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DEVELOPMENT OF THE WELDBOND PROCESS FOR JOINING TITANIUM

ABSTRACT

This paper presents a digest of work performed under Contract F33615-71-C-1099 for the Fabrication Branch, Manufacturing Technology Division, AFML, Air Force Systems Command, Wright Patterson Air Force Base, Ohio. Data discussed within the scope of this paper resulted primarily from this program which established the basic parameters for joining titanium alloy using the resistance spot weld-adhesive bonding (Weldbonding process).

The writer wishes to gratefully acknowledge the technical and administrative efforts of Mr. Fredrick R. Miller, Air Force Manager for the Weldbond Program, and Mr. Gail E. Eichelman, Acting Chief, Metals Branch, AFML. The efforts of both Mr. Miller and Mr. Eichelman have contributed greatly to the advancement of Weldbonding from a specimen stage to a full scale production process.

INTRODUCTION

Beginning in 1965, experimental work at Lockheed-Georgia Company in resistance welding through high strength structural adhesives produced a process whereby exceptionally high mechanical strength properties could be obtained in aircraft joints fabricated from aluminum alloys. Continued work with adhesive formulations, and continued improvement in welding techniques further advanced the repeatability of the process to a point where large scale test structures could be produced.

In July, 1969, the Fabrication Branch, Manufacturing Technology Division, Air Force Materials Laboratory awarded a contract to Lockheed-Georgia Company for the purpose of building and testing a full scale aluminum aircraft fuselage section joined by the spot weld-adhesive bonding (Weldbonding) process.

Results from the successful completion of the program encouraged the continued development of a weldbonding technology that would encompass other materials and other conditions.

Many military aircraft operate under conditions of stress and temperature that are beyond the design limits of aluminum alloy, regardless of the type joint fastening system used. Development and utilization of the weldbonding process in titanium alloys would greatly increase the usefulness of the weldbonding process for the military customer.

The overall objective of the program discussed herein was to further advance manufacturing methods related processes of weldbond in high strength, heat and corrosion resistant alloys.

In order to establish basic joint static strength criteria for weldbonded titanium joints at room and elevated temperatures and to establish weldability using various adhesives, the following program objectives were outlined:

1. Select an adhesive for optimum compatibility with weldbonding of titanium alloy.

2. Establish resistance spotweld schedules and obtain certifications of weldbond joints to meet minimum requirements of MIL Specification MIL-W-6858C.

3. Fabricate and join single and multiple spot lap and butt shear joints to establish basic static strength of weldbonded joints in titanium 6Al-4V alloy.

4. Compare static strength of multiple and single row weldbond joints with conventional resistance spot weld joints, and to similar specimens joined by mechanical fasteners and by structural adhesive bonding.

5. Record and document data related to weldability of titanium using high temperature type adhesives and compare joint strength at room and elevated temperature.

MATERIALS

TITANIUM

Titanium sheet material type 6Al-4V in the solution treated condition in thicknesses of 0.045" and 0.063" was used in one series of tests during this program. Thitanium sheet material type 6Al-4V in the annealed condition in thicknesses of 0.020" and 0.025" was used in other tests during this program.

MECHANICAL FASTENERS

The following mechanical fasteners were used to join specimens made during this program:

1. 5/32" diameter Hilok Universal head, stock No. STSAF004-05-02.
2. 5/32" diameter Hilok Flush head, stock No. STSAF015D05LN02.
3. 5/32" diameter Hilok nut, stock No. STSAE007-05.

ADHESIVES

The following adhesives were selected from several candidate adhesives and were used to join the specimens tested during this program:

1. 3M Company Adhesive EC3419. The adhesive is a one part, 100% solids thermosetting heavy liquid. The adhesive is light grey in color. The adhesive base is a modified epoxy resin. Recommended cure procedure for optimum results is 350°F for 60 minutes.

2. 3M Company Adhesive type EC2214 Hi-Flex. The adhesive is a one part, 100% solids, thermosetting liquid adhesive. The color is light grey. Recommended cure temperature is 250°F for 60 minutes.

EQUIPMENT

WELDING EQUIPMENT

A Sciaky, three phase, variable pressure resistance spot welder shown in Figure 1 was used to join all welded and weldbonded tensile specimens tested during this program. The welder is rated at 150 KVA and is equipped with turret heads and automatic electrode dressers.

TESTING EQUIPMENT

A Tinius Olsen testing machine shown in Figure 2 was used throughout the program. The machine is rated at 60,000 pound capacity and has a test accuracy of two percent of indicated load. The testing machine was equipped with an Olsen Atcotran recorder, a model S-1 Electronic Extensometer, and a type D-2 Deflectometer. The testing machine was also equipped with a Marshall Electric Furnance, serial number 6510742, for an elevated temperature testing range 78°F to 1800°F.

DESIGN OF TEST PARAMETERS

TEST DESIGN LOGIC

Design of test parameters for evaluation of static strength of weldbond joints in titanium alloy required that first consideration be given to probable use of the developed process. Since a high percentage of titanium used in military aircraft would involve areas either exposed to high stress and/or elevated temperatures, strength at elevated temperatures would have to be given prime consideration. Where titanium would be used in structures not exposed to elevated temperature, generally the choice would be made because of better strength to weight advantages of titanium as compared to aluminum or other alloys. Joint thickness ratios were selected in this program with strength/weight considerations paramount.

Realistic evaluation of weldbonded joints in titanium required that whereever possible weldbond joint strength would be compared directly to strength of other type joints. Joints were designed utilizing spot welds only, mechanical fasteners only, mechanical fasteners with adhesive, and structural adhesive bond only. Joint configurations, joint overlap, and joint thickness were kept identical in order to obtain a direct strength comparison at room and elevated temperatures.

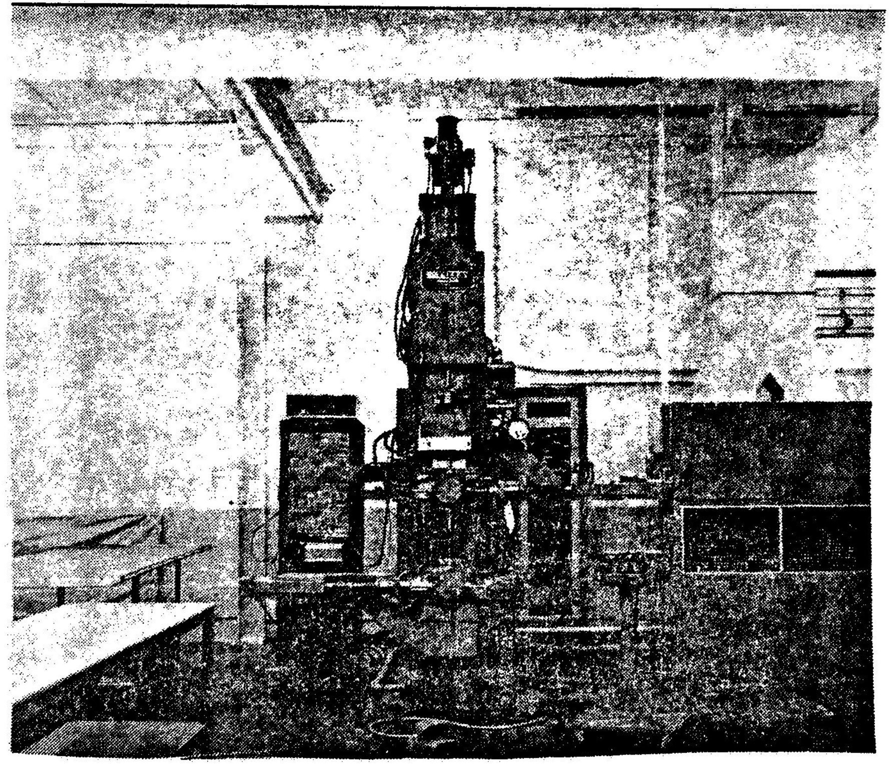

FIGURE 1 - SCIAKY THREE PHASE, VARIABLE PRESSURE, TURRET HEAD WELDER USED TO WELDBOND TITANIUM

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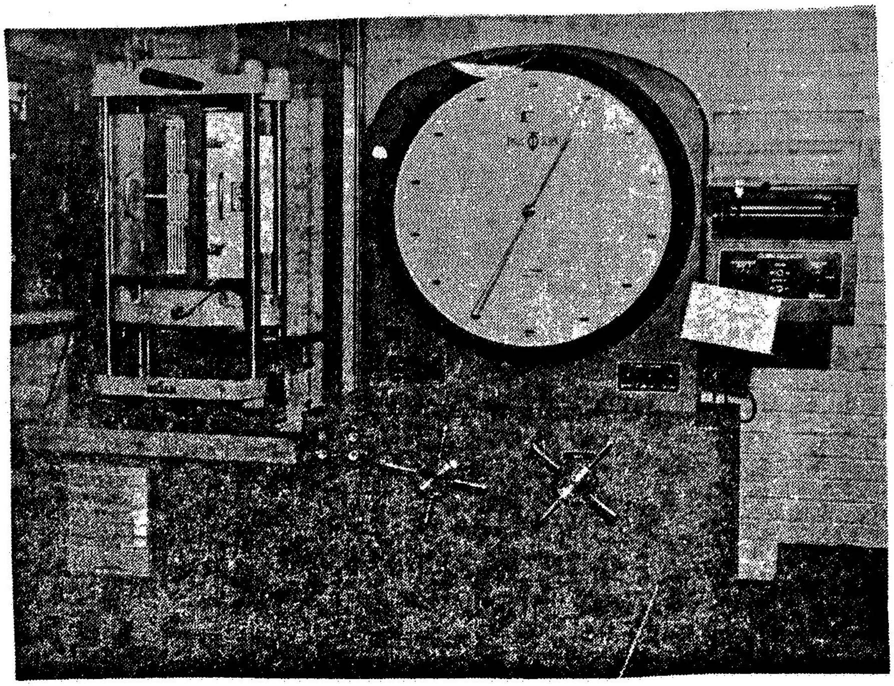


FIGURE 2 - TINIUS-OLSEN TENSILE TEST MACHINE

TEST SPECIMEN DESIGN

Typical test specimen design for multispot, double row weldbond and fastener bond joints is shown in Figures 3 through 5. Elevated temperature test specimens were of the same essential configuration except they were made 18 inches long in order to allow for heating of the specimen within the specimen gage length during testing.

WELD SCHEDULE DEVELOPMENT

WELD SCHEDULES

In order to obtain weldbond titanium joint strength data that could be compared qualitatively and quantitatively with other joining processes, basic welding schedules were needed. Machine schedule setups were made to establish adhesive weldability, correct spot weld nugget diameter and penetration, and other criteria as required by Military Specification MIL-W-6858C. It was necessary to vary weld schedule setups as various types of adhesives were tested. Weld current and weld pressure settings were found to differ with variation in adhesive type and/or viscosity.

WELD CERTIFICATION

Weld certifications were obtained for the following joint combinations tested within the scope of this program.

1. Titanium type 6Al-4V in the annealed condition, 0.025" thick weldbonded to titanium 6Al-4V in the solution treated condition, 0.063" thick.

2. Titanium type 6Al-4V in the solution treated condition, 0.045" thick weldbonded to titanium type 6Al-4V in the solution treated condition, 0.063" thick.

3. Titanium AMS4900 (Commercially Pure) 0.025" thick weldbonded to titanium 6Al-4V in the solution treated condition, 0.063" thick.

Weld certifications met Class A requirements for Group C, (titanium) alloys, MIL-W-6858C, Welding, Resistance Spot and Seam. Some difficulty was encountered in obtaining certified schedules in the commercially pure titanium to type 6Al-4V joints. This difficulty was due primarily to the difference in welding characteristics of the two alloys and not to the effect of adhesive at the joint interface.

CLEANING PROCEDURES

Preliminary cleaning and welding tests were made at the beginning of this program to determine if resistance welding could be accomplished in titanium that had been chemically cleaned for structural metal bonding. All attempts were unsuccessful as measured by standard weld certification requirements of MIL-W-6858C. It was determined that the passivation treatment (immersion in Trisodium Phospate (Na_3PO_4) used prior to bonding inhibited the passage of welding current during the welding operation and caused highly erratic weld quality.

Since high strength bonds could be achieved on parts cleaned for resistance welding, (except for passivation the two cleaning processes were essentially the same), all weldbonding accomplished within the scope of this program was done on parts cleaned by the chemical process used for resistance welding.

ADHESIVE SELECTION

ADHESIVE WELDABILITY

Adhesive weldability as discussed herein relates to the compatibility and/or incompatibility of the adhesive with the resistance welding process, and conversely, the effect of the welding process on the adhesive. First requirement of any adhesive candidate for the weld through process of weldbonding is that the adhesive have the capability of being moved under pressure of the welding electrodes in order for metal to metal contact to occur at the joint interface.

A second requirement for an adhesive candidate was that the heat resulting from the spot weld would cause only limited detrimental effect on the strength of the bond. The strength of the bond in titanium alloy joints, the adhesive and/or cohesive failure characteristics of the adhesive all entered into the final selection of the adhesive.

Final selection of the adhesives used during this program was based on overall weldbond properties at room and elevated temperatures as related to titanium weldbond joint strength.

ADHESIVE SCREENING AND SELECTION

A listing of the adhesives screened for use during this program and results of the screening are detailed as follows.

1. 3M Company epoxy adhesive type XA3919 is a roll coatable paste adhesive. XA3919 is a temperature resistant, 70% solids version of AF130 adhesive film. XA3919 exhibited adequate weldability and fair strength at 350°F temperature, but showed poor lap shear strength at room temperature.

2. 3M Company epoxy type XA3410 is a one part, 100% solids, thermosetting liquid adhesive advertised as being resistant to temperatures up to 350°F. XA3410 exhibited fair weldability, but showed low strength at all temperatures.

3. 3M Company adhesive XA3435 is a one part, 100% solids, thermosetting liquid advertised as offering superior strength up to and including 350°F temperature. XA3435 showed good weldability but exhibited only fair strength at all temperatures.

4. 3M Company adhesive type EC3419 is a one part, 100% solids, thermosetting heavy liquid advertised as having exceptionally high strength properties from -40 to 350°F. This adhesive exhibited excellent weldability on titanium alloy 6Al-4V and showed fair to good strength at elevated temperature and at room temperature. EC3419 was one of the adhesives selected for use during this program.

5. 3M Company adhesive type EC2214 Hi-Flex is a paste epoxy adhesive with filler designed for use from -40 to 250°F. This adhesive exhibited excellent weldability and showed cohesive type failures both at room and elevated temperature. Room temperature shear strength in titanium

joints was superior to all others tested. EC2214 was selected for use in this program.

6. Hysol Corporation adhesive ADX347 and ADX373, and Whittaker Corporation adhesive X6800 were also subjected to preliminary tests in titanium joints but exhibited adhesive failures with low lap shear strength at room temperature.

FABRICATION AND JOINING OF SPECIMENS

Specimens used for preliminary evaluation of adhesives were finger panel type. These specimens were stamped from titanium sheet stock and are of the type normally used for process control tensile testing as required by Military Specification MIL-W-6858C and Federal Specification MMM-132.

Specimens used to obtain the final test results were sheared from titanium sheet and machined to the configurations shown in Figure 3.

TEST PROCEDURES

TENSILE TESTS

Room temperature static tensile tests were performed on the Tinius-Olsen tensile testing machine shown in Figure 2. Test load pounds were all within a range of 500 to 12,000 pounds which allowed a test machine accuracy of two percent of indicated load.

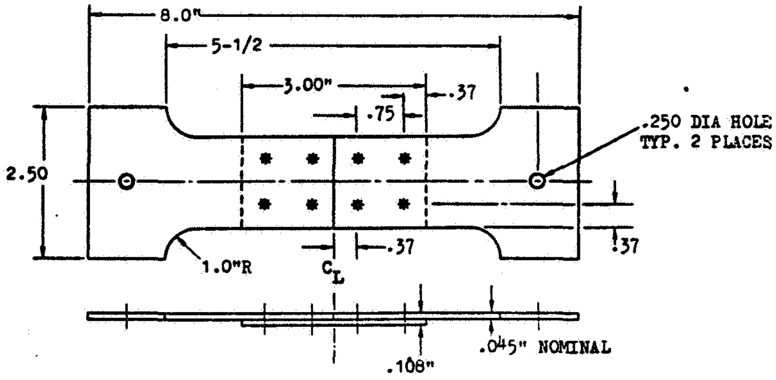
Load deflection curves were obtained for each of the tests. Ultimate strength, yield strength, and percent elongation were obtained for each specimen. Yield strength was determined using the 0.2% offset method.

Figures 3 through 5 show joint description and static shear strength of the specimens tested during this program.

Elevated temperature static tensile tests were made on the Tinius-Olsen testing machine using the Marshall specimen furnace as shown in Figure 2. Welded, weldbonded, adhesive bonded, mechanically fastened, and mechanically fastened and bonded specimens were subjected to various temperatures under load to failure. Static shear strength and mechanical properties of the joints at different temperature levels are shown in Figures 3 through 5.

FIGURE 3 - STATIC SHEAR STRENGTH, BUTT SHEAR DOUBLE ROW, MULTISPOT WELDBOND, 0.045" TO 0.063"

SPEC NO.	WIDTH IN.	OVER LAP IN.	EDGE DIST.	FAST DIA.	LOAD LBS.	LBS. IN.^{2}	TEST TEMP (°F)	ADHESIVE	JOINT PROC.	JOINT TYPE	FAIL MODE	JOINT COMB.	PITCH IN.
18-1	1.50	1.50	.37	None	11100	4933	RT	2214	WB	BSDR MS	N.E.	.045 TO .063	.75
18-2					11150	4955							
18-3					10950	4866							
18-4					10740	4773							
18-5					10830	4813							
18-6					11080	4924							
18-7					10850	4822							
18-8					10730	4768							
18-9					10720	4764							
18-10					10930	4857							
				Average	10900	4847							
18A-1	1.50	1.50	.37	None	10270	4564	150°	2214	WB	BSDR	N.E.	.045 TO .063	.75
18A-2					9940	4417	200°						
18A-3					10070	4475	200°						
18A-4					9490	4217	325°						
18A-5					9650	4288	325°						



SPEC NO.	WIDTH IN.	OVER LAP IN.	EDGE DIST.	FAST FIA.	LOAD LBS.	LBS. IN.^{2}	TEST TEMP (°F)	ADHE SIVE	JOINT PROC.	JOINT TYPE	FAIL MODE	JOINT COMB.	PITCH IN.
• 20-1	1.50	1.50	.37	5/32 FLUSH HEAD	6710		RT	None	Fast Hi-Lok	BSDR MF	HEAD SHEAR	.045 TO .063	.75
• 20-2					7200								
• 20-3					6740								
20-4					7685								
20-5					7750								
20-6					7120								
20-7					7440								
20-8					8050								
20-9					7350								
				Average	7665								
20A-1	1.50	1.50	.37	5/32 FLUSH HEAD	6630		150°	2214	Fast Hi-Lok	BSDR	HEAD SHEAR	.045 TO .063	.75
20A-2					6750		200°F	2214		MF	SHEAR FAST		
20A-3					6895		200°	None		MF	SHEAR FAST		
20A-4					5865		325°	2214		MF	FAST SHEAR		
20A-5					6940		325°	None		MF	FAST SHEAR		

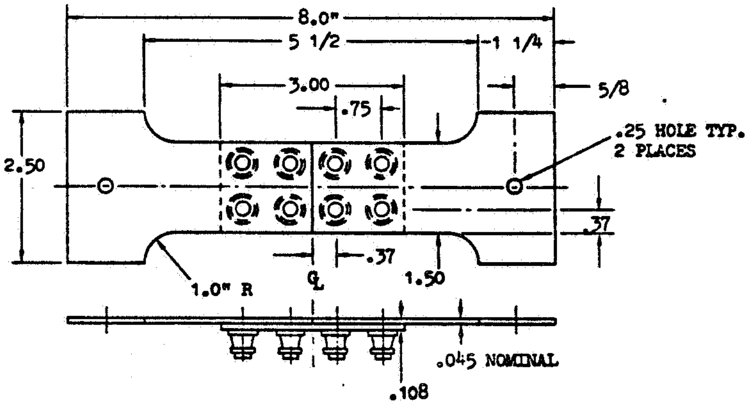


FIGURE 4 - STATIC SHEAR STRENGTH, BUTT SHEAR DOUBLE ROW, MULTIPLE FASTENER, 0.045" TO 0.063"

SPEC NO.	WIDTH IN.	OVER LAP IN.	EDGE DIST.	FAST DIA.	LOAD LBS.	$\frac{LBS}{IN.^2}$	TEST TEMP (°F)	ADHE SIVE	JOINT PROC.	JOINT TYPE	FAIL MODE	JOINT COMB.	PITCH IN.
24-1	1.50	1.50	None	None	7500	3333	RT	2214	Bond	BSSB	SHEAR	.045 TO .063	None
24-2					5700	2533							
24-3					7500	3333							
24-4					6900	3066							
24-5					4230	1880							
24-6					6230	2768							
24-7					5240	2328							
24-8					6460	2871							
24-9					6030	2680							
24-10					6220	2764							
				Average	6200	2755							
24A-1	1.50	1.50	None	None	5660	2515	150°	2214	Bond	BSSB	SHEAR	.045 TO .063	None
24A-2					3520	1564	200°						
24A-3					3140	1395	200°						
24A-4							325°						
24A-5					230	102	325°						

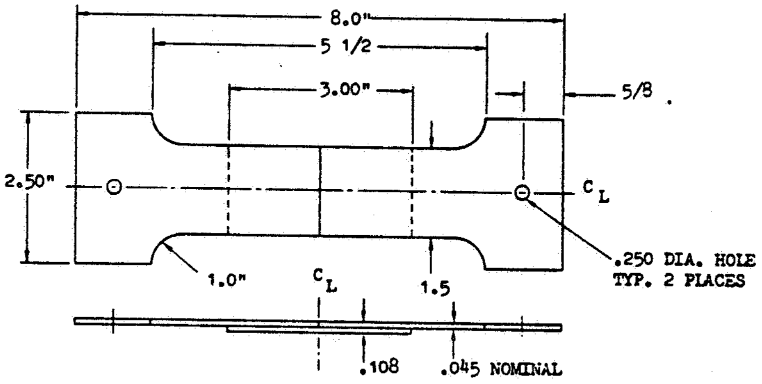


FIGURE 5 - STATIC SHEAR STRENGTH, BUTT SHEAR STRUCTURAL BOND, DOUBLE ROW MULTIPLE SPOT EQUIVALENT 0.045" TO 0.063"

PEEL TESTS

In order to test the combined strength of both the bond and the spot weld, peel specimens typical of those shown in Figure 6 were tested in a peel test fixture at room temperature.

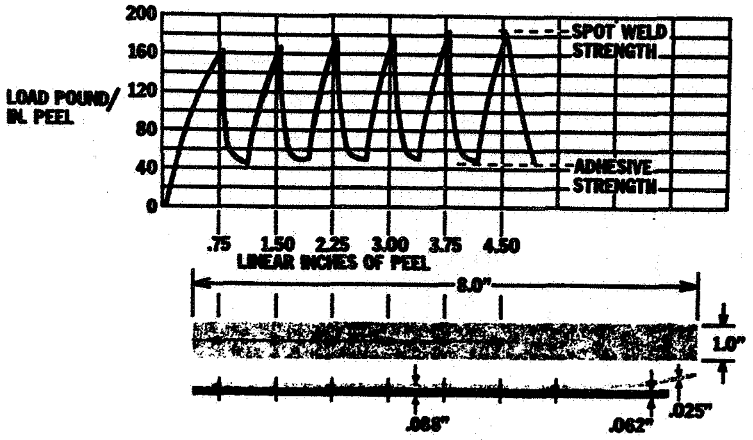


FIGURE 6 - DIAGRAM SHOWING TYPICAL PEEL STRENGTH OF WELDBONDED JOINTS IN TITANIUM

TEST RESULTS ANALYSIS

ROOM AND ELEVATED TEMPERATURE TEST RESULTS

Comparative strength of the different joining methods is shown in Figures 7 and 8. Strength of the joints is plotted in ultimate load pounds versus temperature in order to obtain a direct strength comparison of the various joining techniques.

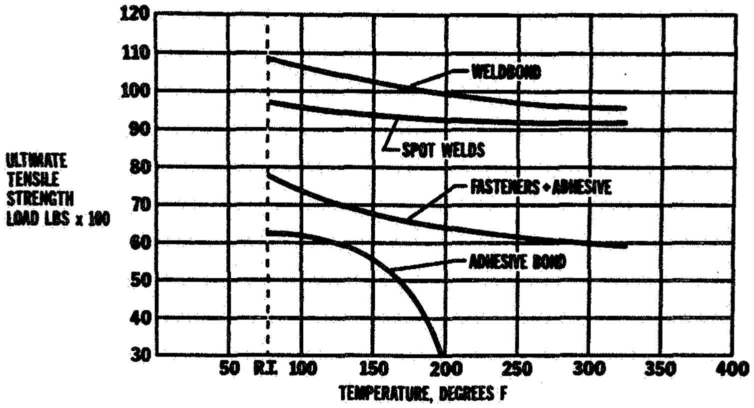


FIGURE 7 - COMPARATIVE JOINT STRENGTH, BUTT SHEAR DOUBLE ROW, 0.045" TO 0.063" TITANIUM

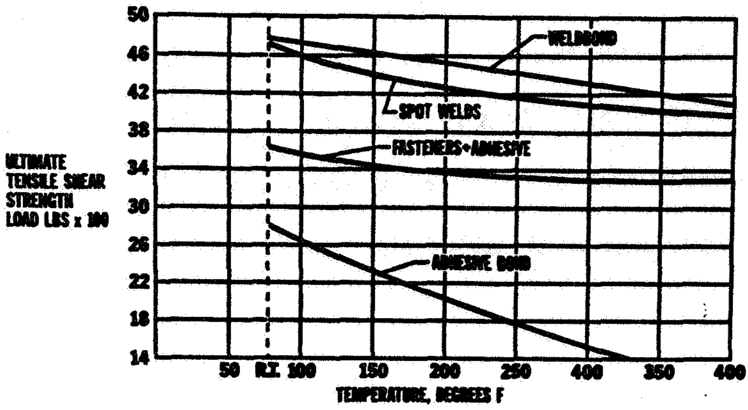


FIGURE 8 - COMPARATIVE JOINT STRENGTH, BUTT SHEAR SINGLE ROW, 0.025" TO 0.063" TITANIUM

Weldbond joints show a superior strength at room temperature in all joint types tested. The double row, and double row multiple spot type joint showed the greatest superiority in weldbond strength as compared to other joining methods.

Spot-welds were inferior only to the weldbond joint at room temperature in all categories tested. Mechanical fasteners plus adhesive showed the third highest strength properties at room temperature in all joint categories except in the single row, 0.045" to 0.063" condition. Structural adhesive bond joints were inferior to all other type joints tested at room temperature.

Weldbond strength at elevated temperatures varied not only with the temperature but also as a function of the type adhesive used and the type of joint design used. As shown in Figure 7 and Figure 8, weldbond joint type double row, multiple spot, exhibited a definite strength superiority from room temperature through 325°F.

Weldbond joints and/or spot-weld joints were superior in strength in all categories from room temperature to 400°F as compared to other joining methods. The structural adhesive bond joints made with EC2214 Hi Flex adhesive lost approximately 50% of their effective strength at 200°F. The structural adhesive bonded joints made with EC3419 retained approximately 50% of their strength at 325°F.

DISCUSSION

High quality resistance spot-welds meeting the requirements of Military Specification MIL-W-6858C were produced when welding through epoxy adhesive on titanium alloys. No special machine modifications were required for weldbonding titanium alloys.

Weldbond joints were produced that were consistently stronger than those of either mechanical fasteners, structural adhesive bonds, or mechanical fasteners with adhesive at the joint interface. Weldbond joints and/or spot weld joints showed superior strength at all temperature ranges as compared to other joints tested.

Adhesives having a strength above 3000 psi at 400°F need to be developed for weldbonding in order to achieve optimum joint efficiency in titanium alloys at elevated temperatures.

The combined peel strength of spot welds and adhesive bond joints was approximately five times greater than that of a bond joint alone.