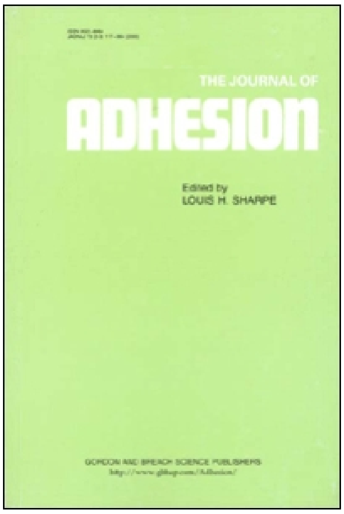

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LASAB - Laser Activated Spot Adhesive Bond - Analysis and Experimental Verification

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LASAB - Laser Activated Spot Adhesive Bond - Analysis and Experimental Verification

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A new material bonding technique utilizing a CO_2 laser and thermally-activated adhesives is proposed for the assembly of similar as well as dissimilar materials where time is crucial and global thermomechanical hazard intolerable. Computerized numerical analysis is presented for the pertinent time transient heat transfer problem with arbitrary material properties and boundary conditions. Bond strength results as well as qualitative and quantitative experimental experiences are discussed.

I. INTRODUCTION

The recent proliferation of miniaturized elements and small components for which they are building blocks poses an ever increasing problem for the technology involved in their assembly. Traditional mechanical fastening of materials (rivets, screws, springs, etc.) are found unsuitable due to the scale of the physical components involved. Thermomechanical or welding procedures are hindered by restrictions imposed by these small dimensions or in themselves pose too great a thermomechanical hazard to components being assembled. Incompatibility caused by the material properties of dissimilar materials imposes additional severe restrictions. Acousto-mechanical techniques are subject to all of the reservations expressed above and are further subject to problems of special equipment design.

Solutions for the particular problems of bonding in the small are, however, to be found in chemical bonding. Similar as well as dissimilar materials can be bonded with minimal modifications to geometry at minimal material

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and labor cost. Such bonding is performed by the application of two-component chemical systems activated by heat.

Multicomponent systems arose to satisfy the requirement of dormant chemical behavior prior to use. However, accurate metering and thorough mixing are required to insure bond product uniformity. The sensitivity of bonds generated to the delicacy of such operations, coupled with the obvious need to thoroughly purge applicators detracts from the universal acceptance of two-component system bonding solutions.

The single-component system eliminates the undesirable requirements of metering, mixing and purging. However, it requires the application of heat to process the bonding reaction and thus poses a global thermal hazard to the total assembly.

It is thus fortunate that the demands made by miniaturization have come at a time when a generation of reliable off-the-shelf industrial CO_2 laser systems has become available. The satisfaction of bonding demands, integrated with the availability, form the subject matter of the following material.

The inherent properties of laser systems in general are exploited to satisfy the demands of miniaturized bonding in particular. The laser can generate a spot in which a fixed amount of thermal energy is delivered. It can also vary this amount as well as scan this spot in a pattern with repeated accuracy. Furthermore, this can be done with no thermal source contamination in an on–off mode. The combination of these properties recommend laser activated bonding for quick, automatable assembly of delicate and small components with localized thermal hazard.

The magnitude of the concentrated energy delivery rate implicit in high power laser irradiation is coupled with transfer through a geometry where characteristic dimensions include bondline thicknesses. This combination invalidates prior experience with conventional heat transfer calculations of bonded assemblies. Detailed knowledge of temperature distributions in time and space are required to prevent thermal destruction and assure polymerization levels. An analysis procedure and results satisfying these stated needs are presented in the following material.

II. ANALYSIS

Definition of problem

Given n plates of infinite width, finite thickness l_i and finite length $2L$, consider them to be individually characterized by distinct density ρ_i, conductivity k_i and specific heat c_i. Let the boundaries be subject to convective heat transfer. Submit the surface $X = 0$ to a line source of strength $q(y, t)$, at

$Y = L$ and find the time-dependent two-dimensional temperature surface associated with a cross section through the normal to the layers and the line source, Figure 1a. Assume the material properties to be independent of temperature and time.

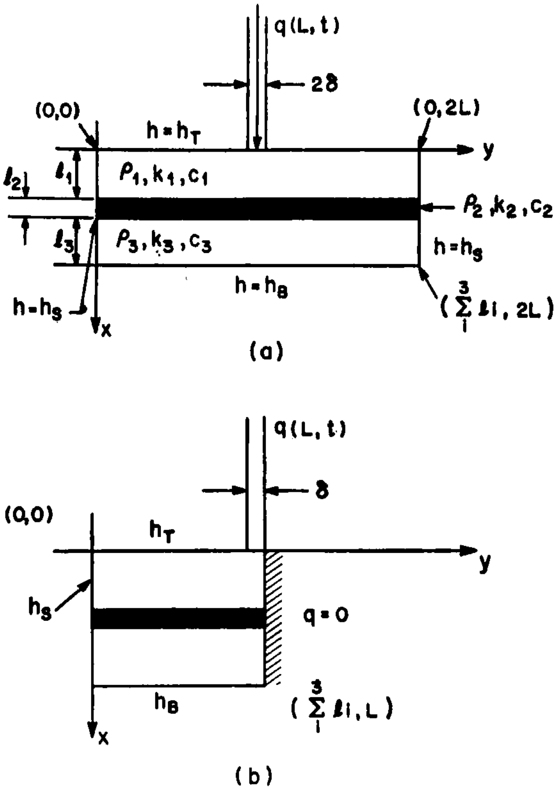


FIGURE 1 Problem and geometry definition.

The surface generated as a solution to the problem posed above is qualitatively indicative of the transverse (X) and axial (Y) temperature distributions caused by a lasing source irradiating a spot in a three-layer material strip. The model is quantitative when the beam is scanned at speeds which exceed the thermal response time of the material involved.

Method of solution

The piecewise isotropic Fourier field equation is written as

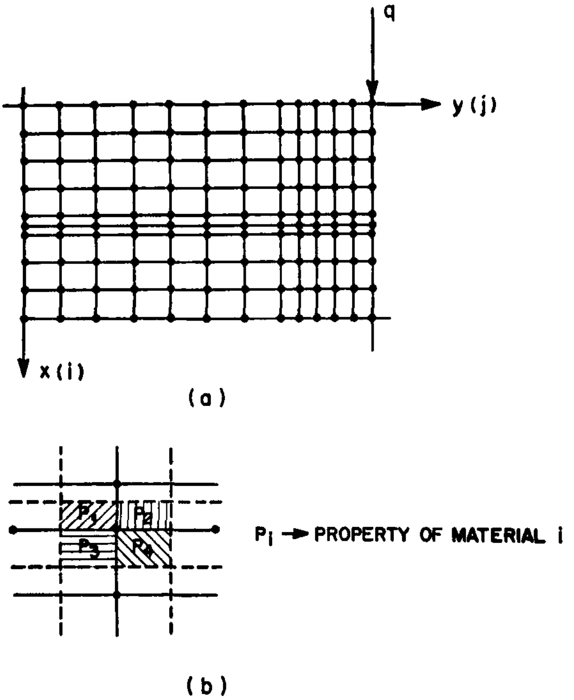
$$\frac{\partial T}{\partial t} = \left(\frac{k}{\rho c}\right)\left\{\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right\} \tag{1}$$

with boundary conditions

$$hA(T-Ta)\,dt = k\frac{\partial T}{\partial n}; \qquad \text{surfaces } X \neq 0,\ Y \neq L \tag{2}$$

$$q = kA\frac{\partial T}{\partial n}; \qquad X = 0,\ L-\delta \leqslant y \leqslant L+\delta \tag{3}$$

This finite, two-dimensional, spatially variable property problem with mixed boundary conditions stipulated by Eqs. (1–3), is not amenable to closed form analytic solution[1]. Advantage has to be taken of the analytic tools available in numerical analysis.



(a)

(b)

FIGURE 2 Discretization geometry.

The rectangular region is easily covered by a mesh (Figure 2a) whose node points are boundary or internal in character. Associated with each node are up to a maximum of four elements (Figure 2b) which bear the identity of the material character and physical dimensions of the region. Corner nodes have one, boundary nodes have two, and internal nodes have four associated elements. The boundary elements in turn can have up to a maximum of two sides exposed to different boundary conditions. The latter can be characterized by time-dependent convection coefficients, heat flux, insulation or a time-dependent temperature profile.

The solution is obtained by writing an energy balance for each node. Heat flux across the elements is summed and equated to the net increase in temperature of the volume associated with the respective point. For nodes (i, j) interior to boundaries having elements n_c of unit depth, volume $V_{i,j,u}$ properties ρ, c, k associated with each element u and area A_u across which energy is transferred, the balance may be written as;

$$\sum_{u=1}^{n_c} \{V\rho c\}_{iju}\{T_{ij}(t+t)-T_{ij}(t)\} = \sum_{z=1}^{N_i} \sum_{s=1}^{N_j} \{Ak\}_{iju} \times \{T_{zs}(t+\Delta t)-T_{ij}(t+\Delta t)\} \tag{4}$$

where N_i and N_j are the immediately neighboring nodes in the i and j direction respectively from which heat is transferred.

The set of relations obtained, after writing Eq. (2) in a similar manner for boundary nodes, can be transformed into one demanding the solution at each time step of a set of equations.

$$A_{ij}\Psi_{ij}+B_{ij}\Psi_{ij-1}+C_{ij}\Psi_{ij+1} = R_{ij}, \qquad i = 1 \ldots M, j = 1 \ldots N$$

This solution is obtained by recourse to a column inversion technique[2].

III. RESULTS AND ANALYSIS

The preceding analysis was implemented on a Honeywell H6000 GCOS Bell Laboratories system using Fortran IV. Central processor requirements were met with 38K words for a 30 × 30 meshpoint capability.

The variable X, Y grid was used to detail two layers of 0.150 cm separated by a layer of 0.004-cm thickness. All three materials were assumed to terminate at a length of 2.25 cm. At this distance the symmetry of the irradiation geometry permits the imposition of insulation heat transfer boundary conditions. The remaining free surfaces are subject to convection boundary conditions. With respect to geometry, vertical top and bottom heat convection coefficients were assumed to be respectively $h_s = 1.34 \times 10^{-4}$, $h_t = 1.88 \times 10^{-4}$ and $h_b = 9.93 \times 10^{-5}$ cal/(sec cm^2 deg C). Irradiation by 50 watts was translated into a continuous input of heat over an X interval of 0.25 cm, Figure 1b.

The first case considered was that of a reference aluminum block. The three layers were directed to have identical aluminum material properties. The irradiation of such a sample results in the prediction that at 30 seconds there is practically no transverse temperature variation. However, the axial temperature from the irradiated end to the free end is seen to attain a maximum value of 167°C and a minimum of 153°C respectively (Figure 3).

The introduction of 0.004 cm of epoxy which has a thermal conductivity three orders of magnitude lower than that of aluminum, as the intermediate layer, has a severe effect on retarding the flow of heat to the unirradiated layer. It further restricts the dissipation of heat through that layer and elevates the average temperature of the top layer (Figure 4).

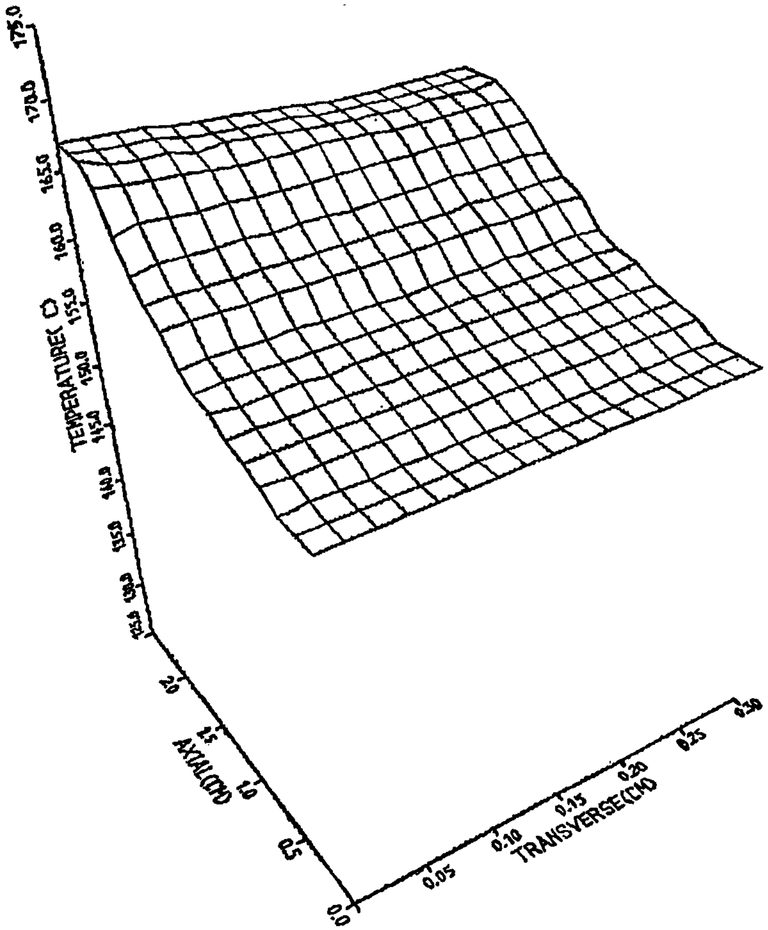


FIGURE 3 LASAB temperature surface—aluminum-aluminum-aluminum.

The substitution of steel for the unirradiated layer results in a dramatic change at the same 30-second observation time. Overall temperatures are lowered. The maximum temperature in the aluminum is 153°C. A minimum of 130°C appears in the aluminum location farthest from the irradiation. Steel in the corresponding substrate location records only 128°C. It is apparent that steel, with its greater heat capacity, at this level in the transient process is acting as a heat sink and thus in general is decreasing the thermal gradients in the assembly (Figure 5).

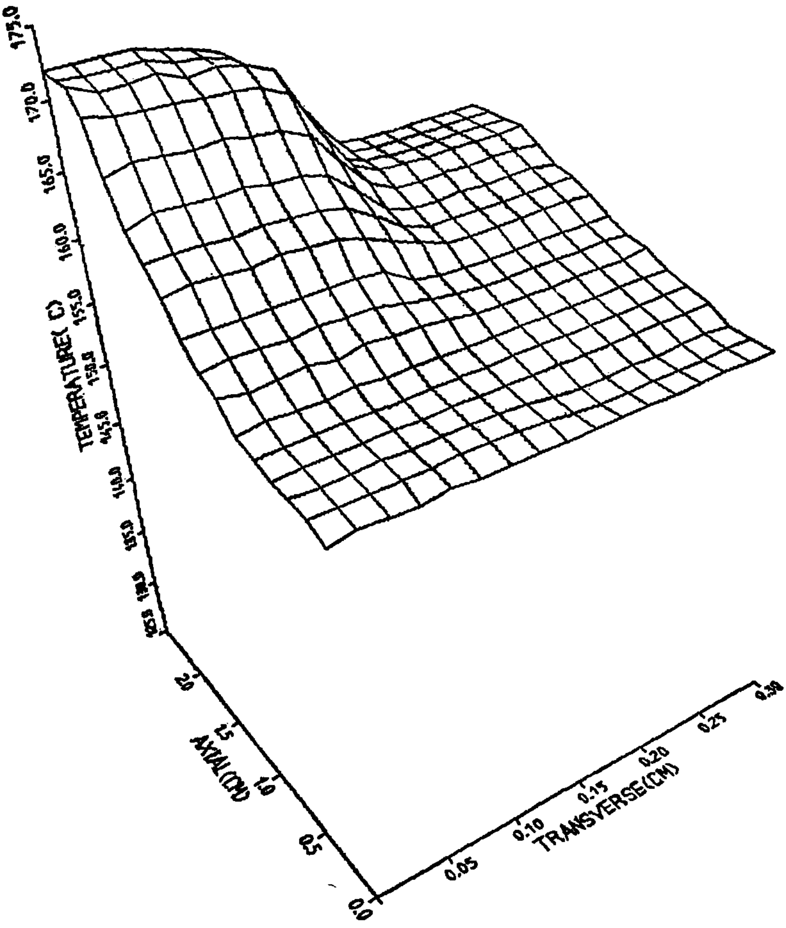


FIGURE 4 LASAB temperature surface—aluminum–epoxy–aluminum.

Reversal of aluminum and steel for irradiation results in an even more dramatic temperature surface at 30 seconds in the transient. The lower conductivity of the steel which is now subject to the concentrated input of heat flux results in an accentuation of the localized high temperature region. Indeed, the level of that region is elevated at the expense of the rest of the assembly. It is seen that due to the resistance of the first layer to the transmission of heat, the role of the epoxy as a thermal barrier is locally overcome and paths are found to elevate the temperature of the aluminum sublayer at the expense of the steel above. A maximum temperature of 170°C as well as a minimum of 125°C are obtained in the steel (Figure 6).

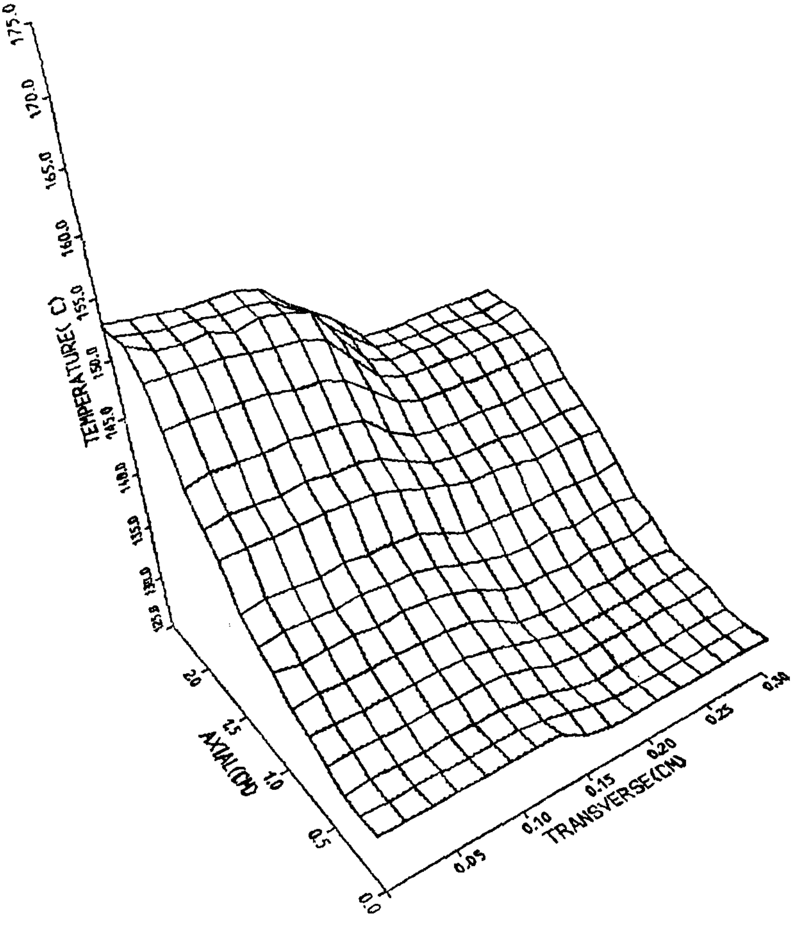


FIGURE 5 LASAB temperature surface—aluminum–epoxy–steel.

The surface represented in Figure 7 reveals the effect of irradiating a highly conducting surface backed by a thin epoxy layer and then by an equivalent thickness layer of a very poorly conducting material consisting of wood. There is minimal transmission of the incoming heat to the ambient through the insulators. Indeed, wood has a minimum temperature of 134°C. As a consequence, the aluminum temperature rises rapidly at 30 seconds to a maximum of 240°C dropping to 213°C in the axial direction. The bondline temperature follows that of the aluminum and therefore carries with it the coupled effects of rapid temperature elevation for polymerization and attendant possibility for quickly exceeding the temperature levels compatible with survival of organic materials.

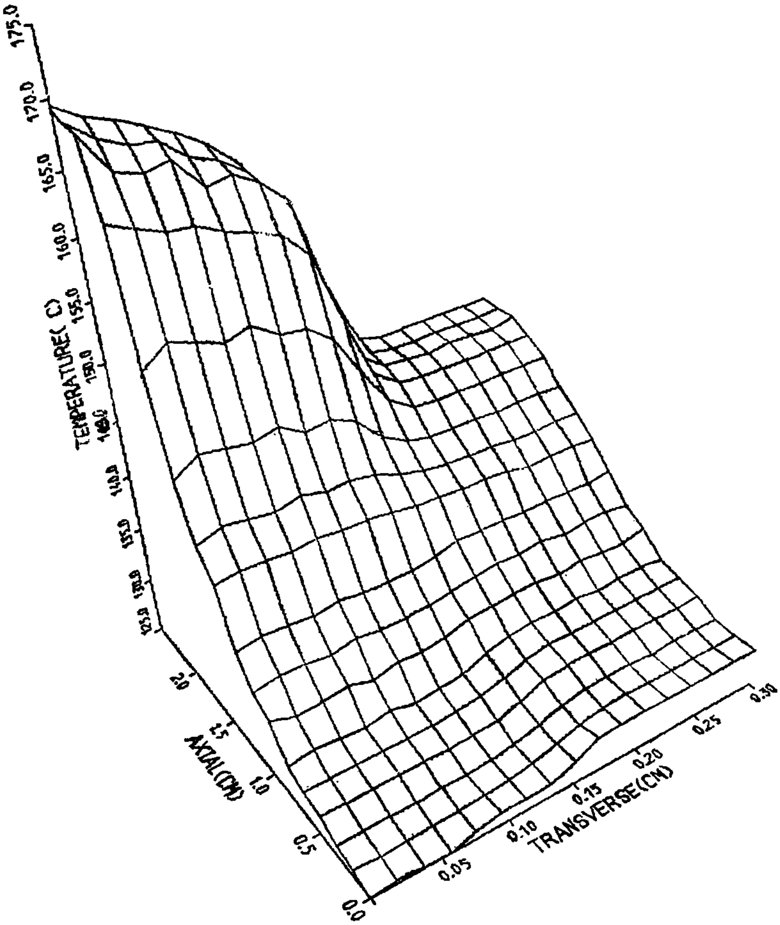


FIGURE 6 LASAB temperature surface—steel–epoxy–aluminum.

Increasing the conductivity by an order of magnitude but maintaining it within, but lower than, the order of epoxies results in the temperature surface of Figure 8. Here quartz is used as the unirradiated substrate. It is evident that with such material, matching an intermediate case between aluminum–epoxy–aluminum and aluminum–epoxy–wood is obtained.

Space limitations in this paper prohibit the exploration in detail of the temperature surfaces generated in time. The detailing of numerical predictions of the temperature variation across the adhesive layer and at the interface between adhesive and adherend available in the data used to generate Figures 3–8 will be the subject of a future publication.

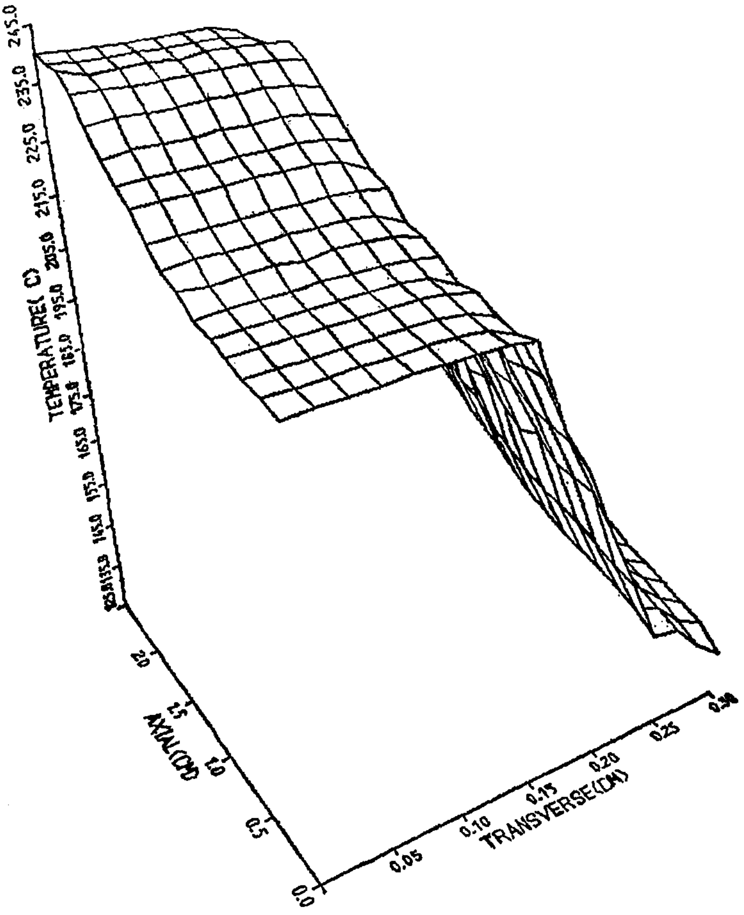


FIGURE 7 LASAB temperature surface—aluminum–epoxy–wood.

It is clear from the evidence at hand that such information is going to be needed to guarantee that suitable irradiation times and power levels will be set in the laboratory so that polymerization is achieved at both interfaces and organic destruction avoided. The effects of varying adhesive thickness as well as adherend thicknesses will have to be presented to guide proper laboratory exploration and product application of the LASAB procedure.

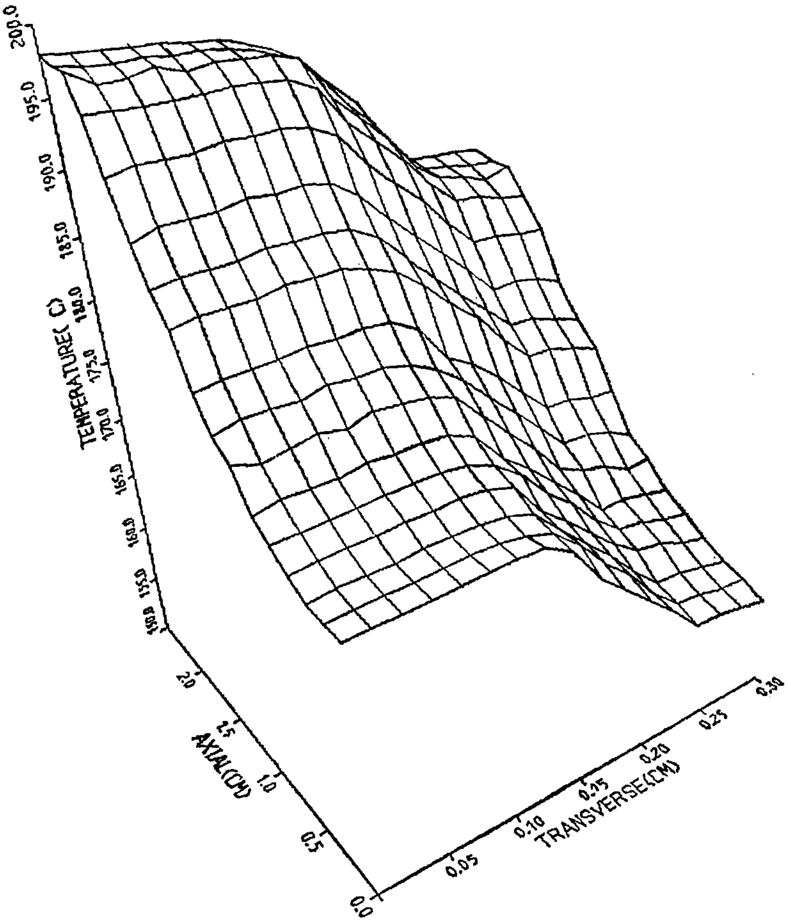


FIGURE 8 LASAB temperature surface—aluminum–epoxy–glass.

IV. EXPERIMENTAL FEASIBILITY

Qualitative experimental results

Laboratory experimentation was undertaken to explore the qualitative versatility of LASAB bonding by subjecting various material combinations to the proposed irradiation procedure.

Use was made of a continuous 50-watt CO_2 laser emitting a 5 mm diameter beam. Specimens were exposed for various time durations while being held in a fixture (Figure 9). The adhesive used was a nitrile-modified structural epoxy (3M-EC2186). Adhesive film thickness was held uniform by the insertion of a 0.008 cm wire segment and by loading the overlap with spring clips.

Aluminum was successfully bonded to itself, steel, wood and glass. Steel was similarly bonded to itself, aluminum and copper. All bonding times were less than 5 minutes using an adhesive which otherwise requires a cure time of one hour at 175°C.

Qualitative insight concerning substrate thermal response was obtained by monitoring a thermocouple instrumented, aluminum-steel bonded lap shear specimen. It was found that energy input and temperature profiles can be readily manipulated by laser pulsing and by altering convection conditions surrounding the sample. Total energy transmitted to the assembly could be increased without exceeding a prescribed maximum bondline temperature by pulsing of the beam. The gradient with respect to time of bondline temperature could be altered by hosing the specimen portions with an air stream. The maximum bondline temperatures could be similarly affected.

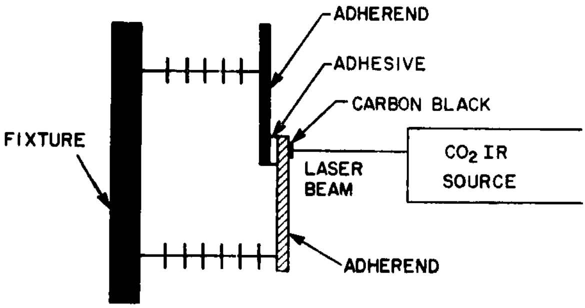


FIGURE 9 LASAB irradiation schematic.

From the experience noted above, it can be concluded that the critical bonding parameters of temperature, time and energy delivered can be controlled for the LASAB procedure.

To determine the effects of temperature level and energy delivery rate on polymerization and material degradation, the thermal cure response behavior of the adhesive was examined using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).

TGA results show that even at low energy input rates of 10°C/min, weight loss, indicating organic decomposition or loss of volatiles occurred at 125°C in air at 0.1 LPM (liters per minute) flow rate, reaching 3% at 200°C. No more than 4% loss occurred by 300°C but the loss increased rapidly thereafter indicating rapid material deterioration (Figure 10). The significant temperatures of 125, 200, and 300°C were attained at 9.5, 17 and 27 minutes respectively.

Increasing the heating rate to 50°C/min. reveals the onset of deterioration to be at 175°C with a 2% loss obtained at 225°C. Conditions are stable until the onset of rapid deterioration at 325°C. At this heating rate, the temperatures noted have been attained at 2.8, 3.8 and 5.8 minutes respectively.

The thermal response lag associated with increased heating rate in TGA measurements is due to the nature of the instrument and decreases the significance of the shift in the noted onset of material deterioration. A lower limit for this temperature is indicated to be 125°C or 50° below the manufacturer's recommended cure temperature of 175°C. It is furthermore indicated that elevated heating rates do not pose an apparent hazard in terms of lowering the onset of deterioration of this particular adhesive. The temperature level for the onset of rapid deterioration appears to be similarly unaffected.

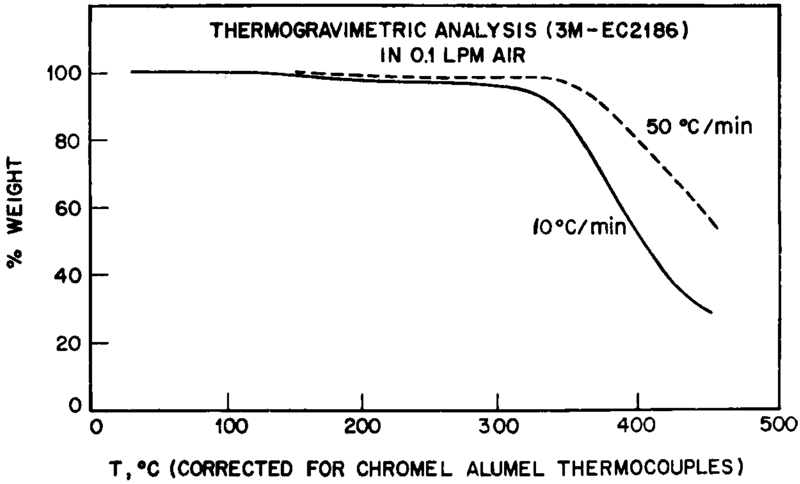


FIGURE 10 Thermogravimetric analysis (3M-EC2186).

TGA data were gathered in an air atmosphere to simulate the worst conditions for the adhesive exposed to the ambient. Nitrogen and air were used for the DSC measurements to simulate internal and external boundary effects respectively.

The DSC experiments were initially performed under similar conditions of 0.1 LPM air and a temperature increase of 10°C/min. The adhesive begins to exotherm and thus polymerize at 165°C. The exotherm peaks at 195°C and is complete at 235°C. The minimum mass cure rate time at this heating rate for primary polymerization is therefore 1.4 min/mg. Increasing the heat delivery rate so that the temperature is driven at 20, 40 and 100°C/min reveals an increase in the maximum exotherm generated at a temperature of 225°C accompanied by a decrease in the mass cure rate time to 0.56 min/mg.

If a nitrogen atmosphere is used, simulating polymerization of the material in the interior of the adhesive geometry, the cure rate time is increased by about a factor of two at the 100°C/min excitation rate. This effect is also present in the lower 10°C/min runs but is not as dramatic, yielding 1.8 as opposed to 1.4 min/mg in nitrogen and air respectively. The maximum temperature during polymerization appears to be unaffected by the presence of nitrogen (Figure 11).

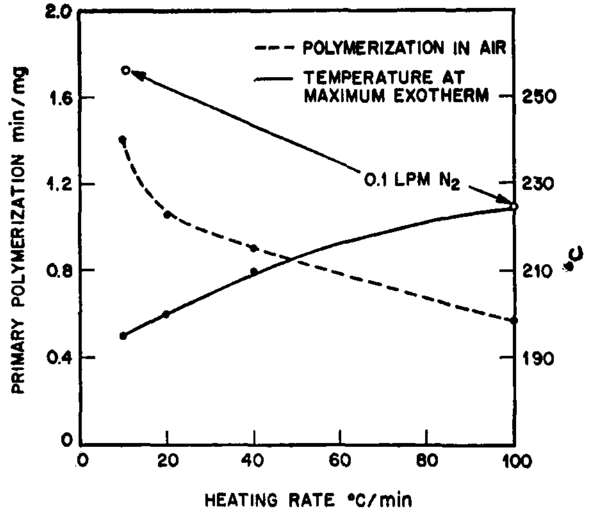


FIGURE 11 Differential scanning calorimetry results (3M-EC2186).

The DSC and TGA results thus indicate that increasing the rate at which energy is supplied increases the rate of primary polymerization reactions and does so at minimal loss of material involved.

The actual bonding of the various substrate combinations noted previously yielded several qualitative insights about the LASAB procedure. It was found that severe disparity in substrate thermal properties could be tolerated, providing judicious choice of laser irradiation was made. Figure 12 illustrates the bond formed by aluminum and quartz viewed through the quartz slide at 10× and 20× magnification. The imbedded wire apparent in both photographs is of 0.008-cm diameter.

Wood could also be joined to aluminum providing, of course, that the aluminum was exposed to the radiation. A 0.158-cm thick plate could be bonded to wood with a bond strength such that the attempt to fracture the specimen results in failure of the wood adherend itself (Figure 13).

The attempt at bonding aluminum to aluminum was initially frustrated. However, recognition that heat was being dissipated away from the bondline by the conductivity of the material allowed successful bonding when geometric thermal barriers were introduced in the sample.

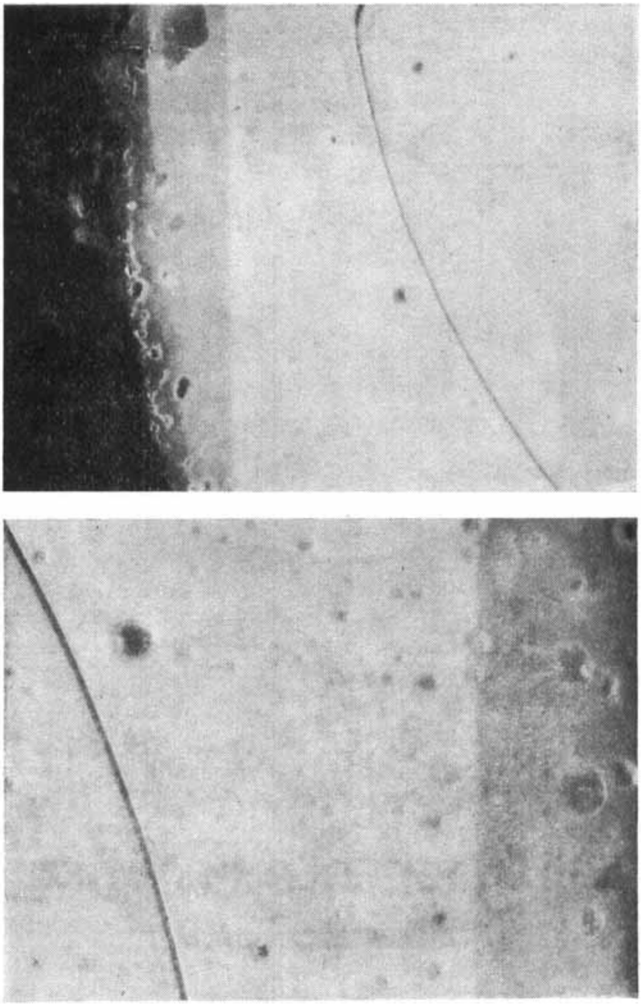


FIGURE 12 LASAB—aluminum–quartz bond.

The reciprocal problem of joining steel to aluminum and then aluminum to steel illustrates the role of thermal diffusion. Irradiation of aluminum resulted in longer laser bonding times typically by a factor of 1.5. The adhesive acts as a thermal barrier and the aluminum conversely as a fin dissipating heat delivered.

When steel is the irradiated adherend, its lower conductivity reduces dissipation and allows a more rapid elevation of the adhesive temperature. Steel-to-steel bonding accentuates the effect noted above. Bonding times are decreased to about 3 minutes. When such time limits are exceeded, degradation of the organic material results from excessive temperature generation (Figure 14). Proper exposure results in the bond represented in the fractured specimen of Figure 15.

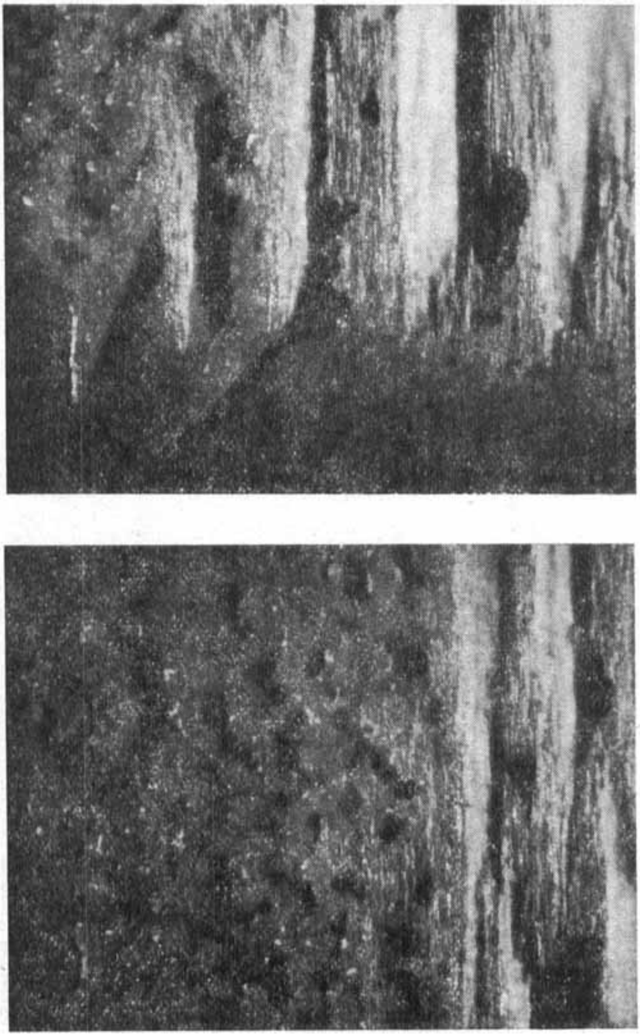


FIGURE 13 LASAB—aluminum-wood bond.

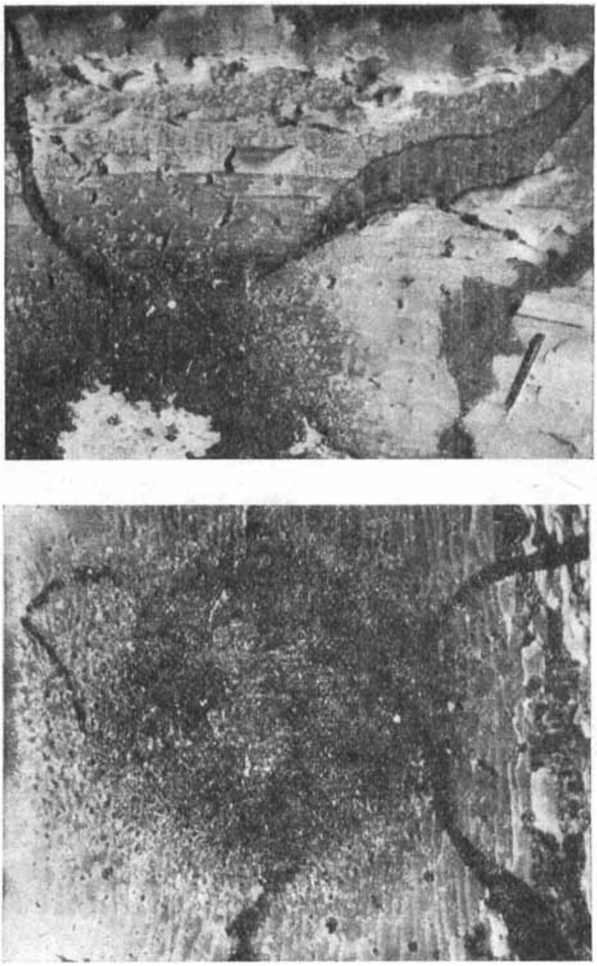


FIGURE 14 Effect of material deterioration.

Quantitative experimental results

The quantitative evaluation of bond strength resulting from LASAB bonding requires optimization in time, laser power, spot size and relative motion of the irradiated substrate. It is clearly evident that a focused beam can locally destroy an organic material in a time interval which does not allow polymerization of the remaining material. An unfocused beam with sufficient power can similarly destroy organic materials when irradiating a substrate of low thermal conductivity.

With due respect noted for the reservations cited above, standard 1.27 cm overlap shear specimens were prepared using 2024-T3 aluminum and 1010 cold rolled steel as substrate combinations. The aluminum surface was coated with carbon black and irradiated for varying time intervals and power concentrations. The steel–steel configurations was similarly coated. Irradiation was again varied for this material assembly. The assembly was held in a fixture with adherends separated by an adhesive film (3M-EC2186) of 0.008 cm thickness. Spring clips and a gold wire insert maintained bond-line uniformity.

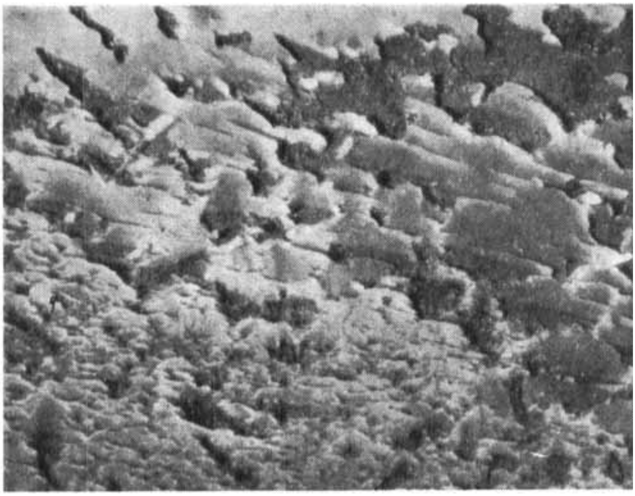


FIGURE 15 Fracture surface of good steel–steel LASAB bond.

Aluminum–steel and steel–steel samples were prepared according to standard procedures. The adherends were first vapor degreased in perchloroethylene, then immersed in a detergent solution and then rinsed in deionized water. The aluminum was subsequently treated with sulfuric acid–sodium dichromate solution followed by immersion in a reducing bath and another deionized water rinse. Steel samples were etched in a phosphoxic-nitric acid bath, rinsed and then immersed in a solution of potassium permanganate and sodium hydroxide. The standard rinse in deionized water followed. Adequacy of this cleaning rinse in deionized water followed. Adequacy of this cleaning procedure was established by satisfactory wettability of the surfaces.

One adherend was coated with a layer of adhesive (3M-EC2186). Uniformity of adhesive thickness was again maintained by use of a gold wire of 0.008 cm diameter. The samples were held in a six-sample rack and weighted by a 2.3 kg load. This configuration was held at 175°C for one hour in a circulating air oven. Samples thus prepared were pulled on an Instron *at a crosshead speed of 0.254 cm/min. These standard oven-cured* aluminum–steel and steel–steel combinations yielded average values of 1298 and 1241 kg loads respectively prior to failure. LASAB processed assemblies, as expected, yielded varying results which were a function of irradiation and processing conditions.

Severe load carrying capacity loss is experienced for 50 watt irradiation with no clamping, for 2 and 3 minutes irradiation for steel as well as steel–aluminum specimens. Steel–steel averages fall by a factor of 2.84 and show thick films as well as uncured adhesive material. Reduction of laser power to 35 watts with spring clips exerting a minimal preload results in a 980 kg load carrying capacity. Although evidence of uncured adhesive persists, the difference between the oven reference and LASAB is only 24%. Translated into an average stress this lap shear specimen indicates 303 kg/cm^2 can be sustained by this relatively uncured assembly. Potential for tacking or chemical fixturing of assemblies by this procedure is thus evidenced. Clamped aluminum–steel adherends irradiated at 35 watts for 3 minutes evidence a more severe drop in load carrying capacity, with an average of 778 kg or only 60% remaining from the initial reference load carrying capacity. The result is dramatic but fully in line with the theoretically observed property of aluminum to dissipate heat and prevent both adherends from attaining sufficient temperature and or temperature duration for polymerization.

When 50 watts are used for irradiation and the specimens are clamped, aluminum–steel combination yields 1227 kg and steel–steel 1080 kg load carrying capacity. It is thus seen that suitable parameter variations are available to produce bonds with strengths varying from those useful for fixturing only to those capable of meeting the elevated strength requirements of structural assembly.

V. CONCLUSIONS AND RECOMMENDATIONS

The successful short processing time bonding of dissimilar materials using single component chemical systems, establish LASAB as a viable candidate for further investigation and research. Several needs are immediately pressing to take this initial effort to logical conclusions.

The theoretical numerical heat transfer analysis has to be an integral part of any further exploration. The value of previous bonding experience diminishes with the decrease in characteristic dimensions of the geometries involved as well as with the increase in the rates and concentrations of energy delivery provided.

The typical temperature surfaces noted in this work should be the basic references from which laboratory experiment directions are taken. Detailed exploration of bondline interface and crossection temperature distributions have to be made to insure the viability of different material combinations and attendant processing demands.

Adhesive characterization in terms of polymerization rates and thermal degradation levels as a function of irradiation intensity and rate have to be obtained for each application envisioned. The rapid delivery of energy to the exposed system is again beyond the realm of previous experience in bonding technology.

Beam delivery and scanning optics should be explored to extend the current static effort to the versatility implicit in dynamic laser beam manipulation.

Chemical fixturing, alluded to in passing above, should be explored further. The possibility of rapid setting of an assembly which attains ultimate strength with long-term cure on the shelf or in transit to a required location has to be examined.

Molecular sieves containing high-temperature sensitive components can be envisioned as dormant curing systems locally activated by LASAB for precise localized bonding of adherends. Possible uses in chip and beam lead bonding where global thermal or mechanical hazards are intolerable suggest themselves for immediate application to practice.

In conclusion, it has been previously said that lasers are solutions looking for a problem to solve. It is this author's contention that LASAB answers a part of this quest and in itself poses one of its very own.

Acknowledgements

The author would like to express his appreciation to his colleagues for their contributions to the realization of this effort. Mr. S. G. Seger, Jr. is thanked for his help in characterizing the specimen thermal response to laser irradiation. Mr. M. H. Ross' TGA and DSC measurements and assistance in the preparation of specimens is acknowledged with gratitude. Finally, a special continuing acknowledgement is due to Dr. L. H. Sharpe for his continuing encouragement and stimulating creative discussions.

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