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Braze Joint Strength

(Remelt Temperature vs Various Stress Levels and Bend Tests)

by

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ABSTRACT

This report provides a strength evaluation of the braze alloys used to assemble the various components of the linear accelerator under construction at the Los Alamos Scientific Laboratory.

INTRODUCTION

The test results covered by this report compare the joint strength of seven braze alloys used by the furnace brazing production facility at Los Alamos. These comparison tests were performed on copper and stainless steel test bars of the same material grades as used to fabricate accelerator components for the Los Alamos Meson Physics Facility (LAMPF).

Step brazing in a hydrogen gas atmosphere is used in the accelerator fabrication process. High temperature joints are made as high as 1940°F and a few lower temperature joints are made at 1380°F. Several major accelerator components have five separate braze heats; therefore, some understanding of the effects of reheating a brazed joint is important. It is felt by this writer that the data in this report adds important information to the understanding of braze joint behavior at various brazing temperatures.

Anyone contemplating a selection of braze alloys and the use of step brazing methods, involving a brazing furnace, is certain to find the remelt data in this report helpful. It is hoped that the data that follows will provide a degree of guidance in leading a designer's parts through the step braze process without the surprise of having previously attached parts drop off during subsequent heats.

In addition to providing strength vs remelt temperature data, test bars representing each material and alloy were subjected to a bend test at room temperature.

ALLOY SELECTION FOR TESTING

Except for two alloys (82 Au, 18 Ni and 63 Ag, 27 Cu, 10 In), the actual usage assignments of the braze alloys for LAMPF accelerator fabrication appear in a report written by H. G. Worstell.¹ Mr. Worstell based the alloy selection assignments on his successful brazing development studies and prototype work prior to the start of LAMPF accelerator construction. This test report, therefore, is limited to the alloys listed in Mr. Worstell's report plus the two other alloys used in earlier accelerator prototype fabrication.

DESCRIPTION OF TEST BAR BLANKS AND BRAZING METHOD

The blanks were machined from 3/4 in. diam bars of oxygen free copper and from 3/4 in. diam bars of 304L stainless steel. Steps were machined on the parts to allow for the placement of a 1/2 in. diam braze alloy .004 in. thick (two .002 in. thick foil disks were used). Braze surface perpendicularity to the longitudinal centerline and its flatness was controlled to within .001 in. The placing of the alloy foil at the brazing surface of these parts is shown in Fig. 1.

Figure 1

All test bar blanks used in this study were furnace brazed in a dry hydrogen gas atmosphere (dew point lower than -65°F). The method of brazing was patterned after the furnace production practices in use at LAMPF. This method, in brief, uses a steady flow of hydrogen throughout the entire braze cycle and requires a temperature stabilization soaking period at, or slightly below, the liquidus temperature of the alloy. Then, using full furnace power the work load temperature is increased until the brazing temperature is reached. Upon reaching the brazing temperature, the furnace is quickly removed from over the atmosphere retort to allow fast cooling and the solidifying of the braze alloy.

Test bar blanks joined with a particular alloy were brazed at the same time, in the same heat, with materials matched in the following combinations:

1. Stainless Steel to Stainless Steel
2. Copper to Copper
3. Copper to Stainless Steel

MACHINED TEST BARS

After furnace brazing, the test bar blanks were machined to a $3/8$ in. diam reduced section using a template controlled tracer lathe. This machine allowed excellent reproducibility of size and the diameters of all test bars were controlled to within $.001$ in. The machined bars ready for remelt testing are shown in Fig. 2. Standing in the background are test bar blanks prior to machining.

Figure 2

Each test bar was subjected to a proof load test after machining. This test, in the form of a room temperature tensile load, produced a minimum stress of 5000 psi at the braze joint. All test bars used in remelt heats and bend tests were proof loaded to this stress level.

REMELT TEST SET-UP

Four stress levels were used in this test: 0 psi, 10 psi, 50 psi and 100 psi. (This stress range overlaps the stresses encountered in LAMPF step brazing.) The test bars stressed at 100 psi were run with four bars in each heat. The lower stressed test bars were run in groups of three, at each of the stress levels. These groups consisted of the same alloy and material combinations, such as all copper to copper, all copper to stainless steel, or all stainless steel to stainless steel. An actual test set-up is shown in Fig. 3.

Figure 3

As shown in the above figure, each bar was suspended from a plate by a 1/4 in. diam Monel rod passing horizontally through a hole in the test bar. The plate is supported on a pedestal, which is electrically isolated

from this plate, thus permitting the test bars to be monitored for electrical continuity without interference from the pedestal. Conventional Chromel-Alumel thermocouple leads were used for the continuity monitoring. These wires also provided a thermocouple junction for temperature indication in accordance with the "Law of Intermediate Metals"² and was accomplished by attaching the Alumel wire to the upper end of the test bar and the Chromel wire to the lower end of the test bar. A separate combination was used on each of the test bars. After attaching the monitor wires to the test bar, a static load was suspended from the bars, producing the desired stress level at the braze joint. The bar to the right in Fig. 3 shows a wired and stressed arrangement. A temperature monitor bar, to the left in Fig. 3, with conventional thermocouple leads attached, was used only to monitor the temperature during the heating cycle and provided an independent temperature check.

REMELT TEST RUN

A retort (16 in. diam x 24 in. high) was placed over the test bar set-up and after a hydrogen gas cycle with steady gas flow of 20 ft³/hr (dew point lower than - 65°F) was underway, a 14 kW electric furnace was positioned over the retort and the furnace control set point placed at the maximum operating temperature of 2100°F. This permitted the maximum heating rate of the furnace to be maintained throughout the test. The temperature of the test bars was monitored on a strip chart recorder in order to provide a permanent record of the test bar temperature when failure (loss of electrical continuity) of the braze joint occurred. Also, the chart showed the rate of rise and the relative time of failure during the heat cycle. The strip chart recorder printed a temperature indication ten times per minute for each thermocouple junction.

Heating was continued until the recorder strip chart showed a loss of continuity through the remelt test bars. The bar temperature just prior to the first indication of failure was taken as the joint failure temperature at that particular stress level. Upon the completion of the test run, the furnace was removed from over the retort, cooling allowed to take place, and then the test bars were removed and another test set-up was made.

Figure 4 shows the test bar set-up after failure has occurred and just prior to removal of the bars. The failed test bar to the right in this figure was stressed at 50 psi, the bar to the left (0 psi) had no stress other than the weight of the bar itself. It also failed and is resting on a support block. The thermocouple wires are still attached to the separated bars.

Figure 4

The three test bars in Fig. 5 show the braze surface of these bars shortly after removal from the test set-up.

Figure 5

PRESENTATION OF REMELT TEST DATA

A data sheet was made for each of the seven braze alloys. These seven sheets appear at the end of this report. They were prepared using the temperature information from the strip chart recorder run of each heat. A temperature vs time plot was made for each alloy and this plot appears at the top of the appropriate data sheet. Time is shown as minutes before the liquidus temperature of that particular alloy, and in minutes after liquidus temperature of that alloy. Also shown on the plot is a liquidus and a braze temperature line intersecting the temperature-time curve; these two lines are then projected downward.

The vertical liquidus temperature line, labeled L.T., serves as a base line for the three groups of horizontal lines. These horizontal lines, in bar graph form, are used to indicate the failure temperature and time from L.T. that joint failure occurred. Each of the three groups is labeled as to its test bar material combination. Stress levels for each of the test bars appear in the left hand column of the data sheet and the actual failure temperature and time from L.T. appear in the right hand column.

The braze temperature line, labeled B.T., which is projected downward from the temperature-time curve serves as a reference line to indicate how far from actual braze temperature the failure occurred.

A total of 84 remelt test bars were used to compile the results shown on the seven data sheets. The writer's observations of the remelt test data follows the bend test section of this report.

BEND TEST

Samples from each test bar material combination of each braze alloy were bent around a 1-1/4 in. diam rod, with the test bar ends unrestrained, until joint failure occurred or an approximate 45° angle was obtained. If the braze joint showed no sign of failure up to this point, bending was continued without the rod up to 180° or the occurrence of joint failure. Figure 6 shows test bars at a 180° bend angle.

Figure 6

The bar on the left of the above figure, copper to stainless steel, shows a typical shift of the bend radius caused by the large difference in strength between copper and stainless steel. This shift occurred noticeably before the 45° bend angle was reached. The like material bars, copper to copper and stainless steel to stainless steel did not show this radius shift. It is important to note that the radius shift may not have produced the amount of bending stress directly at the braze joint that the like material bar combinations produced just prior to and after the 45° bend angle. The other two bars in Fig. 6 are of like materials.

A comparative tabulation of the bend test data is as follows (based on 42 test bars):

<u>Alloy</u>	<u>Failures Occurred Between the Following Bend Angle*</u>		
	<u>Stainless Steel to Stainless Steel</u>	<u>Copper to Copper</u>	<u>Copper to Stainless Steel</u>
62 Cu, 35 Au 3 Ni	180°**	150°-180°	180°**
50 Au, 50 Cu	180°**	180°**	180°**
82 Au, 18 Ni	110°-180°†	180°**	180°**
60 Au, 20 Ag, 20 Cu	15°-30°	140°-150°†	180°**
71.15 Ag, 28.1 Cu, 0.75 Ni	5°-10°	180°**	30°-60°†
72 Ag, 28 Cu	~ 2°	180°**	20°-40°†
63 Ag, 27 Cu, 10 In	~ 1°	110°-180°†	35°-40°†

* Bend angle as measured from the longitudinal centerline of the bar.

Figure 6 shows a 180° bend angle and Fig. 7 an approximate 20° bend angle.

**No joint failure.

† During the last 5° to 10° of the bend motion, a partial failure occurred at the joint, separating less than 25% of the braze joint area. Figure 7 shows this type of failure.

Figure 7

The above bend test data revealed that alloys with gold and copper or with gold, copper and/or nickel withstood at least a 110° bend on all three test bar material combinations. It also shows that the stainless steel to stainless steel bars joined with braze alloys containing silver, but no gold, appear to be brittle. These joints failed completely at relatively small bend angles and occurred suddenly during the bend test. An examination of the failed surface indicated that failure was caused by braze alloy separation. All copper to copper test bars withstood at least 110° of bend with most of them allowing the full 180° bend. The copper to stainless steel test bars, brazed with alloys that contain gold, allowed 180° of bend. Those brazed with silver braze alloy group showed joint separation prior to reaching a 45° bend angle.

OBSERVATIONS - REMELT TEST

Stainless Steel to Stainless Steel Bars

In every instance the stainless steel to stainless steel unstressed test bars did not fail during the remelt heats. All test bars in this group reached a minimum temperature of 2000°F. A visual examination of the un-separated braze joint area did indicate blush* on the bars joined with braze alloys containing silver. The blush condition also appeared on the stressed test bars that did fail in the group of four braze alloys containing silver. The three other braze alloys made up of only gold and copper, or gold, copper and/or nickel, did not blush significantly. The bars did not stretch or elongate permanently as a result of the remelt test.

An examination of the failure plane on the stressed bars showed no deformation or pitting, and only a smooth, uniformly wetted surface was observed (Fig. 5).

Only one of the seven alloys (82 Au, 18 Ni) withstood all four stress levels above its normal liquidus temperature; the 100 psi stressed bar failing at approximately 20°F below the actual braze temperature of 1820-30°F, the other two stressed bars failed at, or above, the original braze temperature of 1820-30°F. A significant observation is that the other six alloys used to join stainless steel to stainless steel failed below their liquidus temperature at the two highest stress levels (50 psi & 100 psi).

* Blush is defined as the movement of the alloy out of the joint area, not having an apparent thickness, but having a wetted appearance.

Copper to Copper Bars

Failure occurred at the braze joint of all copper to copper test bars. The group brazed with the gold and copper or the gold, copper and/or nickel alloys withstood all four stress levels to within a few degrees of the original alloy braze temperatures. The test bars brazed with the silver group of alloys failed below their respective liquidus temperatures at the 50 psi and 100 psi stress levels. The 0 psi and 10 psi stressed bars failed considerably above their liquidus temperatures. A pattern of blush occurred around the joint area of the bars brazed with silver alloys, and, with one exception, the joint planes were smooth and evenly wetted with braze alloy. The exception was the braze alloy 72 Ag, 28 Cu. These bars showed very large amounts of erosion around the joint area, with the eroded material collecting at the lower end of the test bars. Test bars brazed with alloys containing both gold and copper (62 Cu, 35 Au, 3 Ni and 50 Cu, 50 Au) showed a slightly eroded condition on the joint plane.

There was no change in length detected on any of these remelt test bars.

Copper to Stainless Steel

With two exceptions, these test bars followed the failure pattern of the copper to copper test bars. These exceptions were the 0 psi stress level which did not fail. These were brazed with 63 Ag, 27 Cu, 10 In and with 71.15 Ag, 20.1 Cu, 0.75 Ni. The bars brazed with gold and copper or gold, copper and/or nickel alloys retained their joint strength beyond their liquidus temperatures and to within a few degrees of the original braze temperatures. The four alloys containing silver failed below their liquidus temperatures at the two highest stress levels of 50 psi and 100 psi.

The test bars brazed with the highest temperature alloy (62 Cu, 35 Au, 3 Ni at 1930-40°F) showed a rough, pitted surface on the copper braze plane. The other test bar braze surfaces of this material combination were smooth and evenly wetted.

The lengths of these bars did not change, as noted in the other material combinations.

General

The remelt test bars brazed with four alloys containing silver, and at the two highest stress levels during the remelt heat, failed at the braze joint below their original liquidus temperatures. This occurred on test bars of all three material combinations. Joints brazed with the three alloys containing gold and copper or gold, copper and/or nickel on the copper to copper bars and the copper to stainless steel bars, retained their strength at all four stress levels up to at least a few degrees of their original braze temperatures. The stainless steel to stainless test bars at the two highest stress levels, failed below the liquidus temperature when joined with two of the gold alloys (62 Cu, 35 Au, 3 Ni and 50 Au, 50 Cu). The third gold alloy (82 Au, 18 Ni), withstood all four stress levels, not only beyond its liquidus temperature, but to within a few degrees of its original braze temperature on all three test bar material combinations.

Braze joint areas of the failed test bars were examined after each test run. They indicate that braze alloy separation occurred at the particular failure temperature in every case.

Stress Level - psi

100 -
50 -
10 -
0 -

L.T. B.T.

Failure Temp. &
Time from L.T.

1808°F 19 min. before
1832°F 9 min. before
2000°F 21 min. after
No Failure - Max. 2005°F

Stainless Steel to Stainless Steel

100 -
50 -
10 -
0 -

L.T. B.T.

1927°F 8.5 min. after
1930°F 9 min. after
1940°F 11 min. after
1950°F 13 min. after

Copper to Copper

100 -
50 -
10 -
0 -

L.T. B.T.

1925°F 8 min. after
1936°F 10 min. after
1950°F 12 min. after
1952°F 13 min. after

Copper to Stainless Steel

ALLOY - 62 Cu, 35 Au, 3 Ni

Stress Level - psi

100 -
50 -
10 -
0 -

Failure Temp. & Time from L.T.

1770°F 1.5 min. before
1773°F 1 min. before
1789°F 1 min. after
No Failure - Max. 2015°F

100 -
50 -
10 -
0 -

1898°F 20 min. after
1869°F 14 min. after
1869°F 14 min. after
1921°F 23 min. after

100 -
50 -
10 -
0 -

1826°F 8.5 min. after
1850°F 10 min. after
1868°F 12 min. after
1927°F 21 min. after

ALLOY - 50 Au, 50 Cu

DATA SHEET NO. 3

Stress Level - psi

100 -
50 -
10 -
0 -

L.T.

B.T.

Failure Temp. &
Time from L.T.

1804°F 11 min. after
1825°F 14 min. after
1845°F 17 min. after

No Failure - Max. Temp. 2055°F

Stainless Steel to Stainless Steel

L.T.

B.T.

100 -
50 -
10 -
0 -

1832°F 13 min. after
1832°F 13 min. after
1860°F 18 min. after
1871°F 20 min. after

Copper to Copper

L.T.

B.T.

100 -
50 -
10 -
0 -

1819°F 8.5 min. after
1812°F 8 min. after
1850°F 14 min. after
1882°F 18 min. after

Copper to Stainless Steel

ALLOY - 82 Au, 18 Ni

S.P.K. 12/7/70

Stress Level - psi

100 -

50 -

10 -

0 -

Failure Temp. & Time from L.T.

1543°F 1.5 min. before

1550°F 1 min. before

1563°F 1 min. after

No Failure - Max. 2002°F

100 -

50 -

10 -

0 -

1474°F 8.5 min. before

1505°F 5 min. before

1592 °F 5 min. after

1705°F 19 min. after

100 -

50 -

10 -

0 -

1527°F 3 min. before

1528°F 3 min. before

1575°F 2 min. after

1760°F 24 min. after

ALLOY - 60 Au, 20 Cu, 20 Ag

DATA SHEET NO. 5

17

Stress Level - psi

100 -
50 -
10 -
0 -

Stainless Steel to Stainless Steel

Failure Temp. &
Time from L.T.

1419°F 5.5 min. before
1429°F 4 min. before
1423°F 5 min. before
No failure - Max. 2010°F

100 -
50 -
10 -
0 -

Copper to Copper

1423°F 4.2 min. before
1425°F 4 min. before
1536°F 6 min. after
1853°F 43 min. after

100 -
50 -
10 -
0 -

Copper to Stainless Steel

1429°F 3.5 min. before
1432°F 3.5 min. before
1631°F 22 min. after
No failure - Max. 1900°F

ALLOY - 71.15 Ag, 28.1 Cu, 0.75 Ni

Stress Level - psi

100 -
50 -
10 -
0 -

Stainless Steel to Stainless Steel

Failure Temp. &
Time from L.T.

1416°F 1.2 min. before
1425°F 1 min. before
2000°F 76 min. after
No failure - Max. 2030°F

100 -
50 -
10 -
0 -

Copper to Copper

1418°F 2.2 min. before
1420°F 2 min. before
1460°F 3 min. after
1689°F 26 min. after

100 -
50 -
10 -
0 -

Copper to Stainless Steel

1433°F 1 min. before
1431°F 1 min. before
1431°F 1 min. before
1805°F 47 min. after

ALLOY - 72 Ag, 28 Cu

DATA SHEET NO. 7

19

Stress Level - psi

100 -
50 -
10 -
0 -

Failure Temp. & Time from L.T.

1267°F 6.8 min. before
1315°F 2 min. before
1475°F 12 min. after
No failure - Max. 2000°F

Stainless Steel to Stainless Steel

100 -
50 -
10 -
0 -

1292°F 5 min. before
1309°F 2 min. before
1371°F 3 min. after
1731°F 38 min. after

Copper to Copper

100 -
50 -
10 -
0 -

1325°F 1 min. before
1325°F 1 min. before
1365°F 3 min. after
No failure - Max. 1655°F

Copper to Stainless Steel

ALLOY - 63 Ag, 27 Cu, 10 In

S.P.K. 12/7/70

REFERENCES

- ¹ H. G. Worstell, "Mechanical Engineering 805 MHz Structures," MP-3-44 Internal Report, 8/12/68.
- ² T. G. Beckwith and N. L. Buck, "Mechanical Measurements," Chapter 13, Addison-Wesley Publishing Co., Inc.