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Report No. FAA-SS-73-27

TITANIUM STRUCTURES TECHNICAL SUMMARY

DOT/SST Phase I and Phase II

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D6-60304

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16. Abstract

The U.S. Supersonic Transport (SST) program resulted in many significant developments in titanium technology such as metallurgy, brazing, welding, and aircraft structural analysis. A two-phase follow-on program was funded by DOT/FAA to document areas of significant development completed during the SST effort and to expand selected technological areas most applicable to future American aerospace and other industry technology. This report summarizes the work conducted on titanium structure during the two-phase DOT/SST program and provides a concise reference to the more detailed reports available.

Report on SST Technology Follow-On Program. Continuation of Contract DOT-FA-SS-71-12. See also AD-913 365 and AD-B000 286L.

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1.0 INTRODUCTION

At the time of cancellation of the American SST effort, the state of the art of titanium processing and design of titanium structure was developing at a very rapid pace. In order to preserve this vast amount of relatively undocumented research and development work and bring promising developments to a point of usefulness to American industry, the Department of Transportation (DOT) funded a two-phase SST follow-on program covering titanium technology. The first phase of the program was aimed at documentation of existing data and completion of tests in progress at termination of the SST. The second phase was directed at expansion of specific promising developments and areas of technology where additional data were needed by industry. Phase I was conducted under contract DOT-FA-SS-71-12 and Phase II was conducted under contract DOT-FA-72WA-2893.

This report provides an overall summary of the advancements in the state of the art of Ti-6Al-4V metallurgy, joining, and structural design concepts resulting from the DOT two-phase program. The report is organized into three sections: (a) Ti-6Al-4V Mill Products, (b) Joining of Titanium, and (c) Titanium Structure.

The section on Ti-6Al-4V mill products discusses the effect of texture, microstructure, chemistry, and interstitial level on mechanical and fracture properties. The compatibility of Ti-6Al-4V with materials likely to be encountered in service and during manufacture is summarized, and the characterization of sheet, plate, bar, forgings, extrusions, and tubing is presented.

The section on titanium joining reviews aluminum brazing and fusion welding developments and details process limits, economics, properties, and acceptance criteria.

The section on titanium structure presents work on shear beams, honeycomb sandwich, integrally stiffened and skin stringer structure, and fail-safety considerations.

A total of 27 technical documents were released on the Phase I and Phase II programs for titanium technology. A listing of these documents and subjects covered is contained in appendix A.

2.0 Ti-6Al-4V MILL PRODUCTS

2.1 BACKGROUND

The United States SST development program was based on the concept of a Mach 2.7 aircraft with anticipated skin temperatures approaching 500° F. Titanium alloy was selected as the most suitable material for this flight environment.

During the early stages of the development program, two titanium alloys, Ti-6Al-4V and Ti-8Al-1Mo-1V, were selected as most promising. Preliminary tests revealed the Ti-8Al-1Mo-1V alloy was susceptible to stress corrosion and thermal instability. Consequently, the Ti-8Al-1Mo-1V alloy was deleted from the program, and all subsequent development effort was confined to the Ti-6Al-4V alloy.

The investigation of Ti-6Al-4V alloy was directed toward four major areas:

- Metallurgical effects on mechanical and fracture properties to establish a basis for achieving improved properties.
- The effect of hydrogen on environmental and physical properties.
- Compatibility of Ti-6Al-4V alloy with associated manufacturing and flight service materials.
- Characterization of the various mill product forms (sheet, plate, bar, extrusions, forging, and tubing).

2.2 METALLURGICAL PARAMETERS AFFECTING MECHANICAL AND FRACTURE PROPERTIES

The mechanical strength, modulus, and fracture resistance of Ti-6Al-4V are significantly influenced by a number of metallurgical parameters. The following paragraphs summarize the findings of references 1, 2, and 3.

2.2.1 Yield Strength

The tensile yield strength (TYS) and compression yield strength (CYS) are affected primarily by oxygen content and the basal plane crystallographic texture of the wrought product. Increasing the oxygen level results in increased TYS and CYS. Increasing the texture of basal planes results in wider variation between longitudinal and transverse properties (fig. 1) and can result in a 15- to 20-ksi variation to yield strength. Texture is most pronounced in highly worked wrought products, with continuously rolled sheet demonstrating the most extreme case.

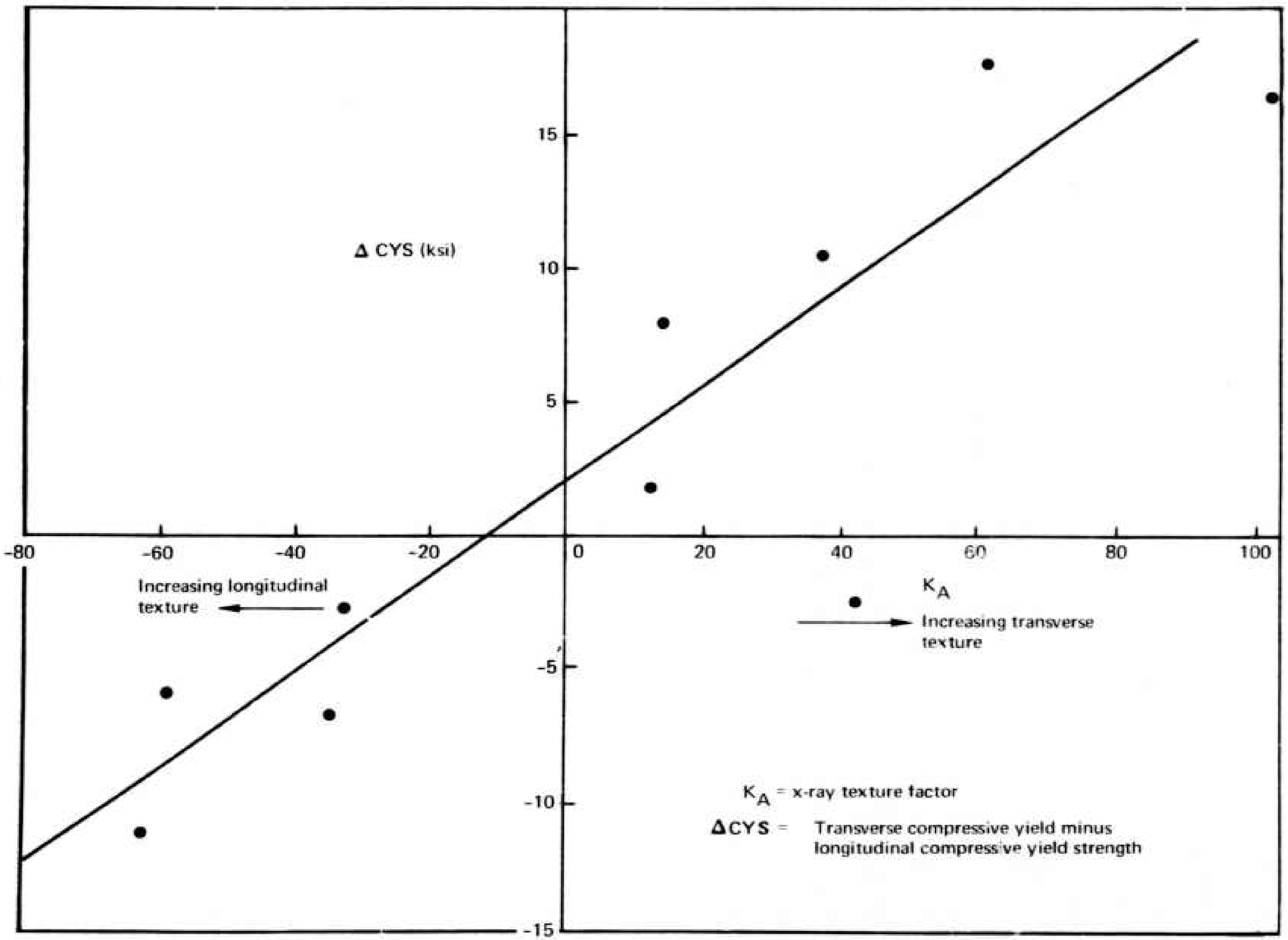


FIGURE 1.—EFFECT OF CRYSTALLOGRAPHIC TEXTURE ON YIELD STRENGTH

2.2.2 Elastic Modulus

The elastic modulus of Ti-6Al-4V is dependent on oxygen and aluminum content, heat treatment, and texture. Values of elastic modulus have been observed to vary between 15.0 to 18.0 x 10^6 psi. Increasing oxygen and aluminum content increases the modulus value. Texture can either increase or decrease the modulus, depending on orientation and degree. The effect of heat treatment is the least significant of parameters influencing elastic modulus. Heat treated material, however, demonstrates a slightly higher modulus than annealed material.

2.2.3 Environmental Cracking (K_{SCC})

The property most sensitive to a variation of metallurgical parameters is the resistance to crack growth in a saline environment (K_{SCC}).

The oxygen content of the alloy has the greatest effect on K_{SCC}. Oxygen levels greater than 1100 ppm result in a drastic decrease in K_{SCC}, as illustrated in figure 2.

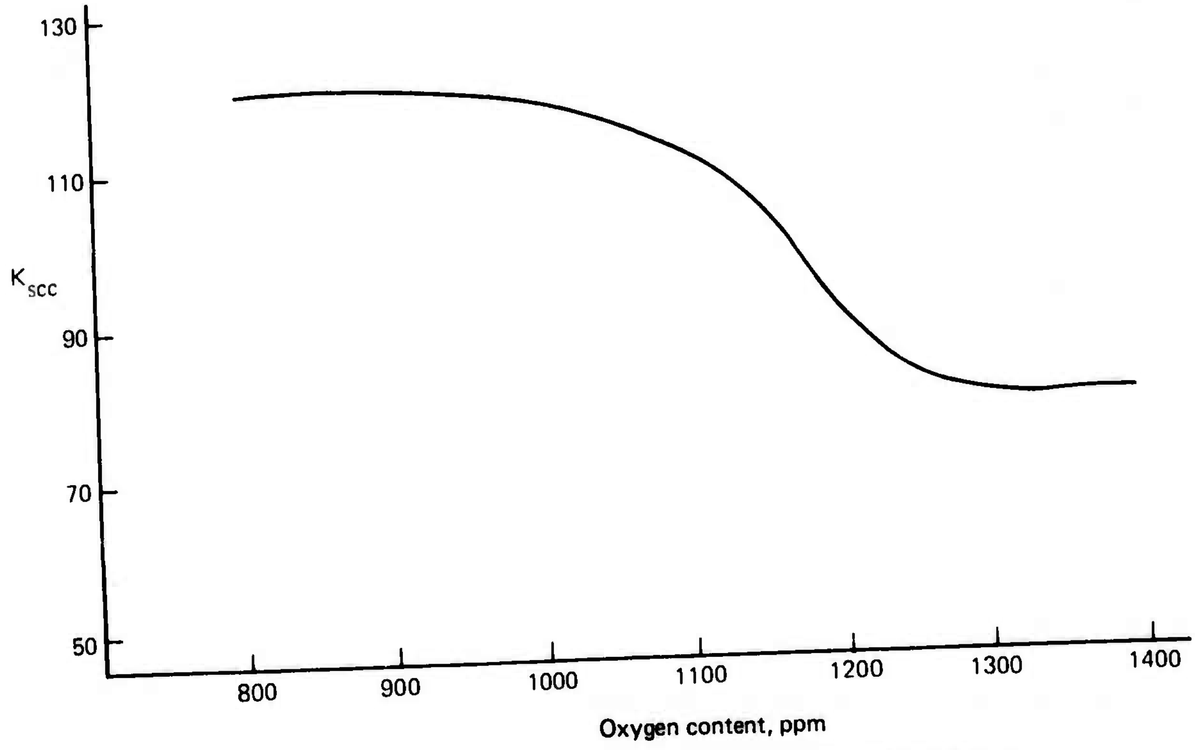


FIGURE 2.—EFFECT OF OXYGEN CONTENT ON K_{SCC}

Texture also significantly influences K_{SCC}. Its effect on K_{SCC} can either increase or decrease the value, depending on the texture direction and crack orientation. In general, for alpha-beta microstructure, for every 1.0 ksi difference between longitudinal and transverse TYS, the value of K_{SCC} will change 2.3 ksi $\sqrt{\text{in}}$. The value of K_{SCC} decreases when the crack is nearly parallel to the basal planes.

The value of K_{SCC} is also significantly influenced by the amount of ordering (Ti_3Al) occurring in the matrix. The decrease possible in the value of K_{SCC} as a result of severe ordering can be as high as 21 ksi $\sqrt{in}$. Ordering is promoted by slow cooling from temperatures above 1300°F when aluminum content is greater than ~ 6.2%. Careful consideration should be given to the aluminum content of material to be diffusion bonded or high-temperature brazed. Ordering effects are more dramatic in highly textured Ti-6Al-4V products.

Microstructure was found to have significant effect on K_{SCC} and also on fracture toughness (K_{IC} and K_Q). Beta annealing of wrought products resulted in a pronounced increase in fracture resistance both at low and high oxygen content. The effect of beta annealing was significantly greater than observed texture effect.

2.3 HYDROGEN EFFECTS

Hydrogen can be introduced into titanium by thermal or chemical treatments. The quantity introduced during thermal treatment is related to the partial pressure of hydrogen, titanium surface condition, microstructure, and temperature. Temperatures above 1000°F are required for hydrogen pickup, as is a relatively oxide-free surface on the titanium. Hydrogen can also be removed from titanium by reversing this sequence. A practical manufacturing sequence of exposing the titanium to 1150°F for 1 hour in a vacuum of 50 torr has been demonstrated to reduce hydrogen content from over 400 ppm to less than 150 ppm.

Hydrogen can also be introduced into titanium by chemical milling. Excessively long periods in the solution, or improper solution and procedure, can result in much more than the typical 20 ppm pickup acceptable by most specifications. Prior thermal treatments that affect the beta percentage and beta morphology in the microstructure can also influence hydrogen pickup in chemical milling (fig. 3).

The effect of hydrogen on static tensile and fracture properties is insignificant. It appears to have some effect on K_{SCC}, at least in cases where the oxygen level is in the typical range. Hydrogen can definitely cause delayed failure in titanium, as illustrated in figure 4. The time required for failure is a function of the hydrogen content and the applied stress level at the notch tip.

The results and data presented in this section were taken from page 33 of reference 1, and from reference 4.

2.4 COMPATIBILITY OF SUBSTANCES WITH TITANIUM

A detailed analysis of the compatibility of titanium with hundreds of compounds that might be encountered during airplane service or during manufacture of titanium structure was made during the SST program. A listing of the broad classes of substances evaluated is presented in table 1.

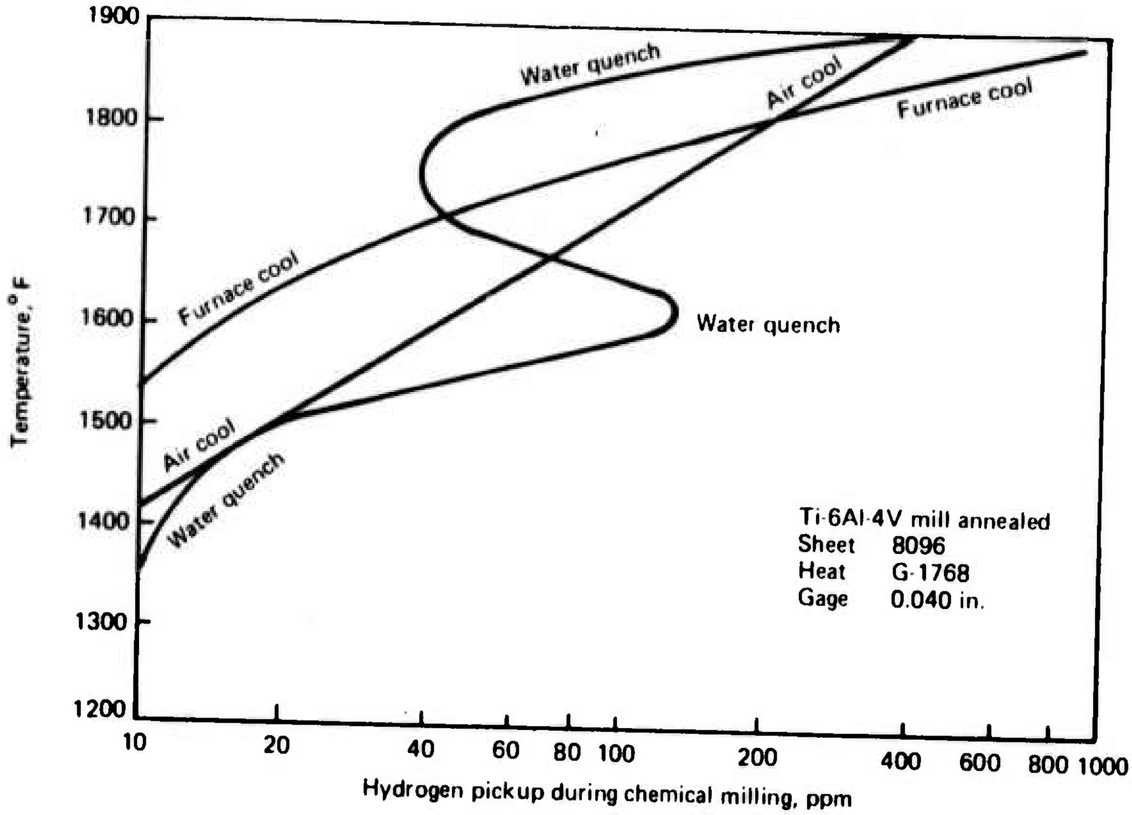


FIGURE 3.–EFFECT OF PRIOR THERMAL CYCLES ON THE SUSCEPTIBILITY OF Ti-6Al-4V TO HYDROGEN PICKUP DUE TO CHEMICAL MILLING (REF. 10)

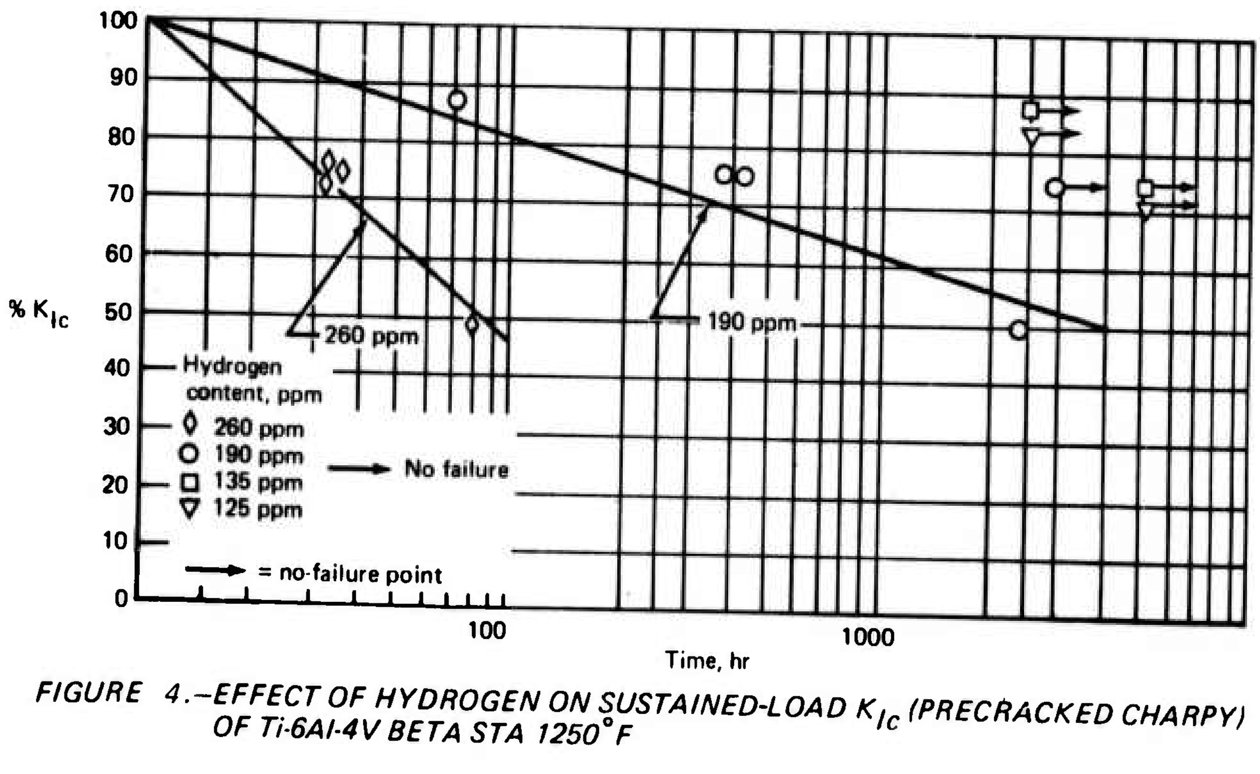


FIGURE 4.–EFFECT OF HYDROGEN ON SUSTAINED-LOAD K_{Ic} (PRECRACKED CHARPY) OF Ti-6Al-4V BETA STA 1250°F

TABLE 1.—BROAD CLASSIFICATIONS OF MATERIALS EVALUATED FOR COMPATIBILITY WITH TITANIUM

Acid	Marking, Temporary
Additive	Metal
Adhesive	Paint
Cleaner	Penetrant Inspection Fluid
Coating	Protective Coating
Deicer, Runway	Resin
Elastomer, Fluorocarbon	Rubber
Fastener	Rubstrip
Fluids	Sealant
Food	Smoother, AErodynamic
Heat Treat Aid	Solvent
Insulation	Stabilizer, Machining
Lubricant	Stripper, Paint
Machining Lubricant	Tape
Marking, Electrochemical	

The evaluation included ductility changes as measured using simple U-bend and Heimerl-Braski specimens; surface embrittlement using the Allison bend specimen; measurements of emittance; and analysis for hydrogen, oxygen, and chlorine content of the titanium or test substance.

A rating of compatible or incompatible was assigned for each material-specimen test parameter. References 5 and 6 present the detailed results of this evaluation.

2.5 CHARACTERIZATION OF CONTINUOUSLY ROLLED AND LARGE HANDMILL ROLLED Ti-6Al-4V SHEET

2.5.1 Continuously Rolled Sheet

One of the developments of the SST prototype program was the continuous rolling of titanium sheet in thicknesses from 0.016 to 0.187 inch, although thicknesses greater than 0.090 inch could not be considered to have a production status at the end of the SST program. The material produced by continuous rolling demonstrated properties that are somewhat unique as a result of the more uniaxial rolling. Table 2 characterizes some of the static mechanical properties of continuously rolled Ti-6Al-4V sheet. The thicknesses represented in the table are 0.040 to 0.060 inch. The aluminum and oxygen content was 6.2% to 6.4% and 0.13% to 0.15%, respectively. Fracture values were typically 130 to 160 ksi $\sqrt{in.}$ for 0.060 inch and thinner material.

TABLE 2.—CHARACTERISTIC PROPERTIES OF CONTINUOUSLY ROLLED Ti-6Al-4V SHEET

Grain direction	Tensile strength ksi	Tensile yield strength ksi	Compression yield strength ksi	Elongation 2 in., %	E_T x 10^6 psi	E_C x 10^6 psi
L	146.1	131.5	135.1	11.6	16.1	16.5
T	148.5	138.5	157.4	11.4	17.9	18.5
45°	137.0	128.7	138.7	12.9	16.2	17.2

The continuously rolled material in thicknesses greater than 0.060 inch exhibited considerably more directionality. Fracture resistance (K_C) was 25% lower than fracture values typically measured for 0.060 inch and thinner material.

2.5.2 Handmill Rolled Sheet

Handmill rolled sheet received for SST prototype fabrication was considerably wider and longer than material available prior to prototype development. Typical sizes were 48 to 54 inches wide and 240 inches long. This compared to 36 inches wide by 96 inches long—the typical size prior to the prototype effort. This necessary size increase resulted in metallurgical and mechanical property changes. Extensive developmental effort was required to control properties to acceptable limits. The mechanical properties characteristic of the large sheet purchased for the SST prototype are presented in table 3. The material typically had an aluminum and oxygen content of 6.3% and 0.14%, respectively.

TABLE 3.—CHARACTERISTIC PROPERTIES OF 20-FT-LONG HANDMILL ROLLED Ti-6Al-4V SHEET

Grain direction	Tensile strength ksi	Tensile yield strength ksi
L	144.4	133.2
T	144.7	138.0

More detailed information on continuously rolled and handmill rolled Ti-6Al-4V sheet is contained in reference 7.

2.6 CHARACTERIZATION OF BETA PROCESSED PLATE

A significant development of the SST prototype program was the beta processing of titanium plate (thicknesses greater than 0.187 inch) to improve the fracture toughness and resistance to environmental crack growth (K_{SCC}). Beta processed material, heated and/or worked above 1800°F, consistently demonstrates environmental toughness values more than 20 ksi $\sqrt{in.}$ greater than the same plate in the alpha-beta condition. The beta processed plate is observed to have a more random texture than alpha-beta plate. Rolling reductions below the beta transus temperature (~1800°F) can result in lower fracture and K_{SCC} values due to a rather strong **transverse** texture which develops. This condition can be corrected by reannealing above the beta transus temperature.

Characteristic static tensile and fracture properties of beta rolled Ti-6Al-4V procured for the SST are presented in table 4. The properties are not optimized for toughness as described in reference 2. The oxygen and aluminum contents are typically 0.13% to 0.20% and 6.1% to 6.5%, respectively. More detailed information on beta processed plate is contained in reference 3.

TABLE 4.–CHARACTERISTIC PROPERTIES OF BETA ROLLED Ti-6Al-4V PLATE (ANNEALED)

Grain direction	Tensile strength ksi	Tensile yield strength ksi	Elongation in 2", %	K_{salt}[a] ksi $\sqrt{in.}$
L	143.3	129.9	12.2	85.2
T	145.1	131.9	11.9	87.1

Average properties for gages to 1.00 inch.

[a]Fracture toughness in 3.5% salt water environment.

2.7 CHARACTERIZATION OF BAR AND FORGINGS

Ti-6Al-4V was found to be a compromise alloy for use in heavy-section bar and forgings due to its relatively low strength. Its stability and good resistance to environmental crack growth, however, led to its selection. Additionally, the environmental crack growth resistance could also be significantly improved by beta processing. The bar and forging data were characterized by a large scatter in properties. This was partly due to chemistry variation but also due to mill process variations, which were evident in the microstructure. With proper control, however, thick-section properties can be achieved that nearly equal thin-section properties. Table 5 characterizes the data developed for annealed Ti-6Al-4V bar and forgings. More detailed information is contained in reference 8.

TABLE 5.–CHARACTERIZATION OF Ti-6Al-4V BAR AND FORGINGS

Property	Mean	Maximum[a]	Minimum[b]
Ultimate strength, ksi	136.9	164.0	121.1
Tensile yield strength, ksi	125.0	154.1	108.5
Elongation in 2 in., %	12.2	20.0	5.0
K_{salt}, ksi $\sqrt{in.}$	88.6	135.8	62.3
Oxygen, %	0.16	0.20	0.11
Hydrogen, %	0.0067	0.0129	0.0018
Aluminum, %	6.3	6.7	5.9

[a]Highest individual values
[b]Lowest individual values

2.8 CHARACTERIZATION OF EXTRUSIONS

Characterization testing of Ti-6Al-4V extrusions demonstrated that they were highly variable in mechanical, fracture, and metallurgical properties. Extensive testing revealed that the variability could be reduced by more stringent control of composition, microstructure, and crystallographic texture. Table 6 characterizes the properties of annealed Ti-6Al-4V extrusions procured for the SST prototype. More extensive data are presented in reference 9.

TABLE 6.—CHARACTERIZATION OF Ti-6Al-4V EXTRUSIONS

Property or composition	Mean	Maximum[a]	Minimum[b]
Ultimate strength, ksi	142.2	157.0	128.3
Tensile yield strength, ksi	129.2	152.0	117.5
Compressive yield strength, ksi	137.5	153.4	123.9
Elongation in 2 in., %	13.2	20.0	15.4
K_{ISCC}, ksi$\sqrt{in.}$	L-41/T-35	L-59/T-59	L-34/T-20
Oxygen, %	0.174	0.218	0.100
Hydrogen, %	0.0063	0.0120	0.0006
Aluminum, %	6.3	6.8	5.5

[a]Highest individual values
[b]Lowest individual values

2.9 CHARACTERIZATION OF Ti-6Al-4V and Ti-3Al-2.5V HYDRAULIC TUBING

Ti-6Al-4V in the annealed condition is very attractive for use in aircraft hydraulic systems; however, its higher strength results in process difficulties. Adequate tube quality was not achieved on a production basis. Ti-3Al-2.5V in the cold-worked and stress-relieved condition provides a compromise between Ti-6Al-4V and conventional steel tubing such as AM350 and 21-6-9; therefore it was selected for the SST prototype. Table 7 characterizes annealed Ti-6Al-4V and cold-worked and stress-relieved Ti-3Al-2.5V tubing procured for the SST prototype program.

TABLE 7.—CHARACTERIZATION OF ANNEALED Ti-6Al-4V AND CW + SR Ti-3Al-2.5V TUBING

Property	Ti-6Al-4V	Ti-3Al-2.5V
Tensile strength, ksi	143.9	130.0
Tensile yield strength, ksi	129.2	111.3
Elongation	17	15.1
Minimum bendradii	NA	3 diameters

The most significant problem encountered with titanium tubing was defects on both inside and outside surfaces. The most common defects consisted of laps, pits, sanding scratches, and cracks. Under pressure inpulse loading, the defects developed into fatigue cracks and resulted in leaks. Titanium tubing was also found to be very sensitive to fretting at attachment points. Coatings were very successful in minimizing this problem. Crystallographic texture was found to be very important to the properties of titanium tubing. More detailed data are contained in reference 10.

2.10 SYNOPSIS

The development work conducted on Ti-6Al-4V alloy mill products during the SST program and DOT/FAA follow-on programs resulted in considerable improvement in metallurgical characterization of the alloy and properties of various mill product forms. The effects of variations in alloying elements have been more clearly delineated, and revised composition limits were developed to ensure more consistent properties. New specifications have been established for procurement of the improved material (ref. 2). One of the most significant property improvements achieved was a marked increase in stress corrosion cracking resistance, as illustrated in figure 5.

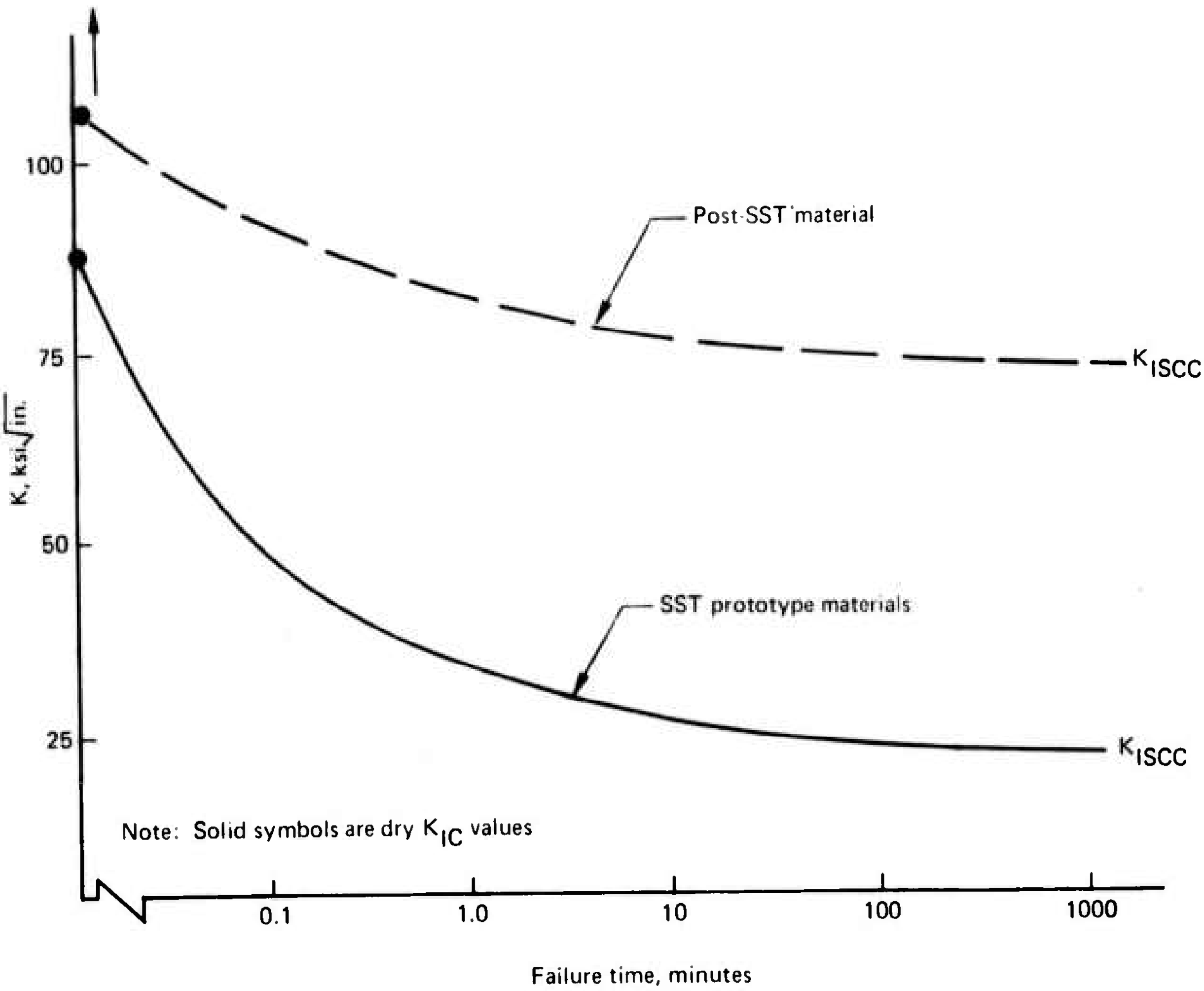


FIGURE 5.—Ti-6Al-4V STRESS CORROSION CHARACTERISTICS

3.0 JOINING OF TITANIUM

3.1 ALUMINUM-BRAZED TITANIUM HONEYCOMB SANDWICH DEVELOPMENT

The use of aluminum-brazed titanium honeycomb structure was a major development of the SST prototype program. Aluminum was investigated because of the low brazing temperature and a lack of a tendency to embrittle the titanium. The development was continued after the prototype cancellation by two follow-on contracts sponsored by the DOT. Detailed information, of which a brief summary follows, is contained in references 11 through 14.

3.1.1 Process Description

The aluminum braze process was originally developed for honeycomb sandwich material and did not include faying-surface joints. Subsequent development has made it possible to use faying-surface joints, provided attention is paid to details of joint faying-surface spacing.

Aluminum alloy 3003 has been found to have the best combination of properties and cost of the more than 100 candidate braze alloys investigated.

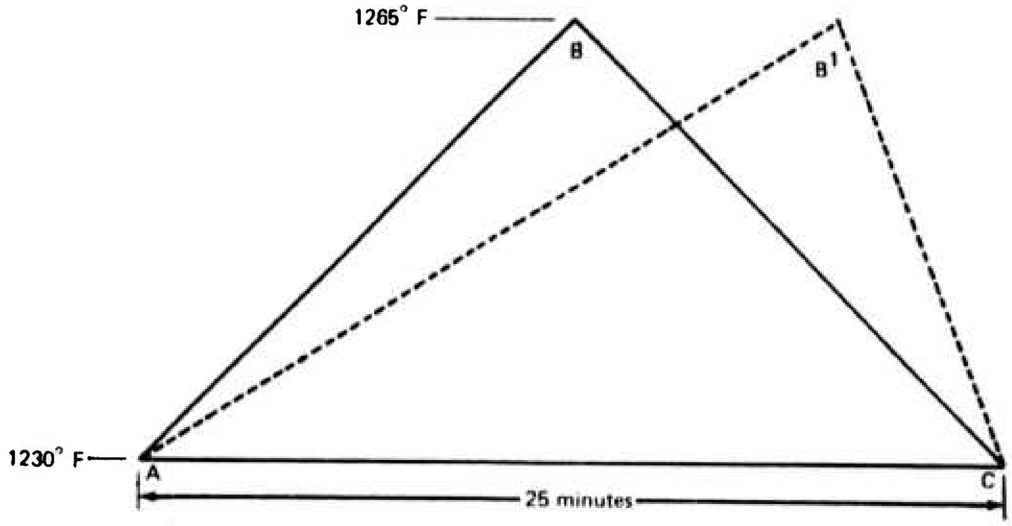
It has been said that the three most critical aspects of the entire brazing system are (1) cleanliness, (2) cleanliness, and (3) cleanliness. Titanium, because of its high reactivity, is particularly critical. Practical cleaning methods and procedures, however, have been developed to provide the required cleanliness. The aluminum braze alloy must be degreased, then deoxidized. Trace element contamination by lead must be avoided at all cost.

The braze cycle for aluminum brazing must be well controlled. The aluminum does not react sufficiently with the titanium below 1230°F to produce good bond integrity. Temperatures above 1270°F result in excessive braze fluidity and conversion of the aluminum to $TiAl_3$. Figure 6 illustrates the acceptable braze envelope. Except where perforated face skins are used, the brazing must be accomplished at a retort pressure $\leq$5 torr.

3.1.2 Process Limitations

Aluminum brazing of titanium honeycomb sandwich structure is feasible for core cell sizes ranging from 0.125 to 0.750 inch, and core depths up to and including 3.0 inches. The quantity of braze alloy required is related to core density and depth as illustrated in figure 7.

Brazements have been successfully made using solid and perforated face skins in flat, complex contoured, wedge, and 360° cylindrical configurations. Nominal face-skin thicknesses up to 0.150 inch have presented no problem. Net size brazements are feasible; however, close attention must be paid to retort cleanliness and pumping capacity to ensure removal of residual contaminants and vaporized stopoff binder.



1. Each thermocouple trace shall fall within a triangle ABC. The triangles may be shifted or skewed (AB'C) as desired.
2. The minimum acceptable exposure shall be 1230° F; no minimum time.

FIGURE 6.–ACCEPTABLE BRAZE ENVELOPE–NORMAL CYCLE

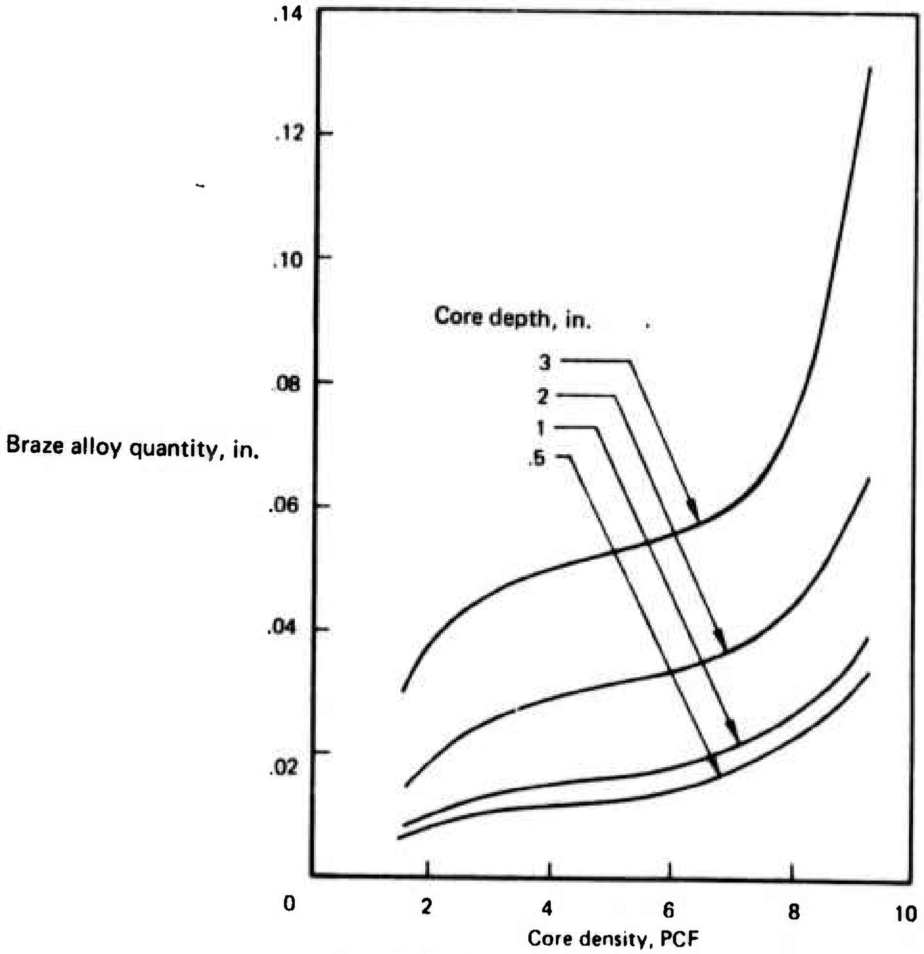


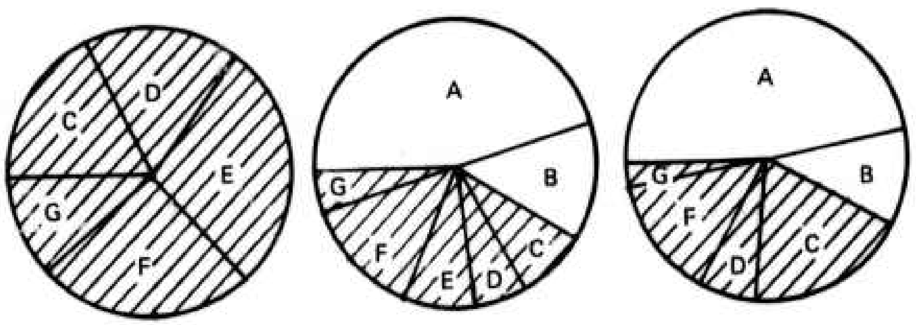
FIGURE 7.–BRAZE ALLOY REQUIREMENTS

Postbraze welding of aluminum-brazed structure has proven feasible and is currently being used on military aircraft (B-1). It is important that the braze alloy be removed from the weld zone to avoid contamination of the weld metal.

3.1.3 Process Economics

The cost of aluminum-brazed titanium honeycomb sandwich is now estimated to be $200 to $900 per square foot, depending on panel complexity. This is a significantly lower cost than predicted for structural sandwich a few years ago. At that time, the cost of silver-brazed stainless steel sandwich was reported as $4000 per square foot, and aluminum-brazed titanium sandwich was estimated as $2000 per square foot.

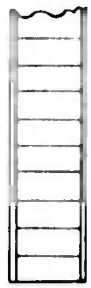
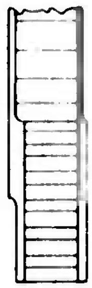
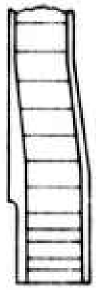
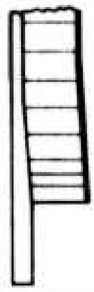
The economics of the aluminum braze process are highly dependent on the design. Figure 8 shows that approximately 65% of the cost of semicomplex or complex parts is the result of design-induced detail machining and core splicing. This is further illustrated by the detailed cost analysis presented in table 8.



A—Machining and flattening
B—Core splicing
C—Layup
D—Weld retort and leak check
E—Braze
F—NDT
G—Miscellaneous

FIGURE 8.—PRINCIPAL COST ELEMENTS FROM PRELIMINARY COST STUDY

TABLE 8.—RELATIVE COST FACTORS FOR ALTERNATE DESIGN CONCEPTS (% OF BASELINE TOTAL)

	Baseline	SST	Alternate 1	Alternate 2
Design concept				
Relative cost	1.0	3.1	2.3	2.0
Fabrication effort, %	100	100	100	100
Skin fabrication				
Machining		19.2	17.3	10.8
Other	2.4	1.6	2.2	2.5
Core blanket assembly				
Splice	1.5	17.4	21.6	23.0
Machine	33.1	23.0	14.3	16.8
Other	3.0	2.7	3.6	1.5
Braze operations				
Clean	6.5	3.1	3.5	4.8
Trim braze alloy and layup	3.8	9.4	6.5	4.5
Weld retort and leak check	8.0	2.6	3.5	4.1
Braze	8.5	2.8	3.7	4.3
Nondestructive testing	26.1	15.2	19.7	22.9
Miscellaneous	7.1	3.0	4.1	4.8

3.1.4 Material Properties and Structural Performance

The mechanical properties of aluminum-brazed titanium honeycomb sandwich are considerably greater than would be expected by calculations based on the strength of the aluminum braze alloy. Mechanical properties are highly dependent on core density, as illustrated in figure 9. Flatwise tension strength is also dependent on core foil thickness. The brazed sandwich is capable of supporting usable sustained loads to 800°F for exposures in excess of 10,000 hours and exhibits short-term strength even at 1000°F.

Extensive laboratory, accelerated, and flight service testing of the aluminum-brazed sandwich hardware for up to 4.5 years has demonstrated that no galvanic corrosion problem exists, and that aluminum-brazed structural and acoustic panels can be used for applications under anticipated commercial and military aircraft service conditions.

Aluminum-brazed titanium honeycomb sandwich details are currently flying or are planned for the F-14, F-15, B-1, and 737 aircraft. Figure 10 shows a flight-certified Model 737 spoiler that has been developing service experience for over 6 months and that will continue in service for approximately 48 months under one of the most severe corrosion environments experienced by commercial aircraft. Allowables for aluminum-brazed titanium honeycomb sandwich are presented in reference 13.

3.1.5 Development Status

Table 9 summarizes the technological progress that has occurred in the development of the aluminum-brazed titanium system since termination of the SST prototype effort.

3.2 FUSION WELDING

3.2.1 Process Description

The fusion welding of Ti-6Al-4V alloy has been developed to provide a reliable joining method for primary aircraft structure. Process specifications and design allowables have been established for four basic fusion-welding processes. These processes are:

- Gas tungsten arc welding (GTAW)
- Gas metal arc welding (GMAW)
- Plasma arc welding (PAW)
- Electron beam welding (EBW)

Data related to process control, environmental effects, and hardware producibility on a scale-up basis were developed. The effect of weld imperfection, as allowed by process specifications, was evaluated.

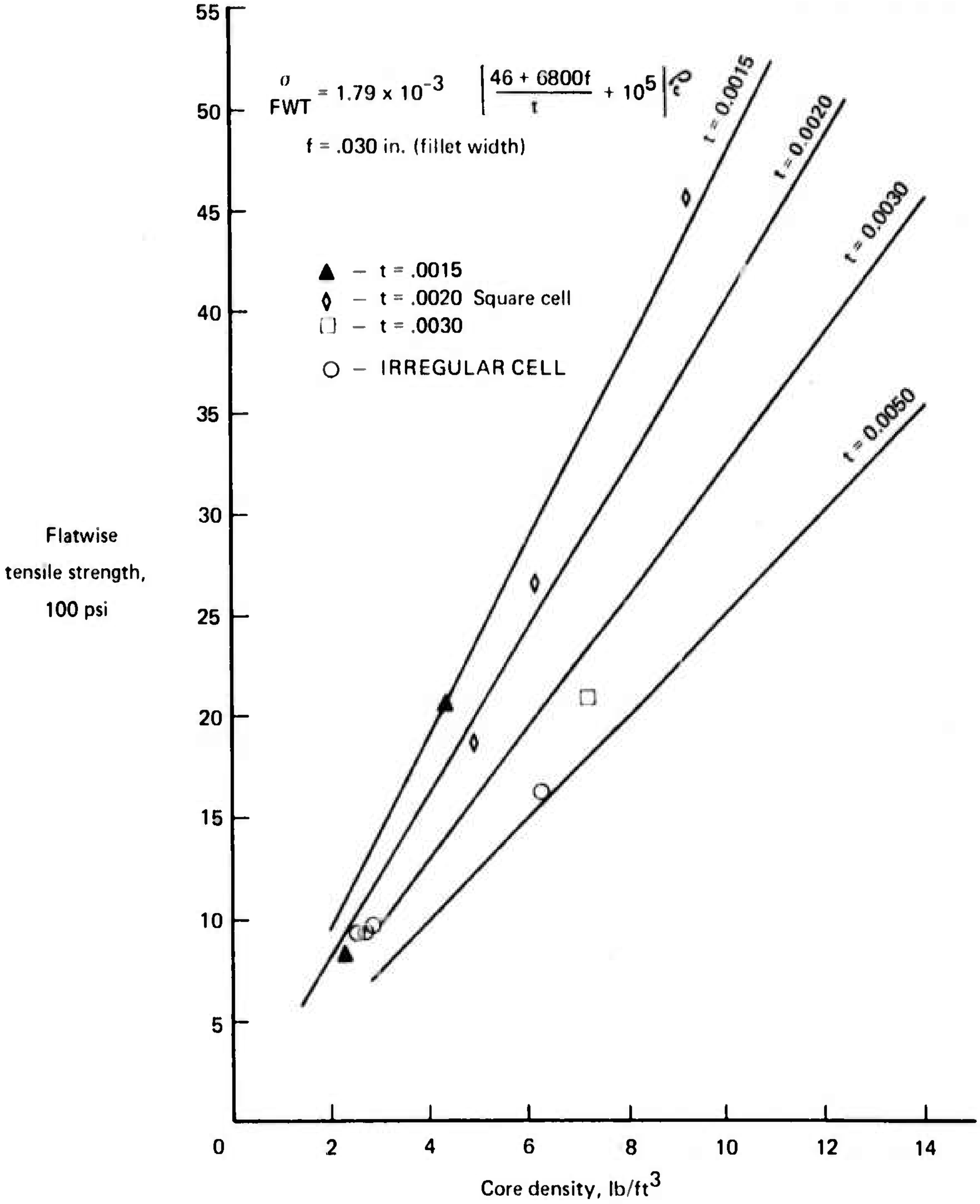


FIGURE 9.—COMPARISON OF ANALYTICAL AND EXPERIMENTAL FWT DATA

FIGURE 10.—737 FLIGHT SPOILER

A process derivative of GTAW, "in place" welding of aircraft tubing systems, was also evaluated. The welding techniques, mechanical property data, and metallurgical studies evolved from this investigation are reported in reference 15.

Process specifications and structural property data for fusion-welded titanium assemblies have been established. The results of the fusion-welding investigation indicate that:

- Gas tungsten arc welding, plasma arc welding, and electron beam welding of titanium alloys, particularly Ti-6Al-4V, and in-place GTA welding of titanium alloy Ti-6Al-4V and Ti-3Al-2.5V tubing and Ti-6Al-4V fittings, were developed as reliable production processes.
- Plasma arc welding is least prone to internal weld imperfections, such as porosity, with EB welding ranking next and GTA welding rating third.

*TABLE 9.—ALUMINUM-BRAZED TITANIUM SYSTEM TECHNOLOGICAL PROGRESS**

Key category	Specific technological progress	Status	
		SST Prototype (1970)	DOT/SST Phases I & II (1974)
Process research and development	1 Maximum core depth	1.5 in.	3.0 in.
	2 Minimum core density	5 pcf	1.6 pcf
	3 Maximum braze angle	25°	360°
	4 Wedge-shaped sandwich	No	Yes
	5 Acoustic sandwich	No	Yes
	6 Faying-surface braze	No	Yes
	7 Post-braze weld assembly	No	Yes
	8 Minimum node permeability requirement	No	Yes
Scale-up technology	1 Maximum nominal skin thickness	.09 in.	.15 in.
	2 Panel end-load capability	18,000 lb/in.	30,000 lb/in.
	3 Flight hardware capability demonstrated	No	Yes
	4 Wedge-shaped structure	No	Yes
	5 Acoustic structure	No	Yes
	6 Faying-surface braze	No	Yes
	7 Net-brazed edge capability	No	Yes
Material properties	1 Core depth data	1 in.	1/4, 1, 2, 3 in.
	2 Core configuration data	SS 2-20, SC 4-20, SC 4-30	SS 2-20, SC 3-15, SC 3-20, SC 4-20, SC 4-30, SC 6-15, SC 8-20
	3 Evaluated temperature data	RT, 450°F	RT, 450°, 600°, 800°, 1000°F
	4 Minimum thermal conductivity	9 Btu-in./hr-sq ft-°F	2.5 Btu-in./hr-sq ft-°F
	5 Stress-rupture data	1000 hr @ 450° & 600°F	10,000 hr @ 450°, 600°, & 800°F
	6 Analysis of effect of brazing on fatigue	No	Yes
Structural verification	1 Compression panel design data verified	No	Yes
	2 Structurally efficient single-surface edge joint designs	No	Yes
	3 Acceptable constraints for access hole design	No	Yes
	4 Flight hardware certification	No	Yes
Corrosion resistance	1 Flight service evaluation	2 airplanes - 1 yr	21 airplanes up to 4 yrs
	2 Accelerated corrosion tests	3 months	18 months
	3 Galvanic corrosion	Indicated none occurs	Established none occurs
	4 Stress corrosion	Unknown	Established none occurs
	5 Protection for honeycomb fastener holes	Sealant filled	Not required
	6 Faying-surface braze	Not permitted	Permissable with restrictions
	7 Corrosion mechanisms established	No	Yes
	8 Inspection test methods established	No	Yes
	9 Engine exhaust tests	No	Yes
Producibility	1 Principal cost elements identified	No	Yes
	2 Cost effective alternatives identified	No	Yes

*Further confirmation of the viability and integrity of the system has been its selection for a variety of structures on the F-14, F-15, and B-1 airplanes. In addition, the system has been selected for acoustic sandwich structures for the Boeing/NASA Refan program to develop new concepts for jet engine noise reduction.

- Annealed Ti-6Al-4V appears to be insensitive to heat input and cooling rate, permitting a wide range of welding conditions and repairs to be used in a variety of prior heat treatment conditions without subsequent heat treatment except for stress relief.

3.2.2 Properties

It can be concluded from the fusion-weld mechanical property tests that:

- Stress relief of welded Ti-6Al-4V is required in order to (a) minimize the possibility of delayed weld cracking, (b) improve fatigue (S-N) characteristics, and (c) minimize the possibility of premature failure in service. Figure 11 indicates the effect of residual stress on the fatigue properties of 6Al-4V titanium.

- Extensive tensile property data exist for Ti-6Al-4V weldments in a wide range of heat treatment and welding conditions. Joint efficiencies were at least 90% of the base metal properties, provided Ti-6Al-4V filler or no filler (base metal fusion only) were used. The data are available in reference 15.

- The fracture toughness and stress corrosion resistance of Ti-6Al-4V weldments and elevated temperature-stress stability of Ti-6Al-4V GTA weldments, although in many cases somewhat lower than that of the base metal, were considered to be adequate for the SST airplane (see table 10).

3.2.3 Effect of Defects

Weld porosity was the single most common weld defect encountered in the welding investigations. Cracking and heavy metal inclusions were rarely observed, although mismatch, undercut, and lack of penetration were observed occasionally. Figure 12 indicates the effect of porosity and of repair welds on fatigue performance. Repair welds have no significant effect on the static strength of annealed Ti-6Al-4V.

3.3 SYNOPSIS

Marked advancements were achieved in design and manufacturing criteria for both welded titanium structure and aluminum-brazed titanium structure. System capabilities were successfully demonstrated by fabrication, test, and analysis of welded and brazed hardware encompassing a wide range of configurations, structural load capacities, and test conditions. Results substantiate that both processes are well suited for aircraft applications.

The aluminum braze system has been selected for use on the F-14, F-15, and B-1 airplanes. Control surface assemblies have been fabricated and certified for service evaluation on commercial subsonic aircraft.

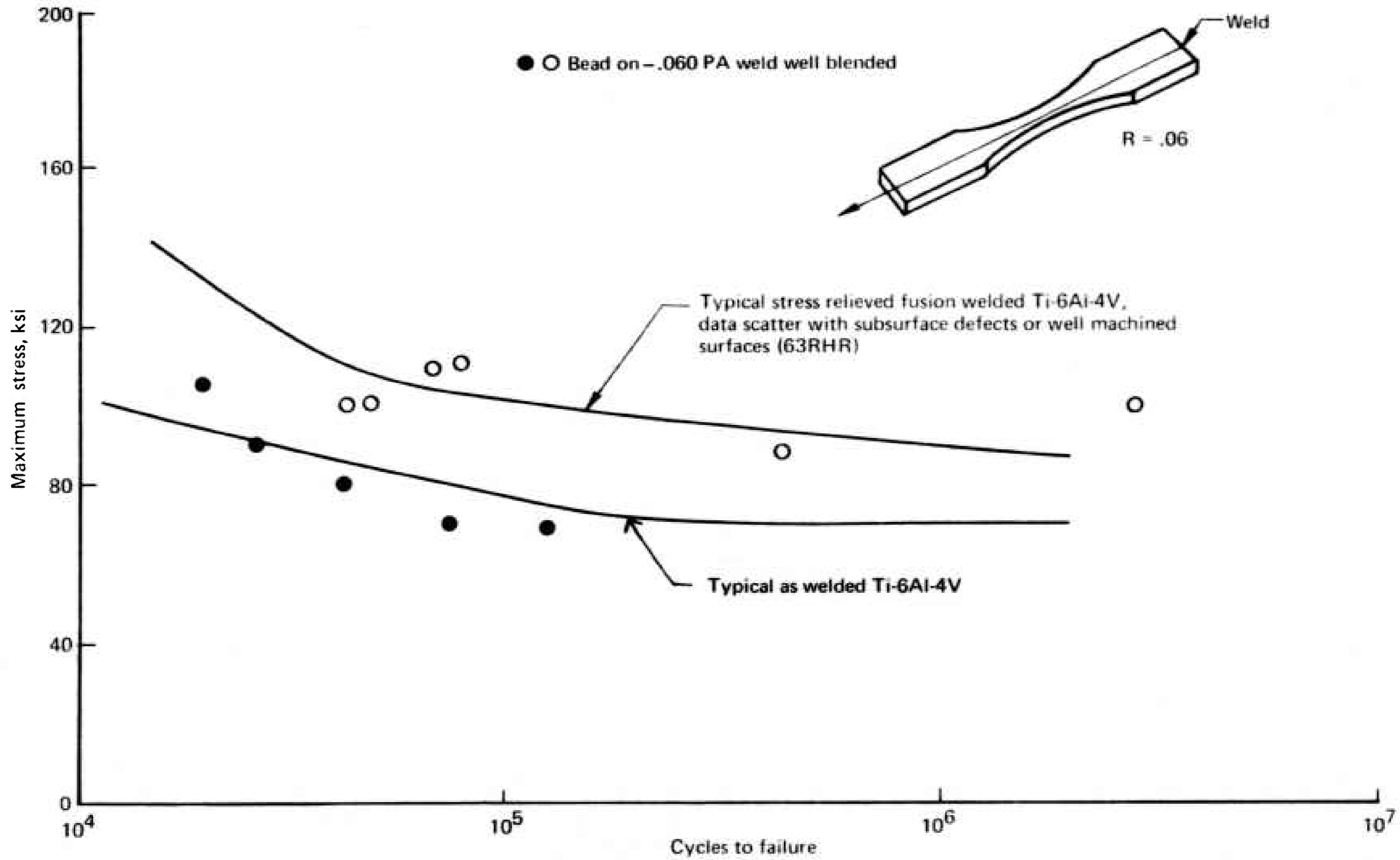


FIGURE 11.—EFFECT OF RESIDUAL STRESS ON FATIGUE OF Ti-6Al-4V WELDS

TABLE 10.–TOUGHNESS AND PRECRACKED THRESHOLD STRESS CORROSION[1] STRESS INTENSITY VALUES FOR Ti-6Al-4V AS INFLUENCED BY PRIOR THERMAL TREATMENT AND FILLER WIRE[3]

Gage/process	Thermal treatment[2]	Filler wire	Fracture toughness K_{IC} (ksi $\sqrt{in.}$)			Stress corrosion threshold K_{Ii} (ksi $\sqrt{in.}$)		
			Weld ℄	HAZ	Base	Weld ℄	HAZ	Base
0.250/GMA	Mill annealed	CP	140	117	70	122	98	50
0.500/GMA	Mill annealed	CP	105	72	50	55	36	24
0.250/GTA	Mill annealed	3Al	125	82	70	112	70	40
0.250/GMA	Mill annealed	5Al-2.5Sn	–	115	–	73-108	88	67
0.500/GMA	Mill annealed	5Al-2.5Sn	95	90	67	76	67	55
0.250/GMA	Mill annealed	6Al-4V	115	92-100	105	90-100	70-80	75
0.250/GMA	Beta annealed + STA 1000	5Al-2.5Sn	120	105	75	55	80	50
0.250/GTA	Beta annealed + STA 1000	5Al-2.5Sn	115	102	100	70	85	45
0.250/GTA	Beta annealed + STA 1000	6Al-4V	110	102	88	94	90	45
0.250/GMA	Beta annealed + STA 1000	6Al-4V	98	100	75	90	70	49
0.250/GTA	Beta annealed + STA 1250	3Al	125	135	115	110	122	80
0.250/GMA	Beta annealed + STA 1250	5Al-2.5Sn	115-135	115	100-105	60-130	92-100	80
0.250/GTA	Beta annealed + STA 1250	6Al-4V	98	105	117	95	70-95	88
0.250/DGTA	Beta annealed + STA 1250	None	78	84	84	45	50	58
0.500/GTA	Beta annealed + STA 1250	CP	98	102	85	65	67	55
0.500/GTA	Beta annealed + STA 1250 + Exposure[4]	CP	85	85	68	58	52	40
0.500/GTA	Beta annealed + STA 1250	5Al-2.5Sn	100	85	85	55	65	55
0.500/GTA	Beta annealed + STA 1250 + Exposure[4]	5Al-2.5Sn	89	85	68	48	62	40
0.500/GTA	Beta annealed + STA 1250	6Al-4V	92	98	84	65	69	53
0.500/GTA	Beta annealed + STA 1250 + Exposure[4]	6Al-4V	97	82	–	52	50	–

(1) 3.5% salt water solution

(2) Stress relieved, 30 min at 1250°F

(3) Very close to ELI grade

(4) 25 ksi and 550°F for 5000 hr

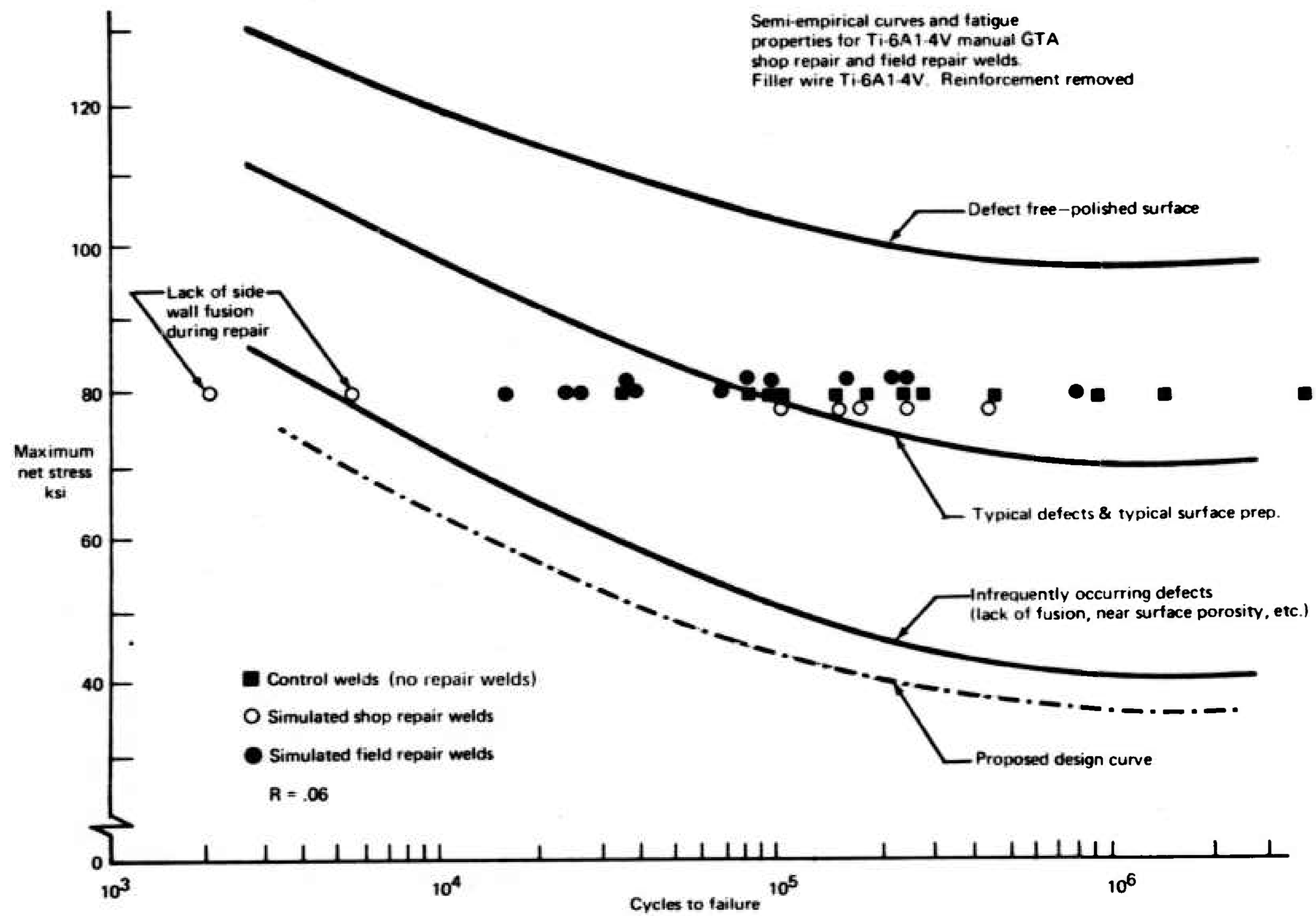


FIGURE 12.—EFFECT OF WELD DEFECT ON FATIGUE

4.0 TITANIUM STRUCTURE

4.1 SHEAR BEAM ANALYSIS

Existing methods of analysis of intermediate tension field beams were extended from aluminum structure to titanium structure in support of the SST program. Two separate methods of analysis—(1) a semiempirical technique based on NACA TN 2661 and (2) an analytical approach based on the minimum potential energy theorem—were subjected to a comprehensive development program. The semiempirical method was found to function quite well for both aluminum and titanium intermediate shear beams. The analytical approach was accurate only for square single-panel beams. It was inadequate for rectangular and multiple-panel beams. Details of the extensive analytical and experimental program are presented in reference 16.

4.2 HONEYCOMB SANDWICH STRUCTURE

The area where the most significant development took place during and following the SST effort was that of aluminum-brazed titanium honeycomb sandwich structure. The evolution of joint technology for joining brazed honeycomb sandwich structure since the SST termination can only be described as spectacular. Single surface joints having properties equaling those of double surface joints, which are significantly more costly, have been designed and successfully tested (fig. 13). Deficiencies associated with double surface joints at panel access holes have been identified and design solutions defined using less costly single surface joint technology. The mechanical attachment of fittings to sandwich honeycomb structure subsequent to brazing has been demonstrated and successfully tested using mechanical blind fasteners. Detailed information is presented in references 17 and 18.

4.3 COMPRESSION STRUCTURE

A comprehensive experimental effort has been devoted to evaluating the performance of honeycomb sandwich, skin-stringer, and integrally stiffened structural panels under conditions of uniaxial and biaxial compression loading at room and elevated temperature. The test results were correlated with structural analysis methods. It was found feasible to employ analytical methods to predict buckling and ultimate panel failure loads. The complexity of the results does not permit more detailed inclusion in this summary. Detailed data and discussion are presented in references 19 and 20.

4.4 FAIL SAFETY

The static and fatigue crack growth characteristics of titanium structure are quite different from aluminum structure. Consequently, analytical techniques employed for fail-safe design must be modified. Elastic analysis considering rigid fasteners is quite adequate for ultimate failure (fig. 14). Prediction of fatigue crack growth rate, however, requires the use of a more complex elastic-plastic solution using flexible fasteners. Reference 21 presents detailed fracture data and analytical correction factors for a range of panel configurations, fasteners, and loading conditions.

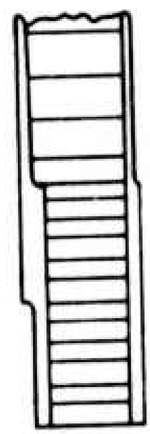
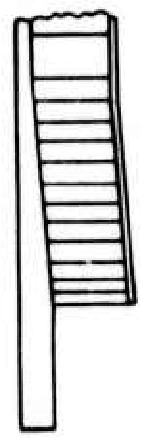
	SST double surface	Phase II redesign dense core edge
Design concept		
Property		
Static		
Tension, ksi	145.5	130
Compression, ksi	146	140.5
Fatigue (R = .3)		
Maximum cyclic gross area stress, ksi	34	34
Life, cycles (log average)	128,000	260,000
Relative cost	1.6	1.0
Fabrication effort, %	100	100
Skin fabrication		
Machining	19.2	10.8
Other	1.6	2.5
Core blanket assembly		
Splice	17.4	23.0
Machine	23.0	16.8
Other	2.7	1.5
Braze operations		
Clean	3.1	4.8
Trim braze alloy and layup	9.4	4.5
Weld retort and leak check	2.6	4.1
Braze	2.8	4.3
Nondestructive testing	15.2	22.9
Miscellanious	3.0	4.8

FIGURE 13.—COMPARISON OF JOINT PERFORMANCE AND RELATIVE COST FACTORS FOR ALTERNATE DESIGN CONCEPTS

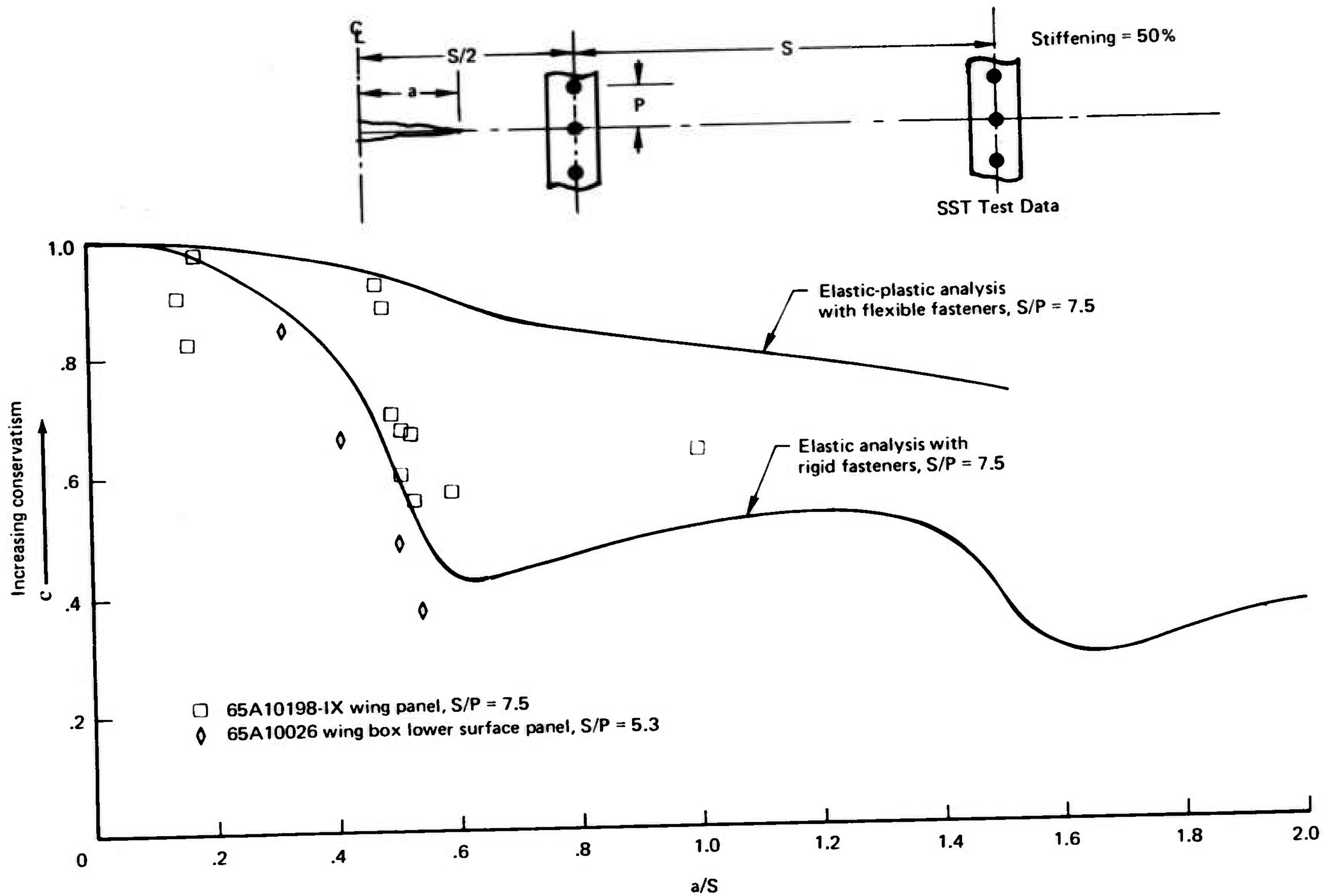


FIGURE 14.–STRESS INTENSITY CORRECTION FACTOR C FOR MIDBAY SKIN CRACK WITH 50% STIFFENING

4.5 SYNOPSIS

All the work performed during the SST effort and after SST termination demonstrates the excellent load-carrying capabilities of titanium structure. It can be treated basically the same as other material structure except in the case of fail-safe design where special consideration must be given to fastener flexibility.

5.0 REFERENCES

	REPORT NUMBER*	TITLE
1.	FAA-SS-72-13	Titanium Alloy 6Al-4V Mechanical/Metallurgical Testing
2.	FAA-SS-73-4	Development of Improved Titanium 6Al-4V Mill Products
3.	FAA-SS-72-00	Beta-Processed Titanium Alloy 6Al-4V Plate
4.	FAA-SS-72-07	Titanium Alloy 6Al-4V Hydrogen Effects
5.	FAA-SS-72-08-1	Compatibility of SST Materials With Titanium Alloys; Vol. I, Flyaway Materials
6.	FAA-SS-72-08-2	Compatibility of SST Materials With Titanium Alloys; Vol. II, Manufacturing Aid Materials
7.	FAA-SS-72-01	Titanium Alloy 6Al-4V Sheet
8.	FAA-SS-72-04	Titanium Alloy 6Al-4V Bar and Forgings
9.	FAA-SS-72-06	Titanium Alloy 6Al-4V Extrusions
10.	FAA-SS-72-05	Titanium Alloy 6Al-4V Tubing
11.	FAA-SS-72-03	Development of Aluminum Brazed Titanium Honeycomb Sandwich
12.	FAA-SS-72-14	Corrosion/Creep Testing, Aluminum-Brazed Titanium Honeycomb Sandwich
13.	FAA-SS-72-10	Aluminum-Brazed Titanium Sandwich Allowables
14.	FAA-SS-73-5	Development and Evaluation of the Aluminum-Brazed Titanium System; (Vol. I-VIII)
15.	FAA-SS-72-9	Titanium Alloy Welding
16.	FAA-SS-72-11	Titanium Intermediate Shear Beam Analysis
17.	FAA-SS-73-5-5	Development and Evaluation of the Aluminum-Brazed Titanium System; Vol. V, Structural Verification

*Documents prepared by Boeing for the FAA.

18. FAA-SS-73-5-7 Development and Evaluation of the Aluminum-Brazed Titanium System; Vol. VII, Producibility and Costs

19. FAA-SS-72-12 Titanium Compression Panel Analyses and Tests

20. FAA-SS-73-9 Integrally Stiffened Panel Biaxial Compression Tests

21. FAA-SS-73-8 Crack Propagation and Residual Strength Testing of Titanium Structure

APPENDIX

TABLE A1.–PHASE I FINAL REPORTS
Titanium Structures

DDC-AD number	DOT report number	Boeing document number	Title
AD-902-450L	FAA-SS-72-00	D6-60200	Beta-Processed Titanium Alloy 6Al-4V plate
AD-902-451L	FAA-SS-72-01	D6-60201	Titanium Alloy 6Al-4V Sheet
AD-902-452L	FAA-SS-72-02	D6-60202	Titanium Alloy 6Al-4V Mechanical Property Data
AD-902-453L	FAA-SS-72-03	D6-60203	Development of Aluminum Brazed Titanium Honeycomb Sandwich
AD-902-454L	FAA-SS-72-04	D6-60204	Titanium Alloy 6Al-4V Bar and Forgings
AD-902-455L	FAA-SS-72-05	D6-60205	Titanium Alloy 6Al-4V Tubing
AD-902-456L	FAA-SS-72-06	D6-60206	Titanium Alloy 6Al-4V Extrusions
AD-902-457L	FAA-SS-72-07	D6-60207	Titanium Alloy 6Al-4V Hydrogen Effects
AD-902-458L	FAA-SS-72-08-1	D6-60208-1	Compatibility of SST Materials With Titanium Alloys: Vol. 1, Flyaway Materials
AD-902-459L	FAA-SS-72-0B-2	D6-60208-2	Compatibility of SST Materials With Titanium Alloys; Vol. II, Manufacturing Aid Materials
AD-902-460L	FAA-SS-72-09	D6-60209	Titanium Alloy Welding
AD-902-461L	FAA-SS-72-10	D6-60210	Aluminum Brazed Titanium Sandwich Allowables
AD-902-462L	FAA-SS-72-11	D6-60211	Titanium Intermediate Shear BEam Analysis
AD-902-463L	FAA-SS-72-12	D6-60212	Titanium Compression Panel Analyses and Tests
AD-902-464L	FAA-SS-72-13	D6-60213	Titanium Alloy 6Al-4V Mechanical/Metallurgical Testing
AD-902-465L	FAA-SS-72-14	D6-60214	Corrosion/Creep Testing, Aluminum Brazed Titanium Honeycomb Sandwich

TABLE A2.–PHASE II FINAL REPORTS
Titanium Structures

DDC-AD number	DOT report number	Boeing document number	Title
AD-920-802L	FAA-SS-73-4	D6-60276	Development of Improved Titanium 6Al-4V Mill Products
AD-920-794L	FAA-SS-73-5-1	D6-60277-1	Development and Evaluation of the Aluminum Brazed Titanium System–Volume I, Program Summary
AD-920-795L	FAA-SS-73-5-2	D6-60277-2	–Volume II, Process Research & Development
AD-920-796L	FAA-SS-73-5-3	D6-60277-3	–Volume III, Scale-up Technology
AD--920-797L	FAA-SS-73-5-4	D6-60277-4	–Volume IV, Material Properties
AD-920-798L	FAA-SS-73-5-5	D6-60277-5	–Volume V, Structural Verification
AD-920-799L	FAA-SS-73-5-6	D6-60277-6	–Volume VI, Corrosion Resistance
AD-920-800L	FAA-SS-73-5-7	D6-60277-7	–Volume VII, Producibility and Costs
AD-920-801L	FAA-SS-73-5-8	D6-60277-8	–Volume VIII, Process Specifications
AD-917-344L	FAA-SS-73-8	D6-60280	Crack Propogation and Residual Strength Testing of Titanium Structure
AD-913-422L	FAA-SS-73-9	D6-60281	Integrally Stiffened Panel Biaxial Compression Tests
(NA)	FAA-SS-73-27	D6-60304	Titanium Structures Technical Summary– DOT/SST Phase I and Phase II