NEW ADVANCEMENTS IN TITANIUM TECHNOLOGY AND THEIR COST AND WEIGHT BENEFITS

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SUMMARY

A new technology is emerging that promises to revolutionize the field of metal fabrication and design, particularly that of titanium. A process that combines both the superplastic and diffusion bonding properties of metal into one concurrent operation is being developed at Rockwell International. Estimates using this technology have indicated that this combined process will result in cost savings up to 70 percent when compared to conventional construction methods, while also saving weight. Many structural forms are possible including sandwich structures made by expanding face sheets and core against die forms. The classic difficulties normally associated with fabricating sandwich structures, such as parts fit-up, close tolerances, adhesive or braze alloy strength, do not exist with this technique. The total potential of Rockwell's patented new processes is limited only by the ingenuity of the designer and is expected to effect significantly future airplane concepts and criteria.

INTRODUCTION

The science of aircraft technology is continually being pressured to develop new and innovative concepts to produce aircraft with higher performance and lower cost. This is particularly true in the field of aircraft structures, since this discipline represents a large fraction of the cost and weight of aircraft. A new technology is emerging in the field of titanium fabrication which promises substantial progress in the state-of-the-art towards meeting the challenge of reducing airframe costs. These new and inventive processes combine superplastic forming and diffusion bonding (SPF/DB) into a single process that promises to revolutionize titanium fabrication and structural design.

New design concepts heretofore considered impractical because of high costs and fabrication difficulties are now possible using the SPF/DB process. These concepts include sandwich structures in which face sheets, core, and edge members can be formed and bonded into a practical structure, all in one operation. Other structures such as beaded panels, corrugated or sine wave spars and frames, panels with integral frames, etc, are now possible, at low cost, with these processes.

These complex configurations have been produced in titanium by the SPF/DB processes in a single cycle which could otherwise not be fabricated by conventional methods. Manufacturing feasibility and cost savings potential have been established through both Rockwell IR&D efforts and Air Force contracts. Cost savings of up to 70 percent and weight savings up to 40 percent have been estimated when compared to conventional titanium fabrication methods, because of the large reduction in labor costs and the ability to design more efficient structure made available by SPF/DB technology.

PROCESS DESCRIPTIONS

Superplasticity in titanium is a phenomenon in which very large tensile elongations may be realized because local thinning (necking) does not occur under the proper conditions of temperature and strain rate (figure 1). Diffusion bonding is the joining of titanium under pressure at elevated temperature without melting or use of bonding agents. Fortunately, through a natural occurrence, superplastic forming and diffusion bonding of titanium can be accomplished under identical parametric conditions. This is the basis for the combined SPF/DB processes.

Superplastic Process

Rockwell has pioneered the superplastic forming (SPF) of titanium alloy sheet components. Much additional work was done, under Air Force contract, with the Air Force Materials Laboratory (ref. 1). It has been shown that SPF monolithic components can replace designs requiring numerous details and large numbers of fasteners while realizing significant cost and weight savings (figure 2). In this example, a superplastic frame was redesigned to replace a conventional frame composed of eight separate hot-sized and machined parts and 96 fasteners. As shown in the figure, cost estimates indicating savings of 55 percent are possible, accompanied by weight savings of 33 percent. SPF is an approved process for the B-1, with Aircraft 1 through 3 having several superplastically formed components. Aircraft 4 will incorporate much more additional SPF structure. Space shuttle components, also being made by SPF, include windshield seal frames which replace an aluminum design using formed sheet and machined details. Six SPF/DB frames replace 25 machined fittings, 72 sheet metal details, 30 splice plates, and 396 each of screws, washers, and nuts (figure 3).

In the Rockwell patented SPF process, a metal diaphragm, possessing superplastic properties, is placed across a die (figure 4) containing the desired part configuration, and sealed by the top plates in an hydraulic press. Argon gas is introduced and heat applied through ceramic platens to heat the diaphragm to temperatures at which the material becomes superplastic. For titanium, this temperature is 925° C (1,700° F). Argon gas pressures up to a maximum of 2×10^3 kPa (300 psi) are varied to produce stretching at the material's proper strain rate. This is an arbitrary pressure limit and is a function of tooling limitations rather than forming limitations. The actual forming time at temperature is a function of the part configuration and strain rate limitations and can be as low as 20 minutes. The resulting part will exactly match the die configuration, since there is no springback associated with the process.

Structural configurations which were previously considered impossible with conventional forming methods are easily fabricated with this process. Figure 5 shows a sine wave beam made using SPF which is an efficient structural shear member, particularly in lifting surface structure. The frame shown previously in figure 2 also produces an efficient shear-resistant structure, with beads or corrugations forming an integral part of the structure.

Superplastic Forming Combined with Diffusion Bonding (SPF/DB)

Titanium temperatures required for diffusion bonding are fortunately coincidental with those required for superplasticity. The inventive combination of these two processes has yielded impressive results. The Rockwell SPF/DB patented process allows not only the forming of complex sheet metal structure, but, by preplacing details in the tooling, selected areas of the structure can be reinforced, padded, or otherwise joined to functional fittings or attachments, as shown in figure 6. The argon gas provides the pressure required for diffusion bonding of the details, while the plasticity of the materials ensures a perfect part fit to produce highly reliable, repetitive components.

A further extension of the process utilizes diffusion bonding and expansion forming, as shown in figure 7. This illustrates the formation of a waffle or beaded-type structure into a die cavity by inserting a gas pressure source between two sheets, thereby expanding the material superplastically into a die cavity. Prior to this operation, the interfaces are diffusion bonded together either by applying die pressure where desired, or by using gas pressure to diffusion bond the interfaces.

The gas pressure method requires the use of an interface material (stop-off compound) to prevent diffusion bonding where desired. This material is applied to the sheets by either spraying or through the use of a silk screen process. This stop-off, then, prevents diffusion bonding in selected areas where applied and controls the shape of the finished part through the applied stop-off pattern and forming die. A more reliable part is produced in this manner because the gas pressure is uniformly distributed and die fit-up is not critical as would be the case using the die pressure approach. This procedure is explained in more detail later in this paper under "B-1 APU Door."

Expanded Sandwich

A particularly important development in SPF/DB is the method of expanded sandwich structure. In this Rockwell patented process, at least three titanium alloy sheets are diffusion bonded in selected areas and then expanded apart by internal pressure into the containment tooling. Thus, an integrally stiffened sheet metal structure may be produced in one operation.

The process (figure 8) is similar to that described in the foregoing except that the stop-off compound is applied to both sides of a core sheet to prevent diffusion bonding. The multiple sheet pack is inserted into the die, heated to SPF/DB temperatures, gas pressure applied to one side of the pack to diffusion bond the interfaces, and then applied between the face sheets (on both sides of what will become the core sheet), and expanded to final shape. No differential pressure is applied across the core sheet during this cycle. The core sheet is formed into final shape by pulling of the core apart through the diffusion bonds at the face sheets. This effectively stretches the core sheet superplastically into final shape as the face sheets are forced into the die cavities by the argon gas pressure. The final shape of the part is dictated by the die shape and the stop-off pattern applied to the core sheet.

The sandwich core produced by this process is a function, therefore, only of the pattern produced by the stop-off prior to stretching of the core. No tooling is required to produce the core, no inserts requiring removal are used, no fit-up problem exists, and all edge members are produced simultaneously with the core forming process. Additionally, other structural forms can be preplaced in the die as desired and concurrently diffusion bonded to form attachment angles, fittings, etc (figure 9). Compound contours are not a problem with this technique since fit-up problems are nonexistent and the forming and bonding are done in a superplastic state. A large variety of sandwich core configurations are also possible with this technique. Since no tooling is required to form the core, its final configuration is strictly dependent on the stop-off compound pattern and the ability to stretch the core from its original flat sheet configuration. Figure 10 shows typical representative core configurations that have been fabricated to date. These include a truss core, dimpled core (core bonded to face sheets in intermittent spot pattern), and sine wave core (core bonded in a parallel sine wave pattern). The process also readily permits core variations within the same panel; i.e., all types of core can be utilized within the same panel by varying the stop-off pattern if an advantage can be gained with this approach.

MATERIAL PROPERTIES

Experience accumulated on SPF/DB hardware to date indicates (1) that the strength levels resultant in the hardware are equivalent to that obtained with the SPF cycle only, and (2) diffusion bonds have been 100-percent complete to the limit of NDT detection, and possess essentially parent metal properties.

Under a current Air Force SPF/DB program (ref. 2) and under a Rockwell IR&D program on sandwich development, a variety of strength data has been obtained. Property comparisons were made among the data from DB and SPF areas of a SPF/DB-processed part, data from superplastic-formed parts, and data from diffusion-bonded parts. The comparison indicates that the mechanical properties of the Ti-6Al-4V parts subjected to SPF, DB, or SPF/DB processes are similar.

The results of single lap-shear tests showed 5.44×10^5 kPa to 6.1×10^5 kPa (79.0 to 89.5 ksi) ultimate shear strength at the DB interface (table I). The shear values agree well with those obtained on double lap-shear tests of 5.522×10^5 kPa to 5.93×10^5 kPa (80.1 to 86.1 ksi) for the fully bonded interface, indicative of parent metal strengths. The slightly larger scatter in test results for the single lap-shear tests is believed to be caused by the off-centered or asymmetric loading of the specimen.

Static peel tests resulted in parent metal fracturing without evidence of peeling at the bond plane (table II). The sheet gage used and the part geometry simulated in the test parts are representative of the SPF/DB full-scale parts to be fabricated. The peel test fracturing mode signifies that the DB joint strength exceeds that of the SPF metal.

The strength tests to date on sandwich, limited to the truss core type, are summarized in table III. In all tests, load fall-off resulted from predictable buckling, wrinkling, or crushing of the structure, as delineated in the table. No separation of diffusion bond joints occurred in the tests. No cracks were developed in the metal at maximum load. Maximum load was a function of the structure geometry and the properties of the 6Al-4V titanium alloy. Loading deflections far beyond the deflection at maximum load were required to develop cracks in the structure. The tests showed that the diffusion bond joints were sound and did not reveal any indication of material degradation by the process used to produce the structure.

At present, prediction of the structural capability of discrete designs will require specific verification. However, generalizations emerging from current and future work will allow increasing ability to predict structural behavior with confidence.

B-1 APU DOOR DEMONSTRATION

A significant milestone for the application of the SPF/DB process to a full-scale B-1 part was accomplished as a function of a present Rockwell/AFML development contract (ref. 2). A 0.39 m^2 (600 square inch plan area expanded laminate part was bonded and formed in a single operation. Figure 11 shows the door configuration after trimming. A picture-frame doubler in between the two face sheets and a smaller doubler were required as part of the basic door. In addition, the smaller doubler was bonded to the diaphragm prior to forming and was subsequently superplastically expanded into a female cavity. The SPF/DB cycle was applied with a predetermined pressure time cycle in a 40 x 10^6 newton (4500 ton) hydraulic press with existing heating platens. The door configuration obtained was well defined and the hollow sections fully formed, including the one area where two diffusion-bonded sheets were also weld joined. The demonstration of the concurrent SPF/DB concept on a complicated expanded section of the 0.39 m^2 plan area door was successful. Subsequent ultrasonic inspection indicated diffusion bonding continuity with no detectable disbonds.

Tooling

Tooling consists of an upper plate, an insert, and a container. The upper plate incorporated a projection to effect the seal during the process cycle. The container was a thick block of steel with a machined cavity to receive the insert. Ramps were provided around the interior periphery of the container to ease removal of the insert. The container has two main purposes: (1) To act as a venting cavity for the argon gas to escape as forming progresses which prevents gas entrapment, and (2) to provide the means for gas pressure diffusion bonding to the lower side of the diaphragm. In addition, the container becomes a universal holder for other expanded laminates by the utilization of different inserts.

The container and insert were machined using numerically controlled methods, while the top plate was conventionally machined. Figure 12 shows the machining being accomplished, and figure 13 shows the three completed tooling sections.

Stop-Off Application

An important consideration in assembly of the titanium sheet metal details is the application of stop-off material to those areas of the diaphragm which are not to be bonded. Locating the stop-off pattern for correct alignment with the tool cavity requires the use of templates indexed to the titanium sheet and the tool. A recently developed method of applying stop-off utilizes a silk screen process. The application of the stop-off and the resulting pattern on the titanium sheet are shown in figure 14. The stop-off slurry must, of necessity, be of a specific consistency and able to retain wetness. Dimensional accuracy can be maintained by use of the silk screen through proper locating points.

Door Fabrication

The completed door shown in figure 11 was highly successful both in quality of bonds and accuracy of forming. As stated previously, the basic door consisted of two sheets formed into a hat-stiffened structure with a doubler required around the periphery and one in an area of the center section where a fire access door is added later.

The picture-frame doubler was made up of four individual sheets welded together with a rectangular opening. The interior edge incorporated a 60-degree chamfer to allow the preforming of the diaphragm during the bonding cycle, as shown in figure 15.

The full-scale APU door was fabricated by diffusion bonding in selected areas, as determined by the stop-off pattern, and superplastically expanded to complete the part. Diffusion bonding time and pressure were determined by an analytical prediction curve which had been verified through previous subscale tests. For this part, the diffusion bonding cycle used 2×10^3 kPa (300 psi) argon gas pressure applied for 1-1/2 hours.

The forming, or superplastic expansion cycle, was selected on the basis of two separate tool depths (cavities). A cycle was selected so as to allow the material to form into the shallow cavity bottom surface without rupturing. At this point, the pressure-time profile was changed to form effectively the deeper cavity.

After completion of the SPF/DB cycle, the pack was allowed to cool to 650° C (1200° F) with a continuous flow of argon gas through the tooling and the formed part. The part was removed with ease at a temperature of approximately 600 - 650° C (1100° - 1200° F).

Part Evaluation

The APU door was cleaned and evaluated visually and by NDT. The following observations resulted:

(1) The part was fabricated in a manufacturing environment using production facilities.

(2) Full forming occurred on the diaphragm side and conformed to the die configuration.

(3) Part cleanliness was good, verifying that shielding during elevated temperature exposure was adequate.

(4) Ultrasonic inspection showed satisfactory bonds throughout.

COST/WEIGHT IMPACT

Evaluations conducted to date have shown significant cost/weight reductions using this process, when compared to conventional construction methods. Additionally, substantial reductions in part count, fasteners, and tool quantities have resulted. Some examples of types of estimated savings are as follows.

Typical Fuselage Structure

A comprehensive conceptual study was conducted on a typical fuselage-type structure consisting of titanium sheet metal and machined ribs, longerons, and chem-milled skins fastened together with a standard riveting system. This design is illustrated in the exploded view of figure 16. An alternate design using a concept similar to the expanded waffle, where diffusion bonded skins with hat-section stiffeners form the basic skin panel, was designed to include integral frame structures. This is shown in figure 17. The structure is expanded into a die in a manner similar to the procedure used in the APU door. Except for the fact that deeper drawn sections and larger panels are required, the concept is very similar to the APU door configuration with doublers bonded to the integral frame as it is formed into the die cavity. Sine wave webs are formed in the frames to provide shear-resistant structure. The results of this conceptual design study are shown in table IV. As indicated, estimated weight savings of approximately 40 percent and cost savings approaching 50 percent can be realized with the SPF/DB concept.

Cost and weight savings were also estimated for the APU door previously described to determine the impact of SPF/DB. Figure 18 illustrates the potential cost savings of the SPF/DB concept over that of the original design which was machined from a titanium plate. Weight savings of 30 percent were realized while cost savings of 50 percent were estimated for production B-1 aircraft.

Equivalent cost savings were also estimated for sandwich structure. Figure 19 shows sandwich structure savings when compared to other S-O-A sandwich structures. One of the structures of figure 19 is a welded sandwich panel compared to a truss core SPF/DB panel. Savings of 45 percent were realized. Figure 19 also shows a comparison of an engine shroud with the original design a brazed-titanium honeycomb panel. Cost savings of 45 percent can be realized using the SPF/DB concepts.

All of the foregoing estimates were based on production quantities of 240 aircraft. They were estimated from drawings using Rockwell cost estimating procedures and are used for comparison purposes only and are not intended to represent absolute cost data.

Advanced Supersonic Aircraft Studies

SPF/DB can obviously impact a large airplane such as an advanced high-speed transport aircraft since this aircraft will use large amounts of titanium. To determine its impact, a study was undertaken under a NASA contract (ref. 3) to evaluate its potential cost and weight savings on an arrow wing supersonic transport commercial aircraft. The evaluation used as a baseline a brazed-titanium honeycomb wing structure and a skin/stringer titanium fuselage. Trade studies were conducted comparing this baseline with several types of SPF/DB concepts including integral frames, truss core, dimpled core, superplastic spars, and superplastic frames. A typical concept applicable to both wing and fuselage is shown in figure 20. This concept consists of a truss core expanded sandwich for the fuselage skin and wing skins. Sine wave frames for the fuselage and full depth sine wave spars for the wing spars were used. As expected, large cost savings and substantial weight savings were realized. The results of the studies are shown in figures 21 and 22 for this and several other concepts. Potential cost savings up to 60 percent can be realized with potential weight savings up to 30 percent.

CONCLUDING REMARKS

The effort expended to date on the SPF/DB processes has definitely proven the design advantages and manufacturing feasibility of this technology. Cost evaluations conducted on a variety of concepts producible by these techniques have indicated substantial savings over present state-of-the-art means of titanium construction and, in some instances, over aluminum construction. It appears inevitable that SPF and SPF/DB will be extensively applied to future aircraft.

However, much work remains to be accomplished. Although small hardware parts have been demonstrated to actual aircraft requirements, application to large-scale hardware remains to be accomplished. A giant step in this direction will be the successful fabrication of a large B-1 engine access door some time during the first quarter of 1977. This contract has recently been signed to design, fabricate, and test one of these doors for the B-1 to demonstrate the transferability of SPF/DB technology to large-scale hardware. Figure 23 illustrates the door configuration and structural concept that will be pursued. This structure will be a corrugated sandwich using SPF/DB techniques and will be fabricated in one operation using expanded sandwich structure, including concurrently diffusion bonded hinge fittings as well as latch structures. Estimates have shown the SPF/DB design will be 40 percent less costly than an equivalent aluminum honeycomb design and 20 percent lighter. The successful culmination of this effort into a 1.22 x 2.74 m (4 x 9 ft.) structural section will conclusively demonstrate the feasibility of SPF/DB technology for large-scale aircraft hardware.

The potential impact of this technology on advanced transports and military aircraft can obviously be very significant. However, the data base for this technology does not presently exist to permit the design and fabrication of a complete aircraft. Although some structural design data are available, much more work must be accomplished before an airplane can be completely designed with this technology. Such structural design data as static allowables for new structural concepts must be developed. Fatigue data, fracture mechanics data, new materials applications, crack stopping techniques, and long-term environmental effects are among those requiring characterization.

The SPF/DB technology is expected to revolutionize the field of aircraft structural design and fabrication. New design concepts heretofore impossible or extremely difficult with state-of-the-art methods are relatively easily made with SPF/DB technology. To date, the potential of these patented processes has only been scratched. The future will see new concepts, as yet unthought of, limited only by the ingenuity of the design/producibility team.

REFERENCES

1. Superplastic Forming of Titanium Structures, AFML-TR-75-62, April 1975.

2. Manufacturing Methods for Superplastic Forming/Diffusion Bonding Process. IR 798-5 (I, II, III, IV, V) 1975. Air Force Contract No. F33615-75-C-5098.

3. Evaluation of Low Cost Titanium Structure for Advanced Aitcraft. NASA CR-145111, 1976.

TABLE I.- RESULTS OF SINGLE LAP-SHEAR TESTS

Test area	Grain direction	Specimen ID	Test thickness		Shear ultimate strength	
			mm	(in.)	MPa	ksi
DB	L	4-19	5.8	0.230	555	80.6
		4-20	5.8	.230	588	85.3
	LT	15-15	3.9	.155	595	86.3
		15-16	3.9	.155	552	80.1
		15-17	2.56	.101	617	89.5
		15-18	2.56	.101	569	82.6
	L	8-23	2.1	.084	561	81.4
		8-24	2.1	.084	600	87.1
		16-35	2.6	.103	576	83.5
		16-36	2.6	.103	581	84.3
	LT	8-21	2.1	.084	545	79.0
		8-22	2.1	.084	588	85.3

TABLE II.- PEEL TEST RESULTS, SPF/DB CORNER INTERSECTION

Test area	Specimen ID	Gage		Peel strength	
		mm	(in.)	N/mm	lb/in.*
DB/SPF juncture	15-1	1.8	0.071	258	1475
	15-2	&	&	251	1435
	15-3	1.8	.071	229	1310
	15-4			262	1495
	13-1	1.8	.071	224	1278
	13-2	&	&	230	1312
	13-3	3.2	.125	236	1350
	13-4			232	1325

*Parent metal (SPF member) failed.

TABLE III.- MECHANICAL PROPERTIES OF EXPANDED SANDWICH STRUCTURES

Type test	Specimen size mm (in.)	Thickness: Face sheets mm (in.)	Thickness: Core mm (in.)	Test direction	Maximum stress MPa (psi)	(
Flatwise tension	12.7 x 44.5 x 44.5 (1/2 x 1 3/4 x 1 3/4)	1.8/1.5 (0.070/0.060)	0.3 (0.012)	-	>3.287 (>476.8)	Adhes speci fixtu
Flatwise compression	12.7 x 50.8 x 50.8 (1/2 x 2 x 2)	1.65 (.065)	.3 (.012)	-	1.15 (167.4)	Core
	10 x 76 x 76 (.4 x 3 x 3)	.81 (.032)	.3 (.012)	-	2.2 (319.3)	Core
Edgewise compression	12.7 x 76 x 76 (1/2 x 3 x 3)	.46/.4 (.018/.016)	.3 (.012)	Transverse	79 (11,458)	Face
	12.7 x 76 x 76 (1/2 x 3 x 3)	.48/.46 (.019/.018)	.3 (.012)	Transverse	79 (11,523)	Face
	12.7 x 76 x 76 (1/2 x 3 x 3)	.46/.43 (.018/.017)	.3 (.012)	Longitudinal	653 (94,728)	Core buckl
	12.7 x 76 x 76 (1/2 x 3 x 3)	.48/.46 (.019/.018)	.3 (.012)	Longitudinal	702 (101,927)	Core buckl
Core shear	12.7 x 38 x 127 (1/2 x 1 1/2 x 5)	1.65 (.065)	.3 (.012)	Transverse	1.047 (151.9)	Core
	12.7 x 50 x 101 (1/2 x 2 x 4)	1.65 (.065)	.3 (.012)	Longitudinal	6.16 (894.7)	Core
Beam bending	11.9 x 66.6 x 232 (.47 x 2 5/8 x 9 1/8)	.43/.5 (.017/.020)	.43 (.017)	Transverse	110 (16,000)	Face
	11.9 x 50 x 229 (.47 x 2 x 9)	.46/.5 (.018/.020)	.3 (.012)	Transverse	110 (16,200)	Face
	10.9 x 76 x 178 (.43 x 3 x 7)	.48/.5 (.019/.020)	.3 (.012)	Longitudinal	>643 (>93,300)	Core loadi

TABLE IV.- POTENTIAL BENEFITS FROM NEW TECHNOLOGY

	EXISTING DESIGN	PROPOSED DESIGN
• NUMBER OF PARTS	680	84
• NUMBER OF FASTENERS	9940	1112
• NUMBER OF TOOLS	400	100
• ASSEMBLY WEIGHT	75 kg (600 lb)	41 kg (360 lb)
• ASSEMBLY COST	$ 295, 336	$154, 726

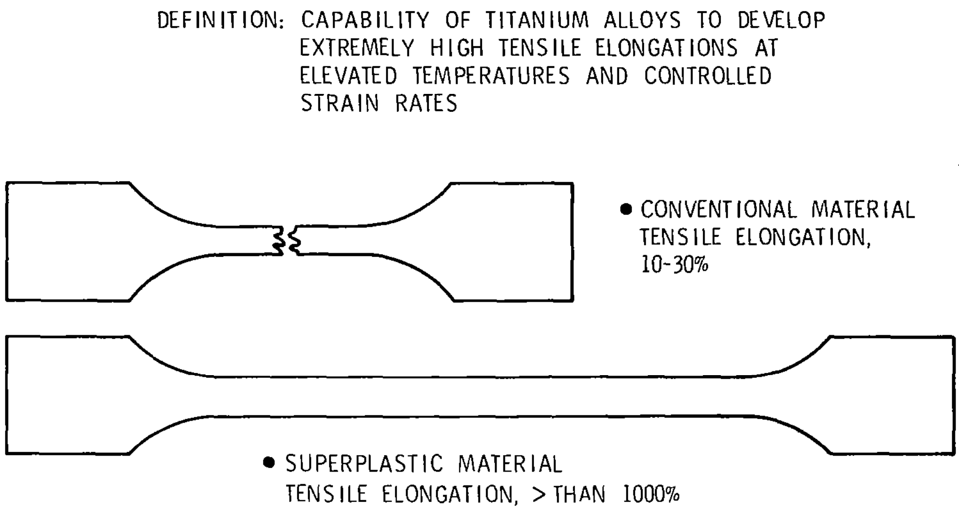

Figure 1.- The superplastic phenomenon.

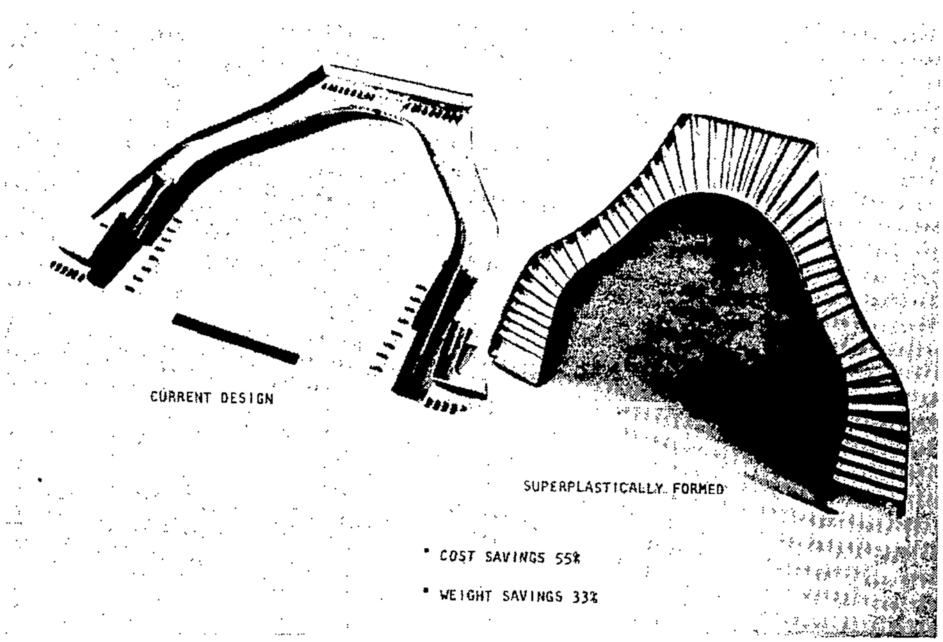

Figure 2.- Nacelle frame redesign comparison.

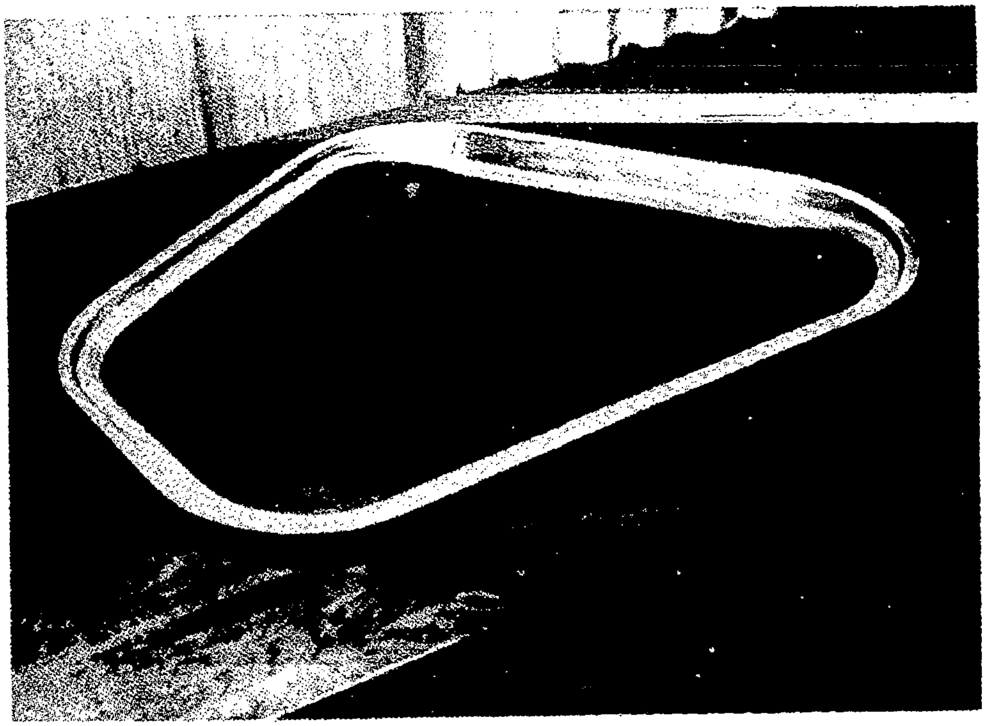

Figure 3.- Superplastically formed space shuttle windshield frame.

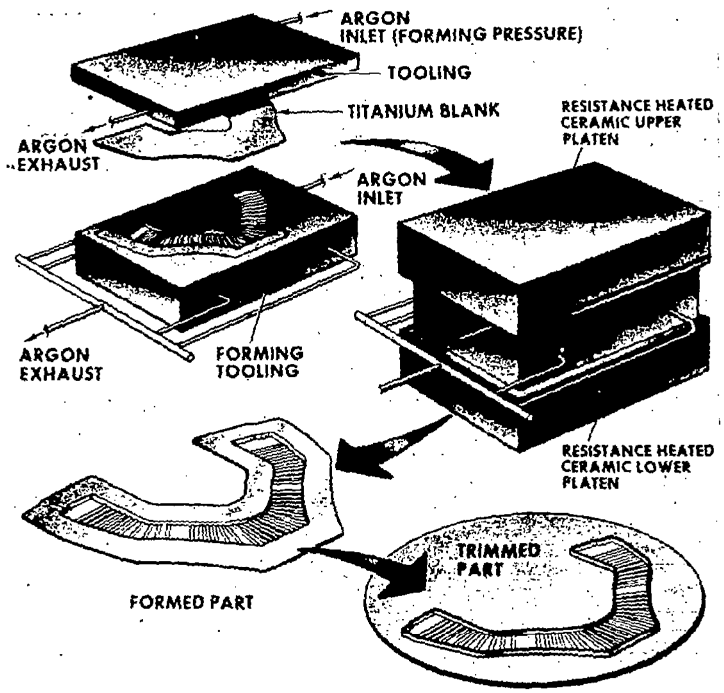

Figure 4.- Superplastic forming of titanium.

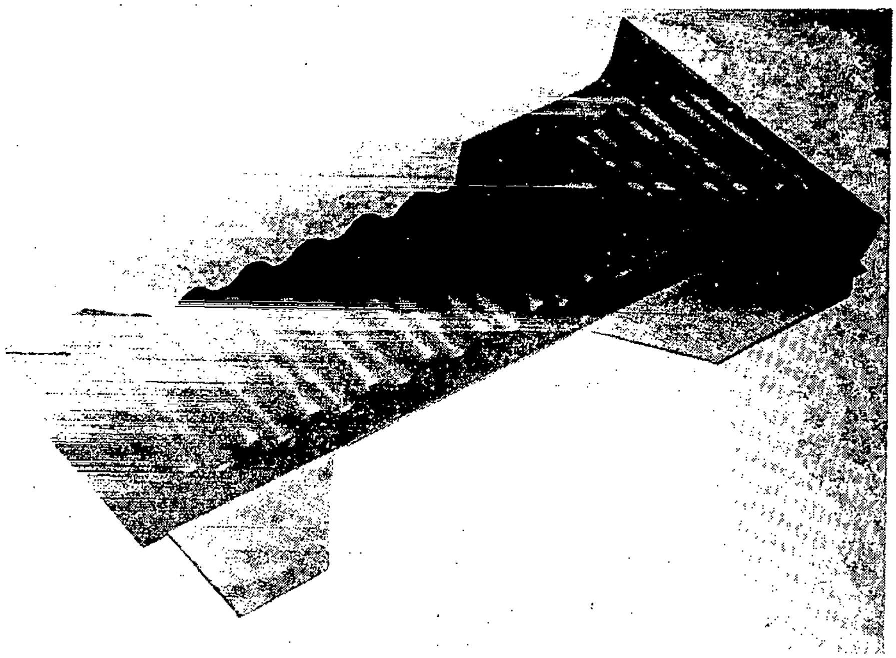

Figure 5.- Superplastically formed sine wave beam.

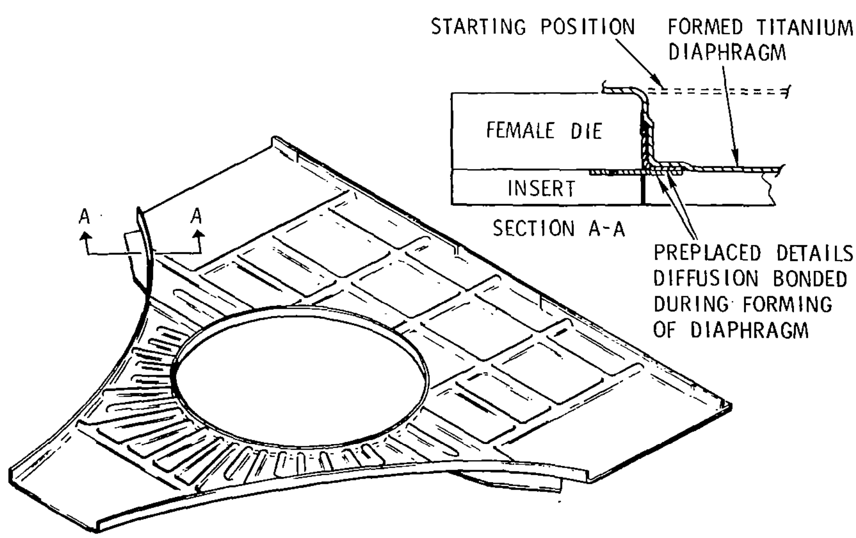

Figure 6.- Concurrent superplastic-formed/diffusion bonding cycle.

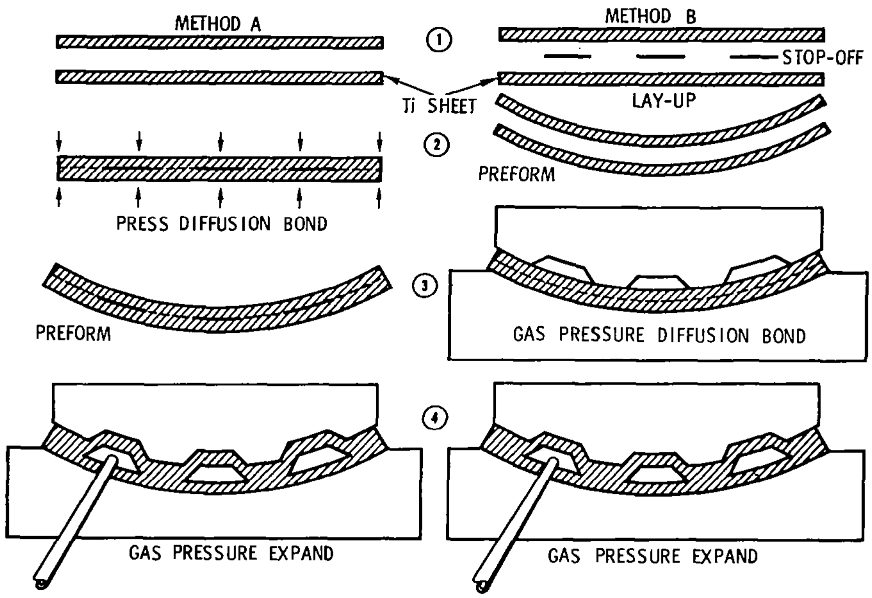

Figure 7.- Superplastic-formed/diffusion bonding expansion process.

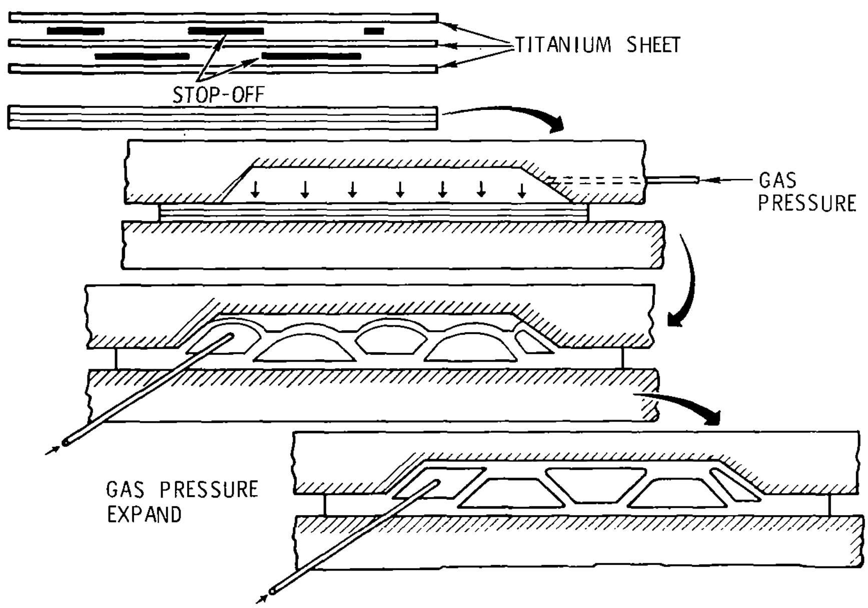

Figure 8.- Expanded sandwich process.

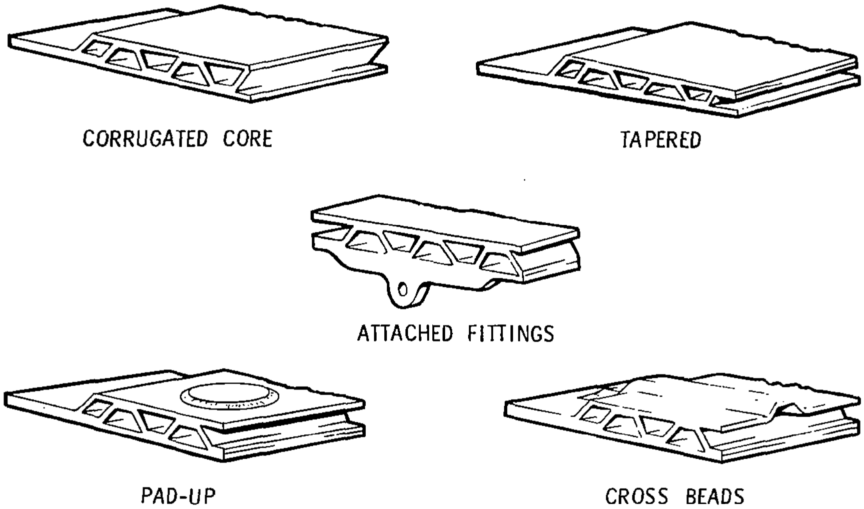

Figure 9.- Possible superplastic-formed/diffusion bonding configuration.

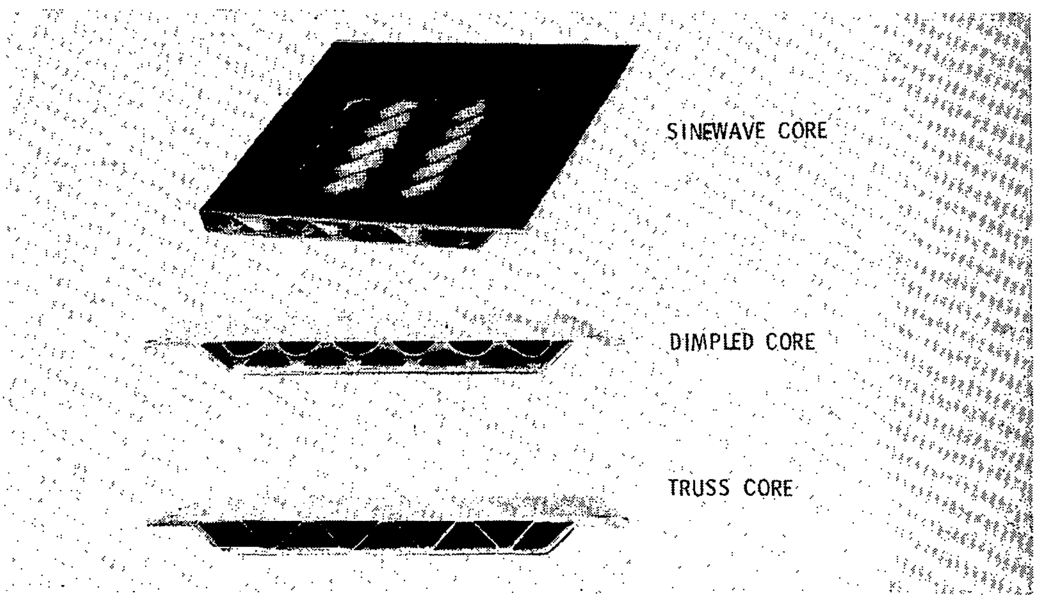

Figure 10.- Examples of actual expanded sandwich hardware.

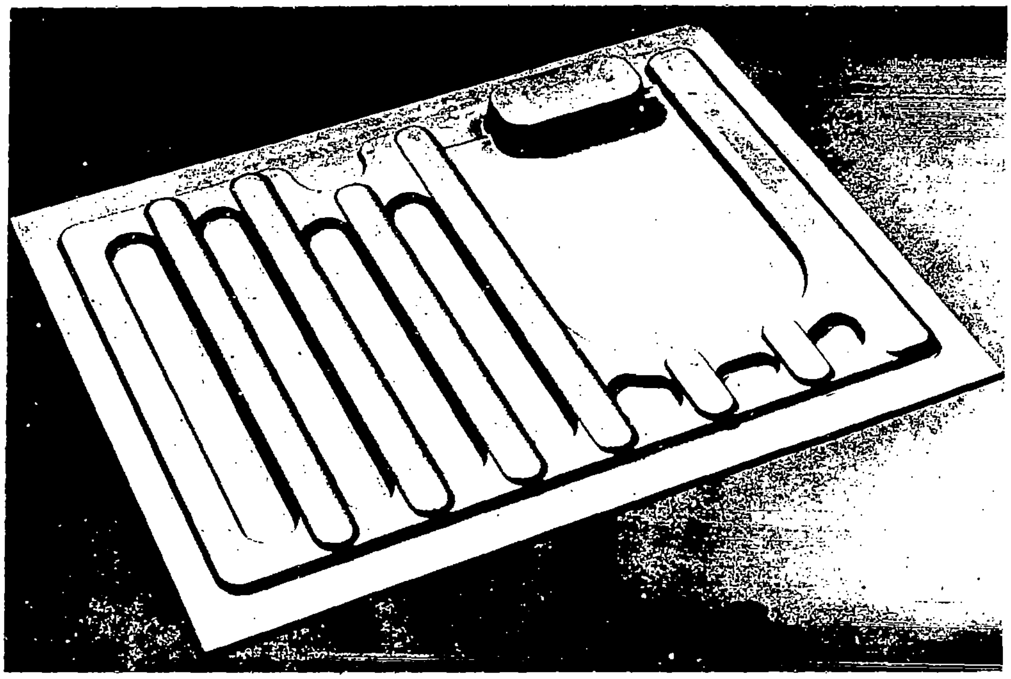

Figure 11.- B-1 superplastic-formed/diffusion-bonded APU door.

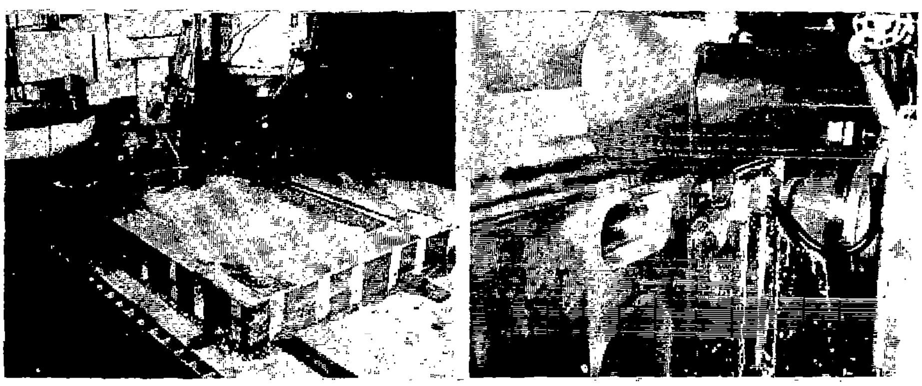

Figure 12.- Machining of APU door tool insert and container.

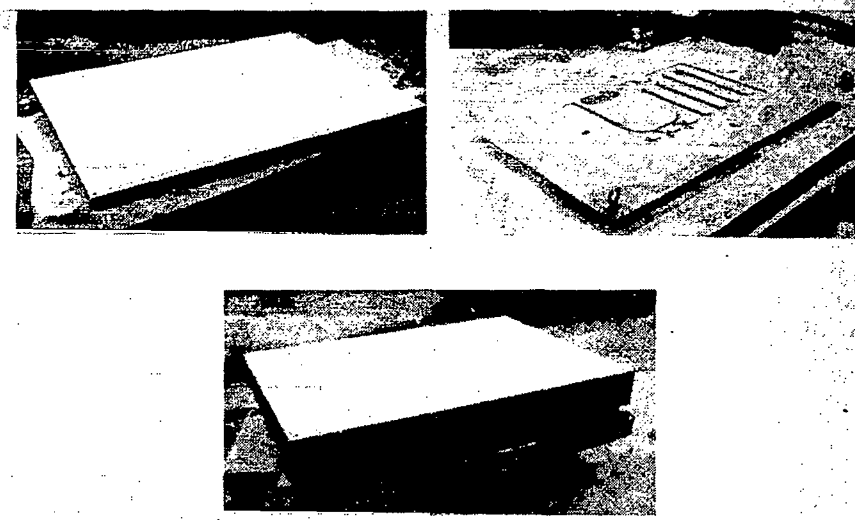

Figure 13.- Tooling subsequent to machining.

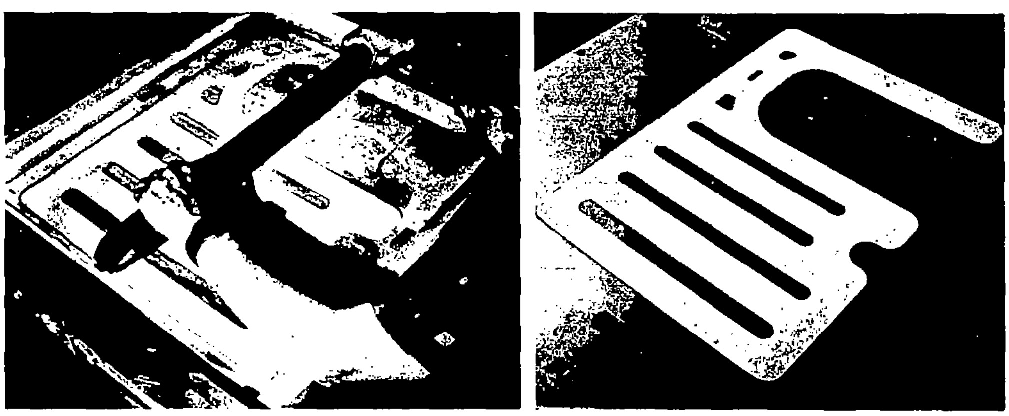

Figure 14.- Silk screen operation for APU door stop-off pattern.

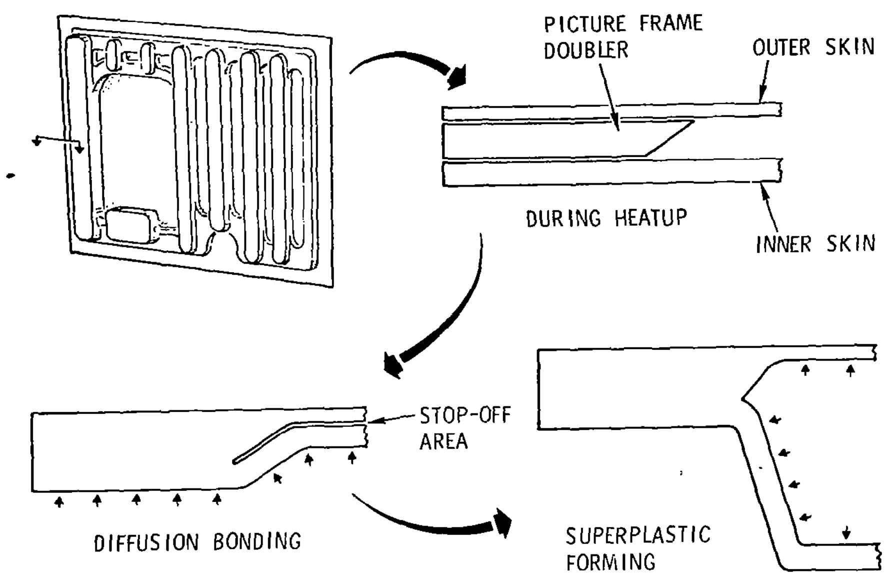

Figure 15.- Preforming of titanium sheet during diffusion bonding cycle.

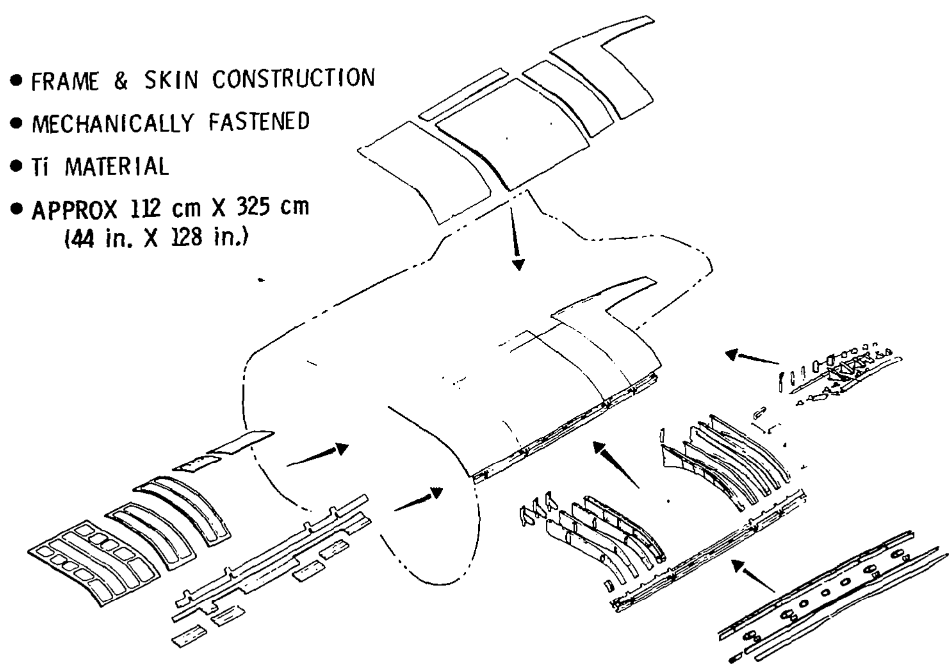

Figure 16.- Typical state-of-the-art sheet metal fuselage assembly.

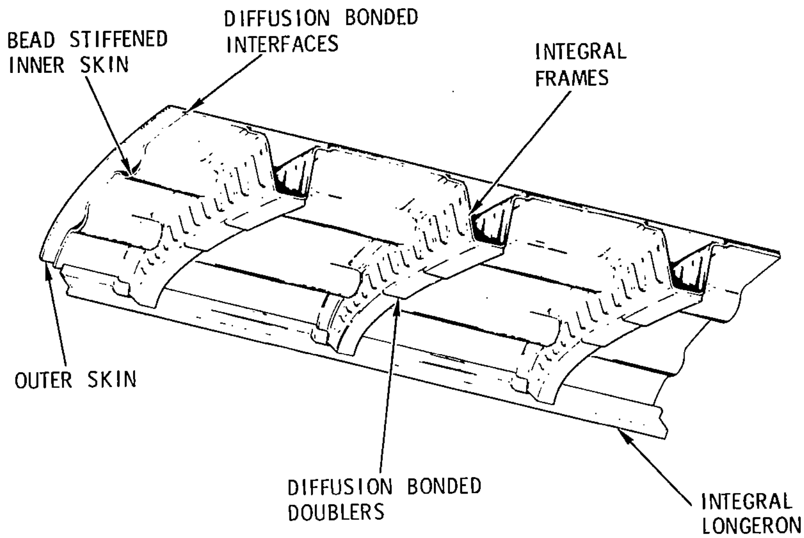

Figure 17.- Fuselage-type structure using SPF/DB with integrally formed frames.

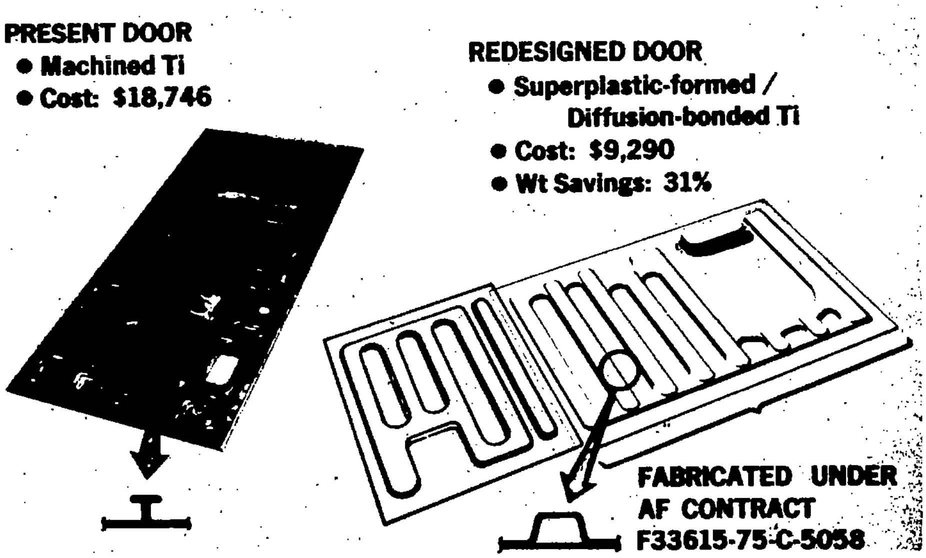

Figure 18.- SPF/DB APU door saves 50 percent.

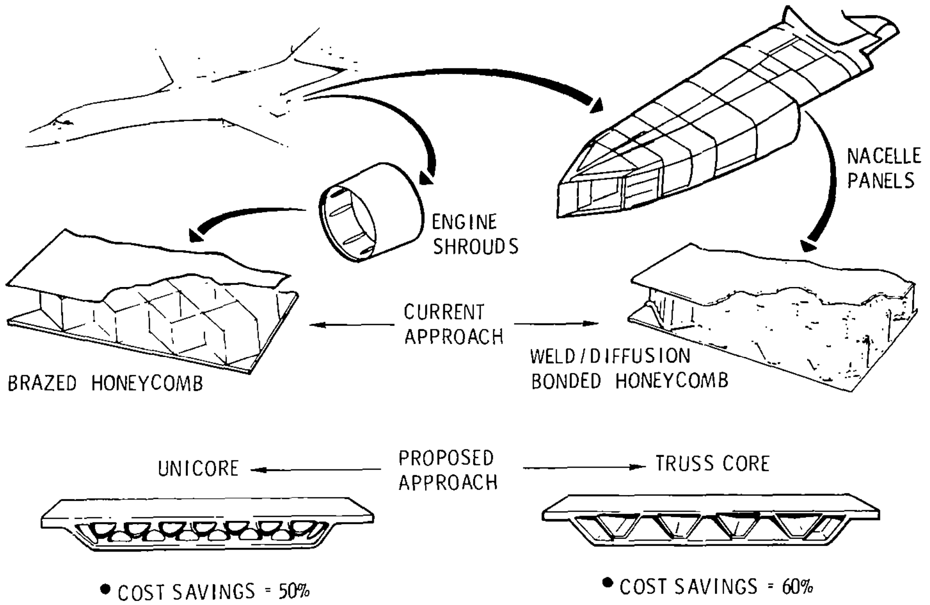

Figure 19.- Expanded sandwich comparison to present state-of-the-art methods.

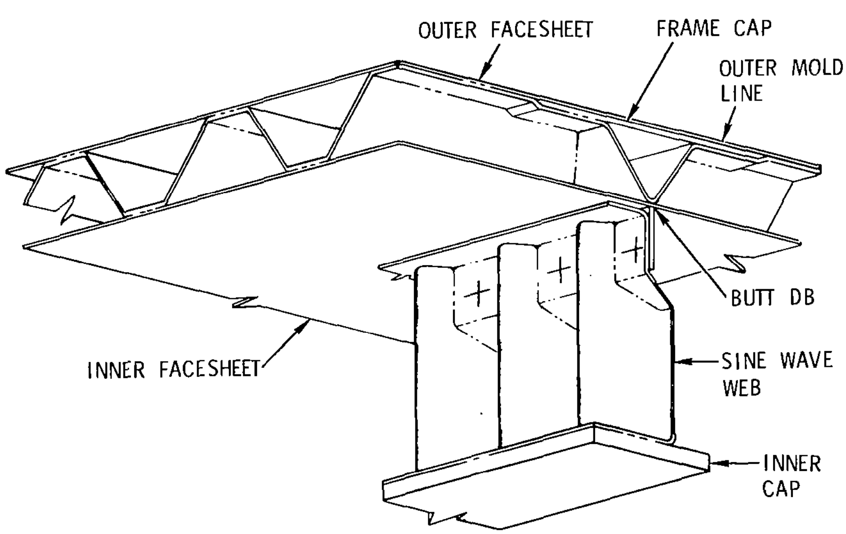

Figure 20.- Typical wing/fuselage structure using SPF/DB process.

	FORWARD			INBOARD			OUTBOARD		
CONCEPT	HAT	TRUSS	DIMPLE	DIMPLE	TRUSS	HAT	HAT	D-T	TRUSS
% WT SAVINGS	-22	-14	-6.4	-31	-14	-33	+22	-18	-20
% COST SAVINGS (100 AIRCRAFT)	-61	-51	-43	-48	-47	-45	-49	-50	-53

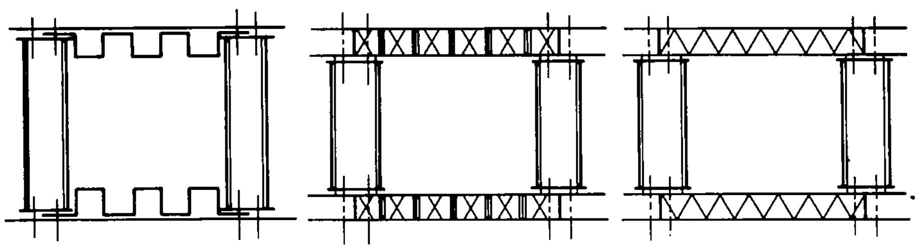

Figure 21.- Advanced supersonic aircraft wing cost/weight comparison.

	FORWARD			AFT		
CONCEPT	SANDWICH	HAT	INTEGRAL	SANDWICH	HAT	INTEGRAL
% WT SAVINGS	-8	+2	+3	-15	-2	-4
% COST SAVINGS (100 AIRCRAFT)	-22	-9	-28	-59	-49	-65

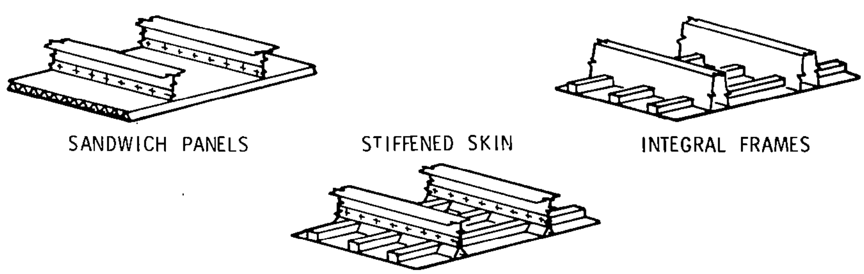

Figure 22.- Advanced supersonic aircraft fuselage cost/weight comparison.

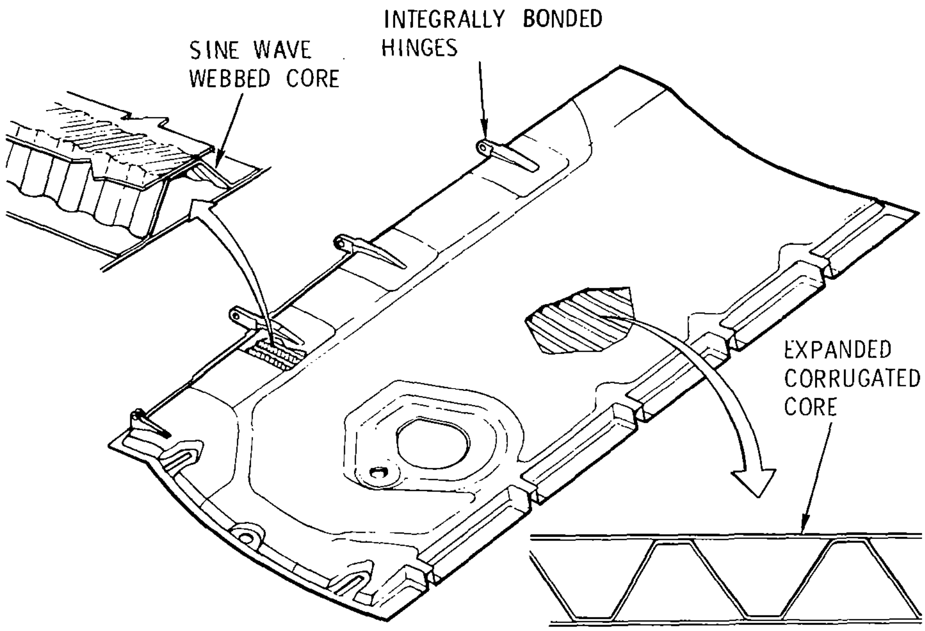

Figure 23.- Proposed engine door design.