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DMIC Report S-17
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DEFENSE METALS INFORMATION CENTER
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THE ROLL-DIFFUSION BONDING OF STRUCTURAL SHAPES AND PANELS

by

J.A. Houck and E. S. Bartlett

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
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THE ROLL-DIFFUSION BONDING OF STRUCTURAL SHAPES AND PANELS

J. A. Houck and E. S. Bartlett*

SUMMARY

This report summarizes the progress in recent and current research and development programs to advance the state of the art of the roll-diffusion-bonding process as applied to the manufacture of structural panels and shapes. At the present time, there are seven such NASA and DOD programs in progress. These are reviewed in this report.

Most of these are concerned with the development of process parameters for producing prototype aerospace structures of titanium alloys. Included are the fabrication of the following structures:

(1) A simulated Y-ring segment for the Saturn S-1C fuel tank, of the Ti-8Al-1Mo-1V titanium alloy.

(2) "T"-stiffened skin panels of the Ti-8Al-1Mo-1V titanium alloy for the Saturn S-1C fuel tank.

(3) Construction of a prototype tankage assembly for the Titan III vehicle using roll-diffusion-bonded Ti-6Al-4V alloy truss-core panels as the base material.

(4) Fabrication of structural shapes such as "T" and "I" sections, approximately 40 feet long, of Ti-6Al-4V alloy.

Although the state of the art is most advanced for titanium alloys, laboratory studies are in progress to develop the processing parameters for producing roll-diffusion-bonded structures of other materials. The latter include: beryllium, maraging steel, Inconel, PH14-8Mo stainless steel, and titanium-beryllium composites.

In addition to the Government-sponsored programs, the McDonnell-Douglas Corporation, Lockheed, General Dynamics, and Battelle Memorial Institute have conducted extensive in-house research activities to advance the state of the art of roll-diffusion bonding. The most significant results of these studies are also summarized.

Currently, the prototype titanium-alloy structures are in the final stages of fabrication. Full-scale titanium-alloy truss-core panels, T-stiffened skin panels, and Y-ring segments have been successfully rolled on commercial mills, inspected, and formed into the target configurations. The results thus far indicate that the roll-diffusion bonding process is a satisfactory technique for fabricating structural panels and shapes of titanium alloys.

The development of process parameters for structural materials other than titanium has been limited to the fabrication of small laboratory panels. Thus far, good quality panels of Inconel and PH14-8Mo stainless steel have been produced, and the fabrication of scale-up panels is planned. A laboratory-size truss-core panel of beryllium has also been successfully fabricated.

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INTRODUCTION

Minimum structural weight and structural integrity are of primary importance in the design of aerospace vehicles. To achieve these goals, the design engineer is usually confronted with a trade-off between the most desirable structural configuration and the ability to produce that structure economically. Many of the structural configurations, such as stiffened skin panels and sandwich structures are produced by joining separate pieces of structural material by welding, brazing, or organic bonding. Some structures are produced by simply hogging out sections from solid metal plates.

All of these methods have deficiencies which limit their usefulness for fabricating the structural configurations required for advanced aerospace vehicles. For example, fusion welding and brazing of the new high-strength materials often produce undesirable joint properties such as low strength and low remelt temperatures. Also, locked-in stresses often produce distortions which are particularly detrimental in thin-gage materials. Low joint strength and low operating temperature are obvious limitations for organic bonding.

Recently solid-state diffusion bonding has been receiving increased attention in the aerospace industry as a technique for joining materials to produce the lightweight configuration required in modern aerospace structures. The diffusion-bonding process is particularly attractive because the mechanical and metallurgical properties of a complete diffusion-bonded joint are comparable to those of the base metal; thus, joint efficiencies approaching 100 percent are possible. The design engineer can, therefore, ignore limitations in joint properties and can assume homogeneous material properties throughout the entire structure. These properties can, of course, be achieved by machining the structure out of solid material, but this technique is usually impractical or too expensive with the new high-strength structural materials.

Diffusion bonding of metals can be divided into two general categories: deformation-diffusion bonding and diffusion bonding without deformation. Deformation-diffusion bonding is accomplished by gross plastic flow, whereas diffusion bonding involves only microscopic plastic flow. Roll-diffusion bonding, which is the subject of this report, is an example of deformation-diffusion bonding. The diffusion-bonded joint between structural details is accomplished by gross plastic flow during hot rolling.

Within the past 3 years, there has been a marked increase in activity in applying the roll-diffusion-bonding process to the fabrication of aerospace structures. At the present time, there are seven DOD- and NASA-sponsored programs in progress to advance the state of the art of roll-diffusion bonding with the ultimate objective of using this technique to fabricate structures for modern aerospace vehicles. These are identified and outlined in Table 1.

It is the purpose of this report to review the progress in these programs and summarize the current state of the art of the roll-diffusion-bonding process as applied to the manufacturing of aerospace structures. Since these programs are still in progress, no final reports have been issued. Accordingly, the data presented herein have been selected from progress reports.

In addition to these Government-sponsored programs, several in-house research activities on roll-bonded structures have been conducted by the McDonnell-Douglas Corporation and Battelle Memorial Institute. Results from both of these organizations' programs are also reviewed.

THE ROLL-DIFFUSION-BONDING PROCESS

The essence of the process is to form a diffusion bond between two or more structural members, which are supported by a removable matrix, by hot rolling. In its essentials, the roll-diffusion-bonding process includes:

(1) Preparation of the core by corrugating or shaping to the desired configuration

(2) Filling in spaces between the corrugations or spaces of the core using an appropriate, removable material

(3) Positioning of face sheets on the core and filler bar section

(4) Placing of the sandwich in an appropriate yoke

(5) Welding covers to the yoke to form an airtight pack

(6) Evacuation of the pack to protect against oxidation

(7) Hot rolling of the pack to the desired reduction in thickness

(8) Contouring of the pack, if required, by an appropriate hot or cold forming process

(9) Removing the cover plates mechanically

(10) Removing the filler material, either mechanically or chemically.

Historical Background

The feasibility of preparing structural panels by the roll-diffusion-bonding process was established over the period of 1955-1958 at Battelle's

TABLE 1. SUMMARY OF CURRENT NASA AND DOD RESEARCH AND DEVELOPMENT PROGRAMS TO ADVANCE THE STATE OF THE ART OF ROLL-DIFFUSION BONDING

Contract No.	Company	Program Title	Program Objective
NAS8-20384	Harvey Aluminum, Inc. Harvey Engineering Laboratories Torrance, California	Development of Solid-State Bonding Technique	Development of roll-diffusion bonding technique for producing structural panels of Be and Be-Ti composite panels
NAS8-20530	North American Aviation, Inc. Los Angeles, California	Titanium S-1C Skin Section	Fabricate simulated T-stiffened skin sections of Ti-8Al-1Mo-1V titanium alloy for the S-1C fuel tank by roll-diffusion bonding
NAS8-20533	North American Aviation, Inc. Los Angeles, California	Research and Development for Fabricating a Simulated Y-Ring Segment for the S-1C Fuel Tank	Fabricate a simulated Y-ring segment for the S-1C fuel tank of Ti-8Al-1Mo-1V titanium alloy by roll-diffusion bonding
AF 04(611)-10752	North American Aviation, Inc. Los Angeles, California	Liquid Rocket System Conjugate Structure and Tankage Program	Construction of prototype tankage assembly for Titan III launch vehicle using roll-diffusion bonded Ti-6Al-4V alloy truss-core sandwich structure as base material
AF 33(615)-1117	McDonnell-Douglas Corp. St. Louis, Missouri	Titanium Structural Sections Produced by Roll Bonding on Bar Mills	Study feasibility of producing roll-diffusion-bonded titanium structural shapes on bar mill equipment
F 33615-67-C-1113	North American Aviation, Inc. Los Angeles, California	Manufacturing Process Development for Roll Bonded Titanium Alloy Structural Sections	Produce structures which can compete with and/or surpass those which can be made by present extrusion processes
DA-19-066-AMC-308X	Battelle Memorial Institute Columbus, Ohio	Development of Practice for Composite Rolling of Structural Metal Panels	Development of process parameters to produce structural metal panels of several materials

Columbus Laboratories. The initial work was supported by the Battelle Development Corporation, a wholly owned subsidiary of Battelle, which was granted a basic patent on the process. Subsequent research and development on this process at Battelle was supported by several outside organizations of which the main supporting group was the Douglas Aircraft Company (now the McDonnell-Douglas Corporation). This collaboration of interests between Battelle and Douglas has continued to the present time, and both have an agreement in which proprietary aspects of the process are shared and either party can establish sublicensees under the original patent or subsequent patents.

The initial experimental work upon which this process was based involved hot rolling of A-55 grade, unalloyed titanium, vertical rib sandwich structures which were contained in either copper or steel pack assemblies. These experiments were successful in demonstrating that a reliable solid-state diffusion bond with the wrought-base-metal properties could be effected between the titanium-alloy structural members during hot rolling. Furthermore, it was shown that excellent geometrical and dimensional control of the panel components could be maintained during the hot-rolling process. The steel or copper pack materials which supported the structure during fabrication were removed by leaching in chemical reagent.

The collaboration between Battelle and Douglas led to a number of significant developments in the process. It was shown that the process was applicable to several structural materials. Table 2 lists the various structural materials and supporting filler and pack materials which have been explored in this work.

Another significant development included the demonstration of the function of carbon in the steel to form a diffusion barrier of TiC, preventing iron diffusion into the titanium. Also demonstrated

TABLE 2. STRUCTURAL MATERIALS AND FILLER BAR/YOKE MATERIALS EXPLORED IN BATTELLE-DOUGLAS ROLL-DIFFUSION-BONDING STUDIES

Structural Materials	Pack Materials: Filler Bars	Pack Materials: Yoke and Pack Covers
Aluminum Alloys	Copper	Copper
2014	Copper	Copper
2024 Alclad	Copper	Copper
5050	Copper	Copper
5052	Copper	Copper
6061	Copper	Copper
Titanium Alloys		
Unalloyed, Grade A-55	Copper 1020 carbon steel	Copper 1020 carbon steel
Ti-13V-11Cr-3Al	1020 carbon steel	1020 carbon steel
Ti-8Al-1Mo-1V	1020 carbon steel	1020 carbon steel
Ti-6Al-4V	1020 carbon steel	1020 carbon steel
Beryllium	1020 carbon steel	1020 carbon steel
Inconel	1020 carbon steel	1020 carbon steel yoke and stainless steel pack covers
Rene 41	1020 carbon steel	1020 carbon steel yoke and stainless steel pack covers
PH15-7Mo	1020 carbon steel	1020 carbon steel
Unalloyed molybdenum	1020 carbon steel Ingot iron	1020 carbon steel
Unalloyed columbium	1020 carbon steel Ingot iron	1020 carbon steel
Tungsten	Molybdenum	Molybdenum

was the use of high-manganese steel cores, which can be mechanically removed.

It was also demonstrated that a variety of core configurations could be produced. Although the bulk of the work was done with a truss-core configuration, T-stiffened skins, multi-ply, hex cell, and T and H structural shapes were fabricated successfully on a laboratory scale. The first composite-rolled T and H structural shapes were fabricated of the Ti-8Al-1Mo-1V titanium alloy and were approximately 4 feet long.

Success with laboratory-size panels demonstrated that the process was ready for scale up. Accordingly, a 3-foot wide x 6-foot long x 1/4-inch thick A-55 titanium panel was assembled at Battelle and rolled successfully in January, 1961, at Eastern Stainless Steel Company, Baltimore, Maryland. This was the first "large" roll-diffusion-bonded panel ever produced, demonstrating the feasibility of producing commercial-size panels at commercial installations. This panel, which was fabricated in a copper pack assembly, was of the truss-core configuration and consisted of 0.016-inch-thick skins with 0.008-inch-thick ribs. Copper was selected as the pack and core material to facilitate the leaching operation and to conduct room-temperature forming operations. Sections of this panel were subsequently formed into domes and cylinders at room temperature by Douglas Aircraft Company.

Laboratory studies at Battelle early in 1962 showed carbon steel to be a more suitable pack and core material for the fabrication of high-strength titanium alloys. To prove out the process with steel, a 3-foot wide x 6-foot long x 1/4-inch thick Ti-6Al-4V alloy truss-core panel was fabricated successfully in a 1018-grade carbon steel pack on Titanium Metals Corporation of America's 60-inch production plate mill. A second Ti-6Al-4V alloy panel of similar dimensions and pack materials was rolled on Luken Steel's 120-inch plate mill in January, 1963. Sections from these panels were hot formed with the steel matrix material in place into domes and cylinders using commercial equipment. Other studies which were conducted in 1962 demonstrated that joining, reinforcing, and attachment members could be incorporated in the pack assembly and bonded to the structure during the hot-rolling operation.

As a result of the success with fabricating full-scale panels at commercial installations, Battelle and Douglas Aircraft technical personnel were convinced that the process was ready for the production of prototype aerospace hardware. Accordingly, a joint promotional effort between Battelle and Douglas was undertaken starting in February, 1963. A number of demonstration samples were prepared and a team of Douglas and Battelle technical representatives presented the process to the aerospace industry through a series of technical presentations and discussions. These promotional efforts stimulated widespread interest in the process throughout the aerospace industry and Government agencies which culminated in the award of a number of contracts for the development of roll-diffusion-bonded prototype hardware.

To provide material for the aerospace industry to conduct secondary fabrication studies, Battelle fabricated approximately 100 square feet of Ti-6Al-4V alloy truss-core sandwich material at Bethlehem Steel Company's 160-inch plate mill at Sparrows Point, Maryland, in September, 1964. This was the first "production run" of roll-diffusion-bonded structures fabricated on a commercial automated rolling mill.

Elements of the Process

By way of introduction, Figure 1 shows a schematic illustration of the steps required in preparing a pack for roll-diffusion bonding and Figure 2 illustrates various structural configurations which have been produced by this process.

The process starts with the design of the initial composite pack consisting of the core, face sheet(s), and filler material which are encased in a yoke with cover plate.

In designing the initial pack configuration, consideration must be given to the fact that the pack is rolled in only one direction. This direction should be parallel to the ribs or supporting members. This results in increases in length of the structure that are proportional to the reduction in thickness. The change in length as a function of thickness can be calculated as follows:

$$L_f = L_o \frac{T_o}{T_f} \quad ,$$

where L_f = finished length, L_o = original length, T_o = original thickness, and T_f = final thickness.

For example, a structure which is reduced approximately 67 percent in thickness would be increased in length about three times. Although some side spread does occur during rolling, it does not have a significant effect on the geometry of production-size panels. Horizontal details, such as facing sheets of sandwich structures, are reduced in thickness by the same factor as that by which the pack is reduced. Vertical members, such as the ribs in a stiffened skin structure, are reduced in height by the same factor. Inclined details such as the ribs in a truss-core sandwich structure are reduced in thickness in the direction perpendicular to the skin sheet surface.

The final structure must be translated into a starting pack design that takes into account the

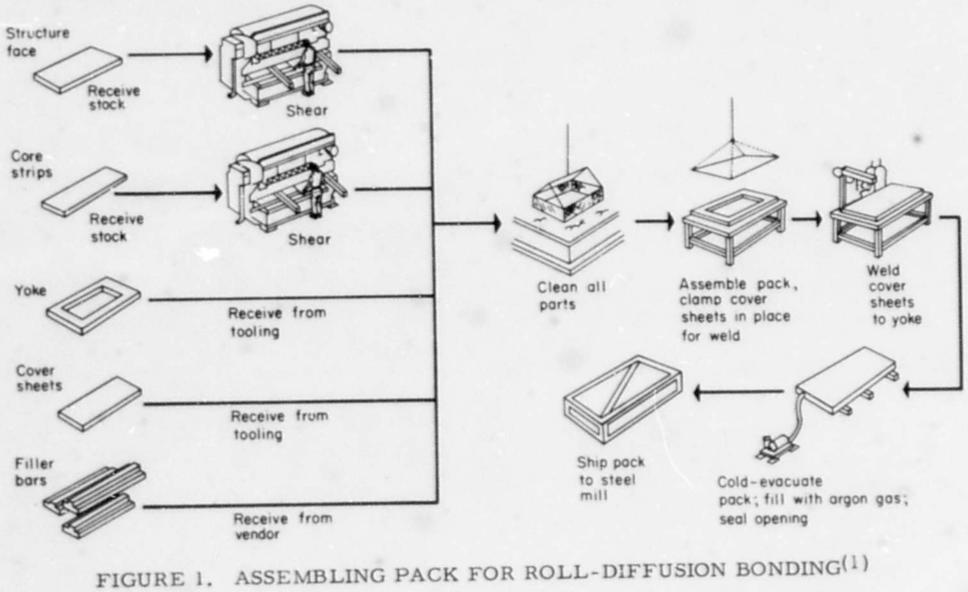


FIGURE 1. ASSEMBLING PACK FOR ROLL-DIFFUSION BONDING(1)

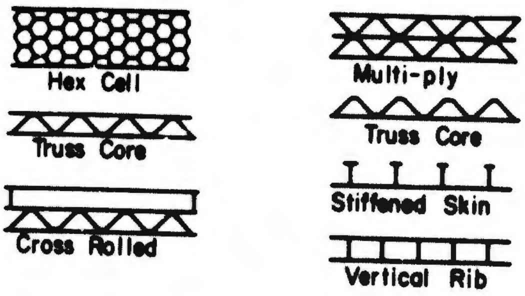
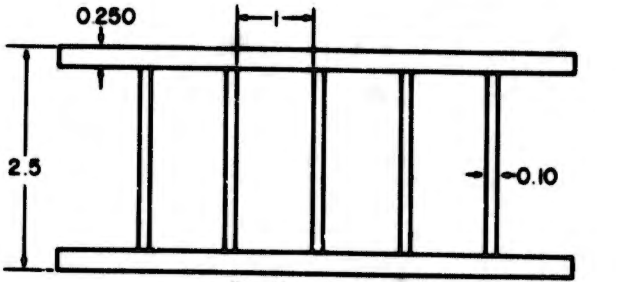
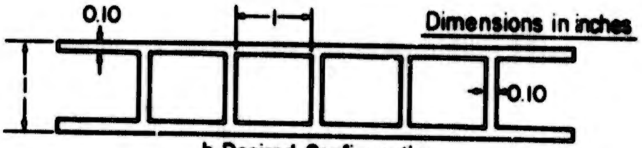


FIGURE 2. CONFIGURATIONS PRODUCED BY ROLL-DIFFUSION BONDING(1)

foregoing factors. For simple structures which contain only vertical members, the pack design is simple, as illustrated in Figure 3 which shows the initial and final configurations for a vertical-rib structure rolled through a 60 percent reduction.



a Starting Configuration



b. Desired Configuration

FIGURE 3. DESIGN CONFIGURATIONS FOR A VERTICAL-RIB STRUCTURE(2)

Note that no change in thickness of vertical components occurs during rolling.

How a given postrolling configuration for a truss-core sandwich structure is translated into a starting pack design is illustrated in Figure 4.

The calculations for the initial rib angle and rib thickness to result in the configuration shown in Figure 4, based on a hot-rolling reduction of 60 percent, are as follows:

(1) Rib thickness for a 45-degree truss-core panel with 0.008-inch-thick ribs after rolling 60 percent total reduction:

$$th_f(V)(rib) = \frac{0.008 \text{ in.}}{\cos 45} = 0.0113 \text{ inch}$$

$$th_o(V)(rib) = \frac{0.0113}{1-0.60} = 0.0283 \text{ inch}$$

$$th_o(rib) = 0.0283 \times \cos 68.2 \text{ degrees} = 0.0105 \text{ inch.}$$

(2) Rib angle (θ°):

$$\tan \theta° = \frac{t_o \times \tan \theta_f}{t}$$

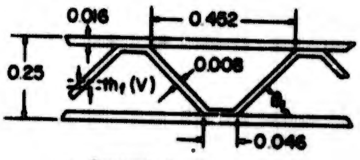
where:

t_o = original structure thickness

θ_f = final rib angle

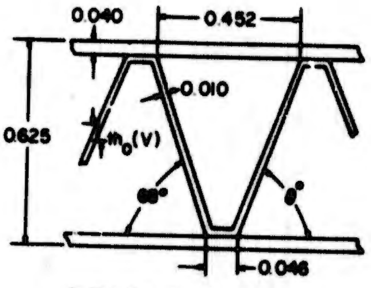
t = final structure thickness

$$\tan \theta° = \frac{(0.625) \times 1}{0.250} = 2.5; \quad \theta° = 68.2.$$



a. Desired Configuration

Dimensions in inches



b. Starting Configuration

FIGURE 4. DESIGN CONFIGURATIONS FOR A TRUSS-CORE SANDWICH PANEL FOR 60 PERCENT REDUCTION(2)

Low-carbon structural steel has been most commonly used as the filler and yoke material. The filler bars, which occupy the spaces between the structural members, are either machined or drawn to close tolerances to insure a good fitup and thus minimize void space within the pack assembly.

The core elements and filler bars are then positioned on the face sheets with the aid of a machined or welded yoke. This is illustrated schematically in Figure 5 which shows a pack

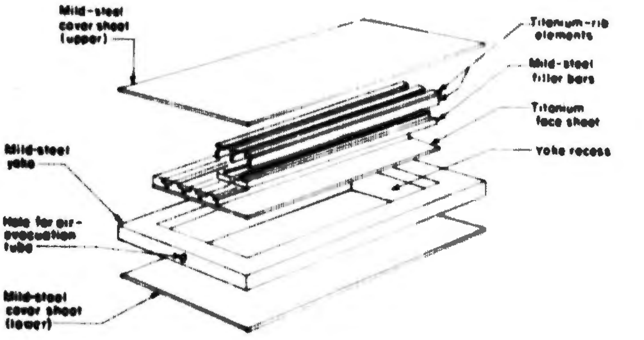


FIGURE 5. EXPLODED PACK ASSEMBLY FOR ROLL-DIFFUSION-BONDED-STRUCTURE STIFFENED PANEL(1)

assembly for fabricating a titanium alloy T-stiffened skin panel. As shown, provision is made for evacuation of the pack to remove air and contaminants by means of a purge tube which is connected to a vacuum pump. Usually the purge tube is sealed off close to the pack by welding just prior to the rolling operation. It is essential that the pack remain gastight during the prerolling heating periods and initial stages of rolling to protect the structural materials from oxidation and contamination.

In rolling composite panels, it has been established that mill reductions ranging between 40 and 90 percent of the starting thickness are feasible. However, most of the production-size structures which have been rolled on plate mills have been reduced approximately 60 percent in thickness. It is essential that the packs be transferred rapidly from the preheat furnace to the rolling mill and that the rolling be performed as fast as possible to maintain a high finishing temperature. Reheating during the rolling cycle is to be avoided, if possible, to reduce the rate of diffusion between the structural materials and the supporting details. Typically, rolling of a mild steel pack containing a Ti-6Al-4V panel is initiated from a furnace at 1750 F.

One of the virtues of roll-duffusion bonding is that the finished composite structure can be handled in postrolling operations like a solid plate. Thus, contouring can be done with conventional metal-forming tools and processes, including rollforming, bending, press forming, and spinning.

Forming operations for most materials are conducted at elevated temperatures to reduce forming-equipment power requirements and prevent cracking of the structure which is encased in the steel pack. Hot forming of titanium-alloy structures is normally done at temperatures between 1200 and 1600 F.

Following contouring operations, the supporting matrix material is removed either mechanically or by chemical leaching. For certain open-type structures such as stiffened skin panels, waffles, I's, T's, channels, etc., a combination of leaching and mechanical stripping can be used. On the other hand, for closed structures such as truss-core or vertical-ribbed sandwich structures, the present technique is to leach the entire supporting matrix away by flowing a chemical reagent into the panel core. This is a rather slow process; however, recent experimental work (described later) has demonstrated that the leaching process can be greatly accelerated by using composite bars in which the cores are extracted mechanically after rolling. Using this technique, leaching time for production-size panels can be reduced from several hours to a few minutes.

Representative Mechanical Properties

The joints produced by roll-diffusion bonding are metallurgically indistinguishable from the base material, as shown in Figure 6. Consequently, structures which have been properly bonded show that base-metal properties can essentially be retained across the joined section.

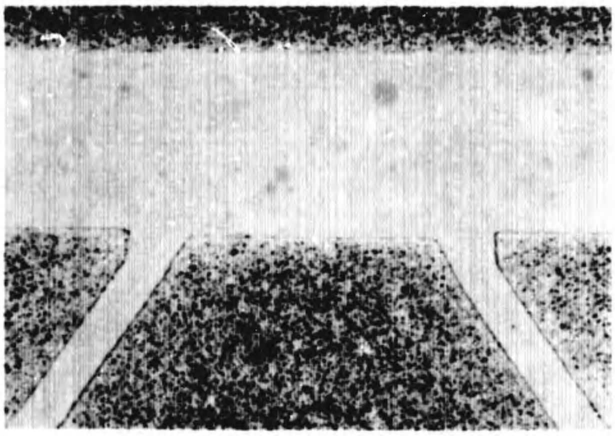


FIGURE 6. TYPICAL JOINT IN A ROLL-DIFFUSION-BONDED Ti-6Al-4V ALLOY TRUSS-CORE PANEL(3)

This was first shown in a program conducted for Lockheed-California by Battelle's Columbus Laboratories in 1964. Mechanical properties of roll-diffusion-bonded joints of Ti-8Al-1Mo-1V alloy were directly compared with those of integral material (no bond joint). Bonded and base-line specimens, nominally 0.1-inch thick, were arranged in packs to accomplish 40 and 60 percent reductions in strip width (not thickness). Bond plane orientation was thus normal to the plane of the resulting sheet, and tensile, bend, and fatigue specimens were machined so as to apply stresses in a direction normal to the bond plane. Reduced sections of tensile and fatigue specimens were described by smooth arcs of 3/8-inch radius, with bond lines located at the minimum cross section.

Tensile tests showed no significant differences in strength between bonded and baseline specimens, nor between materials reduced 40 and 60 percent. Ductility (reduction in area) was less for bonded specimens than for baseline specimens, however. Tensile data are summarized below:

Class	Fabrication Reduction Level, %	Yield Strength, ksi	Ultimate Strength, ksi	Reduction in Area, %
Base	40	145	152	29.5
Bonded	40	148	153	22
Base	60	145	152	32
Bonded	60	145	152	10

Closed-die bend tests with maximum bending stresses at the bond area showed the bend ductility of roll bonds to be as good as that of the parent material. These data are summarized below.

Class	Fabrication Reduction Level, %	Minimum Successful Die Radius Specimen Thickness, in.
Base	40	3
Bonded	40	3
Base	60	3
Bonded	60	2-1/2

Tension-tension fatigue tests showed no significant differences in fatigue lives at various stresses between base-line and bonded materials fabricated similarly. However, fatigue lives of base-line and bonded specimens reduced 40 percent in the roll-bonding operation were significantly greater than those of material reduced 60 percent, as summarized below:.

Type	Fabrication Reduction Level, %	Mean Fatigue[(a)] Life Cycles at Indicated Stress 60 Ksi	80 Ksi	100 Ksi
Base or bonded	40	700,000	230,000	110,000
Base or bonded	60	300,000	81,000	40,000

(a) A = 0.95 (R = 0.05); tested at 1750 cycles/min.

Although existing data do not permit a direct comparison, duplex-annealed Ti-8Al-1Mo-1V would be expected to have greater fatigue life than the 40 percent reduced material under the test conditions. The observed decrease in fatigue life with varying degrees of fabrication is probably due to the unusual fabrication texture relative to usual sheet texture developed in the test materials. Because of edgewise compression during rolling of the test materials (i.e., the condition that exists in rib components of a vertical-ribbed roll-bonded sandwich structure), basal planes of the hcp crystallographic structure predominating in Ti-8Al-1Mo-1V were probably aligned nearly normal to the fatigue tension axis, rather than lying in the tensile direction as is normal for sheet material.

Double-lap roll-bonded shear-test specimens with a total shear area of less than the cross-sectional tensile area were also prepared and evaluated. Shear strengths were between 87,000 and 94,000 psi, but, more important, shear failures occurred on a plane that was inclined between 10 and 15 degrees relative to the plane of bonding, and shear failures crossed the bond plane without propagating bond failures. Thus, shear strength of the roll-bonded joints was at least equal to that of the parent material.

Additional investigations of mechanical properties of roll-diffusion-bonded samples of Ti-6Al-4V and Ti-8Al-1Mo-1V alloys have been conducted at North American Aviation's Los Angeles Division(4). Figure 7 illustrates the type of cruciform-ribbed structure that was produced by rolling sheet stock of both alloys through a 60 percent reduction and the type and location of test specimens that were used. Tensile properties, in both the transverse and longitudinal directions, as well as shear properties across the roll-bonded joints were determined and compared with the properties of the base metal for both alloys.

Figure 8 compares the tensile-property data for the roll-bonded joints with those for the base metal of the Ti-6Al-4V material.

These data points represent five longitudinal, four transverse, and six short-transverse specimens. The minimum ultimate-strength value for the diffusion-bonded specimens was 97 percent of the typical value for the mill-annealed material. The minimum yield-strength, value for the diffusion-bonded specimens was 91 percent of the typical value for mill-annealed materials. The percent elongation in the bond area has dropped from the typical mill-annealed material value of 15 percent to a minimum of 10 percent. These values indicate that roll-diffusion bonding produces joints with strength characteristics equal to 97 percent of those for the parent material.

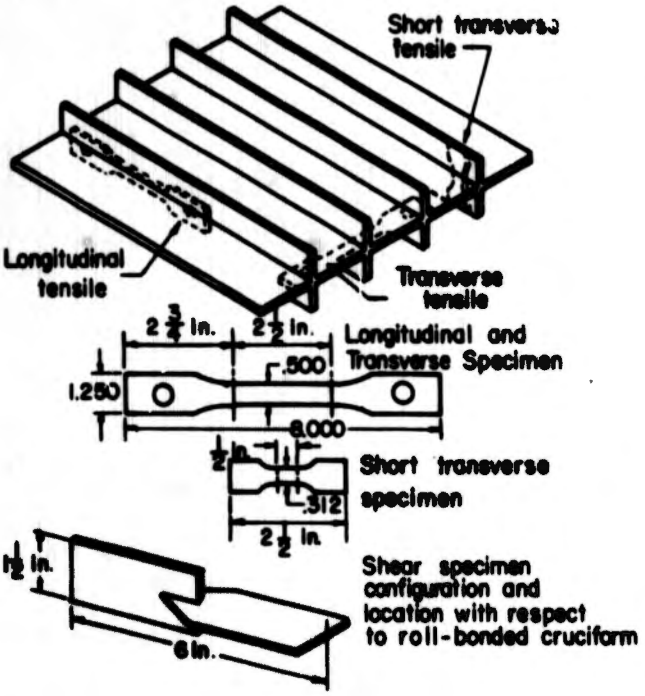


FIGURE 7. ROLL-DIFFUSION-BONDED STRUCTURE AND TEST SAMPLES USED TO EVALUATE MECHANICAL PROPERTIES OF Ti-6Al-4V AND Ti-8Al-1Mo-1V ALLOYS[4]

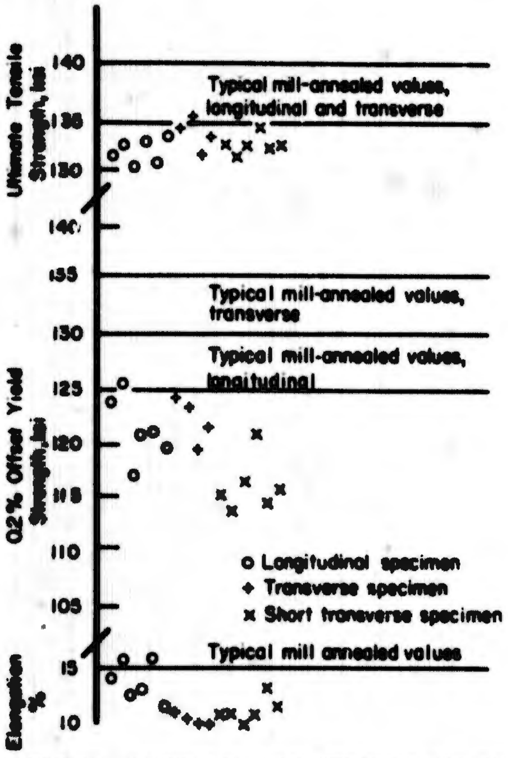


FIGURE 8. TENSILE PROPERTIES OF ROLL-DIFFUSION-BONDED VS MILL-ANNEALED Ti-6Al-4V SHEET SAMPLES[4]

Compression tests (data not detailed in Reference 5) "indicated that no change in properties" had occurred as compared with typical mill-annealed material.

Tensile tests were also performed on roll-bonded samples of Ti-6Al-4V after two different heat treatments, i.e., a "standard" solution-treat-and-age (STA) treatment as well as an overaging treatment. These data are given in Table 3. The bonded samples given the "standard" treatment showed average strength values equal to 98 percent of those achieved in typical mill-heat-treated samples. Data for the overaged test sample were included "to indicate the ability" of this type of treatment "to increase the elongation characteristics" of the diffusion-bonded material.

Shear test data for the Ti-6Al-4V specimens indicated "a diffusion bond-line shear allowable of 93,000 psi". For comparison, a similar shear specimen was machined from 2-inch-thick mill-annealed Ti-6Al-4V titanium-alloy plate stock. This machined specimen indicated a shear allowable of 86,000 psi.

TABLE 3. TENSILE PROPERTIES FOR ROLL-BONDED Ti-6Al-4V HEAT TREATED AS INDICATED[4]

SPEC. IDENT.	Ftu, ksi	Fty, ksi	Elong. 2 in, %	Heat Treatment
1	160.2	150.2	9.0	Standard Ti-6Al-4V heat treatment
2	166.5	157.2	5.0	
3	174.8	161.5	6.0	
Avg	167.2	159.7	6.5	
4	152.7	144.7	9.0	Overaged heat treatment
5	147.9	140.2	10.5	
6	151.3	140.4	8.0	
Avg	150.5	141.8	9.0	
Typical mill heat treated (STA) values	170-175	155-160	8-10	Condition STA

Tensile data on the roll-bonded Ti-8Al-1Mo-1V samples are summarized in Figure 9. These data points represent three longitudinal, seven transverse, and four short-transverse specimens. The minimum ultimate-strength value for the diffusion-bonded specimens was 100 percent of the typical value for mill-annealed specimens. The minimum yield-strength value for the diffusion-bonded specimens was 95 percent of the typical value for mill-annealed properties for specimens. The percent

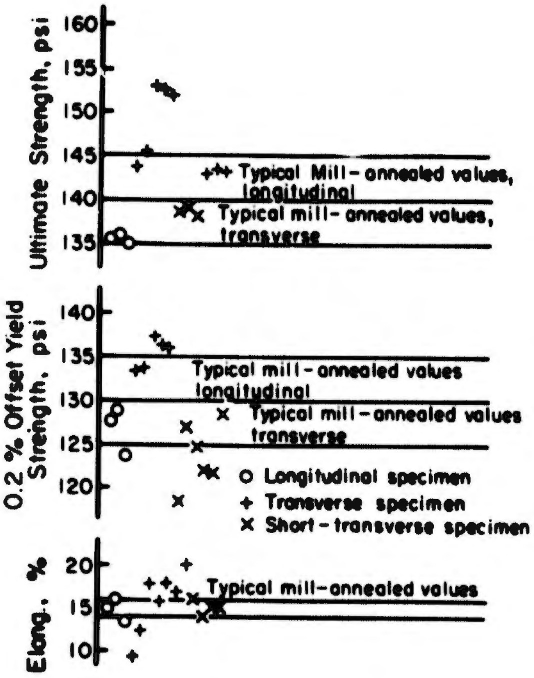


FIGURE 9. TENSILE PROPERTIES OF ROLL-DIFFUSION-BONDED VS MILL-ANNEALED Ti-8Al-1Mo-1V SHEET SAMPLES[4]

elongation in the bond area is equivalent to the typical values for mill-annealed specimens.

STATUS OF ROLL-DIFFUSION-BONDING PROGRAMS

Saturn S-IC Titanium Thrust Structure

Program Scope and Objectives

Under NASA sponsorship, the Convair Division of General Dynamics completed a development program aimed ultimately at the production of a highly loaded, high systems cost effectiveness, roll-diffusion-bonded and fusion-welded Ti-8Al-1Mo-1V Saturn S-IC Thrust Structure.[5] The specific objectives of the development work were to determine (1) limits for processing parameters effective in roll-diffusion bonding Ti-8Al-1Mo-1V components into unitized construction parts, and (2) the suitability of the processing parameters in assembling simulations of anticipated Saturn S-IC structure detail.

Process-Parameter Optimizations

Fourteen process parameters were explored, using relatively small and simple packs made of mild carbon steel (meeting ASTM Specification A-7 or equivalent) with mill annealed Ti-8Al-1Mo-1V bars of mostly rectangular shape. The principal parameters explored and results obtained are described in the paragraphs which follow.

Reheating-temperature and -Time Effects. Encapsulations of Ti-8Al-1Mo-1V in mild carbon steel were prepared and used to examine microstructural changes that occurred after heating to temperatures of 1800, 1900, 2000, and 2100 F for times of 0.5, 1, and 2 hours. This work showed that significant interalloying between the titanium alloy and steel occurred at 1900 F in times as short as 0.5 hour. Increasing time or temperature promoted an increased rate of contamination-layer growth, and heating to 1800 F for times to 2 hours was indicated as optimum for the conditions examined.

Rolling Temperatures. Four simple titanium alloy - mild steel packs were used to determine the effect of temperature on the rolling characteristics, bond, and parent-metal strengths. These packs were heated for 1 hour at 1800, 1900, 2000, and 2100 F prior to rolling through a 60 percent reduction in nine successive passes.

All of the encapulations exhibited some irregularities in finished thickness and shape, which indicated the need for changes in design of the steel-pack supporting members. Also, all items were subject to iron-titanium alloy formation at the steel-titanium interfaces. Tensile properties (summarized below) showed that bond strengths in the Ti-8Al-1Mo-1V did not vary appreciably but ductility decreased as rolling temperatures were increased above 1800 F. The material rolled after preheating at 2100 F was too severely interalloyed with iron to prepare useful tensile specimens.

Heating Temp, F	UTS, ksi	YS, ksi	Elong., %	RA, %
1795	143.2	130.9	17.8	44.4
1890	142.9	130.9	6.7	11.4
2000	140.6	128.7	8.6	18.4

Evacuation Pressure. This work indicated that evacuation of the packs to an encapsulation pressure of 1 mm of mercury or less prior to rolling was desirable to minimize the degradation of mechanical properties in packs rolled after preheating to 1900 F.

Titanium Component Size. Fifteen small packs were rolled at three different temperatures to determine the effect of filling from 5 to 50 percent of the cross sectional area of the yoke cavity with Ti-8Al-1Mo-1V. The balance of the yoke cavity was apparently left empty rather than being filled with solid support material. Problems were encountered with the collapse of encapsulation cavities during rolling and no relationship between rolling pressure and the cross-sectional area occupied by the titanium was noted. Best mechanical properties were obtained with the lowest finish rolling temperatures used (1825 to 1850 F).

Finishing Temperature. No advantages were demonstrated for dropping the finish rolling temperature of packs (initially rolled from a 1900 F furnace) to temperatures of 1630 and 1735 F.

Thickness Reduction Variations. Four packs were rolled through reductions from 30 to 60 percent after preheating to 1900 F. Tensile properties for Ti-8Al-1Mo-1V samples from these are given below and show that the best properties were obtained with the highest reduction used.

Thickness Reduction, %	UTS, ksi	YS, ksi	Elong., %	RA, %
30	130.3	122.8	8.5	3.1
40	135.8	126.1	6.6	14.3
50	137.1	126.2	9.5	20.6
60	140.0	128.0	11.2	27.7

Transverse Bonding. One T-shaped Ti-8Al-1Mo-1V section was rolled (with the bonding plane lying in the direction of rolling but normal to the rolling plane) at 1900 F through a 60 percent reduction. Although experimental difficulties were encountered (excessive spread of the pack and contamination of bonds by both iron and gaseous impurities), it was indicated that transverse bonding is feasible.

Edge Taper Experiments. Three packs with constant-width titanium inserts having various tapers (one edge parallel to the bonding plane) were rolled at 1900 F. The tapers included ratios of 1 to 3, 1 to 4-1/2, and 1 to 9 and introduced a 20 percent change of initial specimen thickness from end to end. In general, these tapers exerted little influence on bond strengths or mechanical properties.

Bauschinger Effects in Hot Forming. Four encapsulated Ti-8Al-1Mo-1V bars were rolled through a 60 percent reduction at 1900 F, then formed to radii of 8-, 12-, 16-, and 20-inches at 1800 F. After subsequent annealing, tensile and compressive properties at room temperature showed that the Bauschinger effect was not active under these conditions of hot forming.

Structural-Detail Simulations

The following structural details were prepared, rolled, disassembled, and examined:

(1) Four 10.5 x 42 inch panels, each carrying two 1.75-inch-high T stiffeners with 1-inch-wide flanges

(2) Two 5 x 5 x 30-inch overall thrust-post simulations

(3) Two 10.5 x 42 inch panels, each carrying two 1.75-inch-high by 1 inch wide hot-section stiffeners

(4) One 24 x 80-inch stepped-thickness skin panel carrying seven 1.75-inch-high T stiffeners with 1-inch-wide flanges.

The quality of all of these items was unsatisfactory. This was largely attributed to inadequacy in the encapsulation design which resulted in excessive internal distortion during rolling. This distortion collapsed the support intended to position the Ti-8Al-1Mo-1V components for rolling-pressure application. Thus, bonding pressures were inadequate and resulted in unbonded or partially bonded items.

Simulated Titanium Alloy Y-Ring Segment for the S-1C Fuel Tank

NASA's Marshall Space Flight Center is considering the use of more efficient materials and new manufacturing techniques for future booster systems to reduce cost and vehicle weight. A critical structural component in the Saturn V vehicle is the aluminum alloy Y-ring, a device which joins the sections of the fuel tank bulkhead to the tank wall (see Figure 10). A comparative weight analysis has shown that substitution of a roll-diffusion-bonded Y-ring of the Ti-8Al-1Mo-1V alloy for the aluminum ring can result in a 32 percent weight saving, which amounts to about 780 pounds per vehicle.

For a constant-size fuel tank, an adjustment was made in the weight of the narrower titanium Y-ring (i.e., 18.24 inches in width versus 23.6 inches for the aluminum ring). The added weight, using aluminum, represents the slightly longer cylindrical skin section. Figure 11 shows a drawing of the full-scale titanium Y-ring.

A program to develop a fabrication procedure for a roll-diffusion bonded Y-ring structure of the Ti-8Al-1Mo-1V alloy is in progress at North American Aviation, Inc., Los Angeles Division.(6) The selection of this alloy for this program was based on its characteristic of high strength, high toughness, and high modulus of elasticity, together with low density, good formability, and weldability.

Program Scope and Objective

The primary objective of this program is to produce an improved Y-ring structure by combining the advantages of good properties of the Ti-8Al-1Mo-1V alloy with those of the roll-diffusion-bonding process and improved design concepts. Ultimately, two full-scale

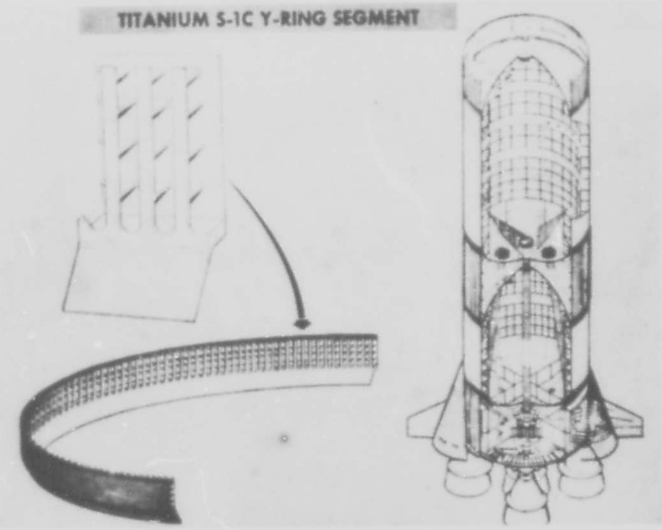


FIGURE 10. TITANIUM S-1C Y-RING SEGMENT

Y-ring segments are to be fabricated and evaluated in a four-phase program.

Initially, three basic fabrication concepts were explored for roll-diffusion bonding the desired Y-ring structure. Figures 12 and 13 illustrate, respectively, the design of the final structure cross section and the fabrication-layup concept that was finally selected.

The fabrication sequence selected for fabricating the full-scale Y-ring segment is outlined below:

(1) Production planning
(2) Material procurement
(3) Pack layup and seal
(4) Roll-diffusion bond
(5) Yoke and cover-plate removal
(6) Inspection
(7) Machine flange radii
(8) Hot contour and duplex anneal
(9) Machine pockets
(10) Steel tooling removal (leaching)
(11) Surface clean-up (chem-milling)
(12) Inspection and evaluation
(13) Shipment.

Fabrication and Evaluation of Developmental Packs

Nine subscale Y-ring segments were rolled to establish the bonding parameters and processing techniques such as machining, hot forming, thermal treatment, and other related processes required for the fabrication of the full-scale Y-ring segment. These subscale Y-rings were one-half the thickness and height of the full-scale Y-ring. The initial size of the subscale packs was 16 x 18 x 24 inches, and these were 4 feet long after rolling.

Prerolling pack temperatures from 1795 to 1850 F were explored with the subscale packs. Finishing temperatures (recorded immediately after the final rolling pass) ranged from 1630 to 1875 F. From evaluations of the subscale Y-ring segments, the optimum rolling-temperature range was determined to be 1835 to 1840 F.

Dimensional analysis of the rolled Y-ring segments showed that good thickness control was achieved for horizontal components. For example, the average deviation from the target thickness ranged from 0.003 to 0.006 inch, depending on the ratio of steel to titanium at the point of measurement. Some irregularities in rib spacing and rib-to-skin angles were noted. These resulted from side spread of the packs during rolling. The increase in overall width of the structure due to side spread was typically 6 to 7 percent.

Metallographic evaluation of the stiffener-to-facing sheet joints in the subscale Y-ring segments showed 1835 F to be the optimum temperature for effecting complete metallurgical bonds. Figure 14 shows a photomicrograph of a typical stiffener-to-facing sheet joint that was produced.

Tensile tests were conducted on specimens cut from two subscale Y-ring segments to determine bond integrity. The round tensile specimens were cut so that the diffusion-bonded joints were located in the reduced section. The data are tabulated in Table 4. All tensile properties met the NAA/LAD material specification for duplex-annealed material.

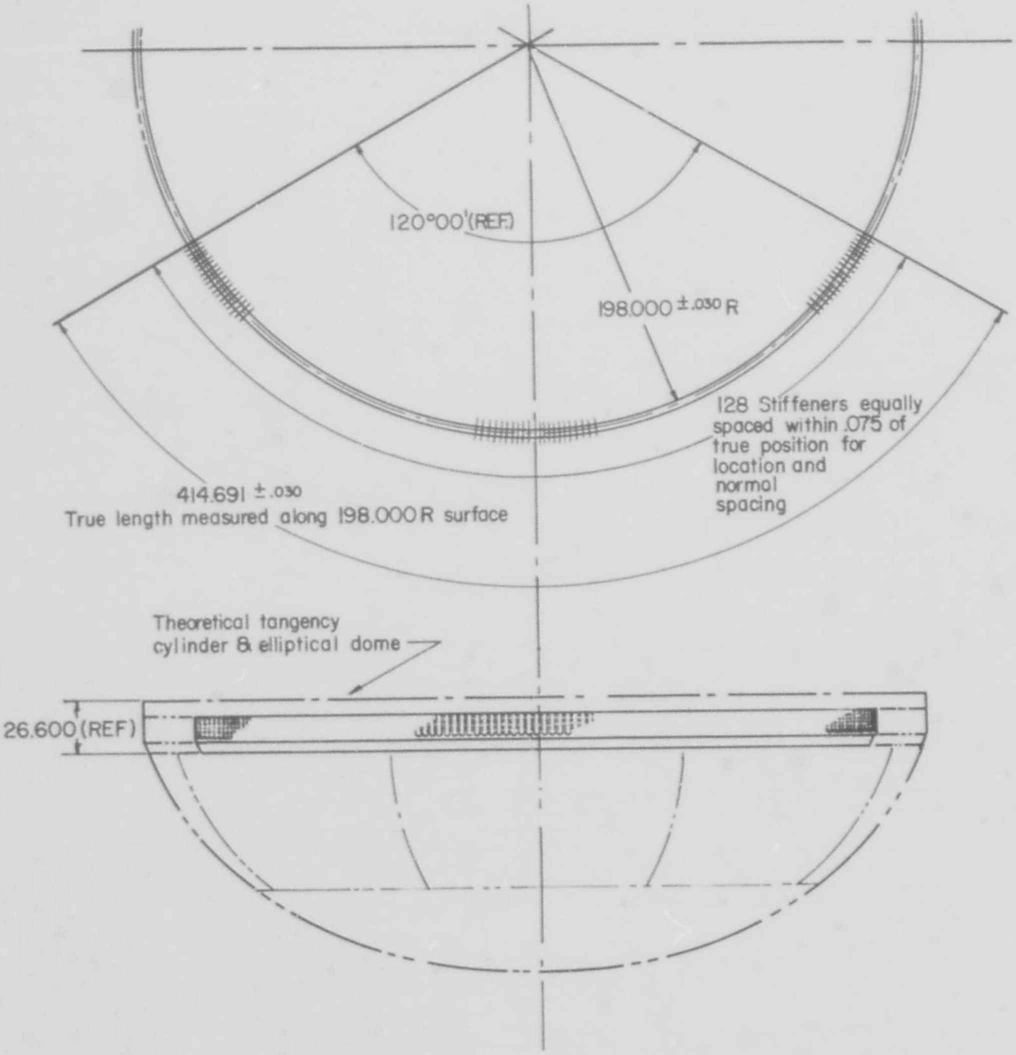


FIGURE 11. DRAWING OF FULL-SCALE Y-RING SEGMENT FOR THE S-1C FUEL TANK(6)

Additional joint test specimens were machined in the form of an I from the stiffened panel area. The test data are tabulated in Table 5. In general, three types of failure occurred:

(1) Some specimens failed in shear with one side of one of the legs shearing off adjacent to the supporting web.

(2) In some specimens, failure occurred in the web after initial shear in the leg.

(3) Failure occurred by shear through the cap and subsequent failure through the web (tear) near the cap.

It was concluded that the tension tests on roll-bonded specimens of the I configuration are useful in evaluating bond integrity and should be examined from the standpoint of fracture location and mode as well as from the standpoint of the load required to produce failure. However, it was also concluded that because of limitations imposed by specimen geometry or notch effect, the stress measurements were not a direct measure of bond strength.

Interstitial-element pickup in the titanium alloy during roll-diffusion bonding was determined by analyses before bonding, after bonding, and after postbonding chemical milling. The data which are shown in Table 6 indicate no detrimental amounts of interstitial-element pickup during the roll-diffusion-bonding process.

Bend tests which were conducted on roll-bonded material after chemical milling show no loss in ductility.

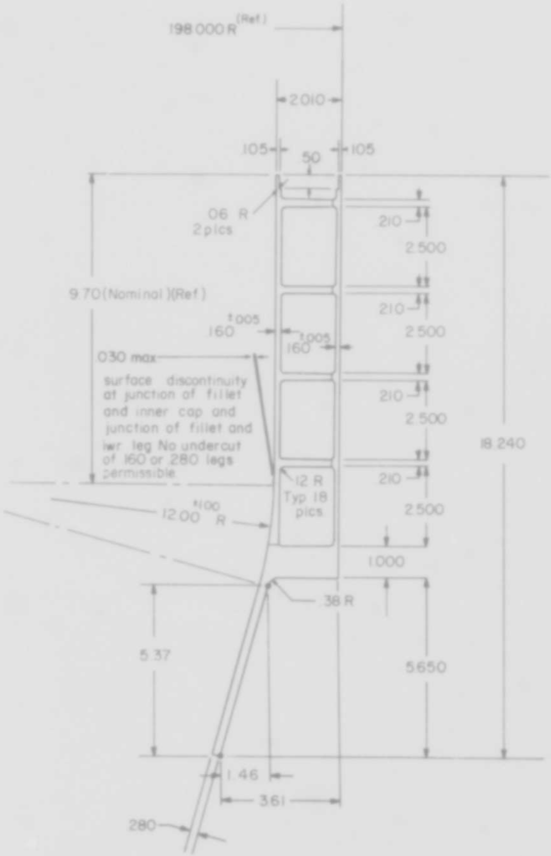


FIGURE 12. CROSS SECTION SHOWING DESIGN OF FINAL Y-RING STRUCTURE(6)

Material for the inner and outer facing sheets and the circumferential stiffeners was tensile tested in the prebond and postbond conditions. The data are given in Table 7. As indicated, the ultimate and yield strengths of the rib and facing materials were significantly reduced, by about 15 to 20 ksi, while the elongation of both materials was increased. Despite these changes, however, the properties of both the rib and facing material still met the minimum values specified by NAA for the Ti-8Al-1Mo-1V alloy.

The subscale Y-ring segments were machined to the design configuration to provide parts for forming studies and to evaluate the basic machining concept to be used in machining the full-scale Y-ring. As noted earlier, this operation is performed after the pack covers are removed prior to forming. Figure 15 shows a machined developmental pack and illustrates how the flange radii and pockets were machined after rolling the pack. The technique selected to remove the steel matrix material after pocket machining was chemical leaching.

FIGURE 13. FABRICATION LAYUP DESIGN USED TO PREPARE Y-RING STRUCTURE(6)

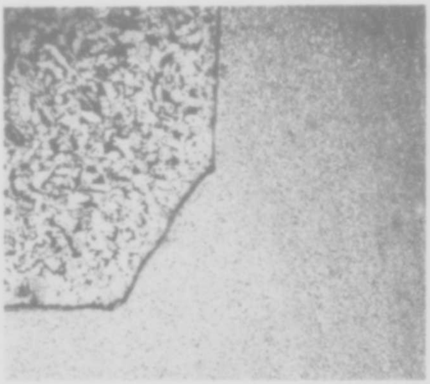


FIGURE 14. STIFFENER-TO-FACING JOINT OBTAINED IN Ti-8Al-1Mo-1V CHAMFERED FILLER BAR PACK(7)

Hot-forming experiments were conducted on the subscale Y-ring segments after machining to develop the forming technique to be used on the full-scale Y-rings. This work indicated that the optimum procedure is an incremental hot form/size technique.

On the basis of the successful forming of subscale Y-ring parts by these techniques, it was decided to apply the same basic fundamentals to forming the full-scale Y-ring segment.

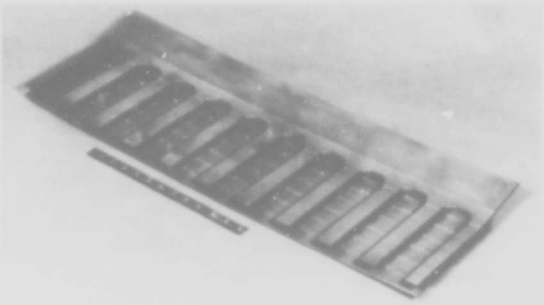


FIGURE 15. COMPLETELY PROCESSED SUBSCALE Y-RING SEGMENT(7)

TABLE 4. ROOM-TEMPERATURE TENSILE TESTS OF ROLL-BONDED Ti-8Al-1Mo-1V-ALLOY SPECIMEN TYPE (BOUND -- TAKEN FROM 1-1/4-INCH-THICK SECTION ACROSS BONDS)(7)

Sample	Stress, ksi Ultimate	Stress, ksi 0.2% Yield	Reduction in Area, %	Elongation, % in 4D
1	140.2	130.5	33.6	12.5
2	137.8	127.4	37.6	15
3	136.5	126.3	43.3	12.5
4	138.1	138.1	34.9	15
5	141.0	128.0	35.8	12.5
Average	138.7	130.1	37.0	13.5
Minimum duplex-annealed properties - NAA Spec. LB0170-177	125.0	115.0	--	10.0

TABLE 5. ROOM-TEMPERATURE TENSILE TESTS OF ROLL BONDED Ti-8Al-1Mo-1V ALLOY "I" SECTION (Facing Sheets - To Circumferential Stiffeners)(7) Pack No. 8

Specimen Identification	Ultimate Web Stress, psi
A (a)	112,800
B (a)	112,300
C (a)	107,700
Avg	110,933
PM 1	137,800
PM 2	135,600
PM 3	125,200
Avg	132,870

(a) Nitric acid etch; pickled; no indication of cracks using die penetrant.

TABLE 6. INTERSTITIAL ANALYSES OF SUBSCALE Y-RING PACK STIFFENER AND FACING MATERIAL(7)

	Analyses, percent					
	As Reported by Supplier	Prior to Roll Bonding	After Roll Bonding	After Chemical Milling Facing	After Chemical Milling Rib	Max Allowable (NAA Spec. LB0170-177)
Hydrogen	0.006	0.0044	0.0061	0.0076	.0048	0.0125
Oxygen	0.108	0.091	0.115	0.104		0.2
Nitrogen	0.011	0.012	0.01	0.021		0.05
Carbon	0.073	0.02	0.04	0.02		0.08
Aluminum	7.89	8.15				7.50-8.50
Molybdenum	1.20	1.19				0.75-1.25
Vanadium	1.05	0.94				0.75-1.25
Iron	0.22	0.18				0.3

TABLE 7. TENSILE PROPERTIES OF ROLL-BONDED Ti-8Al-1Mo-1V PACK STIFFENER AND FACING MATERIAL(7)

	As Received, As Reported by Supplier	Prior to Bonding	After Bonding		Min Duplex-Annealed Properties, NAA Spec. LB0170-177
			Rib	Facing	
Tensile Strength, ksi	153.9 (T)	163.7	143.1	145.8	130
	149.4 (L)	165.2	141.8	145	
		160			
Yield Strength, ksi	147.1 (T)	154.8	137	138.6	120
	137.2 (L)	157.7	136.5	136.4	
		153.2			
Elongation, in 2 Inches, %	14 (T)	11.5	17	13	10
	13 (L)	9.0	17.5	--	

Fabrication of Full-Scale Y-rings

The layup of the two full-scale Y-ring packs was completed and the two packs were rolled on a 160-inch plate mill at Bethlehem Steel Company, Sparrows Point, Maryland. These 35-foot-long packs are the largest titanium structures fabricated to date by the roll-diffusion-bonding process.

After rolling, the yoke material surrounding each segment was flame cut and removed. The top and bottom pack cover plates were then simply stripped off by lifting with a magnet at the mill.

Postrolling ultrasonic inspection indicated excellent overall bond quality in both Y-ring segments. Figure 16 is a photograph of the full-scale Y-ring after the flange-machining operation.

Following the flange-radii-machining operation, both segments were successfully hot contour formed into the final configuration. This was accomplished by feeding the 35-foot-long parts through a 6-foot-long hot contour forming die in approximately 6-inch increments. The die was heated to 1450 F, and the preheated part was fed through the die with approximately 10 minutes of dwell time. About 300 tons of pressure was applied to the part at each increment. Upon exit from the forming die, the structure was received in a special handling fixture which allowed the part to cool at rates that would accomplish a duplex anneal (1450 to 900 F within 60 minutes). The entire forming cycle was completed in about 13 hours. The forming of the Y-ring was judged extremely successful, as indicated by achievement of the desired contour and smooth surfaces. The structures are to be shipped to NASA-Huntsville for testing.

Titanium S-1C Skin Section

The stiffened skin panels which are used on the S-1C fuel tank are currently being fabricated of aluminum. In an effort to reduce costs and weight and improve structural efficiency, a program is under development at North American Aviation, Inc., Los Angeles Division, to evaluate the potential of producing the structure from the Ti-8Al-1Mo-1V alloy by the roll-diffusion-bonding process.(9)

Program Scope and Objectives

The primary objective of this program is to establish design requirements and process parameters for fabricating simulated skin sections for the S-1C fuel tank from the Ti-8Al-1Mo-1V alloy by roll-diffusion bonding. An additional objective of this program is to show the weight advantage of titanium versus aluminum in the S-1C tank structure. The program is being conducted in four phases, with the ultimate objective being to fabricate a full-scale Ti-8Al-1Mo-1V alloy S-1C skin section for testing and evaluation at NASA-Huntsville. To establish the design and process parameters for fabricating the full-scale panel, several subscale developmental panels representative in crosssection of the full-scale panels were rolled and evaluated.

Fabrication and Evaluation of Subscale Panels

Six subscale panels were fabricated in Phase I of the program. The design of these panels was based on the results of a computer study which screened potential concepts for relative efficiency in strength and weight. In addition, a parallel study was conducted on cost and technical feasibility of the roll-diffusion-bonding process as related to the conceptual designs under study. The results of these

FIGURE 16. FULL-SCALE Y-RING AFTER MACHINING OPERATION(8)

parallel studies were integrated into the six development packs. These consisted of a T-section stiffener for both internal- and external-stiffener-panel designs. The final selected configurations are shown in Figure 17.

The developmental panels, which measured 15-3/4 x 55 inches after rolling to a 60 percent reduction, were enclosed in a carbon steel pack with prerolling dimensions of 18 x 24 x 6-1/2 inches.

The subscale packs were assembled at NAA/LAD and rolled at the U. S. Steel Research Mill at Monroeville, Pennsylvania. The packs were heated to 1800 F and then rolled to a 60 percent total reduction in 10 to 16 passes.

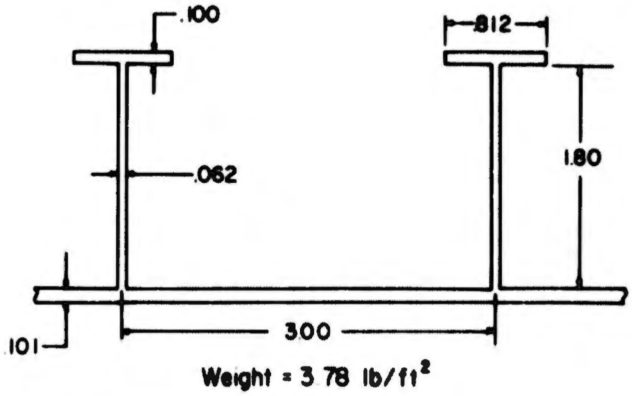
Pack Disassembly and Inspection. Following rolling, the packs were shipped to NAA/LAD and disassembled. Postrolling evaluation included dimensional analysis of panels, evaluation of bond integrity, tensile properties, analysis for interstitial elements, and structural testing.

A study of postrolling dimensions of the subscale panels showed that some lateral spread had occurred. In all panels, the finish dimensions between the vertical webs averaged 0.083 inch greater than the target dimensions. Also, the webs were not parallel to each other and the spacing between them tended to increase toward the center of the panel.

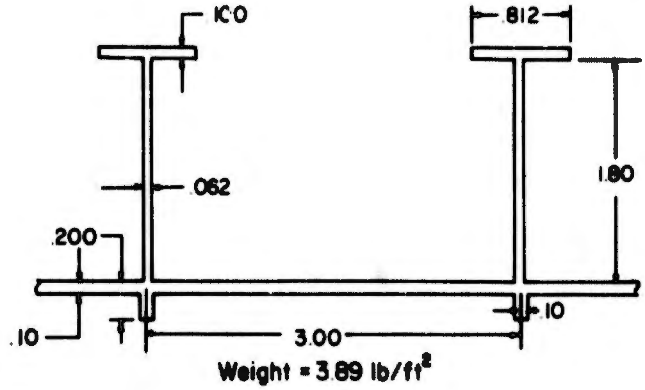
Measurement of the T-cap thickness, face sheet thickness, and T-height indicated a fairly consistent 60 percent reduction in the thickness of the horizontal members. However, it was concluded that deviations from target tolerances would not be acceptable in production panels.

Postrolling evaluation of bond quality was accomplished by metallographic examination of representative joints and by destructive testing. Test specimens were machined from the roll-diffusion-bonded test panels to the configurations shown in Figure 18 and tested in tension. The resultant strengths are listed in Table 8. Characteristically, most of the specimens had cracks on the surface or radii. The specimens were hand filed and pickled in an attempt to remove the cracks. When tested, the specimens usually failed through the upper cap strip or face sheet.

Metallographic inspection of the test panels showed complete bonds with no voids. On the basis of the joint strength tests and metallographic examination, it was concluded that parent or near-parent material strength can be achieved at all diffusion-bonded joints.



a. Internal integral tee configuration



b. External integral tee configuration

FIGURE 17. TARGET CONFIGURATIONS OF SUBSCALE PANELS[19]

The major metallurgical problem revealed in this study was the development of postrolling cracks in the titanium structure. The more severe cracks were attributed to thermal-shock treatment which had been used in an attempt to facilitate removal of the steel matrix from these samples. This treatment, which had shown promise in earlier work, consisted of soaking the pack at -120 F, then plunging it into 204 F water. The cause of the smaller surface cracks is still under investigation.

The interstitial content of two subscale panels was determined after fabrication. Although some increases in the hydrogen, oxygen, and nitrogen content of the Ti-8Al-1Mo-1V material were observed, the final values for these impurity elements were all within the limits specified for this alloy.

Phase I Supplemental Program

After evaluation of the first six subscale panels was completed, it was decided to fabricate a seventh test pack before proceeding with the full-scale production packs. This pack was designed to incorporate numerous features and experiments to develop improved techniques for solving problems encountered in the first six development packs. These design features and variables are discussed in the paragraphs which follow.

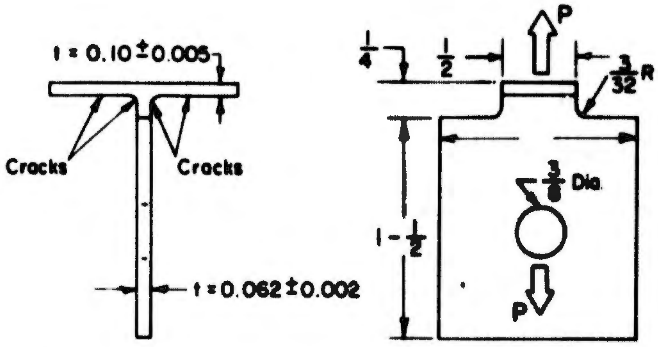


FIGURE 18. BOND ADHESION TEST SPECIMENS[9]

TABLE 8. TENSILE STRENGTHS OF RIB-TO-SKIN JOINTS IN SUBSCALE PANELS[10]

Pack	Specimen	Ultimate Strength, ksi
F	B-1	Broke during machining
F	B-2	Cracked during machining
F	B-3	112.8
F	B-4	150.6
F	B-5	168.8
F	C-1	178.6
F	C-2	172.1
F	C-3	179.3
E	B-2	145.5
E	B-3	142.8
E	B-4	162.0
E	B-5	144.7
E	C-1	178.1
E	C-2	173.9
E	C-3	138.9
E	C-4	Broke during machining

Four-Piece Yoke Assembly. The full-scale-pack yoke design was intended to employ a four-piece yoke assembly. To determine whether this type of construction would withstand the hot-rolling pressures, a four-piece yoke assembly was used for the seventh subscale pack. The four-piece yoke construction withstood the hot-rolling pressure but caused pack-assembly difficulties owing to warpage of the bars during welding. A one-piece yoke was recommended for the full-scale packs.

Bond-Joint Fillets. Various radii and chamfers were machined on the filler-bar corners which were interfaced with the titanium details. The purpose of varying the radii was to determine which geometry provides an ideal void into which the titanium would flow during rolling to create a fillet. An additional experiment included the placement of a titanium wire along the filler-bar radius to determine if the wire would bond to the titanium details to form a joint fillet. The results indicated that the best fillet condition was obtained by placing a 0.125-inch radius on the corners of filler bars.

Welding of Titanium Details Prior to Rolling. To determine what happens to titanium weld joints during rolling, three weld joints were incorporated into the titanium pack details as follows:

(1) A skin sheet spliced parallel to the rolling direction

(2) A vertical weld (joint perpendicular to the face sheet) in a rib manner.

(3) A transverse weld across one of the cap strips containing simulated cracks.

Postrolling evaluation showed that the longitudinal weld in the titanium face sheet was improved by rolling. On the other hand, simulated cracks in the transverse weld did not heal, but were extended and became an open void.

Preassembly Outgassing of Steel Parts. In the first series of subscale packs, hot outgassing of the pack details was done after the pack was assembled and sealed. To compare interstitial-element pickup with that of the previous packs, the seventh pack steel components were hot outgassed before layup. This was done by enclosing the steel parts in a stainless steel retort and hot evacuating the unit at 1200 F for 16 hours. Postrolling interstitial analysis of the titanium details showed no significant differences from packs which were conventionally outgassed, indicating that prelayup outgassing of steel components is not necessary.

Full-Scale S-1C Skin Section

Figure 19 is a schematic drawing which illustrates the dimensions and configuration of the skin section to be produced in this program. As indicated, this section requires the rolling of two packs, one of which is to be retained at full size and the other to be cut approximately in half (lengthwise) and joined to the former by welding. The cross sectional dimensions and details of the Ti-8Al-1Mo-1V skin structure are shown in Figure 20.

At the time this report was prepared, the final report describing the work completed on the full-scale panels was not available to DMIC. However, according to preliminary information, two full-scale panels have been rolled, leached, and inspected. Sufficient good-quality material was obtained from these panels to complete fabrication of the single full-scale skin section. Figure 21 shows a section of one of the production-size panels in the rinsing operation after leaching.

Titanium Conjugate Tankage Structure

In 1965, the United Technology Center(12) completed a study in which new conjugate structure and tankage designs, utilizing roll-diffusion-bonded sandwich structure, were developed for Stages II and III of the Titan III Standard Space Launch Vehicle. These designs showed that a potential weight savings of approximately 400 pounds over the existing designs might be realized. Accordingly, on the basis of this design study, a contract was awarded to North American Aviation, Inc., Los Angeles Division, to "demonstrate and verify" the potential of roll-diffusion-bonded titanium sandwich material in "obtaining a higher stage mass fraction for liquid rocket system structures and tankage".(13)

Program Scope and Objective

The ultimate objective of this program is the construction of a prototype tankage assembly using roll-diffusion-bonded Ti-6Al-4V alloy truss-core sandwich structure as the base material. The program is divided into two phases. Phase I includes a redesign of the reference tankage design developed in the U.T.C. study, preparation of a manufacturing

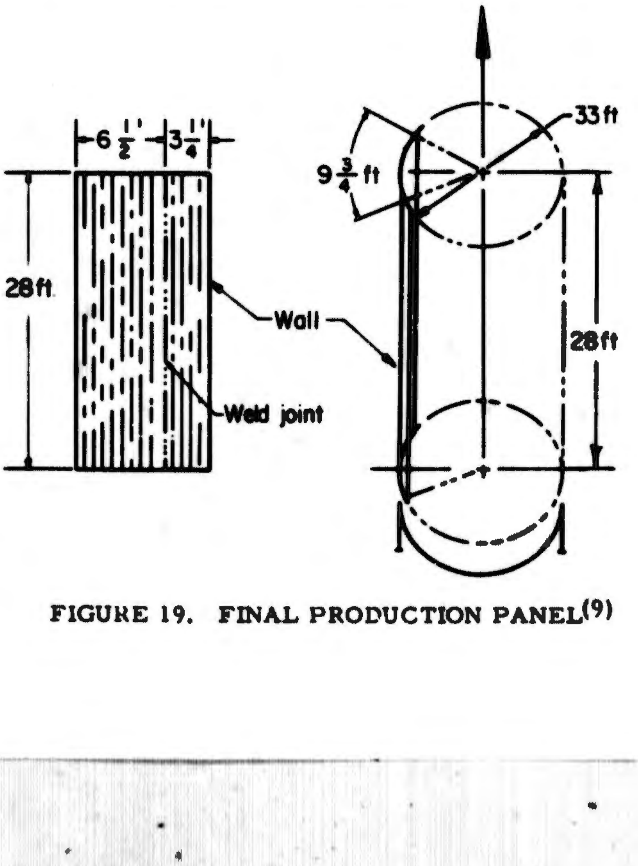
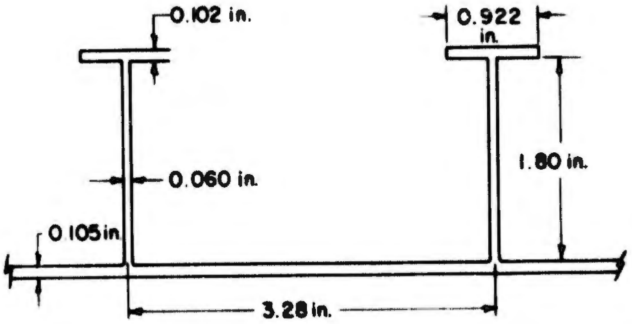


FIGURE 19. FINAL PRODUCTION PANEL(9)



Material: Ti-8Al-1Mo-1V duplex annealed

FIGURE 20. INTEGRAL TEE-CONFIGURATION STIFFENERS INSIDE CYLINDER(9)

plan to be used in Phase II, and performance of laboratory studies to develop processing parameters for fabrication of the truss-core panels. Phase II requires the fabrication of tankage approved as a result of Phase I, and quality assurance testing and certification by the contractor.

Redesigned Tankage Configuration

The redesigned tankage configuration which was generated in the NAA/LAD Phase I study is shown in Figure 22. As indicated, truss-core sandwich configuration has been specified for both the fuel tank cylinder section (approximately 66 inches long) as well as the oxidizer tank portion (approximately 39 inches long).

In this design, no fluid flows through the fuel tank internal passage, but fuel flows through the oxidizer tank wall to a manifold located at the base of the cylindrical section. Ti-6Al-4V alloy is used throughout the structure, except for the two skirts, which are fabricated from 7178-T6 aluminum alloy.

One of the significant design features incorporated in this program is the sandwich "plywood" concept. This concept involves the design and fabrication of only one standard truss-core configuration with thick face sheets, as shown in Figure 23. The face sheets can thus be chem-milled to the exact load requirement for each particular application. The original U. T. C. design had called for five optimum truss-core panel configurations.

The approach taken in this program was similar to that of other roll-diffusion-bonded prototype hardware-oriented programs, i. e., the development of process parameters by fabricating subscale panels followed by fabrication of the full-scale panels.

Subcontractor Support Program

Under a subcontract to this program, Battelle's Columbus Laboratories assisted NAA/LAD with a research and development task that was successful in solving a number of problems to further advance the state of the art of the rolling-diffusion-bonding process.(3) The most significant results from this subcontracted effort are summarized in the following paragraphs.

Mechanical-Assisted Filler-Removal Techniques. The usual practice for removing the steel matrix material from a closed structure (panel with two face sheets) has been to dissolve the entire bar away by flowing a nitric acid solution into the panel ends. This is a costly and time-consuming operation.

Earlier studies at Battelle indicated the feasibility of mechanically removable composite filler to alleviate the leaching problem. This was further studied for NAA/LAD in a joint experiment between Battelle and Atlas Steel Company. This experiment demonstrated that panels could be fabricated using extractable-core fillers to provide continuous holes through each filler bar for the circulation of leaching solutions. Furthermore, it was shown that the panels could be contoured after core extraction without closing the leach holes.

This technique involves adaptation of the hollow-core-drill steel manufacturing concept to the roll-diffusion-bonding process. This concept is based on the use of a composite 1020 carbon steel and austenitic steel filler bar as shown in Figure 24. After rolling and before contouring, the tough austenitic steel cores are separately stretched and pulled out of their surrounding steel jackets, leaving a continuous hole. Figure 25 shows an end view of a subscale panel after rolling, core extraction, and hot forming to a 12-inch radius. Note that the postextraction contouring operation has not closed the through holes.

Effect of Filler Composition on Titanium Pack Details. Diffusion couples were prepared by sandwiching commercial-grade Ti-6Al-4V alloy sheet material between various grades of carbon steel. These were heated, under a compressive load, in vacuum to temperatures of 1650, 1750, and 1850 F for times to 4 hours. Metallographic examination showed that the carbon contained in the steel led to the formation of titanium carbide at the steel/titanium interface and that this carbide layer provided an effective barrier against diffusion of the iron into the titanium. The effectiveness of this carbide layer in retarding iron diffusion into the titanium can be seen by comparing the microstructures in Figure 26. Evaluation of the diffusion-couple data indicated that carbon levels in the surface zones of the steel face details should be at least 0.20 percent to retard iron diffusion into the Ti-6Al-4V.

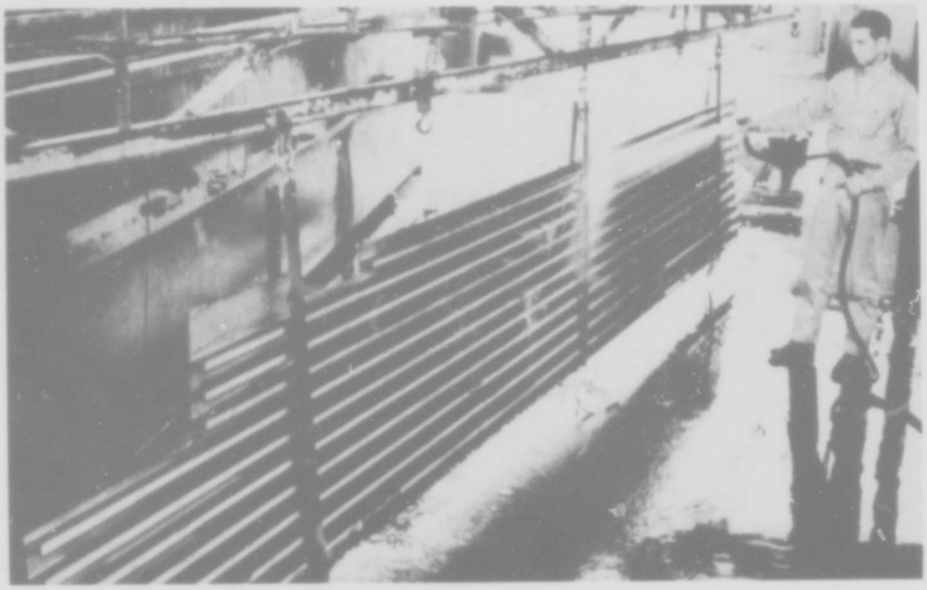


FIGURE 21. RINSING SECTION OF FULL-SCALE PANEL(11)

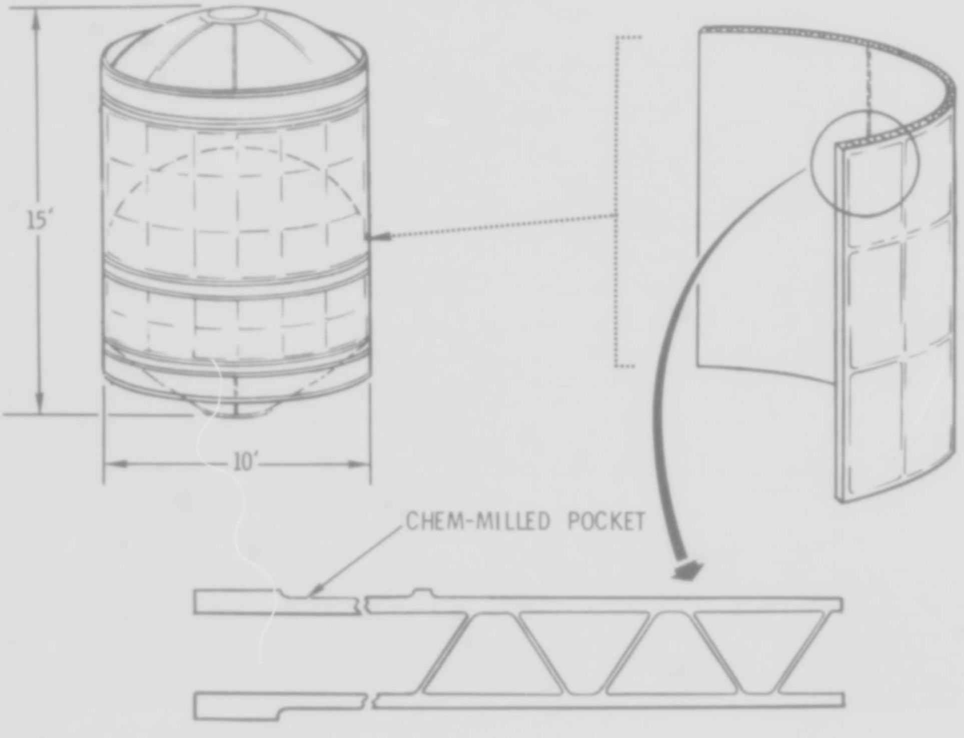


FIGURE 22. TITANIUM CONJUGATE TANKAGE STRUCTURE.(13)

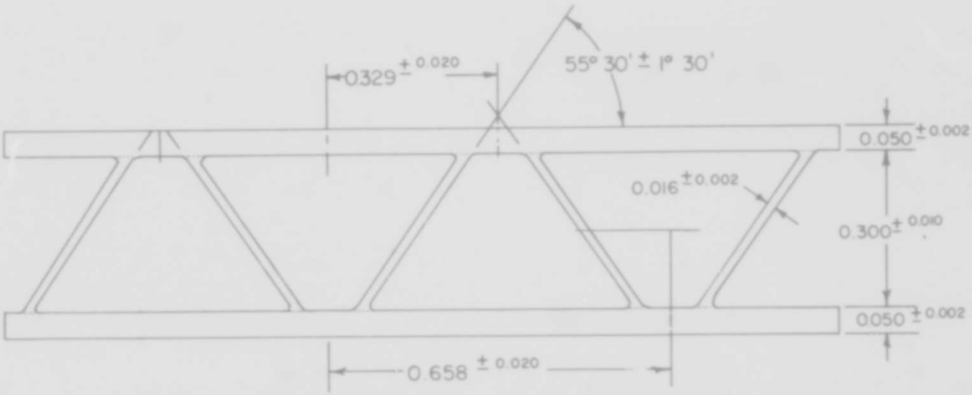


FIGURE 23. STANDARD Ti-6Al-4V PANEL DESIGN(13)

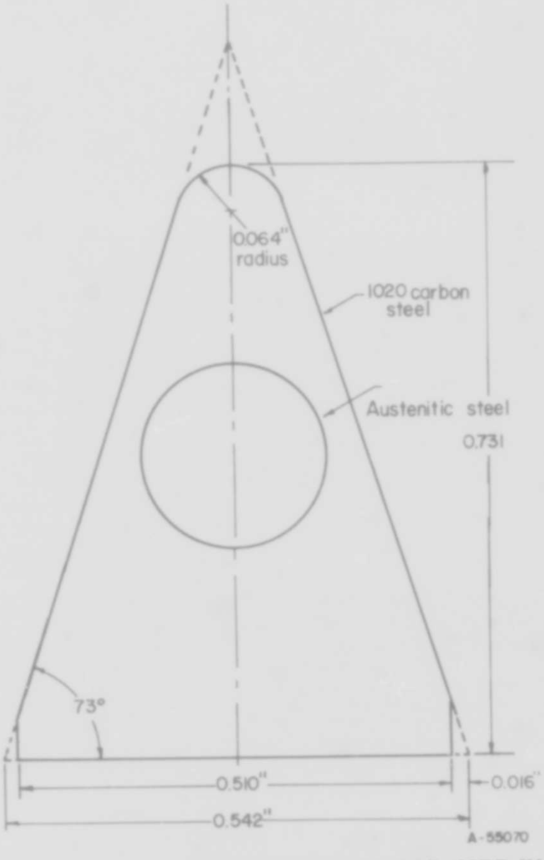


FIGURE 24. COMPOSITE FILLER BAR USED IN MECHANICAL-ASSISTED FILLER-REMOVAL EXPERIMENTS(3)

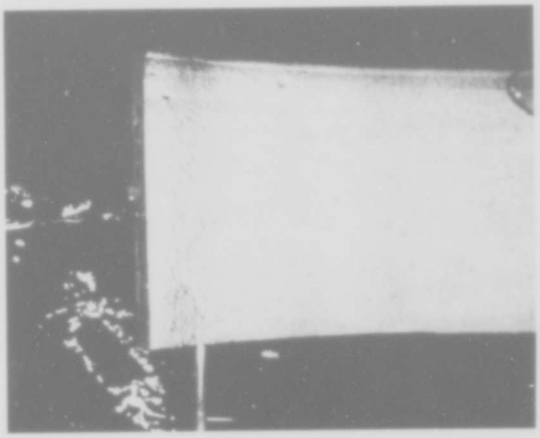


FIGURE 25. TOP VIEW OF FORMED PANEL SHOWING WATER FLOW THROUGH OPEN CHANNEL(3)

The results of the diffusion-couple studies were confirmed in other pack-rolling experiments in which various grades of carbon steel were used as the matrix material.

Development of Filleting Techniques. The results of other studies showed that fillets can be produced at the rib to skin joints by radiusing or chamfering the filler-bar corners. The shape of the fillet generally conforms to the shape of the void space geometry at the filler-bar corners as a result of plastic flow of the titanium details during hot rolling. An example of this type of roll-diffusion-bonded joint which resulted from radius filler bars is shown in Figure 27.

Optimization of Rolling Parameters. By rolling a series of subscale packs, identical in cross-section configuration and dimensions to the intended full-scale packs, an optimum rolling practice was established. Correlation of these data with metallographic evaluation of the rolled

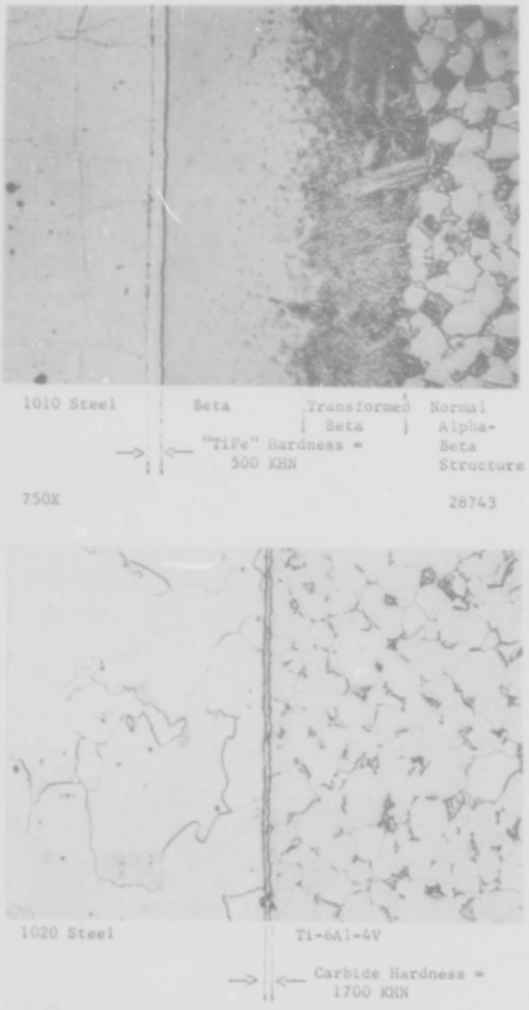
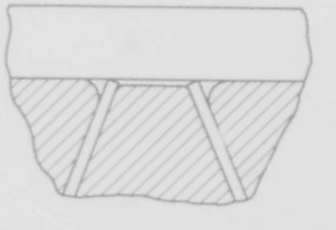


FIGURE 26. MICROSTRUCTURES OF STEEL Ti-6Al-4V DIFFUSION COUPLES AFTER 4 HOURS AT 1650 F

panels showed that the best results were achieved, from the standpoint of bond integrity and metallurgical properties, when the packs were heated to 1750 F and reduced rapidly to final size in five or six rolling passes without reheating. Reheats were shown to be of no benefit in effecting complete bonds, since bonding is essentially complete after the first rolling pass.

Fabrication and Evaluation of Developmental Packs

To proceed from a laboratory approach to a production approach, approximately 120 square feet of sandwich material, in panel sizes of 4 x 5 feet, were fabricated to establish and verify the manufacturing process.



A. Schematic Layup - 0.020-Inch Radius On Filler Bar Base Corners, Slight Radius On Apex Corners

FIGURE 27. LAYUP AND TYPICAL JOINT IN PANEL 11[(3)]

Core Lay-up Technique. The first two developmental packs contained a dual-cavity yoke to incorporate two types of layup (strip and corrugation) in one pack assembly for evaluation. The titanium for the strip-core layup was simply sheared oversize and edge ground to the desired tolerance. The titanium for the continuous corrugation was preformed at room temperature on a brake forming corrugation die and then hot sized to fit the internal tooling bars. After evaluation of these two techniques, the strip layup technique was selected for succeeding packs, primarily because of lower fabrication costs.

Dimensional Control and Panel Geometry. In general, excellent dimensional control and panel geometry was achieved in the developmental packs. However, some defects did occur; these were eliminated in follow-on packs by alteration of layup techniques and fabrication procedures. One condition which was characteristic of some of the developmental panels was parallelogramming. This condition, which is shown in Figure 28, was caused by failure to "square-up" the packs between rolling passes. The out-of-squareness was less pronounced in subsequent packs.

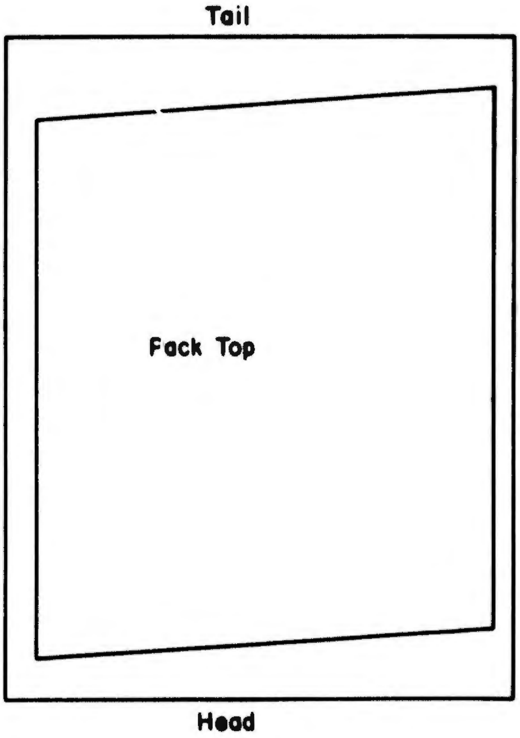


FIGURE 28. OUT-OF-SQUARE CONDITION PRODUCED IF PACK IS NOT LINED UP BETWEEN PASSES DURING ROLLING[13]

The importance of a precise fitup of the matrix components was shown in a pack in which a longitudinal crease developed during rolling because of underwidth filler bars in this area. In rolling, the total minus tolerance produced a void space and the resulting crease. This condition was corrected in succeeding packs by placing shims in the packs to correct for cumulative negative filler-bar tolerances.

Metallurgical Evaluation. Generally, metallographic examination of the developmental panels showed complete metallurgical bonds between the rib and face members of all panels.

Several of the ribs showed severe "undercutting" or rib thinning owing to intrusion of the steel filler bars. The same condition existed with both the strip and corrugation layup. Later studies showed that this undercutting or rib thinning could be eliminated by using the strip layup and by a more precise fit between cavity components.

Mechanical-Property Evaluation. Mechanical tests were conducted to establish mechanical-property characteristics. The types of tests conducted included flatwise tension, shear, bending, burst, and edgewise compression. The specimens were prepared from a full-scale production-type panel and were distributed so as to be representative of all areas of the panel. The details of the testing program are discussed in the following paragraphs.

Flatwise tension tests were conducted on nine specimens using a specially designed fixture. The results are shown in Table 9. The mode of failure in all flatwise tension tests was rupture of the truss ribs near the bonded joints. No failures occurred in the diffusion-bonded joint.

TABLE 9. FLATWISE-TENSION-TEST RESULTS[13]

Specimen	Rib Thickness, inch	No. of Ribs	Ultimate Stress, psi
Ft - 1	.014	4	30,520
- 5	.014	4	16,840
- 7	.0145	4	34,140
- 14	.014	4	21,280
- 15	.015	4	35,450
- 19	.014	4	29,490
- 21	.014	4	21,880
- 22	.014	4	31,480
- 23	.014	4	34,320

Core shear tests were conducted. Shear was evaluated in a direction both transverse and longitudinal to the core direction. The shear-test results are listed in Table 10. Figure 29 shows a typical stress-deformation curve for both transverse and longitudinal specimens.

Shear beam tests were conducted on 2-1/2 x 12-inch specimens, with the corrugation running the length of the beam. Loads were applied 2.75 inches from the beam supports, with 5.50 inches between loads. The test results are listed in Table 11. Typical stress-deflection curves for beams with 0.032 and 0.040-inch face sheet are shown in Figure 30.

Burst tests were conducted on 3 x 3-inch specimens, in which the face sheets had been chem-milled to thicknesses of 0.032 and 0.040 inch. The specimens were clamped between the pressure plates in a test fixture and internal pressure was applied by a hand-operated hydraulic pump until failure occurred. Failure was indicated by a sudden pressure drop on a pressure gage. Results of the burst test are shown in Table 12.

Panel compression tests were conducted in which the core was placed parallel and transverse to the load direction. The test results are listed in Table 13. Typical stress-deformation curves for both longitudinal and transverse loading and for both 0.032 and 0.040-inch face sheets are shown in Figure 31.

In general, these mechanical-property evaluations showed the panel to be uniform in properties, and no evidences of bond failure were detected.

TABLE 10. SHEAR-TEST RESULTS(13)

Specimen	Core Direction	Failure Stress, psi based on Rib Area	Failure Stress, psi based on Panel Area	Failure Mode
11	Long.	64898	2504	(a)
20	Long.	66632	2596	(a)
6	Trans.	---	1244	(b)
8	Trans.	---	1238	(b)

(a) Cracking and wrinkling of the truss-core ribs.

(b) Cracking of the truss-core ribs.

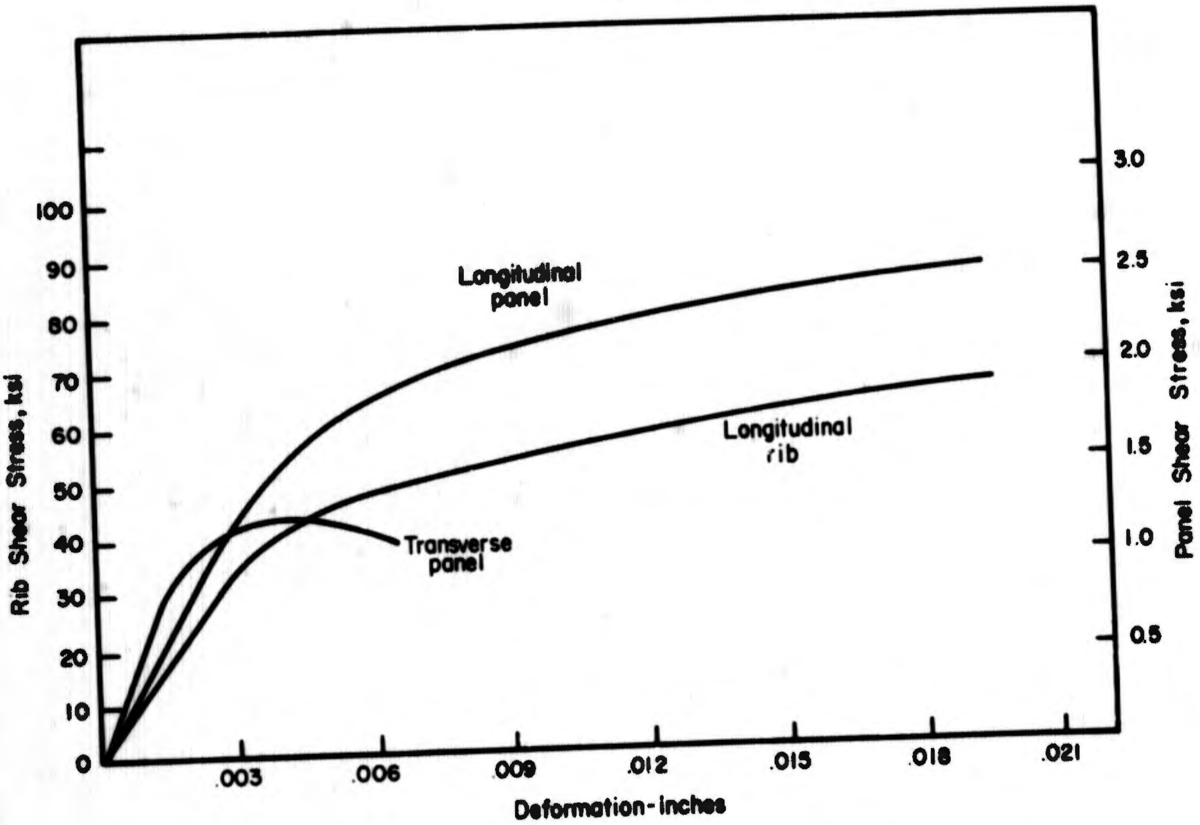


FIGURE 29. TYPICAL CORE SHEAR TESTS(13)

TABLE 11. SHEAR-BEAM BENDING-TEST RESULTS(13)

Specimen	Face Sheet Thickness, in.	Max Stress(a), psi	Max Deformation, in.	Failure Mode
13	0.032	63191	0.8	(b)
33	0.032	60143	0.7	(c)
12	0.040	79106	0.76	(b)
32	0.040	81915	0.85	(c)

(a) Maximum stresses were calculated, using the following beam formulas:

$$\sigma = \frac{M \times \frac{h}{2}}{I}$$

$$I = 1/12\ bh^3$$

$$M = P \times a$$

or

$$\sigma = \frac{Pa \times \frac{h}{2}}{1/12\ h^3\ b}.$$

(b) Failed by buckling between the applied loads, approximately at the point of maximum stress.

(c) Failed by buckling at one of the applied load locations.

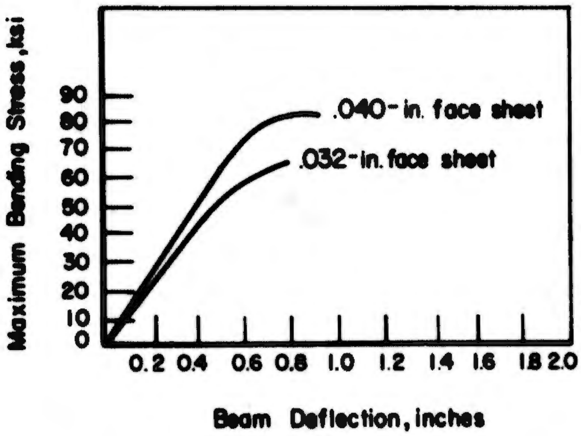


FIGURE 30. TYPICAL SHEAR-BEAM BENDING TESTS(13)

TABLE 12. BURST-TEST RESULTS(13)

Specimen	Face Sheet Thickness, in.	Pressure at Failure, psi	Failure Mode
18	.032	4525	(a)
30	.032	4525	(a)
10	.040	5550	(b)
31	.040	5100	(b)

(a) Failure of face sheet and ribs.

(b) Failure of ribs.

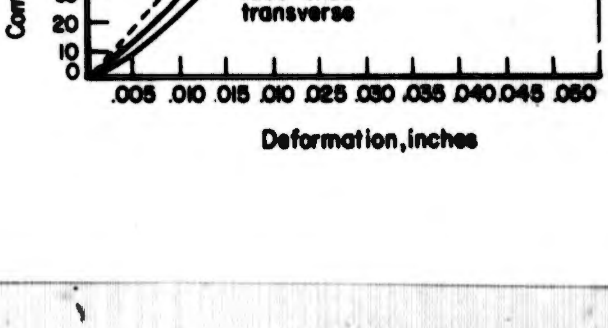


FIGURE 31. TYPICAL EDGEWISE-COMPRESSION-TEST CURVES(13)

TABLE 13. EDGEWISE-COMPRESSION-TEST RESULTS(13)

Specimen	Face Sheet Thick, in.	Core Dir.	Failure Stress, psi	Failure Mode
2	.032	Trans.	48573	Face sheet buckling
24	.032	Trans.	44581	
16	.040	Trans.	69688	
25	.040	Trans.	63298	
3	.032	Long.	119100	Face sheet and rib buckling
4	.032	Long.	124800	
26	.032	Long.	126200	
27	.032	Long.	118700	
9	.040	Long.	123300	
17	.040	Long.	129000	
28	.040	Long.	127700	
29	.040	Long.	126300	

TABLE 14. STATUS OF FULL-SCALE PACKS(14)

Pack	Type	Size, ft	Rolled
1, 2	Devel.	4 x 5	9/17/65
3	Devel.	4 x 5	11/2/65
4	Devel.	4 x 5	12/16/65
5, 6	Preprod.	4 x 7.5	2/11/66
7 to 10	Prod.	4 x 7.5	6/10/66
13, 15, 16	Prod.	4 x 7.5	7/8/66
11, 12, 14	Prod.	4 x 7.5	8/9/66
17, 18, 19	Prod.	4 x 7.5	10/11-12/66
20 to 23	Prod.	4 x 7.5	12/22-23/66
24 (Special)	Prod.	4 x 10	

Fabrication and Evaluation of Production Panels

A total of 23 full-scale truss-core panels and one special panel, a vertical-stiffened-frame web panel, are scheduled for fabrication. Table 14 lists the types and sizes of these packs, all of which had been scheduled for rolling by the end of calendar 1966. The special panel, which consists of vertical stiffeners approximately 0.040 inch high on both sides of the web, is to be used for an internal ring frame supporting the bottom of the oxidizer tank.

Postrolling Evaluation. Inspection of the rolled product includes metallographic inspection of diffusion-bonded joints and surface layers of the titanium sandwich material, mechanical properties of the diffusion bonded joints and face sheets, and chemical analysis.

As of December, 1966, 13 of the production panels (Panels 7 through 19) had been rolled and evaluated. The results show that all of the panels were acceptable for production. Some of the panels show debonds at the panel extremeties. However, these areas were removed by trimming and the panels were forwarded to the production department for forming and leaching.

Tankage Fabrication and Assembly. Following postrolling inspection, the panels are being creep formed, leached, hot-sized, chem-milled, ultrasonically inspected, and delivered to the assembly area.

The method adopted for forming the cylindrical sections for the conjugate tankage structure consists of hot-creep forming the panels to conform roughly to the final tank wall configuration with the filler bars in place. The final configuration is achieved by a hot-sizing operation after the filler bars are leached.

For the initial forming operation, the dies and sandwich panel are heated to about 1250 F. Following leaching, the panels are hot sized at 1050 F to the final tank wall configuration. Using this technique, excellent conformity to contour has been obtained without crushing or buckling of the core. As of January, 1967, the eight lower tank sandwich panels had been completed through the creep-forming, leaching, and hot-sizing operations.

The steel matrix material is being leached from the production panels at a faster rate than was earlier anticipated. Figure 32 shows a section from a full-scale panel after leaching and trimming.

A postleaching inspection of the lower tank panels disclosed that intergranular corrosion of the Ti-6Al-4V alloy surface had occurred to a maximum depth of about 5 mils during leaching. Laboratory investigation showed that this resulted from a selective attack of the nitric acid leachant on iron-rich areas in the Ti-6Al-4V surface layer. These areas of high iron content resulted from the use of steel pack details which had decarburized surfaces. As noted earlier, the Battelle supporting work had indicated that the presence of about 0.20 percent carbon in the steel surface was necessary to inhibit iron diffusion into the Ti-6Al-4V alloy.

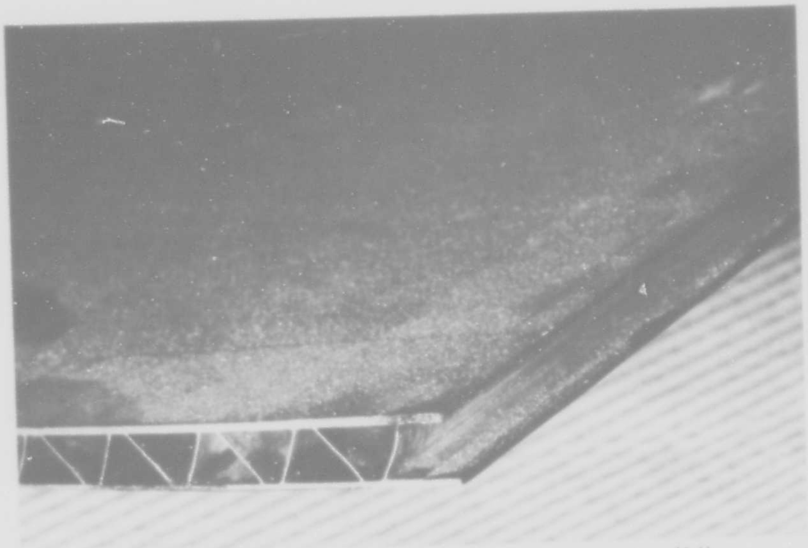


FIGURE 32. LOWER TANK PANEL, TRIMMED AND MACHINED(14)

Chemical-milling experiments in full-scale panel sections showed that the face sheets could be chem-sized without corroding the panel cores by filling the cores with a plastic material (Paraplast 33). The Paraplast is removed after chem-milling by heating the panel to 350 F and soaking in hot water.

Titanium Structural Sections

Program Scope and Objectives

In another phase of its roll-bonding activities, The Los Angeles Division of North American Aviation is conducting a program to develop a base of information to promote the use of roll-diffusion-bonded product in the Aerospace industry.(15) This program has three major objectives:

(1) To produce structural shapes which can compete with state-of-the-art extruded and machined Ti-6Al-4V alloy shapes

(2) To produce closed-section extruded-type structural shapes which cannot be made by current state-of-the-art extrusion processes from Ti-6Al-4V

(3) To generate mechanical-property data representative of roll-diffusion-bonded joints in Ti-6Al-4V.

The program has four major aspects: (1) definition of roll-bonded airfoil-shape problem areas; (2) development of a full-scale roll-bonded airfoil shape typical of jet-engine-inlet guide vanes, compressor stator blades, and helicopter rotor blades; (3) development of roll-bonded structural shapes typical of aircraft wing and fuselage stringer shapes; and (4) a mechanical-property evaluation of roll-bonded material.

Progress to date is summarized below.

Preparation of Airfoil Shapes

In preliminary work, roll bonding of a 3-foot-long airfoil shape of the Ti-6Al-4V alloy was completed. Figure 33 shows details of the cross section of the pack layup used. This pack, which initially was 3 x 6-1/2 x 14 inches, was rolled through nine successives passes (approximately 68 percent reduction) to 1.35 x 7-1/2 x 38-3/4 inches.

Postrolling inspection showed that excellent bonds were produced at all joint areas. However, some bowing of the vertical stiffener occurred as a result of an excessive reduction in the initial rolling pass.

Subsequently, a full-scale airfoil-shape pack was prepared and roll bonded. This is illustrated in Figure 34.

Structural Shape Development

In this part of the program, two packs are to be rolled to produce an extrusion-type product. This consists of a simple vertical rib sandwich structure of the general design shown in Figure 3. The two packs will differ only in panel skin thickness.

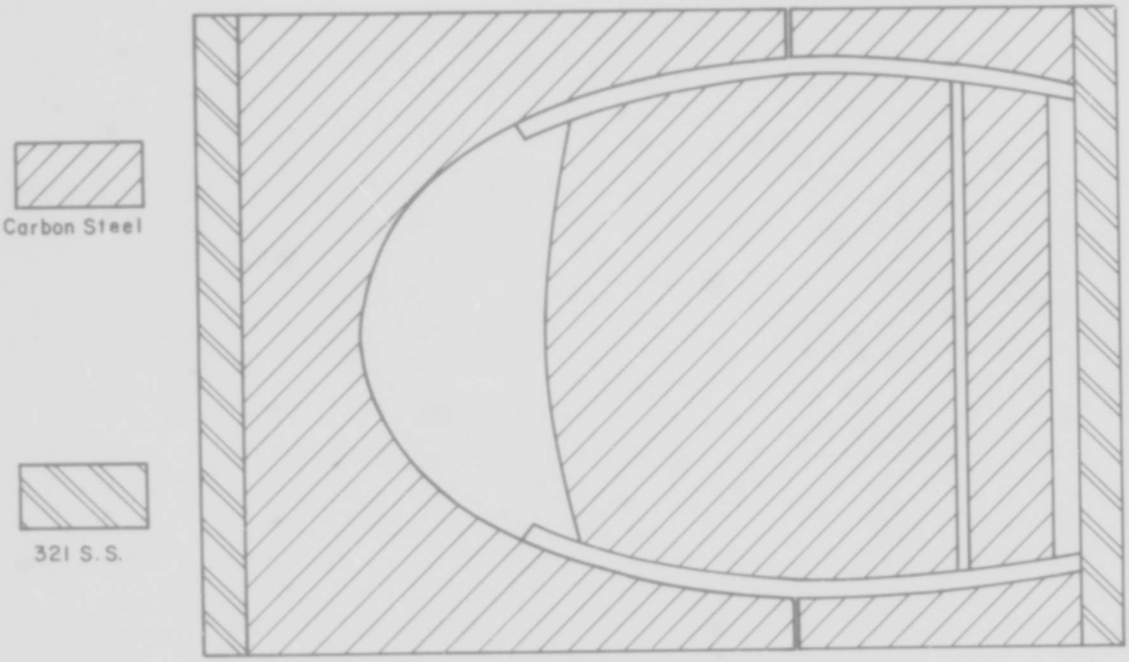


FIGURE 33. CROSS SECTION OF TITANIUM AIRFOIL LEADING EDGE PACK DETAILS(15)

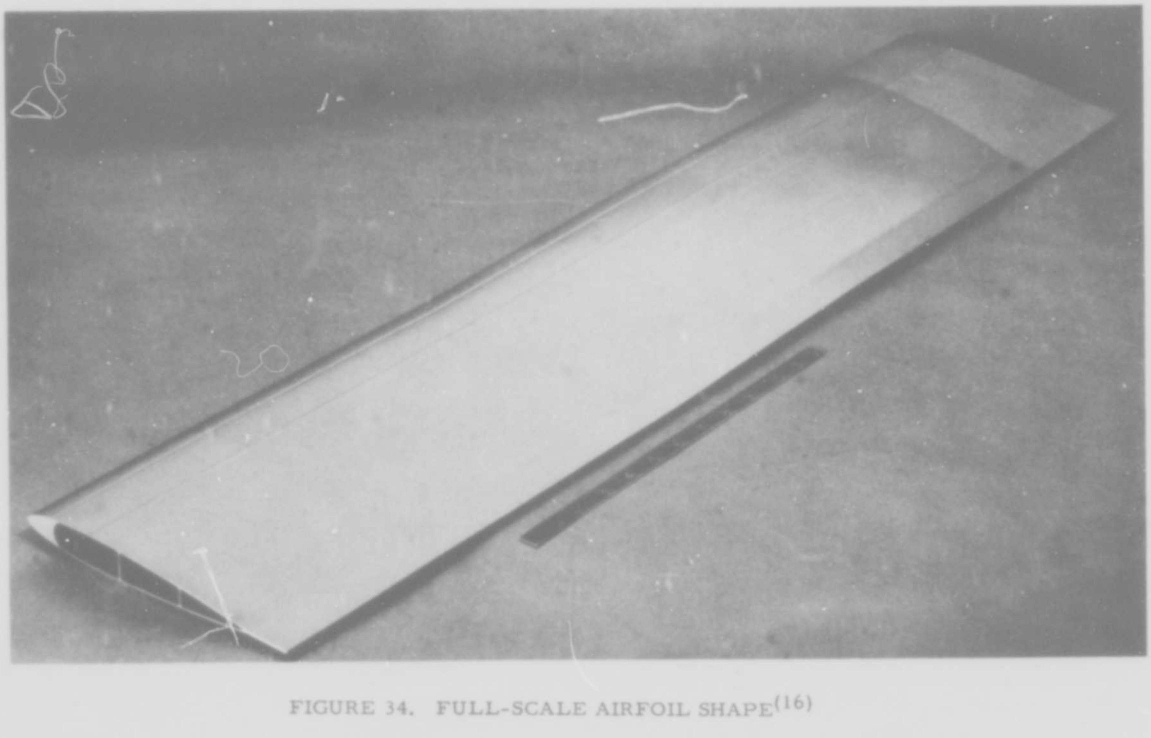


FIGURE 34. FULL-SCALE AIRFOIL SHAPE(16)

The first pack has been designed to yield a panel with 1/8-inch-thick skins and eight 1/8-inch-thick, 1 inch tall vertical ribs spaced 1.5 inch apart across the section. This pack, which has external dimensions of approximately 6.5 x 30 x 85 inches, has been assembled and scheduled for rolling.

Mechanical-Property Evaluations

Nine rectangular bars, each approximately 0.2 x 2.5 x 36 inches, of Ti-6Al-4V were rolled in a single pack to produce the material for use in this study. Six of these bars contained a single joint at the midsection (i.e., across the 0.2 inch section) along the entire bar length. The three remaining bars were of solid, unjoined material to represent parent metal.

Numerous test samples are now being prepared to obtain tensile, Charpy-impact, stress rupture, and bend properties of the joined material. The test conditions to be used will include as-bonded material as well as mill-annealed and solution-treated-and-aged material.

Bar Mill Rolling of Titanium Structural Sections

The McDonnell-Douglas Corporation program(16) involves the fabrication of roll-diffusion-bonded structural shapes on bar mill equipment. In bar rolling, reductions occur in two dimensions, rather than only one as in plate rolling. As a result, greater lengths are normally achieved for a given length of starting stock in bar- as opposed to plate-rolling operations. Figure 35 compares finished lengths of bar vs plate rolled for given reductions in one dimension. In this context bar-product yield varies inversely with the square of reduction, whereas plate yield varies inversely with reduction in a linear fashion. In this respect, development of bar-rolling practice would provide greater versatility for production of long roll-bonded shapes.

Figure 36 shows the pack sizes required to produce 20- and 40-foot structural shapes on the basic of a 66 percent rolling reduction. Other advantages of bar mill rolling, according to the McDonnell-researchers are (1) that because laid-up dimensions of the titanium details are heavier, they are more tolerant of in process contamination, and (2) that the smaller-sized finished packs are more compatible with postrolling heat treatment.

Program Scope and Objective

The purpose of the program is to study the feasibility of producing roll-diffusion-bonded structural shapes on bar mill equipment. Roll-diffusion-bonded titanium structural shapes will be compared with equivalent titanium shapes

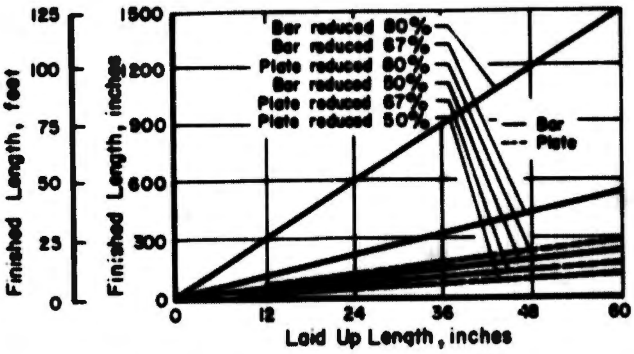
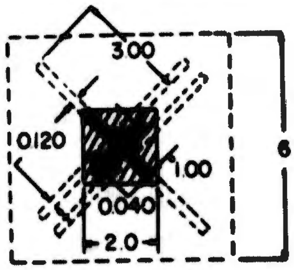


FIGURE 35. COMPARISON OF BAR AND PLATE MILL ROLLING ON FINISHED LENGTH OF ROLL-BONDED SECTIONS(16)

Pack sizes: 6 inches x 6 inches x 3 feet (5.2 feet) before rolling
2 inches x 2 inches x 27 feet (47 feet) after rolling
Pack weight: 360 pounds (629 pounds)



Pack sizes: 16 inches x 16 inches x 4 feet (6 feet) before rolling
5.33 inches x 5.33 inches x 36 feet (54 feet) after rolling
Pack weight: 3400 pounds (5200 pounds)

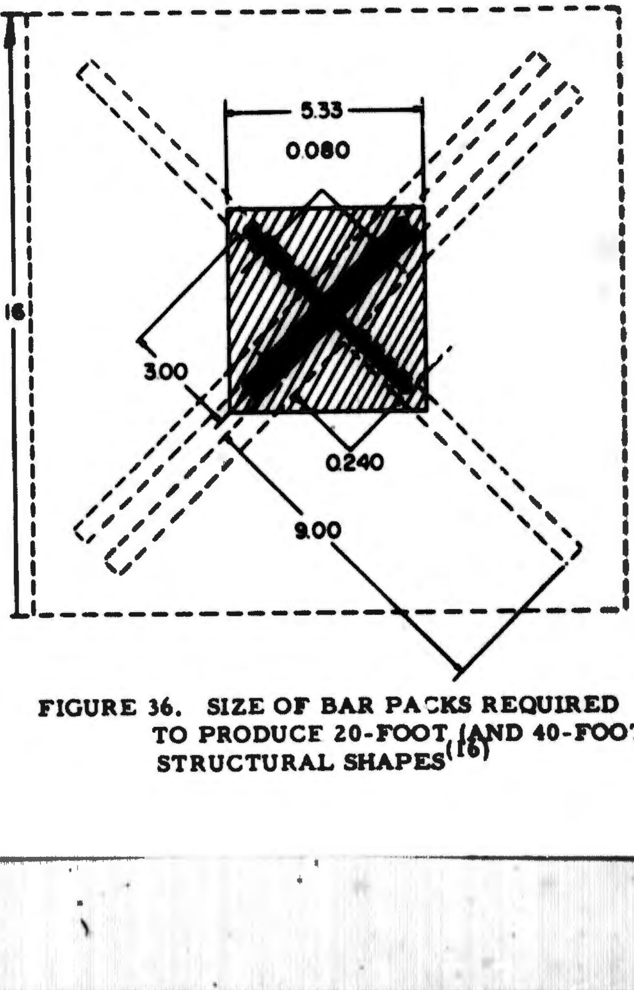
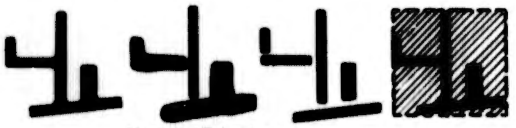


FIGURE 36. SIZE OF BAR PACKS REQUIRED TO PRODUCE 20-FOOT (AND 40-FOOT) STRUCTURAL SHAPES(16)

produced by other methods (e.g., extrusions, hog-outs from bar, or welded sections) to determine whether roll-diffusion-bonded structural shapes offer structural weight, fabrication, quality, or economic advantages over conventionally produced shapes. Figure 37 compares the relative merits of producing a complex structural shape (now in use on the F-4 aircraft) by roll bonding.



	Roll Bonded	Machined Extrusions and Weldments	Weldments	Machined Bar
Cost	A	B	C	D
Weight Efficiency	A	B	B	A
Quality	A	B	B	A
Overall	A	B	C	D

FIGURE 37. COMPARISON OF VARIOUS METHODS FOR PRODUCING TITANIUM ROLL-BONDED SHAPES(16)

The program is being conducted in two phases. Phase I is a preliminary investigation of process feasibility. A simple T configuration is being fabricated of Ti-6Al-4V alloy to determine how well structural-shape geometry can be maintained during rolling. Experimental packs will be used to investigate factors such as pack design, and size shape orientation, or variation in rolling practice on geometric quality.

The objective of Phase II will be to scale up the process to produce structural shapes 40 feet in length. Initially, duplicate packs containing two shapes made from the Ti-6Al-4V material will be rolled. These structures will be evaluated for dimensional control, surface finish, mechanical properties, and freedom from contamination. To check out the reproducibility of the process, four additional structural shapes will be fabricated. The alloys selected for the reproducibility study are Ti-6Al-4V and Ti-6Al-6V-2Sn. The evaluation program will be essentially the same as that followed for the initial scale-up structures.

Progress to Date

Thus far, six packs to produce up to 37-foot lengths of Ti-6Al-4V structure have been rolled in the Phase I studies. Variables have been shape (T, complex), shape orientation within the packs and pack layup technique, rolling temperature (preheat at alpha-beta and beta temperatures), and roll design (diamond-square at Laclede, gothic-diamond at Universal Cyclops; box passes will be tried at Armco). Evaluations are not yet complete, but several observations and conclusions are evident.

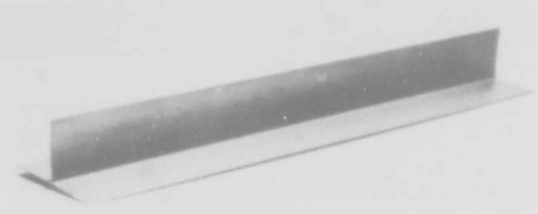
All structures have been well bonded. Because of slight heterogeneity in working throughout the cross sections, finished component thicknesses have varied by about ±5 percent from nominal, and some structural irregularities have resulted. Figures 38 and 39 illustrate general quality typical of the experimental products to date. Pack-design modification (e.g., degree of fillet control) and perhaps process modifications (e.g., use of guides) may be effective in improving geometry. McDonnell has found it very important to match starting size of the bar to the specific mill to avoid overfill and excessive heterogeneous deformation.

Preheating temperatures above the beta transus resulted in very coarse grain structure in the titanium alloy, and consequent rough, irregular, surface finish. In this regard, one and only one component in one pack rolled at 1750 F (supposedly well below the beta transus for Ti-6Al-4V) unexplainably showed a coarse "beta" grain structure. Analysis showed this to be Ti-6Al-4V. The possibility of especially low interstitial content of this particular piece was inferred by the researchers.

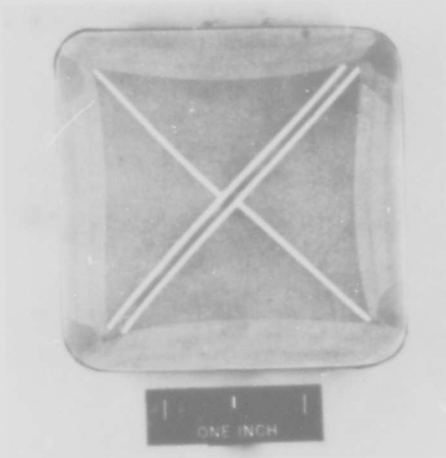
McDonnell In-House Roll-Diffusion Bonding Programs(17)

In addition to their Air Force program on roll-bonded titanium structural sections, the St. Louis facility of the McDonnell-Douglas Corporation has conducted extensive in-house studies of roll-diffusion-bonded structures in several materials for a variety of potential applications. Most of this effort has been concentrated on titanium alloys, particularly Ti-6Al-4V alloy; however, some limited work has been done with Ti-6Al-6V-2Sn, Ti-8Al-1Mo-1V, and Ti-5Al-2.5Sn as well as René 41 superalloy and Cb-752 columbium alloy. In the latter materials, poor surface finishes resulted from inadequate matching of hot deformation resistance between structural and pack materials.

McDonnell has investigated a variety of geometric configurations, including corrugated-truss core sandwiches, stiffened-skin structures, and structural shapes (I's, T's, and complex shapes). Many packs have been rolled, with starting sizes ranging from 8 x 6 x 2 inches to 60 x 60 x 3 inches. The largest Ti-6Al-4V roll-bonded truss-core sandwich panel produced was 48 x 120 x 0.6 inch. Particular emphasis has been placed on light-gage structures (0.010 inch) although heavier sections in Ti-6Al-4V have been evaluated (up to 0.25 inch).

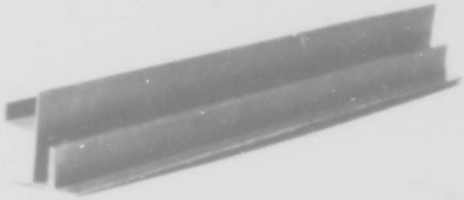


(a) Roll-Bonded Shape

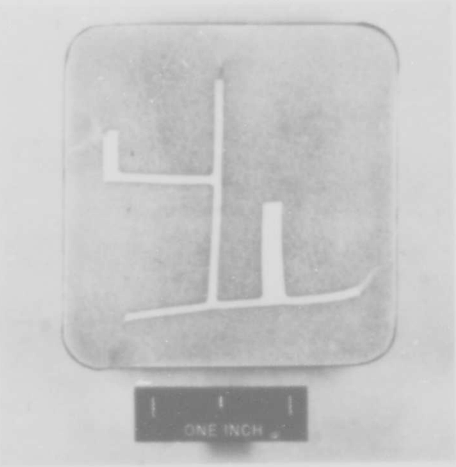


(b) Macrosection of Bar

FIGURE 38. GEOMETRY OF TEE SECTION



(a) Roll-Bonded Shape



(b) Macrosection of Bar

FIGURE 39. GEOMETRY OF COMPLEX SHAPE

McDonnell has studied the influence of carbon content of the steel-support structure, and their conclusions are in agreement with experimental results of work conducted at Battelle in support of NAA/LAD; e.g., carbon content should be 0.20 percent or more to prevent iron diffusion into the titanium. McDonnell has also done research on mechanically assisted filler-removal techniques. They have fabricated composite filler bars consisting of a high-manganese-steel core surrounded by a carbon-steel jacket. Panels were fabricated using these bars as support members. Using these bars, good panel geometry was maintained during rolling and the cores were successfully extracted from the panels after rolling, leaving through-holes for the circulation of leaching solutions.

McDonnell has conducted extensive property evaluation of roll-bonded structures, leading to the general conclusion that satisfactory properties can be maintained in roll-bonded materials. For example, tensile and notch-tensile properties of Ti-6Al-4V samples cut from as-rolled bonded structures have been determined at room temperature. Notched (K_t = 6.5)-to-unnotched tensile-strength ratios were reported typically as 1.06 to 1.16. McDonnell concluded that the properties for Ti-6Al-4V alloy specimens from rolled panels were within AMS specifications for annealed material.

Battelle Program for Rolling Various Structural Metal Panels

Program Scope and Objectives

Battelle's Columbus Laboratories is currently engaged in a program[(18)] for the U.S. Army Materials and Mechanics Research Center to develop design and processing methods necessary to produce structural metal panels of a variety of different materials by the roll-diffusion-bonding process. Included in these studies have been 18Ni-250 maraging steel, PH 14-8Mo precipitation-hardening stainless steel, Inconel, two advanced laboratory titanium alloys (a beta alloy, Ti-8Mo-8V-2Fe-3Al, and a texturing alpha grade, Ti-4Al-0.2O_2), and a specific titanium-beryllium composite.

Initial studies were conducted on small vertical-rib sandwich structures. Rolling temperature, reduction schedule, support material, and filler-removal methods for the various structural materials were investigated. Bond quality was assessed by metallographic examination and by tensile tests of I-sections removed from the rolled panels.

For the titanium alloys, a rolling temperature of 1650 F was required to develop satisfactory bonds. A somewhat greater tendency for bond-line contamination (residual oxygen) in the $Ti-4Al-0.2O_2$ alloy was observed than is usual for most commercial alloys. This may be due to the somewhat reduced oxygen sink capability of this alloy. Both titanium alloys responded normally to carbon content in the supporting steel matrix, i.e., >20 points of carbon is necessary to permit formation of continuous TiC at the interface to prevent iron contamination of the titanium.

The nonreactive structural metals investigated (Inconel, maraging steel, PH stainless) were shown to be potentially bondable at rolling temperatures of 2000 to 2200 F. However, at these temperatures (>1800 F) plain carbon steels and iron were found to outgas, contaminate faying surfaces, and prevent good bond development during roll bonding. Maraging steel was found to be the most sensitive to bond-line contamination of the materials evaluated, while Inconel was least affected. Special preoutgassing, the use of getter materials (tantalum or titanium foil) in the pack layup, and purging with hydrogen prior to rolling were, at best, only marginally effective. The use of titanium-killed, low-carbon (<6 points) steel was effective in producing good bonds, however. Low-carbon support materials are required for these metals to prevent carbon contamination during roll bonding. Figure 40 shows a bond formed in PH14-8Mo steel. The second phase initially present in the as-received material is seen to retain its lamellar directionality (note different directionality - that of the original sheet components - in rib and skin components) throughout the roll bonding process. Bond regions in Inconel were somewhat depleted in chromium as a result of preheating at 2000 F in the evacuated packs prior to rolling. This is indicated in Figure 41 by poor grain-boundary definition in the bond region. This had little affect on bond strength.

Filler removal by leaching in nitric acid (no problem with Inconel or PH 14-8Mo) proved difficult with the 18Ni maraging steel. Although a limited range of HNO_3 concentration and temperature was defined within which attack on support material was rapid and the maraging steel was not appreciably affected, the operating ranges were so narrow as to be difficult to control in a production operation. Maraging-steel experiments were thus deferred.

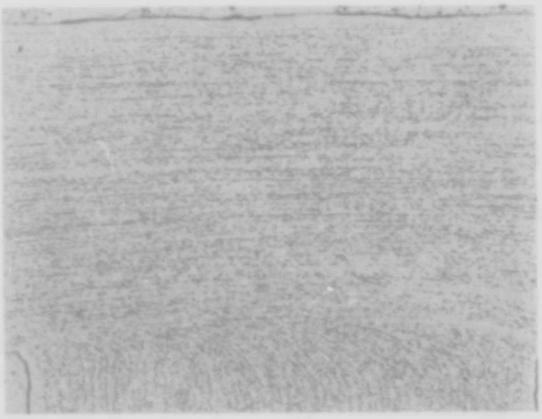


FIGURE 40. PHOTOMACROGRAPH OF A TYPICAL SKIN-TO-RIB BOND OF PH 14-8Mo STEEL PANEL IN AS-ROLLED CONDITION(18)

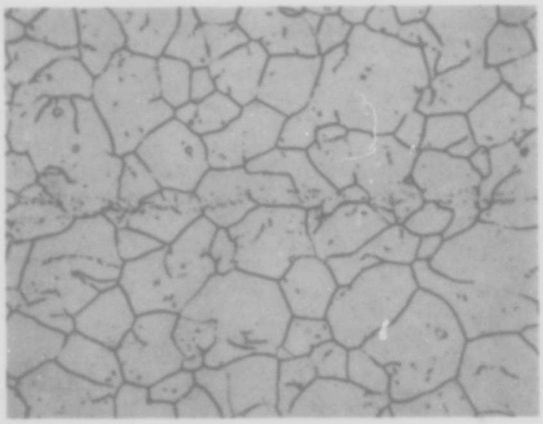


FIGURE 41. PHOTOMICROGRAPH OF A SKIN-TO-RIB BOND OBTAINED IN THE INCONEL PANEL USING TITANIUM CONTAINING STEEL AS SUPPORT MATERIAL(19)

The beryllium-titanium composite design comprises embedding beryllium strips in skins of a titanium sandwich for reinforcement. A silver interlayer was found to prevent the formation of brittle titanium beryllides and provide potential stress transfer within skin components. Cracking of the beryllium reinforcement strips during processing has not yet been eliminated.

Present studies will substitute René 41 for Inconel, and scale-up to larger panels of a modified, truss-core design is planned for the near future. Also, in view of the excellent potential for eliminating the leaching-time problems, the development of the practice of using composite filler bars and mechanical extraction of cores will be emphasized.

Technique For Bonding Beryllium to Beryllium And Titanium

Program Scope and Objectives

Harvey Engineering Laboratories$^{(19)}$ is conducting a program to develop process techniques for roll-diffusion bonding of beryllium to beryllium and beryllium to titanium to produce rib-stiffened panels for space-vehicle applications. A secondary purpose is to extend the state of the art of roll-diffusion bonding. The work is being conducted in two phases as follows:

Phase I. This phase is concerned with the design, fabrication, rolling, and testing of three kinds of samples which are representative of the type of diffusion-bonded joints required in the final assembly. The three types of experimental samples are shown in Figures 42, 43, and 44. By fabricating and testing these small-scale composite structures, the optimum parameters for fabricating the full-scale structure are to be established.

Phase II. This phase is concerned with the design and fabrication of full-scale parts based on the process-development techniques established in Phase I. Two full-scale stiffened skin panels will be prepared. One of these will be subjected to tests designed to examine the integrity of the bonded joints and determination of the material properties. Both destructive and nondestructive tests will be involved. The second panel will be subjected to only nondestructive tests and will be delivered intact to NASA-MSFC.

Progress to Date

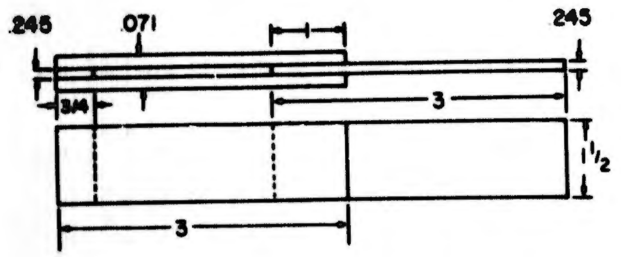
All of the work completed to date has been conducted under Phase I. About 30 lap-type samples of the configuration shown in Figure 42 were prepared and rolled under various conditions. These efforts were unsuccessful owing to excessive oxidation of the beryllium surfaces and fracture of the thin beryllium strip at the joints of the stainless steel spacer and the thick beryllium strip. It was concluded that bonds could not be produced by rolling across the joint without cutting through the thin strip. Accordingly, the lap-joint-specimen assembly design was modified according to the drawing in Figure 45. All subsequent samples were rolled in this type of jacket assembly. Since no provision was made for evacuating the assemblies, zirconium chips were placed at each end of the assembly to getter the residual air in the pack and protect the beryllium from oxidation in the event of a pack leak.

The lap-type specimens were fabricated in steel jackets at temperatures from 1500 to 1700 F. Rolling reductions of 5 to 15 percent per pass and total reductions of 20 to 75 percent were used. Examination of metallographic specimens from these samples indicated that bonding was obtained in specimens rolled from 60 to 75 percent total reduction at 1600 to 1700 F. This work indicated that total reduction was more important in promoting bonding than was rolling temperature, soak time, or reduction per pass.

Douglas Program on Roll-Bonding of Beryllium

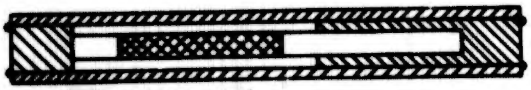
As described earlier, Douglas Aircraft Company pioneered the roll-diffusion-bonding process in sponsored studies at Battelle's Columbus Laboratories and in several in-house programs to fabricate and evaluate a variety of bonded structures. Recent interest at Douglas has emphasized adaptation of the roll-diffusion-bonding process to beryllium structures. With the assistance of Battelle, several small (~10 x 5 x 1/4 inches) beryllium structures have been successfully fabricated. These have included vertical-rib (Figure 46) and truss-core sandwich (Figure 47) structures and T-stiffened skins.

Processing variables have been established to result in excellent bond quality so that bond strength does not limit structure performance. The major problems in fabricating beryllium structures by roll-diffusion bonding result from the low biaxial ductility of beryllium at ambient temperatures. These can be minimized to produce crack-free structures by proper selection of processing variables.



a. Dimensions (in inches) Based on assembly before rolling specimens to be made

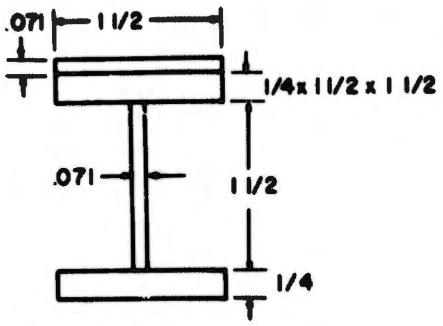
Type I-A1 .071 in. Be to 0.250 in. Be
Type I-A2 .071 in. Be to 0.250 in. Be (with Ag in joint)
Type I-C1 .071 in. Ti to 0.250 in. Be
Type I-C2 .071 in. Ti to 0.250 in. Be (Ag in joint)
Major variables: rolling temperature and reduction per pass



▩ Stainless steel
▨ Low-carbon steel

b. Assembly
Jacket welded and evacuated to exclude active gases and to maintain alignment of parts

FIGURE 42. TYPE 1 SAMPLES - FLAT LAP BONDS(19)



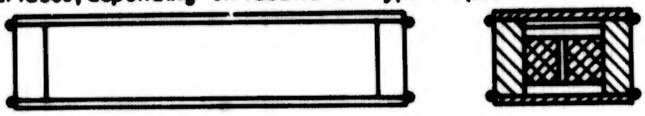
Length of sample: 3 inches

a. Section of type 2 samples

All dimensions (in inches) based on assembly prior to rolling and predicted on 50% total reduction by rolling

Type 2-A1: All beryllium parts
Type 2-C1: Titanium top and pads and beryllium web and foot pieces
Type 2-C2: Titanium top and beryllium pads, web, and foot pieces

Some of these samples may have silver between bonding surfaces, depending on results of Type I Specimens.

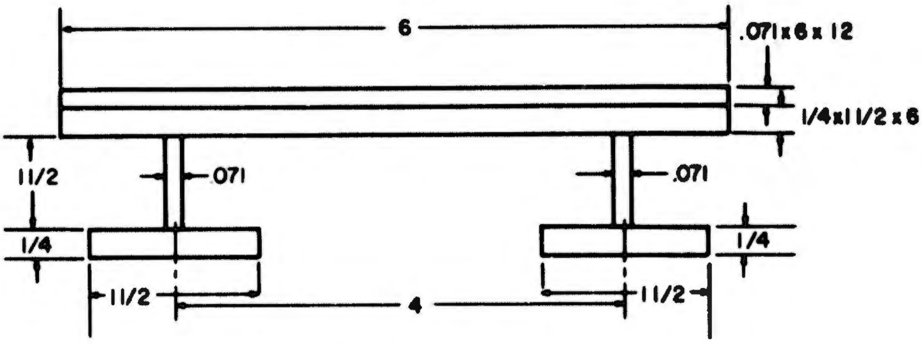


▨ Low Carbon steel ▩ Stainless steel

b. Assembly

Jacket welded and evacuated to exclude active gases and to maintain alignment of parts.

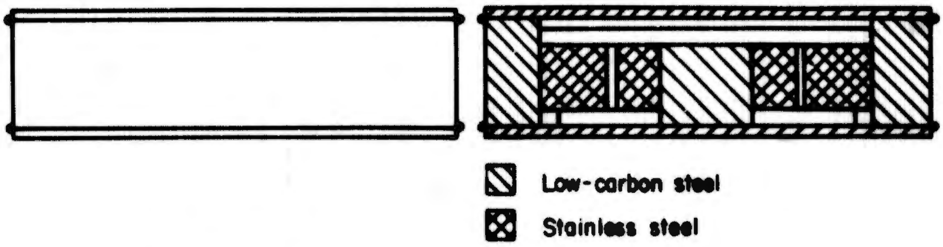
FIGURE 43. TYPE 2 SAMPLE, BLOCK 1 BONDING(19)



a. Length: 12 inches; end pads: 1/4 x 1 1/2 x 6 inches

Samples to be made:

Type 3-A: All beryllium parts	5
Type 3-B1: Titanium top sheet and pads and beryllium web and foot pieces	5
Type 3-B2: Beryllium top sheet and pads and titanium web and foot pieces	5
	15



b. Assembly

FIGURE 44. TYPE 3 SAMPLE - PROTOTYPE(19)

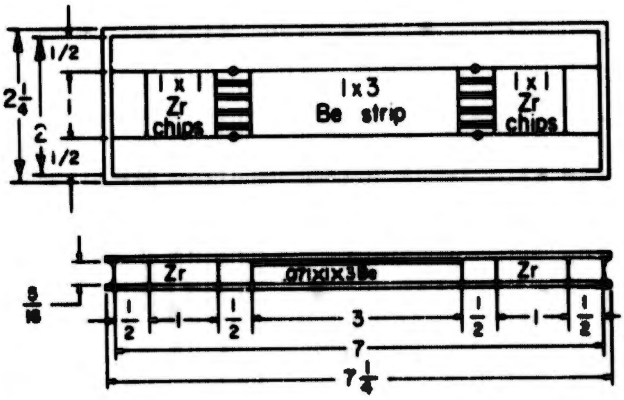


FIGURE 45. MODIFIED LAP-BOND ASSEMBLY(19)

Zirconium chips are used as a getter to protect the beryllium from oxidation.

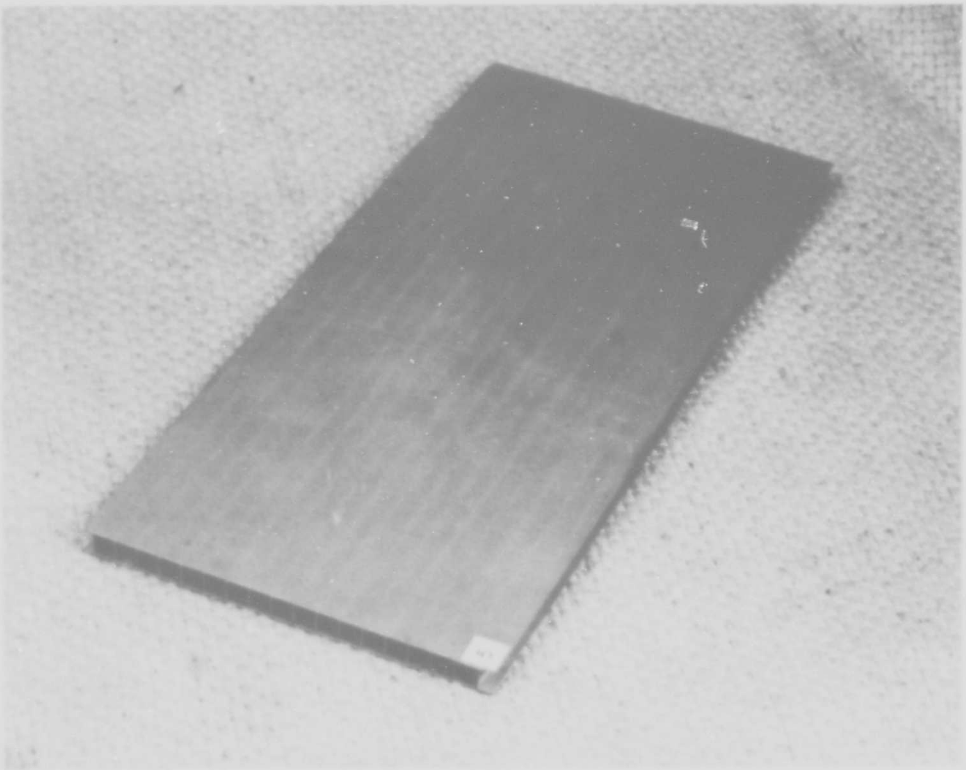


FIGURE 46. A VIEW OF ONE SURFACE OF BERYLLIUM PANEL 66-5 AFTER LEACHING

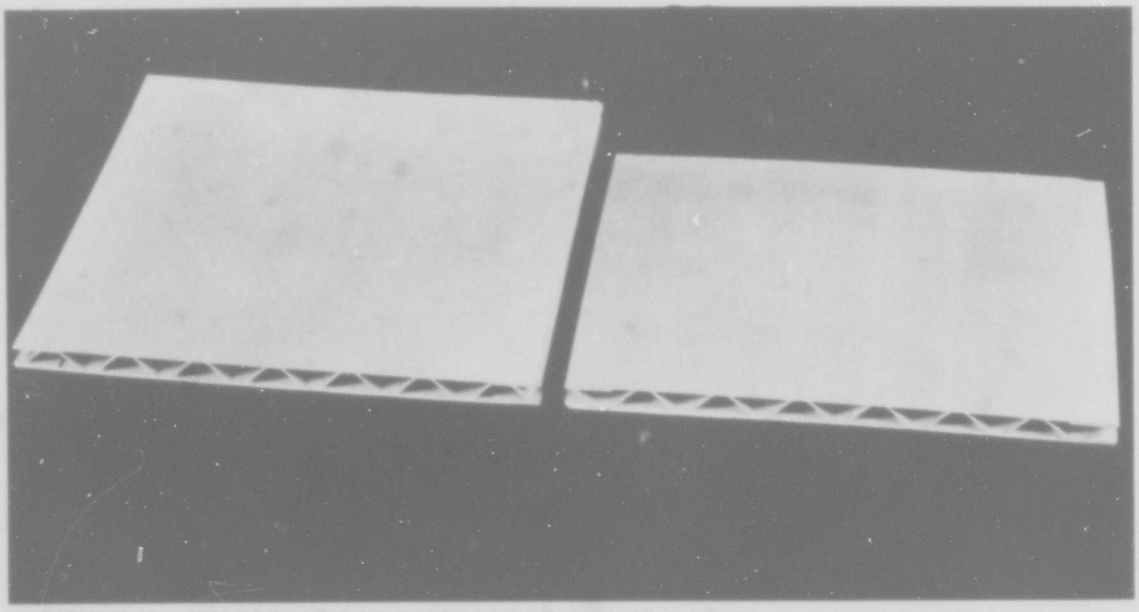


FIGURE 47. PHOTOGRAPH OF BERYLLIUM PANEL 67-1 AFTER SECTIONING AND LEACHING

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(19) Preliminary information reported by Harvey Engineering Laboratories under Contract No. NAS 8-20384.

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13. ABSTRACT

The ~~This~~ report summarizes the progress in recent and current research and development programs to advance the state of the art of the roll-diffusion-bonding process as applied to the manufacture of structural panels and shapes. At the present time, there are seven such NASA and DOD programs in progress. These are reviewed in the ~~this~~ report.

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Bonding						
Roll Bonding						
Roll Welding						
Welding						
Pressure Welding						
Forge Welding						
Fabrication						
Panels						
Ti-8Al-1Mo-1V						
Titanium-Base Alloys						
Inconel						
Nickel-Base Alloys						
PH14-8Mo						
Stainless Steels						
Beryllium						
Maraging Steels						
High Alloy Steels						
Steels						
Saturn S-IC						
Fuel Tanks						
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