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New Tests for Determining Adhesive Abrasivity

Data Correlates to Real Life in Auto Plant

Over the past 20 years, the world has seen an enormous growth in the use of adhesives and sealants by the automotive and truck industry. In North America, an average of 13 pounds of adhesives and 35 pounds of sealants are now used in the construction of every vehicle.[1] Due to the wide variety and changing preferences in the substrates to which these adhesives/sealants must bond, a significant number of different types of adhesive and sealant formulations are required. To meet this need, adhesive and sealant manufacturers must utilize a wide variety of resins and fillers that inherently affect both the selection and operation of application equipment.

All surfaces in application equipment (e.g., pumps, applicators and meters) that come into contact with an adhesive or sealant may exhibit a reduced lifetime due to degradation resulting from chemical reaction or excessive wear. These contact surfaces include the seals, ball valves, rods and cylinders in piston pumps and shot meters; the nozzles or tips in applicators; and the gears or other moving parts in flow-measurement devices.

Chemical degradation usually manifests itself in the form of corrosion on metal surfaces or through a reaction with the elastomeric materials (i.e., seals) present in the application equipment. The occurrence of wear in application equipment is usually confined to sliding surfaces, parts intruding into the flow path and the small orifice in applicator nozzles.

The test methodologies currently used to investigate wear phenomena are limited in their ability to measure the abrasivity exhibited by different adhesives and sealants. Although the classical tribological tests (pin on disk, particle impingement, etc.) are useful in measuring sliding friction and the wear resistance exhibited by different materials, these tests were not designed to be run in the presence of a liquid test medium other than a small amount of a lubricant. In addition, the accuracy of abrasion tests designed to operate in the presence of a liquid medium, such as the Miller/SAR Number test[2], are hindered by the rheological properties exhibited by most adhesives and sealants.

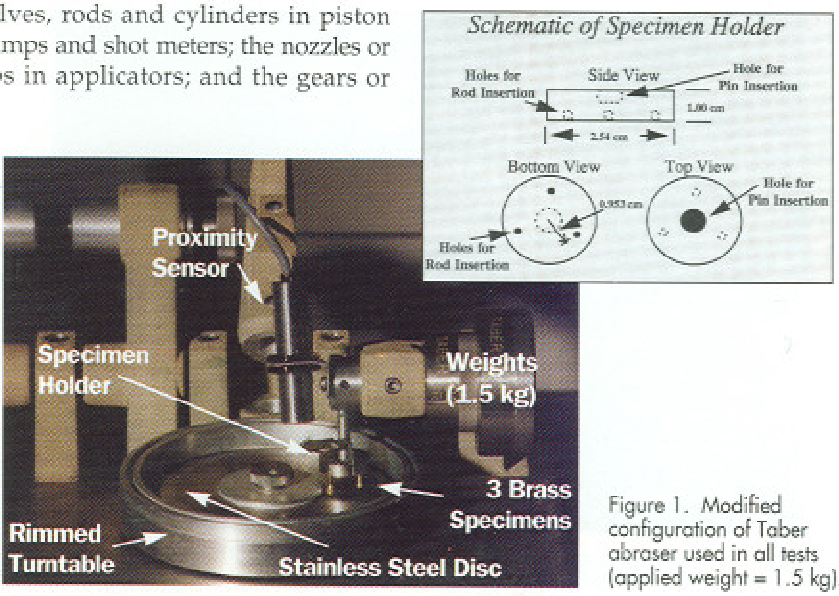

Figure 1. Modified configuration of Taber abraser used in all tests (applied weight = 1.5 kg).

Two laboratory test methods, namely a modified Taber™-abraser test (sliding wear) and a flow bench test (erosion), can be used to obtain a comparative measure of the abrasivity exhibited by adhesives and sealants.

Experimental Details

To demonstrate the usefulness of the following two laboratory tests, the results obtained from each test were compared to the wear that actually occurred in equipment used to move and apply an identical adhesive formulation in an automotive manufacturing environment.

Adhesive Selection — Epoxy-based adhesives used in an automotive hem-flange application were selected for initial experimentation due to the large differences in the amount of wear they cause to application equipment operated in an assembly plant. All the adhesives used in this study were actual commercial samples sold to the automotive industry.

In total, epoxy-based adhesives from three different manufacturers (identified as I, II and III) were examined. Several formulations from these manufacturers — containing different types of fillers — were evaluated. Table 1 provides a generic

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description of the different fillers present in the epoxy-based adhesives used in this study.

Table 1. Description of the Filler Types Present in the Epoxy-Based Adhesive Formulations

Adhesive Identification	Description of the Filler Type(s) in the Epoxy-Based Adhesive Formulation[†]	Estimated Range of Hardness Exhibited by Filler Content[††]
I-a	Inorganic Oxides & Minerals	500-600 Knoop, 5.75-6.25 Mohs
I-b	Glass Spheres & Inorganic Oxides	500-700 Knoop, 5.75-6.60 Mohs
II-a	Inorganic Oxides & Minerals	20-2100 Knoop, 1.00-9.00 Mohs
II-b	Inorganic Oxides & Minerals	20-800 Knoop, 1.00-6.90 Mohs
II-c (12 runs)	Inorganic Oxides & Minerals	20-800 Knoop, 1.00-6.90 Mohs
II-d	Glass Spheres, Inorganic Oxides & Minerals	20-800 Knoop, 1.00-6.90 Mohs
II-e	Inorganic Oxides & Minerals	20-800 Knoop, 1.00-6.90 Mohs
III-a	Inorganic Oxides	500-600 Knoop, 5.75-6.25 Mohs
III-b	Glass Spheres	500-700 Knoop, 5.75-6.60 Mohs

[†] Filler composition obtained from manufacturer's Material Safety Data Sheets and technical bulletins.

[††] Hardness range obtained from *CRC Handbook of Chemistry & Physics*, 67th ed., ed. R. C. Weast, (Boca Raton, Fla.: CRC Press Inc., 1986) and *Material Science & Engineering Handbook*, 2nd ed., ed. J. Shackelford, (Boca Raton, Fla.: CRC Press Inc., 1994).

Modified Taber Test — A Taber abraser (Model #5150, Taber Industries, North Tonawanda, N.Y.) was used in all tests. This equipment is normally used to evaluate the wear resistance of a sample material when exposed to an abrading Calibrase® wheel.[3]

The modifications made to the Taber abraser for this study included changes to both the rimmed turntable and the weighted arm/beam system as shown in Figure 1. First, the height of the rim around the rotating turntable was increased to reduce the potential of any adhesive spillage. Second, the arm/beam system was modified by replacing the Calibrase wheel with a stainless steel pin (rounded bottom). This pin is used to apply a force against the stainless steel fixture that holds the rod-shaped test specimens. These brass specimens (Cu63/Zn37, #CUO27910, Goodfellow Corp., Berwyn, Pa.) exhibited a hardness of 74-75 Rockwell (B scale).

The rod-shaped specimens were allowed to contact the AISI 304 stainless steel disc and adhesive medium (~100 ml) in each test for a maximum of 41,000 revolutions of the turntable. The steel disc (hardness = 86-87 Rockwell B scale, surface finish = 0.1-0.8 μm) mounted on the rimmed turntable was observed to rotate at a rate of 60 rpm in each of the tests.

Since the rotation rate of the specimen holder varied between tests, the number of rotations made by the specimen holder was measured in each test using a proximity sensor. Upon completion of each test, the three brass rods were rinsed — first in methyl ethyl ketone and then acetone. Each rod was weighed, and the resulting weight loss was recorded.

Flow Bench Test — The flow bench test was designed to evaluate nozzle wear (Figure 2). The apparatus used in this test was a miniature circulation system that contained two piston pumps with accompanying ram plates, a manifold in which the specimen nozzles were placed and a cooling system. The volume of adhesive consumed in each test was 18.9 liters (5 gallons). The adhesive was forced to flow from its original container via one of the pump/ram combinations through stainless steel pipe with a

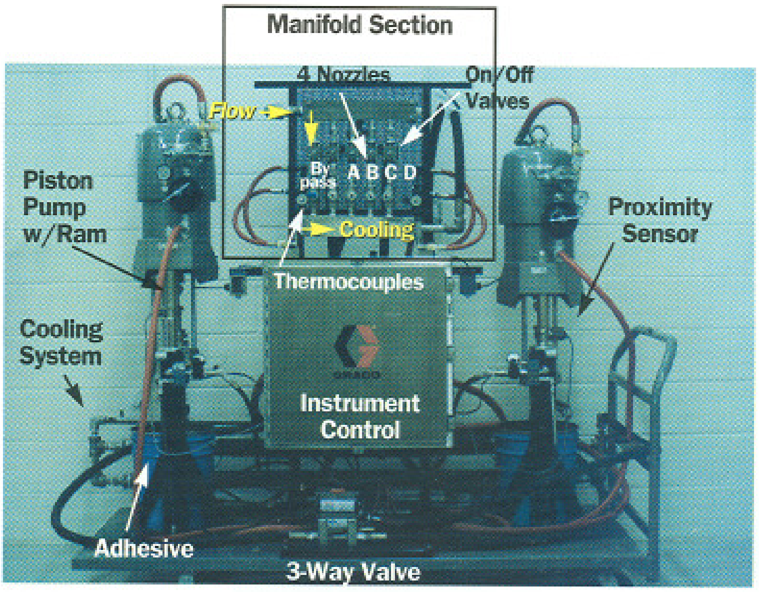


Figure 2. Flow bench apparatus designed to detect nozzle wear caused by sealants and adhesives.

Table 2. Comparison of the Wear Induced by Various Epoxy-Based Adhesives in the Modified Taber-Abraser Test

Adhesive Description	Distance Traveled, d_t (cm x 10^5)	Volume Loss, V_V (cm^3 x 10^{-3})	Wear Intensity, I_h (unitless x 10^{-7})
Control #1	2.431	2.13	2.79
Control #2	4.863	0.21	0.14
Ia	9.974	2.97	0.95
Ib	5.957	1.85	0.99
IIa	1.741	12.25	22.39
IIb	4.389	12.96	9.40
IIc†	5.88	5.48	2.86
IId	1.834	0.70	1.22
IIe	3.242	1.25	1.23
IIIa	6.301	0.90	0.45
IIIb	8.094	1.68	0.66

†Values represent the mean average of 12 replicated runs.

diameter of 2.54 cm (1.00″), a nozzle manifold and a cooling system into a reservoir connected to the other pump/ram assembly. This process was then repeated in the reverse direction.

The manifold was connected to both pumps via a three-way, solenoid-actuated valve. This valve was used to assure that the adhesive always entered and exited the manifold in the same direction. A proximity sensor was mounted on each pump cylinder to monitor the displacement of the adhesive from each reservoir and control the initial flow rate established in the system. The total volume of adhesive that passed through each nozzle was recorded along with the occurrence of any changes in the pressure or temperature of the system.

All tests were performed at a system pressure of 1.21 x 10^7 N/m^2 (1,750 psi) and a temperature of 25°C (78°F). The cooling system was able to maintain the temperature within ±2°C. The flow rate of the adhesive at the start of each test was 1.9 liters/min (0.5 gal/min). The flow rate in each test increased as the specimen nozzle in the manifold began to wear. A "rationalized erosion rate" plot was determined in each test by comparing the measured mass loss exhibited by the nozzles against the volume of adhesive allowed to flow through each nozzle.

The orifice in the specimen nozzle was 0.18 cm (0.070″) in diameter and 1.35 cm (0.53″) in length. The test nozzles used in this study were made from brass (ASTM B16-HLF Hard SR, Earle M. Jorgensen Co., Minneapolis), exhibiting a hardness of 70-71 Rockwell (B scale). The Reynolds number exhibited by the epoxy-based adhesives under the flow conditions established in the specimen nozzle at the start of each test was determined to be less than one.

The conditions described above for the flow bench test are believed to closely approximate the operating parameters to which the adhesive is exposed during the automobile manufacturing process. In an automotive assembly plant, these epoxy-based adhesives are routinely applied at a temperature between 25°C to 30°C (77°F to 85°F) and a system pressure less than 1.72 x 10^7 N/m^2 (< 2,500 psi) through a nozzle with an orifice diameter between 0.10 cm to 0.15 cm (0.040″ to 0.060″).

Results and Discussion

The two tests complement each other because they evaluate very different wear processes. The modified Taber-abraser test evaluates the wear incurred by sliding components in application equipment, while the flow bench test determines the erosion that occurs in applicator nozzles. The common feature between these two wear processes (sliding wear and erosion) resides in abrasion being the dominant wear mechanism. The experimental results of both tests are discussed in the context of the abrasivity exhibited by different, epoxy-based adhesive formulations.

Modified Taber-Abraser Test — The most appropriate method of presenting the results obtained in the modified Taber-abraser test is to determine a value for the specific-wear or linear-wear intensity, I_h, encountered in each test. Wear intensity is defined as being equivalent to the measured wear volume (V_v) divided by the product of the distance traveled (d_t) and the apparent area of contact (A_n) as shown in the equation:[4,5]

$$I_h = V_v/(d_t)(A_n)$$

The geometric, mechanical-wear model through which this wear intensity is derived has been shown to agree very well with experiments in which the interacting substrates differed in hardness.

In the modified Taber-abraser test, the brass specimens (hardness = 74-75 Rockwell B scale) and the steel rotating discs (hardness = 86-87 Rockwell B scale) were selected because of their difference in hardness and wear characteristics. This wear model assumes that any differences in the sliding speed encountered between tests is insignificant. Although the speed at which the rimmed-disc holder travels (60 rpm) is constant, the speed at which the specimen holder travels depends upon the rheological properties exhibited by the adhesive.

The apparent contact area was held constant in all tests by using test specimens with a standard diameter of 0.200 cm (0.079″). Both the volume wear loss and the distance traveled were experimentally determined in the modified Taber-abraser test.

The wear volume was determined by multiplying the measured mass loss by the density (8.45 gm/cm^3) of the test

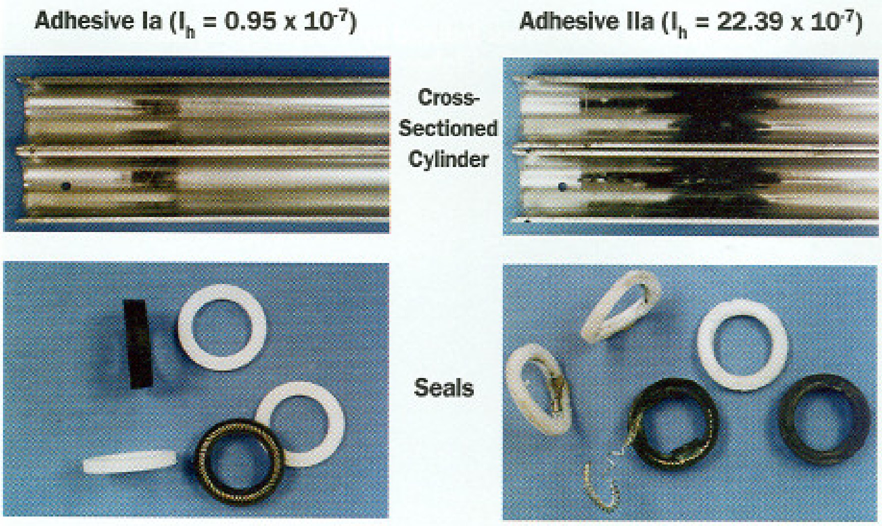


Figure 3. Wear occurring with the piston cylinder and seals in application equipment exposed to selected, epoxy-based adhesives.

specimens. The distance the test specimens travel in each test, d_t, was obtained by integrating the speed at which the rimmed turntable moved relative to the speed at which the specimen rods moved over the entire time interval for the test.

A comparison of the wear induced by various epoxy-based adhesives is provided in Table 2. The wear-intensity values exhibited by different adhesives was found to range from approximately 22.39 x 10^{-7} for adhesive IIa to less than 1.25 x 10^{-7} for adhesives Ia, Ib, IId, IIe, IIIa and IIIb. This means that adhesive IIa induced greater than 18 times the wear that occurred in the presence of adhesives Ia, Ib, IId, IIe, IIIa and IIIb; eight times as much as adhesive IIc; and twice as much as adhesive IIb. The average wear intensity observed for all 12 replicated runs using adhesive IIc was determined to be 2.86 x 10^{-7} with a standard deviation of ±0.63 x 10^{-7}. The experimental error associated with the modified Taber abraser test is small enough in magnitude not to significantly impact the comparison of test data obtained at different travel distances.

The adhesives that exhibited a wear intensity below 1.25 x 10^{-7} have been found to result in minimal damage to the sliding components present in conventional application equipment (Figure 3). Similarly, excessive wear in application equipment has been observed to occur in the presence of adhesive IIa (I_h = 22.39 x 10^{-7}).

Very little difference in the amount of wear induced in the modified Taber-abraser test was observed upon replacing part of the inorganic filler in an adhesive formulation with glass spheres. Direct comparisons were possible between adhesive formulations containing glass spheres (Ib, IId and IIIb) with similar formulations without glass spheres (Ia, IIe and IIIa) for all three manufacturers.

As previously stated, the magnitude of the wear that occurs in the equipment used to apply the epoxy adhesives in an automotive manufacturing plant appears to correlate with the wear intensity determined for these adhesives in the modified Taber-abraser test (Table 2). This wear is prevalent on both the seals used in the equipment and the walls of all cylinders subjected to the action of a sliding piston as shown in Figure 3.

The seals exposed to adhesive Ia (I_h = 0.95 x 10^{-7}) during the manufacturing of 10,000 automobiles exhibited very little to no wear, while the seals exposed to adhesive IIa (I_h = 22.39 x 10^{-7}) were significantly deformed. Similarly, the inner-cylinder surfaces exposed to adhesive IIa exhibited significant wear (i.e., mass loss and increase in surface roughness) as compared to identical cylinder surfaces exposed to adhesive Ia. Further evaluation of the cylinder surfaces exposed to adhesive IIa identified the existence of scratches and significant depletion of the protective chrome plating.

The value of the wear intensity determined in Control #1 (Table 2), run in the absence of any adhesive medium, was 2.79 x 10^{-7}. This test was stopped after 10,000 turntable rotations because a layer of brass was observed to be adhering to the surface of the rotating, stainless steel disc. The adherence of brass to steel is known to occur as a result of sliding friction in the absence of any lubrication.[6]

The occurrence of localized adherence of the brass to the stainless steel disc was not observed when a liquid medium was present. In fact, very little to no wear was observed to occur with Control #2 (Table 2), which was performed using a hydrocarbon-based oil.

The results of the control tests and the tests performed with the various adhesives suggest that the wear that occurs in the modified Taber-abraser test is caused by a combination of the abrasivity and lubricity exhibited by the adhesive.

The various compositions, shapes and sizes of the solid fillers used in the adhesive dominate the abrasivity of the formulation. The lubricity of the adhesive is determined from the polymers present in the formulation, as well as the presence of other additives and filler surface treatments.

A comparison between the hardness, shape and size of the solid fillers in each adhesive formulation provides some insight about the large wear-intensity differences encountered in the modified Taber-abraser test. First, the upper hardness limit (~2100 Knoop, 9.00 Mohs) for the type of filler particles present in adhesive IIa is significantly harder than the type of filler particles (~800 Knoop, ~6-7 Mohs) used in all the other formulations

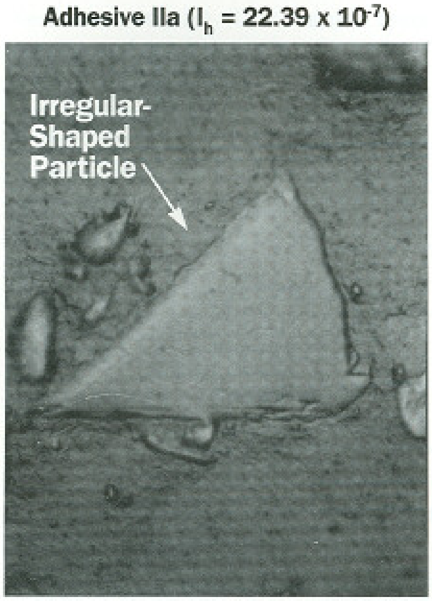


Figure 4. Scanning electron micrograph (1,000x) shows the irregular shape of the filler present in adhesive IIa as received from the manufacturer.

(Table 1). Second, the shape of the particles present in adhesive IIa was found to contain very sharp and ragged edges as shown in Figure 4. Third, very little difference could be found between the various epoxy-based adhesives upon analysis of the size distribution exhibited by the particles present in each formulation.

Although the elevated wear intensity exhibited by adhesive IIa, as compared to the other adhesives evaluated in the modified Taber-abraser test, can be explained by the extreme hardness and irregular shape of the filler, the hardness, shape or size of the particles cannot account for the differences observed in the abrasivity exhibited by the other adhesive formulations (IIb > IIc > Ia ~ Ib ~ IId ~ IIe ~ IIIa ~ IIIb) described in Table 2. For these cases, the wear observed in the modified Taber-abraser test, as well as in equipment used to apply these adhesives, is very dependent upon the lubricity exhibited by the adhesive formulation.

The modified Taber-abraser test has several limitations that should be addressed before extending the utility of this test to the measurement of the abrasivity exhibited by other adhesive formulations. The current test cannot be used to evaluate adhesives and sealants that either contain volatile components or require heat conditioning (e.g., hot melt adhesives). Even with these limitations, the modified Taber-abraser test represents a feasible laboratory method for comparing the abrasivity exhibited by various adhesive formulations. The wear observed in the modified Taber-abraser test provides a good indication of the amount of wear that will occur with the moving (i.e., sliding) parts present in application equipment.

Flow Bench Test — Similar to the modified Taber-abraser test, the flow bench test compares the abrasivity of various adhesive formulations using a standard test specimen (nozzle). The most straightforward approach to quantify the wear damage that occurs during this test is to monitor the weight or mass lost by the nozzle. The wear volume associated with each test nozzle can be determined from this weight loss measurement because the density of the material is known (brass density equals 8.45 gm/cm^3).

To directly compare the wear incurred by nozzles exposed to different adhesive formulations, one must ensure that an identical amount of adhesive passes through the orifice of the specimen nozzle during each test. Recall that in each test the initial flow rate and overall system pressure are held constant. Specimen nozzles exposed to 227 liters (60 gallons) of adhesives Ia and IIa exhibited a total mass loss of 0.6493 and 0.8724 grams, which corresponds to a volume loss of $7.684 \text{ x } 10^{-2}$ and $10.324 \text{ x } 10^{-2}$ cm^3, respectively. The nozzle exposed to adhesive IIa exhibited a greater mass or volume loss than the nozzle exposed to adhesive Ia. Thus, adhesive Ia will cause less erosive wear to the nozzle of an applicator than adhesive IIa.

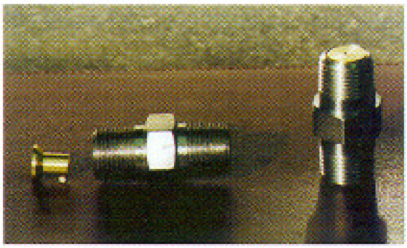
The mass or volume loss incurred by the specimen nozzles in the flow bench test (IIa > Ia) correlates with the wear-intensity values determined from the modified Taber-abraser test (Table 2), mainly because abrasion is the dominant mechanism in both erosive and sliding wear.[7,8] In this sense, the shape, size and hardness of the filler particles present in the adhesive formulation play a critical role.

The range in the amount of wear caused by the different adhesives in the flow bench test (i.e., volume loss per fluid volume) is much smaller than the range in the wear-intensity numbers determined for the same adhesives in the modified Taber-abraser test. This effect is caused by several uncontrollable variables in the two abrasivity tests.

First, several mechanisms besides abrasion (e.g., adhesion, etc.) contribute to the amount of wear observed in the modified Taber-abraser test.[7] Second, a difference exists in the degree to which various material characteristics affect the wear results obtained in each test.

For example, wear-intensity numbers measured in the modified Taber-abraser test include a certain amount of wear caused by the lack of lubricity exhibited by the various additives present in the adhesive formulation. In the flow bench test, the density exhibited by the filler particles is a contributing factor in the amount of erosive wear that occurs at the high velocities encountered in the specimen nozzles.[9]

Nozzle Assembly



Wear Incurred by Nozzles with Adhesive Ia

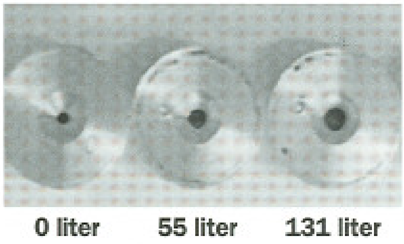


Figure 5. Wear incurred by nozzles during flow bench test.

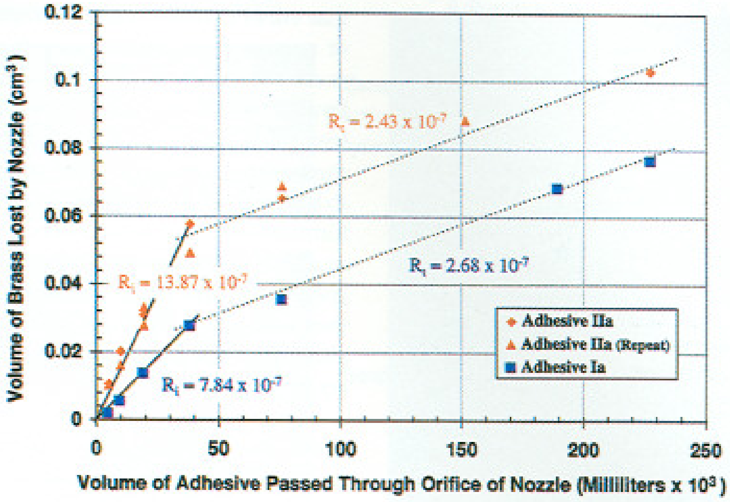


Figure 6. "Rationalized erosion rate" plot for nozzles exposed in the flow bench test to adhesives Ia and IIa (R_i = initial rate, R_t = terminal rate).

An increase in the amount of adhesive that flows through the nozzle with respect to time was observed during the flow bench test. This increase in flow rate is caused by the enlargement of the nozzle orifice due to erosion, as shown in Figure 5.

The increase in flow rate that occurs in the flow bench test differentiates this nozzle wear test from other, known particle-impingement tests. All of the known particle-impingement tests assume a constant flow rate and/or particle velocity in their determination of a wear rate (volume loss as a function of time) for different solid test substrates subjected to an abrasive slurry spray.[10,11,12] These particle-impingement tests do not consider that the flow conditions have changed during the test due to wear incurred by the spray nozzle. This dynamic change in a key operating parameter is taken into account in the flow bench test with the nozzle as the test substrate.

A "rationalized erosion rate" plot can be determined for each adhesive using the flow bench test by allowing different quantities of the adhesive to flow through identical nozzles, as shown in Figure 6. This "rationalized erosion rate" is defined as the volume of material lost by the nozzles divided by the total volume of adhesive that passed through the nozzle.[13] In each series of tests, the initial flow rate and overall system pressure are held constant. The Reynolds number exhibited by the adhesives under the flow conditions established in the specimen nozzle at the end of each test was determined to be less than one.

A plot of the "rationalized erosion rate" for each adhesive is characterized by a large initial rate (R_i) followed by a slow decrease to a smaller, terminal erosion rate (R_t). The initial and terminal erosion rates represent a unitless quantity depicted by the slope of the plotted erosion data (Figure 6). The initial erosion rate for the test nozzles exposed to adhesive IIa (13.87 x 10^{-7}) was found to be substantially greater than that exhibited by the nozzles exposed to adhesive Ia (7.84 x 10^{-7}). The rate at which the test nozzles erode was observed to decrease after being exposed to approximately 40 liters of either adhesive formulation. The terminal erosion rate exhibited by the test nozzles exposed to adhesive Ia (2.68 x 10^{-7}) and adhesive IIa (2.43 x 10^{-7}) were found to be similar.

The amount of wear observed to occur with the brass nozzles in the flow bench test provides a good estimate of the degree of wear that will occur in applicator nozzles used in an automotive production environment. Excessive wear in an applicator nozzle will result in an unacceptable change in the size of the adhesive bead applied to an automobile.

The nozzle in the equipment used to apply adhesive IIa to 10,000 automobiles had to be replaced three times due to the occurrence of excessive wear. The combined mass loss incurred by the three nozzles exposed to adhesive IIa was 0.102 grams.

In a similar trial, adhesive Ia was found to cause minimal wear to the nozzles used in the application process. The nozzle exposed to adhesive Ia was able to adequately apply adhesive to the full 10,000 automobiles. The mass loss incurred by the nozzle used in conjunction with adhesive Ia was 0.035 grams.

The flow bench test represents an efficient method of estimating the wear that will occur in applicator nozzles when used with various adhesive formulations. This test provides the unique ability to be adapted to the conditions encountered in a real production environment. That is, the pressures and initial flow rates established in the test can be adjusted to the values required by different manufacturing processes. This test also can be performed at elevated temperatures, allowing for the measurement of the abrasivity exhibited by adhesive formulations that require heat conditioning.

The one limitation in the flow bench test that will need to be monitored for different classes of adhesives and sealants is the point at which particle attrition occurs. To compare the amount of nozzle wear caused by different adhesives and sealants using this test, one must be sure that the test methodology does not alter the abrasivity exhibited by the formulation.

The abrasivity of an adhesive or sealant may decrease as a result of circulating the fluid through the test equipment multiple times. This change in abrasivity is typically caused by a change in the shape of the particles (e.g., increased smoothness, increased roundness, etc.) in the adhesive or sealant. In the flow bench tests performed in this study, the epoxy-based adhesives did not exhibit a decrease in abrasivity as shown by our ability to reproduce the "rationalized erosion rate" plot for adhesive IIa (see Figure 6) with a new set of nozzles using the same adhesive formulation.

Conclusion and Future Direction

The modified Taber-abraser test and the flow bench test can be used to obtain a reproducible measure of the abrasivity/lubricity exhibited by an epoxy-based adhesive formulation. This conclusion is based on the observation that the results of both wear tests parallel the performance data obtained with application equipment using identical adhesives in an automotive assembly plant.

The amount of wear observed to occur in the modified Taber-abraser test provides a good estimate of the degree to which an adhesive formulation will cause the moving (i.e., sliding) parts in pumps and shot meters to wear. The amount of wear observed to occur in the flow bench test provides a good estimate about the effect the adhesive will have on the nozzle of an applicator.

These two wear tests should be considered for adoption as standard characterization techniques for both material R&D and quality control. To accomplish this task, additional testing designed to measure the precision and demonstrate the reproducibility of these tests in the presence of various types of adhesives and sealants is necessary.

The linear wear intensity, I_h, calculated in each test from the measured wear volume, the traveled distance and the apparent contact area was determined to be the most appropriate method of presenting the results obtained in the modified Taber-abraser test. Adhesives exhibiting a wear-intensity value less than 1.25×10^{-7} were found to cause very little wear damage to the sliding components present in application equipment.

The most straightforward approach to quantify the wear that occurs during the flow bench test was determined to be the mass loss incurred by the specimen nozzle. A "rationalized erosion rate" plot determined for each adhesive in the flow bench test was found to exhibit different rates of initial and terminal erosion. The initial rate of erosion by the nozzles was significantly greater than the corresponding terminal rate of erosion. The abrasivity exhibited by the various adhesives in the flow bench test was found to correlate with the wear intensity determined for the same adhesives in the modified Taber-abraser test. In both tests, adhesive IIa was found to be more abrasive than adhesive Ia.

The limitations associated with each test will need to be explored before extending this test methodology to all classifications of adhesives and sealants. The modified Taber-abraser test will need to be adjusted to handle adhesive and sealant formulations that contain volatile components or require elevated temperatures. Attention will need to be given in the flow bench test to particle attrition to compare the abrasivity exhibited by different classifications of adhesives and sealants. ●ASI

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Additional information on the two tests described here is available from Dr. Keith D. Weiss, Graco Inc., Russell J. Gray Technical Center, PO Box 1441, Minneapolis, MN 55440-1441; 612-623-6437; fax 612-623-6273.

For additional information on the Taber abraser, contact Taber Industries, 455 Bryant St., N. Tonawanda, NY 14120; 716-694-4000 or 800-333-5300.

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