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RAPID INDUCTION BONDING OF COMPOSITES, PLASTICS, AND METALS

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ABSTRACT

The Toroid Bonding Gun is an induction heating device. It is a self contained, portable, low powered (0.1-2 kilowatt) induction welding system developed at Langley Research Center for bonding or joining plastic, ceramic, or metallic parts. Structures can be bonded in a factory or in the field. Bonding times for laboratory specimens have been cut by a factor of 10 to 100 times compared to standard press or autoclave bonding. This type of equipment allows for applying heat directly to the bond lines and/or the adhesives without heating the entire structure, supports, and fixtures of a bonding assembly. The induction heating gun originally developed for use in the fabrication of space structures has been expanded. Gangs of bonders are now used to rapidly join composite sheet and structural components. Depending on the type of bonding equipment, composite structures can be joined in a factory or in the field. Other NASA-developed applications of this bonding technique include the joining of thermoplastic composites, thermosetting composites, metals, and combinations of these materials. Inductron Corporation has been granted an exclusive license to practice the technology. Inductron has developed techniques and tools for annealing and brazing metals, manufacturing thermocouples, shrinking Cryo-fit (TM) hydraulic couplings, and flexible induction heads for complex structure repair/ manufacture. Inductron will have a booth to display commercially developed hardware at Tech 2000.

INTRODUCTION

In the fabrication of large space structures (Figure 1), a portable induction heater requiring minimal or no external cooling is desired when sealing seams and joining components. This portable heater used little power and is controlled by miniaturized components. The toroid joining gun is a self-contained, portable low powered (.1-2 Kilowatts) welding system developed at Langley Research Center for joining plastics, metal, and ceramic parts using induction heating techniques (Figure 2). The device developed for use in the fabrication of large space structures (Figure 3) can be used in any atmosphere or in a vacuum. Components can be joined in situ, whether on earth or on a space platform. The expanded application of this welding gun is in the joining of thermoplastic composites, thermosetting composites, plastics, metals, and combinations of these materials, annealing and brazing of metals, making of thermocouples, and shrinking of Cryo-fit hydraulic couplings.

Induction heating is well known in industry. When a current passes through a conductive coil, a magnetic flux is produced inside and around the coil. When a mass of conducting material is moved in this magnetic field or is subjected to a changing flux, induced currents, called eddy currents, circulate in the mass. In most instances, eddy currents are, wasted energy, but in induction heating they are actual producers of heat.

The objective of this bonding system was to provide a method and apparatus for joining thermoplastic matrix composites and other compatible materials which could be used in outer space, on earth, or in motionless surroundings. The ability of a low-powered toroid gun (Figure 5) to heat metal, and a recently developed non-metal ceramic, is used to inductively join pieces of thermoplastic and thermoplastic composite. In a toroid pole piece, magnetic flux remains inside the toroid core when the system is energized. To divert the path of the magnetic flux from the toroid to an adjacent susceptor, the toroid must be altered. This alteration is accomplished by cutting a segment out of the toroid and placing the air gap in the toroid on the surface of a plastic matrix composite sandwich consisting of a susceptor positioned between the two composite components to be joined (Figure 5). When the toroid is energized, flux will flow through the toroid, through the plastic composite (which is transparent to magnetic flux) into the susceptor back through the plastic composite into the toroid. Alternating current produces inductive heating instantly in the susceptor causing the plastic interfacing on either side of the susceptor to melt and flow into perforations made in the susceptor forming the joint. Joining is accomplished in minutes.

Inductron Corporation has expanded the applications of the Toroid Bonding Gun to include brazing and heat treatment of metals, shrinking of Cryo-fit hydraulic couplings, making of thermocouples, and repair/fabrication of ceramic, metallic, and plastic components. To accomplish the expanded applications of the U.S. Government patent, Inductron has modified and improved circuit and head design, included temperature control, temperature monitoring, timers, and in some cases, included temperature recording.

BONDING AND TESTING

Shear Specimen Bonding

Overlap shear specimens were bonded in a configuration conforming to the American Society for Testing Materials (ASTM) standards D1002 and D3163. The technique similar to that used for spot welding metallic structures was used for rapid bonding of lap shear specimens made of thermoplastic composites, thermoset composites, metals, and combinations of these materials (Figure 4).

The rapid bonding equipment for laboratory shear specimens is shown in Figure 6. The press is identical to that for conventional specimen bonding, as are the load cell and temperature and load indicators. Replacing the conventional heated platens is a toroidal high frequency induction heater and its power controller. The specimen is located in a fixture for ease of alignment When power is applied, the toroid rapidly heats the susceptor, such as a metal screen, which has been impregnated with a thermoplastic adhesive or is sandwiched between thermosetting adhesive films. For lap-shear specimens, the metallic or fiber-reinforced plastic composite material adherends are placed above and below the susceptor in the sample fixture, and bonding pressure is applied. The susceptor heats the adhesive or thermoplastic composite adherend rapidly, usually within a minute, to the bonding temperature. The heat is maintained from one to several minutes to promote adherend joining. When power is turned off, the specimen rapidly cools to a temperature below which the adhesive or thermoplastic composite is sufficiently set, and pressure is removed. Some of the composite materials tested are shown in Table 1. When rapid bonding was compared directly with laboratory-press/heated-platen bonding the strengths of the toroid bonds were found to be significantly higher than those obtained by press bondiig (Table 2). This process is more controllable and more energy conserving than conventional bonding with heated platens or an autoclave (1, 2).

BONDING APPLICATIONS-NASA

In addition to the lap shear mechanical property tests obtained on adhesives, a number of applications have been found for using this technology.

Panel Bonding

An overall view of the Rapid Adhesive Bonding (RAB) equipment of overlap panel assemblies is shown in Figure 7. Six air-cooled 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. The power supply controller and load indications are on the transverse slide, while thermocouple sensor monitors of panel specimen temperature on the bed. The panels to be bonded, 2 feet long in this figure, are located in a simple insulated panel support. The power supply shown (which uses approximately 1000 watts or less at 60 Hz and 120 volts for each toroid) provides the required circuitry for a self-tuning induction-heating circuit which operates at 30,000 to 100,000 Hz. Susceptors concentrate the induction heating effect in the bond line. The most successful of these developed for this application are the flattened 1008 carbon steel screen and a perforated 410 stainless steel foil.

Temperature - Temperature monitoring in the adhesive bond line is considered to be an important requirement of this Induction Bonding Process, because heating is concentrated in the bond line in all applications in which a susceptor is used. A series of thermocouples are positioned an inch apart in the bond line of a test specimen for each of the materials to be bonded.

Bonding Procedure - The bonding procedure consists of installing the parts to be bonded in a fixture, positioning the toroid heads over a dummy "on-ramp" specimen of the same material and geometry as the work, bringing the dummy specimen (with a thermocouple in the bond line) to the bonding temperature, and initiating a traversing carriage movement at the required rate.

Graphite/epoxy panels bonded with the HT-424 adhesive are shown in Figure 8. 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 without a susceptor. 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 and D3163). Other samples were tested at RT and 180°F, after 1000 thermal cycles from -100° and 180°)F, 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 supplier's literature.

Rapid Strain Gauge Attachment

A new method has been developed for bonding film gauges (e.g., strain gauges) to high reluctance, low reluctance, and no reluctance structures.

Conventional methods for bonding film gauges to be operated at elevated temperatures are typically time consuming due to clamping and baking procedures. Because it is impractical to utilize an oven for curing purposes in the field, different procedures and equipment must be implemented.

Previous methods of mounting gauges require the use of contact adhesives and epoxies. Contact adhesives for mounting gauges are limited to low humidities during installation, low temperature during use, and 90 days of useful data measurements. Epoxies require the use of heat lamps, hair dryers, and electric heater devices to generate heat to cure the epoxies. The use of epoxy as a strain gauge adherent requires substantial time and power.

A new method of bonding strain gauges that reduces adhesive cure schedules from a matter of hours to minutes has been developed. This procedure, which incorporates the use of a toroid joining gun, is primarily applicable to elevated (up to 204°C) temperature strain gauge requirements. The toroid gun can concentrate high temperatures in localized areas through the induction heating principles. When bonding a sensor to the surface of the insulator, such as fiberglass, which has no reluctance and poor thermal conductivity, a ferric material in the form of a thin (1/8") plate is placed between the sensor and the energy source.

The ferric plate generates inductive heat which is transferred to the gauge region to activate the adhesive. The heat is obtained from the induction bonder which is placed on the gauge with approximately 5 pounds of pressure per square inch and energized for 2 minutes (Figure 10). Pressure is maintained for an additional 1 minute during cool down. For this process, a hand held gun is used, as shown in Figure 9C. Once the gauge area has cooled down, leads are attached, and testing begins.

Test data shows that strain gauges bonded to structural speciments using the toroid induction bonder produce results equal to the data obtained using standard bonding techniques (4). The advantages of using the toroid joining gun over existing methods are lower power, rapid bonding, lightweight equipment, localized heat on the strain gauge adhesive, and portability.

One-Step Joining and Electric Conduction

This process relates to electromagnetic heating and, in particular, to a fastener to be used between two thermoplastic or composite objects for induction heating and joining purposes.

Induction heating using a metal fastener is a common method of joining. The metal fastener may be a solid sheet of eddy current conducting metal placed adjacent to the materials to be joined, or an apertured or screened sheet (metallic or nonmetallic) placed between the materials. Electromagnetic induction heats the metal when one of several known induction heating methods is used; the heat generated softens and joins the nonmetallic material.

Often the step following the joining of thermoplastics is that of providing electronic circuitry thereupon. An electrical conduction system is usually separately fabricated and fastened to the joined materials. No means have been provided for inductively heating sheets and simultaneously fixing electronic circuitry into the system.

In the one-step dual joining technique (5), a screen is placed between a thermoplastics at the area to be joined and is inductively heated using the toroid joining gun. The materials to be joined soften and join at the apertures of the screen. After joining, the screen lends-structural support, and the copper wires therein may be used to conduct electricity (Figure 11a and b). Insulation allows conduction without the danger of short circuiting, and the thermoplastics, themselves insulators, ensure safe conduction. The conducting wires may lead to any electronic component, and render separate electronic circuitry unnecessary.

Typically a 26-mesh screen of carbon steel inductor wires is integrated with two or more insulated copper wires. This integrated screen is placed between two sheets of plastic. The toroid joining gun produces sufficient heat to join the sheets of plastic. After cooling, the copper wires are able to conduct electricity through the now joined sheets of plastic.

Conducting wire or bundles of wires may be used. Some inductor wires are necessary for formation of the bond; their number relative to conductor wires is chosen according to the desired heat of joining and conductivity of the joined sheets. Since the sheets bond to each other around the wires, the number of conductor wires present within the sheets does not affect the strength of the final bond.

A large fabrication of sheets and wire screen may serve as a wall panel in, for example, a house (Figure 11a and b). The copper wires lead to conventional electrical outlets or switches.

In an even larger fabrication, copper wires within sheets making up cylindrical tubes connecting components of a large space structure, could transmit data in electrical form between components.

BONDING APPLICATIONS - INDUCTRON

Rapid Field Repair with Susceptors

Inductron has developed a device (Flexible Heating Head) to meet a need for a better way of repairing aircraft windscreens, metallic and composite structures (Figure 12a, b, and c). Conventionally, windscreens and composite panels are repaired by using mechanical fasteners to clamp a patch, by fusing the patch with the damaged structure (e.g. windscreens), or by adhesive bonding of the patch. Each method has drawbacks; mechanical fasteners require hole preparation and special hardware, fusing thermoplastic composite material requires fixturing and time for curing.

The simply operated flexible induction welding gun employs magnetic flux to a susceptor generating heat to the parts to be joined. In a typical aircraft repair, the only preparation required (e.g., composite, metal,...) is cutting a susceptor and patch slightly larger than the damaged area. The susceptor is placed between the damaged component and the patch. The susceptor is impregnated with a thermoset or thermoplastic adhesive. The flexible welding gun is positioned directly above the damaged area. When the flexible head is energized, the alternating current produces inductive heating in the susceptor, the susceptor transmits the heat to the bond line, causing the adhesive to melt, flow, and cure (thermoset) forming a bond (Figure 13).

Rapid Field Repair Without Bond Line Susceptors

Inductron has developed a repair process for damaged ceramics, metals, and plastics eliminating the need of bondline susceptors (Prior Art). This is accomplished through the use of a flexible ceramic susceptor. The susceptor is placed above the damaged area, which is comprised of a patch, adhesive and damaged component. An induction welding gun (flexible head) is positioned directly above the susceptor. When the induction welding gun is energized, the alternating current produces inductive heating in the susceptor, the susceptor transmits the heat to the patch, adhesive and damaged component causing the adhesive to melt, flow, and cure (thermoset) forming a bond.

COMMERCIAL EQUIPMENT - INDUCTRON

Making of Thermocouples

Inductron Corporation has developed a rapid, reliable, inexpensive method of manufacturing thermocouples. A thermocouple is composed from two wires of dissimilar metals joined at one end.

Inductron has developed a brazing process to join the dissimilar metals of a thermocouple. Inductron Corporation has redesigned the Toroid Bonding Gun to include a susceptor in the gap. Once the bonding head is energized alternating current flows in the susceptor, a braze alloy and flux are now used to tin the susceptor. The two thermocouple wires are twisted and placed in the soft brazing material, on the susceptor, for 5 seconds and removed forming a thermocouple (Figure 14).

Flexible Susceptor

Inductron Corporation has developed a repair process for metals, ceramics, and composites utilizing a flexible ceramic susceptor.

The flexible susceptor can be inductively heated outside the bondline as a means for joining metals, plastics, and ceramics using thermoset/thermoplastic adhesives. The flexible susceptor may be used as a heating element (susceptor) in the bondline to melt thermoplastics or for curing thermoset adhesives.

TOROBRAZER

A new concept (TOROBRAZER) has been developed by Inductron Corporation for brazing and annealing bandsaw blades utilizing an induction heating process.

The TOROBRAZER can concentrate high temperature levels in localized areas through induction heating principles. A half inch gap has been cut from the toroid. When the power source is energized, a current passes through the coil generating a magnetic flux which travels to the gap of the toroid. The flux is then conveyed to the saw blade through the chassis top plate which is transparent to magnetic flux. Resulting eddy currents produced int he blade generate heat sufficient for brazing (Figure 16) and annealing the blade joint.

Coupling Head

Inductron Corporation has developed a coupling head (Figure 15a) for heating metallic heat-to-shrink couplings and fittings (Figure 15b).

The coupling head is capable of reliably generating high levels of heat within the coupling using an induction heating process. A gap has been cut in the toroidal core. When the power source is energized a current passes through the core to the toroidal gap. The resulting hysteresis losses produced in the coupling (positional in the gap) generate heat sufficient for shrinking the coupling (440°F). The power source is then automatically deenergized by the temperature controller.

CONCLUSION

Induction Bonding concepts and equipment have been developed at NASA and Inductron. 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 environmental stability for these rapid bonds, including those which contain steel screen or stainless steel foil susceptors in the bond lines.

The Induction Bonding 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 polymer matrix composites or titanium alloy to titanium honeycomb were proven feasible.

The inherent portability of Induction Bonding 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 field bonding of patches of titanium allot and graphite/epoxy composite materials could be bonded to typical aircraft panels.

Furthermore, variations of the Induction Bonding process can be used to repair polycarbonate or acrylic windscreen material and hydraulic tubing; anneal metals; fabricate thermocouples; mount strain gauges; and braze metals.

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3. Spinoff 1984: Portable Welder, p. 98; NASA Office of External Relations, Technology Utilization and Industry Affairs Division by Haggerty, J.J., July 1984.

4. Schott, T.D.; Fox, R.L.; and Buckley, J.D.: Inductive Energy for Rapid Strain Gauge Attachment, U.S. Patent 4,767,484, August 1988.

5. Buckley, J.D.; Swaim, R.J.; and Fox, R.L.: One-step Dual Purpose Joining Technique, U.S. Patent 4,313,777, February 1982.

TABLE I

COMPARISON OF BONDING PARAMETERS OF RAPID ADHESIVE INDUCTION BONDING WITH CONVENTIONAL BONDING

Composite Material	Bonding Parameters							
	Press., psi		Temp., °F		Heat Rate, °F/mm		Hold Time, min	
	Conv.	RAB	Conv.	RAB	Conv.	RAB	Conv.	RAB
Vinyl Ester/Gp	50	10	350	350	9	350	15	2
Epoxy/Gp	50	10	350	350	9	350	15	2
PEEK/Gp	200	10	750	750	9	300	15	2
PEI/Gp	100	50	625	625	9	1200	15	2
LARC-TPI/Gp	100	50	650	650	9	500	15	2

TABLE II

COMPARISON OF RAPID ADHESIVE INDUCITON BONDING WITH CONVENTIONAL BONDING

Composite Material	Overlap Shear Strength at Room Temp., psi	
	Conventional Bonding	Toroid Induction Bonding
Vinyl Ester/Gp	3,000	3,800
Epoxy/Gp	3,000	4,500
PEEK/Gp	4,500	7,000
PEI/Gp	4,000	5,100
LARC-TPI/Gp	4,780	4,850

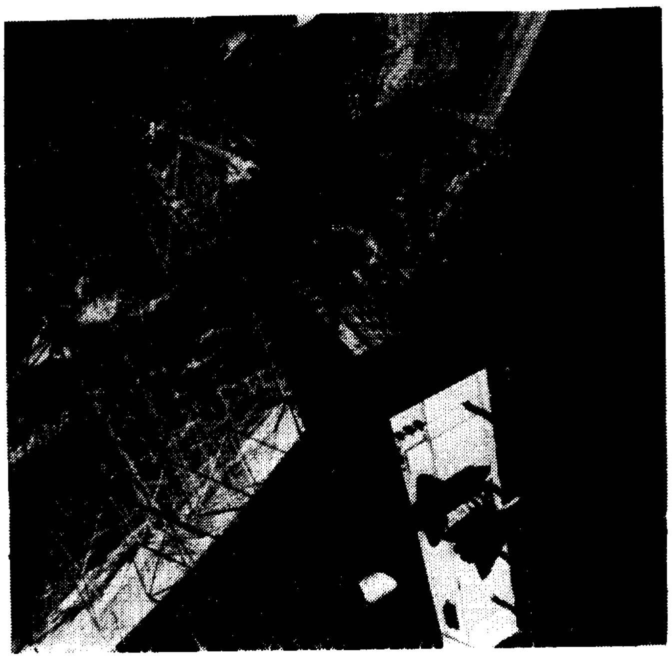

Figure 1. **Concept-Space Shuttle participating in construction of large area space structure**

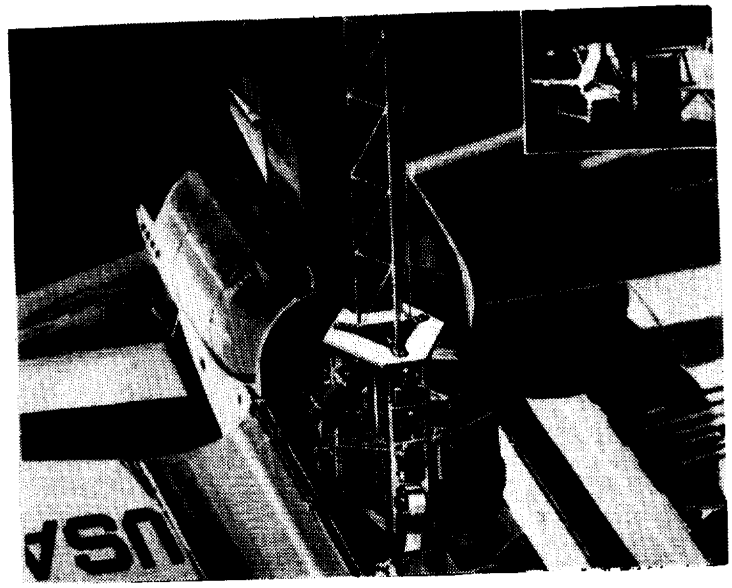

Figure 3. **Induction bonding system used in space manufacturing of beam structures**

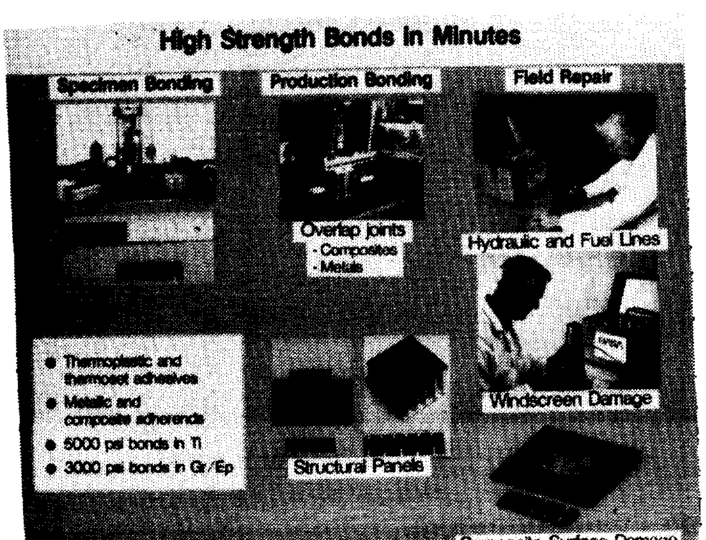

Figure 2. **Induction heating for high strength bonds in minutes**

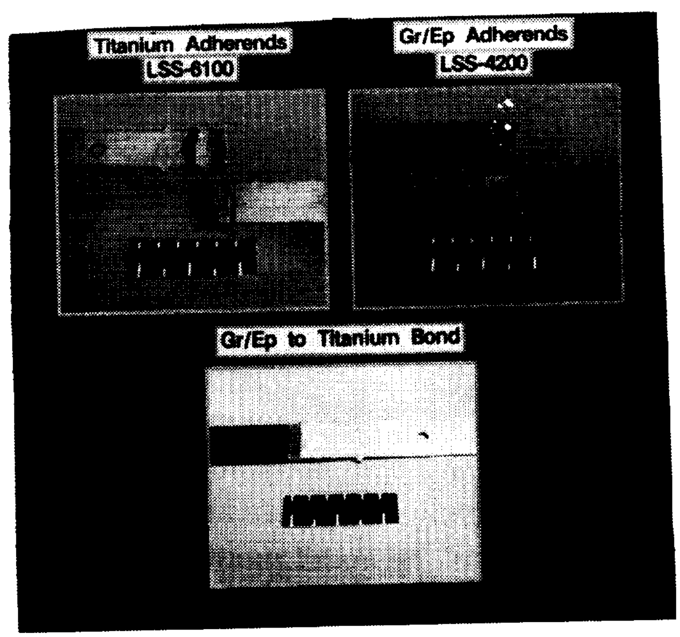

Figure 4. **Typical induction bonded overlap shear test specimens**

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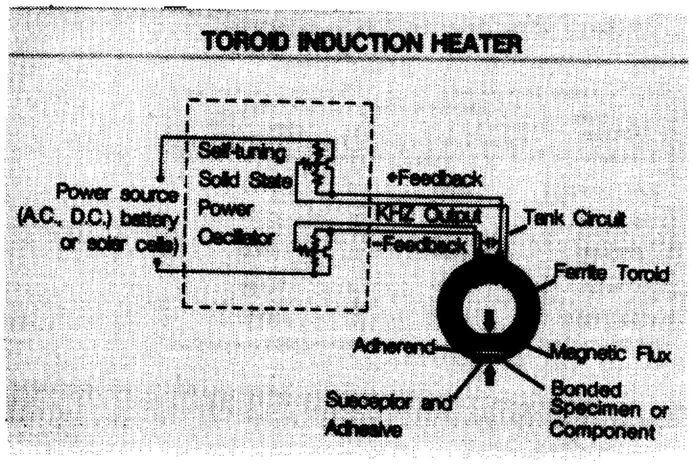

Figure 5. Schematic of toroid induction heating concept

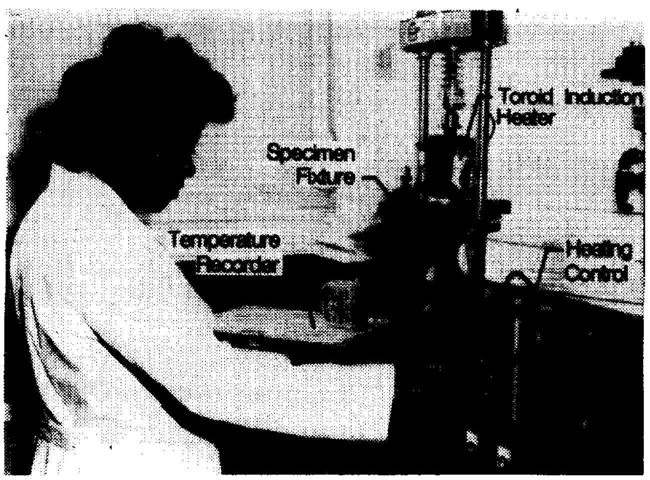

Figure 6. Toroid induction heater specimen bonding equipment

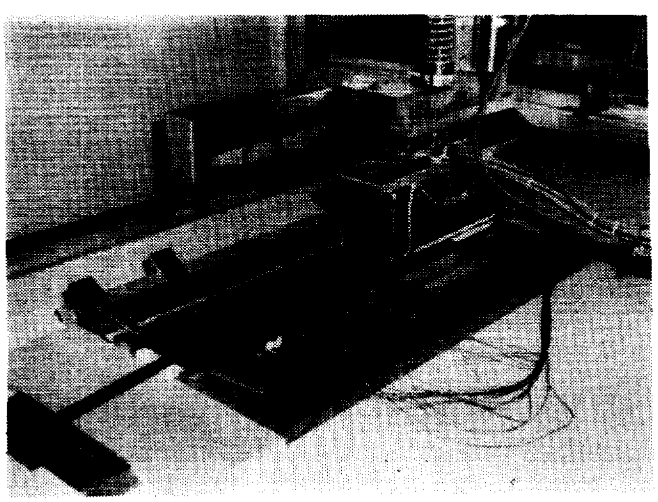

Figure 7. Six-headed induction seam bonding machine

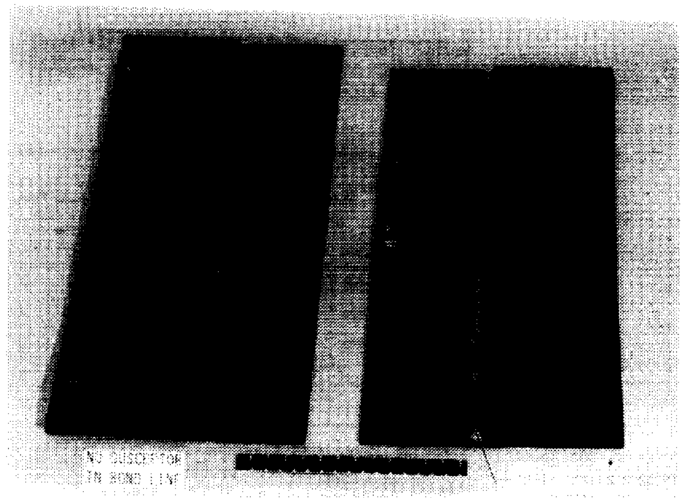

Figure 8. Seam bonded graphite epoxy panels (23 in. x 10 in. x .255 in.) 1. No susceptor 2. screen susceptor

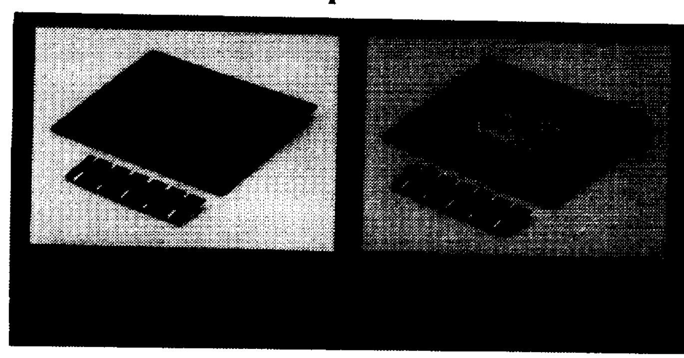

Figure 9(a). Repair of graphite/epoxy composite laminate

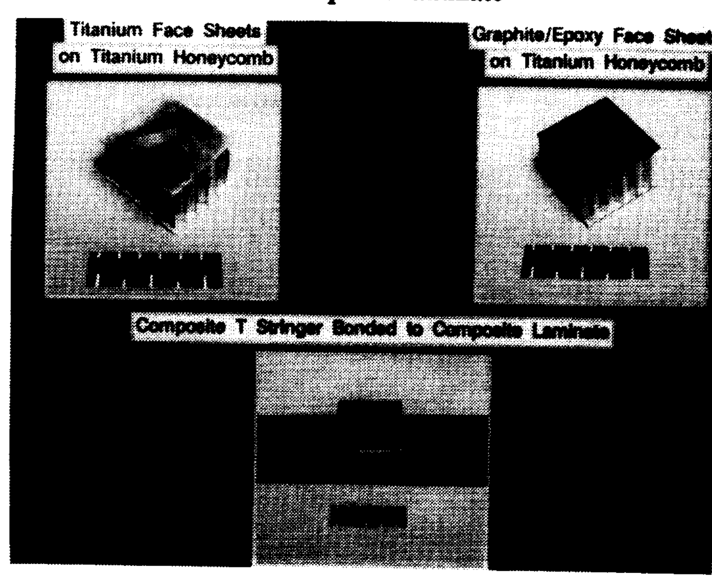

Figure 9(b). Manufacture of honeycomb and T stringer structures

Figure 9(c). Repair of the canopy of an F-84 aircraft

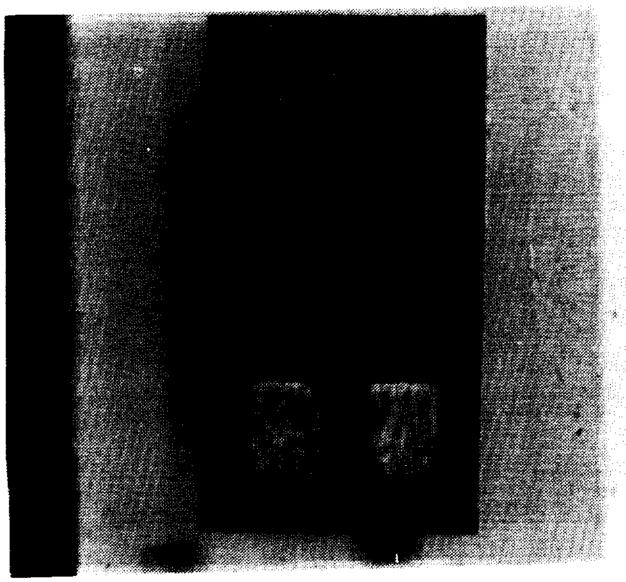

Figure 10. Induction bonded strain gauge on fiberglass composite test specimen

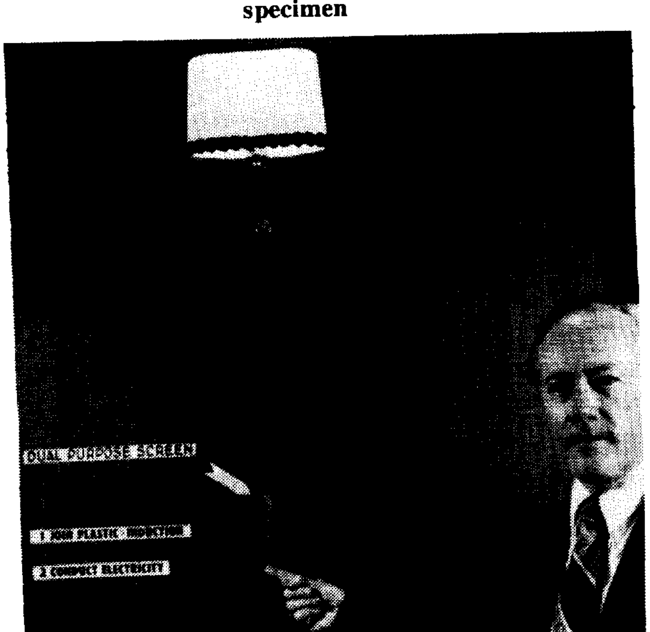

Figure 11(a). Dual purpose bonding technique in a wall section

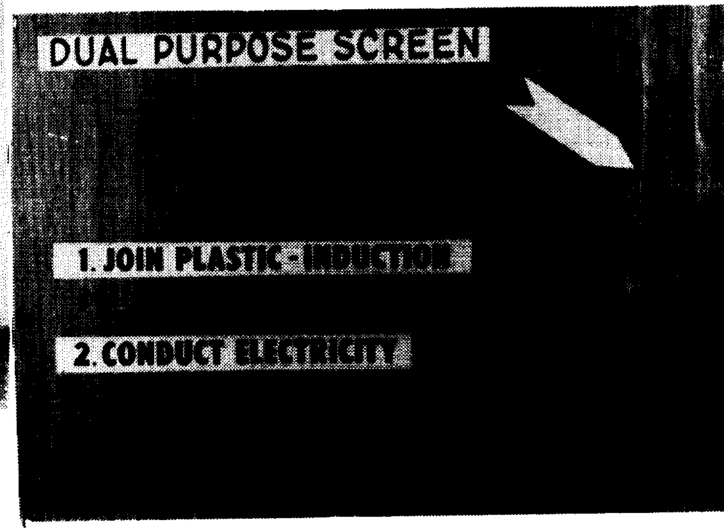

Figure 11(b). Dual purpose bonding technique for bonidng structures and conducting electricity

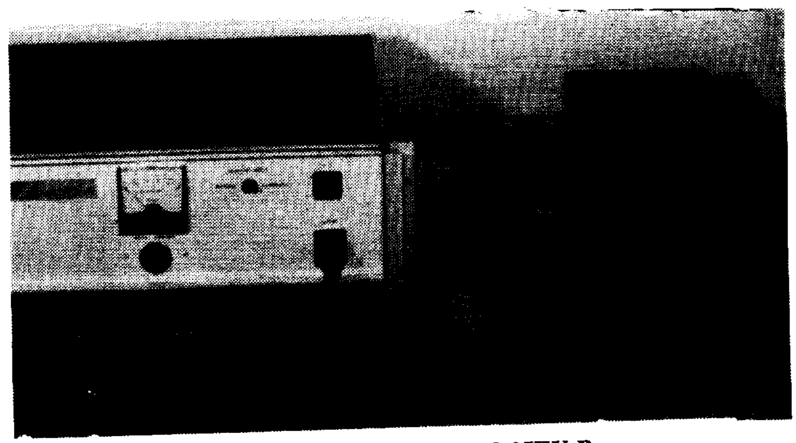

Figure 12(a). Flexible Head and 2KW Power Supply

Figure 12(b). 12" Flexible Head

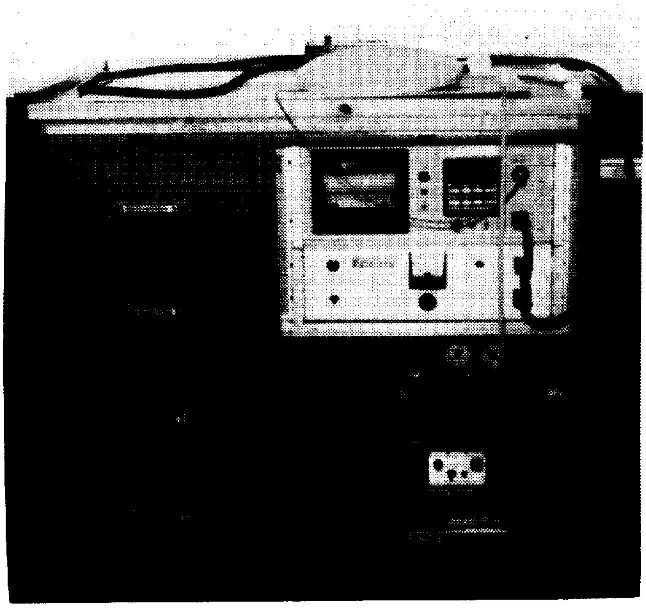

Figure 12(c). **Field Repair System**

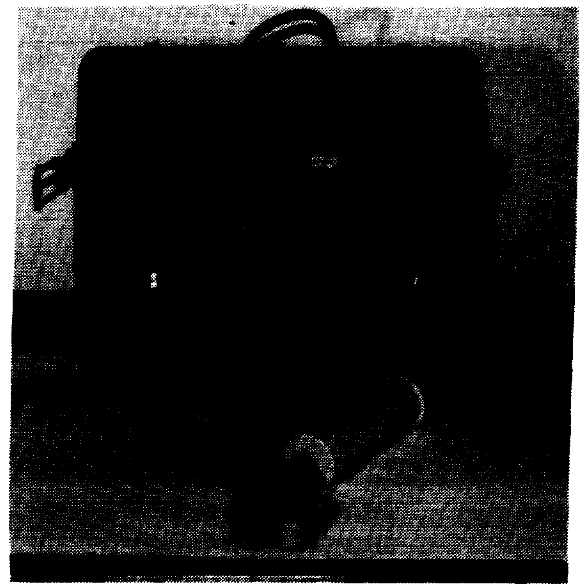

Figure 15(a). **Heat to Shrink Coupling Head**

Figure 13. **Composite Repair**

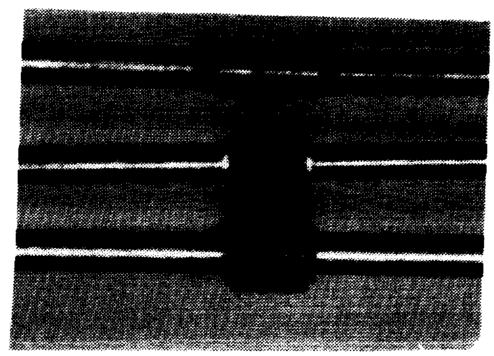

Figure 15(b). **Heat to Shrink Coupling**

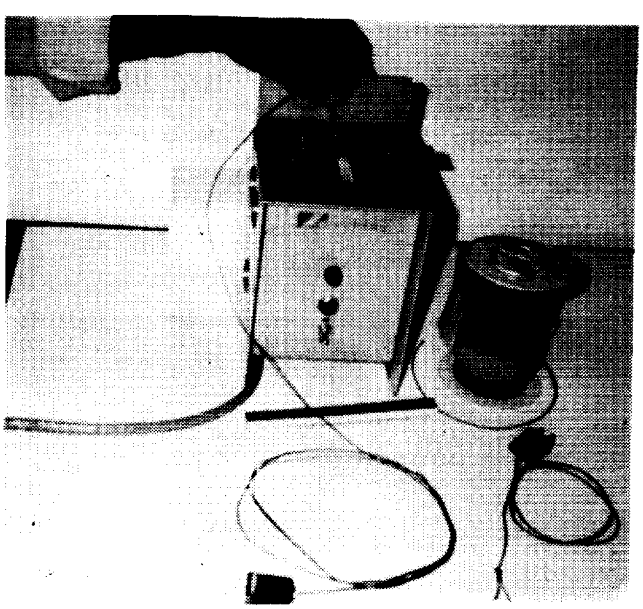

Figure 14. **Making of Thermocouples**

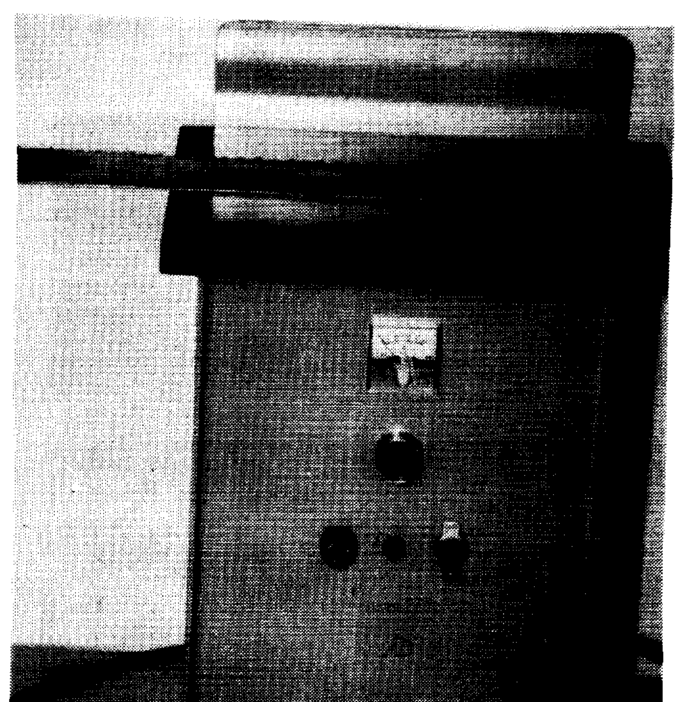

Figure 16. **Induction Anneller**