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RAPID ADHESIVE BONDING AND FIELD REPAIR OF AEROSPACE MATERIALS

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ABSTRACT

Adhesive bonding in the aerospace industry typically utilizes autoclaves or presses which have considerable thermal mass. As a consequence, the rates of heatup and cooldown of the bonded parts are limited and the total time and cost of the bonding process are often relatively high. Many of the adhesives themselves do not inherently require long processing times. Bonding could be performed rapidly if the heat was concentrated in the bond lines or at least in the adherends.

Rapid Adhesive Bonding concepts have been developed at the NASA Langley Research Center to utilize induction heating techniques to provide heat directly to the bond line and/or adherends without heating the entire structure, supports, and fixtures of a bonding assembly. Bonding times for specimens can be cut by a factor of 10 to 100 compared to standard press or autoclave bonding. This paper reviews the development of Rapid Adhesive Bonding for lap shear specimens (per ASTM D1002 and D3163), for aerospace panel or component bonding, and for field repair needs of metallic and advanced fiber reinforced polymeric-matrix composite structures. Equipment and procedures are described for bonding and repairing thin sheets, simple geometries, and honeycomb core panels. Test results are presented for a variety of adhesives and adherends. Lap shear strengths greater than 4000 psi for titanium adherends and greater than 3000 psi for graphite/epoxy composite adherends are routinely achieved.

The promise of advanced composite and bonded metallic structures for improvements in structural efficiency and cost is limited by current processing and repair technology. Rapid Adhesive Bonding concepts can advance that technology significantly.

INTRODUCTION

RAPID ADHESIVE BONDING CONCEPTS DEVELOPMENT AT LANGLEY RESEARCH CENTER

TECHNOLOGY NEED

RAPID, ENERGY EFFICIENT, RELIABLE ADHESIVE BONDING TECHNIQUES FOR HIGH PERFORMANCE AEROSPACE COMPOSITES AND METALS

RAB OBJECTIVES

- DEVELOP IN-HOUSE CAPABILITY FOR BONDING OF ADHESIVE SPECIMENS
- DEVELOP RAPID PRODUCTION BONDING CONCEPTS AND PROTOTYPES
- DEVELOP FIELD REPAIR BONDING CONCEPTS

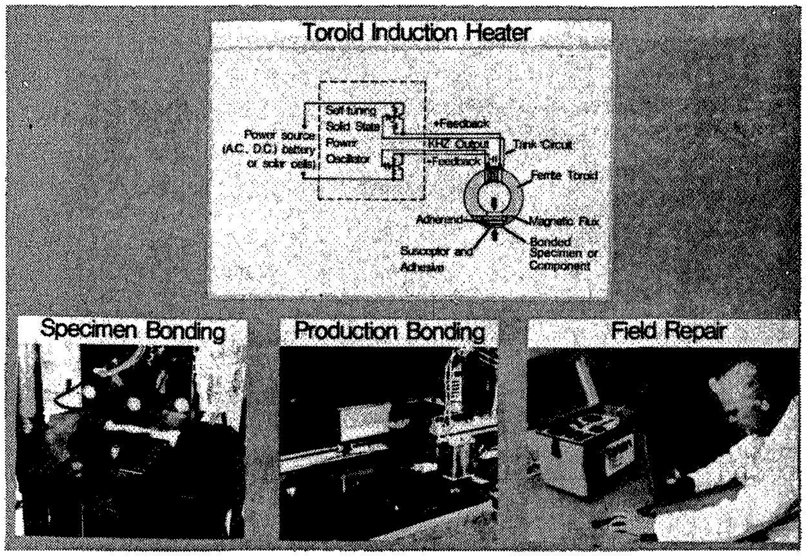
APPROACH

COMBINE LaRC AND INDUSTRIAL THERMOSET AND THERMOPLASTIC ADHESIVE TECHNOLOGY WITH INDUCTION HEATED JOINING DEVELOPMENTS

Adhesive bonding of metallic and fiber reinforced plastic composite structural components and specimens using thermosetting phenolic or epoxy adhesives is a widely used technology in the aerospace industry and thermosetting materials are receiving increasing attention. Adhesive bonding is particularly important for joining composite materials because load transfer paths through mechanical fasteners (such as rivets or bolts) can cause local overloads and damage in the relatively brittle composites. Most adhesive bonding is performed in heated platen presses or autoclaves which have considerable thermal mass, limiting the heating and cooling rates of the work considerably. Thermoplastic adhesives and some thermosetting adhesives do not inherently require long processing times. A few minutes to achieve a viscosity low enough to obtain flow and wetting of the adherend surfaces (plus a short time for cure for the thermosets) are sufficient. Some research and development of adhesive bonding processes using induction heating have been reported in the literature (ref. 1). These can produce rapid bonds, but their typical frequencies of operation (in the MHz range) can limit depth of penetration and cause internal sparking in graphite fiber reinforced composites.

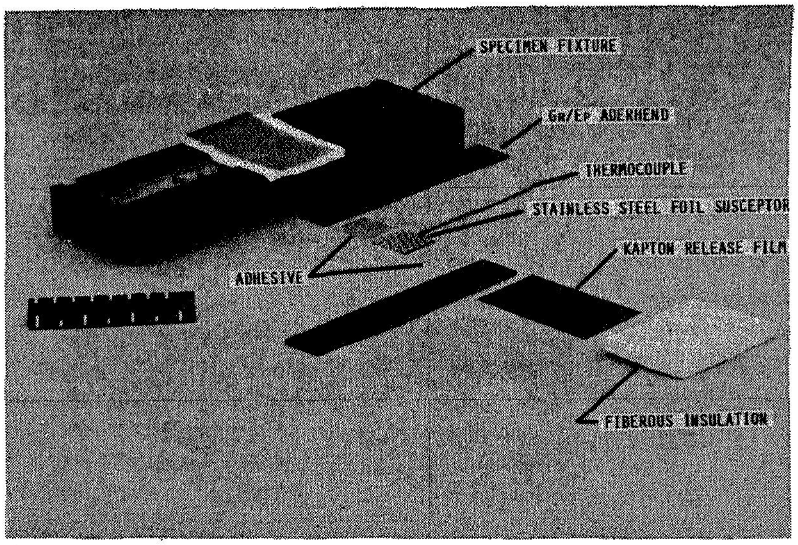
Recognizing the economic savings possible if adhesive bonding processes for typical aerospace components could be accomplished in minutes, concepts have been developed at the Langley Research Center (LaRC) to bond a variety of materials and geometries, using advanced induction heating technology at KHz frequencies. These concepts are designated as Rapid Adhesive Bonding (RAB) concepts for specimens, components, and field repair. The technology utilizes a combination of aerospace adhesives developed at LaRC and by the U. S. aerospace industry with induction heating developments from LaRC which produced lightweight, compact, energy efficient prototype equipment. Details of the background, and criteria for these concepts, equipment and bonding procedures, and of the test data which prove the efficacy of RAB are presented in ref. 1.

RAPID ADHESIVE BONDING EQUIPMENT



The rapid adhesive bonding equipment is based on a self-tuning solid-state power oscillator, which may be powered from a variety of sources, feeding kilohertz power to a ferrite toroid. The toroid geometry induces a uniform, concentrated magnetic flux into the specimen or component to be bonded, causing eddy currents to flow in a ferromagnetic susceptor and/or paramagnetic adherends. These currents heat only the bond line or its vicinity. Feedback circuits provide a degree of self tuning in the oscillator/toroid/specimen circuit, which usually operates at 30 to 80 kHz. The power required to heat a 1-in^2 bond area to temperatures above 800°F within approximately 1 minute is <300 watts. Maintaining the bond line temperature at 350 to 800°F typically requires less then 200 watts. Since no large fixtures are being heated, the cooling rate of the work is rapid, typically less than 2 minutes from the bonding temperature to below the glass transition temperature of the adhesive, at which time the bonded specimen/component may be removed from the RAB equipment. The specific prototype equipment for specimen bonding, production, and field repair, shown in the above photographs, is detailed subsequently.

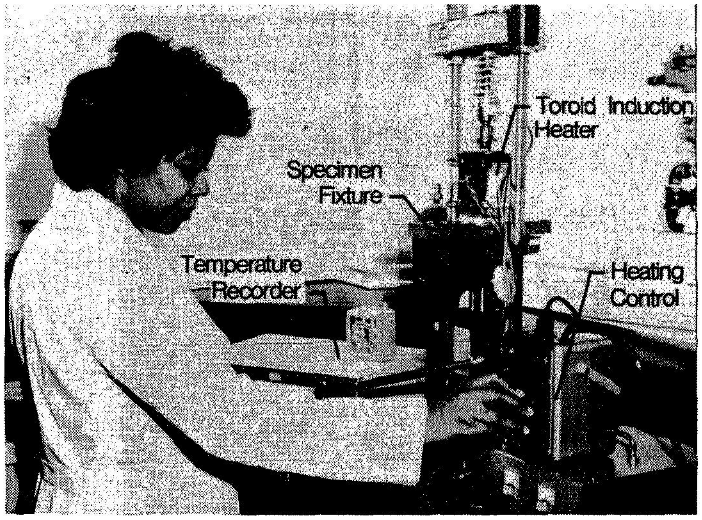
COMPONENTS OF RAPID ADHESIVE BONDED OVERLAP SHEAR SPECIMEN (ASTM D1002)



The components of an overlap shear specimen which conforms to ASTM D1002 or D3163 are shown above. In this example the adherends are high-strength fiber-reinforced polymeric composites, but similar adherends of aluminum alloy and titanium alloy have also been bonded, with excellent results (described subsequently). A perforated stainless-steel foil susceptor sandwiched between layers of adhesive is the other component of the specimen. (Flattened steel screen susceptors also work well.) Adherend surface treatments generally consist of a solvent wipe, a grit blast, and another solvent wipe for both composite and metal specimens. If long-term high-temperature exposures are to be conducted, an oxide treatment should be applied to the titanium alloy adherends.

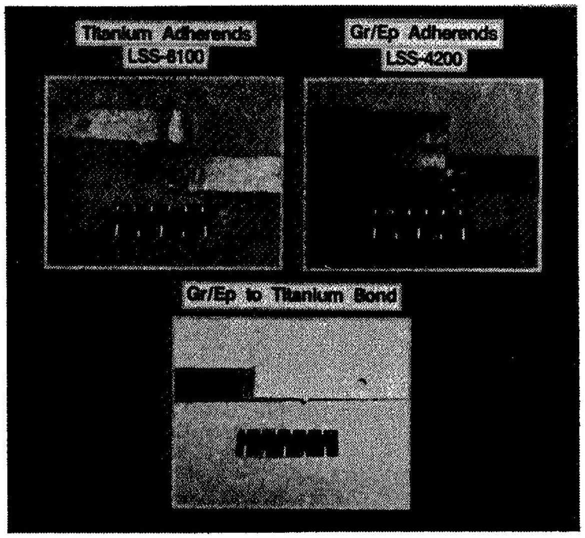
A special fixture was devised to align the specimen components prior to bonding. The fixture is shown above. It may be fabricated from any nonconducting material. In this case the base was machined from Bakelite, with cutouts for the adherends. In the bonding region the cutout is deeper and fibrous ceramic insulation topped by a Kapton® film was used under the specimen. Another layer of Kapton®, topped by fibrous insulation, is placed atop the specimen to prevent heat conduction losses and to avoid bonding of specimen flashing to the toroid head. This fixture and the materials used in it functioned well for bonding temperatures to at least 850°F, since the heat is concentrated in the specimen bond lines, and the bonding times are relatively short.

RAB SPECIMEN BONDING EQUIPMENT



The RAB overlap shear specimen bonding equipment is shown. Much of the equipment is identical to that used for conventional bonding, including a load cell, the temperature recorder, and the laboratory press. In the laboratory press, the conventional heated platens have been replaced by a toroid induction heater. Bonding is accomplished by assembling the specimen in the specimen fixture, placing the fixture in the press under the toroid head, applying hydraulic pressure, and applying the induction field with the heating control. A thermocouple attached to the susceptor where it protrudes from the bond overlap is used to monitor bond temperature. Typical bonds are made at pressures from 10 to 200 psi, with heating rates from 100 to 1200°F/min., short holds at bonding temperature, and rapid cooling to temperatures below the adhesive Tg. The entire process is typically completed in less than 5 minutes. Both the temperature and pressure histories on the specimen could be readily automated, but they are easily controllable manually.

TYPICAL RAB OVERLAP SHEAR TEST SPECIMENS



The appearance of typical overlap shear test specimens is shown. All specimens were bonded with commercially available thermosetting adhesives, using moderate pressures, and heating rates above 500°F to the bonding temperature. Bonding temperatures were about 100°F above those suggested for autoclave or press bonding. Hold time at bonding temperature was 2 minutes. Cooling times were about 2 minutes to temperatures below the Tg of the adhesive, at which time the specimen was removed for testing.

The RT overlap shear strength of the titanium specimen at the upper left was 6100 psi; the failure mode was cohesive failure of the thermoset adhesive. The RT overlap shear strength of the Gr/Ep specimen at the upper right was 4200 psi; the failure mode was adherend delamination. The versatility of RAB is shown for the lower specimen, where a Gr/Ep adherend is bonded to a titanium alloy adherend. Strengths on the order of 3000 psi were generated for such specimens.

MATERIAL APPLICATIONS FOR RAPID ADHESIVE BONDING
THERMOPLASTIC ADHESIVES

ADHERENDS	ADHESIVES	BONDING TEMPERATURE, TIME, PRESSURE; °F, MIN, PSI	R. T. OVERLAP SHEAR STRENGTH, PSI
Ti/Ti Gr/PI//Gr/PI	P1700 (POLYSULFONE)	800, 2, 80 800, 2, 80	4600 3900
Ti/Ti	$PISO_2$ (POLYIMIDESULFONE)	650, 2, 50	4400
Ti/Ti	TPI (THERMOPLASTIC POLYIMIDE)	650, 2, 300	6500
Ti/Ti	PEEK (POLYETHERETHERKETONE)	750, 2, 50	6100
Ti/Ti	PPQ (POLYPHENYLQUINOXALINE)	800, 2, 100	3600
Gr/ULTEM//Gr/ULTEM	ULTEM (POLYETHERIMIDE)	625, 2, 5	5000
Ti/Ti	LARC-TPI (ENDCAPPED WITH SILANE)*	450, 3, 100	3500
Ti/Ti	LINEAR PI WITH SILOXANE*	450, 3, 100	4400
Ti/Ti	HOT MELT POLYIMIDE (ACETYLENE TERMINATED)*	450, 3, 100	4000

*EXPERIMENTAL

The versatility of Rapid Adhesive Bonding has been demonstrated for a number of adherend combinations with both thermoplastic and thermosetting adherends. All thermoplastic adhesives investigated to date have responded to RAB with moderate to high lap shear strengths after short bonding cycles. The data shown are for a number of commercially available and experimental high-performance aerospace adhesives, utilized in film form or on fiberglass cloth carriers with a steel screen or perforated stainless-steel foil susceptor in bond line. In obtaining this adhesive screening data, the surface treatments on the adherends usually consisted of a methyl alcohol solvent wipe, a grit blast, and another solvent wipe. It is recognized that more extensive surface treatments and possibly surface priming should be used for optimum bond strength and environmental resistance, but the lap shear strength values shown above indicate high bond strength potential. Continuing bonding studies indicate that lower bond pressures could be used than those listed above to make equally strong bonds.

MATERIAL APPLICATIONS FOR RAPID ADHESIVE BONDING
THERMOSETTING ADHESIVES

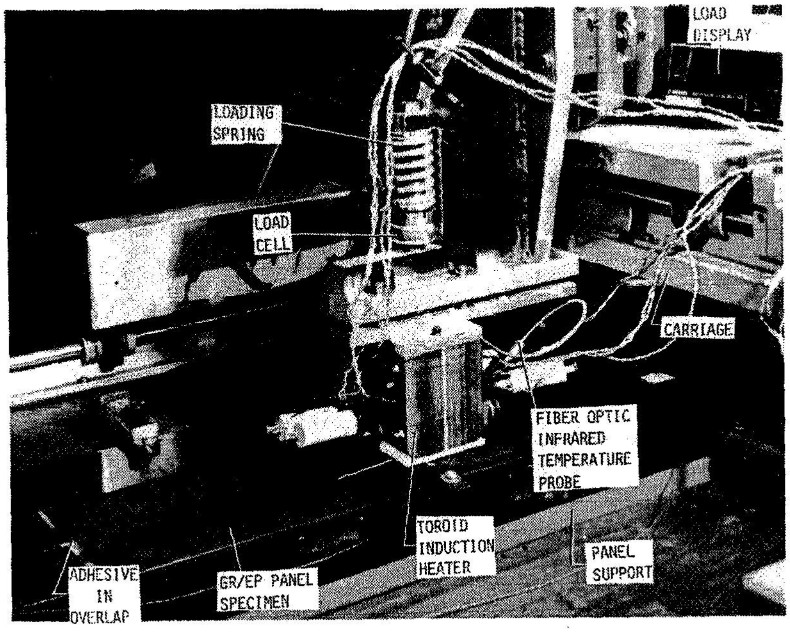
ADHERENDS	ADHESIVES	BONDING TEMPERATURE, TIME, PRESSURE; °F, MIN, PSI	R. T. OVERLAP SHEAR STRENGTH, PSI
Ti/Ti	HT-424	450, 2, 40	4000
Ti/Al	(EPOXY-PHENOLIC ON	400, 5, 80	3300
Gr/Ep//Gr/Ep	GLASS CLOTH CARRIER)	450, 2, 10	3500
Ti/Ti	EC-1386	415, 3, 10	6200
Gr/Ep//Gr/Ep	(EPOXY PASTE)	415, 3, 10	3200
Ti/Ti	AF-163	350, 2, 10	5600
Gr/Ep//Gr/Ep	(ELASTOMER MOD.EPOXY FILM)	350, 2, 10	4000
Ti/Ti	BISMALEIMIDE*	450, 3, 100	2100
Ti/Ti	GENERAL PURPOSE EPOXY	450, 3, 50	5000

*EXPERIMENTAL

A number of thermosetting adhesives have been found to make acceptable bonds between titanium and composite adherends via RAB. These bonds are achieved by heating rapidly to cure temperature and curing for short times at temperatures considerably higher than those suggested by the adhesive supplier for autoclave or press cure. (It must be noted that some thermosetting adhesives will not respond to RAB. Each potential adhesive/adherend combination must be screened.)

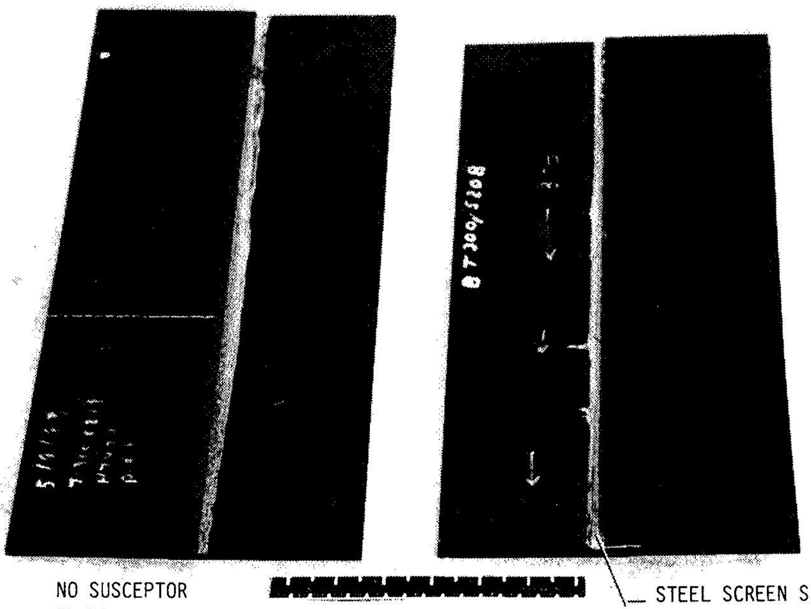
The above table lists the thermosetting adhesives and adherends which have responded to RAB to produce moderate-to-high-strength bonds. Bonding conditions of temperature, hold-time, and pressure are given, along with typical room temperature overlap shear strengths. The high strengths for the titanium specimens usually have accompanying cohesive failure modes. Failure modes in the composite specimens are typically adherend delamination.

RAPID ADHESIVE PRODUCTION BONDING EQUIPMENT
-BOND IN PROGRESS-



RAB equipment for continuous seam bonding of overlap panel assemblies is shown in operation. Two toroid induction heaters are mounted with a load cell on a support structure, which in turn is mounted to a transverse alignment slide. That slide is located on a longitudinal traversing carriage which travels along a standard machine bed. In this photograph, the toroids are moving at 0.5 inch per minute above the overlap between two graphite/epoxy panels and applying a bonding pressure of 20 psi while they are melting and curing the HT-424 epoxy-phenolic adhesive at 450°F as they pass. Two layers of adhesive with a flattened steel screen susceptor between them are in the bond line.

RAPID ADHESIVE PRODUCTION BONDING
T300/5208 GRAPHITE/EPOXY PANELS
HT 424 EPOXY-PHENOLIC ADHESIVE

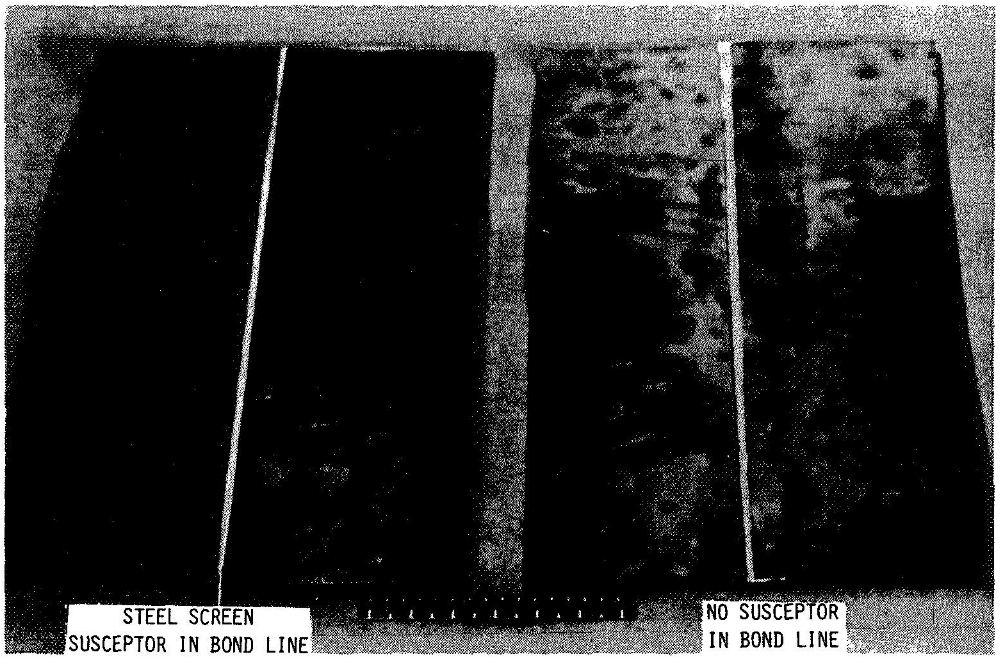


NO SUSCEPTOR
IN BOND LINE

STEEL SCREEN SUSCEPTOR
IN BOND LINE

Graphite/epoxy panels bonded with the HT 424 adhesive are shown. They were made with and without susceptors in the bond line. An important finding in this application of RAB is that graphite/epoxy laminates can be heated directly in the induction field of the toroid heaters. Some lap shear specimens, cut from a graphite/epoxy panel bonded with HT-424 epoxy-phenolic adhesive and with the steel screen susceptor, were tested at room temperature and at 180°F (in accordance with ASTM D1002 or D3163). Other samples were tested at RT and 180°F after 1000 thermal cycles from -100 to +180°F, and at RT and 180°F after a 72-hour boiling water exposure. The RAB process had no degrading effect on shear strength of Gr/Ep//HT-424//Gr/Ep bonds, compared to standard bonding, and thermal cycling did not significantly degrade these properties. The water boil exposure degraded bond strengths about 35 percent at room temperature and 28 percent at 180°F. This degradation is approximately the same as that noted for the HT-424 adhesive in the adhesive supplier's literature.

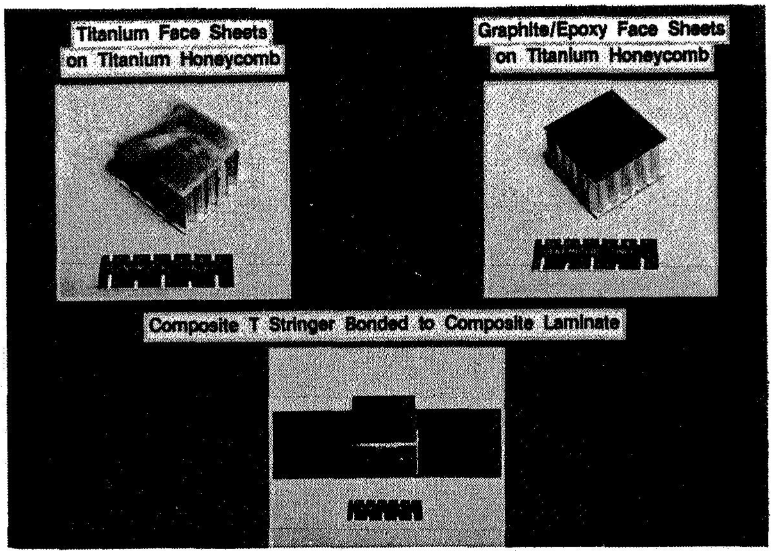
RAPID ADHESIVE PRODUCTION BONDING
Ti-6Al-4V TITANIUM ALLOY PANELS
LARC-TPI ADHESIVE



Titanium panels bonded with LaRC-TPI thermoplastic polyimide adhesive are shown. These panels were made by placing one sheet of titanium on the panel support atop several layers of fibrous insulation. The panels had previously been cleaned by simple degreasing and grit blasting. The titanium sheet was not primed before bonding. A 3/4-inch wide strip of adhesive tape the length of the panel was laid on this sheet with 1/8-inch protruding along the edge. If a susceptor was used, it was placed over the adhesive and another strip of adhesive tape placed on it. The other sheet of titanium was then laid on this assembly to produce a 1/2-inch overlap, the length of the sheets. As this photograph and the previous figure indicate, distortion in these panels was not excessive, considering that unstiffened sheets were bonded. The distortion was on the same order as that seen in similar panels bonded in a press or autoclave.

ORIGINAL PAGE IS
OF POOR QUALITY

TYPICAL AEROSPACE SPECIMEN GEOMETRIES FABRICATED BY RAB



Panels or structures of many geometries can be bonded by the RAB process. Examples, shown above, are stiffeners or stringers on panels, honeycomb core panels, repair patches, etc. Simple fixtures would have to be designed to hold the specific geometries in place. The only significant geometric limitation with the current prototype equipment would be that one of the adherends must be 1/4 inch or less in thickness and the toroids must traverse and apply pressure to the outer surface of that adherend. The use of steel screen or stainless-steel foil susceptors in the bond lines of polymeric composite face sheet honeycomb core panels or stiffened panels may provide an additional advantage for aerospace applications - lightning strike protection. In a very complex structure, where autoclaving or press bonding with shaped platens is advantageous, RAB may still have an important role. RAB can be used in a "spot bonding" mode to hold parts in place before they are inserted into the autoclave or press, thus alleviating the need for a good deal of expensive fixturing.

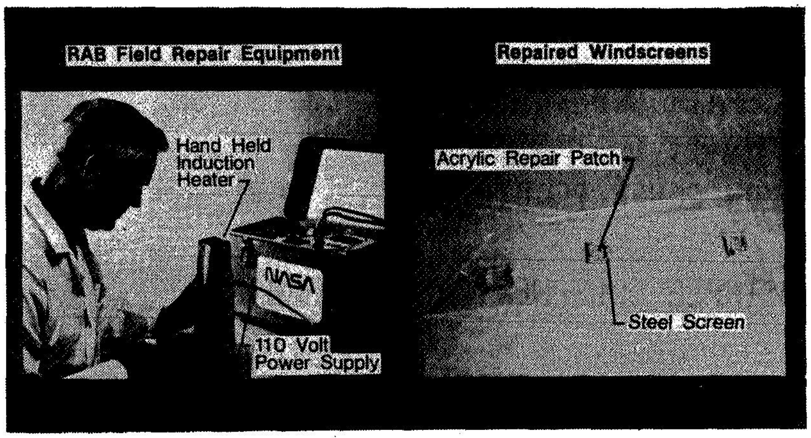
FIELD REPAIR REQUIREMENTS

- **FAST REPAIR THAT IS STRUCTURALLY SOUND**
- **REPAIR UNDER ALL FIELD CONDITIONS**
- **LOW POWER REQUIREMENTS**
- **SIMPLE EQUIPMENT REQUIREMENTS**
- **EASY EXECUTION OF REPAIR**
- **LOW COST**

Field repair is the most challenging area of aircraft maintenance. The requirements for repair integrity and quality are difficult to meet because of the constraints of field operations. Bolted or riveted metallic panels are currently the most commonly used methods for structural field repairs in the aerospace industry. Such repairs utilize simple, readily available equipment and are usually easy to accomplish. However bolted or riveted repairs usually encompass areas much larger than the original damage, are heavy, and may have long-term durability problems. Adhesive bond repairs would be desirable but the problems of bulky, heavy equipment with high power requirements limit the applicability of current adhesive bonding techniques.

Field repairs must be executed in the shortest possible time with simple, lightweight equipment and low-power requirements. The repairs must be possible under severe weather conditions in primitive shelters. Repair materials must remain stable and handleable at temperatures from below 32°F to 120°F.

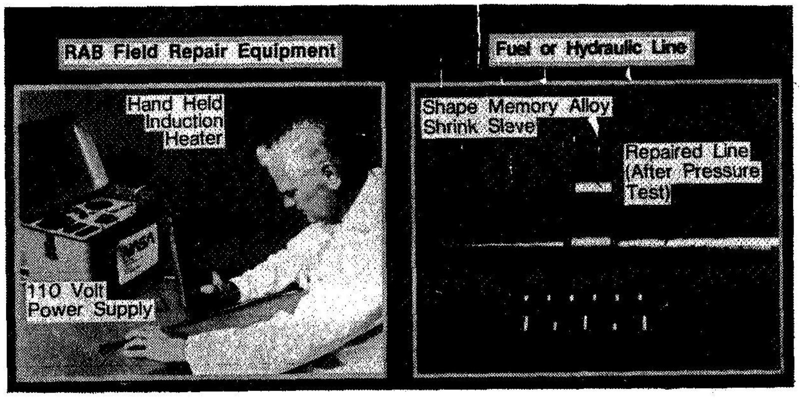
RAB FIELD REPAIR OF HELICOPTER WINDSCREEN



The Rapid Adhesive Bonding concepts described previously have been further developed to meet typical field repair requirements. The induction-heating power supply has been engineered into a "ruggedized" solid-state electronics unit, in a one-cubic-foot package weighing 20 pounds. A hand-held bonding gun weighing 3 pounds plugs into this power supply on a long power cord. The maximum power required for the single-toroid head is 300 watts. Adhesive bonds are attained rapidly by directly heating the susceptor and the adhesive in the bond line with minimal heating of the structure surrounding the bond line. Lightly loaded repair bonds can be made in several minutes at an average power input of 150 watts on metallic, polymeric, or polymeric-matrix composite secondary structures.

The repair of a helicopter windscreen in the field is currently achieved by "stop-drilling" the cracks emanating from the damage region. An acrylic or polycarbonate patch is drilled with matching holes and "laced" to the damaged windscreen with safety wire. This patch does not seal out the environment during operations. The above photograph illustrates the potential for RAB field repair of such a windscreen. Several "damage holes" were made in a polycarbonate windscreen with a .45 caliber service pistol to simulate battlefield damage. The polycarbonate patch and a ring of steel susceptor screen were cut from stock and laid over the holes. The hand-held induction head applied the required pressure while heating the screen to the melt temperature of the polycarbonate. The head was moved around the circumference of the patch to complete the bond in less than 10 minutes per hole. The patches formed doubler plates over the cracks emanating from the bullet holes to restrain crack propagation. The bonded patches should be effective in sealing the helicopter interior from rain and dust during operations. The RAB field repair technique provides a faster, simpler, stronger repair than the conventional field repair technique.

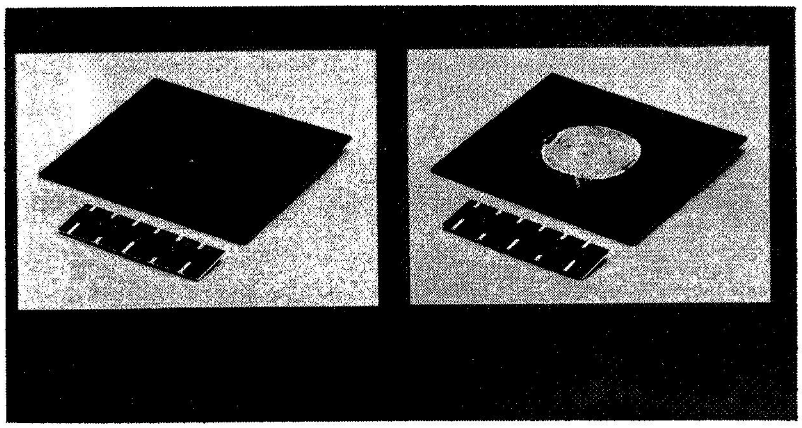
RAB REPAIR OF FUEL OR HYDRAULIC LINES



Another potential application for RAB is field repair of hydraulic fluid and fuel lines. Current fluid line repair procedures often utilize shrink sleeves (fabricated from "shape memory" alloys and an adhesive). An open flame from a torch is often used to heat the sleeves to the temperature at which they shrink (415°F) and bond to the line, effecting the repair. In the confined spaces of an airframe, fuel or hydraulic line vapors from the damaged line are often present; any open flame procedure can be hazardous. Furthermore, the uneven heating of a torching procedure can overheat the fittings. Oxidation, adhesive damage, uneven shrinkage, and warpage of the fluid line can result.

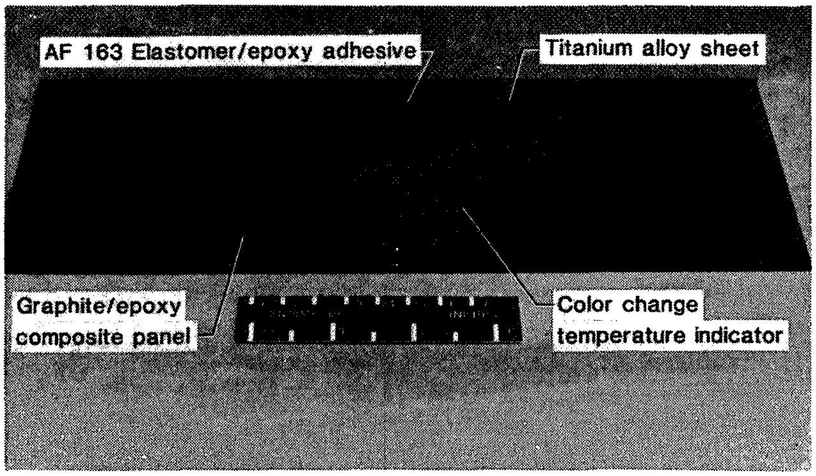
The RAB process was investigated as a simple method to heat the sleeves more uniformly and far more safely than a torch process. The results of these investigations are very promising. The RAB process heated the fittings uniformly and rapidly with minimal effect on surrounding areas. The hydraulic line repaired by RAB was tested to more than twice its rated operating pressure with no leakage. Repair of fluid lines in aerospace structures appears to be a very promising application for RAB.

RAB REPAIR OF GRAPHITE/EPOXY COMPOSITE LAMINATE



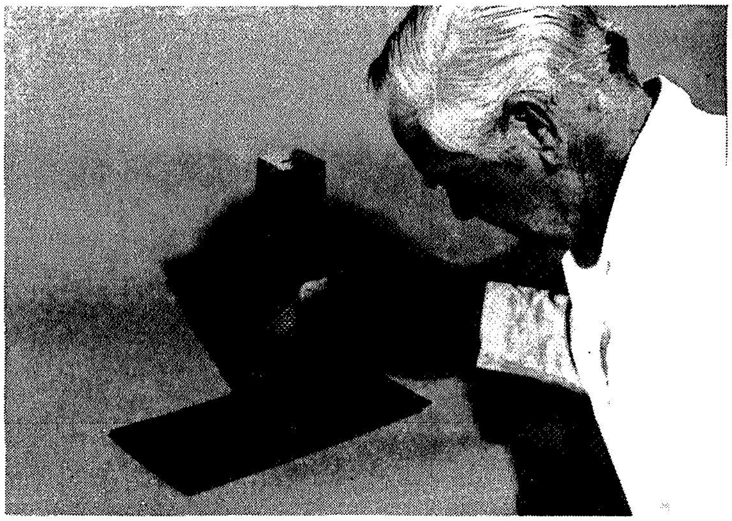
A common aircraft supportability requirement is the repair of small surface defects such as dents and gouges caused by impacts from runway debris, minor bumps, inadvertent occurrences during repair, etc. These are not structural concerns, but must be repaired to maintain surface integrity and, in many cases, aerodynamic smoothness. Rapid Adhesive Bonding techniques can be used to repair such minor defects. A patch of metallic or composite material, susceptor, and adhesive can be readily prepared with simple hand tools to fit the required repair geometry. A short bonding cycle using the hand-held unit shown previously is all that is required to wet the surfaces and cure the adhesive into a bond with adequate strength. The repaired surface can then be smoothed, if necessary, with conventional tools for this purpose. Such a patch on a graphite/epoxy composite panel surface is shown above.

RAB REPAIR MATERIALS



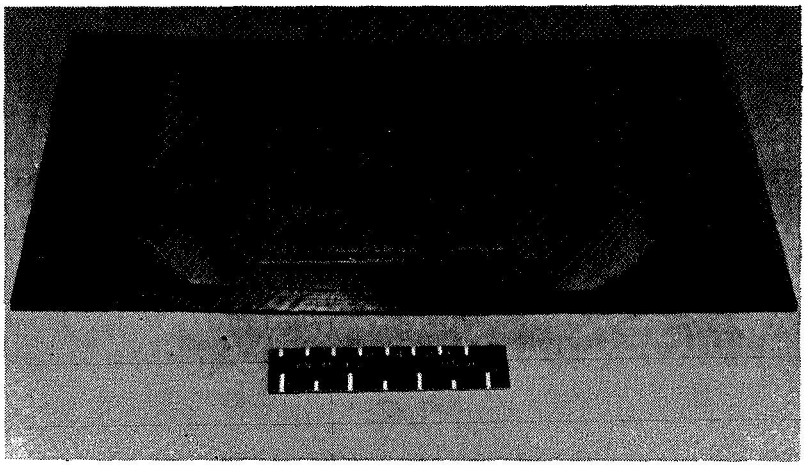
A preliminary feasibility study has begun on a structural RAB repair concept for a graphite/epoxy composite panel. The patch is composed of several laminated titanium alloy sheets, bonded sequentially using AF 163 elastomer modified epoxy adhesive. Color change indicators are used on each of the patch laminations to indicate that the bonding process has achieved the required adhesive cure temperature.

RAPID ADHESIVE BONDING REPAIR OF Gr/Ep COMPOSITE PANEL USING LAMINATED TITANIUM SHEET



The hand-held RAB unit is again utilized in performing this laminated titanium sheet repair. Hand-induced bonding pressure is applied by the technician as he moves the bonding head in a path which traverses the entire patch. If a spot has not reached bonding temperature (as indicated by a lack of color change in the temperature indicating markings), he can return to that spot and reheat the adhesive.

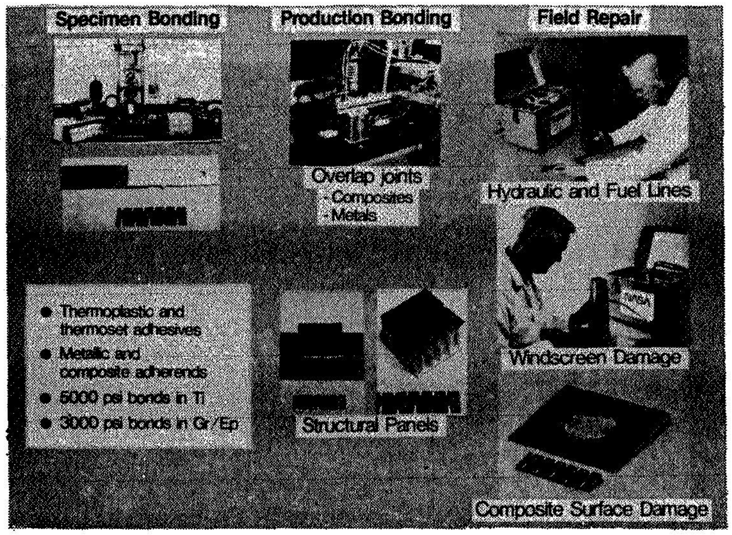
RAB LAMINATED TITANIUM REPAIR OF GRAPHITE/EPOXY PANEL



The initial feasibility specimen of a RAB laminated titanium alloy repair of a graphite fiber reinforced epoxy panel is shown. Process feasibility was demonstrated. Process enhancement studies are in progress. Structural tests on such panels have not yet been performed.

CONCLUDING REMARKS

RAPID ADHESIVE BONDING
High-Strength Bonds in Minutes



In conclusion, Rapid Adhesive Bonding (RAB) concepts and prototype equipment have been developed at Langley Research Center for specimen bonding, production bonding (including depot repair), and field repair. RAB utilizes induction heating methodology to provide heat directly to the bond line and/or adherend without heating the entire structure, supports, and fixtures of a bonding assembly. Bonding times for standard ASTM overlap shear specimens can be cut by a factor of 10 to 100 compared to standard press or autoclave bonding. High lap shear strengths can be generated with a range of adherend materials (including metals and polymer matrix composites) and adhesives (both thermoplastic and thermosetting). Short-term thermal cycling and water boil exposures have shown encouraging environmental stability for these rapid bonds, including those which contain steel screen or stainless-steel foil susceptors in the bond lines. The RAB concepts were extended to continuous seam bonding of metallic and composite panels with promising results for bonding of both like and unlike adherends. Rapid bonding of other geometries such as face sheets of fiber-reinforced polymeric-matrix composites or titanium alloy to titanium honeycomb core were proven feasible.

The inherent portability of RAB equipment suggested that field repair procedures for adhesive bonding of damaged metallic, polymeric, or composite structures are possible. Initial development of these procedures showed that patches of titanium alloy and graphite/epoxy composite materials could be bonded in the field to typical aircraft panels. Furthermore, variations of the RAB process can be used to repair polycarbonate or acrylic windscreen materials and hydraulic tubing. The promise of advanced composite and bonded metallic structures for improvements in structural efficiency and cost is limited by current processing and repair technology. Rapid Adhesive Bonding concepts show promise for significant technology advances.

REFERENCE

1. B. A. Stein, J. R. Tyeryar, and W. T. Hodges: Rapid Adhesive Bonding Concepts. NASA TM-86256, June 1984.