ABSTRACT

Procedures and alloys suitable for brazing titanium were investigated. Commercial brazing alloys were evaluated by making brazed joints of titanium in a furnace containing an atmosphere of high purity argon. The most satisfactory alloys in this type of brazing were silver and silver base alloys. Joints with shear strengths averaging 15,000 psi were obtained by furnace brazing with the following alloys:

100% silver
85% silver, 15% manganese
45% silver, 15% copper, 16% zinc, 24% cadmium

Brazed joints of titanium were also made with the oxy-actylene torch and a commerical brazing flux. The best alloy found in torch brazing was a 45% silver, 15% copper, 16% zinc, 24% cadmium alloy, which produced shear strengths averaging 13,000 psi.

The strengths of brazed joints in titanium were somewhat lower than that of similar brazed joints of the same alloys in carbon steels. The lower strengths are believed to be associated with the intermetallic compounds which formed at the boundaries between the brazing alloy and titanium. Also, broad zones of diffusion were present at some of the boundaries. Some of the intermetallic compounds appeared to be brittle. Silver and the 85% silver-15% manganese alloy were the only brazing alloys that produced joints exhibiting some ductility.

In order to reduce compound formation and diffusion, a few preliminary tests were made using shorter brazing cycles. This was accomplished with induction, resistance, and shielded carbon-arc brazing methods. These tests indicated that the formation of intermetallic compounds can be reduced by using shorter heating cycles. This phase of the investigation will be covered in more detail in a second report.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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WADC TECHNICAL REPORT 52-313, PART 1

BRAZING TITANIUM TO TITANIUM AND TO MILD AND STAINLESS STEELS

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FOREWORD

This report was prepared by the Battelle Memorial Institute on Contract No. AF 33(038)-23338. The contract was initiated under Research and Development Order No. 615-20, "Welding, Brazing and Soldering of Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Major R. E. Bowman and Dr. H. K. Adenstedt acting as project engineers. This report covers the research accomplished during the year ending 21 June 1952. Another report will be prepared for the year ending 21 June 1953.

Brazing Titanium to Titanium and to Mild and Stainless Steels

INTRODUCTION

Titanium and its alloys are assuming an important place in aircraft structures. In using these materials, it is anticipated that brazed joints will often be needed. Recognizing this situation, the Wright Air Development Center authorized this investigation of the brazing of titanium.

The broad objective of the investigation was to evaluate commercially available alloys and to develop new alloys for use in joining titanium to titanium, to mild steel, and to stainless steel. The investigation was conducted through the period from June 21, 1951, to June 21, 1952.

Titanium was successfully brazed with several alloys in a controlled-atmosphere furnace in high-purity argon. It was also brazed with an oxyacetylene torch using a commercial brazing flux. Other brazing methods investigated were resistance, induction, and inert-gas-shielded carbon arc. Good results were obtained on a limited number of preliminary tests with these three methods.

A series of experimental titanium-base alloys and modified commercial alloys was prepared and tested. The melting points of the titanium-base alloys were all above 2000 F, which is too high for good results with slow-brazing cycles of furnace and torch brazing.

During the next contract period, attempts will be made to improve brazing methods and techniques, to improve the quality of brazed joints. Emphasis will be placed on shortening the brazing cycle to a minimum to reduce the formation of intermetallic compounds in the brazed joints. Induction and resistance brazing will be explored. Design of brazed joints will be studied to improve strength.

This report describes the evaluation of various commercial brazing alloys, the brazing equipment and procedures used, metallographic studies of brazed joints, and results obtained in brazing tests. Studies of experimental alloys and fluxes are also discussed.

SUMMARY

The commercially pure Process A titanium used in the brazing studies was melted, forged, rolled, annealed, and pickled at Battelle. This material was used to make single-lap brazed joints of titanium to

titanium, titanium to stainless steel, and titanium to mild steel, using alloys selected from a survey of commercial brazing alloys. This brazing was done in argon in a controlled-atmosphere retort. Some tests were also made by torch brazing using a commercial flux. Double-lap-joint specimens were furnace brazed in an inert atmosphere and torch brazed using five selected alloys which had produced the strongest joints in this preliminary study.

Each alloy selected from the preliminary study was used to braze five specimens of each combination of titanium to titanium, titanium to mild steel, and titanium to stainless steel. These specimens were tested in a tension machine to determine whether their strengths were consistent throughout each series of five tests. In general, furnace-brazed specimens had higher strengths and showed greater consistency than specimens torch brazed with the same alloys. The tests show that pure silver, an 85 per cent silver - 15 per cent manganese alloy, and a 45 per cent silver - 15 per cent copper - 16 per cent zinc - 24 per cent cadmium alloy produced shear strengths averaging 15,000 psi in furnace brazing titanium. The best alloy found in torch brazing was a 45 per cent silver - 15 per cent copper - 16 per cent zinc - 24 per cent cadmium alloy, which produced shear strengths averaging 13,000 psi. The only joints that exhibited ductility were those made in the furnace using pure silver and an alloy of 85 per cent silver and 15 per cent manganese.

A few preliminary tests were made using induction, resistance, and shielded carbon-arc brazing methods. Joints made with these different methods show that greater strengths can be obtained because of the shorter brazing cycles. The shorter brazing cycle prevents dilution of the brazing alloy and formation of intermetallic compounds.

Tests were made with a series of experimental fluxes. Results show that none of the mixtures performed as well as one commercial titanium flux which was used.

A group of titanium-base alloys and modified commercial alloys was arc melted and processed into usable form for brazing tests. Strengths obtained in testing joints of titanium brazed with the modified commercial alloys were not so high as strengths obtained with the best commercial alloys. A single-lap joint in titanium was furnace brazed at 2270 F with an alloy of 75 per cent titanium, 15 per cent manganese, and 10 per cent nickel. In testing, the specimen fractured in the base metal, giving a joint strength greater than 18,000 psi.

The unit-area shear strengths of brazed joints in titanium were low compared with the unit-area strengths of brazed joints in carbon steels made with the same alloys. The low strengths are believed to be associated with the formation of intermetallic compounds between the elements of the brazing alloys and titanium. Also, broad zones of diffusion of the alloys with the titanium were present. All of these features indicate that stronger joints can probably be made if the brazing cycle can be shortened to reduce compound formation and diffusion. Attempts will be made in the future to reduce this brazing cycle and to find alloys which do not produce as much intermetallic compound with titanium. At present, the one metal that looks the most promising for brazing titanium is silver. Silver and an alloy of 85 per cent silver and 15 per cent manganese are the only metals that have produced joints exhibiting some ductility.

PREPARATION OF TITANIUM-BASE MATERIAL

The commercially pure Process A titanium used in the brazing studies was prepared at Battelle for two reasons: (1) titanium in rolled sheet was not readily obtainable without considerable delay; and (2) superior-quality titanium sheet is produced under experimental control with no extra cost.

Sponge titanium was arc melted in an arc furnace using a tungsten electrode. The titanium sponge, which had been screened to -1/2 inch +1/8 inch, was added during melting. The melting was done under an atmosphere of 99.93 per cent argon, and the furnace was purged by evacuating before filling with argon.

The titanium ingots were scalped to remove defects before upset forging at 1650 F. Scale present on the titanium forgings was removed by grit blasting.

The forged billets were rolled at 1450 F to 1/4 inch thick and descaled again by grit blasting. The 1/4-inch sheet was rolled to 5 to 10 per cent over the desired thickness of 1/8 inch at 1250 F. This temperature was used to reduce the absorption of nitrogen, oxygen, and hydrogen. The surfaces were cleaned by sandblasting. The titanium sheets were cold rolled to 0.001 inch over the desired finished thickness of 1/8 inch in order to have a smooth-finished surface. The sheets were then annealed in a vacuum at 1250 F and pickled to size.

EVALUATION OF COMMERCIAL BRAZING ALLOYS

Letters were sent to manufacturers and distributors of brazing alloys requesting information on physical properties, chemical compositions, and melting points of their commercial and special alloys. This was done to obtain samples of as many as possible of the available commercial alloys, so that representative alloy types could be selected for experiments on titanium. Information obtained from this survey is compiled in Table 1.

From this list, a group of representative alloys was selected for testing. The alloys selected are marked with an asterisk in Table 1.

Preliminary Evaluation Tests

Since titanium is very active chemically and combines readily with elements of the atmosphere, it was essential that it be efficiently protected from the air during brazing operations. This feature had an important influence in the selection of a brazing procedure for preliminary brazing studies with commercial alloys.

There were no fluxes available at the start of this work that were known to be satisfactory for titanium; therefore, torch brazing was eliminated from the first studies. Brazing in a salt bath and in vacuum were also considered, but brazing in a completely controlled inert-gas atmosphere was used because of several advantages that it offered. By this method, it was believed that brazing could be done under ideal conditions without the need for fluxes. That is, the metals to be joined and the brazing materials could be cleaned, assembled, and brazed in completely controlled inert atmospheres.

A small single-lap joint shown in Figure 1 was used in these tests. The specimens and brazing alloys were cleaned and assembled in a controlled-atmosphere chamber to prevent contact with the air after preparation. They were also placed inside a small stainless steel retort in this chamber, and a positive pressure of high-purity argon was maintained in the retort while they were removed to a small furnace, where the brazing was done. The retorts were made to hold three lap-joint specimens, so that one joint each of titanium to titanium, titanium to stainless, and titanium to mild steel could be brazed with one alloy at once. Accurate temperatures were obtained while brazing by means of a thermocouple which extended into the retort over the specimens. The argon gas used was given a special purification treatment by passing it through anhydrous magnesium perchlorate and over granulated titanium at 1540 F.

In all of the first tests made by this careful procedure using 10 brazing alloys, the alloys wet the surface of the titanium and good brazed bonds were produced. This showed that it was relatively easy to braze titanium under these conditions.

The cleaning and assembling of specimens in the controlled-atmosphere chamber consumed considerable time and was very costly. Therefore, after it was evident that titanium brazed under these conditions, tests were made in which the cleaning and assembling of specimens was done in the air. As soon as the specimens were assembled, they were

TABLE 1. COMMERCIAL BRAZING ALLOYS

Alloy	Chemical Composition, %											Liquidus, F
	Ag	Cu	Zn	Cd	Mn	Sn	P	Si	Ni	Al	Others	
					Binary Alloys							
*1	100	-	-	-	-	-	-	-	-	-	-	1760
*2	72	28	-	-	-	-	-	-	-	-	-	1435
*3	75	-	25	-	-	-	-	-	-	-	-	1345
*4	85	-	-	-	15	-	-	-	-	-	-	1728
					Ag-Cu-Zn Alloys							
*5	5	58	37	-	-	-	-	-	-	-	-	1600
6	9	53	38	-	-	-	-	-	-	-	-	1565
7	10	50	40	-	-	-	-	-	-	-	-	1590
8	15	80	5	-	-	-	-	-	-	-	-	1445
9	20	48	32	-	-	-	-	-	-	-	-	1500
10	20	45	35	-	-	-	-	-	-	-	-	1500
*11	25	52	23	-	-	-	-	-	-	-	-	1595
12	27	40	33	-	-	-	-	-	-	-	-	1430
13	30	38	32	-	-	-	-	-	-	-	-	1410
14	40	36	24	-	-	-	-	-	-	-	-	1445
15	45	30	25	-	-	-	-	-	-	-	-	1370
*16	50	34	16	-	-	-	-	-	-	-	-	1425
17	50	28	22	-	-	-	-	-	-	-	-	1340
*18	60	25	15	-	-	-	-	-	-	-	-	1325
19	65	20	15	-	-	-	-	-	-	-	-	1325
20	67	28	5	-	-	-	-	-	-	-	-	1395
21	70	20	10	-	-	-	-	-	-	-	-	1360
22	72	23	5	-	-	-	-	-	-	-	-	1400
23	75	22	3	-	-	-	-	-	-	-	-	1425
*24	75	20	5	-	-	-	-	-	-	-	-	1425
*25	80	16	4	-	-	-	-	-	-	-	-	1490
					Ag-Cu-Sn Alloys							
*26	7	85	-	-	-	8	-	-	-	-	-	1805
*27	60	30	-	-	-	10	-	-	-	-	-	1325
28	68	27	-	-	-	5	-	-	-	-	-	1400

TABLE 1. (Continued)

	Chemical Composition, %											
Alloy	Ag	Cu	Zn	Cd	Mn	Sn	P	Si	Ni	Al	Others	Liquidus, F
						Ag-Cu-P Alloys						
29	6	87	-	-	-	-	7	-	-	-	-	1350
*30	15	80	-	-	-	-	5	-	-	-	-	1300
31	2	91	-	-	-	-	7	-	-	-	-	1270
						Ag-Cu-Zn-Cd Alloys						
*32	20	45	30	5	-	-	-	-	-	-	-	1500
33	32	34	15	19	-	-	-	-	-	-	-	1390
*34	35	26	21	18	-	-	-	-	-	-	-	1295
35	40	18	15	27	-	-	-	-	-	-	-	1205
*36	45	15	16	24	-	-	-	-	-	-	-	1145
37	50	15	25	10	-	-	-	-	-	-	-	1170
*38	50	16	16	18	-	-	-	-	-	-	-	1175
39	61	22	7	10	-	-	-	-	-	-	-	1335
						Ag-Cu-Zn-Sn Alloys						
40	40	30	28	-	-	2	-	-	-	-	-	1435
*41	56	32	17	-	-	5	-	-	-	-	-	1205
						Ag-Cu-Zn-Ni Alloys						
42	40	30	28	-	-	-	-	-	2	-	-	1435
43	54	40	5	-	-	-	-	-	1	-	-	1470
44	55	31	12	-	-	-	-	-	2	-	-	1355
						Ag-Cu-Mn-Ni Alloys						
*45	65	28	-	-	5	-	-	-	2	-	-	1445
						Ag-Cu-Zn-Cd-Ni Alloys						
*46	50	16	15	16	-	-	-	-	3	-	-	1270

TABLE 1. (Continued)

Alloy	Chemical Composition, %											Liquidus,
	Ag	Cu	Zn	Cd	Mn	Sn	P	Si	Ni	Al	Others	F
Ag-Cu-Zn-Cd-Sn Alloys												
* 47	60	20	7	10	-	3	-	-	-	-	-	1300
Ag-Cu-Zn-Cd-Sn-Pb Alloys												
* 48	45	17	17	20	-	0.5	-	-	-	-	Pb 0.5	1150
Binary Alloys												
* 49	-	100	-	-	-	-	-	-	-	-	-	1981
50	-	99.9	-	-	-	-	0.05	-	-	-	-	1980
51	-	93	-	-	-	-	7	-	-	-	-	1382
52	-	93	-	-	-	-	7	-	-	-	-	1495
53	-	99.65	-	-	-	-	-	0.35	-	-	-	1980
54	-	60	40	-	-	-	-	-	-	-	-	1634
55	-	58.5	41.5	-	-	-	-	-	-	-	-	1623
56	-	75	-	-	-	-	-	-	25	-	-	2207
* 57	-	70	-	-	-	-	-	-	30	-	-	2237
58	-	92	-	-	-	-	-	-	-	8	-	1904
59	1	99	-	-	-	-	-	-	-	-	-	1972
Cu-Zn-Sn Alloys												
60	-	60	39	-	-	0.75	-	-	-	-	-	1625
Cu-Sn-P Alloys												
61	-	95	-	-	-	4	0.25	-	-	-	-	1922
62	-	94.6	-	-	-	4	0.4	-	-	-	-	1922
63	-	92.95	-	-	-	0.05	7	-	-	-	-	1300
64	-	90	-	-	-	8	0.1	-	-	-	-	1830
*65	-	89	-	-	-	11	0.3	-	-	-	-	1832

TABLE 1. (Continued)

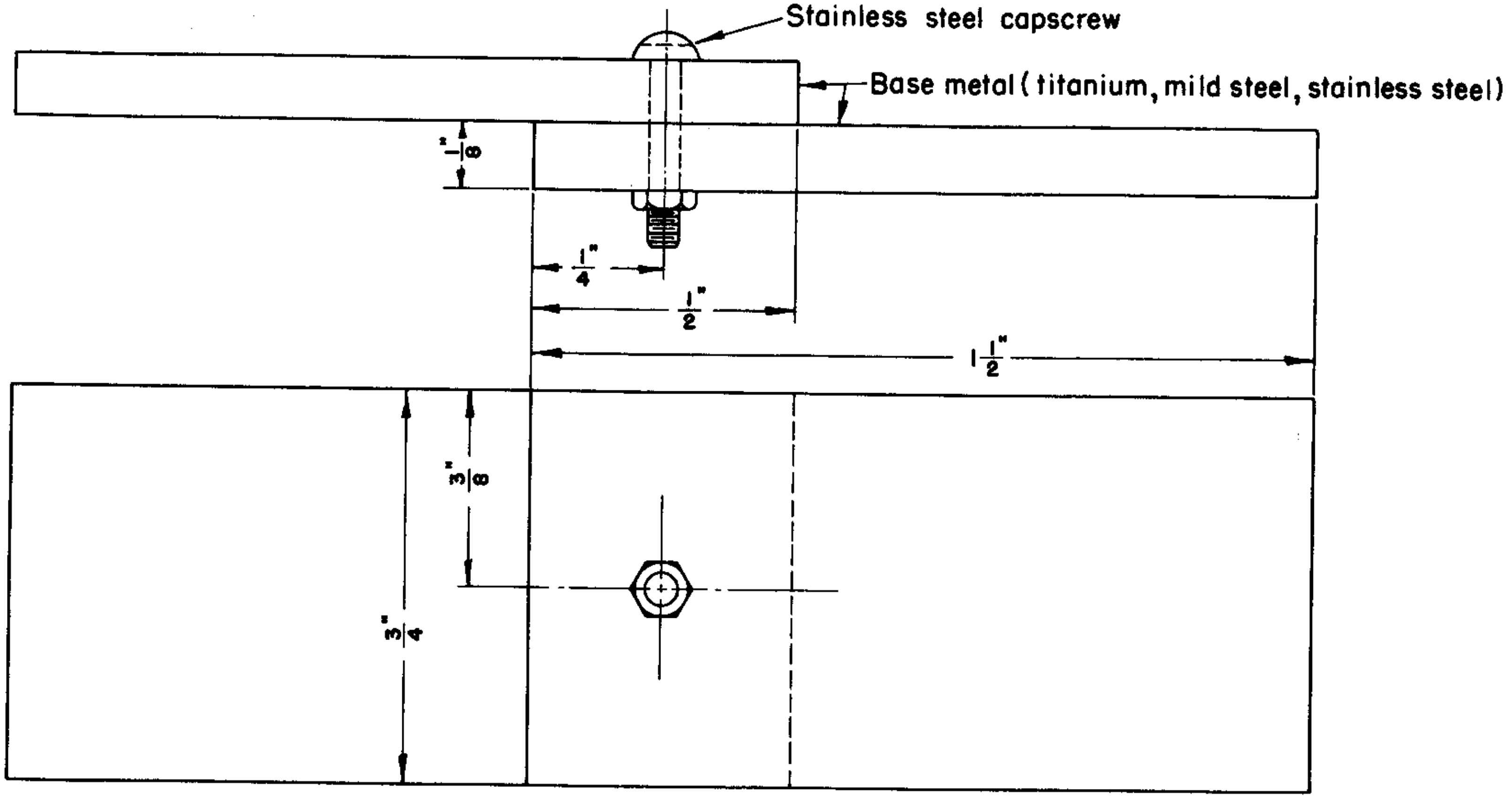
Alloy	Chemical Composition, %											Liquidus, F
	Ag	Cu	Zn	Cd	Mn	Sn	P	Si	Ni	Al	Others	
Cu-Ag-P Alloys												
*66	2	91	-	-	-	-	7	-	-	-	-	1270
Cu-Si-Mn Alloys												
*67	-	96	-	-	-	-	-	3	-	-	Mn 1	1866
Cu-Sn-Fe-Zn Alloys												
*68	-	58	40	-	-	1	-	-	-	-	Fe 1	1650
Cu-Sn-Si-Zn Alloys												
69	-	58	40	-	-	2.4	-	0.25	-	-	-	1590
70	-	59	40	-	-	0.75	-	0.25	-	-	-	1615
Cu-Fe-Si-Zn Alloys												
71	-	59	41	-	-	-	-	0.25	-	-	Fe 0.05	1628
Cu-Zn-Sn-Mn-Fe Alloys												
72	-	59	61	-	0.05	0.75	-	-	-	-	Fe 1	1600
Cu-Ni-Si-Mn-Zn Alloys												
*73	-	48	42	-	0.16	-	-	0.29	10	-	-	1715
Cu-Ni-Si-P-Zn Alloys												
74	-	49	41	-	-	-	0.02	0.1	10	-	-	1706

TABLE 1. (Continued)

Alloy	Chemical Composition, %											Liquidus, F
	Ag	Cu	Zn	Cd	Mn	Sn	P	Si	Ni	Al	Others	
Cu-Sn-Pb-Fe-Zn Alloys												
75	-	49-52	Bal.	-	-	3-4	-	-	-	-	Fe 1 Pb 0.5	1620
Cu-Mn-Si-Sn-Fe-Zn Alloys												
76	-	59	39	-	0.03	1	-	0.1	-	-	Fe 1	1620
77	-	59	38	-	0.3	0.8	-	0.25	-	-	Fe 0.35	1620
78	-	58	39	-	0.03	0.9	-	0.29	-	-	Fe 1	1600

Miscellaneous Alloys

* 79	Ni 61 Mn 30 Ag 9	2000
* 80	Ni 72 Mn 23 Ag 5	2100
81	Ni 78 Cr 18 B 4	2100
* 82	Mg 88 Al 10 Mn 0.1 Zn 1.2 Si 0.3	
83	Cd 95 Ag 5	740
84	Al 86 Si 12 Fe 0.8 Zn 0.2 Cu 0.3 Mg 0.1 Mn 0.15	
85	Pure Nickel	1050
* 86	Pure Aluminum	
* 87	Pure Tin	
* 88	Pure Cadmium	
* 89	Pure Zinc	
* 90	61S Aluminum	



Scale: 3" = 1"

FIGURE I. ASSEMBLED SPECIMEN BEFORE BRAZING placed in the retorts filled with argon. Results obtained were just as good as from the original procedure, so the rest of the preliminary testing of alloys was done using the second procedure.

After many of the commercial alloys were studied by brazing in an inert-atmosphere furnace, a sample of an experimental flux was obtained and tests with several of the commercial alloys were made by oxyacetylene torch brazing.

The single-lap joints made in this study were tested in tension. After testing, the fractured halves of the specimens were placed together and mounted for metallographic study. The results of tension tests and fracture studies are given in Table 2.

These preliminary studies showed several important points, as follows:

1. Nearly all the alloys wet the titanium and flowed readily over its surface.

2. It was possible to braze titanium to stainless steel and mild steel with several of the alloys.

3. The strongest joints were obtained when titanium was brazed to titanium.

4. Many of the brazing alloys penetrated deep into the grain structure of the titanium.

5. Wide bands containing intermetallic compounds were found in titanium joints made with many of the alloys.

6. Torch brazing could be done with one commercial flux.

7. Torch-brazed joints contained more defects and inclusions than the furnace-brazed joints. These defects often contained flux.

8. The furnace-brazed joints contained voids which were filled with gas.

On the basis of results obtained from these limited tests with various alloys, the five alloys that gave the best results were selected for further studies.

TABLE 2. RESULTS OF TESTS WITH FURNACE- AND TORCH-BRAZED LAP JOINTS

Alloy No.	Chemical Composition, per cent								Titanium(1) Brazed to	Furnace Brazed			Torch Brazed			Alloy No.
	Ag	Cu	Zn	Cd	Mn	Sn	P	Others		Shear Strength, psi	Type(2) of Bond	Location of Fracture	Shear Strength, psi	Type(2) of Bond	Location of Fracture	
1	100	–	–	–	–	–	–	–	Ti	8,580	2	Brazing alloy		Not satisfactorily brazed		1
1	100	–	–	–	–	–	–	–	SS	5,560	3	Bond line, Ti side		Ditto		1
1	100	–	–	–	–	–	–	–	MS	8,300	3	Intermetallic compound		"		1
2	72	28	–	–	–	–	–	–	Ti	6,820	2	Bond line, Ti side	5,630	2	Bond line, Ti side	2
2	72	28	–	–	–	–	–	–	SS	5,260	2	Intermetallic compound	6,350	3	Bond line, SS side	2
2	72	28	–	–	–	–	–	–	MS	4,820	3	Bond line, Ti and MS side	11,290	1	Bond line, MS side	2
3	75	–	25	–	–	–	–	–	Ti	4,250	2	Brazing alloy	8,750	2	Brazing alloy	3
3	75	–	25	–	–	–	–	–	SS	5,090	2	Bond line, SS side		Not satisfactorily brazed		3
3	75	–	25	–	–	–	–	–	MS	Not satisfactorily brazed				Ditto		3
4	85	–	–	–	15	–	–	–	Ti	15,600	3	Brazing alloy	8,750	2	Brazing alloy	4
4	85	–	–	–	15	–	–	–	SS	5,970	3	Bond line, SS side		Not satisfactorily brazed		4
4	85	–	–	–	15	–	–	–	MS	7,380	3	Brazing alloy		Ditto		4
5	5	58	37	–	–	–	–	–	Ti	10,470	2	Brazing alloy		"		5
5	5	58	37	–	–	–	–	–	SS	5,150	3	Bond line, Ti side		"		5
5	5	58	37	–	–	–	–	–	MS	6,220	Not examined			"		5
11	25	53	22	–	–	–	–	–	Ti	5,380	2	Between intermetallic compound and braze		"		11
11	25	53	22	–	–	–	–	–	SS	4,440	3	Brazing alloy		"		11
11	25	53	22	–	–	–	–	–	MS	5,300	Not examined			"		11
16	50	34	16	–	–	–	–	–	Ti	8,960	2	Brazing alloy		"		16
16	50	34	16	–	–	–	–	–	SS	6,880	3	Bond line, SS side	5,680	Not examined		16
16	50	34	16	–	–	–	–	–	MS	5,220	Not examined		5,730	"		16
18	60	25	15	–	–	–	–	–	Ti	5,000	3	Bond line, Ti side	6,240	3	Bond line, Ti side	18
18	60	25	15	–	–	–	–	–	SS	7,080	3	Bond line, SS side	4,595	3	Bond line, SS side	18

TABLE 2. (Continued)

Alloy No.	Chemical Composition, per cent								Titanium$^{(1)}$ Brazed to	Furnace Brazed			Torch Brazed			Alloy No.
	Ag	Cu	Zn	Cd	Mn	Sn	P	Others		Shear Strength, psi	Type$^{(2)}$ of Bond	Location of Fracture	Shear Strength, psi	Type$^{(2)}$ of Bond	Location of Fracture	
18	60	25	15	–	–	–	–	–	MS	5,730	3	Bond line, MS side	4,310	3	Bond line, MS side	18
24	75	20	5	–	–	–	–	–	Ti	4,880	2	Between intermetallic compound and braze	Not satisfactorily brazed			24
24	75	20	5	–	–	–	–	–	SS	4,650	3	Between intermetallic compound and braze	10,320	Not examined		24
24	75	20	5	–	–	–	–	–	MS	4,420	3	Between intermetallic compound and braze	10,110	Ditto		24
25	80	16	4	–	–	–	–	–	Ti	1,487	2	Between intermetallic compound and braze	Not satisfactorily brazed			25
25	80	16	4	–	–	–	–	–	SS	8,000	Not examined			Ditto		25
25	80	16	4	–	–	–	–	–	MS	6,080	2	Bond line, Ti side		"		25
26	7	85	–	–	–	8	–	–	Ti	Broke in base metal	1	Not fractured		"		26
26	7	85	–	–	–	8	–	–	SS	3,260	3	Bond line, SS side	4,760	3	Intermetallic compound	26
26	7	85	–	–	–	8	–	–	MS	1,175	2	Bond line, MS side	7,390	3	Bond line, MS side	26
27	60	30	–	–	–	10	–	–	Ti	8,520	2	Intermetallic compound	Not satisfactorily brazed			27
27	60	30	–	–	–	10	–	–	SS	5,680	3	Bond line, Ti side		Ditto		27
27	60	30	–	–	–	10	–	–	MS	3,400	Not examined			"		27
30	15	80	–	–	–	5	–	–	Ti	5,030	3	Bond line		"		30
30	15	80	–	–	–	5	–	–	SS	3,650	3	Bond line, SS side		"		30
30	15	80	–	–	–	5	–	–	MS	Not satisfactorily brazed				"		30
32	20	45	30	5	–	–	–	–	Ti	9,060	3	Brazing alloy	7,830	3	Brazing alloy	32
32	20	45	30	5	–	–	–	–	SS	3,270	3	Brazing alloy	7,290	3	Bond line, SS side	32
32	20	45	30	5	–	–	–	–	MS	5,550	Not examined		5,800	Not examined		32
34	35	26	21	18	–	–	–	–	Ti	5,680	2	Intermetallic compound	6,380	2	Bond line, Ti side	34

TABLE 2. (Continued)

Alloy	Chemical Composition, per cent								Titanium(1)	Furnace Brazed			Torch Brazed			Alloy
No.	Ag	Cu	Zn	Cd	Mn	Sn	P	Others	Brazed to	Shear Strength, psi	Type(2) of Bond	Location of Fracture	Shear Strength, psi	Type(2) of Bond	Location of Fracture	No.
34	35	26	21	18	–	–	–	–	SS	6,850	3	Bond line, SS side	5,760	3	Bond line, Ti side	34
34	35	26	21	18	–	–	–	–	MS	5,070	3	Bond line, MS side	Not satisfactorily brazed			34
36	45	15	16	24	–	–	–	–	Ti	8,340	2	Intermetallic compound	8,060	2	Brazing alloy	36
36	45	15	16	24	–	–	–	–	SS	5,590	3	Bond line, Ti side	5,260	3	Bond line, SS side	36
36	45	15	16	24	–	–	–	–	MS	10,750	Not examined		10,800	Not examined		36
38	50	16	16	18	–	–	–	–	Ti	8,360	2	Bond line, Ti side	7,500	2	Bond line, Ti side	38
38	50	16	16	18	–	–	–	–	SS	Broke before testing	3	Ditto	5,470	3	Intermetallic compound, titanium side	38
38	50	16	16	18	–	–	–	–	MS	6,250	3	"	750	3	Intermetallic compound, titanium side	38
41	56	32	17	–	–	5	–	–	Ti	7,240	3	"	Not satisfactorily brazed			41
41	56	32	17	–	–	5	–	–	SS	4,650	3	Bond line, Ti and SS side	Ditto			41
41	56	32	17	–	–	5	–	–	MS	4,205	3	Bond line, MS side	"			41
45	65	28	–	–	5	–	–	Ni 2	Ti	4,310	2	Bond line, Ti side	Broke before testing	2	Bond line, Ti side	45
45	65	28	–	–	5	–	–	Ni 2	SS	6,400	3	Bond line, Ti side	7,160	3	Bond line, Ti side	45
45	65	28	–	–	5	–	–	Ni 2	MS	7,170	3	Between intermetallic compound, Ti side, and braze	9,940	3	Intermetallic compound, titanium side	45
46	50	16	15	16	–	–	–	Ni 3	Ti	7,820	2	Brazing alloy	Broke before testing	3	Brazing alloy	46
46	50	16	15	16	–	–	–	Ni 3	SS	4,820	3	Bond line, SS side	Broke before testing	3	Bond line, SS side	46
46	50	16	15	16	–	–	–	Ni 3	MS	5,890	1	Bond line, Ti side	Not satisfactorily brazed			46
47	60	20	7	10	–	3	–	–	Ti	4,160	2	Bond line, Ti side	Ditto			47
47	60	20	7	10	–	3	–	–	SS	4,880	3	Brazing alloy	"			47
47	60	20	7	10	–	3	–	–	MS	6,150	3	Bond line, Ti side	"			47

TABLE 2. (Continued)

Alloy No.	Chemical Composition, per cent								Titanium[(1)] Brazed to	Furnace Brazed			Torch Brazed			Alloy No.
	Ag	Cu	Zn	Cd	Mn	Sn	P	Others		Shear Strength, psi	Type[(2)] of Bond	Location of Fracture	Shear Strength, psi	Type[(2)] of Bond	Location of Fracture	
48	45	17	17	20	–	0.5	–	Pb 0.5	Ti	11,260	2	Between intermetallic compound, Ti side, and braze	Not satisfactorily brazed			48
48	45	17	17	20	–	0.5	–	Pb 0.5	SS	5,610	3	Bond line, Ti side		Ditto		48
48	45	17	17	20	–	0.5	–	Pb 0.5	MS	6,310	Not examined		8,800	Not examined		48
49	–	100	–	–	–	–	–	–	Ti	8,070	1	Bond line, Ti side	Not satisfactorily brazed			49
49	–	100	–	–	–	–	–	–	SS	4,900	3	Bond line, SS side		Ditto		49
49	–	100	–	–	–	–	–	–	MS	9,900	3	Between intermetallic compound, Ti side, and braze		"		49
57	–	70	–	–	–	–	–	Ni 30	Ti	4,860	Not examined			"		57
57	–	70	–	–	–	–	–	Ni 30	SS	4,000		Ditto		"		57
57	–	70	–	–	–	–	–	Ni 30	MS	Broke before testing		"		"		57
58	–	92	–	–	–	–	–	Al 8	Ti	Broke before testing	2	Brazing alloy		"		58
58	–	92	–	–	–	–	–	Al 8	SS	Broke before testing	3	Bond line, SS side		"		58
58	–	92	–	–	–	–	–	Al 8	MS	Broke before testing	3	Bond line, MS side		"		58
65	–	89	–	–	–	11	0.3	–	Ti	4,640	2	Between intermetallic compound and braze	6,450	2	Brazing alloy	65
65	–	89	–	–	–	11	0.3	–	SS	4,360	3	Bond line, SS side	7,240	3	Bond line, SS side	65
65	–	89	–	–	–	11	0.3	–	MS	4,680	1	Bond line, MS side	5,420	Not examined		65
67	–	96	–	–	1	–	–	Si -3	Ti	2,890	2	Between intermetallic compound and braze	Not satisfactorily brazed			67
67	–	96	–	–	1	–	–	Si -3	SS	4,350	3	Between intermetallic compound, Ti side, and braze		Ditto		67
67	–	96	–	–	1	–	–	Si -3	MS	4,590	Not examined			"		67
68	–	58	40	–	–	1	–	Fe -1	Ti	8,540	1	Brazing alloy		"		68
68	–	58	40	–	–	1	–	Fe -1	SS	3,750	3	Bond line, SS side		"		68
68	–	58	40	–	–	1	–	Fe -1	MS	3,730	2	Intermetallic compound MS side		"		68
73	–	58	40	–	0.03	0.9	–	Fe -1	Ti	3,695	Not examined		8,580	Not examined		73
73	–	58	40	–	0.03	0.9	–	Fe -1	SS	2,265	Not examined		4,960	Ditto		73
73	–	58	40	–	0.03	0.9	–	Fe -1	MS	Not satisfactorily brazed			4,820	"		73

(1) Ti = titanium, SS = stainless steel, MS = mild steel.

(2) Numbers refer to 3 different types of bonds:
a Brazing alloy penetrated into grain boundaries of base metal;
b Alloying accompanied by formation of intermetallic compounds;
c Sharply defined boundary between braze and base metal.

Tests With Selected Alloys

From the results shown in Table 2, five alloys were selected to be used in a series of brazing tests to determine: (1) consistency of strengths in joints produced with the selected alloys; and (2) comparative strengths of furnace- and torch-brazed specimens. Alloys Nos. 4, 16, 36, 45, and 48 were selected for these tests. The compositions of the alloys are as follows:

Alloy Number	Chemical Composition, per cent						
	Ag	Cu	Zn	Cd	Mn	Sn	Others
4	85	-	-	-	15	-	-
16	50	34	16	-	-	-	-
36	45	15	16	24	-	-	-
45	65	28	-	-	5	-	Ni 2.0
48	45	17	17	20	-	0.5	Pb 0.5

Five tests were made with each of these alloys with each combination: titanium brazed to titanium; titanium brazed to mild steel; and titanium brazed to stainless steel. It was realized that these alloys were selected on the basis of limited data, since only a few tests were made with each alloy in each combination of titanium to titanium, titanium to mild steel, and titanium to stainless steel in the preliminary studies. Some of the other alloys might well have shown comparable strength properties if additional tests had been made with them. However, it was not practicable to make repeated brazing tests with all of the numerous alloys available.

Furnace-Brazing Tests

In order to have a well-controlled atmosphere during brazing, stainless steel retorts were made to hold the specimens in an electric furnace. In early tests, these were made of 2-1/8-inch-diameter stainless steel tubing in which three specimens, titanium to titanium, titanium to mild steel, and titanium to stainless steel, were brazed at one time. In later tests, the stainless steel retorts were constructed to hold ten specimens. A photograph of this retort is shown in Figure 2. Accurate temperatures were obtained, while brazing, by means of a thermocouple which extended into the retort over the specimens. A positive pressure of extra high-purity argon gas was used in the retort while brazing. Oxygen and moisture in the argon gas were eliminated by passing the gas through anhydrous magnesium perchlorate and over granulated titanium at 1540 F.

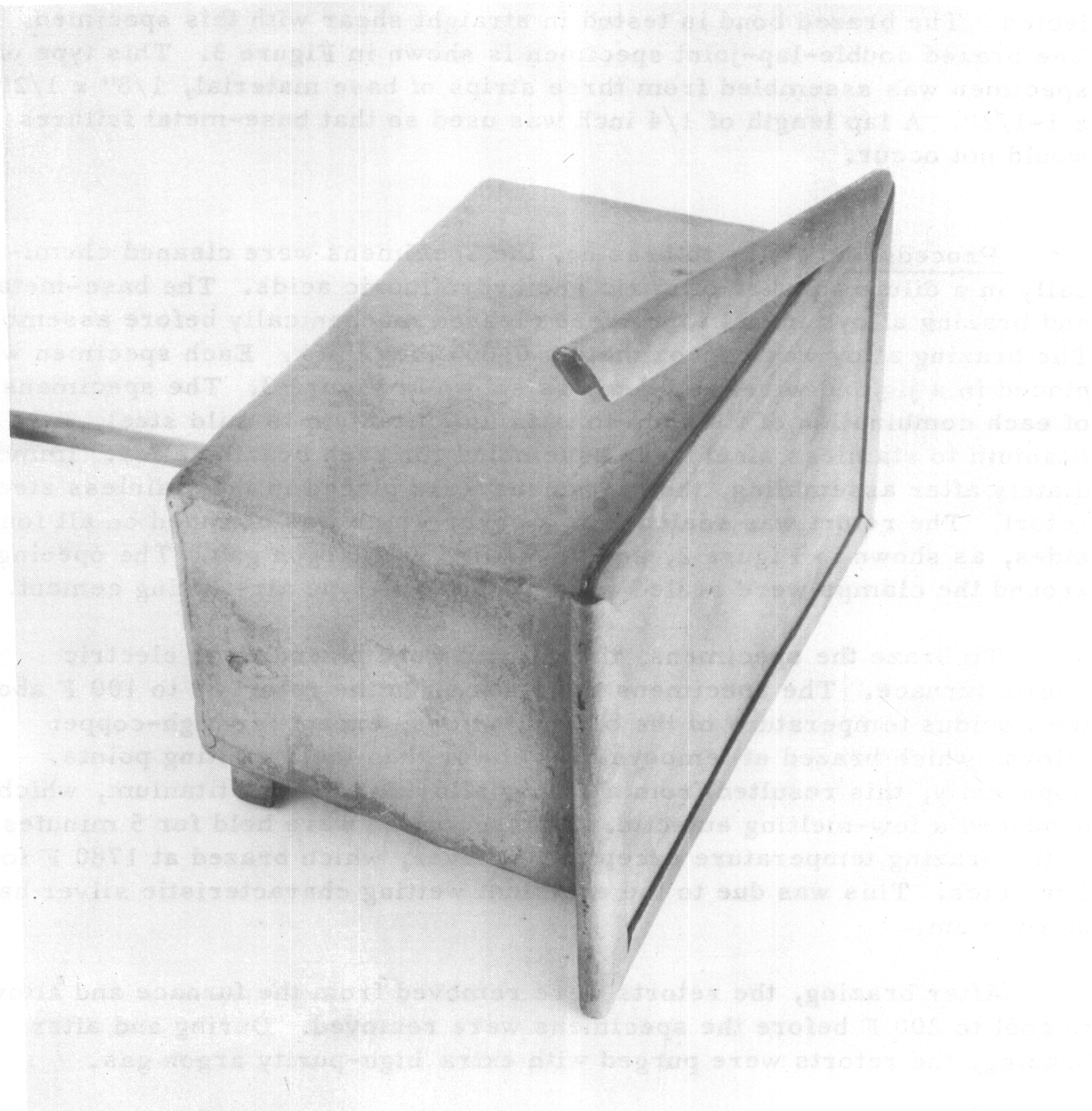


FIGURE 2. RETORT USED IN FURNACE-BRAZING TEST

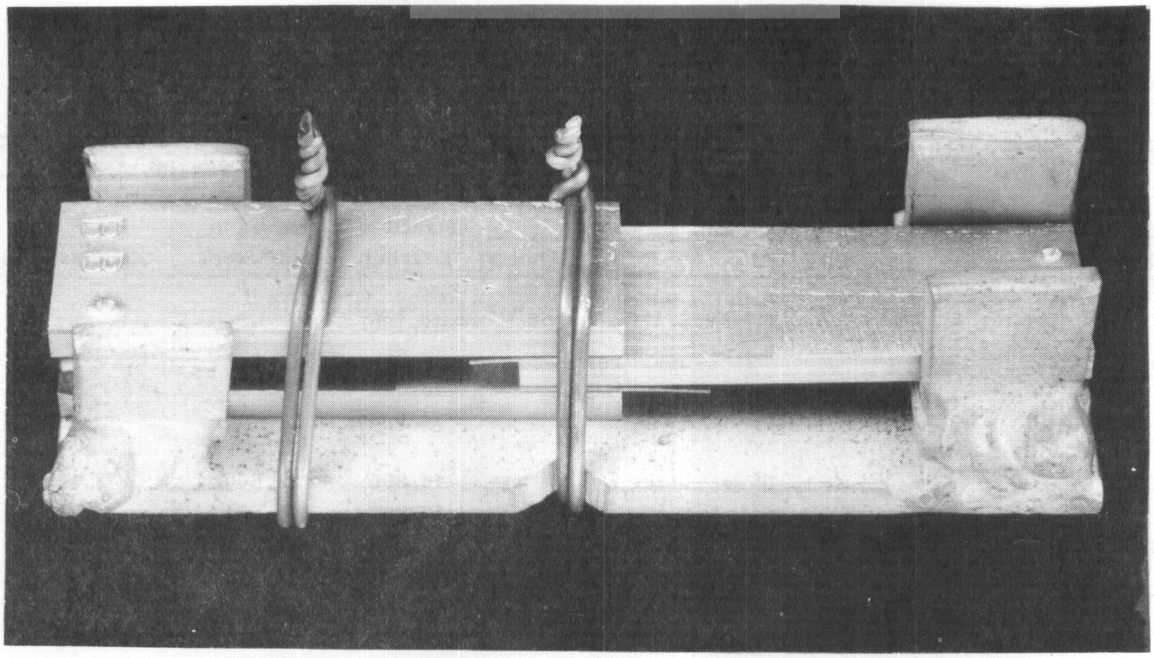
Single-lap-joint specimens were used in the early evaluation tests because of their simplicity and ease of assembly. However, this type of specimen had the disadvantage that the brazed bond was subjected to considerable bending during testing, and therefore was not tested in straight shear. For the consistency tests, a double-lap-joint specimen was selected. The brazed bond is tested in straight shear with this specimen. The brazed double-lap-joint specimen is shown in Figure 3. This type of specimen was assembled from three strips of base material, 1/8" x 1/2" x 1-1/2". A lap length of 1/4 inch was used so that base-metal failures would not occur.

Procedure. Prior to brazing, the specimens were cleaned chemically in a dilute solution of nitric and hydrofluoric acids. The base-metal and brazing alloys in foil form were cleaned mechanically before assembly. The brazing alloy was approximately 0.003 inch thick. Each specimen was placed in a jig and wired in place, as shown in Figure 3. The specimens of each combination of titanium to titanium, titanium to mild steel, and titanium to stainless steel were assembled for each brazing alloy. Immediately after assembling, the specimens were placed in the stainless steel retort. The retort was sealed with a cover which was clamped on all four sides, as shown in Figure 2, and then filled with argon gas. The openings around the clamps were sealed with a porcelain-type air-setting cement.

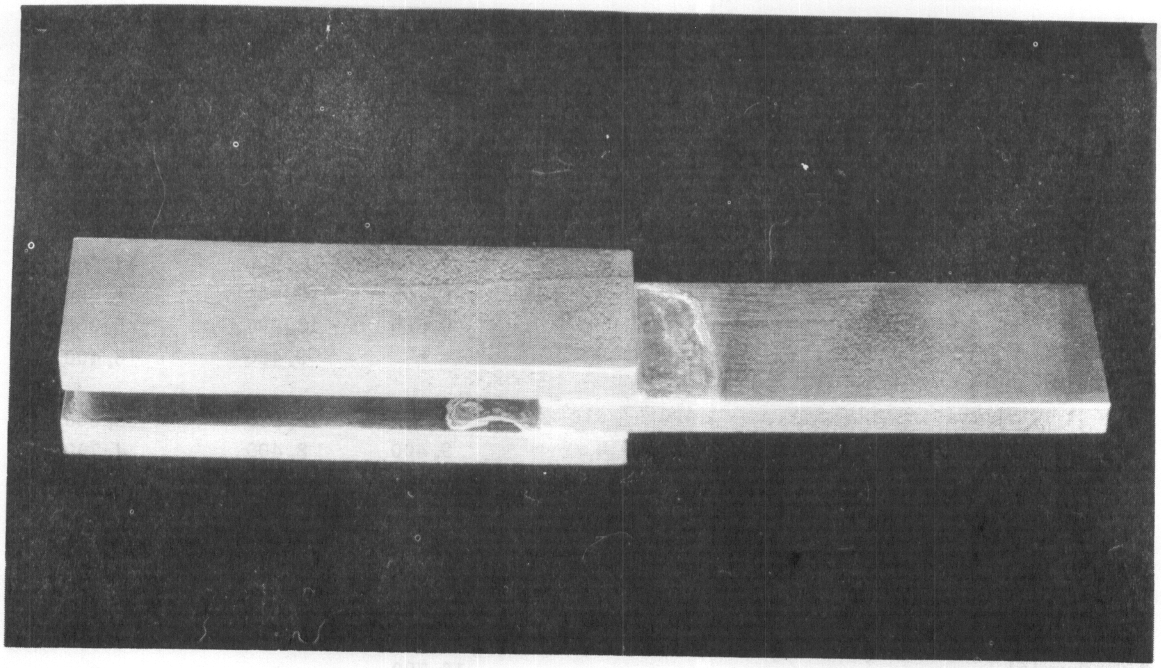
To braze the specimens, the retorts were placed in an electric muffle furnace. The specimens were heated in the retort 50 to 100 F above the liquidus temperature of the brazing alloys, except for high-copper alloys, which brazed at temperatures lower than their melting points. Apparently, this resulted from a strong alloying effect of titanium, which produced a low-melting eutectic. All specimens were held for 5 minutes at the brazing temperature except pure silver, which brazed at 1780 F for 2 minutes. This was due to the excellent wetting characteristic silver has on titanium.

After brazing, the retorts were removed from the furnace and allowed to cool to 200 F before the specimens were removed. During and after brazing, the retorts were purged with extra high-purity argon gas.

Results. The fracture strengths of the brazed specimens were determined by testing in a 5000-pound dynamometer tension machine. Table 3 shows the results obtained from tests with the five selected alloys and additional tests with 61S aluminum and pure silver. Since double-lap joints were tested, the values listed in Table 3 are the strengths in straight shear. The strengths of the brazed joints were fairly consistent. As shown in Table 3, the highest and most consistent joint strengths were obtained with Alloys Nos. 1, 4, and 36.



(A) Assembled in jig before brazing



(B) After brazing

FIGURE 3. DOUBLE-LAP-JOINT SPECIMENS

TABLE 3. RESULTS OF STRENGTH TESTS ON DOUBLE-LAP JOINTS FURNACE BRAZED WITH SELECTED ALLOYS

Alloy No.	Chemical Composition, per cent								Shear Strength, psi		
	Ag	Cu	Zn	Cd	Mn	Sn	P	Others	Titanium Brazed to Titanium	Titanium Brazed to Mild Steel	Titanium Brazed to Stainless Steel
1	100	-	-	-	-	-	-	-	17,100	-	-
									13,300	-	-
									13,300	-	-
									14,000	-	-
4	85	-	-	-	15	-	-	-	14,300	13,800	8,150
									17,200	11,900	4,870
									14,500	11,200	4,330
									14,900	12,000	8,050
									13,400	12,700	4,000
16	50	34	16	-	-	-	-	-	9,400	7,100	5,800
									8,300	7,300	6,700
									7,400	8,100	11,300
									9,400	8,700	10,300
									7,600	6,900	8,200
36	45	15	16	24	-	-	-	-	18,400	15,800	8,200
									15,500	15,000	9,900
									14,700	14,400	5,400
									14,100	16,500	6,800
									13,900	Nil(1)	Nil
45	65	28	-	-	5	-	-	Nil	8,800	12,300	13,300
									7,400	13,700	11,600
									6,100	12,400	8,000
									9,500	13,900	9,900
									-	9,400	6,400
48	45	17	17	20	-	0.5	-	Pb 0.5	15,800	15,200	6,600
									9,400	8,400	4,700
									12,300	10,700	6,000
									12,400	13,000	5,200
									11,200	5,300	Nil
61S Aluminum(2)									10,700	-	-
									14,100	-	-
									16,780	-	-
									11,850	-	-
									11,000	-	-

(1) Specimens broke during handling with little apparent strength.

(2) Nominal composition, per cent: Al - 97.9, Mg - 1, Si - 0.6, Cu - 0.25, Cr - 0.25.

The lowest strengths were obtained in furnace brazing stainless steel to titanium with all of the five alloys. This was expected, since other work has shown that stainless steel is very difficult to braze without a flux. In all cases, furnace-brazed joints produced higher strengths than torch-brazed joints.

Results of metallographic studies showed compounds or alloys formed between the brazing alloys and titanium. A Knoop hardness survey of the joints was made along with the metallographic studies to determine the hardness of these alloys or compounds. Figure 4 shows a joint between titanium furnace brazed with an alloy of 85 per cent silver and 15 per cent manganese with hardness impressions in all zones. It is evident that some of the brazing alloy diffused into the titanium and also the titanium diffused into the layer of brazing alloy.

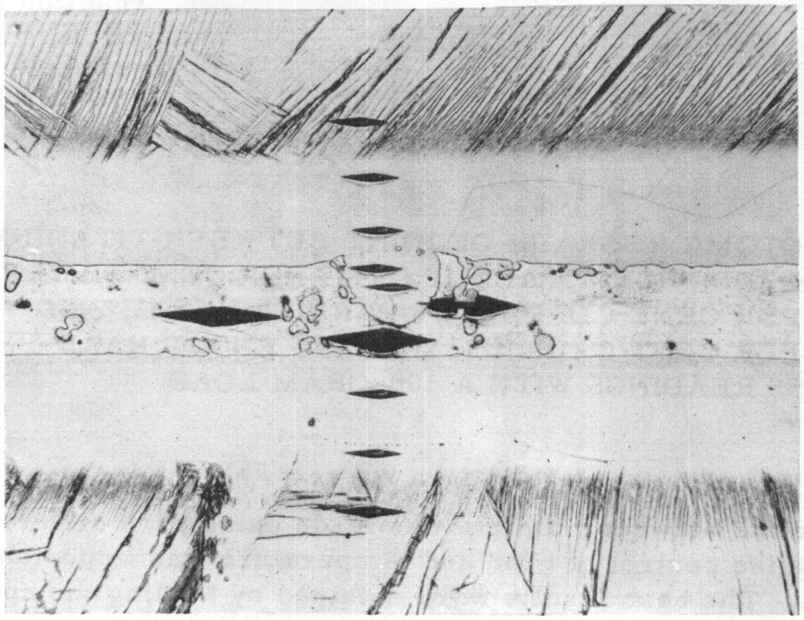


FIGURE 4. PHOTOMICROGRAPH OF JOINT BETWEEN TITANIUM BRAZED WITH AN ALLOY OF 85 PER CENT SILVER AND 15 PER CENT MANGANESE SHOWING KNOOP HARDNESS READINGS WITH A 25-GRAM LOAD

Figure 5 shows a photomicrograph of a joint between titanium brazed with Alloy No. 36 (45 per cent silver, 15 per cent copper, 16 per cent zinc, and 24 per cent cadmium). From the photomicrograph and hardness readings, there appear to be two reaction zones, one of which is hard and would affect the strength of the joint.

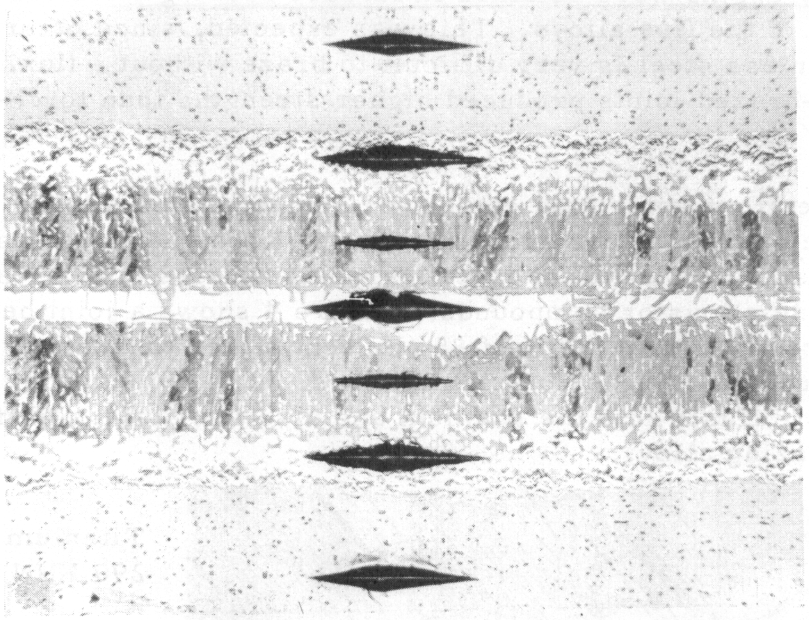


FIGURE 5. PHOTOMICROGRAPH OF JOINT BETWEEN TITANIUM BRAZED WITH AN ALLOY OF 45 PER CENT SILVER, 15 PER CENT COPPER, 16 PER CENT ZINC, AND 24 PER CENT CADMIUM SHOWING KNOOP HARDNESS READINGS WITH A 100-GRAM LOAD

A series of joints between titanium was made using pure silver as a brazing alloy. Precise control of time and temperature was important in these brazing tests. The best results were obtained by holding the specimen two minutes at 1780 F. The results of strength tests show good, consistent results in furnace brazing. Metallographic examination of the joint shows an alloy formed between the silver and the titanium base metal. This zone probably contains intermetallic compounds. Figure 6 shows the joint and fillet produced in brazing.

A Knoop hardness survey was made across the joint brazed with silver, as shown in Figure 7. The reaction zone was found to be approximately twice as hard as the silver zone. The hard zone, which probably decreases the ductility of the joint, may be narrowed with a faster brazing cycle.

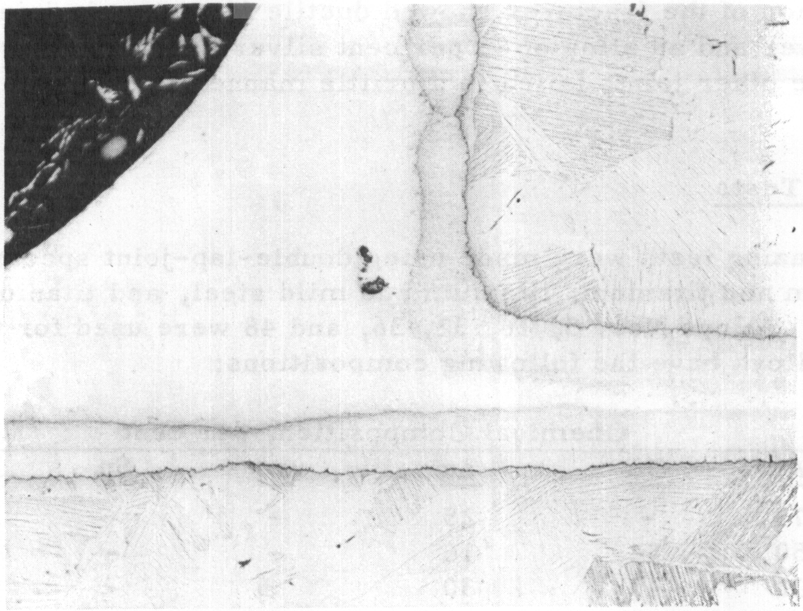


FIGURE 6. PHOTOMICROGRAPH OF A JOINT BETWEEN TITANIUM BRAZED WITH SILVER

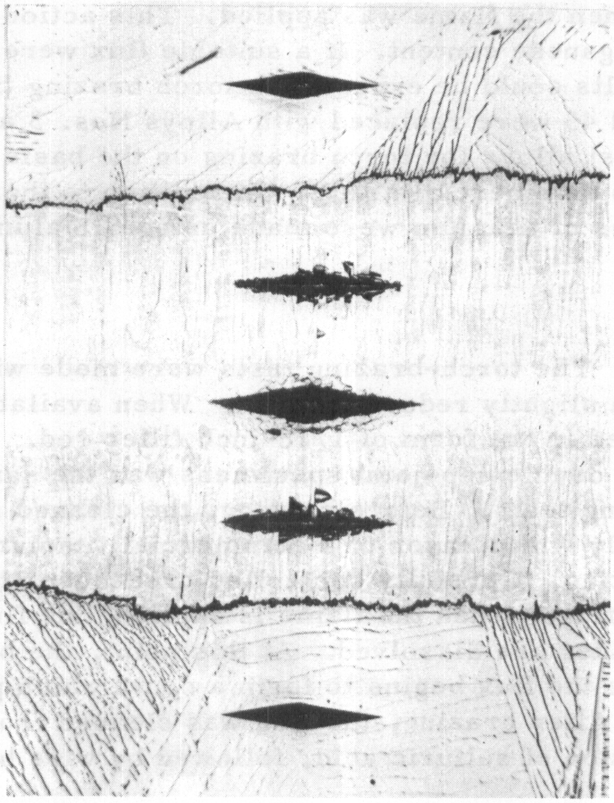


FIGURE 7. PHOTOMICROGRAPH OF A JOINT BETWEEN TITANIUM BRAZED WITH SILVER SHOWING KNOOP HARDNESS READINGS

Examination of the fractures showed ductile fractures in joints brazed with silver and an alloy of 85 per cent silver and 15 per cent manganese. All of the other joints failed in a brittle manner.

Torch-Brazing Tests

Torch-brazing tests were made using double-lap-joint specimens between titanium and titanium, titanium and mild steel, and titanium and stainless steel. Alloys Nos. 3, 16, 32, 36, and 48 were used for these tests. These alloys have the following compositions:

Alloy Number	Chemical Composition, per cent					
	Ag	Cu	Zn	Cd	Sn	Other
3	75	-	25	-	-	-
16	50	34	16	-	-	-
32	20	40	30	5	-	-
36	45	15	16	24	-	-
48	45	17	17	20	0.5	Pb 0.5

Alloys Nos. 4 and 45, which gave good results in the furnace-brazing tests, were not used in the torch-brazing tests, because they appeared to oxidize rapidly when the flame was applied. This action was suspected to be due to the manganese content. If a suitable flux were available for these alloys, good results could be expected in torch brazing titanium with them. Alloys Nos. 4 and 45 were replaced with Alloys Nos. 3 and 32, which were among the five best alloys for torch brazing on the basis of early evaluation tests with various commercial alloys. In addition to these tests, joints between two pieces of titanium were made using 61S aluminum as a brazing alloy.

Procedure. The torch-brazing tests were made with an Oxweld W-29 No. 6 tip, using a slightly reducing flame. When available, the brazing alloys were applied in the form of 1/16-inch filler rod. The cleaning for the 1-1/2" x 1/2" double-lap-joint specimens was the same as that used in the furnace-brazing tests. Before brazing, the cleaned specimens were covered completely with a layer of a commercial titanium flux to limit oxidation during heating. Carefully controlled procedures had to be used in brazing with this flux. When the flame is applied, the flux melts and then turns black as oxides are dissolved. At this point, the brazing rod must be added, because the flux begins to form a crust which prevents satisfactory brazing. After brazing, the flux was cleaned from the specimens with a dilute solution of sulfuric acid, followed by wire brushing.

Results. No difficulties were encountered when brazing titanium to titanium. However, brazed joints between titanium and mild steel, or stainless steel, were difficult to make. When the brazing alloy was applied to these joints, it tended to flow on the mild steel and stainless steel away from the titanium.

Table 4 shows the results obtained in strength tests with the torch-brazing specimens. The combinations of titanium and mild steel or stainless steel had lower strengths and were less consistent in results than straight titanium joints. The strongest joints between titanium and titanium were obtained with Alloys Nos. 3 and 36. On the basis of these tests, Alloy No. 36 appears to be the best all-around alloy for torch brazing. In general, the torch-brazed specimens gave lower strengths in all combinations than did the furnace-brazed specimens. This may have resulted from closer temperature control and better atmospheric shielding in furnace brazing. In addition, flux entrapment in torch-brazed joints reduced the effective bond area.

Examination of the joints pulled in tension showed that they had brittle fractures. This is probably due to the formation of brittle intermetallic compounds and also to the oxygen picked up by the titanium during brazing which diffuses into the alloy.

Figure 8 shows a joint in titanium torch brazed with Alloy No. 36 (45 per cent silver, 15 per cent copper, 16 per cent zinc, and 24 per cent cadmium). The photomicrograph shows the flux inclusions, which have a pronounced effect on the joint strength.

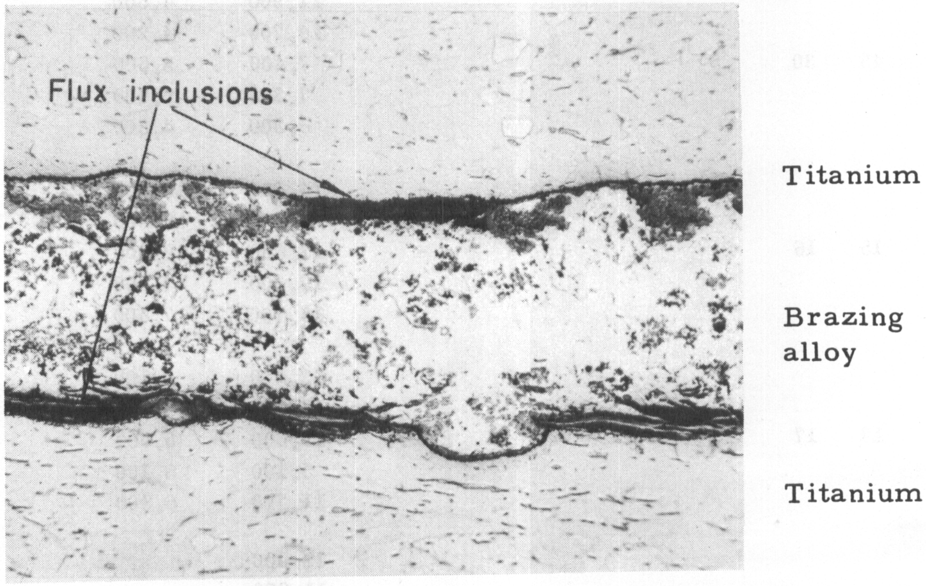


FIGURE 8. PHOTOMICROGRAPH OF A JOINT BETWEEN TITANIUM TORCH BRAZED WITH AN ALLOY OF 45 PER CENT SILVER, 15 PER CENT COPPER, 16 PER CENT ZINC, AND 24 PER CENT CADMIUM

TABLE 4. RESULTS OF STRENGTH TESTS ON DOUBLE-LAP JOINTS TORCH BRAZED WITH SELECTED ALLOYS

Alloy No.	Chemical Composition, per cent								Shear Strength, psi		
	Ag	Cu	Zn	Cd	Mn	Sn	P	Others	Titanium Brazed to Titanium	Titanium Brazed to Mild Steel	Titanium Brazed to Stainless Steel
3	75	-	25	-	-	-	-	-	9,500	9,100	9,100
									12,600	13,900	3,500
									13,100	5,400	10,500
									13,400	9,700	Nil(1)
									9,300	Nil	Nil
16	50	34	16	-	-	-	-	-	8,750	4,300	6,300
									2,900	5,900	10,400
									12,500	Nil	5,300
									7,800	Nil	Nil
									12,100	Nil	Nil
32	20	45	30	5	-	-	-	-	11,900	4,600	4,100
									10,700	4,200	4,400
									7,400	3,600	3,400
									7,300	6,800	4,400
									6,300	4,800	4,300
36	45	15	16	24	-	-	-	-	14,400	13,200	3,500
									13,200	8,600	13,700
									13,600	12,900	5,700
									12,900	3,900	8,000
									15,700	7,600	Nil
48	45	17	17	20	-	0.5	-	Pb 0.5	12,800	9,100	8,700
									4,500	8,900	9,400
									12,000	5,000	9,500
									5,100	5,100	5,000
									11,700	6,800	5,100
61S Aluminum(2)									12,900		
									11,950		
									11,400		
									9,700		
									6,500		

(1) Specimens broke during handling with little apparent strength.

(2) Nominal composition, per cent: Al - 97.9, Mg - 1, Si - 0.6, Cu - 0.25, Cr - 0.25.

Exploration of Other Brazing Methods

Most of this investigation was concentrated on furnace brazing and torch brazing titanium. However, a few tests were made to explore the possibilities of faster brazing processes which would reduce reaction between the titanium and the brazing material. Shorter time at temperature may reduce the extent of formation of brittle intermetallic compounds believed to lower the ductility and strength of the brazed joint. With this thought in mind, a few induction-, resistance-, and carbon-arc-brazing tests were made.

Resistance Brazing. Single-lap joints between titanium were resistance brazed with a Sciaky spot welder using pure silver foil as a brazing alloy. The tests were made in air. Results from only a few tests show higher strengths than were obtained in furnace- or torch-brazing tests. However, these tests were not conclusive, because some of the joints were partially spot welded.

Induction Brazing. One butt joint between titanium was induction brazed with a Tocco unit in a single-turned coil. Titanium pieces in the form of 1/2-inch rounds were used to make the butt joint, and pure silver foil was used as the brazing alloy. The titanium pieces separated by the silver foil were placed in a test tube. During and after brazing, the test tube was purged with welding-grade argon. Visual examination of a cross section of the brazed joint showed a good joint. No other evaluation was made on the joint, but further studies will be made along this line.

Shielded Carbon-Arc Brazing. Single-lap joints between titanium were brazed using the electric-arc method with carbon electrodes shielded with helium. The brazed joints were made using a commercial titanium flux and Alloy No. 36. The brazing action showed good results compared with those using the oxyacetylene method. The carbon-arc heat input is faster, and better wetting of the brazing alloy occurs over the entire fillet, whereas, in the torch-brazing tests, extra manipulation of the torch and rod was necessary for complete wetting. From these studies, it is evident that additional work should be done with faster heating methods for brazing titanium.

EXPERIMENTS WITH BRAZING FLUXES

In the general program of brazing research, a limited amount of work was done on the development of new fluxes. Experimental fluxes were prepared by using varying compositions of fluorides and chlorides. All tests were made with the experimental mixtures on titanium using Alloy No. 36 as the brazing alloy. The brazing procedure used was described in the torch-brazing section of this report.

Table 5 summarizes results of the experimental fluxes in the brazing tests. The results cannot be considered conclusive in that they represent tests on one type of brazing alloy. A mixture of 22 per cent lithium chloride, 48 per cent sodium chloride, and 30 per cent magnesium chloride dissolved in methyl alcohol gave the best results of the experimental mixtures tried, but did not perform as well as the commercial titanium flux.

TABLE 5. RESULTS OF EXPERIMENTAL FLUXES ON TITANIUM

Composition, per cent								Performance
LiF	LiCl	NaCl	$MgCl_2$	KF	NaF	Others	Solvent	
25	75	-	-	-	-	-	H_2O	Poor, no wetting
-	-	48	52	-	-	-	H_2O	Poor, did not remove oxides
2	-	47	51	-	-	-	"	Poor, balls up and rolls off
31	-	-	-	69	-	-	"	Poor, black crust forms
29	-	-	-	61	10	-	"	Poor, black crust forms
-	-	52	48	-	-	-	"	Fair, lacked wetting on upper fillet
20	-	40	40	-	-	-	"	Fair, lacked wetting on upper fillet
40	-	40	20	-	-	-	"	Fair, lacked wetting on upper fillet
40	-	20	40	-	-	-	"	Fair, lacked wetting on upper fillet
20	-	20	60	-	-	-	"	Poor, heavy fuming
40	-	50	10	-	-	-	"	Fair, pulls away from heated zone
40	-	45	15	-	-	-	"	Fair, pulls away from heated zone
-	22	48	30	-	-	-	"	Good, does not wet when first applied
-	22	48	30	-	-	-	CH_3OH	Good, best wetting of all tried
-	70	-	30	-	-	-	CH_3OH	Fair, lacked wetting action

The joints produced using the experimental flux contained large flux inclusions. These inclusions were believed to be caused by the sodium chloride in the mixture. A test was made with a mixture of 70 per cent lithium chloride and 30 per cent magnesium chloride. The results showed that the same types of inclusion were present. It is believed that the inclusions are caused by the magnesium chloride.

DEVELOPMENT OF EXPERIMENTAL ALLOYS

One of the objectives of this investigation was to develop alloys for brazing titanium. Special experimental titanium-base alloys were prepared for brazing titanium in an attempt to obtain joints with higher strength and better corrosion resistance than were obtained with commercial alloys. These alloys were selected on the basis of their melting points and mechanical properties. Some commercial alloys were also modified and studied.

Titanium-Base Alloys

From the standpoint of avoiding contamination and excessive grain growth of commercially pure titanium, the maximum brazing temperature should not exceed 2000 F. The only single-alloy additions that lower the melting point of titanium below 2000 F are iron, copper, and nickel. However, titanium-base alloys containing these elements are brittle at percentages below the eutectic compositions, and cannot be hot worked beyond compositions corresponding roughly to two-thirds of the maximum of the beta-solubility limit. In these composition ranges, the solidus temperatures for binary-alloy systems are all above 2000 F. Therefore, to our knowledge, there is no single alloying element which will reduce the melting point of titanium below 2000 F and still maintain good ductility. Ternary alloys of titanium may have lower melting points than any of the binary alloys, and also show high ductility. With these points in mind, the melts listed in Table 6 were made.

TABLE 6. COMPOSITIONS OF TITANIUM-BASE ALLOYS

Alloy No.	Chemical Composition, per cent							Melting Point, F
	Ti	Mn	Fe	Cu	Ni	Si	Ag	
90	85	15	-	-	-	-	-	2600
91	80	15	5	-	-	-	-	2570
92	75	15	10	-	-	-	-	2280
93	80	15	-	5	-	-	-	2550
94	75	15	-	10	-	-	-	2350
95	80	15	-	-	5	-	-	2460
96	75	15	-	-	10	-	-	2050
97	82.5	15	-	-	-	2.5	-	2500
98	80	15	-	-	-	5	-	2320
99	80	15	-	-	-	-	5	2530
100	75	15	-	-	-	-	10	2390
101	65	15	-	-	-	-	20	2500

Each alloy was melted in a small arc furnace using the same procedure as described to produce the commercially pure Process A titanium. About 70 grams of each alloy were melted into small button-type ingots.

The alloys were placed in a machined steel casing to prevent oxidation, and the casing was sealed by welding. The steel casing containing the alloy was heated to 1550 F and rolled. An effort was made to roll the alloys to foil (0.003 inch thick), but the inherent brittleness of the alloys prevented rolling below a thickness of 0.020 inch.

Results

A single-lap-joint specimen of titanium was furnace brazed at 2270 F using Alloy No. 96 (75 per cent titanium, 15 per cent manganese, and 10 per cent nickel). The alloy melts at 2050 F, but does not flow at normal brazing temperatures. This is believed to be caused by small amounts of oxides present which make a high-melting-point skin around the brazing alloy and prevent wetting on the base metal.

One joint brazed at 2270 F was tension tested. The fracture occurred in the base metal. Metallographic examination of the joint showed a good brazed bond, with most of the alloy diffused into the base metal. Excessive grain growth occurred in the titanium. A photomicrograph of the joint is shown in Figure 9.

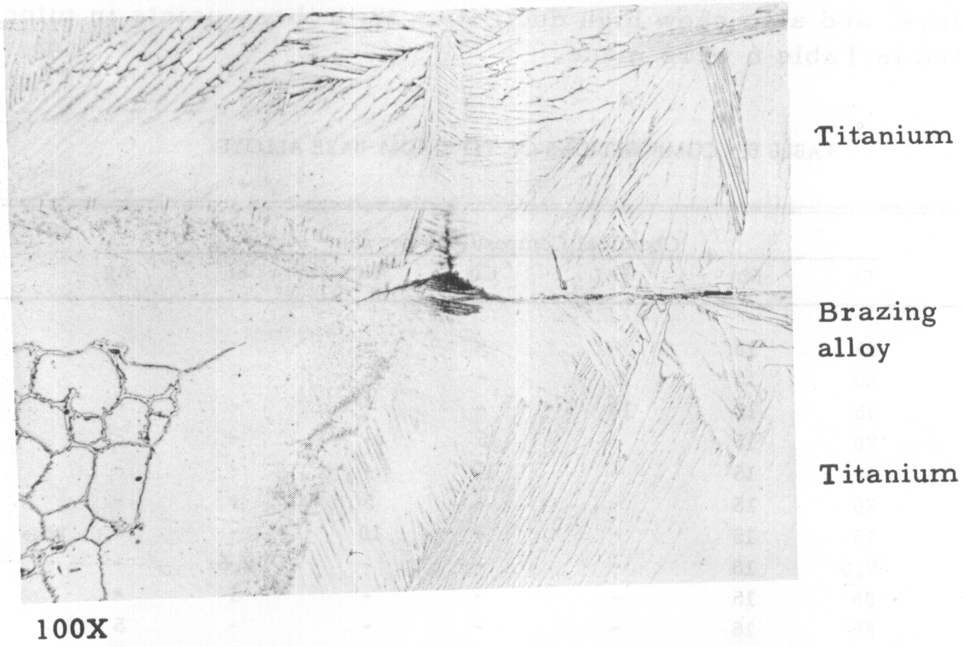


FIGURE 9. PHOTOMICROGRAPH OF A JOINT BETWEEN TITANIUM BRAZED WITH AN ALLOY OF 75 PER CENT TITANIUM, 15 PER CENT MANGANESE, AND 10 PER CENT NICKEL

A modification of Alloy No. 96 was made in an attempt to lower its melting point by adding 5 per cent nickel and to increase its wetting properties by adding 2 per cent palladium. This gave an alloy of 68 per cent titanium, 15 per cent manganese, 15 per cent nickel, and 2 per cent palladium. Melting-point determinations of this alloy were made, and the results showed that the alloy melts at 2175 F. Additional furnace-brazing tests are planned with these alloys at temperatures up to 2400 F. Induction brazing will also be tried with these alloys to speed the brazing cycle to reduce diffusion and grain growth.

Modified Commercial Alloys

Six alloys, in addition to the titanium-base alloys, also were selected for study. These are listed in Table 7. Alloy No. 103 was a modification of Alloy No. 4 (85 per cent silver and 15 per cent manganese). Alloys Nos. 104 and 105 are high-strength alloys which have been used successfully in fabricating stainless steel. Alloys Nos. 106, 107, and 108 are alloys of manganese with copper, nickel, and aluminum, respectively. These were selected because of the good results obtained with manganese-containing alloys in furnace-brazing tests.

TABLE 7. EXPERIMENTAL BRAZING ALLOYS

	Chemical Composition, per cent					Shear
Alloy No.	Mn	Ag	Ni	Cu	Al	Strength, psi
103	20	80	-	-	-	9700
104	30	9	61	-	-	(1)
105	23	5	72	-	-	8800
106	35	-	-	65	-	5250
107	55	-	45	-	-	(1)
108	30	-	-	-	70	4150

(1) A eutectic between titanium and nickel was formed which undercut the base metal.

Results

The results of double-lap joints of titanium brazed with the modified commercial alloys are shown in Table 7. The highest strength was obtained with an alloy of 80 per cent silver and 20 per cent manganese. However, higher strengths were obtained with the commercial alloy containing 85 per cent silver and 15 per cent manganese. Alloys Nos. 104 (30 per cent manganese, 9 per cent silver, and 61 per cent nickel) and 107 (55 per cent manganese and 45 per cent nickel) broke in the base metal during testing. This was caused by an undercut in the base metal made by the eutectic of nickel and titanium.

GENERAL DISCUSSION

The results of work described in this report show that titanium can be brazed to titanium, mild steel, and stainless steel with several commercial brazing alloys by furnace- and torch-brazing methods. The shear strengths of the best joints obtained were from 14,000 to 19,000 psi. This is low compared with the shear strengths of 35,000 to 40,000 psi that are obtained from brazed joints in mild and low-alloy steels. All of the joints were either brittle or exhibited very low ductility, except those made with pure silver or an alloy of 85 per cent silver and 15 per cent manganese. These two brazing materials produced joints with reasonable ductility.

Metallographic studies of the joints gave important clues to the causes of the low shear strength and low ductility. In all of the furnace- and torch-brazed joints, there was evidence of a great amount of diffusion of the titanium into the brazing alloy and elements of the brazing alloy into the titanium. This produced relatively wide hard layers in the brazed joints composed of alloys and intermetallic compounds. These layers undoubtedly had low strength and were brittle, with no capacity to deform and adjust to stresses as load was applied.

On the basis of this evidence, the two obvious methods of improving joint properties are:

1. Speed up the brazing cycle to reduce diffusion and intermetallic-compound layers to a minimum.
2. Select brazing alloys which form a minimum of intermetallic compounds with titanium or produce ductile alloys or ductile intermetallic compounds with titanium.

There is not much possibility of greatly speeding up the cycle of furnace brazing. It might be reduced some over that employed in these tests, but the cycle is certain to be relatively slow. Therefore, the future prospects of improvement in properties of furnace-brazed joints in titanium do not look promising unless the improvement can come from alloy development and possibly by flux improvements.

The brazing cycle used to torch braze the joints studied in this investigation was slow. The technique can be improved and the brazing time can be reduced for the thickness of the materials studied. This would be true in other cases, provided the design of the joints and the thickness of the material being brazed make possible more rapid heating and cooling.

At any rate, it seems reasonable that better properties of torch-brazed joints can be obtained by improved techniques, alloys, and fluxes.

If the above reasoning is correct, then it can be expected that the rapid brazing cycles obtained from resistance and induction methods should produce joints with better properties. It may be possible, in the very rapid brazing cycles, to use brazing alloys that cannot be used to advantage with the slower brazing methods. Also, it may be possible to use alloys with higher melting points, which may have advantages for some applications.

Since all of the joints showed a great amount of diffusion and alloying between the titanium and the brazing alloy, it may be possible to improve brazed joints by first coating the titanium with a barrier layer of some metal. This barrier layer should be a metal that forms a minimum of intermetallic compounds with titanium, or the compounds should have good mechanical properties. If a layer of this kind were used, it would be planned that the brazing alloy would bond to the barrier-metal during the brazing cycle, while that metal would bond by diffusion and alloying to the titanium. It is obvious that careful control of the brazing cycle would be required. The metals that might be used for such a barrier layer are silver, aluminum, tin, molybdenum, columbium, zirconium, vanadium, gold, and tantalum. The barrier layer would be applied by displacement, electrodeposition, dipping, or displacement from molten fluxes. Work with barrier layers will be done in the future.

The metallographic studies of many of the furnace-brazed joints that were made at about 1800 F showed considerable grain growth in the commercially pure titanium. This grain growth may not be detrimental in some applications but would generally be considered to be undesirable. Therefore, it is desirable that brazing alloys for commercially pure titanium should melt at temperatures below 1800 F. The fact that grain growth depends upon time at temperature is another important reason why the brazing cycle should be made as short as possible. If the cycle is sufficiently short, such as in resistance and induction brazing, temperatures higher than 1800 F may not cause much grain growth.

If brazing is considered for joining high-strength titanium-base alloys, then the brazing temperature will need to be lower to prevent damaging the mechanical properties of the base materials. On the basis of present information, the brazing temperature for these materials should not exceed about 1200 to 1300 F, unless very short brazing cycles can be employed. So far, the best results have been obtained with silver-base alloys that require higher brazing temperatures. Therefore, new brazing alloys will need to be developed for the high-strength titanium alloys unless short brazing cycles and higher melting materials can be used successfully.

In the joints described in this report, attempts were made to use from 0.003- to 0.005-inch layers of brazing alloy. Experience on other metals indicates that optimum strength is obtained when joints have about this much brazing alloy. It is quite probable that there is an optimum thickness for braze material in titanium. The above-mentioned thickness may or may not be optimum. Therefore, further work on the design of joints may help to improve mechanical properties.

FUTURE WORK

Future research on brazing titanium will be on the following:

1. Rapid-cycle brazing to reduce alloying and intermetallic-compound formation in the brazed joint and grain growth in base materials.
2. Studies of the use of barrier metals in brazed joints.
3. Improvements in brazing alloys for commercially pure titanium and titanium-base alloys. Alloys with melting points of about 1200 F will be explored.
4. Study of the influence of joint design on strength.
5. Improvement of brazing fluxes.
6. Study of the corrosion properties of brazed joints.

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Data are recorded in Laboratory Notebooks No. 6428, pages 1-78, No. 6931, pages 44-78, and No. 6979, pages 1-8.