The Basics of Materials Engineering

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ABSTRACT

This paper addresses the needs of new and mature materials engineers who do not belong to a large group such as one would find in many aerospace companies. Three of those needs are: What do we do? What do we need to know? How do we get what we need? The wide scope of materials engineering is shown along with the somewhat limited scope of work for the current materials engineers in the high tech industries of aerospace or electronics. Two of the key processes of interest are highlighted. They are: selecting and building the composite and adhesive bonding. The pitfalls for composite design and manufacture and the options for surface preparation are greater at this time than at any time in the past, and these options are presented along with material to aid choice. One typical problem for the lonely materials engineer in a small company is the predilection for other engineers and management to accept a low value for average lap shear, provided it allows a sufficient factor of safety. Examples of actual materials engineering problems and their solutions are given along with approaches for testing, composite fabrication, and adhesive bonding.

1. Introduction

The scope of materials engineering far exceeds the common areas of study required of the typical materials engineer. SAMPE (1) provides a short list, Table 1, that is tailored to their technical symposia and other publications, but the list does not begin to define the broader scope of the materials and processes work.

Other organizations, such as universities generally derive their study matter from the indigenous factories or local abundant raw materials. In New Zealand a large percentage of industry is tied to the land, in farming, fishing, animal husbandry, and production of natural fiber products. The goal of materials and process engineering there is the conversion of "raw and commodity materials from animals, vegetables or minerals into valuable products required by manufacturers or consumers". The definition of materials and processes engineering is quite different (2). Similarly, in regions on the east coast of North America, the early industry was more slanted to metallurgical products. The prominent local industries involved in wire drawing and tin smithing supported the Worcester Polytechnic Institute, which led to extensive metallurgical study courses.

2. History

Historically, the creation of the wheel is viewed as the most important invention. Some aver that the controlling of fire (a process) 500,000 years BP (Before Present) was also a key occurrence. It gave early man the ability to take the fire to other places that did not have burnable supplies. With portable fire early man cooked meat and most importantly fired clay and preserved wooden spear points by carbonization (3).

The number one moment in material history according to Journal of Materials was the defining of the periodic table by Dimitri Mendeleev in 1864 (4). There were several other people who were also working on the problem and were very close to the answer, but the correct prediction of Germanium, Gallium and Scandium meant that Mendeleev won the unofficial competition.

Table 1
SAMPE'S approach to defining Materials Engineering

- Composite materials
- Advanced matrix resin development
- Advanced reinforcement fiber development
- Nano materials
- Metal and composite adhesive bonding
- Ceramics, carbon-carbon and metal matrix composites
- Fire properties of composite materials
- Design and analysis of composite structures
- Technical information exchange under ITAR guidelines
- Platform design-manned and unmanned air vehicles
- Composite materials in ground transportation and advanced marine architecture
- Composite materials in oil exploitation and wind energy development
- Composite materials in recreational products
- Composite materials in infrastructure development
- Blast mitigation and homeland security

3. A Syllabus for new M&P Engineers

3.1 Who are our clients

We only survive because we are valuable to our clients. The principal client is the stress analyst. Hopefully, we can prevent the "GIGO" problem for composites. We get our information from many sources as shown. Of course, the sources and clients will vary with the particular materials arena. The importance of the M&P service is the filtering and assessment of the information. (Fig. 1)

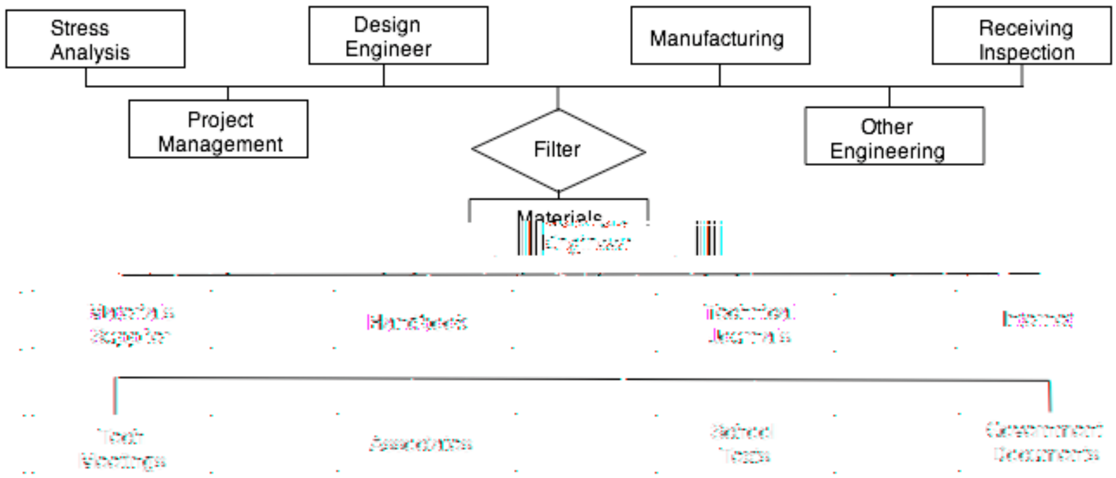

Figure 1
Clients and Information Sources

3.2 Scope/Limitations

The scope for a materials engineer involved in aerospace or aerospace electronics will obviously not involve ore extraction processes. The subjects of interest will probably include ferrous metals, aluminum, titanium, composites, elastomers, ceramics, thermoplastics and thermosets and adhesives. It could be overwhelming, but with some attention to continuing education all of these can be absorbed to some degree. Two materials /processes that are key in the aerospace, that are changing rapidly, and pose great pitfalls for designers, deserve to be highlighted.

3.3 Two Key Jobs for the Aerospace M&P Engineer Building the Composite; Making permanent Joints.

3.3.1 Selecting the material, method

To be able to help the designers in the composites field the materials engineer must be capable of preliminary sizing and analysis so that he can suggest the correct fiber, resin, and process for the design. The depth of knowledge residing with the materials engineer must extend into the processing problems and pitfalls; attach methods, relative costs of different materials and processes.

The design engineer can make a bad choice with any of these variables. It is important to remember that the design of the composite structure drives the choice of manufacturing method. An outstanding example of the need for cost and fabrication knowledge was the fabrication of seven prototype subscale Beech Starship fuselages by filament winding. They were honeycomb stiffened, graphite epoxy skins, wet filament wound.

The company, Fibertek Division of Alcoa/TRE inc. used lightweight tooling that was capable of outward translation to provide curing pressure in female molds (Fig 2).

The filament winder was a two-axis machine with a third axis added by a cam, which controlled the height of the delivery eye.

The filament-winding machine could not have cost more then 50 thousand USD. Each fuselage was wet wound and cured within 24 Hours. Contrast those costs with the 3-6 million USD costs quoted for a Fiber Placement Machine, which would lay down 12 prepreg tows at a maximum of 800 in. per minute (5, 6, 7).

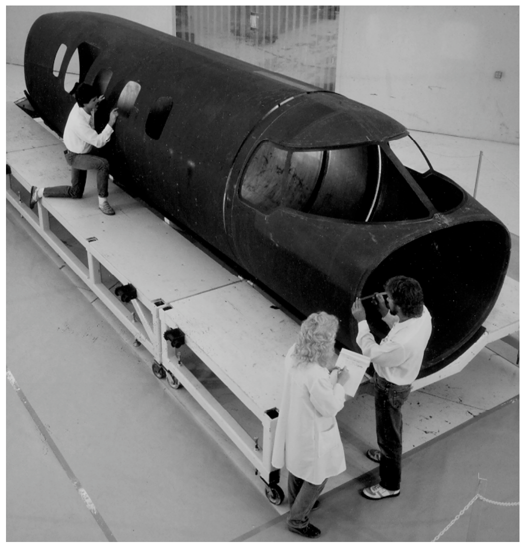

Figure 2
Beech Filament Wound Starship Fuselage
Fibertek Photo

3.3.2 Symmetry and Balance

All composite designers and materials engineers know the rules for symmetry and balance. Most stand-alone computer analysis programs have provisions for compliance. Here are some special problems.

Filament-wound structures, if they are geometrically symmetric, as are pressure vessels, do not need a symmetric laminate layup since the structure satisfies that need. In fact, an unsymmetric laminate may confer some manufacturing advantages (i.e. putting hoop layers on exterior will increase compaction pressure and may lower resin fraction). Thus, duplicating the laminate for testing purposes will most probably require changing of the laminate layup. And, if a sample of the pressure vessel is to be cut out for test specimens, they will invariably warp unless the laminate is thick enough to resist the warp force.

The question to be asked is: How do you replicate the filament wound laminate for testing? The stackup must be changed to achieve symmetry and the helical angle layers must be wound as polar layers. The laminate would normally be wound onto a flat or gently positively curved surface, then removed and cured flat under autoclave or vacuum bag pressure. A laminate results that has somewhat less than optimum correspondence to the actual filament wound laminate. Filament wound helical lamina cannot be wound into a flat test specimen. Thus a laminate that contains them will probably warp.

3.3.3 Need to flip HM fabrics

Low modulus carbon fabrics (Plain Weave) can be handled somewhat like Fiberglass plies. Higher modulus plain weave fabrics 344Gpa (50 msi) or higher fiber modulus must be flipped in the laminate to avoid laminate warping. Flipping is placing the warp or fill facing the warp or fill on the other side of the line of symmetry as a mirror. The poly release film is always on the fill side. This means that one must treat the 0/90 fabric as if it were angle ply.

3.3.4 Comparative tests (Short Beam Shear)

The short beam shear test is useful for assessing the relationship between the fiber and the matrix in a unidirectional laminate. It is a simple test with an uncomplicated test fixture. The data can most appropriately be used to assess the ability of a resin to adhere to differing fiber surface treatments but it does not produce shear data for engineering

3.3.5 Bonding

3.3.5.1 Designing the Joint

There have been innumerable design articles for bonded joints. Here are three critical rules:

1. Do not allow tensile loads into the joint, only shear loads. If there is a possibility of a tensile load, use a bolted joint or a combination.
2. Short bonded joints are more efficient. The peak stress occurs at the ends of the joint and the allowable stress decreases with length. (Fig 6)
3. Avoid eccentricity in the joint, because it produces peel stresses. This means that the adhesive thickness should not be excessive. Most manufacturers recommend joint thickness of 0.005-0.010 in. Besides changing the stress type, thick adhesives are generally weaker (8).

3.3.5.2 Surface Preparation

It seems that the materials engineer comes into play when there is a problem with an adhesive bond, rather that at the beginning of the design cycle when changes to the process are easy. Usually, the problem is with surface preparation. In spite of the many available processes for guaranteeing a reliable bonded joint, the design engineers can come up with new ways to provide some excitement to the process. Below are some of the processes they have introduced along with the right processes and their good and bad points.

Table 2

Surface preparations for Bare Aluminum	*Comments*
No treatment, solvent wipe	Wildly variable due to the non-removal of the weak oxide layer
Grit Blast (GB) plus Conversion Coating	Inconsistent, low values
Grit blast plus solvent wipe	Good initial values, poor durability
Grit Blast plus Mil P 23377 Primer	Low, inconsistent values
GB plus Chem. Film, Mil-P-5541 Cl. 3	Low Values. < 13780MPa (2000 psi)
GB plus Br 127 primer (Note 1)	Good values, Better durability
GB plus FPL Etch plus primer (Note 2)	Good values and durability
GB plus P-2 Etch and primer (Note 3)	Good values and durability
GB plus Silane, BR 127 (Note 4)	Excellent values and durability
GB plus Sol-Gel plus Br127 primer Note 5	Excellent values and durability
GB plus PAA plus Br127 Primer	Excellent values and highest durability

1. Br 127 primer is product and TM of Cytec Industries (one should be aware that there are strict limits on the applied primer thickness)
2. Forest Products Lab, Combination of Chromic and Sulfuric Acids. EPA Limited
3. P-2 etch and optimized P-2 use acids which are not EPA limited
4. Silane treatment used by RAAF, and WRALC (C-141)
5. Sol-Gel patented and developed by Boeing. Extensive testing by AFRL (9)
6 PAA equals Phosphoric Acid Anodize, which may not be available in all venues. It has the highest most consistent values, and best proven durability

Another consideration, initiated with the PABST (10) program, has now matured. There are adhesive data that substantiate claims for durability of the adhesive bond in challenging environments. Hot/wet wedge crack tests have supplied comparative data for a number of surface preparation/adhesive/primer combinations. (9). Australian investigators have supplied acceptance data that is: no greater than 4.9mm (0.20 in.) crack growth per 24 Hour, no greater than 18.37mm (0.75 in.) per 48 Hours and no greater than 5% adhesion failure. (11)

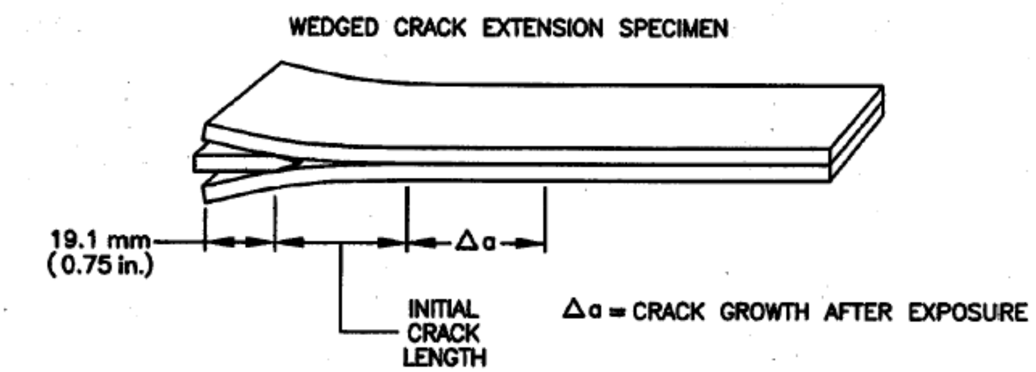

Figure 3
Wedge Crack Extension Test Sample (12)

3.3.5.3 How do We Choose the Surface Preparation

Since most smaller aerospace suppliers do not have the resources to support the PAA technology, and may not have a chemist or materials engineer, the obvious recourse is to use some outside consulting, train someone in Engineering who would be willing to learn this “new” or “strange” technology or to use the simplest, most appropriate technology. For those companies in the latter situation the recommendation would be to use the simplest technology, and that is, at the present, GB plus Sol-Gel plus Br127 primer, primarily because of the large amount of reliable data that has been generated on the system by several agencies. But the adhesive system would have to be defined, since not all adhesives are optimum for this system and the operators must be trained.

3.3.5.4 FPL etch

The FPL etch is in use today in several areas in spite of its disposal problem. The procedure was invented at the Forest Products Laboratory of Madison WI. Before the mixture was used for etching aluminum it was used in chemistry labs for cleaning glassware. Another use is for “etching” of olefinic plastics (polyethylene is one member). The material in its potent form is bright orange; when it depleted or no longer usable it turns green.

A producer of flexible microwave cable was having trouble with intermittent plating on polyethylene-clad cable. They did not know the cause of the problem. The cable had a copper conductor and a thick polyethylene insulation, which was to be etched, then copper plated. The etch solution was in glass containers on the continuous production line and the color of the solution they were using was visible from the other end of the building. It was green. The first part of the job was over quickly.

3.3.5.5 Applying the Adhesive or Sealant

After careful surface preparation, the adhesive, paste or film, must be applied to the surface(s). It is relatively easy to verify the adhesive bond strength with finger panels which have been positioned in a bonding fixture and been pressurized with clamps, or vacuum bag. It is generally another, more difficult task, to properly fit-up and bond real parts. In the manufacturing arena the tooling may not be optimum, the parts may not fit perfectly and the surface preparation is always much more difficult because of access, drainage or other problems. This leads to the requirement for a relatively benign surface treatment for manufacturing.

3.3.5.6 Film Adhesive

The critical item with film adhesive is the conditioning of the adhesive so that when it is time to apply it to the prepared surface it is at room temperature. There are no short cuts here. If there is moisture in the bond wildly variable results will occur. The caution is doubly important when using Cyanate Ester adhesives, they can chemically react with moisture.

3.3.5.7 Peel Plies

Care is needed in choosing peel plies for composite structures that will be subsequently bonded. An extensive study conducted at Boeing, Long Beach (13) found that some peel plies were unreliable as a surface preparation and suggested the use of low-pressure grit blasting for the composite instead.

3.3.5.8 Paste Adhesive

Proper mixing of a paste adhesive infers that the manufacturer's recommendations for mixing ratios are followed and there is no air entrapped in the mix. The mixed adhesive must then be applied to both surfaces and the surfaces brought together under some pressure. Often, one of the surfaces must slide past the other making it difficult to assure that both surfaces are covered and that there are no gaps or "holidays". The operator may twist the two components if geometrically feasible, to insure coverage. Unfortunately, this approach can result in the dreaded "Kissing Bond", where the adhesive from both sides may touch each other but there is no bond. There is no NDT technique that can identify a kissing bond. One recommendation for small components has been to mount a circumferentially symmetric assembly on a rotisserie with an infrared bulb providing heat to the bond line. Spin and heat to lower the viscosity so that the adhesive flows to wet the two surfaces and fill the voids, then after the adhesive will not flow, continue the cure in an oven. One prime contractor has used 66C (150F) as a method of inducing flow. When there is a bond line thickness that can be manipulated by pressure, the use of glass beads (About 1.5%) or wires should be used in the adhesive to retain an optimal thickness

3.3.5.9 Co-curing

The tooling to enable co-curing may be prohibitive for many applications. Also some prominent investigators would suggest the use of grit blast rather than co-curing (14). A filament wound structure can supply half of the tool and the subsequent winding over the bonded structure supplies the other half along with pressure to insure contact. Co-curing just about eliminates any concern about surface preparation or contamination. The only concern is that the cure cycle and the curative for both the adhesive and the filament wound structure are compatible. That was the technique used for the "wound-in-place" aft joint for the Tomahawk Cruise Missile launcher. The canister was wet wound and the adhesive was a film. Somewhat over 900 of these joints have been built with great reliability. (Fig 4,5)

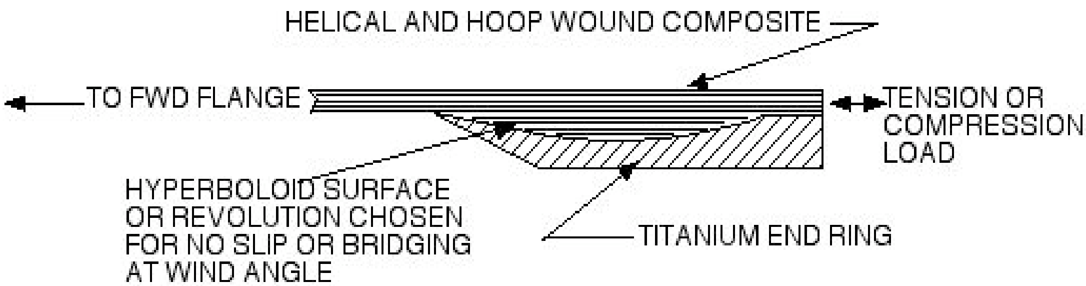

Figure 4
Wound in Place Aft Joint (15)

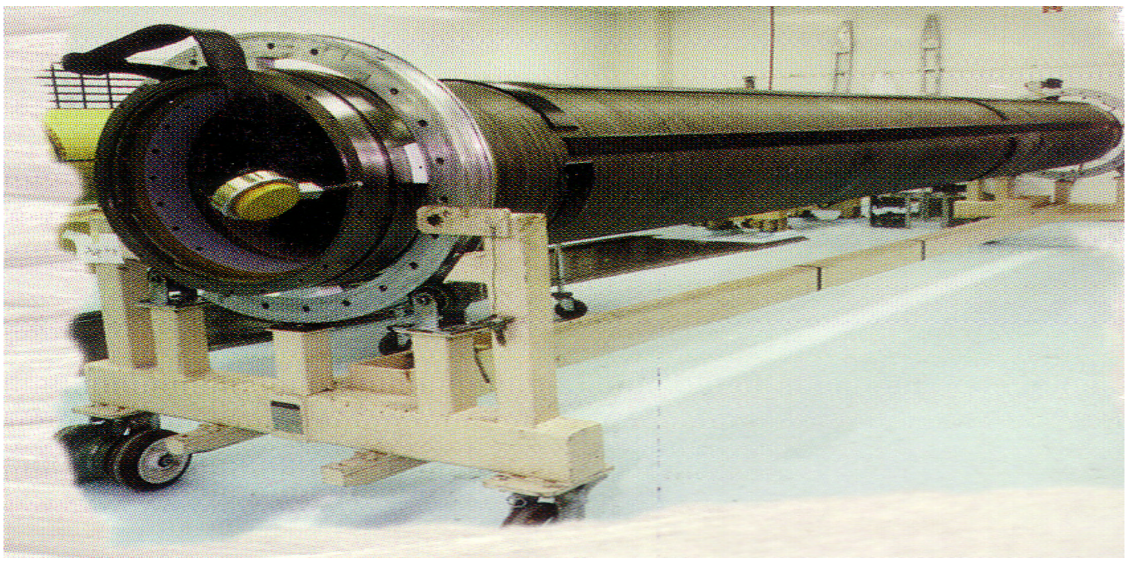

Fig. 5

Tomahawk Cruise Missile Composite Launch Canister (16)

3.3.5.10 Misconception of longer bondline, more strength

Most materials engineers will encounter the belief that increasing the bond line length will increase the load carrying capability of a structural joint. It will increase the load carrying ability, but the allowable stress will decrease. The belief has been popular with some management and it usually takes a test failure to disabuse them of the belief. Most materials engineers have seen the graphic (Fig. 6) that demonstrates the correct approach, but unfortunately there has been limited testing to prove the fact. (Fig. 7)

3.3.5.11 Acceptance of poor shear strength if it meets or exceeds design requirements

The materials engineer understands that the adhesive will have different adhesive properties on different adherends and with different surface preparations and cure conditions. The materials engineer knows that inspection of the bondline after the lap shear test is necessary. However the design engineer, who may need a lap shear strength of 13 MPa (2000 psi) for his design, when he sees the test data that has a wide coefficient of variation but an average of 17.23 MPa (2500 psi), is completely satisfied, although the lap shear strength should have been at least 27.56 MPa (4000 psi). It is important for the materials engineer to evaluate the test specimens, compare the test data to the manufacturer's and published data and to recognize the type of failure as cohesive, adhesive or mixed. It is sometimes difficult to get designers and management to suspect or reject the lap shear data if it meets the design needs.

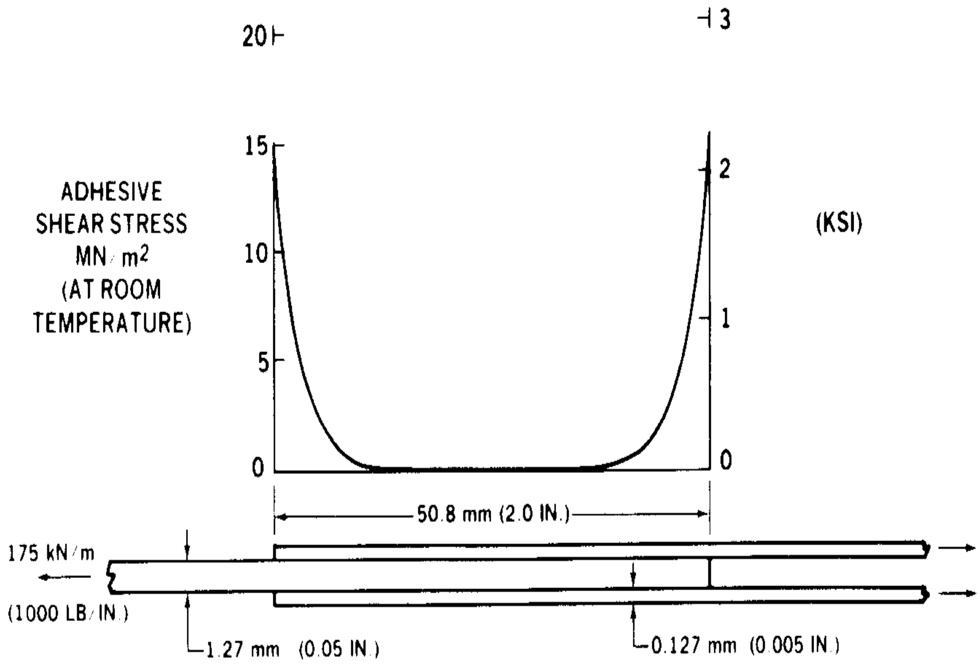

Figure 6
Stress Distribution in a Lap Shear Joint (17)

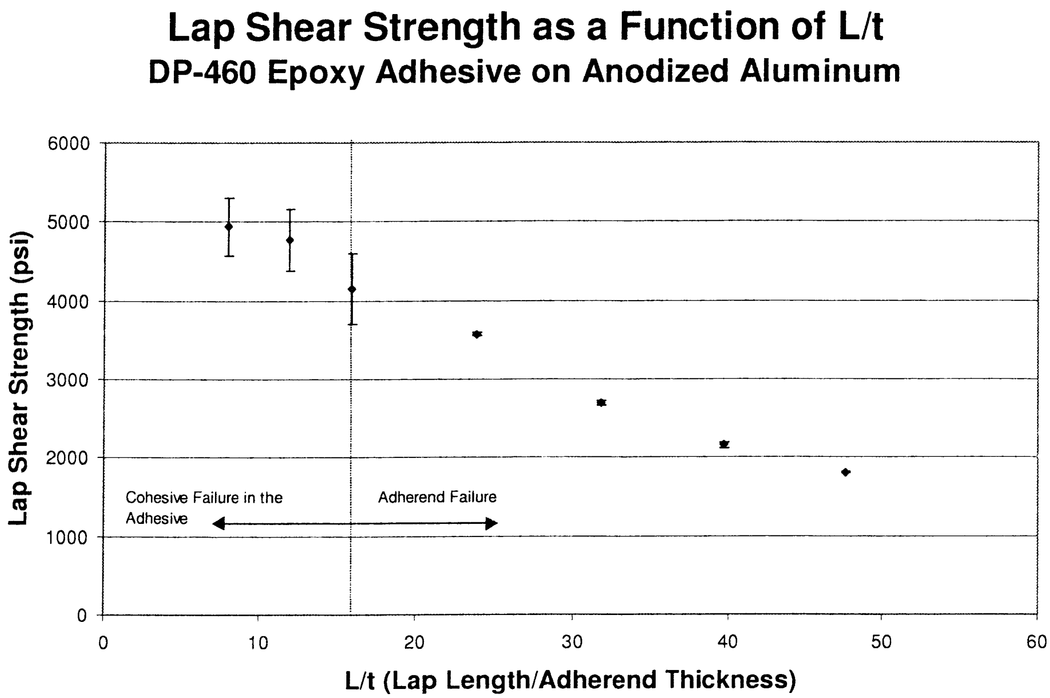

Fig. 7
Effect of Increasing Lap Length (18)

3.3.3 One Sample of Materials Engineering

3.3.3.1 Beilstein Test or the Beauty of a Spot Test

Beilstein was a chemist. He was a Russian though most of the record of his work was in German. He invented an organic chemistry database and a spot test that distinguishes halogen-containing materials from those that do not.

I was called by receiving because the "Neoprene" (TM DuPont) that was ordered was not the right color. I brought my spot tester, which was a thick copper wire embedded into a cork and a propane torch. The copper wire when heated to red hot and put into a chlorine containing material such as salt, (NaCl), vinyl, or Chloroprene (Neoprene) will emit a green glow when the copper wire is put back into the flame. The test is sensitive to most halogens, but TFE or CTFE do not react. Other halogen-containing materials may also be passive.

It turned out the mysterious elastomer was silicone, for which the spot test is simply burning a small portion; the char will be white due to the decomposition of the rubber into silica. Warning Note: Do not do these tests at home or without proper ventilation, the products of the flame are poisonous.

3.4 How do we transmit the information

There are so many paths to successful information transmittal. Successful transmittal means that the intended recipient gets the message and understands the reasons for the particular action. Obviously email satisfies the first part, but it doesn't always transmit the reasoning or the consequences that could happen with the wrong choice. When the program manager watches the lap shear tests, and makes the decision to employ the "easier" surface preparation, the second goal of the communication hasn't been communicated.

Obviously, there has to be some face-to-face interaction to convey the misgivings and the doubts that the materials engineer has about suspect data. Perhaps the answer is more training not for the materials engineer but for the management.

Acknowledgement:

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4.0 References

1 <http://www.sampe.org>

2 http://eng.waikato.ac.nz/programmes/materials_process/

3 Delmonte, John *The origins of Materials and Processes* Technomic Publishing Co. 1985

4 The Materials Society, February 26,2007 Annual Meeting & Exhibition in Orlando, Florida,

5 Hooper, E. H. and Arnold, L. E. "Development of a Full Scale Filament Wound Fuselage Shell" Autocom '89. COGSME, 1987

6 Ashton, Larry J. "Revisiting Cost Effective Filament Winding Technology", 44th International SAMPE Symposium, May, 1999 pp 458-465

7 Wolf, Jeremy Presentation at NorCal SAMPE Composites Workshop 26 March, 2009

8 Baker, A. in P.K. Mallick, ed. *Composites Engineering Handbook*, Marcel Dekker, New York, N.Y. 1997

9 Mazza, James, et. al, *Sol gel Technology for low VOC , Non-Chromated Adhesive Bonding Applications* April 2004 AFRL-ML-WP-TR 2004-4063

10 Potter, D. L. *Primary Adhesive Bonded Structure Technology (PABST) Design Handbook For Adhesive Bonding, Douglas Aircraft Co*., McDonnell Douglas Corporation, Long Beach CA, Jan. 1979

11 Davis, Max, "Best Practice in Adhesive Bonding" Presented to the FAA Workshop,<https://www.niar.wichita.edu/NIARWorkshops/LinkClick.aspx?fileticket=iGBXdAGtWEk%3D&tabid=104&mid=569>

12 ASTM-D-3762 Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test) American Society for Testing and Materials, Philadelphia, PA

13 Hart-Smith, John, in Peters. S. T., ed. *Handbook of Composites, 2nd ed*, pp 667-683, Chapman and Hall 1988

14 Personal Conversation, John Hart-Smith to S. T. Peters

15 Peters, S.T., Humphrey, W.D., and Foral, R.F., *Filament Winding, Composite Structure Fabrication*, 2ond ed., p 11-6, SAMPE Publishers, Azuza CA, 1998
16 Lincoln Composites Photo
17 Hart-Smith, John, in ASTM STP 749, “Joining of Composite Materials” 1981, Keith Kedward, ed, pp. 3-31
18 Pocius, Alphonsius V. “Adhesion Science, Mechanics, Surfaces and Chemistry” presented at The Golden Gate Polymer Forum, May 7-9, 2007, Burlingame, CA