JOURNAL OF APPLIED POLYMER SCIENCE VOL. VI, ISSUE NO. 20, PAGES 210-216 (1962)

Significance of Good Process Control

FLOYD H. BAIR

Applications Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio

Introduction

Adhesive bonding has become a standard method of joining a variety of assemblies, the complexity of which extends to the far reaches of one's imagination. To satisfactorily accomplish the bonding of assemblies a complete, exacting, and suitable process or processes must be developed, followed, and controlled. In considering processing one must take into consideration all or part of the following: the adhesive used; the nature and complexity of the part being bonded; the metal or metals, plastics, wood, rubber, core materials, foams, and any other component parts; as well as the physical and mechanical requirements that the bonded item must satisfy.

Discussion

Evidence of the importance of various process controls is given in Figure 1 which shows the process steps in a typical bonding system. The first step is the preparation of the parts. Each detail of fabrication must be known in order that surfaces may be properly prepared. At first glance, a specific surface preparation might be considered adequate to prepare any surface of a given material; this is not always true. In many cases it must be modified to prepare surfaces that have been exposed to severe contamination such as silicone cutting oils and heavy scale due to heat treatments, etc. One could dwell in considerable detail on surface preparation. For purposes of this paper it suffices to say that the prime requisite for high quality bonding is to prepare surfaces that are conducive to strong bonds with the adhesive used. The layman is prone to condemn the adhesive when a failure occurs, but in reality it is usually due to poor bonding processes, often to inadequate surface preparation.

The next step in the process is transportation and storage. This covers the critical period between surface preparation and application of the adhesive. It should be kept as brief as possible and still be compatible with production schedules. One must determine how long prepared surfaces can be held because adhesives vary widely in their ability to form bonds under varying degrees of contamination. Surfaces after being prepared are in a high energy condition which readily adsorb or chemisorb in a matter of seconds constituents of the air or airborne substances. Some adhesives will produce good bonds after storage under good conditions up to 30 days; others will tolerate a storage of only an hour or less. Some indication of storage time may be obtained from the adhesive manufacturer, but in developing their recommendations all conditions of use cannot be anticipated. Therefore, the only safe way is to conduct tests under the conditions encountered. Now what is meant by good storage conditions? A specially conditioned room with temperature and humidity controlled and air filtered to remove dust, vapors, and other airborne materials is recommended. Handling must be at a minimum using clean lint-free gloves or clean tools preferably made of stainless steel.

Throughout the entire process, one must follow the adhesive manufacturer's instructions, but that in itself is not enough. There are a host of factors or variables that will require consideration. For example, the part may have large masses of metal adjacent to core materials which act as heat sinks. In such cases some areas may not get heated to the adhesive cure temperature, or the time at temperature may not be long enough to cure the adhesive. Many times it is necessary to transport primed or prepared parts to another area for bonding. In so doing, they may pass areas where machines may be giving off oil vapor or through areas where paint is being sprayed. During the

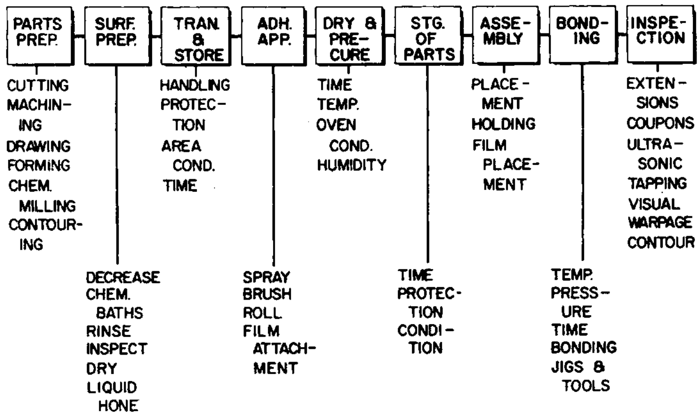

Fig. 1. Adhesive process.

assembly of parts it is possible to do damage that counteracts otherwise careful processing. Jigs and fixtures used time after time must be handled to be placed in position. These are rarely cleaned. Thus, even when handled with clean gloved hands they may contaminate parts being bonded. Sometimes film adhesives are moistened with solvent to "tack" it in place, and the solvent is trapped in the bond. In other cases, a hot iron may be used to fuse the adhesive. This iron may have been placed on a dirty table between use, and during subsequent use contaminate the parts. One case is known in which, after a long successful production run, bond strengths suddenly became inferior. After considerable investigation the difficulty was attributed to a change in the source for the metal adherends. There are many examples showing where with seemingly good processes one secures poor bonding due to overlooked causes.

The many variables encountered in a process become apparent when we consider the bonding of the rotor blade. A manufacturer listed

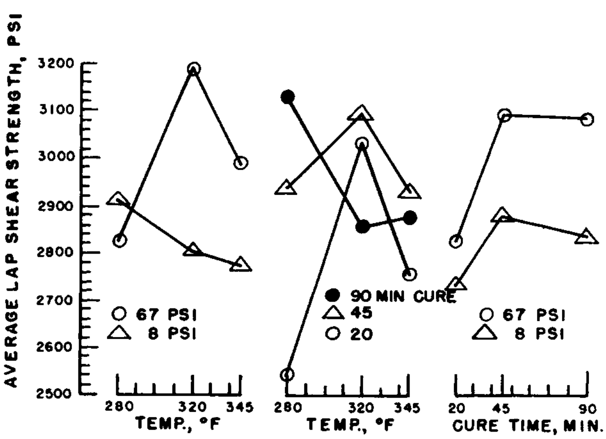

Fig. 2. Process variables for bonding magnesium alloy (no dark Dow areas included).

over two-hundred variables what must be satisfied in bonding the blade containing an aluminum honeycomb core and laminated aluminum facings. Despite the large number of variables, bonding was done successfully and the blade is now in complete production.

This discussion will not completely analyze all of the process variables and their effects. However, several will be considered in some detail. Figure 2 shows data supplied by the Boeing Airplane Co.[1] for bonding surface-treated magnesium alloy with a prime-film type of adhesive system. Dow 7 was used in this case as a surface treatment to protect the magnesium metal from corrosion. Sometimes the color of this coating varies from light to dark due to unknown causes. It was desired to compare the effect of a dark versus a light-colored coating on bondability with the adhesive system, and also to optimize the bonding conditions. Data on this figure are for bonds containing only light-colored coatings. The left side of the figure shows temperature against cure pressure, the center part cure time versus pressure, and on the right side pressure against time. It definitely establishes an optimum of 320°F. for 45 min. at 67 psi pressure. By comparing Figure 2 with Figure 3, showing data on bonds containing dark areas of the coating, a somewhat different picture is shown; the overall strengths are less. In both cases, a 45-min. cure time is affected less by a temperature variable than either the 20- or 90-min. cure.

Sometimes it is necessary to change processes due to available space or equipment for storing materials. In the following example an increase in length of the room-temperature storage period was desired due to limited refrigeration space for storing an adhesive. It would be advantageous to

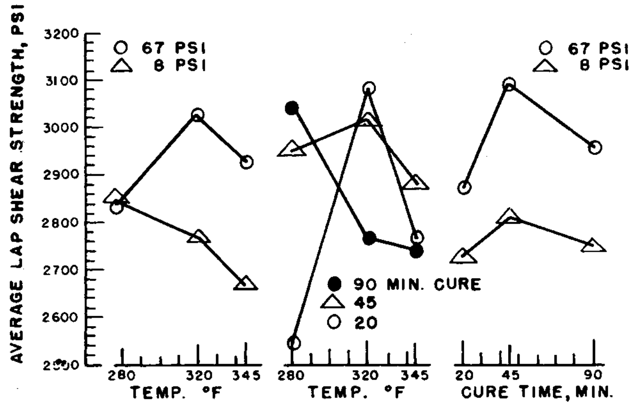

Fig. 3. Process variables for bonding magnesium alloy (dark Dow areas included).

lengthen the room-temperature storage period beyond the specified 64 hr. before applying the adhesive. The manufacturer[2] conducted a series of tests to determine the effect of such room temperature storage on bond properties. It is noted from Figure 4 that the sandwich peel suffered a uniform decrease in strength up to 72 hr. and a more severe drop after 72 hr. Lap shear joints showed little loss in strength up to 48 hr., a slight decrease up to 72 hr., and a more severe drop in strength after 72 hr. If the slight drop in peel strength can be tolerated, a room temperature exposure of the film up to 72 hr. could be justified.

Table I, Boeing[3] data, gives the results of four methods of applying the primer of the adhesive system using four systems as shown. A one-coat application followed by baking is the optimum procedure and was approved over the previous specification standard. Also another report[4] shows that a thin, atomized coat of primer not over 0.001 in. is the optimum method.

It often becomes necessary to change adhesive systems or to select the best adhesive for a specific application. Concurrent with this selection, research, necessary to determine optimum processing conditions, must be accomplished. Hughes Air-

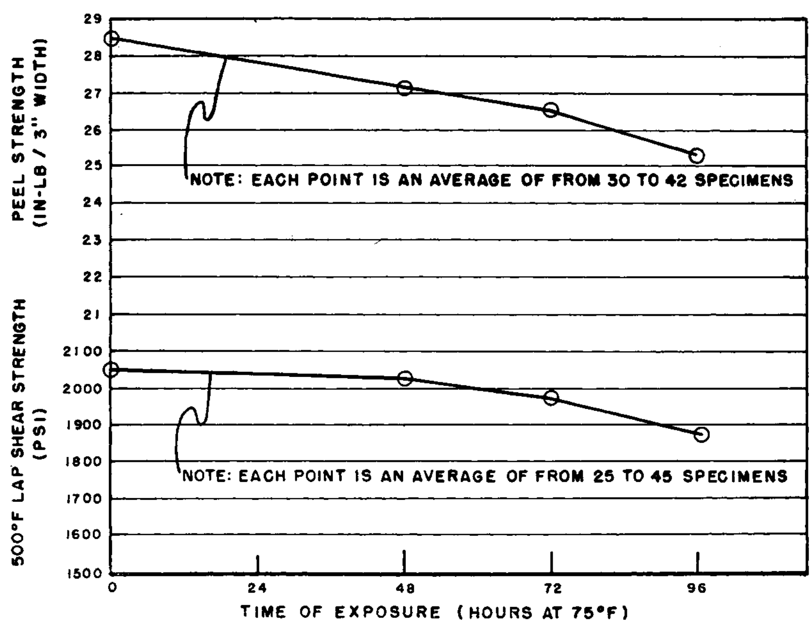

Fig. 4. Effect of room temperature exposure.

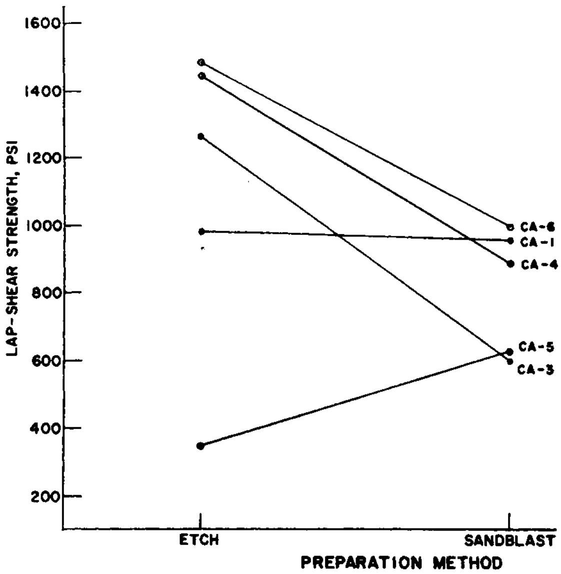

Fig. 5. Effects of metal preparation method on strength

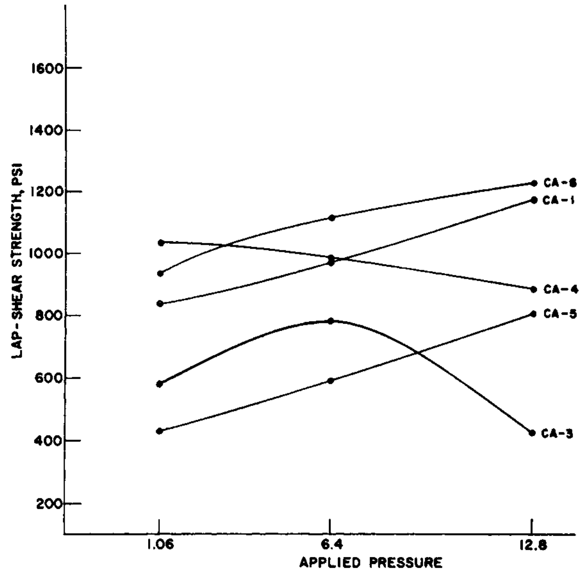

Fig. 7. Effects of applied pressure on strength.

craft[5] showed the effect of such process variations for using five ceramic adhesives used to bond stainless steel assemblies. Figure 5 shows the results of two methods of surface preparation. Adhesives CA-3, CA-4, and CA-6 gave best results with chemically etched surfaces, adhesive CA-5 was best with a sandblast surface and the adhesion of CA-1 was about the same with either type of surface preparation. Figure 6 shows one vs. two firings for cure of adhesives. Adhesives CA-1 and CA-5 were best with one firing, CA-4 was best with two firings and with CA-3 and CA-4 either could be used. Figure 7 shows the effect of cure pressure. Adhesives CA-1, CA-5, and CA-6 gave higher strengths at the highest cure pressure; CA-4 did best at the lowest cure pressure, and CA-3 gave optimum strength at the 6.4-psi cure pressure. Figure 8 shows effect of firing temperatures. Optimum temperature for this test is thought to be about 1750°F. Higher cure temperatures produced better strength with adhesives CA-3 and CA-4, but better strengths with CA-5 were obtained at the lowest firing tempera-

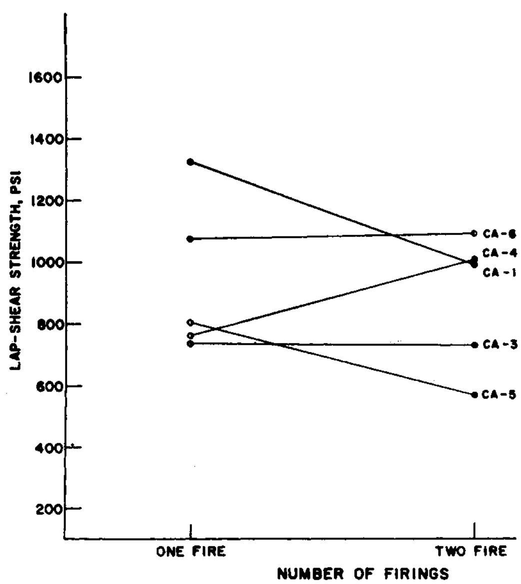

Fig. 6. Effects of number of firings on strength.

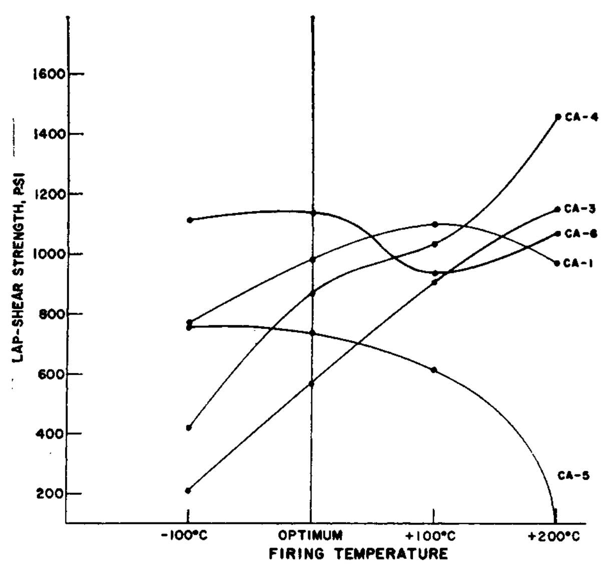

Fig. 8. Effects of firing temperature on strength.

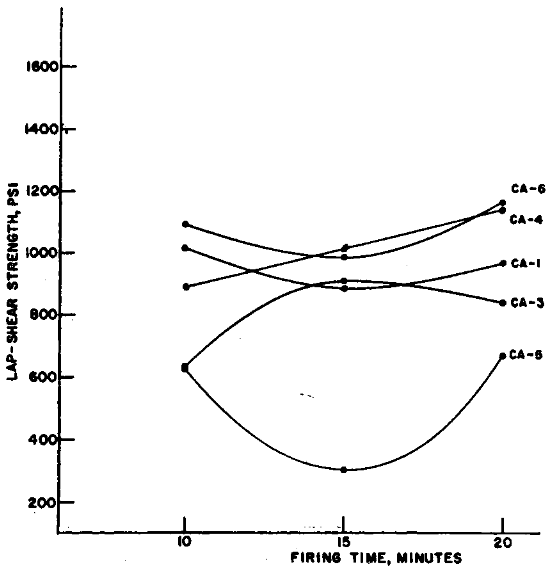

Fig. 9. Effects of firing time on strength.

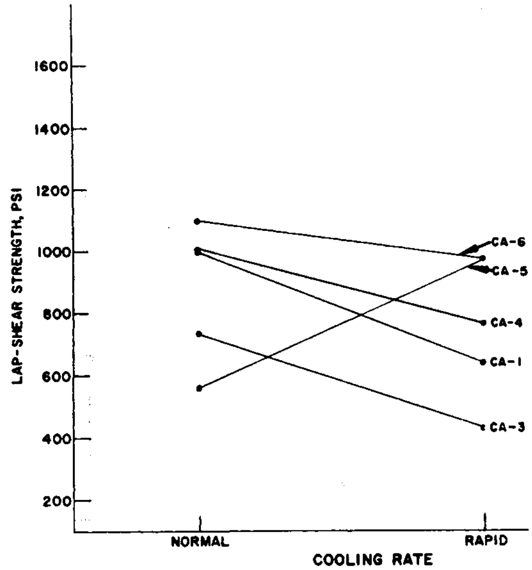

Fig. 10. Effects of cooling rate on strength.

tures used; and CA-1 and CA-6 have optimum maturing or curing temperatures. Figure 9 shows the effect of firing (cure) time at optimum temperature. Adhesives CA-1, CA-5, and CA-6 exhibit less strength when fired for 15 min. than for either 10 or 20 min.; CA-3 develops optimum strength using the 15-min. firing, and CA-4 increases uniformly in strength with firing time up to 20 min. Figure 10 shows the effect from thermal shock on rate of cooling. Here CA-5 increases in strength with rapid cooling. This effect can be associated with the relative thermal expansion coefficients of the adhesives and the adherend. An examination of the above-mentioned figures indicates the magnitude of strength properties in relation to known requirements for an anticipated use, the best overall performance for each adhesive, and the optimum processes necessary for surface preparation time, temperature, pressure, and cooling. The fact that these tests were conducted using inorganic adhesives does not detract from their significance. A similar set of determinations should be made for any adhesive system to be used. It is certain that each adhesive system studied would provide an entirely different set of results.

TABLE I
Optimum Application of BMS 5-15 Primer[a]

		2 coats,[b]	1 coat, baked	1 coat, not baked
	Magnesium Results, psi			
	2,578	2,625	2,848	2,308
	2,633	2,573	2,756	2,249
	2,439	2,766	2,523	2,453
	2,537	2,647	2,608	2,325
Total	10,187	10,611	10,735	9,335
Av.	2,546	2,652	2,683	2,333
	Aluminum Results, psi			
	2,634	2,744	3,306	2,997
	2,732	2,905	3,252	2,893
	2,678	2,922	3,254	2,940
	2,775	2,890	3,261	2,938
Total	10,819	11,461	13,073	11,768
Av.	2,704	2,855	3,268	2,942

[a] BAC5425

[b] Aluminum—2 coats not baked; magnesium—2 coats, first one baked.

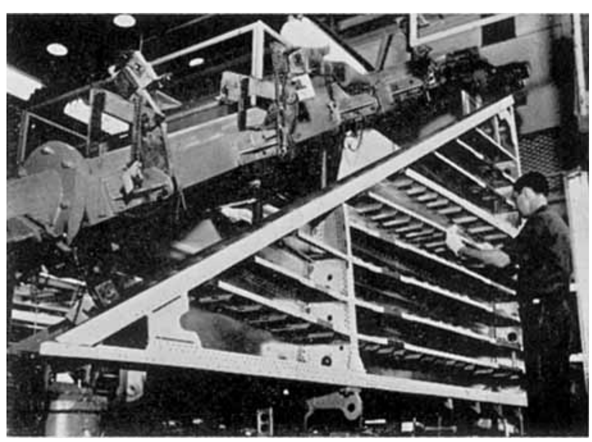

Fig. 11. Structural adhesive application—integral wing tank Convair F-102 airplane.

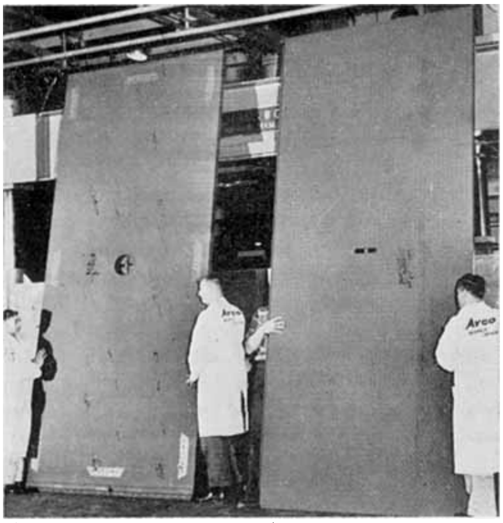

Fig. 12. Launch bridge.

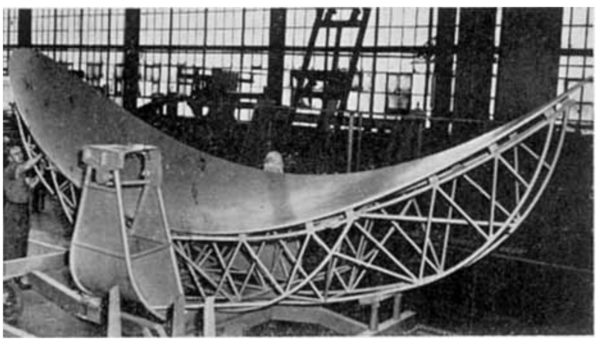

Fig. 13. Antenna reflector back-up structure.

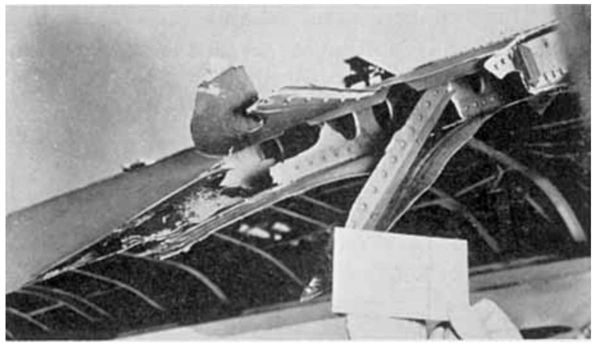

Fig. 14. Box beam wing trailing edge—riveted structure—showing fatigue failure in Boeing B-52.

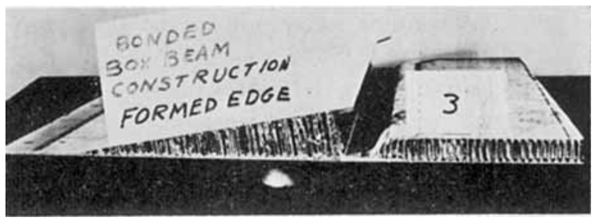

Fig. 15. Box beam wing trailing edge cross-sectional view—bonded sandwich construction in Boeing B-52. New design that performs satisfactorily under sonic fatigue load.

The complexity of various parts will usually dictate that different bonding processes be used. Some complex parts are shown on Figure 11, the integral fuel tanks and wing section of the Convair F-102, Figure 12, an armored vehicle launching bridge used to withstand passage of 60 ton tanks, which was manufactured by Avco Corp., and Figure 13, an antenna reflector back structure containing bonded honeycomb core and multilayer plastic reinforced glass fabric face sheets. It is obvious that different processes for each of these parts have been developed and are used in bonding.

One important factor that is often overlooked in adhesive bonding is the human element. One manufacturer kept very careful records of production, including the people involved, time of day, physical room conditions, etc. They found that some people rarely produce reject parts, others consistently produced many substandard parts, and with some individuals the number of reject parts increased toward the close of a work shift. Also, the temperature and humidity of the work area influenced the amount of rejected parts. This company has established a qualification routine before personnel are assigned to adhesive bonding jobs because many persons do not have the temperament to become competent at such jobs.

There are many conditions that any bonded assembly must withstand during its service life. Certainly the assembly must withstand the environments encountered in service such as load, temperature, shock, vibrations, moisture and chemical resistance. Modern adhesive manufacturers are cognizant of this and are improving their products and processes to meet the ever-increasing demands and use of the materials. However, with all of this there can be no substitute for designing the part to be suited to adhesive bonding and to fulfill the service demands. It follows that with any change in design, new bonding processes must be developed and used. One dramatic example of a change in design and bonding process is in the B-52 aircraft. During early production, the magnitude of sonic fatigue loading was not envisioned. In fact previous to that time little was known about it or the damage it can do. Figure 14 shows what happened to a section of trailing edge due to sonic fatigue. By changing design, materials, and processes the problem was solved; a section of the satisfactory part is shown in Figure

15. These changes involved three aspects no one of which can be considered to be the main reason for the satisfactory performance. Each factor—design, materials, and process—contributed to acceptability of the final item. However, experience has shown that with well-designed parts and with the use of the proper adhesives processing can be the difference between success and failure.

Conclusions

The following must be considered to accomplish consistently good bonding.

1. Design the part to maximize the advantages of adhesives bonding, and minimize the weak properties of adhesives.

2. Select an adhesive to meet the requirements of the part being bonded. Remember it is very costly and time consuming to change adhesive systems.

3. Determine for each case the variables and pertinent factors involved in the bonding process.

4. Conduct sufficient tests to optimize all phases of the process, where variables occur such as surface preparation, time, temperature, pressure, and storage.

5. Select personnel with proper aptitude and train them in the various bonding processes. Try to keep the same people on the specific processes.

6. Develop process specifications for each bonded part, assembly, or an entire process based on test results, not suppositions.

7. Permit no deviations from the process specifications unless based upon supporting test data.

8. Continuously conduct tests, destructive and if possible nondestructive, to assure that high quality parts are being bonded.

References

1. Boeing Airplane Co., Report AP-2-18 "BMS 5-15, Types III and IV Adhesive Bonding Magnesium Over-and-Under Cure."

2. Boeing Airplane Co., Report AP-2-31, "Room Temperature Exposures of BMS 5-17 Adhesive."

3. Boeing Airplane Co., Report AP-2-81, "Optimum Coatings BMS-5-15 Adhesive Systems."

4. Boeing Airplane Co., Report AP-2-43, "Adhesive Spray Technique."

5. Gates, L. E., and W. E. Lent, Hughes Aircraft Co., Reference 4554.5/76, "Development of Ceramic Adhesives for Stainless Steel Honeycomb Wing Structures, Report No. 1."

Synopsis

The important place that adhesive bonding of structural and nonstructural parts has reached is largely due to the recognition and the practice of adequate and exacting processes necessary to produce acceptable parts. The procedures necessary for adhesive bonding are not common for all adhesives, adherends, or parts being bonded. During any process many variables occur that must be satisfied by the results of tests before production is started. This must be followed by quality control tests to continuously assure that high quality parts are being produced. Closely connected with processes are the temperament and capabilities of personnel doing the bonding. It is recommended that a detailed procedure be established in order to develop methods for bonding any specific end item. The purpose of this paper is to examine some processes in relation to their effect on the finished item and to recommend a pattern to follow in establishing good bonding processes.

Résumé

La place importante que le collage de parties structurées et non-structurées a atteint, est due en grande partie à la découverte et à la pratique de procédés adéquats pour la production d'éléments acceptables. Les procédés nécessaire pour le collage ne sont pas les mêmes pour toutes les colles ou tous les adhésifs ni pour tous les matériaux à coller. Durant chaque procédé il faut tenir compte de plusieurs éléments dont les tests doivent être satisfaisants avant que la production ne débute. Celle-ci doit être suivie de tests de contrôle de qualité pour assurer continuellement la haute qualité du matériel produit. Le tempérament et les capacités du personnel effectuant le collage doit également être pris en considération. Il est à recommander qu'un mode d'emploi détaillé soit établi pour le collage de chaque article en particulier. Le but de cet article est d'examiner certains procédés en relation avec leur effet sur l'article fini et de recommander une marche à suivre dans l'établissement de bons procédés de collage.

Zusammenfassung

Die wichtige Stellung, welche die Klebeverbindung von Strukturund Nichtstrukturteilen erreicht hat, ist grossteils auf die Auffindung und Durchführung von angemessenen und genauen Verfahren zur Herstellung annehmbarer Teile zurückzuführen. Die Verfahren für die Klebeverbindung sind nicht für alle Klebstoffe, Materialien oder zu verbindende Teile gleich. Bei jedem Verfahren treten viele Variable auf, die durch Testung ausreichend untersucht werden müssen, bevor die Produktion beginnen kann. Kontrolltests müssen ständig durchgeführt werden, um eine fortlaufende Erzeugung hochwertiger Teile zu gewährleisten. Eng verknüpft mit den Verfahren sind Geduld und Geschicklichkeit des mit der Durchführung betrauten Personals. Es wird empfohlen, dass zur Entwicklung von Verbindungsverfahren für jeden speziellen Fertigartikel ein detailliertes Programm aufgestellt wird. Der Zweck der vorliegenden Mitteilung ist es, einige Verfahren in Beziehung auf ihren Einfluss auf den Fertigartikel zu überprüfen und einen Plan zur Entwicklung guter Bindungsverfahren aufzustellen.