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Potential of Adhesives for the Future

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Introduction

While adhesives date back to the days of the ancient Egyptian pharaohs and possibly earlier, our modern technology is of rather recent origin. Phenolic resins have been available for only about 50 years, epoxy resins for about 25 years, and adhesives derived from these resins have been available only during the last two decades. Considering its recent origin, advances in adhesive technology have made remarkable progress—and augurs well for the future potential of adhesives.

Today, depending upon one's viewpoint, we are either in the Space Age or in the Materials Age. In any case, all will agree that our materials of construction will be called upon to withstand environmental conditions which, until recently, had rarely been considered.

Space programs are now being actively pursued, and it can be expected that they will continue to receive a major portion of industrial and technological energies, whether the program objectives be scientific or military defense in nature, for commercial purposes, or simply because of man's natural curiosity and desire for exploration.

Current aerospace programs include longer range ballistic missiles (such as the Polaris development program); advanced anti-missile missiles; nuclear rockets (such as the Kiwi and Rover programs); manned lunar reconnaissance flights and manned orbiting laboratories (NASA'S project Apollo); planetary studies (such as the current Surveyor, Ranger, and Prospector moon vehicles, Mariner and Voyager flights to Mars and Venus scheduled during the next five years, and flights to Mercury and Jupiter scheduled during the next ten years); programs for the investigation and surveillance of the earth's atmosphere; development of advanced communication systems (such as the Army's Advent satellite program); and, of course, supersonic aircraft for both military and commercial uses.

The exploration of "inner space," which has been defined as "the old, wet, vast and salty domain covering over 70% of Earth's surface,"[1] and increasing emphasis on developments for antisubmarine warfare (ASW) are realities today.

The Army has expressed its desire for lighter and more compact infantry weapons and other means for increasing firepower of the infantryman "without burdening him with complex and heavy gear."[2]

The success of such missions depends upon the ability of the structures and associated components to satisfy design requirements and to withstand the conditions encountered during test phases, storage, and operation. And, needless to say, the component parts can perform only within the limits of the materials used in their construction.

It is well known that achievements during solution of the most difficult and/or critical technological problems will lead to numerous other applications. Accordingly, it can be expected that information and applications developed for adhesives in aerospace programs will substantially advance the overall industrial potential of adhesives.

Discussion

Adhesives have a great potential for the future; and this will be realized through (*1*) development of improved materials, (*2*) development of improved fabrication processes, (*3*) development of improved test methods—especially nondestructive, (*4*) establishment of information on critical properties and design parameters, and (*5*) greater use of the scientific approach.

Undoubtedly adhesives will continue to find wider and more important usage because they do provide certain inherent advantages over other joining methods. Of particular advantage in aerospace applications is the fact that adhesives lend themselves ideally to joining of dissimilar materials—a very significant factor in the rapidly growing field of composites. A composite material system may be defined as a combination of two or more materials into a unit, the component materials being arranged so as to confer upon the resulting

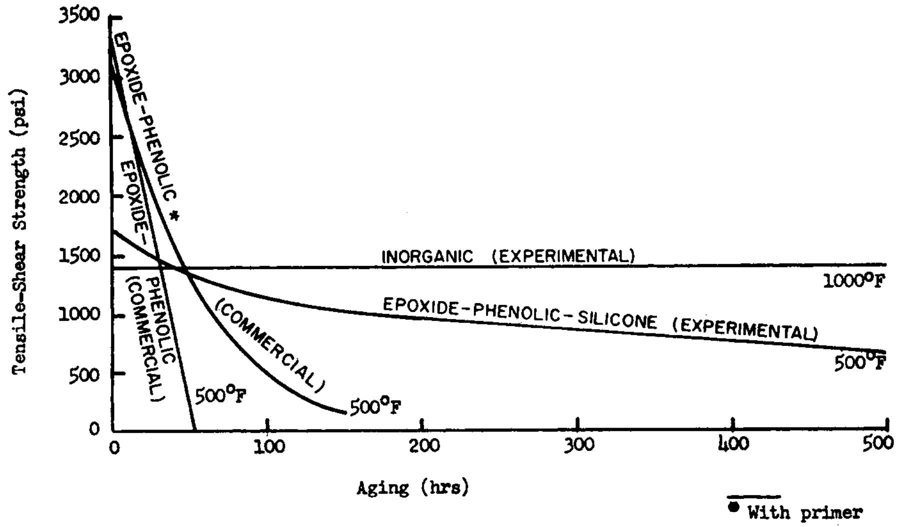

Fig. 1. Adhesive bonding of stainless steel; aging characteristics—present state of art and current programs (courtesy of *Adhesive Age*[3]).

unit the desired properties of each material employed. Composites are essential to achieving optimum aerospace structures from a standpoint of component weight and performance; and hence adhesives must, of necessity, be considered a dominant factor.

Materials

Primarily under the auspices of governmental agencies, programs are being conducted toward development of improved adhesives and of improved resinous materials which subsequently may be used in formulating adhesives with characteristics superior to those currently available.

Greatest developmental efforts are directed toward increasing the upper temperature limitations for structural adhesives. For current aircraft flying at or below Mach 1, surface temperatures generally do not exceed 260°F. However, as vehicle speeds are increased, aerodynamic surfaces will encounter considerably higher heat fluxes and correspondingly higher temperatures. For example, at Mach 3, surface temperatures can reach 650°F. at 30,000 ft. altitude, and close to 1000°F. near sea level; and re-entry temperatures may exceed several thousand °F. The current status and anticipated future requirements are shown in Table I and in Figure 1, showing a plot of tensile-shear bond strength vs. time of aging at temperatures of 500° and 1000°F.[3]

TABLE I
Estimated Temperature Capabilities and Future Requirements of Adhesives for Metals[a]

	Short-time service, 0.1 hr., °F.	Long-time service, 1000 hr., °F.
Current capability	700–800	400–500
1960–1965 requirements	1500	700
1965–1970 requirements	1700	1200

[a] Adapted from "1960 Aerospace Forecast of Technical Requirements," Aerospace Industries Association. Bond strengths at elevated temperatures are considered to be 30–35% of room temperature values.

Considerable research has been done toward development of ceramic-type adhesives suitable for operating at temperatures above 1000°F. and even 2000°F.;[4,5] and work is being conducted toward modifying such adhesives for use in bonded honeycomb sandwich constructions.[6]

High-temperature polymer research is being directed toward development both of new thermally stable polymeric materials and of basic information to better understand material performance at temperature extremes.[7] It is expected that some of these new polymers will find their way into adhesive formulations in order to provide improved thermal stability for bonded structures.

Fabrication Processes

Technological advancement in fabrication processes are urgently needed in order to achieve structures of greater reliability and at lower cost, despite the trend toward increasing complexity and steadily growing demands on performance. Further, excessive expenditures of time no longer can be tolerated.

Adhesive bonding ideally lends itself to reduced fabrication costs and time expenditures. Large areas can be joined in one operation. Tooling and facilities for bonding and associated equipment often can be employed for a wide variety of structures, with little, if any, modification; design changes generally can be readily accommodated. On this basis, also, one can expect to find increasing usage of adhesives.

However, there is considerable need for development of improved bonding processes. Processes need to be simplified and established on a semi-automatic basis. Not only expenditures of time and costs but also "human errors" and concomitant loss of reliability can thus be reduced.

Surface treatment procedures often are too complex and laborious. For the "newer" industrial metals—beryllium, molybdenum, tungsten, etc.—and for ceramics, carbides, and nitrides, there is still need for establishment of suitable surface treatments.

There is much room for improvement of techniques for curing of adhesives. During the past decade, relatively few advances have been made in heating methods. Dielectric heating has been successfully employed in the plywood industry, but little work has been done in applying this mode of heating to bonding of metals and reinforced plastics. Induction heating has found wide application in metal processing but has barely been considered for application to adhesive bonding. Other means of energy transfer, e.g., radiation and sonics, need to be considered also. It is anticipated that more rapid fabrication methods could thus be developed—conceivably, even providing superior mechanical strength properties.

In order to further the use of composite structures, bonding processes need to be established with due consideration to the mechanical and thermal properties of the component materials of the composite so as to minimize undesirable residual stresses, warpage, etc., while enhancing desirable properties. In some cases it is desirable that a component of the composite structure be subjected to a prestress. For example, in certain applications involving lining of a plastic structure with a ceramic material, best performance is achieved when the components are joined so as to leave the ceramic liner in compression. Also, toward this end, better understanding of the effect of heating (curing) and cooling rates will be necessary, especially for bonding of dissimilar materials.

As structures become more complex, larger in size, and more costly, field repairs will become increasingly more important. It may even become extremely desirable to affect certain manufacturing assembly operations at field sites. Adhesives lend themselves well to such applications, and in this respect advances in low-temperature-curing adhesive systems and nontoxic curatives for epoxy-base adhesives have helped to further the potential of adhesives. Some improvements are yet required in field repair procedures. Surface treatments, locating/assembly techniques, and methods for pressurization and heating in isolated field areas, need to be simplified and established so that reproducible results can be achieved.

Test Methods

Test methods for adhesives have achieved a relatively high level of standardization, and are fully described in ASTM and government specifications and in several reference sources.[8,9] Requirements of space missions, however, impose more severe conditions for which adhesives and bonded members must be evaluated.

A rocket motor, for example, is subjected to very rapid pressurization; i.e., structures may be loaded in a matter of a fraction of a second. After the initial rapid pressurization, the load (pressure) is maintained relatively constant during the remainder of the motor operation. During this latter period, the temperature of exposure—due to aerodynamic friction for external surfaces, and due to propellant combustion processes for internal surfaces—steadily rises. Typical idealized pressurization and exterior heating curves for a booster (first-stage) rocket motor are shown in Figure 2. Methods for simulating such conditions are being developed;[10,11] yet there is a need for standardization.

Standardized methods are also required for simulating other environmental conditions—radiation (of various types and intensities), meteorite impact, noise, extreme temperature cycling, and vacuum. Increased usage of cryogenic liquids necessitates establishment of standard methods for testing of adhesives and bonded structures under extreme low-temperature cryogenic conditions.

To exploit further the inherent advantages of adhesive bonding, improved methods must be established and refined for quality assurance testing of bonded structures. When a suitable, economical, nondestructive test for determining quality of the structure is established, it will repre-

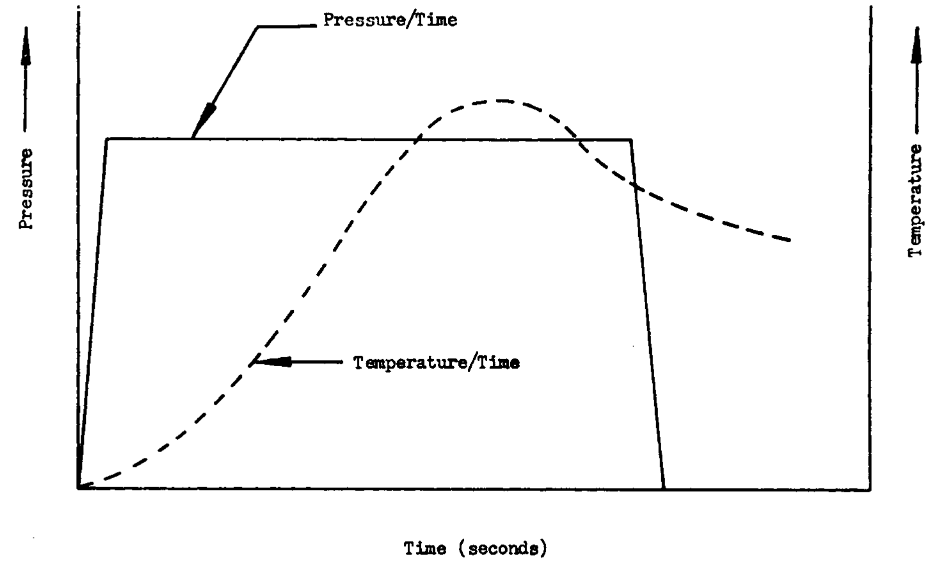

Fig. 2. Typical (idealized) pressurization and heating curves for booster rocket motor.

sent a giant stride forward and certainly will result in significantly increased applications for adhesives.

Production inspection plans for bonded assemblies frequently resort to test tabs and/or destructive testing of the assembly according to a sampling procedure. The use of test tabs is not fully satisfactory because it does not establish the strength of the bonds in the actual structure which subsequently go into service. Destructive testing of selected sample parts not only suffers from this lack of directness but also is extremely wasteful.

Proof testing is frequently employed and does overcome the lack of directness of tab testing and destructive testing of samples. However, in this case it is possible that damage may be done to the structure if the proof load is greater than that to be encountered during service. Conversely, if the proof load is below the service load, operating assurance may still be in doubt. Proof tests are frequently quite costly and time consuming, especially if extensive instrumentation is required.

Local area testing to a selected proof load or to destruction has been successful in some cases. For example, a well-engineered portable shear tester (Portashear) was developed and is being applied to testing of B-58 bonded sandwich wing panels at Convair, Fort Worth.[12] In this technique a skin "button" is first cut and then engaged with the Portashear tester head insert. Measurement is then made of the "shear" force required to fail the button adhesive.

Fully nondestructive tests, of course, would be preferred; and significant advances have been made employing ultrasonic and other energy transmission techniques which do not impair the bond.

"Coin" tapping of bonded panels was probably the first nondestructive test employed in industry and is still highly useful. A trained operator can readily distinguish large void areas from the hollow sound resulting upon tapping. Automation of the tapping operation and magnification of the resulting audible sound have somewhat increased the utility of this test. However, even a highly skilled operator has difficulty recognizing voids less than about one inch in diameter. Also, this method fails to measure bond quality and serves only to locate unbonded (void) areas. Consequently, many manufacturers employ this test only as a rough quality control test to map out areas requiring further test.

Ultrasonic techniques were probably first employed for adhesive-bonded joints by Dietz and co-workers at Massachusetts Institute of Technology about 10 years ago to nondestructively measure elastic modulus changes in adhesive bonds due to various deteriorating influences, especially heat exposure.[13]

More recent work has resulted in ultrasonic bond testers such as the Stubmeter,[14] Coinda-Scope, and Fokker Bond Tester. At present such ultrasonic nondestructive test methods can serve to locate unbonded areas; however, as yet, more work is needed to permit their use for quantitative determination of bond strength of production assemblies. Such studies are being sponsored by the

Navy, Bureau of Naval Weapons, and by the advisory group for Aeronautical Research and Development (AGARD) of the North Atlantic Treaty Organization (NATO).[15] The potential of adhesives, of course, will be substantially augmented with the availability of suitable nondestructive methods for quantitative measurement of adhesive bond quality in production assemblies.

Information

As more experience is gained in the design and application of adhesive-bonded structures, we tend to improve our understanding and refine our designs. We are developing a better understanding of stresses in bonded joints of various configurations, and consequently we are able to select adhesive systems and design configurations with a much higher degree of assurance.

Information is being gathered and reported regarding properties of adhesives, methods of bonding, properties of bonded structures, test methods, applications, etc.[16] With the availability of such information, adhesive-bonded structures can be more easily designed and fabricated, and with a higher degree of confidence.

Scientific Approach

Too often we are prone to resort to empirical or trial-and-error approaches to development of bonded structures; often expediency dictates such approaches.

As structural requirements become more severe, and smaller safety factors need to be tolerated, more sophisticated design and development solutions become increasingly desirable. This has already resulted in a better understanding of stresses in various bonded joint configurations subjected to typical load conditions. Complex analytical studies can be implemented with the aid of computers augmented by mechanical testing and photoelastic stress techniques. Further understanding and application of such methods can be expected to substantially increase the utilization of bonded structures.

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Synopsis

Rapid technological advancements have contributed to the increasing application of adhesives. Because of these accomplishments, because of continuing materials research and process development activities, and because of their inherent advantages, adhesives have a great potential for the future. Requirements for the future impose a severe challenge on developmental capabilities. More severe structural requirements and environmental conditions may be expected. Because of increasing complexity and costs, there are requirements for significantly higher orders of reliability and lower fabrication costs. Improvements in bonding processes and development of comparatively new techniques are desirable. Test methods require further development and standardization—especially nondestructive methods. Continuing work in collecting and reporting pertinent information, especially on properties and design parameters for adhesive bonding is helping to advance the

utilization of adhesives. Current trends indicate that adhesives are progressing from the realm of "art" to science, a factor which should substantially aid in advancing the future potential for adhesives.

Résumé

Des progrès technologiques rapides ont contribué à l'augmentation des applications des adhésifs. A la suite de ces faits, à cause des recherches continuelles de matériaux et de la poursuite des activités de développement, et pour leur advantages inhérents, les adhésifs ont une grande importance future. Les exigences de l'avenir impose une compétition sévère de nos capacités de développement. Des exigences de structure et des conditions d'utilisations plus sévères sont à prévoir. A la suite d'une complexité croissante et de l'augmentation des prix, on exige une reproductibilité beaucoup meilleure de même qu'un coût inférieur de fabrication. Des améliorations dans les procédés de liaison et le développement de techniques nouvelles comparatives sont indispensables. Les méthodes d'essai exigent des développements nouveaux et une standardisation, principalement par des méthodes non-destructives. La poursuite du travail de collationnement et la diffusion d'informations exactes, principalement sur les propriétés et les paramètres caractéristiques des adhésifs est une aide précieuse pour promouvoir leur utilisation. Le progrès actuel indique que les adhésifs sont progressivement passés du stage de l'"art" à celui de la science, facteur qui pourrait considérablement aider l'avancement du potentiel futur des adhésifs.

Zusammenfassung

Rasche technologische Fortschritte haben zu einem Anwachsen der Anwendung von Klebstoffen beigetragen. Wegen dieser Entwicklungen, wegen der fortgesetzten Bemühungen zur Erforschung der Stoffe und Entwicklung von Verfahren und wegen ihrer specifischen Vorteile besitzen Klebstoffe grosse Zukunftsaussichten. Die Erfordernisse dieser zukünftigen Entwicklung geben unseren Entwicklungsfähigkeiten eine starke Anregung. Strengere Strukturerfordernisse und Milieubedingungen sind zu erwarten. Wegen der zunehmenden Kompliziertheit und Kosten besteht ein Bedürfnis für merklich höhere Zuverlässigkeitsgrenzen und niedrigere Erzeugungskosten. Verbesserungen der Bindungsprozesse und Entwicklung vergleichsweise neuartiger Verfahren sind wünschenswert. Testmethoden erfordern eine weitere Vervollkommnung und Standardisierung—besonders zerstörungsfreie Methoden. Weitere Arbeiten zur Sammlung und Veröffentlichung wichtiger Angaben, besonders über Eigenschafts- und Konstruktionsparameter für Klebeverbindungen können zu Fortschritten bei der Verwendung von Klebstoffen führen. Die gegenwärtige Lage ist durch das Fortschreiten der Klebstoffe vom Bereich der "Kunst" zur Wissenschaft gekennzeichnet und dieser Umstand sollte bei der Vorantreibung der zukünftigen Anwendungsmöglichkeiten der Klebstoffe von wesentlicher Bedeutung sein.