"A NONCONTACTING SCANNING
PHOTOELECTRON EMISSION TECHNIQUE
FOR BONDING SURFACE CLEANLINESS INSPECTION"

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PREFACE

This is a synopsis of a paper by Dr. Raymond L. Gause, Chief Engineering Physics Division, NASA Marshal Space Flight Center, Huntsville, Alabama. The paper details how NASA in conjunction with Morton Thiokol of Utah has implemented Surface Quality Monitor, manufactured by Photo Emission Tech., Inc., Newbury Park, CA, as a tool to establish acceptance criteria for surface cleanliness. The technique is being used as an on-going process control tool to Monitor effectiveness of cleaning process and assure good bonding. This technique is now an integral part of the manufacturing process for Solid Rocket Motor (SRM) of the space shuttle.

ABSTRACT

Molecular contamination of bonding surfaces can drastically effect the bond strength. This in turn effects the structural integrity that can be achieved. The presence of thin contaminant films on bonding surfaces can result from inadequate or incomplete cleaning methods, from oxide growth during the time between cleaning and bonding, or from failure to properly protect cleaned surfaces from oxide growth during the time between clearing and bonding, or from failure to properly protect cleaned surfaces from oils, greases, fingerprints, release agents, or deposition of facility

airborne molecules generated by adjacent manufacturing or processing operation.

Required cleanliness levels for desired bond performance can be determined by testing to correlate bond strength with contaminant type and quantity, thereby establishing the degree of contamination that can be tolerated based on the bond strength that is needed. Once the minimum acceptable contaminant level is defined, a method is needed to quantitatively measure the contaminant level on the bonding surface prior to bonding to verify that the surface meets the established cleanliness requirements.

This paper describes a unique photoelectron emission technique for the nondestructive inspection of various bonding surfaces, both metallic and non-metallic, to provide quantitative data on residual contaminant levels.

INTRODUCTION

The performance of many critical components for the Space Shuttle and other flight hardware depends on the quality of bonding achieved during fabrication of the component. An example of a major Shuttle element where quality bonding is crucial to performance, reliability, and safety is the Solid Rocket Motor (SRM). Inadequate bonding of the rubber insulation to the case could result in exposure of the D6AC steel case to the hot gas from the burning propellant and result in burn-thru which could be disastrous. Also, low strength bonds between the various nozzle parts could significantly affect SRM flight success.

Because of the high reliance placed on bonded parts and the wide variability in strength that is often observed, a comprehensive program was initiated by the Materials and Processes Laboratory of the Marshall Space Flight Center (MSFC) to investigate ways of improving bonding process control during the manufacture of critical SRM hardware in order to improve overall bond quality and reduce within-part and part-to-part variability in bonding strength. The process control parameters that affect bonding integrity include adhesive variability, storage, mixing, pot life, contamination of the bonding surface, surface preparation, adhesive application, and curing. Thus, all of these were included in the program. In addition, since bonding process control must be an inherent part of the overall manufacturing process, it has to be specific with respect to the sensitivity of the adhesives, bonding surfaces, and subsequent bonds to the environments (moisture, thermal, contamination) encountered during the manufacturing flow. For this reason, the program was implemented as a joint endeavor between MSFC and the Wasatch Division of Morton Thiokol, manufacturer of the Solid Rocket Motor.

Of all of the above parameters that affect bonding, contamination is probably the most insidious and least understood. The presence of thin molecular films on bonding surfaces can drastically affect the strength of some bonding systems. These films can result from inadequate or incomplete cleaning, oxide growth during the time between cleaning (e.g., grit blasting) and bonding or from failure to properly protect cleaned surfaces from oils, greases, fingerprints, release agents, or deposition of airborne molecular species generated by adjacent manufacturing or processing operations. These films may or may not be uniformly deposited on a large area bonding surface which can lead to variation in bond quality across that surface. The thickness and chemistry of the film, its interaction with the adhesive, and the adherents, and the subsequent response to the curing process can all affect the degree and level of bonding achieved. Often these contaminants are invisible making detection and quantitative measurement difficult and expensive. Thus, in order to eliminate or minimize contamination as a threat to bond integrity, strict contamination control of bonding surfaces is required. To assure the proper degree of control, required cleanliness levels must first be determined. Second, a methodology must be established for the uniform cleaning of the surfaces to the established levels and maintaining them at these levels from the completion of cleaning to the initiation of bonding. Third, pre-bonding inspection of the surfaces is required to verify that they have been properly controlled.

Previously, the contamination control of bonding surfaces was severely restricted due to the lack of a fast, cost effective method for quantitatively measuring contaminant levels on hardware bonding surfaces after cleaning and prior to bonding to verify compliance with established cleanliness requirements. Since such a method was needed for the SRM bonding improvement program, a development effort was initiated by MSFC which resulted in the use of OSEE for this purpose. The successful application of this technique depends on (1) a knowledge of the fundamental performance capabilities and limitations of the photoelectron emission contamination sensor, (2) calibration of the sensor output as a function of contaminant level on the specific surface to be inspected, and (3) the effect of contaminant level on bond quality.

SENSOR CHARACTERIZATION

The contamination sensor used is commercially available from PET, Inc., Westlake Village, California, which advertises it as a surface quality monitor. Since it is a patented device from Smith, Inventor), and there is no other licencee, it is the only instrument of its kind on the market. This type of sensor was selected based on the results of previous development work u sponsored by NASA and other investigations 3, 4, 5 which showed that the photoelectron emission technique, the principle of operation for the PET sensor, has the capability of providing quantitative thin layer contamination data for various types of contaminants and surfaces, e.g., silicone on aluminum, oxides on metals, and oil on silicon wafers. Of course, as for any analytical tool, it has certain operational sensitivities and limitations which must be understood for proper utilization of its inherent capabilities for both laboratory and production applications and environments.

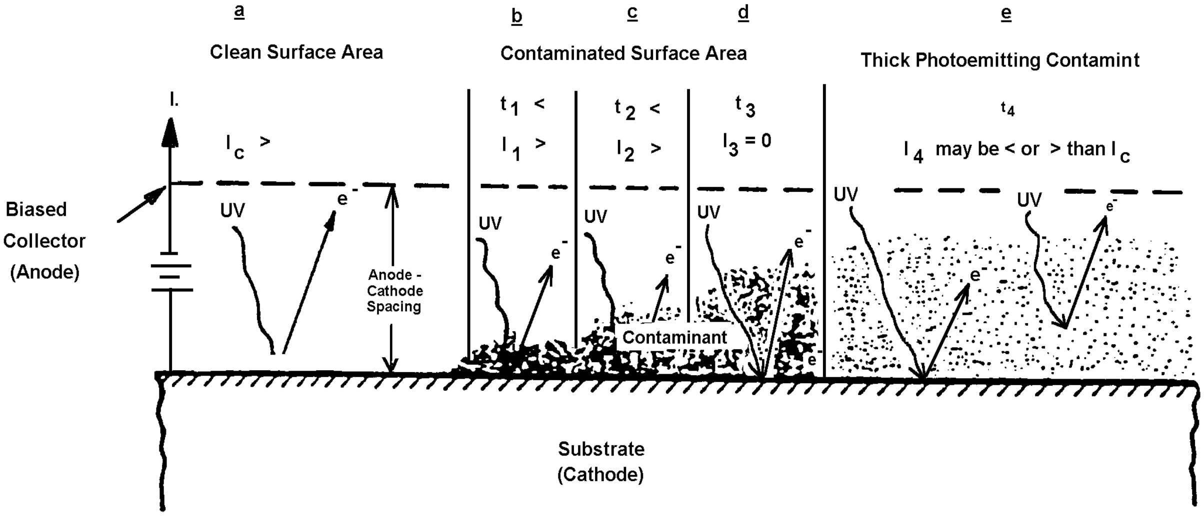
THEORY OF OPERATION

It is well known that when metals or certain other surfaces are illuminated with ultraviolet (uv) light with the proper wavelength (energy) electrons are emitted from the surface. The process by which UV protons interact with the surface to produce electrons is known as photoelectron emission (PEE) or optically stimulated electron emission (OSEE). Smith[4] showed that the emitted and subsequently scattered electrons can be collected across an air gap by a biased collector and measured as a current. If the intensity and energy of the UV light and the surface to collector distance are held relatively constant, changes in the measured photocurrent (which is in the order of 10^{-10} to 10^{-12} amps) can provide information about the surface, e.g., electronic structure, composition, chemistry. Any contaminant on the surface, depending on its own photo emission characteristics, can either enhance or attenuate the inherent emission from the clean surface. In simple electronic terms, the clean surface is a current generator and a non-photoemitting contaminant acts as a resistance because the current is attenuated by interactions between the electrons and the contaminant. The thicker the contaminant, the higher the resistance and consequently the greater the decrease in the measured current.

Figure 1 (a through d) depicts schematically the photo emission process and the effect of various thicknesses of contaminant (t) on the photocurrent (I). If the contaminant is photoemitting, e.g., Conoco HD-2 grease, then the contaminant can act as a resistance and an electron generator. Whether the collected current is attenuated or enhanced will be controlled by the contaminant film thickness and the relative emission characteristics of the contaminant with respect to the substrate surface. If the thickness is great enough to totally absorb the UV so that no UV photons reach the substrate, then the measured current is due only to those electrons emanating from the photoemitting contaminant. If some UV photons reach the substrate, and the film thickness is such that the resulting substrate electrons are not totally absorbed, then the measured current (I) will be the sum of the current from the substrate (Is) and that due to the contaminant (Ic). The case of a photoemitting contaminant is illustrated in *Figure le.*

In theory, the operation of the sensor is straightforward. It is calibrated by measuring the photocurrent from a clean surface and then from identical surfaces with controlled amounts of a contaminant to obtain a correlation between the sensor output (digital display or analog signal) and the contaminant level. By making measurements in the same way on another surface of unknown cleanliness and invoking these data the residual contaminant level can be determined for that surface. In actual application of the sensor for making quantitative, repeatable measurements, there are several complicating actors which can affect the measurement, the most significant of which are discussed in the following sections.

Figure 1

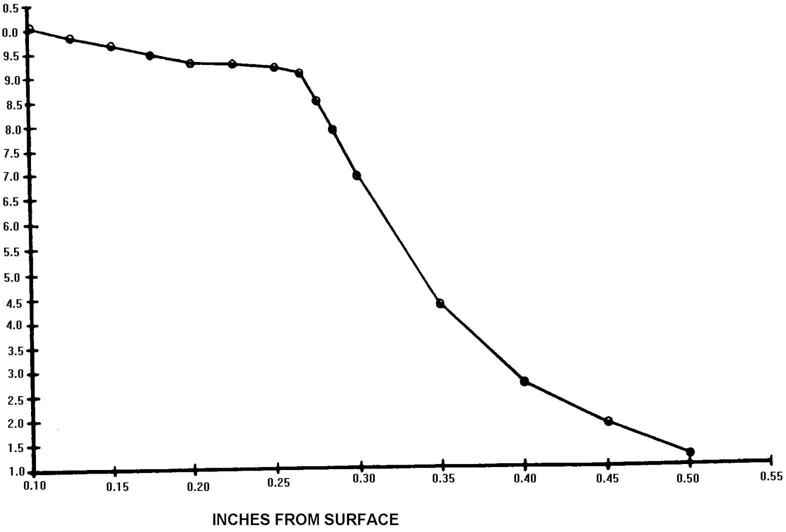


Effect of Sensor to Surface Spacing

The sensor output is dependent on the spacing between the sensor and the surface being measured. This sensitivity is basically due to three factors. First, as the sensor moves further away from the surface, the UV intensity on the surface decreases and fewer photoelectron are produced since the magnitude of the photocurrent is directly proportional to the number of UV photons impinging on the surface per unit of time. Second, with increasing distance the photoelectron have to travel further resulting in electron loss due to increasing number of collisions with the ambient gas molecules. Third, the electric field strength that is developed by the bias voltage between the collector (anode) and the surface (cathode) is dependent on the distance between the two ($E = V/D$) . Thus, as the distance increases the collection efficiency decreases due to the decrease in the field driving the electrons toward the collector. The integrated effect of these three factors on the output from a PET Model OPX1000 Sensor measuring a vapor deposited chrome surface is shown in *Figure* 2.

As shown in the figure, the sensitivity starts dropping significantly at a distance (gap) of approximately 0.275 inch. Thus, if the sensor is used in a non-contact scanning mode, the maximum spacing should be specified at no more than 0.25 inch so that a margin in position control is available for maintaining high sensitivity.

Figure 2



OSEE RESPONSE VS. SENSOR TO SURFACE DISTANCE

Surface Variation Considerations

Materials used in engineering applications rarely, if ever, have perfectly smooth and homogeneous surfaces. in fact, considerable effort is made to provide specific finishes for particular application. Also, alloys are generally used instead of pure metals to obtain improved properties. To complicate things further, the alloys are subjected to different heat treatments to enhance particular characteristics. These processes can lead to different senor responses.

Table 1 shows the results of OSEE sensor measurements made on a GAR S22 microfinish comparator. The results are interesting. For example, the response from a 500 microinch milled finish was 20 percent lower than from a 63 microinch milled finish but a 125 microinch profiled finish had the same response as the 63 milled finish. Not only is the average surface roughness a factor but also the mechanical process by which it is attained. In general, however, as the roughness increases using the same process, the response decreases, probably due to the increased scatter of the UV light and the larger emission angles for the electron which reduces collection efficiency.

TABLE 1. EFFECT OF SURFACE FINISH ON OSEE SENSOR RESPONSE

Surface Roughness Height (μ-in)	**Relative Sensor output***
8 Ground with Periphery of Wheel	658
16 Ground with Periphery of Wheel	700
32 Ground with Periphery of Wheel	688
2 Lapped	870
4 Lapped	835
8 Lapped	750
63 Milled	800

125 Milled	824
250 Milled	640
63 Profiled	863
125 Profiled	799
250 Profiled	520

*Measured on a GAR S22 Microfinish Comparator

Oxide formation on alloys is usually not uniform over the surface which causes a variation in sensor output. Generally, oxides are not photoemitting at the maximum UV energy of 6. 7 electron volts (ev) available from the senor UV source (nickel oxide is an exception). Thus, freshly grit blasted aluminum can give a very high response whereas aluminum with a thick oxide layer can give a very low response since the oxide attenuate the photocurrent. It is therefore important to calibrate the sensor response for each specific surface (material, finish, heat treatment, processing) to be measured. Also, it should be expected that a variation in sensor response can be observed when aluminum or other oxide forming materials are abraded since the oxides are difficult to totally remove. .

Response to Various Materials

The senor respone to various materials generally depends on the magnitude of the photoelectron work function of the material relative to the maximum usable UV energy reaching the surface from the sensor lamp. The principal high energy peaks from the lamp are at 1849 angstroms (- 6.7 ev) and 2535 angstroms (- 5 ev). For relatively large gaps, the 1849 angstrom line will be severely attenuated due to interaction with ambient oxygen molecules. Hence, it should be assumed that - 5 ev is the maximum energy available for measurements. Thus, if a material has a work function less than 5 ev, it should produce a measurable photocurrent. *Table* 2 lists published photoelectron work functions for several materials. Note that all of these are less than 5 ev except for aluminum oxide. Both conducting and nonconducting materials can be photoemitting, examples of which are the materials in *Table* 2. Other examples include the epoxy primer (EA 9228), carbon phenolic, and glass phenolic materials used in the fabrication of the SRM nozzle. In addition to these, successful measurements have been made on graphite/epoxy and fiberglass/epoxy. Some materials which do not exhibit a measurable response include Teflon, glass, and magnesium fluoride. The fact that Teflon is not photoemitting is fortunate in that it can be a detrimental surface contaminant for bonding and is therefore detectable with the OSEE sensor since it will attenuate the photocurrent from the bonding surface.

***TABLE* 2**

ELECTRON WORK FUNCTION (EV) OF THE ELEMENTS

MATERIAL	*PHOTOELECTRIC WORK FUNCTION (EV)**
Ag	3.67
Al	4.08
AS	5.11
Au	4.82
B	4.50
Ba	2.49
Be	3.92

Bi	4.25
C	4.34
Ca	2.76
Cb	3.96
Cd	4.07
Ce	2.84
Co	4.37
Cr	4.37
Cs	1.96
CU	4.86
Fe	4.40
Ga	3.80
Ge	4.29
Hf	3.53
Hg	4.52
Ir	4.57

***TABLE* 2**

ELECTRON WORK FUNCTION (EV) OF THE ELEMENTS (Contd.)

MATERIAL	*PHOTOELECTRIC WORK FUNCTION (EV)**
K	2.24
La	3.30
Li	2.28
Mg	3.68
Mn	3.76
Mo	4.34
Na	2.28
Nd	3.30
Ni	3.67
O	4.55
Pb	3.97
Pd	4.97
Pr	2.70
Pt	4.09
Rb	2.09
Re	5.00
Rh	4.57
Ru	4.52
Sb	4.01
Si	4.20
Sm	3.20

Sn	3.62
Sr	2.74
Ta	4.13
Te	4.76
Th	3.57
Ti	4.17
Tl	3.68
U	3.63
V	3.77
W	4.35
Zn	3.89
Zr	3.73

*Ref. Handbook of Material Science, Volume 1, 1974, CRC Press.

In general, it appears that measurements can be made on most of the materials of engineering importance, which means that the OSEE measurement technique has great utility.

Scan Rate

The sensor response time is dependent on the gain setting used, which is adjustable from 1 to 10. Very good response time is achieved for gain settings of 6 or less. As the gain is increased beyond 6, a notable drop in response time occurs. With the proper gain setting, high scan rates are possible. For example, at a gain setting of 5 on a PET OPX2OO (6" x l/4" inspection area), highly repeatable measurements were made at scan rates of 1 in/sec to 7.5 in/sec on a large test article composed of several surfaces with different photo emission characteristics.

Low scan rates usually are not desirable for some. surfaces such as epoxy primers and paint since the sensor output will decay with time of exposure. This effect is discussed in some detail in References 1 and 2. It is recommended that surfaces exhibiting this decay be scanned at a minimum rate of 1 in/sec unless only the peak reading is being recorded.

Repeatability and Stability

During the MSFC investigations reported in this paper, excellent repeatability and stability generally was demonstrated by the OSEE sensor. However, some problems were encountered that require discussion. It was noted that the sensor would be highly stable for days or even weeks and then a shift in output magnitude would occur. The instrument was being used in a laboratory whose power was relatively stable but fluctuations were known to occur when large welding machines were used in another part of the building in which the laboratory was located. Based on this observation, it was decided to power the instrument through a line regulator. This essentially eliminated the problem. However, when the line voltage dropped below the line regulator limits, the problem repeated itself. A line monitor was used to record out-of-limit changes in voltage and frequency. So long as the voltage and frequency are within limits, no problem is encountered with the instrument. In a production environment, major power fluctuations are frequent, therefore for this application an uninterruptible power source (UPS) is highly recommended. Even this may not be adequate, if the voltage drops below 80 volts which is the control limit for most UPS units. Experiments were made in which the line voltage was decreased in 10 volt intervals from 110 to 10 volts and then suddenly increased to 110v. The output decreased rapidly as the voltage decreased. After the level was quickly raised from 10 to 110 volts the sensor no longer functioned properly. Thus, for stable, repeatable operation the instrument power should not be allowed to vary more than + 2%. To verify that no changes in sensitivity have occurred, a reference surface should be measured periodically. The reference used by MSFC is vapor deposited chrome with a thickness of 2000-3000 angstroms. If properly prepared a smooth homogeneous surface is obtained. The reference is kept covered and handled only at the edges with gloves.

Calibration Method and Results for SRM Case Inspection

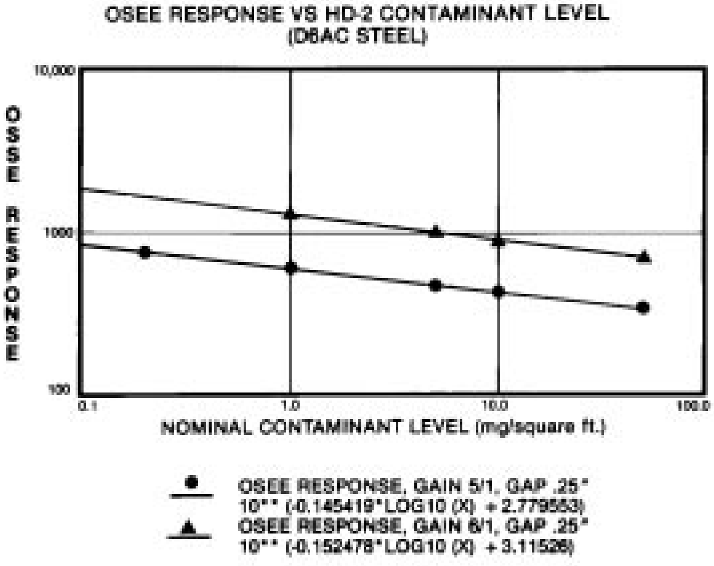
The proper calibration of the sensor for each specific measurement application is necessary if quantitative contamination measurements are to be made. The procedure used and the result obtained for the. inspection of the SRM D6AC steel case are presented below.

The SRM case is made of D6AC steel which is subject to corrosion. A corrosion inhibiting grease, Conoco HD-2, is applied to protect the surface during shipment and storage. Prior to the processing of the case segments for the bonding of the rubber insulation to the steel, the case cylinders (12' diameter by 13-1/2' long) are degreased using a methyl chloro-form vapor degreaser. The cylinders are then inspected using a "black light" to verify that the grease has been removed by the degreasing process. Following the "black light" inspection, the O-ring grooves are carefully greased and two case cylinders are mated to form a casting segment that is approximately 12 ft. diameter and 27 ft. long. The segment is then moved to a pit where the exterior is painted and the Chemlock adhesive system is applied on the interior. Green rubber is then laid on the adhesive and the segment is placed in an autoclave for vulcanization at 100 psi and 300° F for 3 hours. The requirement for the strength of the rubber to case bond is 150 pounds per inch (PLI) in 180 degree peel. Because of the desire to enhance the strength and reliability of this critical bond, an investigation was initiated to determine the case cleanliness level necessary to repeatedly achieve the 150 PLI requirement. In addition, the effectiveness of the "black light" inspection in detecting case contamination was to be established.

To establish the required cleanliness level, peel strength versus contaminant level tests were made. One foot by one foot steel plates were cut from a scrap case cylinder so that surfaces identical to the case were used for the tests. The surface roughness as measured was 100 microinch. The plates were grit blasted and then remeasured to verify that the grit blasting had not changed the finish. After grit blasting they were methyl chloroform vapor . degreased and then ultrasonically cleaned in a methyl chloroform bath. The cleanliness level of each plate was then determined by NVR analysis to be less than 0.25 mg/ft. The plates were contaminated by spray application of Conoco HD-2/methyl chloroform solutions to provide nominal grease levels of 1, 5, 10, 50, 100, 200, 500, and 1000 mg/ft. The levels were checked by spraying one foot by one foot aluminum foil and weighing to verify the quantity of HD-2 grease applied to the plates. OSEE measurements were made on clean plates and those that had been contaminated. The excellent correlation established between the OSEE sensor response and the nominal contaminant level up to 50 mg/ft. is shown in *Figure 3*. A gain change from 5 to 6 increased the response but did not change the slope. OSEE data for 100 mg/ft. and higher levels are not shown since the HD-2 grease is photoemitting.

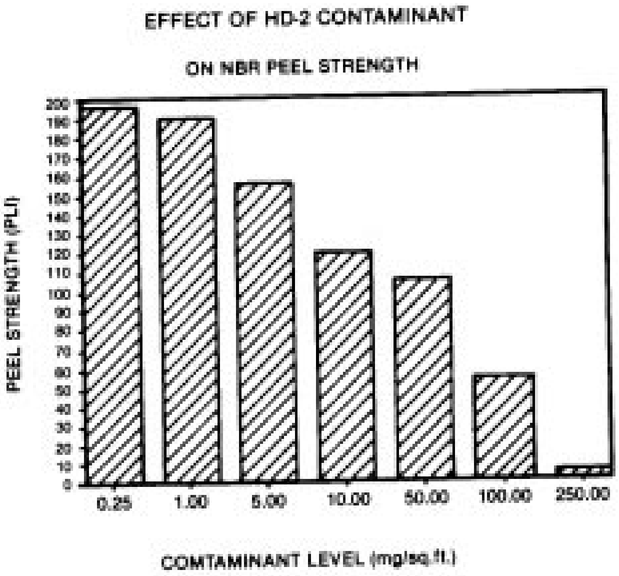
Beyond 50 mg/ft^2 the OSEE response dropped significantly and then increased. This was first due to the complete absorption of the photoelectrons from the steel, then the total absorption of the UV in the grease, and finally the subsequent increased photocurrent from the grease.

Figure 3



Upon completing the OSEE measurements, the Chemlock primer and adhesive and the NBR rubber were applied exactly according to the SRM process. The plates were vacuum bagged and autoclaved. Upon completion of processing, eight 1" wide strips were cut in the rubber on each plate and 180 degree peel tests were made. The test results are graphically depicted in *Figure 4*. No bonding was achieved for HD-2 contaminant levels of 1000 and 500 mg/ft^2. Only 5 PLI average strength was obtained at 250 mg/ft.^{2}, failure was 100% adhesive. At 100 mg/ft^2 a peel strength of 59 PLI was attained and the failure was 60-80% adhesive. For contaminant levels of 50 mg/ft^2 or less the failure was cohesive in the rubber. However, the peel strength continued to increase significantly as the contaminant level decreased. Based on this observation, it was postulated that the HD-2 which has a high vapor pressure, was diffusing through the Chemlock during the vulcanization process (autoclaving at 100 psi, 300° F, 3 hours) and degrading the rubber. Subsequent tests showed that the grease experienced an 80% weight loss under these conditions and residual gas analyzer tests verified that HD-2 would diffuse through Chemlock at 300° F. Additional tests determined the effect on NBR rubber properties due to HD-2 diffusion into the rubber. The diffused grease plasticized the rubber resulting in a decrease in tensile strength from 1234 psi to 935 psi and an increase in elongation from 97% to 522%. These data substantiated the hypothesis that small quantities of diffused HD-2 could significantly affect the post vulcanization mechanical properties of the NBR rubber. It was concluded from these tests that the HD-2 contaminant level must be controlled to a level of 5 mg/ft^2 or less. If a composite bond line peel strength of 150 PLI was to be achieved repeatedly and that a level of 50 mg/ft^2 or less was necessary to assure no failure in the adhesive. It was also demonstrated that the OSEE technique could be used to measure HD-2 levels on D6AC steel over the range of 0.25 to 50 mg/ft^2.

Figure 4



As stated previously "black light" inspection sensitivity was to be determined during these tests. Under optimum observing conditions, a uniform contaminant level of 100 mg/ft^2 or greater could be detected. Thus, the black light and the OSEE technique complement each other. The "black light" is useful for detecting gross contaminant levels but cannot detect the levels necessary to achieve quality bonding. The OSEE technique can detect these low levels but cannot be used for the high levels. Thus, the case should first pass a "black light" inspection and then be inspected with the OSEE technique for verification of cleanliness requirements prior to bonding.

Figure 5 graphically illustrates how the combination of surface finish and contaminant level influenced the peel strength results discussed above. In the figure, the contaminant level is overlaid to scale on a surface profile of the D6AC steel plate. The measured surface finish is 100 microinch or 25400 angstroms. Since the density of HD-2 grease is very near 1 gm/cm^3, a contaminant level of 1 mg/ft^2 is equivalent to a uniform area thickness of ~ 108 angstroms. Thus, a level of 250 mg/ft^2 correlates to a thickness of 27,000 angstroms or roughly 106 microinches. This quantity of grease then would be sufficiently thick to completely cover the surface thereby preventing any adhesion between the Chemlock and the steel. Thus, it is not surprising that there was zero peel strength at levels greater than 250 mg/ft^2. AS the contaminant thickness decreases, the peel strength increases as more steel bonding surface is exposed. Sufficient asperity area is available for good adhesion at the 50 mg/ft^2 since this is where the failure mode transitions from adhesive to cohesive (failure in the rubber). The grease trapped in the valleys then becomes important because the autoclaving temperature and time conditions cause it to diffuse through the Chemlock into the rubber resulting in a degradation of the rubber near the Chemlock-rubber interface. As the quantity of available grease decreases the degree of degradation is less and the strength is greater. If the surface were smoother less grease would be trapped and cleaning would be easier. Conversely, the effective area for adhesive bonding would be decreased since the projected area of the rough surface is greater than that of a smoother surface.

Figure 5

SRM Nozzle

The nozzle is comprised of many large bonded parts. Both metal-composite and composite-composite bondlines are utilized. Also, there is a wide range of potential contaminants including fingerprints, oils, greases, release agents, and silicones which could degrade bond quality. Laboratory testing is in progress to characterize the effects of these contaminants on bond strength and to develop OSEE response and calibration data for the various surfaces and contaminants.

The MSFC OSEE laboratory system used to obtain these data is a PATSCAN system. An OSEE sensor is used to scan test specimens mounted on a computer controlled X-Y table. The desired sensor to specimen spacing is established using a Z-axis translation controller. The area to be scanned and the number and spacing of the measurement points are software selectable. At the completion of a scan, the data are displayed in a 3-D format. The total system including the computer, I/o boards, and special software is commercially available from PET.

Since contaminants from sources other than fingerprints are of concert, preliminary tests were made to determine the capability of the OSEE sensor to detect these on one of the nozzle bonding surfaces. Since EA 9228 epoxy primer is being investigated for improving the bonding between 7075-T73 and its mating surface (glass phenolic), several different contaminants at low levels (on the order of 2-5 mg/Ft^2) were applied on the material surface. *Figure* 6 (shown on page 14) is a scan of the original surface containing an area near the edge with an unknown contaminant. *Figure* 7 (see page 14) shows the effect of various contaminants and *Figure* 8 (shown on page 15) illustrates the result of wiping with methyl chloroform. The effectiveness of flushing the surface is dramatically demonstrated by the scan shown in *Figure* 9 (see page 15).

Figure 6

ORIGINAL SURFACE
EA 9228 Primer

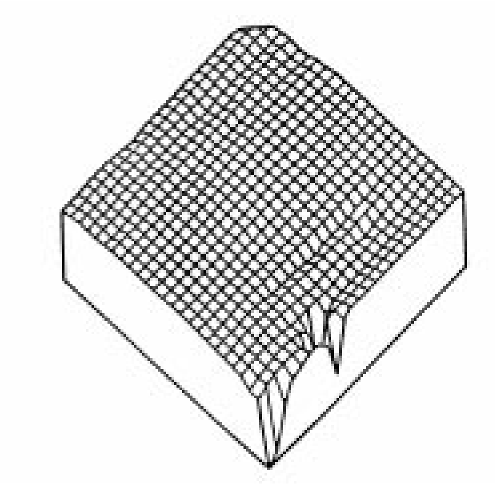


Figure 7

Contaminated Primer Surface

A. UNKNOWN
B. HD-2 GREASE
C. MOLD RELEASE
D. SILICONE
E. TAPPING OIL
F. MACHINING OIL

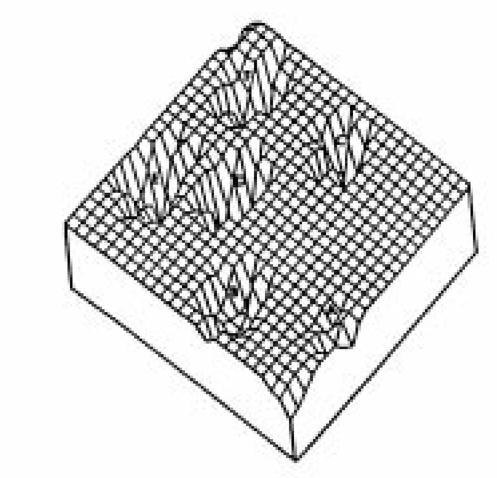


Figure 8

Effect of Double Wiping
Contaminated Primer Surface

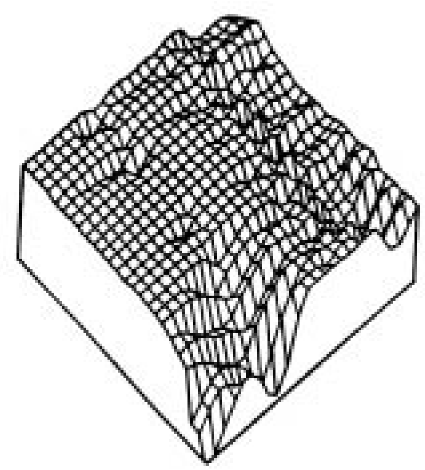
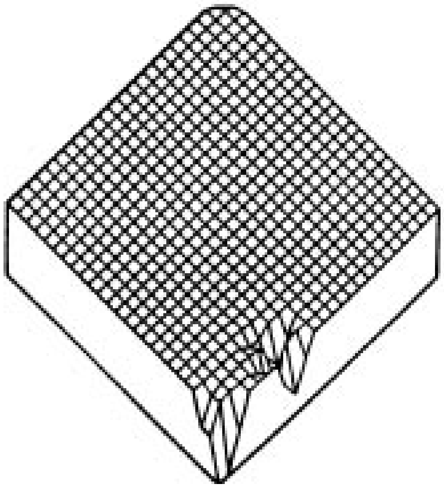


Figure 9

Effect of Flushing
Contaminated Primer Surface



CONCLUSIONS

It is believed, based on the work described above, that the photoelectron emission technique, properly applied, has the sensitivity and operational simplicity required to provide fast and cost effective surface contamination evaluations. Its . application to bonding surface inspection for verifying established cleanliness requirements should result in the significant improvement of overall bond quality for a variety of bonding surfaces. NASA/MSFC plans to continue the development of this technique for a wide range of uses, including not only SRM, BSM, ET hardware bonding surface inspection but also for cure monitoring, location of impact damaged areas in composites, and other applications where knowledge of changes in surface characteristics can provide important insight as to the integrity of the material for its intended application.

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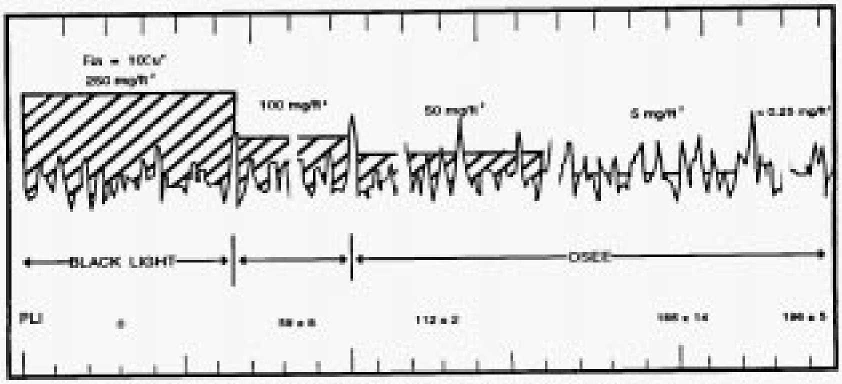

SURFACE FINISH AND CONTAMINANT LEVELS VS PEEL STRENGTH