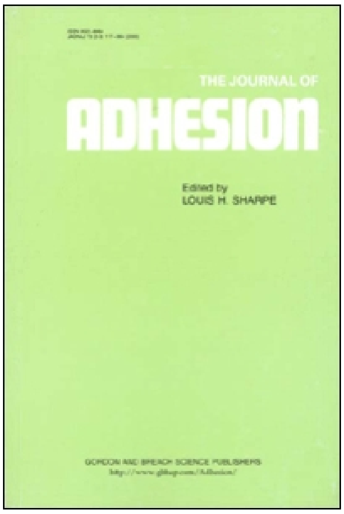

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An Engineer Asks: Is it Really More Important that Paint Stays Stuck on the Outside of an Aircraft than that Glue Stays Stuck on the Inside?

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An Engineer Asks: Is it Really More Important that Paint Stays Stuck on the Outside of an Aircraft than that Glue Stays Stuck on the Inside?

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The purpose of this article is to draw attention to two problems encountered with modern aircraft: the difficulties in making adhesive and paint adhere to composite substrates and the lack of any after-the-fact inspection that can prove that there will not be any interfacial failures at some time during the service life. It is also observed that the response to paint peeling off is more rapid and thorough than to a discovery of separations between internal components that were once believed to have been bonded together. Because there is so much similarity between the processes of making paint and adhesive adhere, it is suggested that some of the efforts to improve adhesion of the paint might also help improve the processes for making adhesives stick. The article focuses on a series of anecdotes about problems and their resolutions, with the hope that the solutions might help others solve or avoid future such problems. It is pointed out that the cost of improving the adhesion of both paint and adhesive has always been insignificant in comparison with the sometimes enormous costs incurred as a result of fleet-wide occurrences of what were perceived to be bond "failures" but which should more properly be characterized as initially undetected nonbonds. A critical issue is the acknowledged absence of any nondestructive inspection capable of distinguishing between bonds that will "fail" in service and those that will not. Experience has shown that none of the apparent interfacial failures to date have occurred on grit-blasted surfaces. Equally, it must be conceded that not all of the bonded composite structures made using peel-ply surfaces can be expected to fail, even though those associated with released peel plies or prebond moisture probably will, because these conditions have been associated with so many of the past failures. The distinction between interfacial failures and impact damage to properly bonded structures is that the former can extend throughout the entire structure, whereas the broken fibers and interlaminar matrix failures associated with the latter will not extend far beyond the impact area. This is one reason why

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it is so important to use only surface preparations that ensure the absence of interfacial failures. It is also noted that there is no counterpart, for the bonding of composite structures, of the peel-type test that was so instrumental in solving the equivalent bonding problem that was widespread in bonded metal structures some 30 years ago. It is recommended that there should be, because the use of only shear-load tests has been found to be insufficient to ensure bond durability for both metallic and composite structures.

Keywords: Adhesion; Adhesives; Aircraft; Bond failure; Bonding to composites; Delamination; Durability; Effects of moisture; Kissing bonds; Mode of failure; Peel-ply; Processing; Service life; Surface preparation

INTRODUCTION

Ordinarily, one would be tempted to think that the answer to the question posed in the title of this article would be obvious. No! However, experience teaches that this is not necessarily always the case. The response to discovering a lot of paint peeled off when an aircraft lands after flying through a hailstorm or has been struck by lightning is typically both immediate and thorough—because the damage is clearly visible. Discovering that two internal components once believed to have been bonded together but no longer are is far more difficult. In addition, it is not always necessary that such damage be repaired, because there may be sufficient mechanical fasteners to carry the loads, whereas the exterior must be maintained for aesthetic reasons.

One purpose of this article is to harness some of the zeal devoted to improving the adhesion of the paint and have it applied to improved bonding techniques as well. After all, the two processes are clearly very closely related. In the author's opinion, the underlying problem is that it is possible to measure a short-term static bond strength without creating a durable interfacial bond between adhesive and substrate. Certainly, this was proved to be the case for bonded metal structures made to U.S. specifications in the late 1960s and early 1970s. The difference between nondurable bonds and those that have lasted for decades in service without failing is that all of the premature failures have been visually interfacial and cannot always be associated with any applied loads. The durable bonds, on the other hand, sustain far higher stresses than those for interfacial separations; they fail cohesively and never simply fall apart with time in the absence of applied load. Unfortunately, because the test coupons that do fail interfacially withstand some load level before failure, there is not yet a universal recognition of the importance of ensuring that the adhesive, or paint, is actually stuck securely. (Even home-repair epoxy glue applied to glass window panes will not fall off immediately, even though we know it will eventually detach itself if the glass had not been cleaned or etched first.) The scientists and engineers who pioneered the introduction of aircraft metal bonding in the 1940s and 1950s in England and Holland based their selection of materials and processes on durability tests they performed *before* they built their structures. This is why their structures did not disbond in service. It seems that they may have been so successful that later exponents of adhesive bonding were lulled into a sense of not anticipating durability problems for newer materials and processes because there was no record of service failures with the earlier applications. The problems with later metal bonding, mainly in the United States, were so extensive that the processes were changed during the late 1970s, as reported by Thrall and Shannon [1], and durability testing was added to the standard quality-assurance tests to supplement the previous short-term lap-shear test. One of the most significant contributions to solving this problem for bonded metal structures was made by a Boeing Seattle engineer, Bert Bethune, who developed a new quality-control test coupon, the wedge-crack test, that was capable of differentiating *at the time of manufacture* between those panels that would separate into their component details in service and those that would not. Since then, some form of peel test in a hostile environment has been used universally in quality-control (QC) tests for metal bonding. Interfacial failures were banished from that point on. The same cannot yet be said for the bonding of fibrous composite laminates, which is why paint and adhesive do not always adhere to these types of materials. Significantly, some surface treatments are very different for the composite structures that are free from interfacial failures and those that are not, whereas others appear to be identical. The same used to be true for metal bonding in the era when durability problems were prevalent.

It should be made clear, at the outset, that the author is not suggesting that there is a widespread safety issue involved here. Neither is he implying that every, or even most, bonded composite panels will revert to their individual pieces, even though those that do fail interfacially *will* eventually disbond globally. Rather, he is drawing attention to the high costs incurred by manufacturers and operators alike as the result of not responding promptly to what he and others see clearly as the result of inappropriate surface treatment techniques that have been tolerated for far too long.[1] Perhaps there has been no response because interfacial failures of bonded aluminum structures were associated with corrosion by the time the damage was located and bonded composite structures were believed, by some, to be free of this problem because they could not corrode.

The reasons for not implementing improvements promptly seem to derive primarily from two sources. The costly inspection techniques used to detect damage to a bonded structure are inherently incapable of detecting nonbonds, or "kissing" bonds as they are more commonly referred to, until a gap has actually opened up between the components. In-service experience has shown conclusively that almost all bond "failures" are interfacial, which is an unambiguous indication that the adhesive was never stuck in the first place. However, it is hard to convince someone who spent a lot of money on ultrasonic inspections at the time of manufacture, without finding any indication of a problem, that there is something wrong with the part. This brings us to the second cause of the problem. The process of adhesion is not understood by a sufficient number of people with the authority to implement improved processing techniques. The only way to make either adhesive, or paint, stick is to prepare the surface *appropriately*. Everyone who has ever painted his own house knows this—and is aware that when he pays someone else to paint it for him, the paint *will* flake off prematurely unless he paid more for proper preparation as well. Why is it that these experiences cannot be transferred to the workplace?

The process of educating the manufacturers about the need for improved surface preparation for bonding has not been helped by the operators, either, despite the fact that they have suffered the most. After reporting the first few of a series of identical disbond failures, if they are advised that each instance was unique and would not affect the rest of the fleet, the aircraft operators would not bother reporting when *exactly* the same problem arose with *every* other bonded assembly as well. This breakdown in communication contributed to the growth in magnitude of the metal-bonding problems before they were solved. The operators must be more persistent in reporting such problems, each and every time, to ensure that there is a response.

[1]The emphasis here on problems with bonding or painting to composite peel-ply surface preparations does not necessarily mean that they should never be used. What *is* advocated is that only those surface preparations that are *demonstrated never* to have any durability problems at interfaces should be used and that there should be mandatory testing to differentiate between reliable and unreliable surface treatments, just as there already is for metal bonding.

The original equipment manufacturers (OEMs) and their suppliers cannot be expected to respond to a problem they do not believe exists. Today's problem with keeping adhesive stuck to newly made components is confined mainly to composite structures, even though keeping the paint stuck is a problem for metallic structures as well. The manner in which the interfacial failure of aluminum-alloy metal-bond structures was cured is still informative today. So many of the bonded aluminum structures made in accordance with U.S. process specifications during the late 1960s and early 1970s were found to have not only disbonded in service but also corroded that the true source of the problem could not be ignored any longer. For a long time, the adhesives manufacturers were blamed. The US Air Force (USAF) funded the former Douglas Aircraft (now Boeing Long Beach) to demonstrate that reliable bonded structures could be made by anodizing the surfaces instead of merely etching them and by using a new phenolic-based primer. (A second generation of improved toughened epoxy adhesives was also developed at that time, but the successful use of the older adhesives on the improved surfaces and new primer confirmed the real problem.) Thousands of bonded honeycomb panels had been totally remanufactured by the operators by then, because the price of spares was so high. New, more durable surface treatments and primers were introduced in production by all OEMs, and the problem was cured, permanently, at least for parts that had not yet been built.[2] (What happened as a result of not also correcting the repair manuals for the parts that had already been manufactured under the older processes is described by Hart-Smith and Davis [2].) This is why it is so important that the OEMs learn of the true magnitude of the composite-bonding problem today, which can be established only by *complete* in-service records.

THE NATURE OF THE PROBLEM

Figure 1 shows a typical peel-ply imprint in a layer of adhesive that had totally separated from the composite surface to which it was believed to be bonded without any visual damage to either the adhesive or the resin in the composite part. In this case, the source of the problem is believed to have been prebond moisture in the cured laminates; in other cases, leaving identical-looking imprints on the surface, the cause has been silicone transferred from released

[2]Ironically, the introduction of phosphoric-acid-anodized honeycomb core took decades more to accomplish. Many years were to pass in which easily corroded core was used in conjunction with properly prepared bonded face sheets.

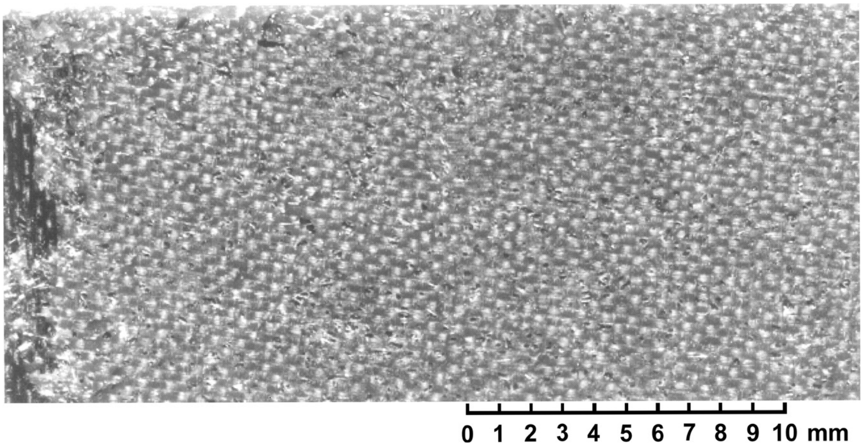

FIGURE 1 Peel-ply imprint left by failure of adhesive to bond to a composite surface.

peel plies. Significantly, *every* such bond "failure" had remained undetected during initial inspections and, to the best of the author's knowledge, no such adhesion failures have ever occurred on surfaces that had been prepared by grit blasting. The real wonder is that adhesives or paint *ever* adhere to surfaces created by merely stripping off a peel ply. For the peel ply to strip off cleanly, without causing delaminations between the underlying layers of fibers, it is necessary that the interface

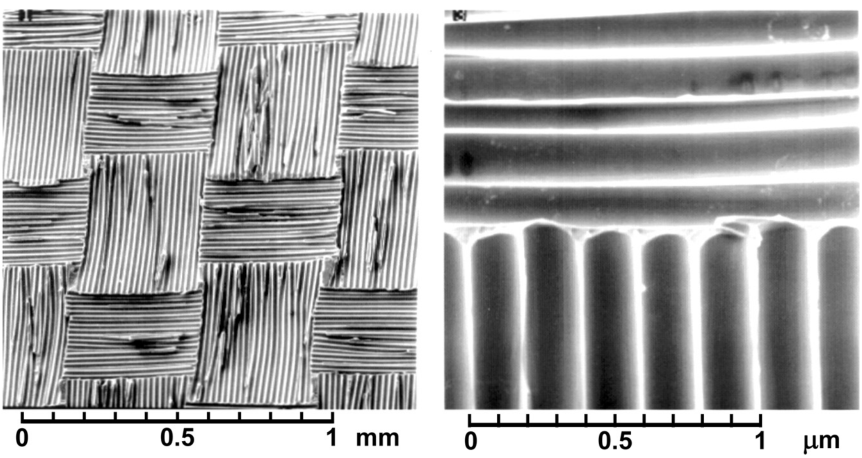

FIGURE 2 Close-up of peel-ply imprint showing slick totally inert bonding surface.

between the peel ply and the resin be totally inert, as is evident in the highly magnified image in Figure 2. Each groove in the photomicrograph on the right is as smooth as glass. And inert surfaces, like dirty glass windows, are notoriously difficult to bond to, unless they are cleaned or etched first. Normally, adhesive and paint will stick to only activated surfaces, not inert ones.

The theory of adhesion has established that the surface energy of the substrate must be *higher* than that of the uncured adhesive, or paint, if the two materials are to adhere. This means that the surface needs to be *activated*, by some means or other. It is also known that absorbed water in the laminate lowers the work of adhesion of composite substrates, as reported by Mahoney [3]. Contamination, for example, in the form of a layer of silicone or other release agent, does also. Nevertheless, it must be conceded that the adhesive seems to have stuck to many peel-ply composite surfaces that are known to have not been contaminated by release agents and known to have been dry at the time they were bonded together. The problem is that there is also no after-the-fact inspection with which to identify which panels *will* fall apart after they have been bonded.

Note the image, at the left of Figure 1, of the equally clear peel-ply imprint left in the skin underneath this layer of adhesive that did not adhere to *either* bonding surface.

The condition in Figures 1 and 2 is typical of all such failures detected in service. Copiously illustrated studies of tests on this subject are reported by Hart-Smith et al. [4, 5]. Many such surfaces have also been observed when repairing panels[3] that had been damaged prior to delivery of aircraft while they were still on the assembly line. It does *not* necessarily take a long time for the bond separations to occur, even though most are not found until some in-service inspection. This would tend to suggest that the separation process does not require the absorption of moisture *after* the adhesive has been cured, but the author's knowledge of the causes of nonbonds is not as great as his knowledge of the consequences, so explanations of exactly what is happening by real polymer chemists would be appreciated.

Discussions about this issue with Prof. Tony Kinloch, of Imperial College, London, have resolved some of the questions raised about the adhesion process for thermoset resins. The author is very grateful for this advice, which is summarized here.

[3]The identities of the aircraft involved with the anecdotes related here are not recorded because they are not germane to the issues being discussed. Nevertheless, all such incidents happened in production unless there is a specific reference to laboratory tests.

The first question was whether there ever was a strong bond between components that, later in their life, are found to have apparently separated cleanly with absolutely no visible damage to the interface, not even when viewed under high-power microscopes. There appears to be no well-established mechanism for properly bonded composite interfaces to degrade progressively in a manner akin to absorbed water in metal-to-metal bonds in which the surfaces had not been prepared properly. In this latter case, the bond strength should be retained if absolutely no water is absorbed. Kinloch's position is that, for composite bonds that simply fall apart from a complete interfacial failure, there never was a proper bond in the first place, even if it could not be detected ultrasonically at the time—and even if the condition is not revealed by the standard lap-shear coupon test. This is a strong argument in favor of mandating the addition of a peel-dominated test as part of the quality-assurance program.

The experiences of Kinloch and his colleagues in regard to prebond moisture confirm the author's assessment, but go further. They have found the equilibrium level of absorbed moisture in cured laminates to be typically 1.5%. The diffusion rate is slow and, therefore, so are the processes of moisture absorption and drying. The issue is that laboratory tests are often not run for a sufficiently long time. (Another colleague and bonding expert at the maintenance and repair level, Max Davis of the Royal Australian Air Force, [RAAF] has expressed similar views about wedge-crack tests of bonded joints, suggesting that more can be learned by testing for a month rather than a day. Davis is referring to research on the subject; he is not advocating QC tests lasting a month before it is known to be safe to prime the detail parts and proceed with the adhesive bonding.) Kinloch's point is that the drying process for repairing parts that have been in service for many years before they were damaged is usually too short. There is still plenty of prebond moisture left to interfere with the bonding process.

In addition, Kinloch and his colleagues have found that, with some adhesives but not all, the prebond moisture can actually react adversely with the catalyst and interfere with the curing process [6], eliminating as much as 80% of the cohesive toughness of adhesive layers, which, apart from this moisture problem, had all of the most desirable attributes for room-temperature-curing adhesives for making bonded repairs. Mahoney [3] also cites work in which as little as 0.2% prebond moisture in the laminate can reduce the measured lap-shear strength, with three different heat-cured film adhesives, to as little as 20% of the strength demonstrated in bonding to dry laminates.

The experiences at Imperial College even exceed the author's observation that prebond moisture can be every bit as bad a contaminant as a layer of silicone as far as adhesive bonding is concerned.

The author was already aware of another moisture-absorption problem whenever uncured adhesive film is left out of storage for too long before it is laid up. Water *in* many uncured adhesives can change the form of the cured adhesive to be weak and powdery. This is why limits are set on the "out time" for adhesives between the time they are removed from the freezer and left at room temperature before they are actually used. The author has seen a popular 250°F (120°C) cured toughened epoxy adhesive cure as a weak crumbly layer if the roll of adhesive were left exposed to the atmosphere for too long (several days) after removal from the freezer. Another similar adhesive was actually removed from the market by its manufacturer, at the start of the Primary Adhesively Bonded Structures (PABST) program, because the same thing was discovered to happen with too short a working life—after a major aircraft manufacturer had completed all of its mechanical tests and decided to use that very adhesive as its standard bonding material for future production.

It is Kinloch's belief that grit blasting does not change the molecular structure of the epoxy. Rather, it can be an extremely reliable technique, if done properly, to remove all "pollutants" that would inhibit the bonding process. There is an associated increase in the area of the treated surface, of course. But this would be of no help if that greater surface were still inert. This position is consistent with inert surfaces left by so many peel plies. There is a tremendous increase in the wetted "bond" area, but that does not overcome any tendency for interfacial failures to occur whenever an attempt is made to bond to an inert surface. Kinloch feels that we just don't create as clean a bond surface every time as we believe we do. He suggested that improvements in bond strength and durability might be achieved by ultrasonic cleaning and that this should be established by test coupons to confirm it. The absence of any improvements, once interfacial failures had been precluded, would confirm that the surfaces had already been cleaned before ultrasonic cleaning. Any observed improvements would be an unambiguous demonstration that the original surface really hadn't been completely clean.

Adhesives manufacturers are aware of these issues and use such techniques as including additives to adhesives to "eat" through some of the surface contaminants that are often overlooked.

The process whereby a cleaned epoxy surface will attract contaminants if left exposed suggests that we should consider the application of a primer after the surface has been prepared, by whatever means, whenever the entire area to be bonded is not to be bonded immediately, as happens with complex structures needing multiple bond cycles.

In essence, Kinloch's experiences (which should be heeded because he *is* a recognized expert on adhesives and adhesion) confirm most of the author's concerns based on 30-plus years of not fully understood observations. Silicone must be excluded. (Everyone knows this now.) Prebond moisture is a very serious underappreciated source of severe bonding problems. Apart from low-pressure grit blasting, none of the standard surface-preparation methods work *all* of the time. There are *no* inspection techniques that can be relied upon to detect non-bonds before the parts have totally separated interfacially. There is a need for the addition of a peel-based durability test to the standard lap-shear test coupons, which, on their own, have been no more effective than they were for metal bonding when there were so many in-service problems on U.S. aircraft some 30 years ago. Kinloch's advice provides credible explanations of some of the lesser-known problems with adhesive bonding of composite structures—along with the encouragement that there is no reason to anticipate progressive deterioration in service *if* the bonding is done properly[4] in the first place.

Some researchers have expressed concern about possible damage that might be done to the surface of composite laminates by grit blasting, even with fine grit at low pressure. Although not belittling this concern in the context of overblasting with large grit at high pressure, if this were always a valid concern, should it not apply equally to the widely used practice of paint stripping by low-pressure grit blasting in preference to the use of chemical paint strippers that might well harm the resin in the laminate as well as the environment? Figure 3 shows a lightly grit-blasted carbon-epoxy surface, at two levels of magnification, in which it is clear that not even all of the surface layer of resin has been removed *anywhere*. The imprint of the peel ply is still clearly evident in the left-hand picture, and the pattern of the weave in the underlying carbon fabric (not shown) would be an order of magnitude coarser.

A noteworthy difference between interfacial failures and damage caused by impact to a laminate that does *not* contain a plane with a weak interface is that failure can be confined to that single weak interface in the former case, but it will occur on several (usually all) interfaces where fibers change direction in the latter case. Breaking of fibers is also more likely to occur in the latter case. It takes far higher loads to spread the initial damage in the latter case, too,

[4]Here, "properly" means in accordance with the laws of physics, not necessarily in accordance with all of the existing process specifications, some of which need to be improved.

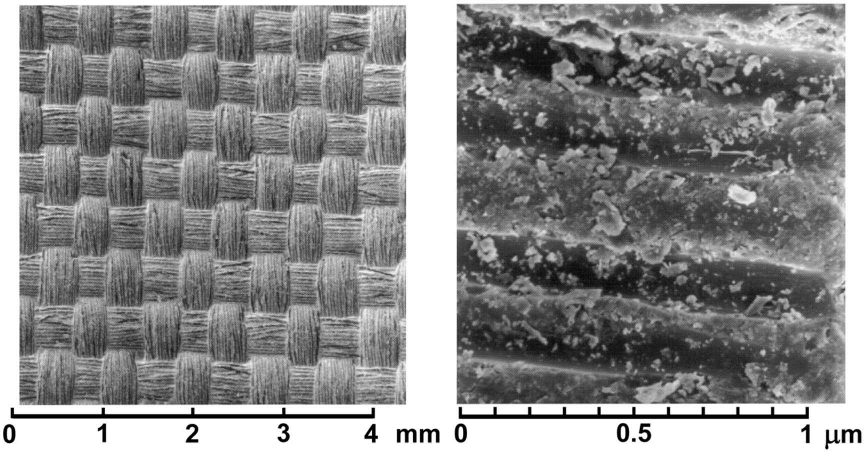

FIGURE 3 Lightly grit-blasted composite surface, retaining imprint of peel-ply and showing no damage to underlying fibers.

so such damage is unlikely to spread. On the other hand, interlaminar planes of weakness are far more easily separated over areas greater than that associated with any initial impact. Through-thickness ultrasonic inspections will not distinguish between these two cases, but it is very important to identify the mode of failure in planning for repairs. In short, damage will be much more confined, and will *stay* more confined, whenever it can be certain that there are no weak bonded interfaces to fail, no matter whether there are fiber failures as well or not.

A BRIEF EXPLANATION OF THE PROCESS OF ADHESION

One of the classic volumes on adhesive bonding of aircraft structures [7] contains an article by one of the greatest pioneers in this field, Norman de Bruyne, that describes several simple experiments to explain the process of adhesion and how critical it is in the creation of durable bonds. Some extracts from his work can still explain these phenomena clearly today. Consider, first, the example of two clean, polished steel blocks. "If we breathe on them before putting (them) together, they will now adhere to one another. Provided a liquid wets both adherends, there will be a force of attraction between them. A water film 10^{-6} cm. thick will exert an attractive force of about one ton per square inch." On the other hand, if a drop of water were placed between two similar clean, polished blocks of glass and they were pressed together, "only a fraction of a second elapses before the (lower) plate falls under the force of gravity." What is the difference? It is the result of different magnitudes of the forces of adhesion and capillarity between these two surfaces. "Capillarity will oppose adhesion, if one or both surfaces cannot be wetted, just as soon as the pressure is removed, the water will push the adherends apart from one another." Some surfaces need to be activated before adhesives will stick. De Bruyne mentions the everyday case of a roll of Sellotape. The only reason it can be unrolled is that only one surface of the cellophane has been treated to make the adhesive adhere. The other has not otherwise, the tape could not be unrolled. He goes on to explain how polyethylene can be "flamed" to convert an unwettable surface into one to which adhesives can adhere tenaciously, citing an increase on bond strength by a factor of about 5:1.

One of his experiments is illustrated in Figure 4, showing a stream of water, at the top, that is repelled by the untreated polyethylene surface on the left, while it clearly spreads across the flamed surface on the right. He describes further significant phenomena, which are presumably well known to polymer chemists nowadays but, unfortunately,

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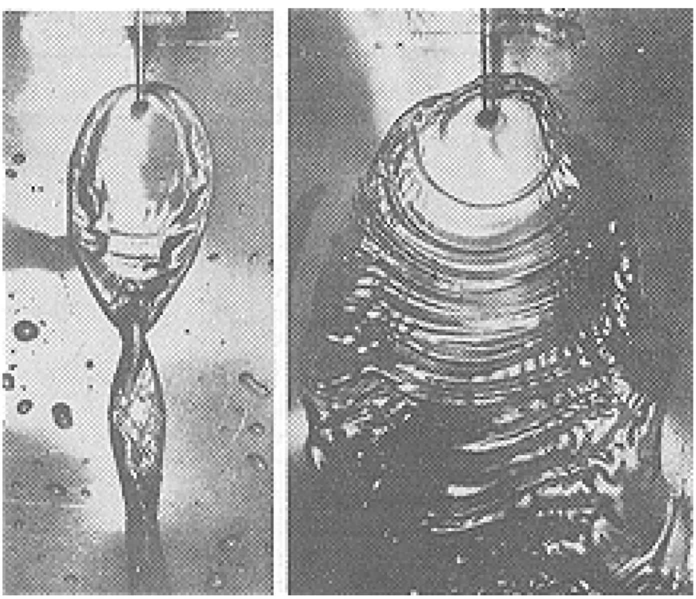

(a) (b)

FIGURE 4 Water repelled by, and wetting, untreated and "flamed" polyethylene plates. a) Water stream, from top, beading on untreated polyethylene plate, and b) water stream, from top, flowing over (wetting) "flamed" polyethylene plate.

apparently unknown by most of the engineers who write processing specifications for adhesive bonding, particularly of polymers. Those who understand this process can make standard epoxy adhesives *adhere* tenaciously to treated Teflon® surfaces, whereas others grapple with Teflon in release agents as a source of contaminants that can absolutely *prevent* adhesion. Clearly more attention needs to be paid to this issue, which affects the adhesion of both paint and adhesive. Almost 50 years ago, de Bruyne was aware of the adverse effects of too low a heat-up rate when making bonded joints. His disciples created the remarkably durable bonded joints on the de Havilland and Fokker aircraft. Those pioneers clearly knew things about the subject that are still of tremendous value today.

Further advice from Kinloch concerns bonding to glass. The author had always believed that glass had an inert surface because it was so hard to bond to. It turns out that *clean* glass has a very *active* surface that attracts low-energy particles from the atmosphere. These form the inert coating that is so hard to bond to. The cleaner the glass, the more rapidly the coating builds up. This is consistent with an explanation given to the author some 25 years ago by a colleague, Vern Hamilton at Douglas Aircraft, about the techniques used to bond mirrors and lenses. The component, or at least the area to be bonded, would be *immersed* in a solvent in which an adhesive primer was dissolved. This would isolate the surface from microscopic particles floating around in the air. The bonded areas would then be gently rubbed (not abraded) to displace the surface contaminants. The primer molecules would then adhere tenaciously to any freshly exposed *cleaned* glass surface. This bond would, as the theory of adhesion explains, be so strong that it would survive the gentle rubbing. With enough patience, the entire area to be bonded would then be covered completely with a durable primer to which the adhesive could then be applied. Kinloch believes that this is a complete analogy with bonding to cured epoxy resins and the like. However, he feels that because the epoxy surface is far less active than glass, the problem of subsequent contamination from particles adsorbed out of the air is far less severe. Indeed, he described cleaned epoxy surfaces as ideal substrates for bonding because they do not tend to deteriorate with time the way glass or even properly prepared metallic surfaces that have not been primed do. He believes that the fundamental problems with bonding thermoset composites is that the cleaning processes used are not always *complete*, even when attention is paid to known contaminants like silicone—and that the laminates are not always dry. Even the seemingly simple process of making paint adhere to aluminum can be complicated. Whereas the pant adheres tenaciously to the shaved heads of slug rivets used in wing-skin construction, it does not always stay stuck to the heads of the smaller rivets used in fuselage construction that had been coated to prevent them from corroding. Yet a strongly adhering layer of paint is one of the best corrosion inhibitors known to man. Would it make sense to revert to shaving rivet heads on fuselages as well, to avoid the occurrence of “rivet rash” in service—an aesthetics problem that costs time and money to fix?

DIFFERENCES AND SIMILARITIES BETWEEN BONDING AND PAINTING TO INERT PEEL-PLY SURFACES

The examples referred to in this section are all secondary structures, with no safety-of-flight issues. The concern is for the in-service inspection and repair costs that would be incurred for the fleets of aircraft if even *one* such panel were found to have separated at the bond surfaces, given the known difficulty in making paint or adhesive adhere to those surfaces created by merely stripping off a peel ply. The history of the nondurable metal-bond structures in the 1960s and 1970s might serve as a reliable indicator of what might happen again.

Several years ago, there was a problem of paint peeling off the outside of many large composite fairings and revealing the underlying texture of the peel ply that had been laid down first to eliminate the task of removing any release agent that might otherwise have transferred from the lay-up tool. The paint adhered to the thin strands of fractured resin between each groove created by removal of the peel-ply fabric. The remainder of the surface showed the black color of the carbon-epoxy layers underneath. (The author has recently been told that the very same phenomenon has recurred on a totally different aircraft type.) Because the same condition reappeared after repainting, the customer was understandably unhappy. The painting problem was solved by grit blasting the exterior surface of the parts before they were painted. The paint no longer flakes off. However, the insides of these same parts were not grit blasted. The adhesive on the inside was still expected to adhere to the peel-ply surface to which, by then, it was known that the paint on the outside would not. Whether it did will not be known until the first scheduled major overhaul some years from now.

Some bonded assemblies have been known to separate without giving any indication of a loss of structural strength. There is a possible explanation for this. Many bonded assemblies are mechanically fastened to the substructure. If the ends of bonded stiffeners are mechanically fastened at their ends, the interfaces may be subjected to only pure shear loads in the absence of any peel loads tending to separate the components. If so, there may be adequate load paths available, whether or not the adhesive remains bonded. The peel-ply texture creates a series of interlocking grooves so that the adhesive does not need to stick to transmit purely in-plane shear loads, which is what bonded joints *should* be designed to do. The texture is characterized schematically in Figure 5 to show how the weave in peel-ply fabrics creates orthogonal ridges that resist shear loads in all directions, like Velcro®. The rivets would be too soft to transfer shear loads. And the adhesive could continue to transfer shear loads without even being bonded!

At another manufacturer, much smaller than the earlier one, where the engineers from their chief on down wanted to grit blast the surfaces to be bonded, the business case did not close, even with encouragement from the local FAA office. The need for grit blasting the surfaces is far greater for paste adhesives than for heat-cured film adhesives used by large aircraft manufacturers, because the heat-cured film adhesives pass through a liquid state of very low viscosity during the cure cycle. Room-temperature-cured paste adhesives do not, so it is far more difficult to make them stay stuck. This had been confirmed years earlier by the experience of British Aerospace (BAe) in Warton' UK. The peel-ply surface they used successfully on their military aircraft, bonded together with a heat-cured film adhesive, was found to be quite ineffective when used in an R&D test program at Cranfield, UK, that involved the room-temperature bonding together of composite parts manufactured for them at Warton. This might not be surprising to polymer chemists, but most aircraft

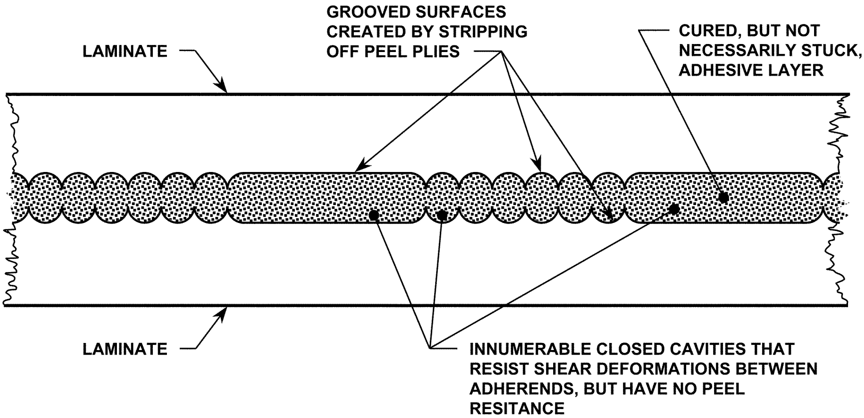

FIGURE 5 Representation of peel-ply imprint showing orthogonal sets of interlocking grooves.

engineers, including the author, do not know all that needs to be known about the adhesion process. The author's knowledge is "tainted" by the unblemished record of bonding to grit-blasted dry composite surfaces and the frequent failures to achieve adhesion to peel-ply surfaces. He cannot say that bonds to *all* peel-ply surfaces will fail, any more than the advocates of peel plies can claim that *all* bonds to peel-ply surfaces will endure. The problem is that the industry does not employ QC tests to distinguish between the possibilities at the time of manufacture. The author has long advocated that we should [8, 9]. Another problem is that those engineers in the aircraft industry who make these decisions do not know either, and many are not even aware that there are potential problems. The adhesive manufacturers *are* aware of these problems and include special additives to promote adhesion, but even they will acknowledge that there is no universal glue. Obviously, as the old adage goes, if there were, we could never get the cork out of the glue bottle!

Returning now to the light aircraft manufacturer's story, their internal tests had clearly indicated the superiority of grit-blasted surfaces, so they would have done so if permitted. Their opportunity came *via* an unexpected route. The same lack of a grit-blast machine in their factory had resulted in an identified cost of hundreds of man-hours spent on each and every aircraft hand-sanding 100% of the exterior surface to achieve an acceptable paint finish. This could be reduced dramatically by the use of grit blasting. The business case for a grit-blast machine that had *not* closed in the context of bonding *did* close in the context of painting. Once the machine had been purchased, of course, it made sense to use it also for preparing bonding surfaces as well, which is exactly what happened. If only there were more such success stories to report.

The author has recently learned of another reason for preferring grit-blasted surfaces to even the best peel-ply surfaces to which to bond and paint that comes from an unusual requirement. Composite components on helicopters are now required to tolerate some level of ballistic damage. At one U.S. manufacturer of helicopters, the ballistic impact testing revealed the plane of weakness associated with even the best peel-ply bond surface that had passed all other tests. All impact damage was confined to that interface and was spread over a far greater area than was affected when the same test was repeated on a bond to their standard grit-blasted surface. In the latter case, the damage was more localized and not confined to that single interface; instead, it was dispersed between several internal interfaces. They have now stopped using peel plies for surface preparation, since some of the flight-critical bonded joints could not tolerate the size of damage inflicted by ballistic impact to bonds made with peel-ply surface preparation.

There are some further interesting clues about nylon peel plies, which differ from polyester peel plies in being thermoplastic rather than thermoset. The former are far harder to bond to, because they are so inert. But there are also very good nylon-epoxy structural adhesives, so there is more to this than meets the eye. There are also different kinds of nylons, with different heat-distortion temperatures, and epoxy adhesives are cured at both 250°F (120°C) and 350°F (180°C). These variables result in different effects that, again, the author does not fully understand. However, another colleague, Dr. Alan Baker of the Aeronautical and Maritime Research Laboratories in Melbourne, Australia, has provided some insight. He has observed that a very thin layer of nylon can transfer over the entire surface, leaving what appears to be a clean imprint of the peel ply, with no release agent on the surface. He has read of other researchers observing the same thing. Given the other advice the author received from another colleague about the different thermal distortional temperatures for different grades of nylons, this could well be a phenomenon that happens only under specific combinations of circumstances, which may explain why bonding to peel-ply surfaces on 350°F–cured laminates is more problematical than bonding to 250°F–cured laminates. When the higher cure temperatures are combined with nylon peel plies having lower heat-distortion temperatures, the epoxy resin and nylon might actually fuse together so that, when the peel ply is stripped off, it would leave a thin layer of nylon behind—a very inert and unbondable surface. This cannot be removed by ultrasonic cleaning; it takes grit blasting to expose the bondable underlying epoxy surface. Perhaps the polymer chemists who know how the very successful 350°F–cured nylon-epoxy adhesives are made might be able to throw further enlightenment on this issue.

THE SIGNIFICANCE OF THE MODE OF FAILURE

Almost 30 years ago, the then Douglas Aircraft Company (now Boeing Long Beach) made a set of 20 carbon-epoxy upper-aft rudders for flight service evaluation on DC-10 aircraft. Some are still flying today, having attained far longer service records than any other composite components, some 80,000 flight hours as of 2002. Most of their service experience has been trouble-free, despite having what was then a very ambitious postbuckled skin design instead of the more traditional honeycomb-sandwich designs. However, there was one event of relevance to the topic discussed here. One aircraft had its rudder re-installed with the lightning strike protection strap accidentally disconnected. It was on an aircraft with a bright white painted tail—when it took off. It encountered a lightning strike on the flight and landed with one of the four rudders all black! It had not been burnt, but all the paint had been stripped off. A study of the causes identified the critical fact. The skins had been laid up directly against the metallic exterior tool surface, which had necessarily been sprayed with mold release, some of which had transferred to the part. The reason for not inserting a layer of perforated release film or peel ply between the skin and the tool was that the part was so large that there might have been overlaps or gaps in such a layer that would have transferred to the exterior surface of the part. This would have been aesthetically unacceptable. The paint had not adhered properly because the surface had only been only lightly hand sanded, rather than grit blasted, and not all of the mold release had been removed. (This light sanding was in accordance with the process specifications of the day.) Nevertheless, the weakly adhering paint had stayed in place for thousands of flight hours and might have stayed stuck even after the lightning strike if the grounding strap had been connected. We will never know, of course. What we do know is that the paint has been stripped off many *other* aircraft, over large areas, when they also encountered lightning strikes. One is forced to conclude that other surface preparation techniques are marginal, too. Aircraft fly through so many thunderstorms that it is not acceptable to the airlines to have to repaint their aircraft after every such incident. Also, as far as the author is aware, this was the *only* component on that DC-10 to lose its paint that day. Presumably the surface preparations elsewhere (all metallic except for the various fairings) enabled the paint to adhere better. What is clear for composite surfaces is that scuff sanding is inadequate to enable paint to adhere. It should not be surprising if it is inadequate for adhesive bonding, too.

The same part photographed in Figure 1, on a different airframe, shows clear evidence of ineffective sanding, as shown in Figure 6.

Only some high points were abraded. At the left of Figure 6 is an area where a stiffener was once “bonded.” The lighter area is adhesive still attached to the skin, with the imprint of the peel-ply on the stiffener just as clearly evident as that shown on the skin. There were no traces of adhesion to either surface, yet this bond had passed all ultrasonic inspections at the time of manufacture.

It is significant that the bonding process specifications for the former McDonnell Aircraft Company (now Boeing St. Louis) stated unambiguously at least 30 years ago that there would be no bonding permitted to peel-ply surfaces. They had first to be abraded and the sanding was not to stop until *all* traces of the peel-ply imprint had

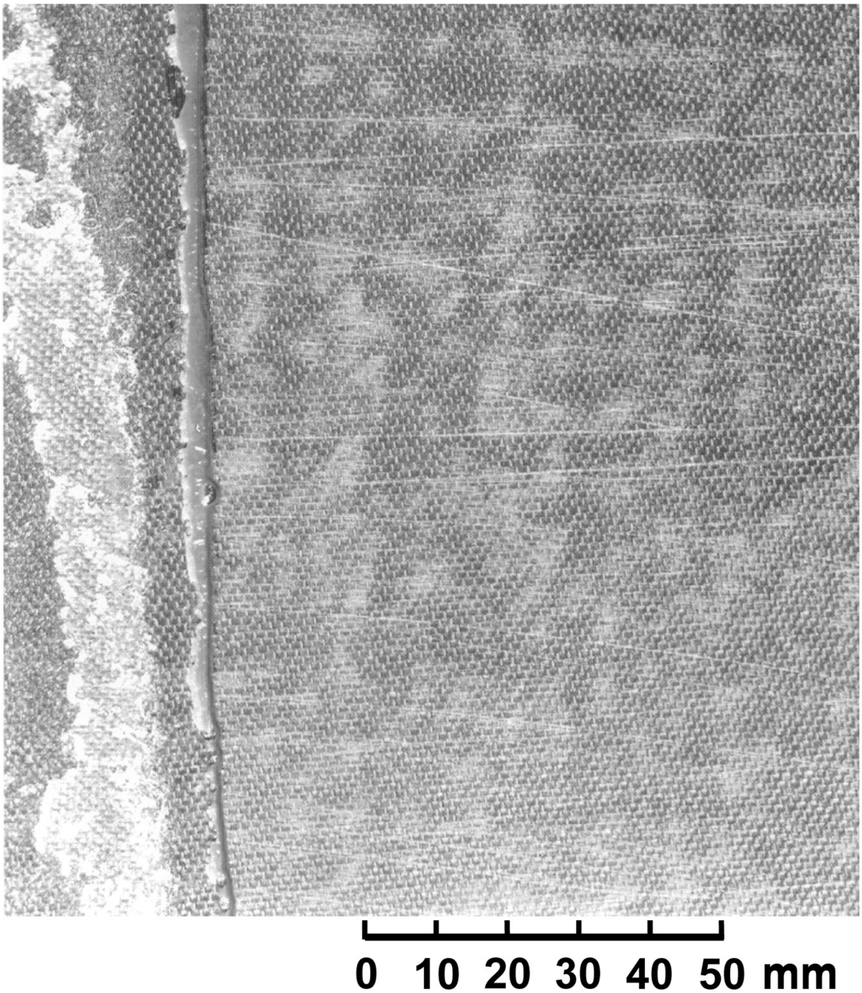

FIGURE 6 Typical totally inadequate scuff sanding used on composite laminates.

been removed! That is possible, on the tape laminates used when composite aircraft structures were in their infancy, but would *require* grit blasting on the later woven-fabric laminates, for which the fine-weave peel-ply texture would have been superimposed on the coarser undulations of the outermost structural layers, if half that top ply were not to be sanded off to remove all of the peel-ply imprint. Significantly, the Boeing St. Louis engineers do not refer to bonding to peel-ply surfaces; instead, they talk about bonding to "sanded" surfaces.

The photos in Figures 1 and 6 were all taken on the same component, but multiple airframes on a different commercial aircraft. The response to the discovery of these interfacial failures is very illuminating in that it shows how more still needs to be understood about adhesion by the average aircraft design engineer and manager.

The investigation into this problem confirmed that the adhesive had been cured according to the proper temperature profile and that there had been no transfer of release agent to the bonding surfaces from the peel ply used. Test panels showed that the design had adequate strength. However, the mode of failure was very different. There was no sign of interfacial failures in the test panels. It was later learned from site inspections that the laminates in the structures had not been dried prior to bonding and that they had been cured at another factory months before they were bonded together. Obviously the test panels had been fabricated more rapidly, with no time for the details to absorb moisture. This is the only known explanation for the difference between the failure modes, which is why this is suspected as the cause of the weak-bonded interfaces.

The investigation was concluded without resolving the weak interface issue because the specifications did not address the mode of failure. The author would like to present a case arguing that they should, because of the following consequences from this ambiguity. Suppose that, at some future date, some laminate is damaged and, upon inspection, it is found that these same separations were found in surrounding areas. It would then be impossible to identify whether these separations preceded damage to the laminates or were caused by it. It would, therefore, also be impossible to establish whether the damage that might occur would have been much smaller in the absence of any preexisting wide-area interfacial weaknesses. The whole industry now knows what the consequences were of the interfacial failures in bonded metal structures. It was a *very* expensive problem, with fleet-wide remanufacture and replacement of many components. Today, only the operators know the consequences of weak bonding interfaces in composite structures because, by and large, the OEMs and their suppliers do not regard the mode of failure as an issue. The following anecdote might well encourage a greater emphasis on making sure that the adhesive, and paint, are properly stuck at the time of manufacture.

The conduct of the preceding investigation was in stark contrast to that of a different nonbond investigation, in which the author was involved [10]. This concerned bonded metallic skin-stringer wing skins for which, at the start of production, some panels exhibited a complete, but undetectable, nonbond between the stringers and the doublers.

The problem was traced to condensate on the adhesive film, which, for one kind of bonding tool, was unable to escape during the cure cycle. From the outset, the investigation focused on why the adhesive did not stick. The stringers were held in place only by the fillets formed along their edges. This held the stringers and doubler in sufficiently close proximity to defeat the world's best nondestructive inspection (NDI) techniques, all of which were used in an attempt to distinguish between those panels that were bonded and those that were not. In this case, the adhesive manufacturer conducted thorough tests to prove that the hypothesis was correct by *replicating all of the details of the original problem* and showing that it could be made to happen or prevented from happening at will. This other incident was no more of a processing problem than that discussed previously, but it was recognized as such at the outset. Corrective action was taken and that problem *never* recurred, during the entire 10-year production run! Significantly, the manufacturers involved found that the defect-free bonds made later were actually far *Less* expensive than the earlier defective ones that had led to the investigation. Edwards Deming was right, yet again, even if it did cost some money in the short term to cure the problem. Improved quality really does reduce overall costs [11].

The need for a durability test[5] as part of the QC for bonded composite structures has been identified previously. But not even the lap-shear test that is run is as reliable an indicator of proper process control as it easily could be. The reason for this is that it is customarily used to validate the strength of individual parts rather than to validate the process being used to make the bond. The distinction is that, in the latter case, the test coupon would need to seek the highest possible strength that *only* a properly processed bond could achieve. This means testing on a high-strength all-0° laminate, regardless of what fiber pattern is used in each part. Almost twice the load can be transferred between all-0° surface plies than is permitted between woven

[5]It should, perhaps, be noted that although the wedge-crack test itself is very useful, its value is often undermined by the specifications associated with it. Specifically, ASTM D3762 defines a *successful* test, in paragraph 10, as crack growth less than 0.75 inch and an average of 0.5 inch when exposed to 50°C and 95% RH for one hour. As a point of reference, *none* of the tests on specimens prepared with the improved processing developed for the PABST bonded fuselage ever showed crack growth in excess of 0.06 inch. Any crack that grew by as much as 0.5 inch in the hostile environment would have been regarded as an abject failure! These PABST tests were all *free from interfacial failures*, which are not excluded by most of the QC tests. They should be! There is far too much emphasis on some *measurement* associated with the test and not enough on the *mode* of failure, which is what determines bond durability—on both metallic and composite surfaces.

fabric laminates, because of the weakness of 90° fibers in transmitting 0° shear loads. Consequently, it is not possible to tell whether an adhesive has been properly cured when tested on anything less than an all-0° laminate thick enough (about 0.08 inch, ~2 mm) to cause a cohesive failure in the very *best* bonded joints. This dilemma will always exist in coupons made to represent the structure being evaluated. There is a real need to distinguish between tests that validate only individual parts, with questionable reliability, and others that validate the process for *every* part.

THE OUTSTANDING RESISTANCE TO THE SPREAD OF DELAMINATIONS IN WELL-BONDED STRUCTURES

Whereas weakly bonded surfaces are prone to *widespread* delaminations, there are many in-service experiences of very large delaminations, initiated by the accidental inclusion of separator films locally in composite lay-up, at the time of manufacture, that were associated with absolutely *zero* growth beyond the initial defect in the years of flying it took to reveal the existence of the inclusions. Many of these inclusions were far larger than the maximum permitted size for repair of damage. Also, in a study conducted of the 30-year service history of U.S. Navy and USAF aircraft with composite structures [12] for the Composite Affordability Initiative at the Boeing Company, it was found there had not been a *single* case of a solid-laminate composite part delaminating as the result of impact. There were numerous cases of such damage to thin-skinned honeycomb-cored parts, which is to be expected but, even then, there was no evidence of disbond growth between whenever the damage had occurred and when it was detected. Even bonded joints were found to be remarkably free from deterioration. The conclusion reached was that there has been far too much concern about delaminations in well-manufactured composite parts.

The embedded separator ply on the next anecdote supporting this position was so large that the part would never have been permitted to fly in that state had it been found at the time of manufacture. (It also indicates how difficult it is to find such defects until a gap has opened up.) A different major airline, however, has since indicated that even larger defects caused the same way have been just as innocuous. This story concerns one of the NASA-funded DC-10 composite rudders mentioned earlier. The basic six-ply skin was reinforced by a local buildup of eight or more additional embedded plies at each hinge station. At one of these stations, a separator ply some 53 square inches (342 cm^2) in size was accidentally left between the skin and the doublers. The aircraft was flown for 3.5 years before the mistake was discovered during a walk-around inspection, from the ground. A minute bulge 30 feet up (3 m) was revealed by the grazing illumination of the setting sun. (On a well-made composite part, the slightest imperfection stands out like a sore thumb.) This discovery was made just before the very busy Christmas season, half way round the world. Naturally, the airline sought reassurance that it was safe to continue to fly the aircraft until it was next scheduled for heavy maintenance, even though the “defect” was some 20 times as large as the tolerable cosmetic repair specified in the repair manual. Suspecting what the trouble was, on the basis of the characteristic shape of the “delamination,” we asked first that they confirm that there was separator ply where there should not have been. This was easily established, because ultrasonic inspections work well when there really is a gap to be found. The defect was at a uniform depth equal to the nominal distance to the interface. A small core drill to only that depth soon produced a piece of red plastic separator ply to confirm the initial diagnosis. A second core drill, straddling the edge of the “delamination,” established that there had been absolutely no spreading of the initial “disbond.” If there had been no growth in 3.5 years, it seemed very unlikely that there would be any the next 3.5 months, so the airline was permitted to continue to fly the rudder unrepaired until the next scheduled maintenance, provided that periodic inspections continued to confirm the absence of any such growth. There still was not any when the rudder was eventually taken off the aircraft to be repaired.

Such an experience is typical of composite structures. Weak bonds are easy to separate and will rapidly spread to 100% of the affected area. Conversely, strong bonds are very difficult to break, and fractures caused by impact damage to structures without planes of weakness tend not to spread beyond any initial damage. There is no mechanism to make delaminations grow under tensile in-plane loads and, in this case, with this postbuckled structure, there was no way to develop any compressive in-plane loads either, because the skin simply deflected out of the way by the precise amount needed to virtually eliminate any compressive membrane stresses. (The stable spars and rib caps limited the overall strains.) Delaminations will grow under applied tensile loads normal to the surface of the part, of course, but they are so weak with respect to such loads that this situation is routinely precluded by careful design. (The other instances cited *were* honeycomb sandwich panels but, in the absence of broken fibers to redistribute the loads, the “detached” face sheets must also have buckled to just the correct amplitude to eliminate any compressive membrane stresses.)

Delaminations due to impact damage of structures with no weak interfaces need to be treated very *differently* from delaminations associated with weak bonds or nonbonds. The former are most unlikely to spread without breaking more fibers, which will make the condition apparent, whereas the latter will eventually spread throughout the entire area of weak bonds, perhaps globally throughout the part, with no early warning that anything has happened. Merely finding a gap by the same inspection techniques that could not find the weak bonds in the first place gives no indication of whether it is likely to grow. However, finding a small gap at a uniform depth below the surface that precisely matched the location of a bond or cocure interface might well enable a part to be disassembled and remanufactured before any of the components suffered damage to the load-carrying fibers, thereby reducing the costs of the repairs appreciably.

AN EXAMPLE OF BENEFITS FROM THE ABSENCE OF PREBOND MOISTURE

The redesign of the tail cone of a large transport aircraft offered an opportunity to show how much less expensive bonded structures are than those that are cocured [13]. But, in the present context, it also provided a very illuminating demonstration of the harmful effects of prebond moisture on the bonding of composites. We were able to benefit from both of the investigations reported previously, so the correct procedures were established quite rapidly this time, and there were no doubts about their correctness.

The potential subcontractor bidding for the new work ran a series of comparative tests with which to select the adhesive and processing to be used in production from the options permitted by the OEM's process specifications. Unfortunately, the combination they wanted to use gave the worst results of all. Fortunately, they had made a mistake while making those particular coupons that had far-reaching beneficial consequences. The roll of adhesive used had not been properly sealed when it had previously been returned to the freezer. They had inadvertently created the very same problem that had been at the root of the problem resolved in Ref. [11]—trying futilely to make adhesive stick when it had been covered with condensate that remained trapped between the adhesive layer and the adherend. When the tests were repeated with fresh, dry materials throughout, the strengths attained were up to expectations and, more important, the mode of failure was now entirely interlaminar in the resin *between* the fibers and the adhesive layer. These are still the *only* peel-ply tests of which the author has first-hand knowledge in which noninterfacial failures had been achieved when bonding to a peel-ply surface.

The manufacturing (curing) process was consequently set up so that no large skin would ever sit between the time it was cured and the time the stiffeners were bonded to it for long enough to absorb any moisture. No skin would be cured late in a week or shortly before a holiday, because it was too large to transport to the drying oven in the opposite corner of the plant. The stiffening beads would normally be cured just before the skin was cured and, if the skin was delayed, they would be dried just before bonding, which was scheduled for the same day as the skin was cured. The peel ply was selected to ensure the absence of silicone, or any other release agent, and steps were taken to ensure the total absence of prebond moisture. To the best of the author's knowledge, the production bonding in this case has been as successful as were the second set of tests. This has, of course, increased the author's conviction about the importance of proper surface preparation, even if he does not know what it is about this particular film adhesive that has overcome the traditional difficulty in bonding to an inert composite surface.

One important observation about this saga is that the manufacturer of these tail cones was blessed by a demonstration of the consequences of failure to ensure that the surface preparation was adequate to ensure, always, that the adhesive would stick *before* any parts were made. It cost very little to learn this lesson at that time, and the company involved *understood* the lesson and both it and all of the downstream customers involved, including Boeing Long Beach, have benefited from it. Why has so much of the industry yet to learn that the *mode* of failure of bonded test coupons is *more important*[6] than the load at which the coupon fails? *All* bonding process specifications should *mandate* that *any* interfacial failures are totally *unacceptable*.

A POSSIBLE EXPLANATION OF THE ADVERSE INTERACTION BETWEEN PREBOND MOISTURE AND THE TEXTURE OF PEEL-PLY SURFACES

A troubling issue about the difficulty of bonding to composite surfaces created by merely stripping off a peel ply is the ambiguity whereby

[6]The author has deliberately used the words *more* important rather than *equally* important because he knows of no instance in which cohesive bond failures have ever been associated with an inadequate strength. Indeed, in recommending peel tests for quality control of bonded composite structures, he has stated a strong preference for *any* test for which it is *impossible* to measure an applied load, precisely to prevent any arguments about the acceptability of an ambiguous test result in which visible interfacial failures occurred in combination with what had been a specified acceptable minimum load level.

only *some* such bonds have been found to “fail” in service. If only it were a universal problem, effective countermeasures would be easier to implement. The author has a plausible explanation, based on the thermodynamics contained in old-fashioned steam tables. If prebond moisture, known to be present, could sometimes, but not always, escape during the cure process, it might well be incapable of doing any harm when it did. There is a precedent for this hypothesis in Ref. [9], in the context of metal bonding. Even though some stiffened panels for *both* the upper and lower wing skins were known to have been bonded with condensate on the adhesive film (that should not have been there, of course), none of the upper skin panels, made in a “beady-ball” tool with an excellent vent path everywhere, showed any sign of the complete nonbonds that occurred over all of the stiffeners on the lower skins. The second tool was very different from the first, using a close-fitting large molded rubber bag, with absolutely no possibility of that water migrating away from where it started—on every stringer flange. The peel-ply surface shown in Figure 5 is strikingly reminiscent of those circumstances. The sharp ridges in the peel-ply surface would dig into the uncured adhesive film, ensuring that any moisture that migrated to the surface during the cure could have no possibility of escaping. In the absence of any such ridges, the edges of the bond layer would be exposed to the vacuum inside the bag all around its periphery. (There would be even more escape paths if small vent holes were drilled through any large bond areas.) The ridges could be removed by sanding surfaces cured against the layup tools. However, removal of those ridges only, without damaging any of the underlying material, from the bag side of the part, which would undulate to match the much coarser weave of woven fabric layers, would require a conformable process, like low-pressure grit blasting. Such a surface would not be smooth, of course, but the absence of any sharp ridges would allow any volatiles generated by the heat used to cure the adhesive to migrate across the surface to any areas exposed to the vacuum inside the bag, around the edges of all overlaps. Support for this hypothesis can be gained from the boiling point of water under pressure. At 40 psi pressure (276 kPa) for typical secondary bonding of precured laminates at 120°C (250°F), the boiling point is 130°C (266°F), *above* the cure temperature. These conditions prevailed for the “bonds” made in Figures 1 and 6. There was no chance for any water at the interface to escape. It could not turn to steam and expand. It would just sit on the bottom, and top, of every groove between the ridges of the peel-ply texture, behaving for all the world like a layer of silicone.

Even at 100 psi (~700 kPa), in an autoclave, water is barely capable of turning into steam, because the boiling point is 165°C, only a little lower than the nominal cure temperature of 180°C (350°F) for cobonded carbon-epoxy laminates and some adhesives. However, the author recalls that, when composites were in their infancy, more than 30 years ago, an attempt was made to cobond composite stringers onto a wing skin cured several months before and left unsealed in a very humid natural environment—and the skin was riddled with internal delaminations from the steam that then formed within the laminate and could not escape. That cure was at this same temperature and pressure, so maybe prebond moisture in laminates can be expelled during secondary bond operations, *provided that a vent path is available* and there is not so much moisture that the panel explodes, as many honeycomb-sandwich panels have when they were heated as part of a repair procedure. (When repairing radomes, it is standard airline practice to remove one skin *completely*, even if it is not all damaged, leaving the other to define the shape, precisely to avoid exploding the panel from relatively massive amounts of water that can collect in the honeycomb cells.)

There is a different, yet strangely similar, precedent for this hypothesis that it is the *trapping* of the prebond moisture that is the problem, not its mere presence if it is able to escape during the cure cycle. It is well known that there is no such thing as *dry* Nomex®, as described in Ref. [7]. Yet, it *was* possible to bond a stabilizing layer of film adhesive to a Nomex core for large trailing-edge sandwich panels if the film adhesive contained a very coarse weave carrier that permitted vent holes to be created by capillary action as the adhesive cured. It was *impossible* to create fillets between the adhesive film and the walls of the core when the adhesive film encapsulating the core contained a fine mesh carrier that sealed the water inside each cell. There was no external sign that the bond had not been made, but after the carbon-epoxy facings had been cured to the stabilized core, those particular skins simply peeled off in flight, but not immediately. (In one case, it even failed on the ground.) (This example is actually more complicated in the sense that the initial core-stabilization step was done in an oven, inside a vacuum bag, and the water did turn to steam, lifting the core away from the adhesive layer in contact with the tool. By the time the steam had escaped and the vacuum bag had pushed the core back in place, the cure of the adhesive had advanced to the point at which it could no longer flow and form a fillet.) The significant message from this anecdote is that, despite the known presence of moisture in the core, because it took as much as 3 h to lay down the adhesive film on such a large complex shape, and Nomex is known to absorb more than 90% of all the moisture it is ever going to in no more than the first 45 min of exposure, not one case of failure was ever found in the panels made with the coarse carrier in the stabilizing layers of adhesive bonded to the core in the first step. The holes in the film, between the cell walls, were very easily visible to the naked eye and undoubtedly contributed to even greater strength in the second bond, when they would been filled up with resin from the second cocure step. Yet that would have been to no avail if the fillets between the core and the *first* layer of adhesive had been defective, as they undoubtedly were on the first few panels made before we learned how to do this properly.

It is also significant that the standard repair procedure at British Airways for honeycomb-sandwich panels involves what they call a "positioning cloth" between the core and one face sheet, which initially provides a vent path for volatiles to escape and which, by the end of the cure, has become fully coated with the adhesive as a result of capillary action. This added step, with respect to conventional practice, would not have been included if their experiences had not shown it to be beneficial.

If this hypothesis about enabling volatiles to escape is correct, and it should be easy to validate or refute it on test panels only about 15 cm (6 inches) square, with peel ply and with smoothly sanded surfaces, with and without prebond moisture absorbed into the laminate, there are some profound implications in bonded repairs to all composite structures in service. (Further improvements may be needed to the vent paths inside the bag for very large structures, once the steam has escaped from the bond line.) There may be a reliable alternative to thorough, and time-consuming, complete drying of laminates before they are bonded. (But remember the caveat that with too much prebond moisture in a laminate, turning it into steam *before* it has reached the surface may do more damage to the laminate than merely not attaching it to the adjacent parts.) The surface of the laminate on the original part will be created either by sanding or by stepped routing. In either case, there will be no sharp ridges like those in a peel-ply surface. And the patch will presumably be fresh, not yet having had time to absorb moisture. If it could be confirmed that providing an adequate vent path during cure will *always* ensure a good bond with high cohesive strength, even when prebond moisture is present, in-service bonded repairs would become a lot easier and quicker to perform. (One should always use dry adhesive, too, of course, but that is nowhere near as difficult to enforce.)

THE REMARKABLE STRENGTH OF EVEN BADLY FLAWED BONDED JOINTS THAT ARE PROPERLY STUCK EVERYWHERE ELSE

The Lear Fan all-composite executive aircraft, the development of which is summarized in Ref. [14], pioneered many developments in composite aircraft. Among these was the insistence on the use of grit blasting to prepare composite surfaces for bonding. However, the associated tooling methods did not always show such enlightenment. In the case of the fuselage, the tools for bonding the skin splices repeated a mistake made earlier at the former Douglas Aircraft Company during the PABST bonded fuselage program [15] in expecting that successful bonds could be made between rigid clamping surfaces on the outside *and* inside of the skins. The solution to the problem is described in Ref. [16]. In short, the outer rigid tooling surface needed to define the shape, and the inner surface needed to be conformable to eliminate gaps. What is important here is that the result of not using conformable inner tools was local disbonds, because of thickness irregularities that were trivial in comparison with the thicknesses of the parts but large in comparison with the nominally 0.005-inch-thick (0.2-mm) adhesive layer. Had the continuous rubber pad facing on the inner tool surface been perforated or replaced by discrete small pads with gaps in between, there would have been no such disbonds. Significantly, these disbonds were not interfacial failures, because the entire bond surfaces had been grit blasted at the insistence of Tom Rose, the engineer in charge of materials and processes initially and later all of manufacturing. Where the two skins were pushed into contact, there were perfect bonds—and where they were not, there were gaps that the adhesive could not fill. These gaps were easy to detect by ultrasonic inspections, whereas interfacial weaknesses would not have been. So many local disbonds were identified (about 50% of the total) that the marks were removed from the aircraft as soon as they had been mapped so as not to discourage the team and any visitors who might walk past. Nevertheless, the remaining bonded areas were more than adequate to carry the required loads, just as had been predicted during the PABST program in which bond defects had been investigated thoroughly by both theory and test. These Lear Fan bonds did not need to be perfect over 100% of their area to attain adequate strength, but they *did* need to be 100% perfect to minimize the inspection costs.

The most important finding pertaining to these numerous disbonds between areas of sound structural bonds on the Lear Fan fuselages was not established until some years later. After the program had folded, several incomplete fuselages were purchased by NASA Langley for crashworthiness tests in their swinging drop tower. In one severe test that was televised, the structure broke into sections but the bonded joints remained intact, in spite of the fact that only some 50% of the overlap was actually bonded. (This was not conservatism in the design; the long overlap was *needed* to minimize the effective eccentricity in load path that would have caused severe bending moments in the skins just outside the joint if the overlaps had been only long enough to barely transfer the load through the adhesive.)

This rather sad ending to an exciting program demonstrated just how much strength bonded joints have when it is possible to *rely* upon the adhesive being stuck properly everywhere, so that the parts actually are bonded together.

CONCLUDING REMARKS

It has been pointed out that there are great similarities in the reasons why paint can sometimes be peeled off the outside of aircraft and why bonded components are sometimes found to be separated by interfacial "failures," usually with no visible damage to any of the detail parts. The common challenge in preventing such occurrences is improving the adhesion between the polymers and the substrate. Technical enhancements in one context can help solve problems in the other.

In both instances, if interfacial failures occur, it is probable that they will eventually extend throughout the entire bonded or painted area. This is in marked contrast to the very local damage that occurs as a result of impact damage on a laminate with no weak interfaces. Also, interfacial failures do not occur whenever the surface has been prepared suitably to create a strong interfacial bond. This is why it is so important that one should strive for such treatments.

Significantly, in-service problems have consistently disappeared as the result of improved surface preparations.

Anecdotal evidence has been presented to identify a difference between surface preparations known never to be associated with interfacial failures and those that sometimes are. Some of these differences are very distinct, as between grit-blasted and peelply surfaces, whereas others are more subtle, such as between film and paste adhesives on the same peel-ply surfaces and the effects of prebond moisture and silicone release agents on peelply surfaces. The problem is that none of the NDI techniques can distinguish between surface treatments that will lead to interfacial separations in service and those that will not. A gap must open first before these methods can find unadhered areas.

The evidence presented here does not imply that no peel plies will ever work. On the contrary, it includes a specific anecdote to the effect that one of them *does* appear to work when care is taken to exclude prebond moisture as well as silicone. Significantly, that very same nonreleased peel ply had earlier been found *not* to work when prebond moisture *was* known to be present.

A great many past and current surface treatments ensure that the adhesive or paint will stick only long enough to pass initial inspection. They do not ensure that the polymers will *stay* stuck in service. These process specifications need to be replaced by others that can be relied upon to achieve long-term adhesion and structural durability.

It is important that both the existence and solution of problems like these be publicized to prevent their recurrence. The whole industry, both manufacturers and operators, benefits. The money saved enables more aircraft to be built and operated if costly nuisance problems are eradicated. If they are not, there is the chance that they will grow into real safety concerns for future applications.

This article was prepared in the hope of acquiring additional information to explain why adhesives and paint do not always adhere permanently to composite surfaces. The feedback received and incorporated in this published version, has confirmed the author's observations that if the "correct" surface conditions are created, the adhesive and paint *will* stay stuck indefinitely. The "correct" surface conditions are known to polymer chemists; they include an *active* substrate surface with higher surface energy than that of the adhesive. It takes positive steps to create that active surface and, in the absence of such steps (such as grit blasting), it is possible that the adhesive and paint will *not* stay stuck. This much seems to be understood. The one remaining issue for which the author has not been able to find a definitive explanation is whether a clear interfacial failure at some time during the service life of the structure is the result of some progressive environmental degradation of an initially "weak" bond to an inactive surface, or if there never was any adhesion in the first place and the quality assurance techniques were simply incapable of detecting it. Any further inputs on this specific issue, to confirm the advice of Kinloch, would be very helpful to the aerospace industry and the cause of adhesive bonding generally. If there really is no such mechanism, then the focus *must* be on surface preparation. We know how to *prevent* this condition from occurring—by proper surface preparation, which is more than mere cleanliness. If we also knew how to detect weak bonds before they failed or how to prevent some mechanism whereby they degraded in strength with time or exposure, there would be greater support for the more widespread application of structural adhesive bonding. (In searching for such new inspection techniques, it is vital that the search be focused on interfacial failures, not on a reduction in cohesive bond strength, which would imply an unrelated issue.)

It has been noted that the eradication of the widespread metal-bond problem that existed some 30 years ago is tied to the development of an additional peel-type test to supplement the earlier shear test, which, on its own, had been incapable of distinguishing between surface treatments that led to global interfacial failures and those that did not. A case has been made that there is an equal need to employ an equivalent QC durability test when composite components are bonded together. So far this has not become standard practice, even though it was once used to verify that a problem with bonding composite laminates together had been eliminated.

Contrary to the author's expectations, Kinloch has indicated that a *truly* clean, and dry, epoxy surface is ideal for bonding to, or painting, without any *further* surface treatment. This implies that such a surface meets the requirements for adhesion in that the surface is already sufficiently active. This would explain why only some such interfaces have failed in service. Assuming that he is right, this would imply not only a need to develop better treatments for *ideal* conditions, but also modifications, some of which have been suggested here, that make the processes more forgiving when the conditions are *not* ideal. Silicone contaminants must absolutely be excluded, of course, but the concept of *ensuring* that small amounts of prebond moisture can *escape* during the cure rather than relying on a system that will *only* work in the total absence of prebond moisture offers hope for in-service repairs which, unlike newly made parts, are almost impossible to dry.

The author has suggested here that it might be possible to tolerate some level of prebond moisture, with no loss of bond strength or durability, if there is an adequate vent path through which prebond moisture could be guaranteed to escape by turning to steam. If proved to be true, this could have a great impact in reducing the cost of, and time taken for, in-service repairs. He, therefore, recommends strongly that this issue be investigated experimentally. The trapping of prebond moisture by the ridges in the texture created by stripping off even uncontaminated peel plies could be the explanation of why bonding to peelply surfaces sometimes works and at other times does not.

In contrast to the trivial costs incurred during the process of improving surface treatments, the benefits from doing so include consistently lower total costs for subsequent production, while some of the costs associated with not carrying out immediate cures that apply to previously completed aircraft *as well as* to future production have reached the millions of dollars. The issue demands that sufficient effort be devoted to understanding the process of adhesion and educating those who make decisions about the design and production of bonded and painted aircraft structures in this subject so that interfacial separations are prevented in the future. The past record indicates that this *is* possible, notwithstanding the numerous instances where inadequate understanding has led to such problems originating in the first place, far too often, or not being solved when there was an opportunity to do so.

Adhesive and paint will not adhere properly to metallic surfaces that are only "clean," rather than "activated." Today, it is customary to etch or anodize metallic surfaces to promote adhesion, but there is no *equivalent* step in the processing of composite surfaces, other than by grit blasting or plasma treatments, which are not mandatory. Perhaps some such process should be included for composite surfaces to be bonded and composite surfaces to be painted.

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