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Low-Pressure Diffusion Bonding of Titanium

J. F. Kenney* and C. Deminet†
The Boeing Aerospace Company, Seattle, Wash.

This paper describes a new manufacturing process for diffusion bonding of titanium alloys. The technique requires the use of high-vacuum furnaces, but allows bonding to be carried out at very low contact pressures. This is possible because the parts are kept separate during outgassing through the innovative use of glass tooling. The main advantages of this new technique are excellent bonds produced with simple, lightweight, low-cost tooling.

Background

SOME of the principal reasons for using titanium alloys are high strength-to-weight ratio, good corrosion resistance, and excellent high-temperature performance. For many aerospace applications, aluminum alloys are ruled out on the basis of one or more of these three factors. The low electrical and thermal conductivity of titanium also suggest additional specialized applications, such as 1) space-rated honeycomb dewar flasks and 2) reduced electromagnetic pulse (EMP) protection requirements in certain geometries.

Titanium alloys are also tractable in the machine shop. They can be cut, ground, chem-milled, and bored. Brazing and welding are possible, but for very high-performance applications, diffusion bonding enhances the utility of these alloys. A necessary condition for diffusion bonding is intimate contact between the faying surfaces. These surfaces are held in such contact for extended periods of time at carefully controlled high temperatures.

Typical of standard diffusion bonding practice is to force the faying surfaces together at high pressure in an inert atmosphere or in vacuum. The lower limit on bonding pressures using these conventional techniques is approximately 60 psi, but pressures of several hundred psi are commonly used. High-quality bonds will be formed only when the surfaces are extremely clean of all contaminant materials. Of particular concern are water and the hydrocarbons from oils, greases, waxes, and solvent residues. Since titanium oxide is soluble in the parent metal, no special procedures are required to remove or break down the oxide layer. Even water and its dissociative products of hydrogen and oxygen are soluble at the elevated bonding temperatures. Unfortunately these dissociative products will cause embrittlement when dissolved in the matrix.

The techniques of high-pressure diffusion bonding leave room for improvement in several areas, such as 1) the high pressure at the faying surfaces does not allow complete outgassing and elimination of volatile contaminants, even in vacuum, 2) tooling becomes extremely massive for large structures, and 3) complex shapes are difficult to form. The problems are compounded for honeycomb panels, because large pressures can cause excessive creep or even collapse of the core.

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*Manager, Applied Physics. Member AIAA.
†Senior Staff Member, Applied Physics. Member AIAA.

An innovative approach to diffusion bonding has been developed which allows the use of very much lower bonding pressures. In this new technique, bonding is carried out in a high-vacuum furnace. Initially the faying surfaces are kept separate by glass tooling blocks, which soften and sag at temperatures above critical outgassing. As a result, the faying surfaces come into bonding contact only after they have been thoroughly outgassed. Excellent bonds have been formed at pressures as low as 1-3 psi for a wide variety of shapes and surfaces.

Manufacturing Process

An illustration is given in Fig. 1 of the tooling required for bonding tapered honeycomb to face sheets which have been machined to form an edge member in a single bonding process. Figure 2 is a sketch of a typical method of fastening this panel into an assembly.

For this particular part, the pieces to be bonded consist of top and bottom face sheets and a honeycomb core. Preparation of the samples consists of milling the bottom face sheet to form a thick edge member and also milling the honeycomb to the desired flatness and taper. The tooling consists of a flat base platen separated from the bottom face sheet by a slip sheet. On top of this is the tapered honeycomb, the top face sheet, another slip sheet, and a thin glass sheet. The top platen serves two purposes; it supplies the dead weight needed for bonding pressure and acts as the upper half of a mold to form the desired final shape.

The top platen is initially prevented from supplying pressure by glass supports that are placed between the base and the dead weight. Vertical guides are also fastened to the

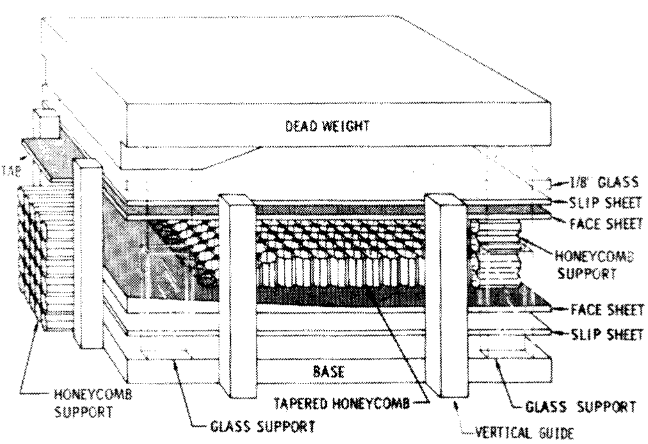

Fig. 1 Typical tooling arrangement for low-pressure diffusion bonding.

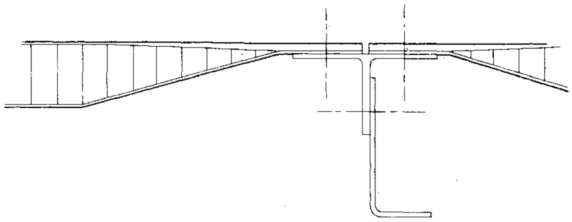

Fig. 2 Typical honeycomb sandwich edge configuration.

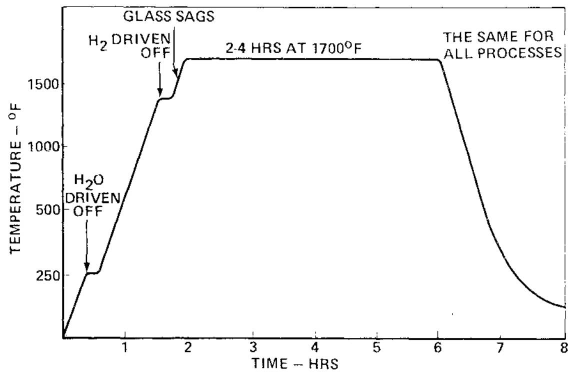

Fig. 3 Time/temperature profile for diffusion bonding.

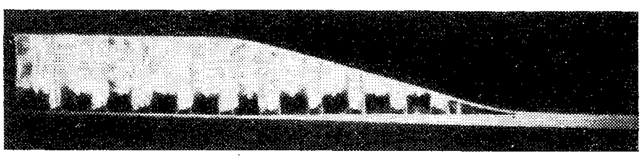

Fig. 4 Tapered honeycomb panel with edge member formed from face sheets.

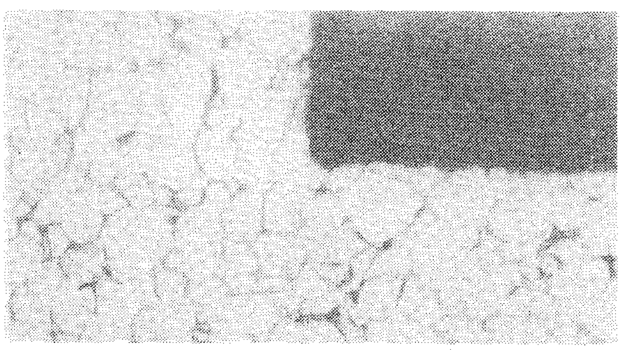

Fig. 5 Photomicrograph of a bond formed in the low-pressure diffusion process.

outside of the base to prevent the dead weight from shifting horizontally as it starts to descend near the end of the bonding cycle. In preparation of this sample, additional honeycomb supports were placed at the extreme edges of the face sheets to prevent excess sagging of the residual tabs on the top face sheet. These tabs were left on the laboratory test sample for testing purposes and would not be required in a production panel.

This assembly is placed in a vacuum furnace and the temperature is allowed to rise as the vacuum is maintained. As shown in Fig. 3, the vertical glass spacers keep the material separate until 1500°F, above the outgassing point of water and hydrogen.

The thin glass pad between the dead weight and slip sheet softens to a very viscous medium near the bonding temperature to assure that a uniform hydrostatic pressure is transmitted to the complex interface of honeycomb and face sheets. Since the contaminants have boiled off and have been

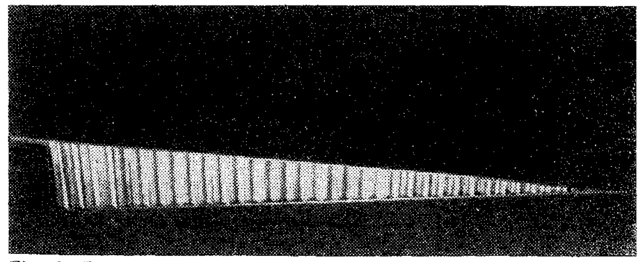

Fig. 6 Diffusion-bonded leading-edge member with reinforced back edge.

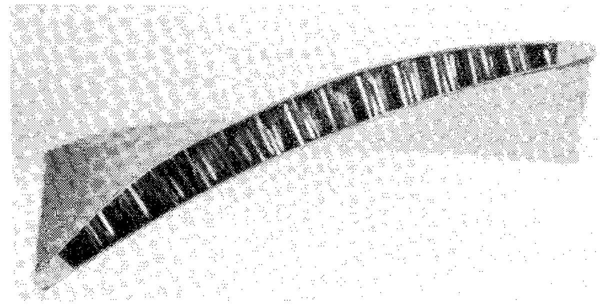

Fig. 7 Compound curvature bonded in the low-pressure process.

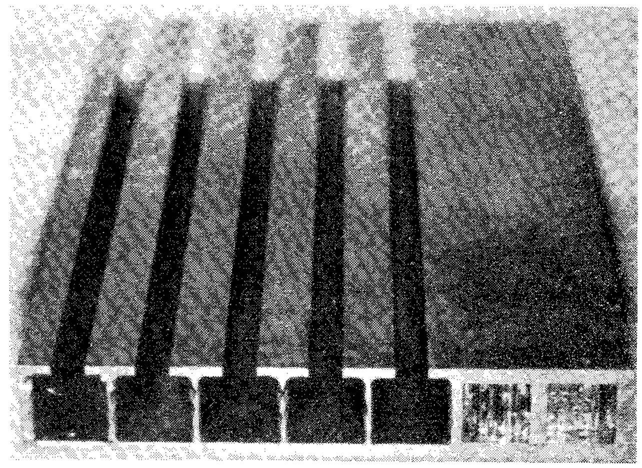

Fig. 8 Slotted heavy-duty structural member.

removed prior to putting any pressure on the bonding surfaces, the molecular-size voids are empty, so that the diffusion bond line can migrate into the grain boundaries. This contrasts with the high-pressure process where grains must compete with trapped material at the molecular void level. A photograph of a part produced in the preceding process is shown in Fig. 4.

Figure 5 is a photomicrograph of a low-pressure diffusion bond between two pieces of titanium to illustrate the quality of the bond. Note that the fillet formed in such a bond is usually of the same size as a grain. This appears to be one of the most serious limitations on this process and requires that adequate design is used to avoid stress concentration in certain structural members.

A requirement for honeycomb panels is to have simple and reliable techniques to fasten the panel to adjacent structures. If the edge of the honeycomb is not reinforced, bolting and riveting processes are ruled out, since the honeycomb may crush. Reinforced edge members must either be formed in the same bonding process as the honeycomb, or additional manufacturing steps must be added. The part described earlier and shown in Fig. 4 was produced in one step. An example of another part bonded in a single step is shown in the photograph of Fig. 6. For this leading-edge member, tapered honeycomb was bonded to a leading edge arrow head,

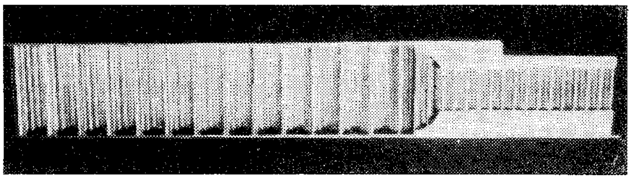

Fig. 9 Diffusion-bonded, dual-honeycomb panel.

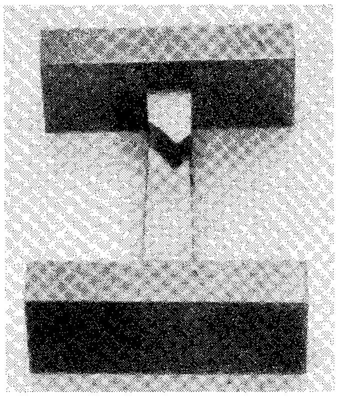

Fig. 10 Results of tensile test on diffusion-bonded structure.

Fig. 11 Tensile test of honeycomb panel showing failure at the perforation line, not the bond line.

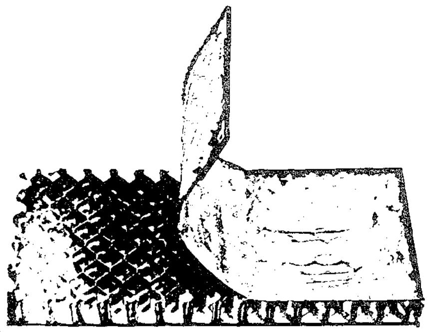

Fig. 12 Peel test of a honeycomb sandwich.

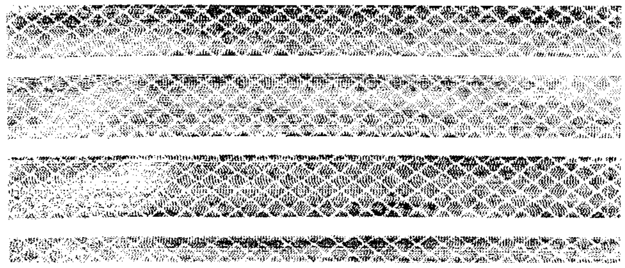

Fig. 13 Pulse-echo acoustic nondestructive test of a diffusion-bonded panel.

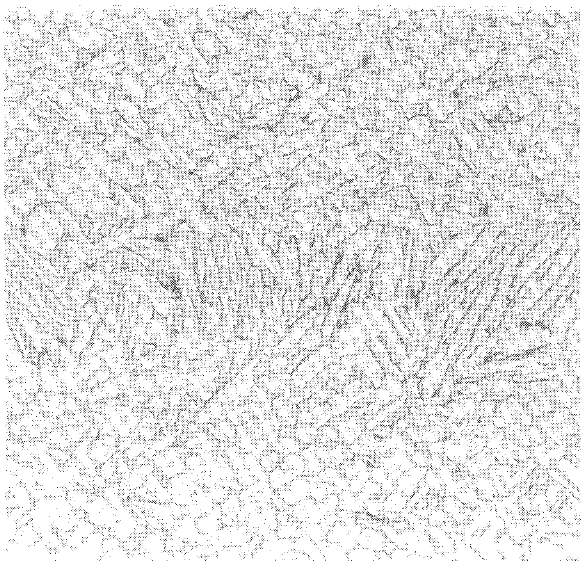

Fig. 14 Bond of alpha- and beta-phase titanium.

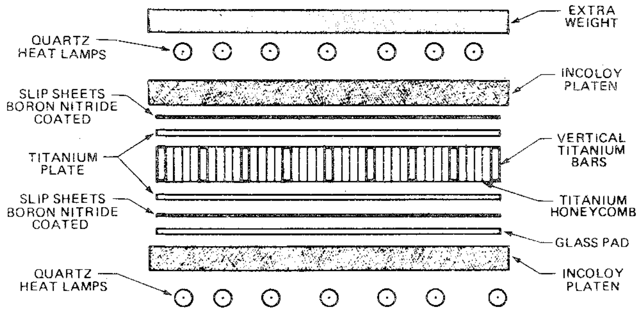

Fig. 15 Quartz heat lamps used in diffusion bonding tooling.

two face sheets, and a C-section edge member in one step. The quality of the bonds is again similar to that shown in the photomicrograph of Fig. 5. Figure 7 is a photograph of a section of a compressor blade showing that even simple compound curvatures can be bonded in this approach.

All of the previous examples consisted of very light honeycomb structures. To demonstrate the capability of bonding heavier structures, an example of ¼-in plate is shown in Fig. 8. The desired final product is shown in the left portion of the photograph, whereas the right-hand section shows the structure as it emerges from the bonding process. The honeycomb is not part of the required final structure, but was used only as tooling to keep the top surface from sagging during the bonding process. After removal from the vacuum furnace, the slots in the top plate were milled, most of the honeycomb was removed mechanically by punching it out, and the final cleanup was done by chem-milling. One useful adjunct of the final chem-milling is less erosion in the restricted areas of the joints. This results in a slightly rounded corner and acts as a fillet for stress relief. Complicated arrangements of different types of honeycomb, thin face sheets, and heavy structural members can also be bonded in one step to produce panels such as the one photographed in Fig. 9.

Test Results

To investigate the quality of the bonds, photomicrographs of selected segments have been made, and both tensile and peel tests have been conducted. A segment of the heavy structure shown in Fig. 8 was cut out and subjected to a tensile test. As shown in Fig. 10, the sample failed in the vertical riser, not at the bond line.

High-quality bonds are also produced in the honeycomb panels. Figure 11 shows a tensile test of a perforated honeycomb panel which failed on the plane of the perforations, not at the bond line. Figure 12 is another example of a peel test which demonstrates that the bonding was uniform across the large area of the face sheet and that the peel involved small segments of the upper portion of the honeycomb. This is of particular interest in view of the absence of a significant fillet at the bond. Nondestructive test (NDT) techniques for honeycomb panels are also available. Figure 13 shows pulse echo acoustic NDT of the structure in Fig. 8 after the bonding process. Satisfactory bonds show up as white in this reproduction, whereas unsatisfactory bonds would be dark in color. Techniques of this nature have been shown to be reliable in detecting unsatisfactory bonds caused by factors such as inadequate degreasing of the honeycomb after machining. Adequate bond inspection is most important if different alloys or the alpha and beta phase of identical alloys are being bonded. Figure 14 is a photomicrograph of an interlayer bond to test the feasibility of bonding the alpha to the beta phase of titanium alloys. The beta phase is the thin interlayer of elongated dendritic granular structure.

High-Pressure vs Low-Pressure Technology

A comparison between this new low-pressure and the more conventional high-pressure techniques involves a series of trades. One of the principal advantages of this manufacturing process is that the tooling is much lighter. This results in lower-cost tooling and significant energy economies. With the lighter tooling, there is much less thermal inertia, so the heating cost is less, and the time spent in going up and down in temperature is lower. This affords faster turn-around in the vacuum furnace. The glass tooling is an additional requirement for this process. However, the glass separator stilts are low-cost and may be discarded after use. The glass pad used for isostatic pressure across the complex surface can be reused if it is slid into a thin stainless steel envelope sealed by e-beam welding. However, a high-quality vacuum is required, which places additional capital acquisition costs on a manufacturing facility.

One final advantage of this process should be described. Since the pieces are kept separate under vacuum until bonding temperatures are almost reached, it is simple and fast to maintain an adequate vacuum. Particularly in the case of panels, there is no reason to use perforated honeycomb, and the resultant product consists of a series of individually sealed vacuum cells. This has the useful attribute of poor thermal conduction through the panel and prevention of "breathing" if the panel is used in an airplane or other system that undergoes pressure changes.

Cost Avoidance

A laboratory investigation was conducted to determine if standard vacuum systems could be adapted to this bonding process. In this experiment, a standard laboratory high-vacuum bell jar was used for the vacuum system with no modifications. Internal to the jar, the tooling, platens, and titanium pieces were surrounded by quartz lamps and reflectors. Standoff insulators were used to cut heat transfer to the bell jar. A sketch of the arrangement without reflectors is given in Fig. 15. Tests have been successful, and a portable heater made of quartz lamps can be used to convert existing high-vacuum facilities into diffusion bonding fixtures without having a capital requirement for construction of new vacuum furnaces.

Summary

A new manufacturing process for low-pressure diffusion bonding of titanium alloys has been described. Excellent bonds can be formed, even for very complex shapes using different metal thicknesses ranging from delicate honeycomb to heavy plate. Complex arrangements, including panel stiffening, leading-edge and trailing-edge members, can all be bonded in one step. The quality of the joints can be investigated by nondestructive techniques including acoustic processes. A high-quality vacuum furnace is needed, but standard high-vacuum systems can be converted to bonding applications by the use of quartz heat lamps and reflectors.

The process has not yet been used in other than a laboratory demonstration system, but there is no apparent limit to scaling up in size. The simple dead weight used for pressure purposes allows the tooling mass to be increased directly proportional to the area. When used properly, this new technology offers the possibility of a wider range of utilization of titanium at lower cost in aerospace products.