Qualification of Surface Preparation Processes for Bonded Aircraft Repair

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ABSTRACT

Metals present extremely high energy, reactive surfaces to the environment. When mechanically or chemically cleaned, they rapidly oxidize and adsorb contaminants such as organic vapors. Polymers present surfaces that are less reactive towards their surroundings. When cleaned by abrasion processes they also show rapid changes due to oxidation and adsorption, but these changes tend to be of lower magnitude.

Successful bonded repair of aircraft structures involves creating a small area of carefully controlled surface composition on metallic or polymeric surfaces. This area to be bonded is located within a larger area of material that may be contaminated with a variety of soils picked up during normal aircraft operation: organic and inorganic soils, fuel, hydraulic fluids, etc. Because of the reactivity of freshly prepared surfaces and the proximity and mobility of contaminants in the surrounding area, cleaning of these surfaces sufficiently to obtain reliable adhesive bonds can be particularly difficult in field situations. Furthermore, because the difference between a well-cleaned surface and a contaminated one may only be a few molecular layers, it can be difficult for the technician to establish when the surface has been properly prepared.

Measurement of the geometry of a liquid drop deposited onto the surface can be done extremely rapidly and form the basis of a sensitive check of surface cleanliness and consistency in a repair depot or in challenging field situations. This paper discusses the use of these rapid wetting measurements for quality assurance of surface treatments for adhesively bonded repairs.

1. INTRODUCTION

1.1 Challenges of Bonded Aircraft Repair

Adhesive bonding processes are increasingly becoming the techniques of choice and/or necessity for many aircraft repair procedures. There are several reasons for this trend. Bonded repairs allow complex shaped patches to be blended into critical aerodynamic surfaces without loss of performance. They also avoid the necessity of introducing the stress concentrations that accompany the holes necessary for mechanical fasteners. Figure 1 shows an example repair that involved bonding a composite patch onto an aluminum aircraft skin. A major concern with any bonded repair are disbonds that can occur at installation of the doubler or at anytime during the service life of the aircraft **[1,2].**

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Figure 1. Bonded boron/epoxy composite doubler for repair of aluminum aircraft **[1].**

A bonded structure consists of at least three components: substrate, adhesive, and substrate/adhesive interface. When a bonded structure is loaded, the strain energy is partitioned between each of these components. If loaded to failure, failure occurs in the component having the lowest fracture toughness. The analogy of a chain that fails in its weakest link is very appropriate (Figure 2).

Figure 2. Bonded graphite/epoxy composite loaded to failure in Mode I. Crack propagation is in the composite, the phase with the lowest fracture toughness in this structure.

The substrate toughness in a bonded repair is generally not in question, and failure is in general limited to failure within the adhesive or at the interface. While incomplete adhesive cure due to poor temperature control, poor adhesive mixing, or improper stoichiometry is possible, the most common reason for failure of bonded repairs is believed to be due to deficiencies in the surface preparation of the area to be bonded [3]. For reasons discussed below, surface preparation is very sensitive to seemingly subtle process variables, and the prepared surface prior to application of the adhesive is fragile and subject to damage. Effective, reproducible surface preparation can be challenging even under controlled laboratory conditions.

1.2 Surface Treatment for Bonded Aircraft Repair

The two general types of surface pretreatments used to prepare aerospace materials for adhesive bonded repairs are *mechanical* and *chemical.* Mechanical treatments include hand sanding and grit blasting. Composite substrates are generally prepared by simple abrasion. Because of the susceptibility of metallic surfaces to corrosion, abrasion on these substrates may be followed with a chemical treatment such as a sol-gel coating **[4]** or an acid etch process to improve long term durability of adhesive bonds.

Mechanical pretreatments are the most commonly used pretreatments for adhesive bonding of aerospace materials, and can produce excellent results. They remove contaminants and weak oxides while roughening the surface. This cleaning and roughening provides for improved wetting **[5]** and allows for mechanical interlocking between the adhesive and substrate **[6-7].** Abrasion can create reactive sites through fracture of the composite which may provide for covalent bond formation in some systems.

The variables associated with mechanical pretreatments are not well understood. Uniformity of hand sanding depends strongly on the skill of the individual mechanic performing the operation. As a manufacturing process, this can be very difficult to control, and results in variable adhesive joint performance. This is an unacceptable outcome for adhesive bonding of critical structures. It is especially a problem for bonds made using room temperature curing paste adhesives, but much less of a problem when using high temperature curing adhesives.

Uniform coverage and reproducible results are more readily obtained using a grit blasting process, particularly when robotic control of the blasting process is used. Grit blasting has been successfully employed for years for preparation of metal surfaces. However, unlike metals, composites are very susceptible to damage from overly aggressive abrasive blasting. This can lead to weakening of surface plies and decreased G1c values for the adhesive joint. Damage may be induced below the surface of the laminate by the blasting process, and has been postulated as a source of weakening of the laminate **[8].** Furthermore, containment of grit can be a difficult issue. As a result, most repair procedures rely on hand or mechanical sanding followed with solvent wiping.

1.3 Quality Assurance of Surface Treatment for Bonded Aircraft Repair

Adhesive bonding is a *wetting* phenomenon, i.e. an interaction between a liquid adhesive and a solid surface. One way of assuring the quality and consistency of a surface prepared for adhesive bonding is through assuring that the surface has the desired wetting properties **[9].** A convenient way to obtain these wetting measurements in a challenging repair environment is through ballistic deposition of a water drop followed by determination of the average contact angle established by the drop perimeter with the surface **[9-11].** This approach has shown excellent sensitivity to consistency of surface treatment of both metal and polymeric surfaces.

An example of bonded repairs is the replacement of captive threaded fasteners (nutplates) that are adhesively bonded to an airframe to allow installation and removal of components and panels for maintenance and repair. Figure 3 shows typical bonded nutplates on a segment of an aerospace structure.

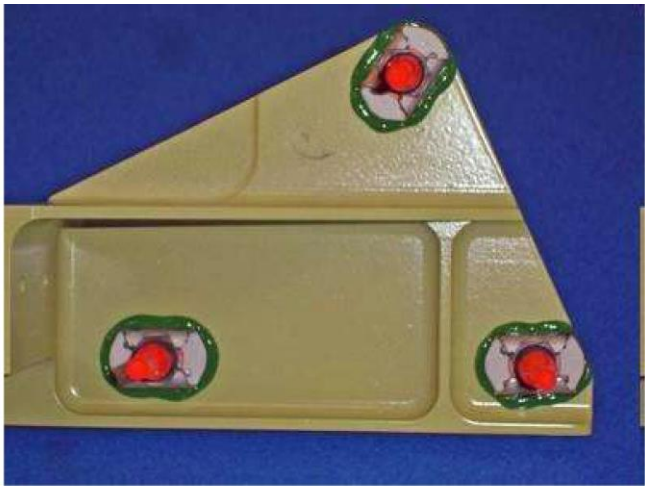

Figure 3. Nutplates bonded to an aluminum casting. Orange elastomer tabs passing through threaded fastener are for fixturing during adhesive cure and are removed prior to use.

Strong and durable bonding of these nutplates is accomplished by abrasion and solvent cleaning of the area to be bonded. The current study presents the results of experiments designed to evaluate the sensitivity of wetting measurements to variables in surface preparation, specifically substrate material, elapsed time between surface preparation and bonding, and the presence of contamination in the form of minute amounts of mold release.

2. EXPERIMENTATION

Three substrates, including Ti-6Al 4V, 2024-T3 Al, and graphite reinforced epoxy laminates, were cut into 2" x 6" x 0.125" panels and drilled with 5 evenly spaced 0.250" holes to accept threaded fasteners. Metal surfaces were prepared for adhesive bonding by abrasion with 180 grit SiC paper followed by wiping with a low vapor pressure degreasing solvent (DS-108, Dysol, Inc.). After solvent wiping and before the solvent had an opportunity to evaporate, surfaces were dry wiped to maximize efficiency of contaminant removal. Some surfaces were allowed to age for various times on the laboratory bench prior to bonding to evaluate the effect of out time. Other surfaces were contaminated after sanding and solvent wiping with a dilute solution of silicone mold release (Frekote 1711-1) in heptane. A 'low' contamination level was created by a single wipe; a 'high' contamination level was obtained by two sequential applications of the dilute mold release. Wetting properties of all surfaces were determined immediately prior to bonding by measuring water contact angles with a Surface Analyst™ instrument (Brighton Technologies Group, Cincinnati, OH). Nutplates (Click Bond, Inc., Carson City, NV) were bonded to these surfaces using the supplied adhesive. Adhesion of nutplates to these surfaces was determined using a push-off test in a universal testing machine (Figure 4).

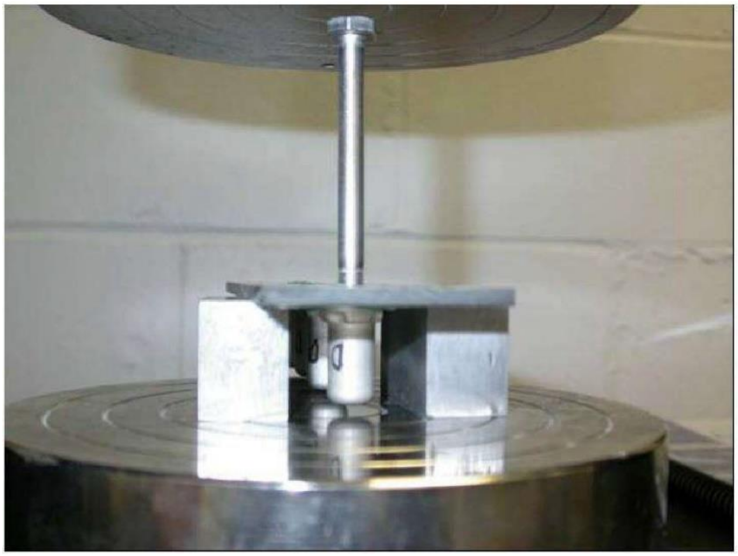

Figure 4. Determination of bond strength of nutplates.

3. RESULTS

Wetting measurements were sensitive to subtle changes in surface composition resulting from aging and deliberate contamination and were predictive of both failure load and failure mode. Figure 5 shows representative images obtained from Ti-6Al, 4V coupons with and without contamination along with images of the adhesive failure surface.

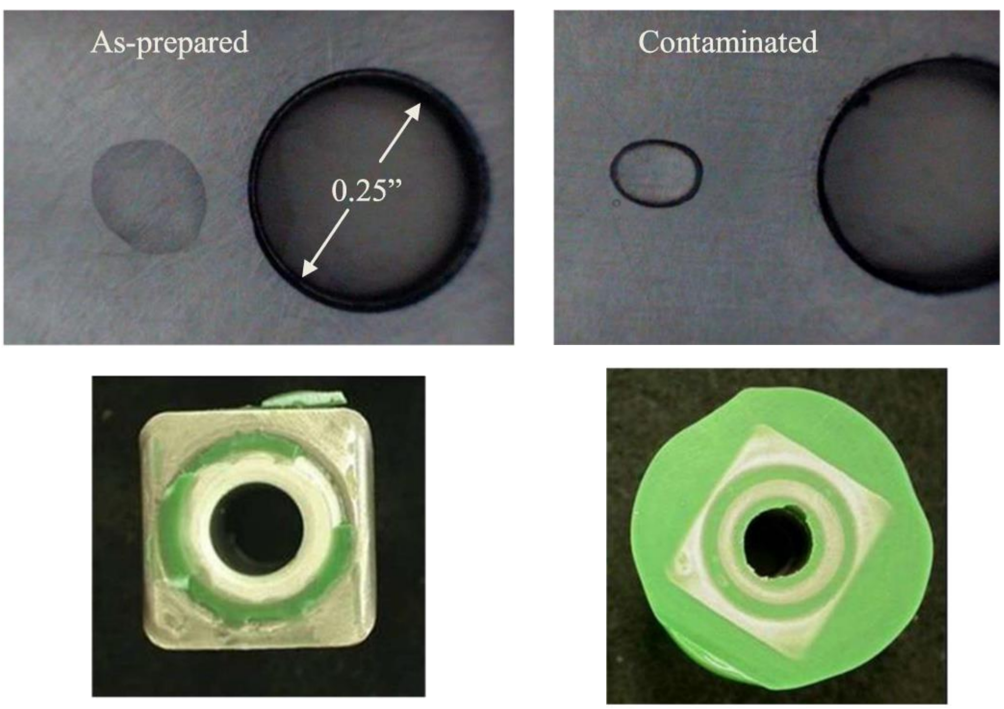

Figure 5.

Top: Ti-6Al, 4V surfaces prepared for bonding by abrasion and solvent wiping.
Bottom: corresponding nutplate failure surfaces.

In these samples the presence of a small amount of contamination made readily visible changes in the wetting behavior of the water droplet applied by the Surface Analyst™ which were also reflected in the transition from a cohesive failure mode to an adhesive failure mode.

3.1 Effects of Aging of Prepared Surfaces Prior to Bonding

Figure 6 shows the effect on wetting measurements and nutplate adhesion of aging of the abraded aluminum surface after preparation. Aging resulted in dramatic increase in the average contact angle measurement (ca. 15°), showing that the aluminum surface was changing as a result of aging. These changes only resulted in modest changes in pushoff load (ca. 18%), however. In this instance the adhesive appears only slightly affected by the surface chemistry changes occurring on the aluminum.

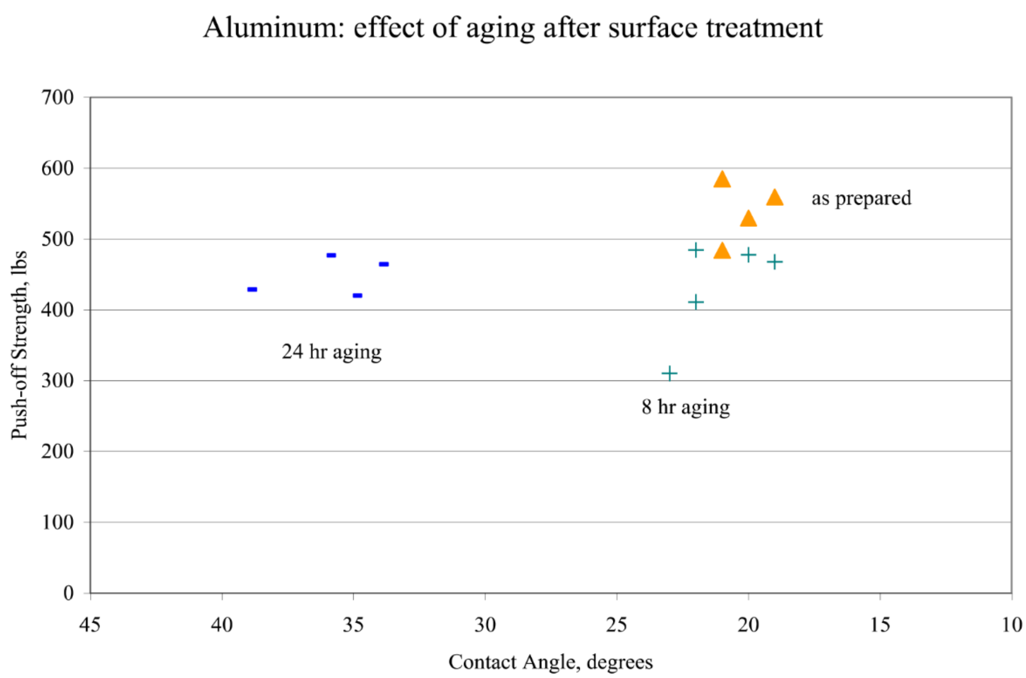

Figure 6. Push off load vs. contact angle for abraded and aged aluminum substrates.

The changes in pushoff load were more dramatic for the titanium and composite substrates. Figure 7 shows the results obtained using the Ti-6Al, 4V substrates. Initial strengths were significantly lower than on aluminum, and there was a linear decrease in the pushoff load with aging that mirrored the increase in contact angle.

Figure 8 shows the results obtained from the composite substrates. Even though such surfaces are generally felt to be stable with respect to modest aging, the almost 10° increase in the contact angle measurements after 24 hours exposure to the relatively clean laboratory atmosphere shows that the abraded surfaces are actually quite active. As for the other substrates, there was excellent correlation between pushoff load and contact angle.

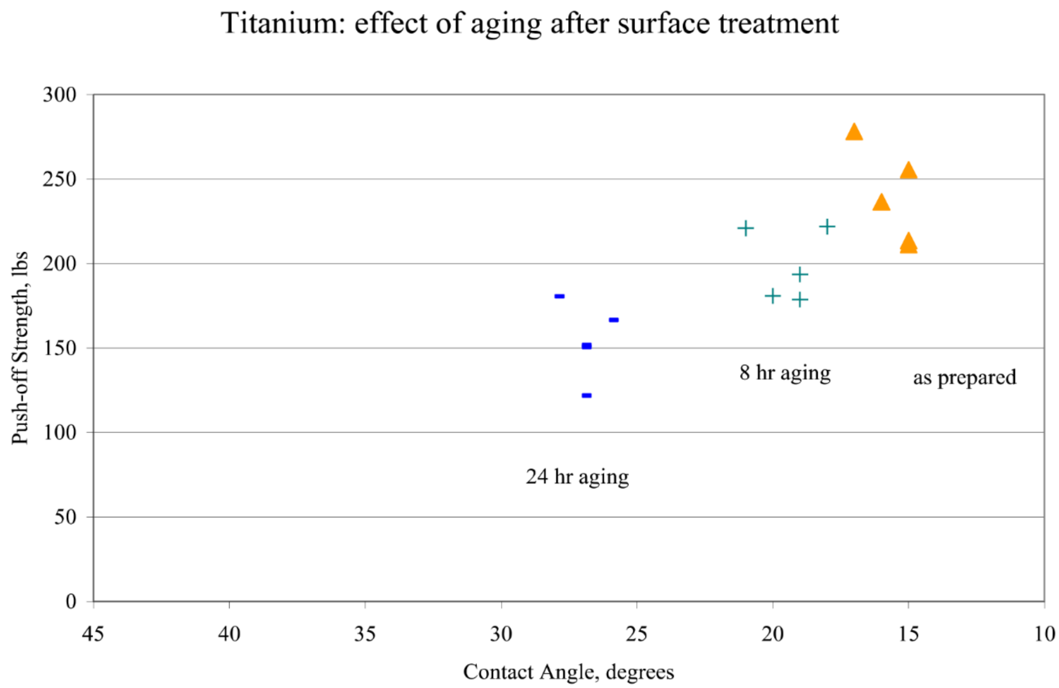

Figure 7. Push off load vs. contact angle for abraded and aged Ti-6Al, 4V substrates.

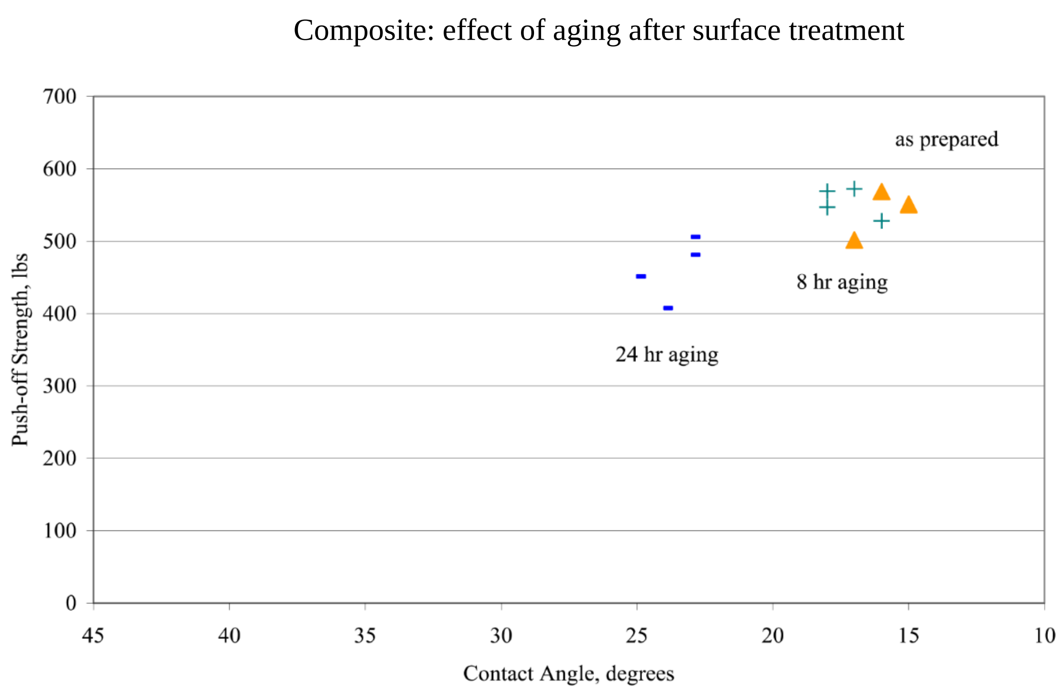

Figure 8. Push off load vs. contact angle for abraded and aged graphite/epoxy substrates.

3.2 Effects of Contamination of Prepared Surfaces Prior to Bonding

Contamination effects were readily observable in both wetting measurements and push off load. In general the 'low' level of contamination caused a large increase in measured contact angles and reduced adhesion to almost nil.

Figure 9 shows the effects on the Aluminum surface. Although the two levels of contamination were readily distinguished via wetting measurements, neither contaminated surface showed a useful level of adhesion.

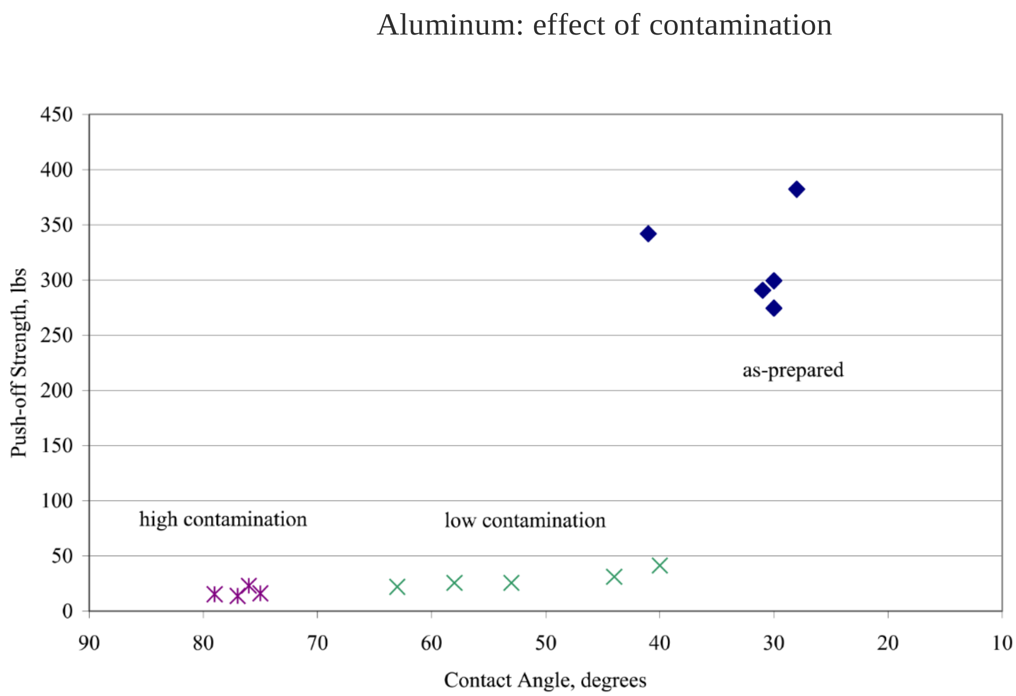

Figure 9. Push off load vs contact angle for abraded and contaminated Al substrates.

Figure 10 shows the results from the Ti-6Al, 4V surfaces. The 'low' contamination level increased the measured contact angles from about 12° to around 35-40° accompanied by a loss of almost all adhesion. Further increase in contamination level was readily detected via wetting measurements and literally dropped adhesion to almost zero.

In contrast to the metal substrates, the graphite/epoxy composite substrates showed significant adhesion at the 'low' level of contamination. Figure 11 shows that the substrates with the low level of contamination still required around 100 lbs. of load to debond the nutplates.

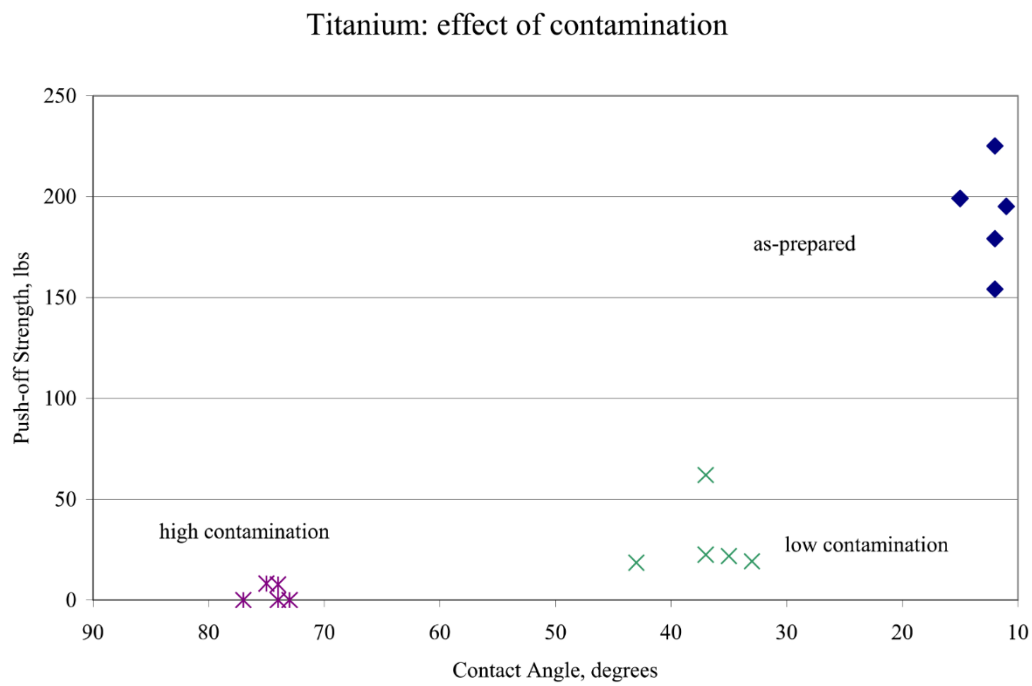

Figure 10. Push off load vs. contact angle for abraded and contaminated Ti-6Al, 4V substrates.

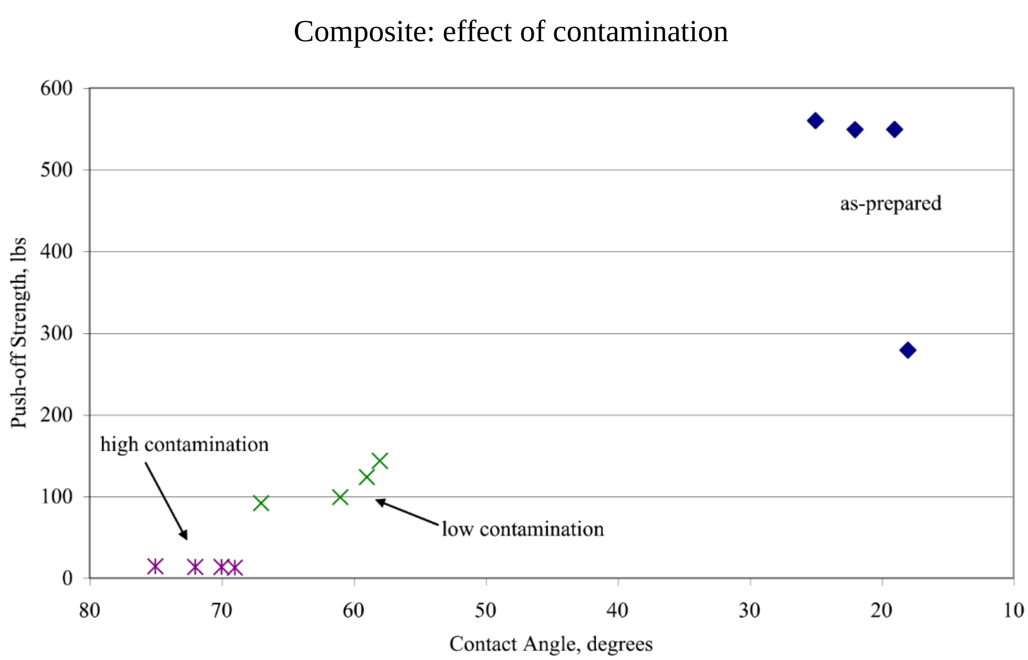

Figure 10. Push off load vs. contact angle for abraded and contaminated composite substrates.

4. CONCLUSIONS

Because adhesive bond performance is so dependent on surface preparation quality and consistency, surface preparation of aircraft structures for bonded repair represents a particular challenge. Reliable surface preparation for bonding under conditions encountered in repair situations (where structures may be contaminated with a variety of soils, where repairs must be performed in a less than ideal work environment) requires sensitive tools for confirming surface condition. The current work helps to establish wetting measurements obtained via contact angles as a way to obtain the quantitative feedback necessary for ensuring the surface quality. This wetting data can form the core of a quality assurance program for surface preparation.

5. REFERENCES

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