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Verification of Surface Preparation for Adhesive Bonding

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Abstract

A survey of solid rocket booster (SRB) production operations identified potential contaminants which might adversely affect bonding operations. Lap shear tests quantified these contaminants' effects on adhesive strength. The most potent contaminants were selected for additional studies on SRB thermal protection system (TPS) bonding processes. Test panels were prepared with predetermined levels of contamination, visually inspected using white and black light, then bonded with three different TPS materials over the unremoved contamination. Bond test data showed that white and black light inspections are adequate inspection methods for TPS bonding operations. Extreme levels of contamination (higher than expected on flight hardware) had an insignificant effect on TPS bond strengths because of the apparent insensitivity of the adhesive system to contamination effects, and the comparatively weak cohesive strength of the TPS materials.

INTRODUCTION

Contamination control is one of the most crucial elements of a bonding system or process. Contamination is the presence of a foreign material on a bonding surface or in an adhesive and can prevent a bond from holding two materials together at full strength. Good, reliable bonds are important in aerospace applications, such as applying TPS to launch vehicles.

The accuracies of current surface inspection methods have been questioned due to variability among operators and a lack of specific data for defining surface conditions. Examination of these criticisms indicated that inspection operations may benefit greatly with automated methods. New inspection techniques, which yield a quantitative surface description, might provide a measurable standard for process improvement and bond reliability.

Critical evaluation of current inspection methods is necessary before evaluating a new inspection system. The objective of this program was to characterize the existing contamination controls for USBI bonding processes by identifying potential contaminants, determining their effects on bonds, and assessing the accuracy of current inspection techniques to detect these contaminants which jeopardize good adhesive bonding.

APPROACH

The program was carried out in three major steps: (a) identify specific contaminants that could be introduced into a bonding process, (b) establish the contamination level of these contaminants that will degrade adhesion, and (c) assess capability of current inspection methods to reject potential unsatisfactory levels of contaminants.

USBI uses bonding processes that may be placed in four distinct groups: thick film spray, thin film spray, trowelled, and fayed (closely fitted) surfaces. Generic methods for identifying potential contaminants and to study process sensitivity were based on three of these processes. Painting (a thin-film spray) was omitted from the test plan, because (for the SRB) hardware processed in this manner does not sit around unprotected. It is a continuous process. Examples of the other three processes include: MSA-2 (thick film), BTA (trowelled), and cork bonding (fayed). Experience gained from problem reports showed that it was necessary to identify contamination caused by the process itself and its assigned work area, and to track down *opportunistic* contamination (i.e., contamination that comes from random exposure to uncontrolled events).

Once potential contaminants were identified, a laboratory study was performed to quantify the effects of bondline contamination using lap shear coupons in a controlled environment. This identified the critical contaminants which actually have a significant effect on bonding using the adhesive from the processes under study.

Next, test panels with controlled amounts of contamination were produced for processing with selected TPS application techniques. The panels were inspected by two commonly used techniques—visual with white light and visual with black light. Inspections were performed by Quality personnel (inspectors). Each contaminant was applied at several levels so that the associated effects may be assessed. Normal bonding operations were performed and the contamination effects on bond adhesion in the process environment were evaluated. Water break-free testing was omitted from the test plan because (for the SRB) this inspection is typically done prior to Alodine treatment and prior to painting, which was not evaluated.

RESULTS AND DISCUSSION

Contaminant Identification

As many potential contaminants as possible were identified in an audit of the USBI SRB processing facility in the operating areas where bonding processes are being executed. Thirty-one contaminants identified in the audit were categorized into three groups: facility, process, and opportunity. Facility contaminants are those generated from installed or permanent fixtures in the processing area. Process contaminants are those from the materials in the process itself. The final group of materials are contaminants of opportunity, materials which reach the process area through auxiliary tasks, or the personnel working in or passing through an area. This last group is often the hardest to track when processing problems occur as they tend to occur intermittently. A broad range of credible contaminants, which are typical of any aerospace hardware processing facility, were identified (e.g., oils and greases, cosmetics, cleaners, insect repellents, etc.) A listing of the 31 materials identified by the survey is presented in table 1.

Facility contaminants were monitored using practices common to the aerospace industry. Standard nonvolatile residue (NVR) plates were deployed as *witness* panels in the major processing areas in Florida. These panels were exposed for 48 days at two different times. The residue from each plate was analyzed to determine a deposition rate and chemical composition. The deposition rates ranged from a low of 0.088 mg/ft^2/month, to a high of 0.239 mg/ft^2/month. This compares favorably with a maximum deposition rate of 1.0 mg/ft^2/month which is the limit for the most tightly controlled payload processing clean rooms. Chemical analysis was performed by gas chromatography and Fourier transform infrared spectroscopy. Two significant peaks were found in the residue. The largest was methyl isobutyl ketone (MIBK), a component of an SRB paint system. The second was ethylene glycol. Even though the deposition rate for these two compounds did not indicate cause for concern, they were added to the potential contaminant list for testing. That they made up an overwhelming majority of the residue, suggested that we should evaluate the effects of large localized deposits which could be a plausible occurrence through facility or process upsets.

Residues which can pass from one processing step to the next were the next major group to be identified. Tape and vacuum bag sealant residue from masking, bonding, and other operations have proved difficult to locate and remove. Residue from incomplete removal of corrosion preventive grease, an ultrasonic coupling agent, and a specialty aluminum detergent were targeted because the ability to detect their presence in follow-up inspections is undocumented. Incorrect use of conversion coatings may leave a powdery surface with poor adhesion characteristics, so that material was added to the list.

Contaminants of opportunity are materials which do not have a documented presence during the normal operation of the facility and process. These materials may come from maintenance activities, leaks or system failures, or personnel working in the area. Four different oils and greases were identified which are normally used in routine equipment maintenance and which could drip or otherwise be transferred to hardware in process. Gloves are not required in all of the processing areas, making fingerprints, hand cream, uncontrolled water, and insect repellent all potential contaminants from personnel. Aerosol sprays (e.g., insecticide, insect repellent, and various cleaners) are suspect contaminants due to a lack of control of their use around hardware. The best method found for identifying these types of items was an informal survey of the personnel tool chests and storage in the processing areas. A second survey of the logistics areas, to determine what materials were available to personnel on an unrestricted basis, also proved beneficial.

Table 1 Contaminants

Contaminant Source	Identified Potential Contaminants
Facility	Ethylene glycol Diesel exhaust MIBK
Process	Perchloroethylene Vinyl tape GS-37 sealant Distilled water Masking tape Rymple cloth Airtec 23 cleaner Conoco grease Paper tape Echo ultragel II 1,1,1 Trichloroethane Alodine 1201
Opportunity	Fingerprints Anchorlube 6-771 Siloo glass cleaner Wasp Killer Bard skin care cream Vacuum pump oil Spray Nine cleaner Sea water Insect repellent Pennzoil EP grease 302 Breathing mask towellette Tapwater Drop dead insecticide Skin So Soft Perspiration Chain and cable fluid

Contaminant Dispersions Method

Contaminant sensitivity testing required a methodology for controlled contaminant application. With an accurate deposition technique, the level or coating weight (mg/ft^2) at which contamination begins to affect bonding may be determined. Acceptable application requires the ability to apply a uniform layer of the contaminant to the test coupons and panels. Through a review of literature, it was determined that an air brush technique using serial dilutions of the contaminants would produce the best results. With this technique, predictable, repeatable levels of contamination were produced. Contaminant levels were determined gravimetrically using clean aluminum foil as a witness surface. Some items such as tapes, sealants, solvents, fingerprints, and different types of water were applied at 100 percent by weight to simulate process conditions. Other contaminants were diluted in solvents and air brushed.

Lap Shear Sample Preparation

A bonding test method had to be selected from which to determine contamination effects. The method would test bonds containing controlled levels of contamination. It was necessary to screen the contaminants in the lab because of the large number, various levels of interest, convenience, and cost. The failure mode of greatest concern for the processes under study is in the shear direction. For this reason lap shear bond testing (per American Society for Testing and Materials (ASTM) D 1002) was chosen as our evaluation method. The adhesive used was EC 2216 two-part epoxy from 3M Corporation. Dedicated control coupons, as well as control specimens adjacent to the contaminated specimens used on each contaminated coupon, provided confidence in the lap shear data.

Theoretically, there are two threshold contaminant weights [mg/ft^2] of interest for each contaminant: (a) the minimum contaminant weight (cw_{min}) (not detected by current inspection techniques) to affect lap shear strength, and (b) the maximum contaminant weight (cw_{max}) (not detected by current inspection techniques) to affect lap shear strengths. A given contaminant may exhibit both, one or none of these defined weights for a given bonding process. In practice, these defined coating weights were not well defined points.

Lap Shear Results (Laboratory)

Each potential contaminant in table 1 was tested in the lap shear study, except 1,1,1 trichloroethane, which was found clean from the gas chromatograph results, and perspiration, for which a consistent supply had not been located.

The 31 contaminants were sorted into three groups defined by sensitivity (i.e., strength loss per coating weight). The three groups are presented in table 2.

Not all potential contaminants could be used in the process testing phase, since the program would have become unwieldy. Thus, based on the lap shear results, seven contaminants with the largest effects were chosen to be used.

Preliminary black light and white light inspections were used to determine detectable levels of coating weights to be used in the process testing. The preliminary inspections were carried out by M&P technicians. Yes and no ratings were used if the contaminant was either observed or not in the lab on white test panels, a preliminary pass or reject rating.

Preliminary inspections performed in M&P labs were similar to Quality inspection of hardware (i.e. panels were not handled and viewing angles were not lighted in optimum conditions).

Hardware Process Sensitivity Study

At USBI, bonding processes may be placed into four distinct groups: thick film spray, thin film spray, trowelled, and fayed (closely fitted) surfaces. Several TPS bonding processes were selected to evaluate contamination effects: the bonding of MSA-2, BTA, and cork. MSA-2 is a two-part epoxy, EC-2216, loaded with solvents and fillers, and is a thick film spray. BTA is filled EC-2216 epoxy and trowellable. Cork is bonded with EC-2216, applied to both surfaces and vacuum bagged, and is a faying surface application. Paint application was omitted from the test plan.

The seven most deleterious contaminants were chosen for testing on the selected TPS application processes. They were masking tape, vinyl tape, ethylene glycol, Conoco grease, Spray Nine cleaner, vacuum pump oil, and Skin So Soft. These materials were selected because of their effect on lap shear strength loss (most deleterious).

The levels of contamination used for the TPS bonding study were determined by the lap shear testing. Based on the threshold criteria (when available) for the lap shear results, levels were chosen to span and enter this contamination range. For example, if a particular contaminant caused a loss in lap shear strength at a given coating weight and was not visible under black or white light, then coating weights lighter and heavier and at that weight were applied on the large test panels for analysis.

Table 2 Contaminant Sensitivity

Material	Reason for Omission in Process Testing
Very Sensitive (Loss per weight range 0.3-21 %/mg/ft²)	
GS-37	Not applied directly to substrate in production
Vinyl tape	(Tested)
Masking tape	(Tested)
Paper tape	Similar to vinyl tape
Perchloroethylene	Perc had broken down, full strength
HD Conoco grease	(Tested)
Pennzoil EP grease	Similar to Conoco
Breathing mask towelette	Not realistic[1]
Echo Ultra Gel II	Not used after painting
Exhaust, Diesel	Small effect at full strength
Sensitive (Loss per weight range 0.008-0.2 %/mg/ft²)	
Skin care cream	Difficult to atomize
Vacuum pump oil	(Tested)
Skin So Soft	(Tested)
Spray Nine cleaner	(Tested)
Drop Dead	Small effect at full strength
Ethylene glycol	(Tested)
Seawater	Not realistic[2]
Wasp Killer	Similar to Drop Dead
Deep Woods Off	No longer used at FL Ops
Chain & cable lube	Low loss/weight
Not Very Sensitive (Strength loss negligible)	
Airtec 23 cleaner	
Alodine 1201	
Anchorlube	
Distilled water	
Fingerprints	
MIBK	
Rymple cloth extract	
Siloo glass cleaner	
Tapwater—FL	

1—Breathing mask towelette residue would not come in direct contact with flight hardware.
2—Seawater would not come in contact with flight hardware after refurbishment.

Note: Throughout this paper, strength losses are designated by negative numbers.

Several differences exist between the lap shear and TPS process bonds. Surface finishes are different: bare etched aluminum for the lap shear coupons and sanded epoxy paint for the process test panels. Mechanical testing was lap shear versus flatwise tensile for the process TPS materials. Lap shear testing was aluminum bonded to aluminum, and process panels were TPS bonded to epoxy paint. Methods of adhesive application and cure schedules differed between the two studies. Epoxy adhesive EC-2216 was common to both lab and process studies.

Sixty 2-by-2-foot painted aluminum panels were contaminated and then bonded with MSA-2, BTA, and cork, i.e., 20 panels of each TPS material. Each panel that was contaminated received only one contaminant coating weight. Standard technical procedures (STPs) were followed during fabrication, with the exception of adding a contaminant to the painted aluminum panel surface that was to be bonded. The process consisted of sanding the panel, applying the contaminant in a predetermined pattern (allowing for uncontaminated control areas), inspection of the panels by Quality inspectors using black light and white light, applying TPS materials, curing, then sectioning and surfacing specimens for flatwise tensile testing.

Contaminants were sprayed in one of nine patterns on each contaminated panel. Areas had to be left uncontaminated on the panels for control purposes. These control areas were masked by aluminum foil, which were used as witness foils to calculate actual panel coating weights. Some panels did not receive any contamination and were also used as controls. Different contaminant patterns were selected, so that Quality inspectors would not catch on to any one pattern when looking for contamination, thereby giving inspectors a significant advantage of finding any contamination. Contaminants were feathered in each case, thus not giving inspectors other visual advantages. Contamination is much easier to spot when there is a definite line of demarcation.

Each panel was inspected by two groups of two Quality inspectors, using both black light and white light. One group would inspect a panel with white light and black light at different times, then the other inspectors would do the same. Each inspector would not know the outcome of any previous inspections since the order of inspecting the 60 panels was changed for each inspection. Inspection results were quantified. During the inspection, each inspector was asked to map out the contamination (on Quality evaluation sheets) that could be seen. Thus, for each panel there existed four maps, two with black light results and two with white light results. These inspection results were compared to the actual contamination pattern. If the inspector found all the contamination, the inspection map received a rating of 10. If the inspector did not see any of the contamination, the inspection map received a rating of 0. Results in between were judged by percent of contamination found and received integer ratings of 1 through 9. Inspectors were not allowed to handle the panels, and used lighting identical to that used when inspecting flight hardware. The inspectors were requested to not clean off the contamination found.

Presented in figures 1 and 2 are the detectability of the contaminants on the TPS test panels using white and black light, respectively, as a function of contamination weight. Tape residue contamination is not included in these figures. From figure 1, white light effectiveness begins in the 30 to 60 mg/ft^2 range regardless of contaminant type, excluding ethylene glycol. This range is identified by the two vertical lines. From figure 2, black light was effective at lower coating weights (approximately 15 mg/ft^2) in some cases, but not fully reliable until higher weights are applied (approximately 95 mg/ft^2), denoted by the vertical line. The scatter in this figure is due to the fact that black light effectiveness is dependent on the fluorescent properties of the contaminant.

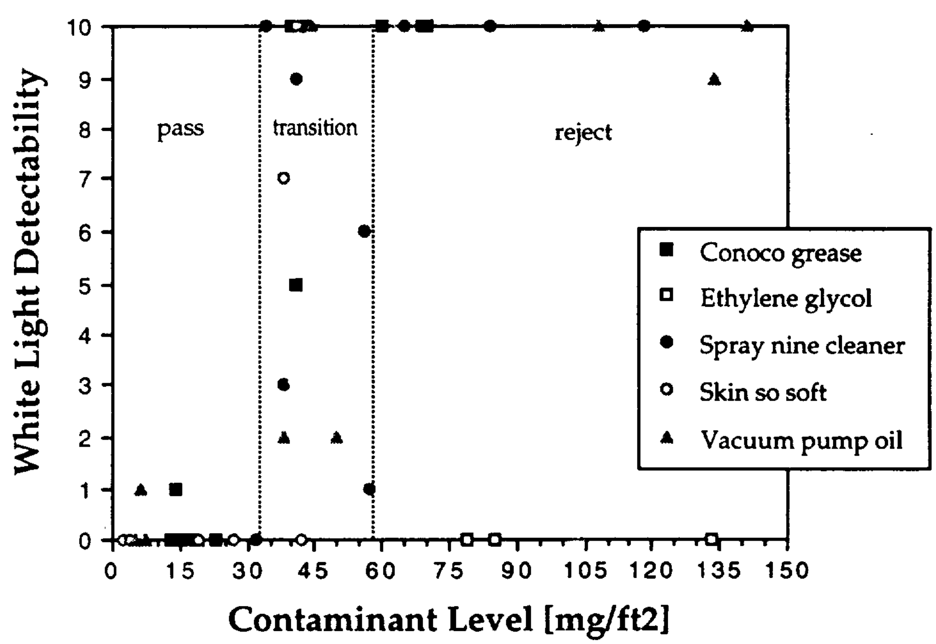

Figure 1 White Light Inspection Results

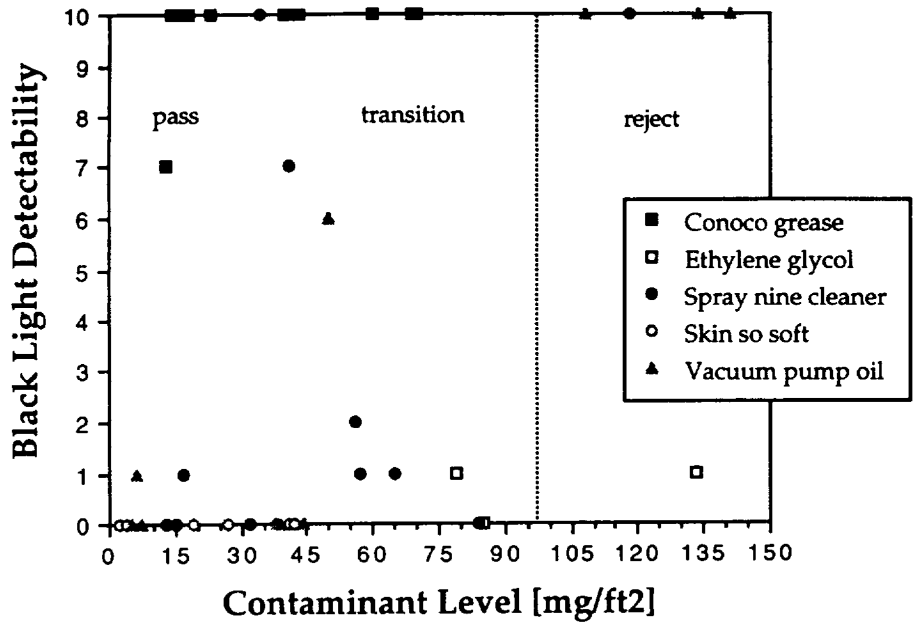

Figure 2 Black Light Inspection Results

Strength Testing

Upon completion of the inspection of the sixty panels, TPS materials were applied to the contaminated panels then bonded and/or cured. The panels were then cut into 2-by-2-inch squares or coupons for flatwise tensile testing (FWT) to evaluate any contamination effects.

To eliminate unnecessary mechanical testing, the highest level of contamination for each contaminant and each TPS material was pulled first. It was hypothesized that if no contamination effects were observed at the highest levels of contamination for all the contaminants, then further testing at lower levels of contamination would not be necessary.

From each contaminated test panel there were four control and six contaminated test specimens cut out and FWT tested. From each control panel there were 10 control test specimens cut out and FWT tested.

MSA-2

The FWT strength data generated on MSA-2 does not support any significant contamination effect. Little or no effect was observed by the contaminants on MSA-2 bonding. Three panels may have exhibited small effects: ethylene glycol (-5.3 ±3.3 percent), vacuum pump oil (-8.0 ±3.6 percent), and Skin So Soft at 19 mg (-4.1 ±7.4 percent). However, Skin So Soft did not show an effect on the one panel at higher contamination (i.e., 38 mg). All failures were substantially above design requirements, 75 psi individual minimum, and 85 psi average. Another way to analyze the data is to compare the average contamination data for each panel (since the contaminated data is more widely distributed spatially than the control areas on the contaminated panel), to the control averages on the two control panels, 143 psi and 150 psi or 147 psi average. Here four contaminated panels pulled less than 147 psi: Skin So Soft (38 mg) at 136 psi, ethylene glycol at 143 psi, Spray Nine cleaner at 145 psi, and Conoco grease at 139 psi. Only one of these panels, when compared to its own control areas, showed a strength loss: ethylene glycol (-5.3 ± 3.3 percent).

BTA

Four panels may have produced small loss effects: Skin So Soft (-5.7 ± 3.6 percent), Conoco grease (-6.1± 7.8 percent), masking tape (-4.0 ± 1.5 percent), and vinyl tape (-4.5 ± 1.5 percent). BTA FWT strengths tended to be randomly distributed over the panels, probably mostly due to material inhomogeniety, and varying combined failure modes. All failures were substantially above design requirements (i.e., less than 100 psi).

Comparison of the average contamination data for each panel to the control averages on the two control panels, 1,475 psi and 1, 140 psi or 1,308 psi average, showed no effect. Only one contaminated panel pulled less than 1,308 psi: Conoco grease at 1,283 psi. Six out of the seven contaminated panels produced small losses in strength when compared to the smaller control areas.

Sheet Cork Bonded with EC-2216 Epoxy

Four out of the seven contaminated panels produced small losses in strength when compared to the control areas, three of these four are ethylene glycol (-7.3 ± 4.2 percent), masking tape (-4.5 ± 6.4 percent), and vacuum pump oil (-3.2 ±3.7 percent). Standard deviation for the masking tape control specimens was 6.4 percent, greater than the 4.5 percent loss. Ethylene glycol and vacuum pump oil controls were the strongest pulled, thus making any loss comparison extra sensitive. These small decreases are believed to be due to cohesive strength variations in the cork sheet and not contaminant effects, because of the cohesive failure modes. All failures were substantially above design requirements (i.e., greater than 50 psi). Comparison of the average contamination data for each panel to the control averages on the two control panels, 161 psi and 167 psi or 164 psi average, showed little effect. Only two contaminated panels pulled less than 164 psi: masking tape at 150 psi and Skin So Soft at 160 psi. Since the cork pulled cohesively, it is believed that the strength variations are in the cork sheet.

Comparison of Inspection Results and TPS Panel FWT Results

Presented in table 3 is a summary of the inspection results and associated strength losses for each contaminant at the highest applied coating weights. The reported percent contamination detected indicates the amount of contaminant coverage detected of that actually present. It was anticipated, from lab testing, that each of these coating weights would have been 100 percent detected by either black light, or white light, or both. This did not occur and cw_{max} was not reached for ethylene glycol and Skin So Soft. Theoretically, higher coating weights may cause significant strength losses where detectability is unknown for these particular contaminants.

Vinyl tape residue (tape dwell—48 hours) was detected by black light and not by white light. Black light inspectors found 87 percent of the tape residue coverage. Operator variability was observed here. Only one of the six black light inspections failed to find 100 percent of the residue. On this panel, one inspector found 100 percent of the residue and the other inspector found 60 percent of the residue. This particular panel had a strength loss of 1.7 percent.

Vacuum pump oil was detected by black light and white light. On the three panels with coating weights of 108 mg/ft^2 and greater, 100 percent of the oil was detected with black light and 97 percent with white light. Strength losses for the panels with coating weights of 108 mg/ft^2 and greater were, -8 percent, and -3.2 percent. Only one of the six white light inspections failed to find 100 percent of the oil residue. On this panel, one inspector found 100 percent of the residue and the other inspector found 70 percent of the residue. This particular panel had a strength loss of -8 percent.

Spray Nine cleaner was detected by white light and not black light. White light inspectors found 100 percent of the cleaner residue on panels with coating weights 65 mg/ft^2 and greater. Strength loss for the panel with a coating weight of 84 mg/ft^2 was -1.9 percent.

Skin So Soft was partially detected by white light and not by black light. White light inspectors found 57 percent of the Skin So Soft residue on panels with coating weights of approximately 40 mg/ft^2. One panel had 100 percent detection by two inspectors, the second panel had 0 percent detection by both inspectors, and the final panel had 100 percent and 30 percent detection by the two inspectors. Strength loss for the one panel was -5.7 percent. Significant operator variability was observed here.

Masking tape (natural rubber on paper) residue, if present, (tape dwell 48 hours) was not detected by either white light or black light. Panel strength losses were small (i.e., -4 percent and -4.5 percent).

Table 3 Inspection and FWT Results for Highest Contamination

Contaminant	Coating Weight	TPS	% Contamination Detected BL	% Contamination Detected WL	Strength Loss
Conoco Grease	60	MSA-2	100	100	NSD
	69	Cork	100	100	NSD
	70	BTA	100	100	-6.1%±7.8%
Vinyl Tape	NA	MSA-2	60	10	-1.7%±3.9%
	NA	BTA	100	0	-4.5%±1.5%
	NA	Cork	100	0	NSD
Vacuum Pump Oil	108	BTA	100	100	NSD
	134	MSA-2	100	90	-8%±3.6%
	141	Cork	100	100	-3.2%±3.7%
Spray Nine Cleaner	57	Cork	10	10	-1.8%±4.8%
	65	MSA-2	10	100	NSD
	84	BTA	0	100	-1.9%±6.3%
Masking Tape	NA	MSA-2	10	10	NSD
	NA	BTA	0	0	-4%±1.5%
	NA	Cork	0	0	-4.5%±6.4%
Ethylene Glycol	79	BTA	10	0	-0.4%±5.4%
	85	MSA-2	0	0	-5.3%±3.3%
	133	Cork	10	0	-7.3%±4.2%
Skin So Soft	38	MSA-2	0	70	NSD
	41	Cork	0	100	NSD
	42	BTA	0	0	-5.7%±3.6%

NSD no significant difference

Ethylene glycol, up to coating weights of 133 mg/ft^2, was not detected by either black or white light. Panel strength losses were -0.4 percent, -5.3 percent and -7.3 percent.

Conoco grease was easily detected by white and black light. White and black light inspectors found 100 percent of the grease residue at coating weights of 60 mg/ft^2 and greater. Panel strength loss at this level was -6.1 percent for BTA.

Out of all the possible combinations of the seven most deleterious contaminants and the three TPS applications (i.e., 21 combinations), four bond losses were observed at contamination levels that were not detected by black light or white light. These are shown in table 4.

Table 4 Undetected Contamination Causing Strength Loss

Contaminant/TPS	Control Strength (psi)	Contamination Strength (psi)	Requirement	Percent Adhesive Failure	Comment
Ethylene Glycol/ MSA-2	155	147	75	Fuzz at Surface	Typical cohesive failure
Ethylene Glycol/ Cork	191	177	50	0	Failure in cork not related to contamination
Skin So Soft/BTA	1,470	1,386	100	0	Failure in BTA not related to contamination
Masking Tape Residue/BTA	1,494	1,434	100	50	

CONCLUSIONS

Based on the results of this study, undetected surface contamination from credible sources is not a significant concern with existing SRB TPS processing operations. The epoxy resin system used is sufficiently resistant to a wide range of potential contaminants. Failures were predominantly cohesive and not at the TPS-contaminated substrate interface. In this study, MSA-2, BTA, and cork performed over and above FWT requirements at reject contamination levels. MIL-STD-1246 NVR levels (less than 25 mg/ft^2) are not significant to the lap shear and TPS bonds evaluated in this study. The residue levels found on the two different sets of NVR plates, which were removed from USBI FL Ops, were well below shuttle processing facilities requirements (1.0 mg/ft^2/month). Contamination levels used in this study were much higher than that anticipated on cleaned hardware, a conservative approach.

Contamination effects were insignificant on the MSA-2 panels. The contaminated MSA-2 panels still pulled well above the design minimum. Contamination effects were not effectively realized due to the relatively low cohesive strength of MSA-2.

Some contamination effects were observed on BTA applications, with very small losses in strength. Contamination effects were realized probably due to the higher inherent cohesive strength. Such contaminated BTA strengths were still way above design minimums.

Surprisingly, cork bonding apparently resisted all contamination effects. Like MSA-2, cork is relatively weak cohesively, which explains the lack of sensitivity to contamination affects. All failures were consistently cohesive.

The inherent weakness of SRB TPS materials makes this class of materials less sensitive to surface contamination effects when compared to lap shear testing. For a purely adhesive TPS failure, a contaminant would have to effectively repel the TPS material or bonding adhesive so that it could release at a level below the cohesive strength of the TPS system, which is *much* lower than the design of the adhesive bond system. As a result, the lap shear test revealed more information concerning contamination effects.

New detection methods are not warranted for these three materials based on the magnitudes of bond loss, (i.e., -4 to -6 percent), the high levels of contamination (greater than 42 mg/ft^2), and the low FWT strength requirements.