Titanium Diffusion-Bonded Honeycomb—Optimum Structure for Material, Joining Medium, and Configuration

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Diffusion-bonded titanium honeycomb has been developed as an outgrowth of all-welded honeycomb in steel and superalloy materials. Uniqueness of the basic concept lies in the minute flanges formed on the core ribbons, which are micro-spot-welded to the skins and in the nesting of ribbons at nodes. High reliability of sandwich panel is achieved by ribbon-by-ribbon installation and automatic welding. Structural components are then fabricated from the panels by conventional shop practices: cutting, forming, crushing, and welding. The lack of a foreign bonding agent reduces weight, eliminates contamination, and eliminates temperature limitations other than the skin material itself. Structural integrity has been proven in the extreme heat and sonic environments of steel thrust reversers on commercial aircraft. Typical applications for welded steel, with 30% weight reduction potentials, compared to brazed steel, are engine components, doors, thrust reversers, nozzles, and heat shields. The initial step for titanium diffusion-bonded honeycomb is identical to that of steel, fabrication of panel on a special welding machine. Then the diffusion bonding is achieved by a simple vacuum-anneal heat treatment, during which diffusion occurs at the core-to-face sheet interface and at the nodal point connections of the core ribbons. Titanium honeycomb shows strength/weight 50% better than brazed steel honeycomb with fatigue tension $K_T \approx 1.5$.

Titanium and Honeycomb—Optimums

FOR over a decade, both titanium as a material and honeycomb sandwich as a design concept have been the minimum-weight selections of aerospace designers for many types of structural application. Titanium, because of its high mechanical properties and low density, achieves a distinct improvement in strength/weight efficiency compared to other homogeneous materials. Honeycomb sandwich, because it permits high stability allowables with thin skins compared to other design concepts, maximizes structural efficiency for stiffness-critical design problems. With the objective of compounding these individual advantages, development of a practical combined titanium honeycomb sandwich has attracted much effort during the past six years, by both government and industry. Success, however, has been somewhat limited. Adhesive bonding and brazing developments have shown drawbacks of temperature limitations, contamination, plus difficulties of repair. In addition, the weight penalty of the filleted bonding agent is a significant 0.2 psf, of times 20% of total panel weight.

Add Diffusion Bonding

As the optimum joining method, diffusion bonding dates back almost to the dawn of civilization, with the early blacksmiths achieving parent metal strength and minimum weight. During the past six years, diffusion bonding of titanium has been the subject of numerous developmental programs in the U. S. Relative success has been achieved for stiffened plates and truss-core configurations, however, the inordinate controls required for honeycomb have precluded broad production application.

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All Three Combined

These three optimum elements, titanium, honeycomb, and diffusion bonding, have now been combined by unique designs, equipment, and processes, so as to produce an extremely efficient structural configuration. Most important both the processes and equipment of manufacture are production-proven. The same type of structure in welded steel honeycomb has demonstrated outstanding service reliability as thrust reverser components, in the most extreme of temperature-sonic-load environments.

There are two main differences between the subject type and conventional honeycomb, either adhesive bonded or brazed. Instead of a fillet of foreign material (adhesive or braze alloy) which attaches core to skins, a unique flange on each core ribbon is micro-spot-welded (subsequently diffusion bonded for titanium) to each skin. The honeycomb panel is fabricated on a special welding machine as a "plywood" concept, producing a product of maximum quality.

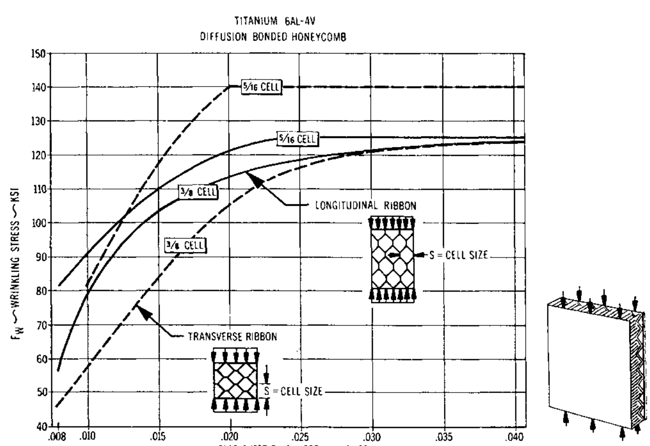


Fig. 1 Edgewise compression titanium diffusion-bonded honeycomb.

The second difference is that the all-homogeneous honeycomb sandwich is subsequently fabricated into the component. This is also in contrast to conventional honeycomb, wherein the honeycomb sandwich is generally made to the final component shape. This difference results in higher component quality, as well as improved producibility (lower costs), since fabrication is similar to sheet metal technology: forming, welding, cutting. In addition, and significant as a new approach to honeycomb components, the core can be "crushed" without loss of structural integrity.

The most significant design data that reflect structural efficiency for any design/material configuration are skin axial compression and fatigue allowables. Test data have been obtained and are presented in Fig. 1. Noteworthy, with regard to the compression allowable data, is the fact that longitudinal compression of over 100,000 psi was obtained with skin gauges of 0.013 and 60,000 psi with skin gauges of 0.008 with a $\frac{3}{8}$ cell. A smaller cell size, $\frac{5}{16}$, recently developed, can produce even higher allowables. Significant are the weights of such panels, 1.0 and 0.7 psf, respectively. In contrast to the weight of adhesive or braze alloy of 0.2 psf, the weight of the flanges is only 0.03 psf. In comparison with conventional brazed steel honeycomb sandwich, sizable increases in strength/weight efficiency, approaching 50%, are thus achievable for stability-critical design applications.

Fatigue tests of flat dog-bone specimens of skin material with attached flanges of ribbon have been conducted and the data is presented in Fig. 2. The effect of the diffusion bonding is reflected in the low effective stress concentration factor K_T (approximately 1.5). Practical experience in design of tension-critical structure has shown that the minimum effective K_T that can be considered for realistic structure is 2.5, reflecting attachments, joints, inserts, area changes, etc. Since the Stresskin basic panel would be well below this critical design threshhold level, it can be used for primary structural applications such as wing lower surfaces. The critical element would not be the panel but the joints, etc., as is the case with conventional sheet metal designs.

Even with conventional all-welded honeycomb in steel (not diffusion bonded), it appears that the micro spot welds are subcritical in size and nature. Bending beam tests were conducted and the results are shown. In contrast to conventional spotwelds with $K_T \approx 4.0$, the results indicate an effective K_T for the untreated micro spot weld of approximately 1.9.

Production-Proven Equipment

The reliability of titanium diffusion-bonded honeycomb is based upon the production-proven processes and equipment, as are used for fabrication with steel and super-alloy materials. The honeycomb core is built up by individual ribbons that are so formed as to have minute flanges at both top and bottom.

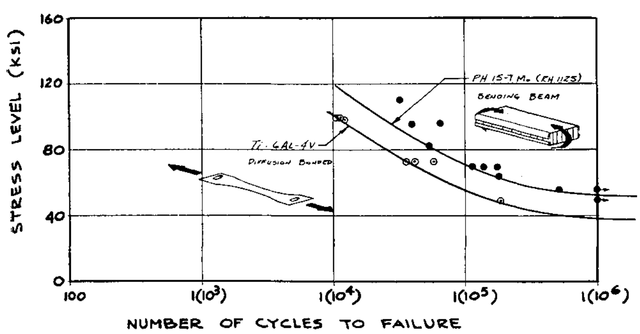


Fig. 2 Tension fatigue tests, welded honeycomb Stresskin; *R* = +0.05, all tests; ⊙ Ti-6Al-4V diffusion bonded, *Ftu* = 146,000 psi, axial tension fatigue; ● PH15-7Mo (RH 1125) *Ftu* = 192,000 psi, bending fatigue, tension face.

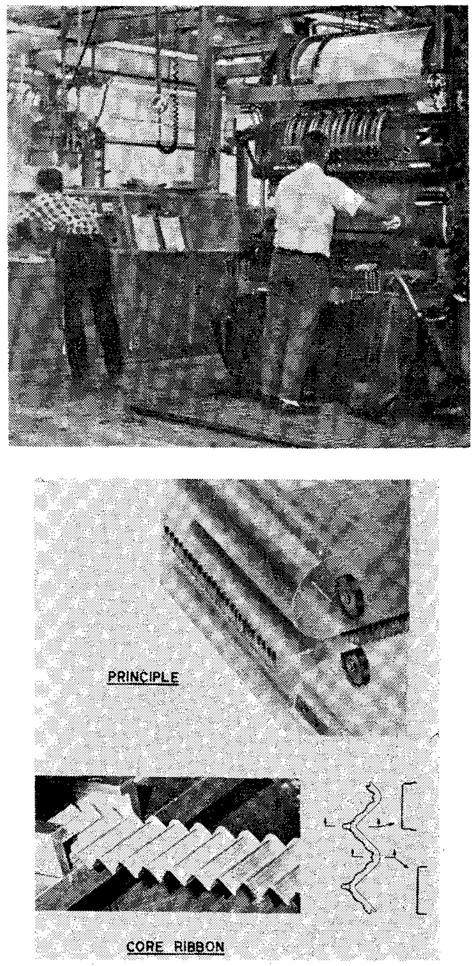


Fig. 3 Welded honeycomb panel fabrication.

This honeycomb core ribbon is then attached to the facing skins by micro spot welding of these flanges. Figure 3 shows the fabrication principle. The facing skins are loaded into the machine as coils. The honeycomb core ribbons are inserted individually and sequentially between the two skin facing sheets. Spot welding of ribbon core to skin is accomplished by welding wheels that roll across the panel. In a subsequent operation, each ribbon is integrally attached to the preceding ribbon by node welding, with an overlap at flange nodal points. This overlap provides additional structural integrity in the transverse direction. The result is honeycomb panel, but without use of any foreign material as bonding or brazing agent. Figure 3 also shows the special welding machine in operation. The control consoles for monitoring current and electronic parameters are visible to the left of the machine.

Plywood Panel Concept

From this basic plywood panel, the structural components are subsequently produced. Several advantages are obtained by this process. First, extremely high and consistent quality is achieved in the honeycomb paneling, due to the automatic spot-welding process, the ribbon-by-ribbon installation with visual inspection, the x ray and other nondestructive test methods, and by "peel" testing of panel edge and excess trim after the component shape has been cut out, as shown in Fig. 4. Secondly, the structural component that is fabricated from Stresskin has higher quality and lower cost, since it can be formed, crushed, welded, or riveted by conventional manufacturing means. Increased structural efficiency and integrity can also be incorporated, since fittings can be integrally welded to the panels.

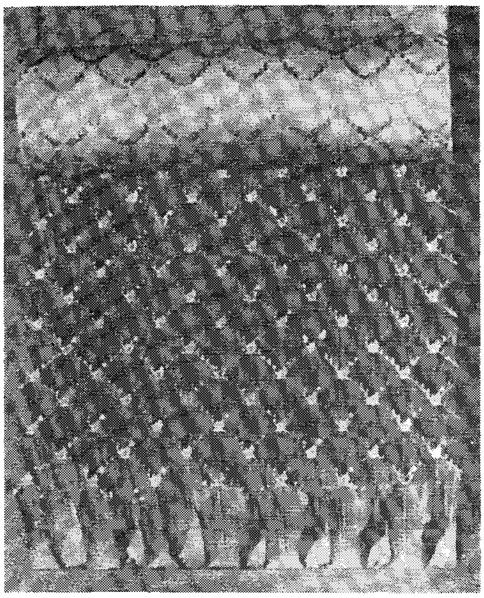


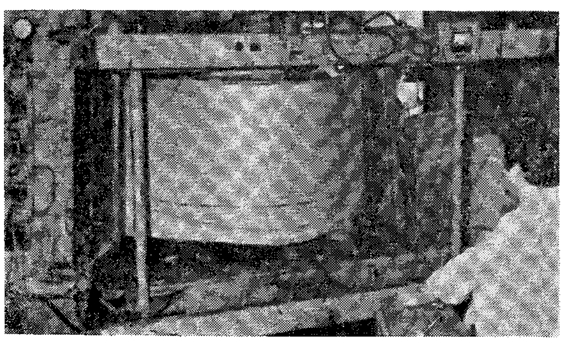
Fig. 4 Peel tests.

Easy Formability

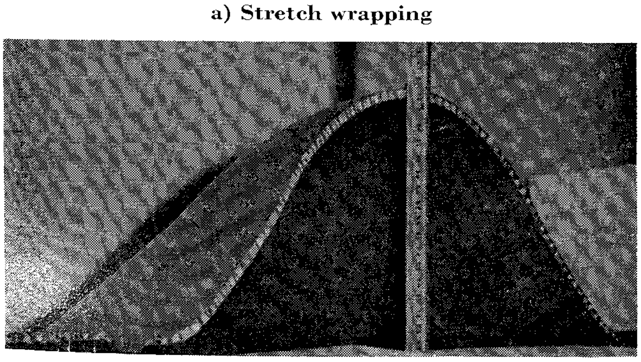
One of the unique features of the process is the flexibility in subsequent manufacturing which is permitted because there is no fillet of foreign material. The panel can be formed by achieving permanent set through tensile elongation of facing skins, with no adverse effect upon the core attachment. Figure 5 shows some of the available cold-forming processes. Titanium paneling can be similarly formed by either cold or hot forming. The adaptability of welded honeycomb to various shape requirements is shown in Fig. 6. Materials are PH15-7Mo stainless steel and Inco 718. All the honeycomb shown is $\frac{1}{4}$-in. panel in thickness, and all parts were cold formed using relatively simple tools.

Of special advantage for many applications is the feature of crushability, Fig. 7. Cold crushing can be done along edges for subsequent seam welding, or in midpanel to permit clearances. During this process, there is no loss of core-to-skin attachment, the core folding in upon itself while still providing stabilization support to the skins. Extremely high structural efficiency at fittings and joints is also achievable through this feature, with load-carrying fittings welded directly and integrally to the skins, Fig. 8a and 8b.

Since there is no foreign agent for bonding or brazing the honeycomb sandwich, the panel can be welded by conventional means, Fig. 8b. Miscellaneous fabrication operations, such as milling, sawing, drilling, and riveting, are also usable.



a) Stretch wrapping



b) Die forming

Fig. 5 Panel forming, steel and Inconel.

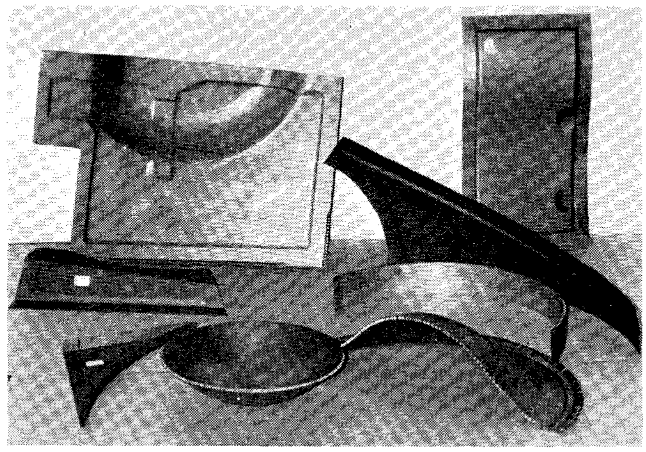


Fig. 6 Representative sections of welded honeycomb. Parts were formed cold. Materials 15-7Mo steel and Inco 718.

Minimum-Weight Frames

The crushing feature of Stresskin is of especial benefit for bulkheads, frames, ribs, etc., Fig. 9. Such components are usually fabricated of flat webs with cap members for attachment to contiguous airframe structure, and with stiffeners to preclude web buckling. With welded honeycomb these members can be eliminated, with considerable weight reduction. A one-piece component is achieved with a highly stable web and integral flanges.

As with other honeycombs, Stresskin permits achievement of high structural efficiency through use of thin skins with high stability allowables, and the tailoring of the dimensional parameters such as skin thickness, cell size, sandwich height, and core thickness to the load requirements. It also demonstrates a high resistance to acoustic energy.

The differences between Stresskin and other honeycombs are primarily inherent in the all-welded or diffusion-bonded construction. Without a foreign bonding agent there is no weight penalty (approximately 0.2 psf), no contamination or corrosion, no temperature limitation other than the material

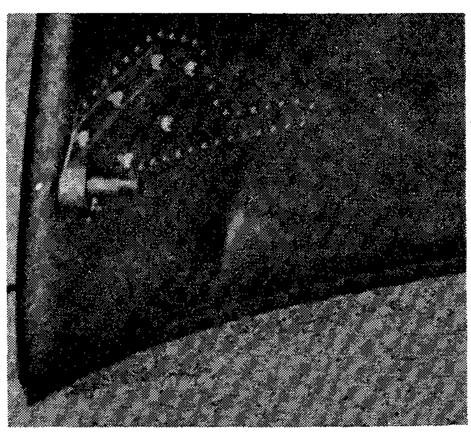


Fig. 7 Edge crush for seamwelding.

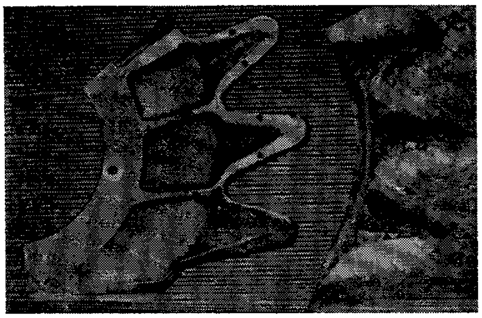


Fig. 8a Crushability for integral fitting welding.

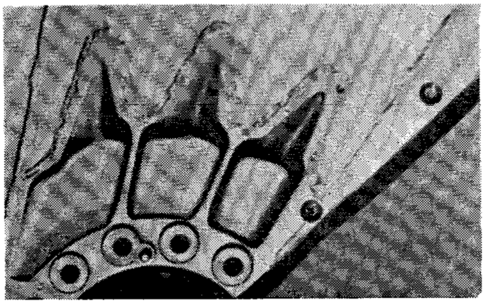


Fig. 8b Casting welding.

itself; and there is high service repairability by conventional welding. The weight of core flange is only 0.05 psf for steel and 0.03 psf for titanium.

Proven Reliability

Welded honeycomb in PH15-7Mo stainless steel has been used to fabricate the thrust reverser doors and clamshell components of a commercial thrust reverser for several years, Fig. 10. Approximately 30–40% weight reduction was achieved. It is noteworthy that, with thousands of steel thrust reverses components having flown thousands of hours in the most demanding of environments, there has not been a single instance of failure developing in an area of crushed core. With diffusion-bonded titanium, the core-skin joint integrity should be even greater.

Welded Honeycomb Sandwich with High-Temperature Materials

Not infrequently in aerospace design, heat shields have been used to protect primary structural components against high temperatures. The development of all-welded honeycomb, however, permits considerable reductions in both weight and cost by use of high-temperature materials directly in the structural honeycomb configuration, and eliminating the heatshield. For example, the Concorde nacelle centerwall, Fig. 11, was originally of brazed steel honeycomb plus protective heat shields. Replacement by Inconel 718 welded honeycomb permitted the elimination of the heat shields. Similarly on space booster heatshields, comparison firing tests on the SIB conducted at Marshall Space Flight Center last year demonstrated that the conventional composite of brazed honeycomb plus plasterlike insulation can be replaced with an all-metal welded honeycomb using high-temperature materials. Such a structure would be considerably lighter, less costly, and more reliable due to the elimination of the protective heat shield.

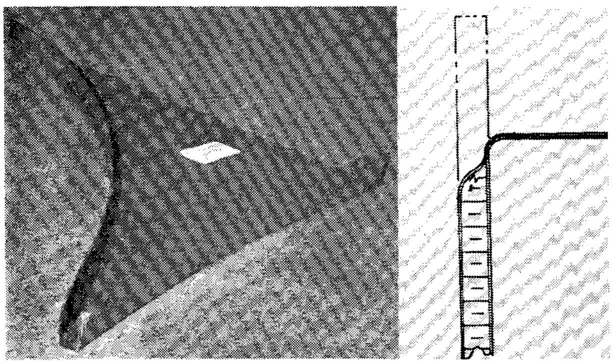


Fig. 9 Integrally flanged frames.

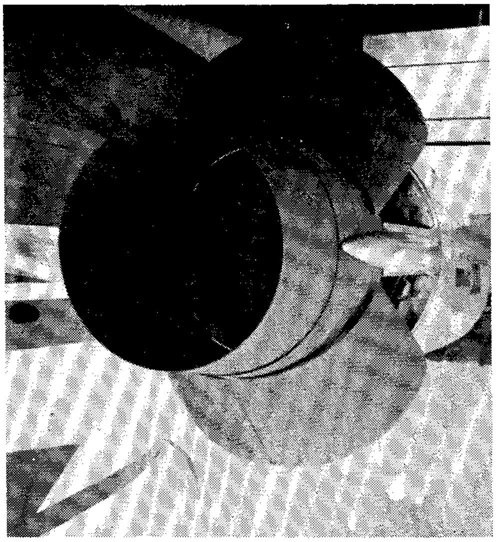


Fig. 10 Production thrust reverser.

Inconel Stresskin has also been used extensively in an advanced test unit structure for the Concorde aft engine structure, including thrust reverser and afterburner variable nozzles. The preproduction configuration test unit, Fig. 12, was designed and produced in less than one year's time, achieved weight reductions of over 25% and has performed excellently under Olympus engine bench tests in France.

Thermal Shock Tests

Since the panel fabrication process is workable with any weldable material, high-temperature materials are readily usable and many have been tested. A point of interest here would be the ability to withstand severe thermal environments and high-temperature gradients. A "hot shot" test was used to thermally shock panels which were constrained against rotation so as to develop maximum thermal stresses, Fig. 13. These tests were to a temperature of 1700°F maximum with a through panel ΔT of 1000°F, and in-plane ΔT of 1200°F. Panels fabricated of Hastelloy performed excellently, with no indication of damage after 200 cycles. Other panels tested were Inco 675, Inconel 718, Haynes 25, and Rene′ 41.

In many design applications, the effects of high-temperatures and severe thermal gradients are reflected in differential expansion and potentially critical thermal stresses. Because of the all-welded process, however, various combinations of

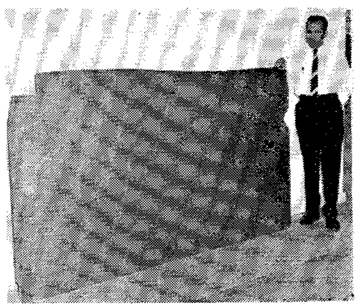


Fig. 11 Concorde nacelle centerwall, Inco 718.

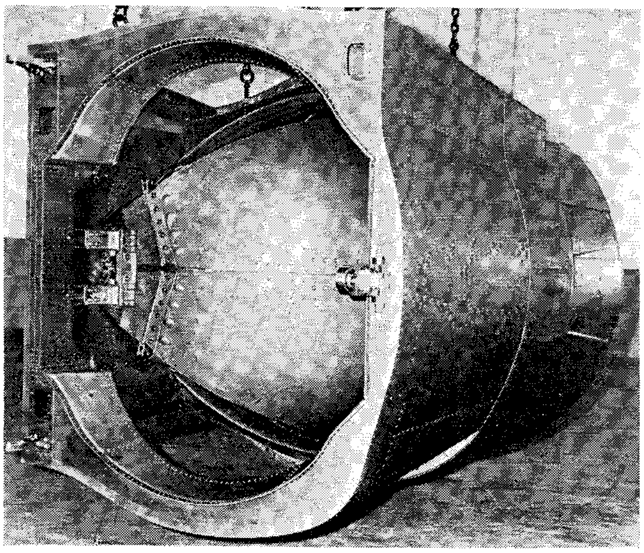


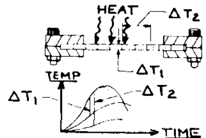
Fig. 12 Concorde aft engine structure, including thrust reverser and afterburner variable nozzles, preproduction configuration.

materials can be used, which, by selection for their thermal expansion coefficients, can drastically reduce the relative thermal strains and stresses to which conventional honeycomb of a single material would be exposed. For example, a composite welded honeycomb can be comprised of Hastelloy B outer skins (coefficient of expansion $\alpha = 6.66$ at 78–1000°F) with an inner skin selected from a material with a high coefficient of expansion such as Multimet ($\alpha = 9.13$ at 78–1000°F). The thermal stresses resulting from such a combination of materials would be significantly lower (approximately 15%) than the stresses of a single-material honeycomb. Considerable latitude for designing material configuration to the requirements of a specific problem is thus provided, the only restriction being compatibility for micro spot welding.

Titanium Diffusion Bonding, Two-Step Process

The achievement of diffusion bonding of titanium is shown by the photomicrographs, Fig. 14. The as-welded configuration shows the discrete line of demarcation between skin and ribbon flanges, and the micro*spot welds. With the low-resistance welding, the typical weld-fused nugget zone is avoided. Heat affected zones occur in the face sheet and core that are generally characteristic of pressure welds.

• SPECIMENS: 8" x 8" x 1/4".
• RESTRAINED IN JIG, TO DEVELOP MAXIMUM THERMAL STRESSES IN SKINS.



SKIN MATERIAL	t	TMAX	ΔT_1	ΔT_2	NO. OF THERMAL CYCLES		
					DIMPLE	BUCKLE	CRACK
INCO 718 (AGED)	.013 .013	1400	1000	1200	—	—	1
INCO 718 (AGED)	.018 .013	1400	1000	1200	—	—	1
INCO 718 (S.A.)	.013 .013	1400	1000	1200	—	18	*
INCO 718 (S.A.)	.018 .013	1400	1000	1200	—	30	*
INCO 625 (A W)	.016 .016	1400	1000	1200	160	200*	*
HAYNES 25	.017 .013	1400	1000	1240	160	200*	*
HAYNES 25	.025 .013	1400	1000	1280	200*	*	*
HASTELLOY X	.020 .015	1400	1000	1240	200*	*	*
HASTELLOY B	.015 .015	1400	1000	1260	200*	*	*
WASPALLOY	.016 .013	1700 1500	1000 700	1400 1200	3* 300*	*	*

* PHENOMENON DID NOT OCCUR.

Fig. 13 Thermal gradient tests on various welded honeycomb panels.

In the photomicrograph taken after the heat treatment process, the diffusion of the titanium atoms is noted across the interface. Such diffusion bonding is also achieved at the nodal point connections. During the postweld anneal there is sufficient intimate surface contact at the interface to permit diffusion bonding to occur.

Diffusion bonding is normally achieved by combining three parameters: pressure, temperature, and time. For titanium Stresskin, however, a unique two-step approach was developed taking two parameters at a time. Step 1 is accomplished in the stresskin machine which applies pressure and temperature to achieve a pressure weld. A normal air atmosphere is used with "clean room" operation. Step 2 is accomplished in a vacuum oven, combining temperature and time to achieve diffusion bonding. The panels are simply hung or laid flat without pressure (unless temperature forming is desired). Two hours at 1600°F in a 10^{-4} atmosphere has been found to be very effective, although a longer dwell at lesser temperature is also satisfactory.

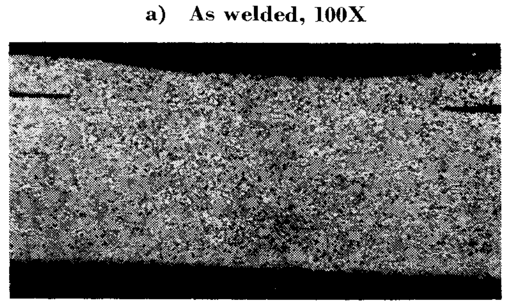
Titanium diffusion-bonded honeycomb benefits from the proven manufacturing and quality control processes currently used for production of steel components. Fabrication of even 0.008 skins has been achieved without any pinholing, and it appears that skin gauges as low as 0.005 mils will be feasible.

Titanium Panel Cost and Cost-Weight Effectiveness

Because of the economies obtainable from the plywood concept from which the panel is subsequently manufactured into a component, relatively complex hardware fabricated of steel has been produced at costs of only $60–70/lb. Estimates for titanium diffusion-bonded honeycomb would be $75–150/lb depending on complexity, volume, etc. On a paneling basis, present prices of approximately $200/ft² are expected to reduce to $75–100/ft² for volume production. This is dependent, however, on material costs of titanium in the quantities and for the gauges required.

Through this paneling concept, the number of detail elements are far fewer than with conventional skin-stringer construction. There is also considerable reduction in the required number of substructural elements such as ribs or

a) As welded, 100X



b) Diffusion bonded; 100X

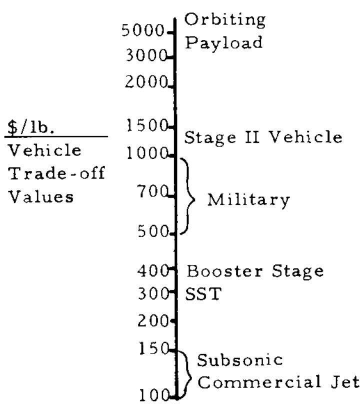
Fig. 14 Titanium diffusion-bonded honeycomb.

STRUCTURAL "COST"/WEIGHT EFFECTIVENESS

I. VEHICLE "TRADE-OFF" VALUE

FUNCTION OF:

- o Vehicle Type
- o Mission: commercial, military
- o Design "growth" factor:
  - Range
  - Payload
  - Etc.
- o Operation
- o Maintenance



II. OPTIMUM STRUCTURAL/MATERIAL DESIGN

TYPICAL COSTS* - AEROSPACE STRUCT.				
Config. \ Mtl.	Alum.	Steel	Ti	Rene, Inco, Wasp, Hast.
Skin-Stringer Frame	30-60	40-70	75-150	75-125
Bonded Honeycomb	10-40	40-70	60-150	-
Brazed Honeycomb	-	75-125	-	-
STRESSKIN	-	60-75	100-150	75-125

*Production quantities, $/lb.

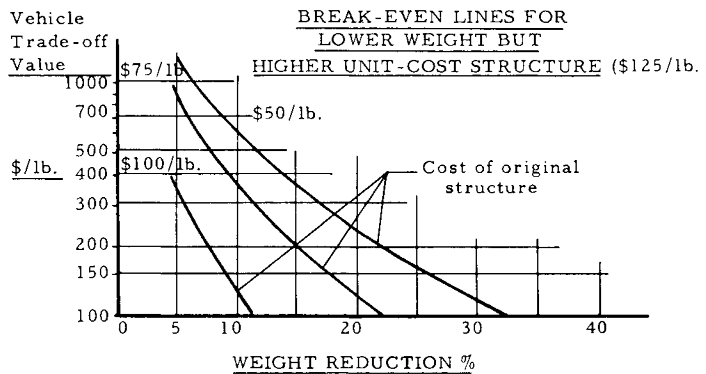


Fig. 15 Structural cost-weight effectiveness.

frames. The result is an anticipated reduction in weight of 15–30%, plus also the potential of cost economies.

Even if unit costs per pound of final structural were greater, vehicle optimization from the viewpoint of structural cost/weight effectiveness points up the benefits of weight reduction vs costs for candidate concepts. For most aircraft, the payload carried represents only a small fraction of the total structural weight. A small reduction in airframe weight therefore has a substantial performance payoff, whether measured in terms of payload gain, range gain, or reduced airframe size to accomplish the same mission objective. The value of weight reduction should be dependent upon vehicle type, the mission (commercial or military), operation, maintenance, etc. Economic analyses have indicated that nominal tradeoff values or premiums per pound of weight saved should be generally about as follows (see Fig. 15): for supersonic transport airplanes approximately $300/lb, for subsonic commercial jets $100–150/lb, for military aircraft $500–1000/lb, for space booster vehicles $400/lb, second stage $1300, and $5000/lb for orbiting vehicles. It is recognized that such numbers can only be approximate. In specific instances, such as when missions cannot be performed without weight reduction, weight savings would be worth considerably more. In other instances, however, an aircraft may be adequate for its mission requirements, and the value of weight savings would then be negligible.

However, during the preliminary or detail design phases, when candidate structural concepts are being compared (weight and cost) in terms of vehicle tradeoff values, significant increases in unit cost can be justified for weight reduction, as shown by the chart. This illustrates the break-even points for lower-weight but higher-cost structure. For comparison purposes, titanium Stresskin is considered at $125/lb. For an aircraft with a vehicle tradeoff factor of $500/lb, a weight reduction of only 12% is necessary for a $125/lb structure to be superior to a $50/lb structure. For a vehicle tradeoff factor of $300/lb, the break-even point compared to structure costing $100/lb would be only 6%.

It is anticipated, however, that not only will the weight reductions be much greater with titanium diffusion-bonded honeycomb (such as 20–30% for many design applications), but also that unit costs per pound will be comparable to, if not lower than, competitive structural configurations. Because of its relative ease of fabrication into components, it should be competitive with complex structures manufactured of sheet metal.