaces lose material due to repetitive stress, such as bending, even where there is no surface-to-surface contact. Where there is such contact, as in ball bearings, the repetitive flexing can cause material fatigue and subsequent cracking and particle emission.

Rabinowicz[1] noted the following: The particles formed as a result of contact wear are often nearer to 1 mm in diameter rather than 1 µm.

Lubricants lower the abrasive wear rate, but raise the fatigue wear rate. Time-before-failure is roughly proportional to the reciprocal of the cube of the load, but these times vary greatly.

Erosion is an additional factor. When particles are carried through a conduit by a high-velocity fluid (gas or liquid), they can impact the surface of the conduit to the degree that the impacts produce particles. Common examples are seen in rocks smoothed by the passage of sand-bearing water or sand-bearing air. Larger, harder particles moving at higher velocities tend to produce more rapid erosion.

Despite its frequently negative consequences, wear can be used as a process indicator. Often ultrasonic baths are used in cleanrooms to accelerate cleaning of materials. Tiny bubbles form and collapse due to the sound compression-rarefaction cycle. This activity accelerates cleaning but can cause damage to some surfaces; such damage to aluminum foil can be used as an indicator of the degree of ultrasonic energy being produced in the bath.

Suspension of Particles

Particles produced by wear can remain attached to surfaces or become suspended in the medium (gas or liquid) in which the wear is occurring. Larger particles and more rapid, turbulent fluid flows are associated with greater suspension. Because of the surface tension of the liquid and the small dimensions involved, wet particles adhere to a surface in air more tenaciously than do particles that start dry. Particles that adhere due to surface tension may subsequently become glued (the “glue” being formed by impurities) to the surface once the liquid dries. Thus, particles generated by abrasion under wet conditions are less likely to become airborne.

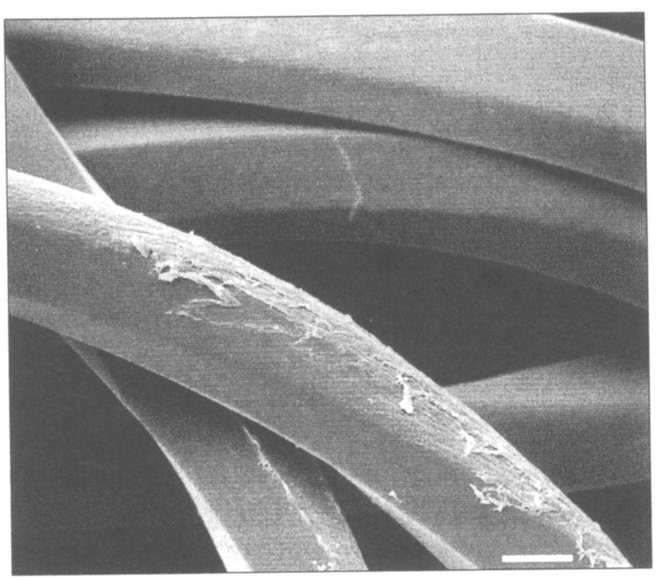

Figure 1. Photomicrograph of polyester fiber with abrasion and abrasion debris. (courtesy H.R. Bhattacharjee Ph.D. Texwipe)

Abrasion from Wiping in a Cleanroom

Wipers are used for cleaning and as clean work surfaces in some cleanrooms. They are used wet and dry, in a range of pressures, on a variety of surfaces.

Tests we have reported elsewhere[2] allowed comparison of wiper types (and perhaps wiper lots) with regard to the particles released by dry abrasion under a specified set of conditions. **Photo 1**, a photomicrograph of a polyester fiber that has undergone abrasion, shows both the abraded region and some wear debris; such debris can become dislodged and contaminate other areas. **Figure 2** shows the means ± the standard errors of the means for the particle generation rates due to the abrasion of knitted polyester wipers.[2] Where the intervals of means ± standard errors do not overlap, the differences between the wiper types can be considered statistically significant. The more closely the usage conditions resemble the test conditions, the more closely the rank ordering of the wiper types and perhaps the ratios of particles generated in use by the wiper types would resemble the results found in the tests.

Although superior to natural fiber wipers, polyester knit wipers were found to produce particles at intervals of means of which varied by as much as a factor of 4x, from wiper type to wiper type.

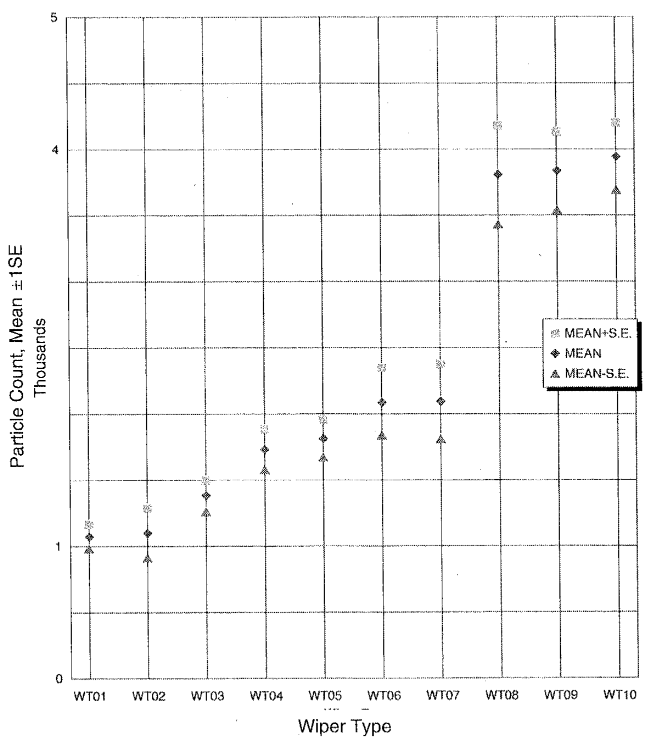

Figure 2. Graphical comparison of the abrasion rates (machine direction plus cross direction) for various types of knitted polyester.

The wipers were tested by being drawn across a metal screen, which allowed the particles (0.5 µm and larger) that were released to be transported to and counted by an aerosol particle counter.

Wiping with the yarn alignment in the cross direction generated more particles than did wiping in the machine direction. Possible causes include differences in the typical local contact geometry and in the relative velocity distributions and more global differences in the stretching of the knit during the motion. The knit produces rows that run along the machine direction like rails, but run at right angles to the cross direction, creating ridges. Factors affecting the susceptibility to abrasion of a knit are likely to include the stress modulus of the basic (bulk) polymer and the treatment of the filaments and the geometry of the yarns and the knit.

Clearly, there is a trade-off between using abrasive material that might be very effective in removing contaminants but might also generate particles in significant amounts and non-abrasive material that might be less effective. Scouring the inside of a process chamber would call for a more abrasive wiper than would cleaning the lens of an optical device. Wetting either wiper could lessen abrasion and improve cleaning, but would be likely to leave behind a liquid film that might include contaminants. Ideally, such wet wiping in either application would be followed by gentle dry wiping.

Conclusions

Minimizing particle generation is an important part of contamination control. Proper design, choice of materials, and operation can help reduce the quantity of particles generated by abrasion. Dilution by mixing with gas or liquid flow or controlled convection, especially by the use of laminar flow, can lessen the transport of contaminants to products. Even wiping of surfaces can be done in ways that are cleaner or less clean, with wet wiping followed by gentle dry wiping often the best approach.

References

1. R. Rabinowicz, *Friction and Wear of Materials*, Second Edition, John Wiley & Sons, New York 1995.

2. O. Atterbury, H.R. Bhattacharjee, D.W. Cooper, and S.J. Paley, "Comparing Cleanroom Wipers with a Dry Abrasion Resistance Wiper Test," *MICRO*, 15 (9), Oct. 1997.

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