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RELATIONSHIPS BETWEEN BRAZING DEFECTS AND BRAZING CONDITIONS

David E. Schillinger

Frankford Arsenal
Philadelphia, Pennsylvania

March 1973

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by

DAVID E. SCHILLINGER

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13. ABSTRACT

The purpose of this work was to examine and define the causes of defects in silver-brazed steel joints, with the ultimate objective of improving the quality of such joints for army applications.

Various conventional and unconventional brazing variables were examined to determine their influence on defect formation. Variables investigated included steel composition, joint clearance, time at brazing temperature, temperature at which filler metal is introduced, orientation of gravitational force, flow path width, filler metal form (foil or wire), and brazing atmosphere.

It was found that all joints made with flux contained large numbers of defects. The use of foil filler metals was the most helpful option in overcoming this problem in that it produced small, regularly shaped defects, whereas capillary flows produced very erratic joint quality, defect size, and defect distribution. Nearly defect-free capillary flows could be achieved in argon atmospheres without fluxes.

It was concluded from these observations that the major cause of defects in the brazed joints was the irregular flow modes produced by the mechanism of flux displacement by filler metal. It is believed that these irregular flow modes are characteristic of the process at its current state of development, and that only revision of the basic system will correct the problems encountered.

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The purpose of this work was to examine and define the causes of defects in silver-brazed steel joints, with the ultimate objective of improving the quality of such joints for army applications.

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INTRODUCTION

The Army, as is the case with other users of brazed joints, has experienced difficulty at times with brazing defects. Both contractor procured and in-house brazed items contain defects that frequently arouse doubt as to the quality of brazed products.

In some items having requirements for a high percentage of bonded area (for example, 85%), defects occur in sufficient degree to cause rejection of items and the usual associated contractual problems. The causes of the defects are not immediately apparent. As a result, various theories are formed and, upon occasion, stopgap experimental programs are set up to try to determine the causes of the difficulty.

Although defects in brazed joints have been recognized as a problem for some time, little scientific attention has actually been given to the problem, probably because the majority of such joints function effectively despite the defects and most applications have been of a noncritical nature. However, in ordnance items, quality brazements are essential.

Probably the most comprehensive and thorough work on defects in brazed joints was done in the 1950's by Bredzs[1] under an Army contract. He was able, for example, to demonstrate that in silver brazing of steel, oxygen diffuses rapidly through the flux and filler metal layers and oxidizes the steel surface. The oxidation of the carbon in the steel produces carbon monoxide bubbles at the steel-brazing alloy interface. This was not shown for actual joints, however, but for molten filler metal layers on steel.

Bredzs also demonstrated that, in hydrogen rich atmospheres, filler metals containing silver and copper can dissolve appreciable amounts of hydrogen. As the filler metal cools toward its freezing point, the solubility of hydrogen decreases and it precipitates out of the liquid metal as bubbles. Bredzs sought to overcome this phenomenon by vacuum melting the filler metals and then brazing in a vacuum. The result of these experiments, however, was that shrinkage voids formed in the filler metal layer. Bredzs then attempted to freeze the brazed joint from the center outward, thus permitting back-filling of shrinkage decrements. This met with some degree of success but was not a practical solution for most real brazing situations.

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[1] N. Bredzs and W. Rostoker, "Fundamentals of Brazing," Armour Research Foundation of the Illinois Institute of Technology (Contract DA-11-022-ORD-975), Final Report, 4 December 1953.

Beyond this point, little study has been given to the causes of defects in brazed joints and, all too often, stock answers such as "unsatisfactory cleaning" are used to rationalize a large variety of phenomena.

In work done under this program[2] prior to that reported here, a number of torch silver-brazed joints were prepared in SAE grade 4340 steel, copper, and a tin bronze. Conclusions drawn at that time were as follows:

1. All brazed joints produced had substantial amounts of defects.

2. The mechanisms responsible for defect formation cannot be generalized, but are peculiar to individual base metal-filler metal-flux systems. Heating methods may also be relevant.

3. Major defects found in silver-brazed steel specimens were frequently involved with flux entrapment.

4. Major defects found in silver-brazed copper were apparently related to changes in filler metal composition and melting point resulting from diffusion and dissolution of base metal.

Other important observations made at that time were that entrapped flux pockets were quite transparent, indicating that saturation of the flux by excessive amounts of oxide was not the probable cause of its entrapment. Additionally, it was observed that vagaries of filler metal flow mode seemed more responsible for the formation of defects than, for example, dewetting phenomena.

This report records further experiments and observations on the causes of defects in silver-brazed steel joints. It contains descriptive material on the experimental setup, the various experiments performed, and the results obtained. Both conventional and unconventional brazing variables were examined.

MATERIALS AND EQUIPMENT

Power for induction heating the brazing specimens was provided by a 20-kilowatt, high frequency, induction heating unit of the electronic tube type.

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[2] D. E. Schillinger, "Defects in Brazed Joints," Frankford Arsenal Status Report, July 1971.

Steel for the specimens was obtained in the form of one-inch bar stock and consisted of the following SAE grades: 1117, 4340, 1021, and AISI 416 stainless steel. Nominal compositions for these steels are shown in Table I.

Filler metal for all experiments was AWS grade BAg-1. This was employed as 0.003 inch thick foil or 0.031 inch diameter wire. The nominal composition of this material is shown in Table II.

Flux used in the experiments was a standard, good quality, commercial silver-brazing flux of AWS type 3A. The composition of such fluxes is not made publicly available by the companies which manufacture them.

METHODS AND PROCEDURES

Induction heating was selected as a heating method because of its speed, observability, and controlled heating rate. Accordingly, a setup employing this heating method was designed and built. A thermocouple recorder-controller was incorporated into the setup to permit establishment and maintenance of preselected temperatures. A bell jar, mechanical vacuum pump, and associated manifolds, valves, and control devices were added to the system to permit vacuum purging of the brazing environment and back-filling with selected gases. The atmosphere system is needle-valve controlled and permits operation of the brazing environment at atmospheric pressure or partial vacuums in flowing or static atmospheres. Figure 1 shows the general arrangement of this equipment. The induction heating power source, bell jar, vacuum pump, and related valves and a recorder-controller may be seen from left to right. A McCleod vacuum gage which was used to monitor vacuum levels in the bell jar, is shown at the bottom of the photo.

Figure 2 shows a more detailed view of the equipment inside the bell jar. From top to bottom may be seen a remote solenoid-operated filler metal release, a quartz filler metal guide tube, and a brazing specimen held inside the induction coil by a spring-loaded fixture which end-loads the specimen at two points. Other items to be seen in the photograph are the power feed-throughs for the solenoid, the thermocouple feed-through to the right, and three ported porcelain crucibles which support and insulate the fixture from the lucite base. The seal ring for the bell jar may also be seen.

It may be noted in Figure 2 that the copper tubing induction coil is actually separated into two major coils, with a decoupled section at the center of the specimen. This is done because of the well-known tendency of induction coils to heat the surface of the work preferentially. By decoupling the coil from the work at the center of the specimen, heating

TABLE I.

Nominal Composition of Steels, SAE Grades

Composition	SAE 1021 (%)	Composition	SAE 1117 (%)
C	0.18 to 0.23	C	0.14 to 0.20
Mn	0.60 to 0.90	Mn	1.00 to 1.30
P	0.040, max	P	0.040, max
S	0.050, max	S	0.08 to 0.13

Composition	SAE 4340 (%)	Composition	AISI 416 Stainless Steel (%)
C	0.38 to 0.43	C	0.15, max
Mn	0.60 to 0.80	Mn	1.25, max
P	0.035, max	Si	1.00, max
S	0.040, max	Cr	12.00 to 14.00
Si	0.20 to 0.35	S	0.15, min
Ni	1.65 to 2.00		
Cr	0.70 to 0.90		
Mo	0.20 to 0.30		

TABLE II.

Nominal Composition of Filler Metal (AWS BAg-1)

Composition	Percentage
Ag	45
Cu	15
Zn	16
Cd	24

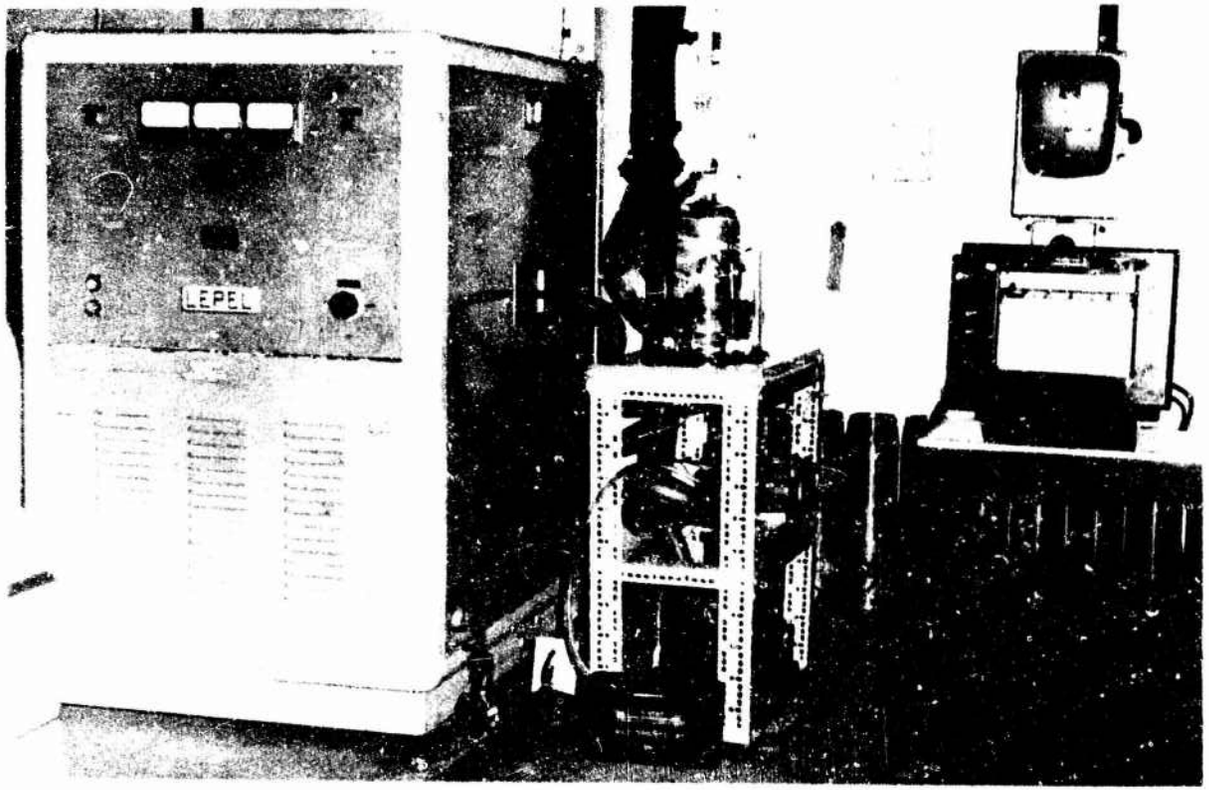


Figure 1. Overall view of Brazing Setup

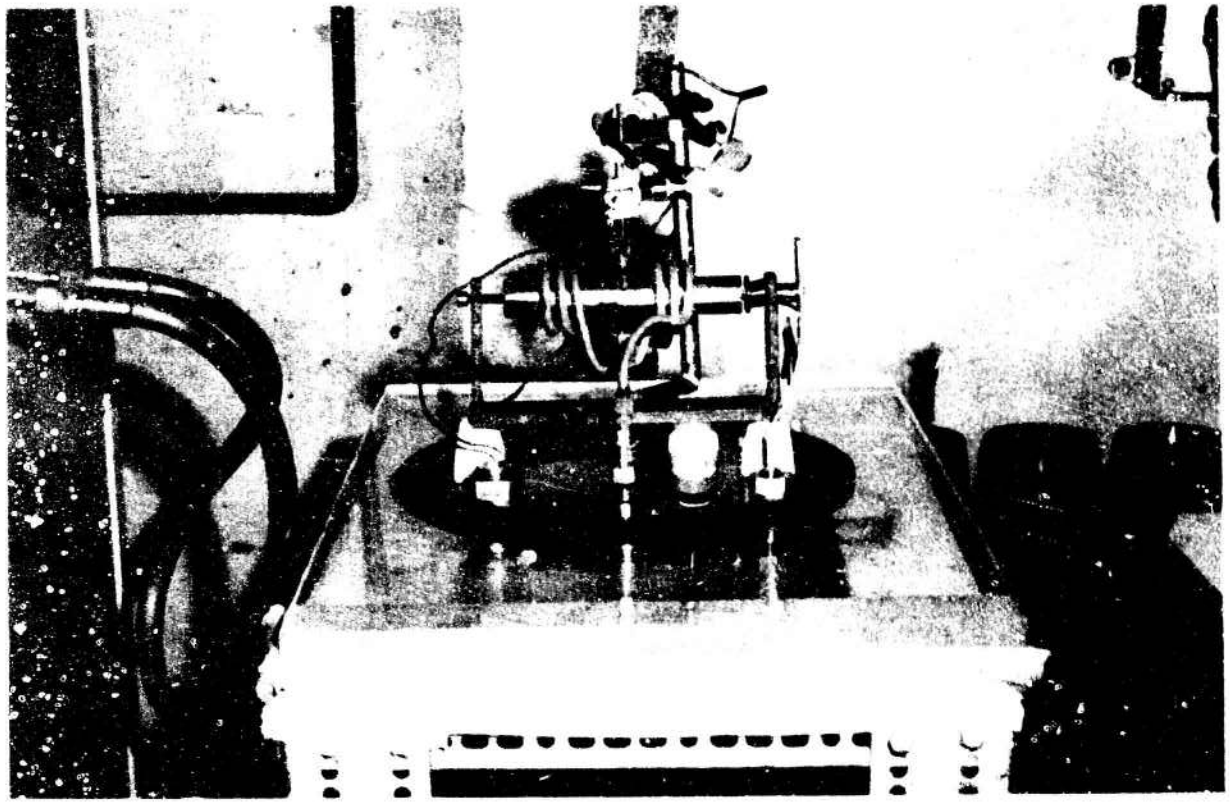


Figure 2. Detailed view of Immediate Brazing Arrangement

at the brazing interface is achieved by conduction from the parts of the specimen immediately within the coils. By judicious spacing of the coils so as to balance conduction into the center of the specimen with radiation losses at the surface of the specimen, even heating of the faying surfaces can be achieved. Experiments to determine this appropriate spacing were carried out by machining a deep groove in a one inch diameter steel bar so that only a small amount of material remained in the center. It was then possible to observe the glowing surfaces in a darkened room and thus detect uneven temperature distributions.

Specimens used for the induction brazing experiments were made from one-inch round bar stock. Figure 3 shows the dimensions and general configuration of a specimen half. Two such halves were butt-brazed together at the beveled ends to provide the brazed specimens. The bevels then formed a notch, which facilitated filler metal introduction and also provided a convenient stress raiser so that the specimens could later be easily fractured through the brazed interface without appreciable deformation of the base materials.

Clearances at the brazing interface were maintained by the insertion of sheet steel shims. Figure 4 shows the dimensions and configuration of the shims that were used in most of the experimentation, although narrower gaps were used in experimentation with flow path width. These shims were inserted from the bottom of the specimens, with clearance at the bottom so as to provide a free path for the brazing alloy and flux and yet maintain the desired clearance throughout the entire brazing cycle. The approximate positioning of such shims for brazing is illustrated in Figure 3.

Specimens were prepared for brazing from one-inch diameter bar stock by facing off the two ends in a lathe, milling the bevel, and then drilling the necessary holes. The surfaces to be brazed were then ground to a 3-microinch finish on a surface grinder. A final step in the preparation of the specimens immediately before brazing consisted of hand grinding the surfaces to be brazed on 1-G grade emery paper, washing in methyl alcohol, and wiping dry with a clean cloth. AWS BAg-1 filler metal in wire or foil form was used in all experimental work.

Eight separate series of experiments were performed, each one having as its objective the investigation of one major variable. These experiments are described below and summarized in Table III.

Experiment 1 - Effect of Steel Composition

In this experiment, two butt-brazed specimens were prepared from each of the four steels: 1117, 4340, 1021, and 416 stainless steel. Joint clearance was 0.002 inch. The filler metal was two inches of 0.031 inch diameter BAg-1 wire, which provided a filler metal volume about 25 percent in excess of the joint volume. A commercial good quality, silver-brazing

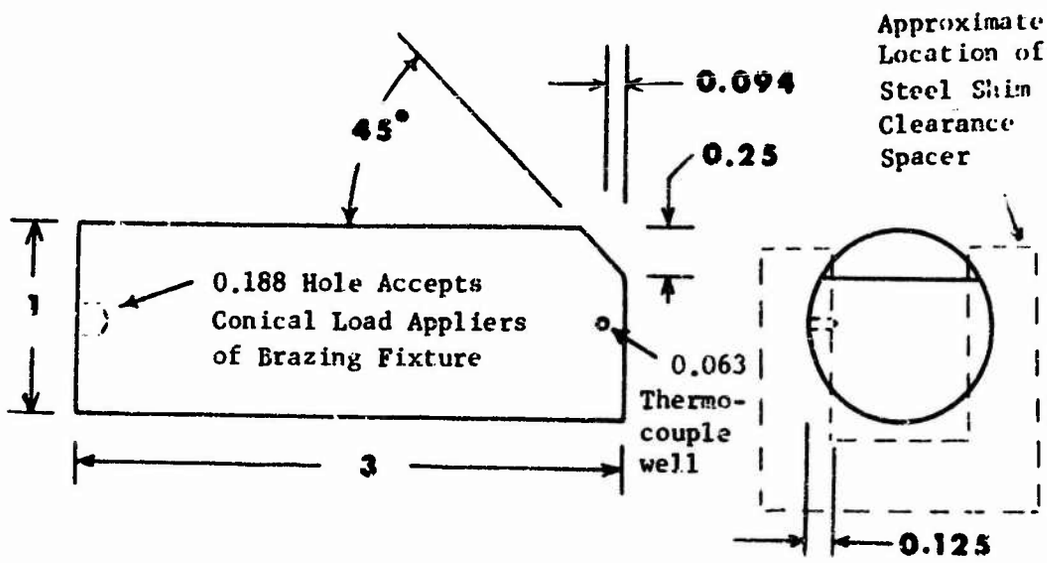


Figure 3. Scale Drawing of Specimen Half Used In Brazing Experiments

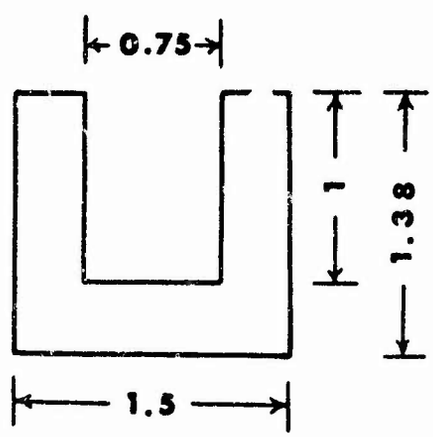


Figure 4. Configuration and Dimensions of Sheet Steel Shims Used to Maintain Joint Clearances

TABLE III.
Summary of Experimental Parameters for Brazed Specimens

Specimen Identification	Steel (grade)	Clearance (in.)	Time (min) at Temperature after Melting	Flux Used	Atmosphere	Filler Metal (BAg-1) Length (in.)	Filler Metal (BAg-1) Dia Wire (in.)	Temp (°F) at Introduction of Filler	Orientation of Flow with Respect to Gravity: Aided by	Orientation of Flow with Respect to Gravity: Opposed	Width of Flow Path (in.)
Experiment 1 - Effect of Steel Composition											
1-A, 1-B	1117	0.002	None	Yes	Air	2	0.031	Room[a]	X		0.75
1-C, 1-E	4340	0.002	None	Yes	Air	2	0.031	Room	X		0.75
1-E, 1-F	1021	0.002	None	Yes	Air	2	0.031	Room	X		0.75
1-G, 1-H	416 SS	0.002	None	Yes	Air	2	0.031	Room	X		0.73
Experiment 2 - Effect of Variations in Joint Clearance											
2-A, 2-B	4340	0	None	Yes	Air	1	0.031	Room	X		0.75
2-C, 2-D	4340	0.001	None	Yes	Air	1	0.031	Room	X		0.73
2-E, 2-F	4340	0.002	None	Yes	Air	2	0.031	Room	X		0.75
2-G, 2-H	4340	0.003	None	Yes	Air	3	0.031	Room	X		0.75
2-I, 2-J	4340	0.005	None	Yes	Air	3	0.031	Room	X		0.73
Experiment 3 - Effect of Time at Brazing Temperature											
3-A, 3-B	4340	0.003	None	Yes	Air	3	0.031	Room	X		0.75
3-C, 3-D	4340	0.003	0.3	Yes	Air	3	0.031	Room	X		0.75
3-E, 3-F	4340	0.003	2	Yes	Air	3	0.031	Room	X		0.73
3-G, 3-H	4340	0.003	3	Yes	Air	3	0.031	Room	X		0.73
Experiment 4 - Effect of Temperature at which Filler Metal was Introduced											
4-A, 4-B	4340	0.003	1	Yes	Air	3	0.031	1200	X		0.75
4-C, 4-D	4340	0.003	1	Yes	Air	3	0.031	1300	X		0.75
4-E, 4-F	4340	0.003	1	Yes	Air	3	0.031	1400	X		0.73
Experiment 5 - Effect of Capillary Flow against Gravitational Force											
5-A, 5-B	4340	0.001	1	Yes	Air	3	0.031	Hand-fed[b]		X	0.75
5-C, 5-D	4340	0.002	1	Yes	Air	3	0.031	Hand-fed[b]		X	0.75
5-E, 5-F	4340	0.003	1	Yes	Air	3	0.031	Hand-fed[b]		X	0.73
5-G, 5-H	4340	0.005	1	Yes	Air	5	0.031	Hand-fed[b]		X	0.73
Experiment 6 - Effects of Variation in Flow Path Width											
6-A, 6-B	4340	0.002	1	Yes	Air	2	0.031	Room	X		0.30
6-C, 6-D	4340	0.002	1	Yes	Air	2	0.031	Room	X		0.38
6-E, 6-F	4340	0.002	1	Yes	Air	2	0.031	Room	X		0.13
6-G, 6-H	4340	0.002	1	Yes	Air	2	0.031	Room	X		0.06
Experiment 7 - Effect of Preplaced Foil Filler Metal											
7-A, 7-B	4340	0.	1	Yes	Air	1 X 1 X 0.003[c]		Room	Not Applicable		1.0
7-C, 7-D	4340	0.003	1	Yes	Air	3/4 X 1 X 0.003[c]		Room	Not Applicable		0.73
7-E, 7-F	4340	0.002	1	Yes	Air	3/4 X 1 X 0.003[c]		Room	Not Applicable		0.73
Experiment 8 - Effect of Brazing in Argon Atmospheres											
8-A, 8-B	4340	0.003	1	Yes	Argon	3	0.031	Room	Not Applicable		0.73
8-C	4340	0.003	1	No	Argon	3	0.031	Room	Not Applicable		0.11
8-D, 8-E	4340	0.	1	Yes	Argon	1 X 1 X 0.003[c]		Room	Not Applicable		1.0
8-F, 8-G	4340	0.002	1	Yes	Argon	3/4 X 1 X 0.003[c]		Room	Not Applicable		0.11

[a] Room - Preplaced at room temperature
[b] Hand-fed - Hand-fed at melting point
[c] Foil

flux was applied to the faying surfaces of the joint. The clearance shim was added, and the joint was predried in the induction coil at about 400° F. The filler metal was cleaned with steel wool, fluxed lightly, and dried in an air-propane torch flame. These predrying cycles for the flux were found to be necessary because otherwise steam, rising from the joint, would foul the quartz filler metal feed tube and prevent proper feeding of the filler metal wire.

A predry cycle may be observed in Figure 5, which shows a typical time-temperature record of a brazed joint prepared in this study. The predrying accounts for the discontinuity in the heating curve at about 435° F. After the predry, the quartz guide tube was placed in position and the dry flux-coated filler metal wire was placed in the quartz guide tube in contact with the previously described "V" notch in the specimen.

The solenoid filler metal release was not employed in this experiment because it was desired that the filler melt as in an ordinary brazing operation.

After placement of the filler metal in the quartz tube, the induction coil was activated. As brazing temperatures were reached, the filler metal wire began to melt and slide down inside the quartz tube, thus feeding the joint in a point-source mode. Upon completion of the melting of the filler metal, the induction coil was deactivated and the completed specimen was left to air cool. Figure 5 may be referred to again for the complete thermal record of a typical brazed specimen.

After cooling, the specimens were stamped with their appropriate identification and were later broken with a hydraulic jack under three-point bent beam loading conditions. The fracture surfaces were then examined macroscopically for joint quality.

Experiment 2 - Effect of Variations in Joint Clearance

Procedures for Experiment 2 were the same as those used in Experiment 1 except that the major variable for this experiment was joint clearance. Grade 4340 was used throughout the experiment, and two specimens were prepared at each of the following clearances: 0, 0.001, 0.002, 0.003, and 0.005 inch. One inch of 0.031 inch diameter filler wire was used for the 0 and 0.001 inch clearances, and 2, 3 and 5 inches of 0.031 inch diameter filler wire were used, respectively, for the 0.002, 0.003 and 0.005 inch clearances.

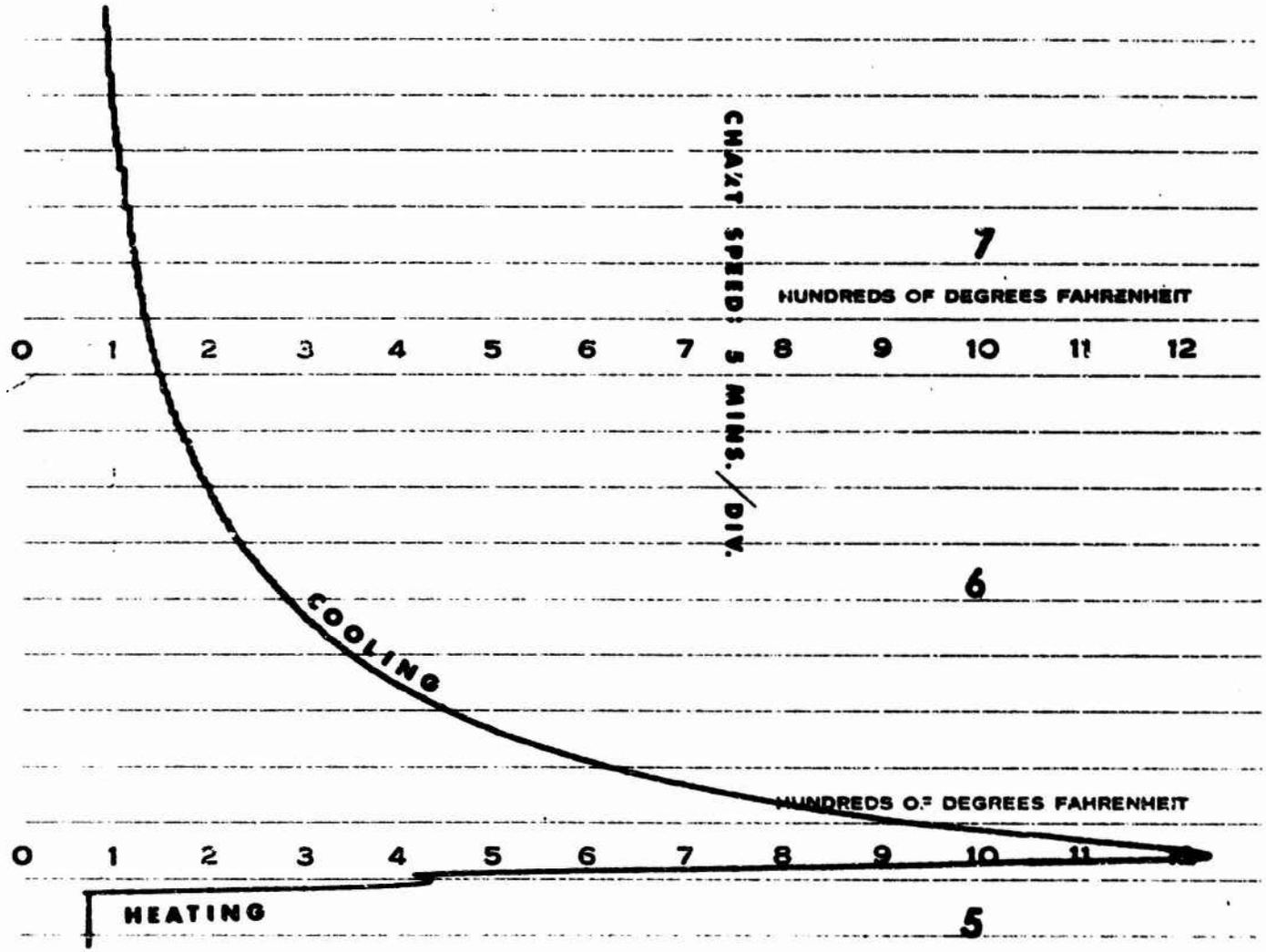


Figure 5. Time-Temperature Record of Typical Brazing Cycle

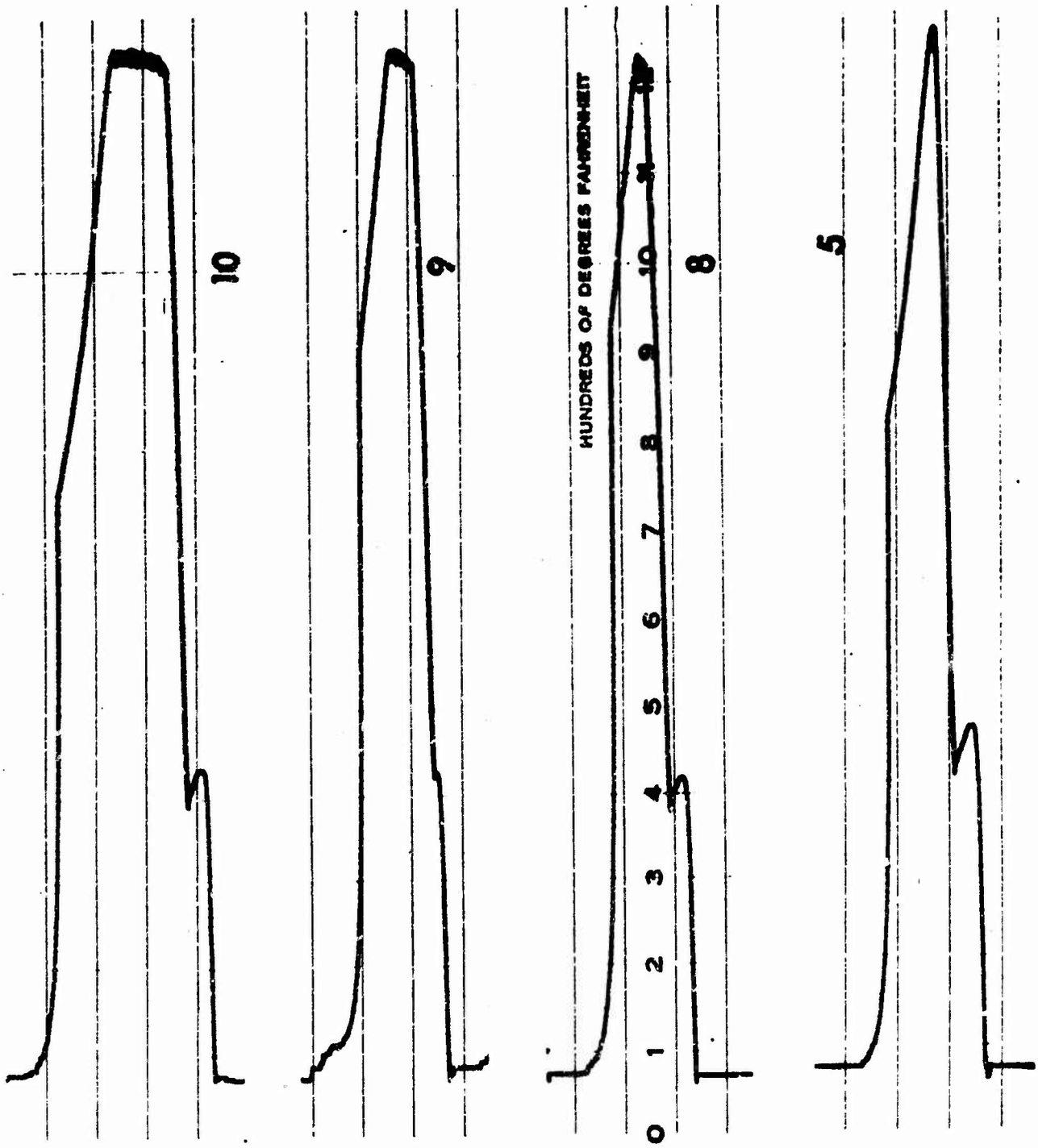
Experiment 3 - Effect of Time at Brazing Temperature

Procedures for Experiment 3 were the same as those used in Experiment 1 except that joint clearance was held at 0.003 inch and the power to the induction coil was left on for various lengths of time after the filler metal melted. A three-inch length of filler metal was used for these specimens. The controlling instrument was set to maintain a temperature of 1250° F at the brazing interface. Two specimens were prepared under each of the following conditions: power off when filler is all melted, power off 30 seconds after filler is all melted, power off 2 minutes after filler is all melted, and power off 5 minutes after filler is all melted.

Figure 6 shows the thermal records for specimens prepared at the various hold times. The interruption in the heating curves is again caused by the previously described drying cycle. The breaks in the cooling curves are not actually experienced by the specimens but are caused by removal of the thermocouple at temperatures between 700° and 1000° F. This is necessary because otherwise the flux freezes the thermocouple in its well. The specimens cool off in accordance with the curve shown in Figure 5.

Experiment 4 - Effect of Temperature at which Filler Metal Is Introduced

In this experiment, grade 4340 steel and a 0.003 inch clearance were again used. The remote filler wire release was used, and a three-inch length of filler wire was released when the specimen reached a preselected temperature. The temperatures were 1200°, 1300°, and 1400° F. Two specimens were prepared at each temperature, and specimens were held at temperature for one minute after the filler metal melted. The experiment was limited to the temperature range described because below a 1200° F specimen temperature the filler wire would not melt, and above 1400° F the flux deteriorated so rapidly as to preclude brazing. In fact, even at 1400° F, power to the induction coil had to be increased so as to heat the specimen rapidly because at this temperature the flux deteriorated in about one or two minutes. Cleaning procedures, etc., were the same as those used in Experiment one. Figure 7 shows typical thermal experience records of specimens in this group.



5 Min. Hold 2 Min. Hold 30 Sec. Hold 0 Hold

Figure 6. Thermal Records of Specimens Held at 1250° F for Various Lengths of Time after Filler Metal Melts

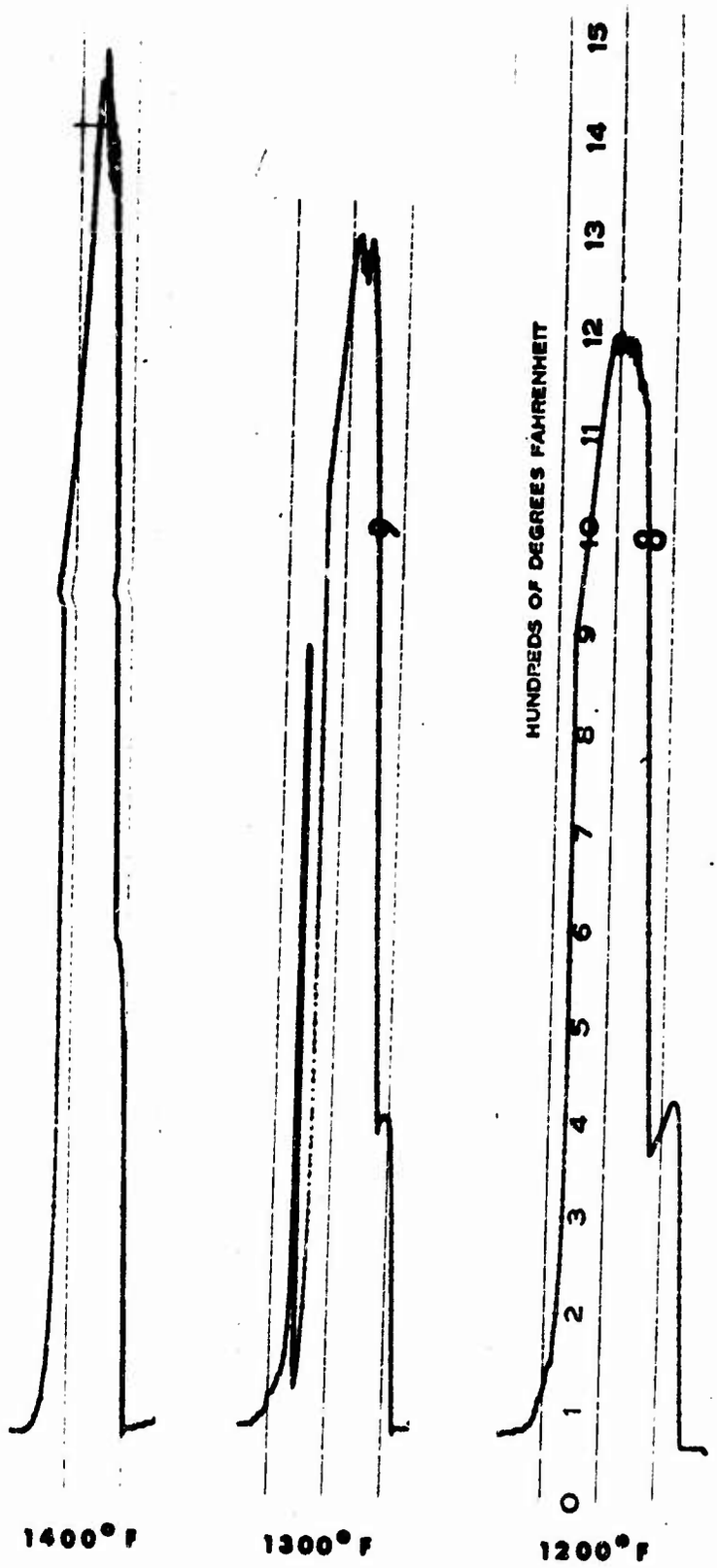


Figure 7. Thermal Records of Specimens Brazed at Various Temperatures

Experiment 5 - Effect of Capillary Flow against Gravitational Force

In this experiment, grade 4340 steel was used at clearances of 0.001, 0.002, 0.003 and 0.005 inch. Two specimens were made at each clearance. The specimens were inverted from their usual position in the fixture and the filler metal was hand fed into the "V" groove on the bottom. Three inches of filler metal were used for each specimen except for those with the 0.005-inch clearance; a five-inch length was used at that clearance. All specimens were held for one minute at brazing temperature (1250° F) after the filler metal completely melted.

Experiment 6 - Effects of Variation in Flow Path Width

In this experiment, flow path width was controlled by the slot in the steel clearance shim. Two grade 4340 steel specimens were made at each of the following widths: 1/2, 3/8, 1/8, and 1/16 inch. Clearance was 0.002 inch. The filler metal was preplaced in the tube guide, and all specimens were held at 1250° F for one minute after the filler metal was completely melted. Two inches of filler metal were used for each specimen. All other procedures were the same as for Experiment 1.

Experiment 7 - Effect of Preplaced Foil Filler Metal

In this experiment, 0.003-inch BAg-1 foil was used as the filler metal. Two specimens were prepared under each of the following conditions: with no clearance spacer, with a 0.003-inch steel shim clearance spacer, and with a 0.002-inch steel spacer. With the "no clearance" and 0.002-inch clearance specimens, the spring-loaded fixture closed up the clearance gap after the filler metal melted. The steel was grade 4340, and one minute was allowed at the brazing temperature (1225° to 1240° F) after the filler metal melted.

Experiment 8 - Effect of Brazing in Argon Atmospheres

The main feature of this experiment was the removal of air from the brazing environment. This was accomplished by brazing in the bell jar which was evacuated by a vacuum pump and backfilled with argon.

Three pumpdowns and backfills were used. Calculations showed that, under the vacuums achieved, this should be sufficient to lower the impurity level added to the argon from residual air, to a small fraction of the impurity level normally present in the argon. Assuming perfect mixing, no leaks, pumpdown to 400 microns, 30 parts/million impurity in the argon, and backfill to 0.8 atmospheric pressure, then about 0.05 percent of the impurities in the final fill will be residual.

In early experiments the pumpdown levels were about 3 to 4 x 10^{-1} Torr. As techniques improved in later experiments, pumpdown levels of about 1 x 10^{-1} Torr were achieved. Special preparation of the specimens was required to avoid contaminating the atmospheres so that, in addition to the usual preparation of the brazing interface, the entire specimens were first washed in acetone and then alcohol to remove grease, oil, or paint that might be present on the surface.

After the pumpdown, the bell jar was backfilled with argon to a pressure of about 0.85 atmospheres. These partial pressures were used to avoid breaking the seal around the bell jar, which is dependent upon atmospheric pressure to retain its integrity. After the final (third) pumpdown, argon was bled into the bell jar to 0.85 of atmospheric pressure, and a needle valve bypass into the vacuum manifold [illegible] opened and adjusted so as to produce a flowing atmosphere at th[illegible]essure.

Predrying of the flux on the specimen and filler wire were accomplished, as previously described, before the addition of the bell jar and the initiation of the first pumpdown.

In the environment described above, specimens were prepared as follows:

Two specimens were made using flux, a 0.003-inch clearance and three inches of filler wire preplaced in the quartz tube. After the filler metal melted, a one-minute period at the brazing temperature was allowed.

One specimen was made with 0.003 inch clearance, three inches of filler metal and no flux, also allowing one minute after the filler metal melted.

Two specimens were made with flux, using 0.003-inch foil, BAg-[illegible] filler metal with no clearance shim, and allowing one minute at the brazing temperature after the filler metal melted.

An additional two specimens were made using flux, 0.003-inch foil filler metal, and a 0.002-inch steel shim spacer, also allowing one minute at the brazing temperature after the filler metal melted.

Figure 8 shows a time-temperature record for a specimen brazed in the bell jar. The long delay after the flux drying cycle is due to the pumpdown and purging cycle for the bell jar. The break in the cooling curve

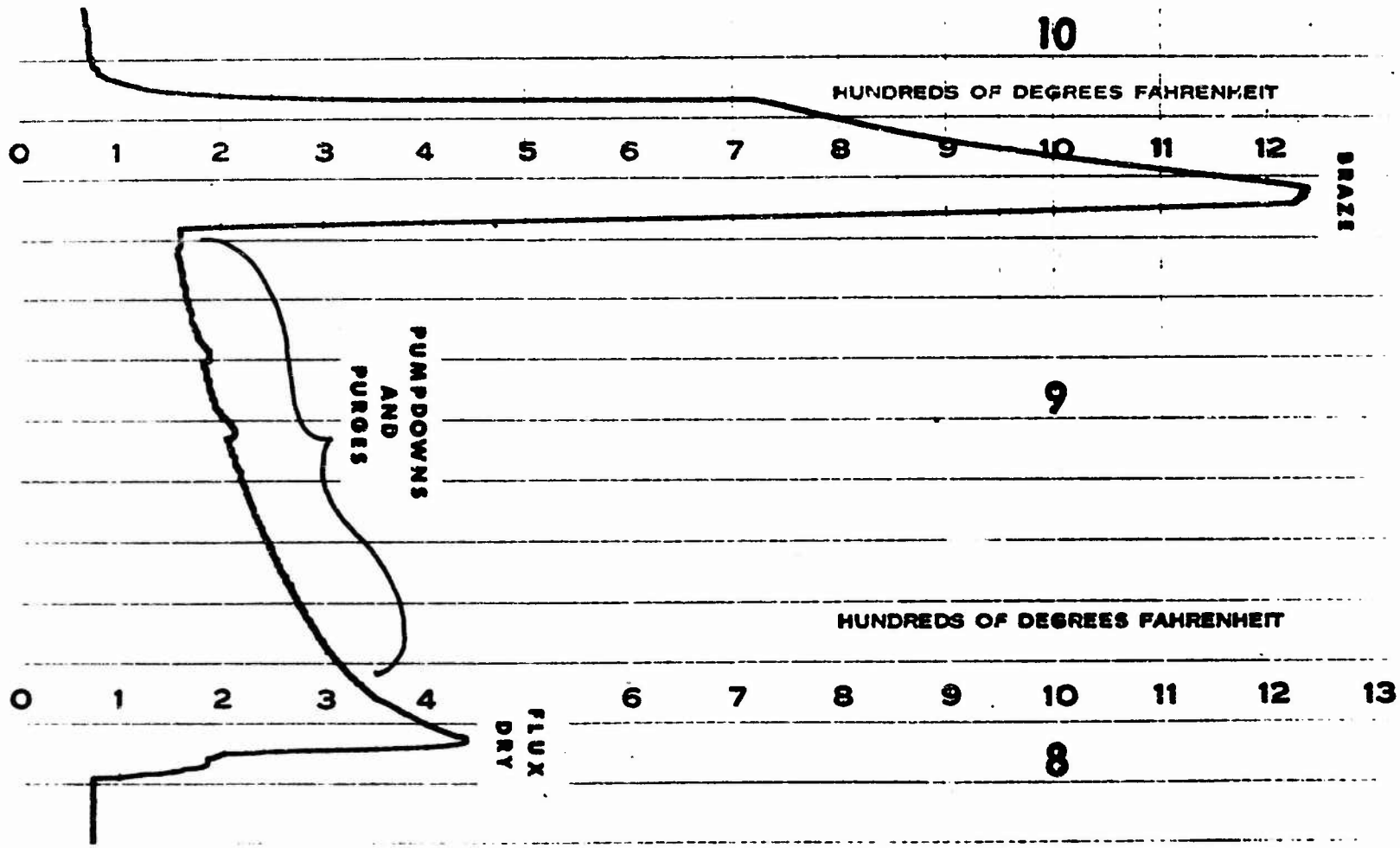


Figure 8. Time-Temperature Record for Specimen Brazed in Argon in Bell Jar

results from removal of the thermocouple after letting the pressure in the bell jar return to atmospheric and removing the bell jar.

RESULTS AND DISCUSSION

Experiment 1 - Effect of Steel Composition

Figure 9 shows the results of Experiment 1. It may be seen that there are substantial differences in the reaction of the various steels to a standard, carefully maintained, excellent quality brazing procedure. The two sulphurized steels (1117 and 416 stainless steel) appear to produce less acceptable capillary flow than the 1021 and 4340 steels. This observation is, of course, not without precedent.

It may also be seen that the quality of the 4340 and 1021 brazements leaves a good deal to be desired. There are numerous voids, some of them large, and in one of the 1021 specimens (1-E), the filler metal did not penetrate all the way through the joint.

All specimens produced, however, would have passed the visual inspection procedure of examining the capillary gap at a point opposite that of filler metal introduction. The gaps at this point were all filled with filler metal, which is normally interpreted as evidence that the filler has flowed satisfactorily through the capillary path.

Specimen 1-E illustrates a problem that became of particular concern in this program and that probably occurs regularly in other practical brazing situations. In this specimen it appears that the filler metal has run around the outside of the specimen and filled the capillary gap from the bottom, thus trapping the flux and preventing further advance of the filler metal from the top of the joint. The filler metal wire is introduc ' in the approximate center of the "V" groove, so it is obvious that the pa' ' around the outside of the specimen is much longer than the path through the capillary gap. Nevertheless, the filler metal seems to flow more rapidly in the 90 degree angle formed between the shim and the specimen than through the capillary gap.

With respect to the particular steel compositions, grade 4340 seemed about the best and was therefore used as the vehicle for all further tests.

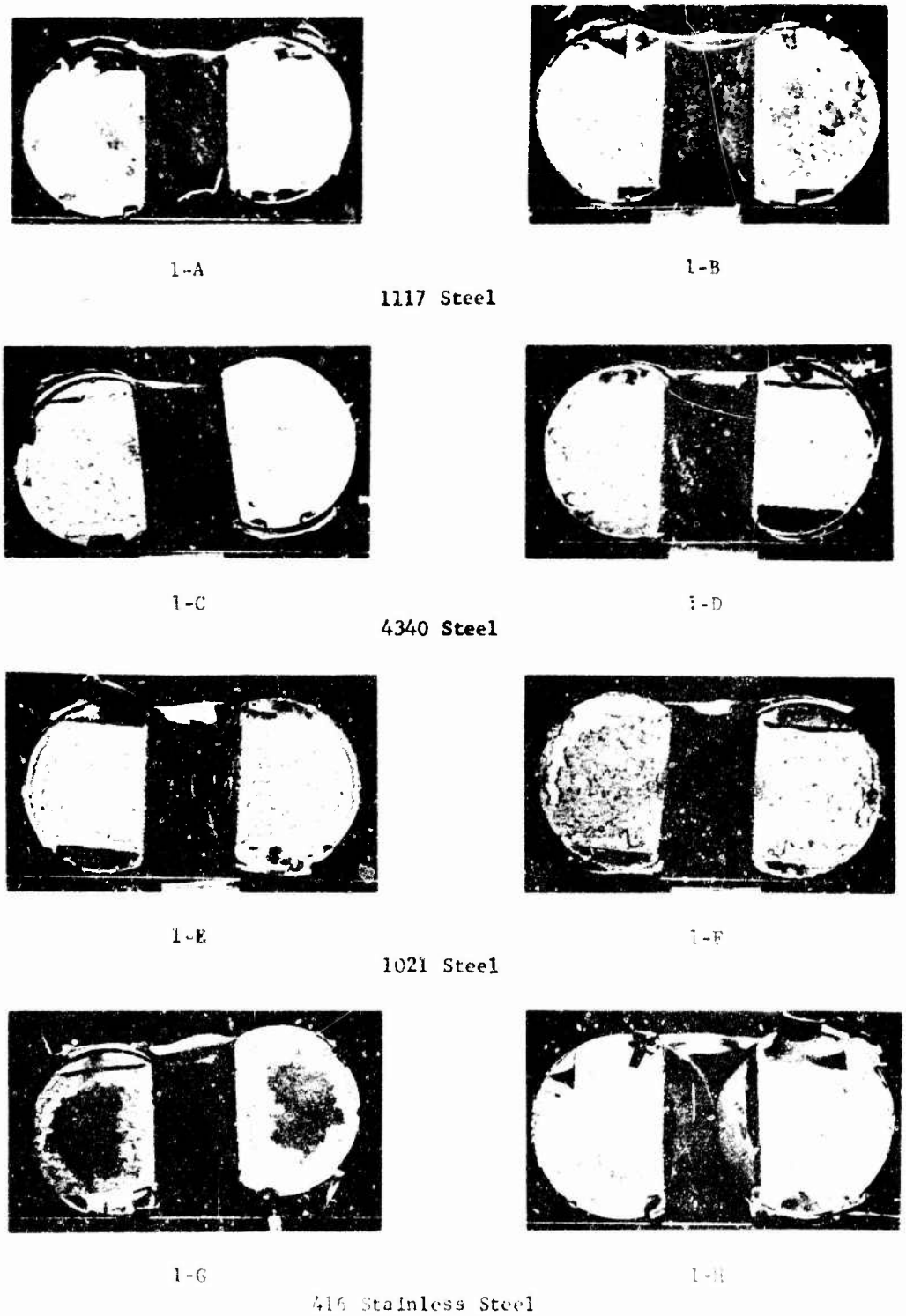


Figure 9. Results of Experiment 1 - Variations in Composition of Steel

Experiment 2 - Effect of Variation in Joint Clearance

Figure 10 shows the fractured interfaces of the specimens brazed in Experiment 2. In general, it appeared from this experiment that the normally recommended joint clearances for BAg-1 alloy (0.002 to 0.005 inch) were also about the best with respect to defect formation. The zero clearance specimens (2-A and 2-B) were obviously complete failures, with very little filler metal actually even penetrating the joint. The 0.001-inch clearance specimens show the general tendency to produce smaller, but more frequent, defects at smaller clearances. Generally, the 0.003-inch clearances produced about the best results and, accordingly, a 0.003-inch clearance was used in most of the succeeding experiments.

Experiment 3 - Effect of Time at Brazing Temperature

Figure 11 shows the fracture surfaces of the specimens held for various lengths of time at the brazing temperature. It can be observed that this variable has no apparent effect, either positive or negative, on the number, size, or general character of the defects.

This experiment also provides an excellent display of the frequency and consistency with which defects appear in brazed joints of this type. In Figure 11, eight specimens are shown which have been brazed under ideal conditions by ordinary brazing standards, yet all of them have many large defects. The conclusion seems inescapable that, as currently prepared, the vast majority, if not all such joints are similarly defective.

Experiment 4 - Effect of Temperature at which Filler Metal was Introduced

Figure 12 shows the fracture surfaces of the specimens produced in Experiment 4. In this series, there seemed to be a reasonably definite trend toward decreasing number and size of defects when the filler metal was introduced at higher temperatures. Specimen 4-F (filler introduced at 1400° F) is obviously better in quality than specimens 4-A and 4-B (filler introduced at 1200° F). Its mate, Specimen 4-E, except for the large defect in the center, also shows smaller and more regularly shaped defects.

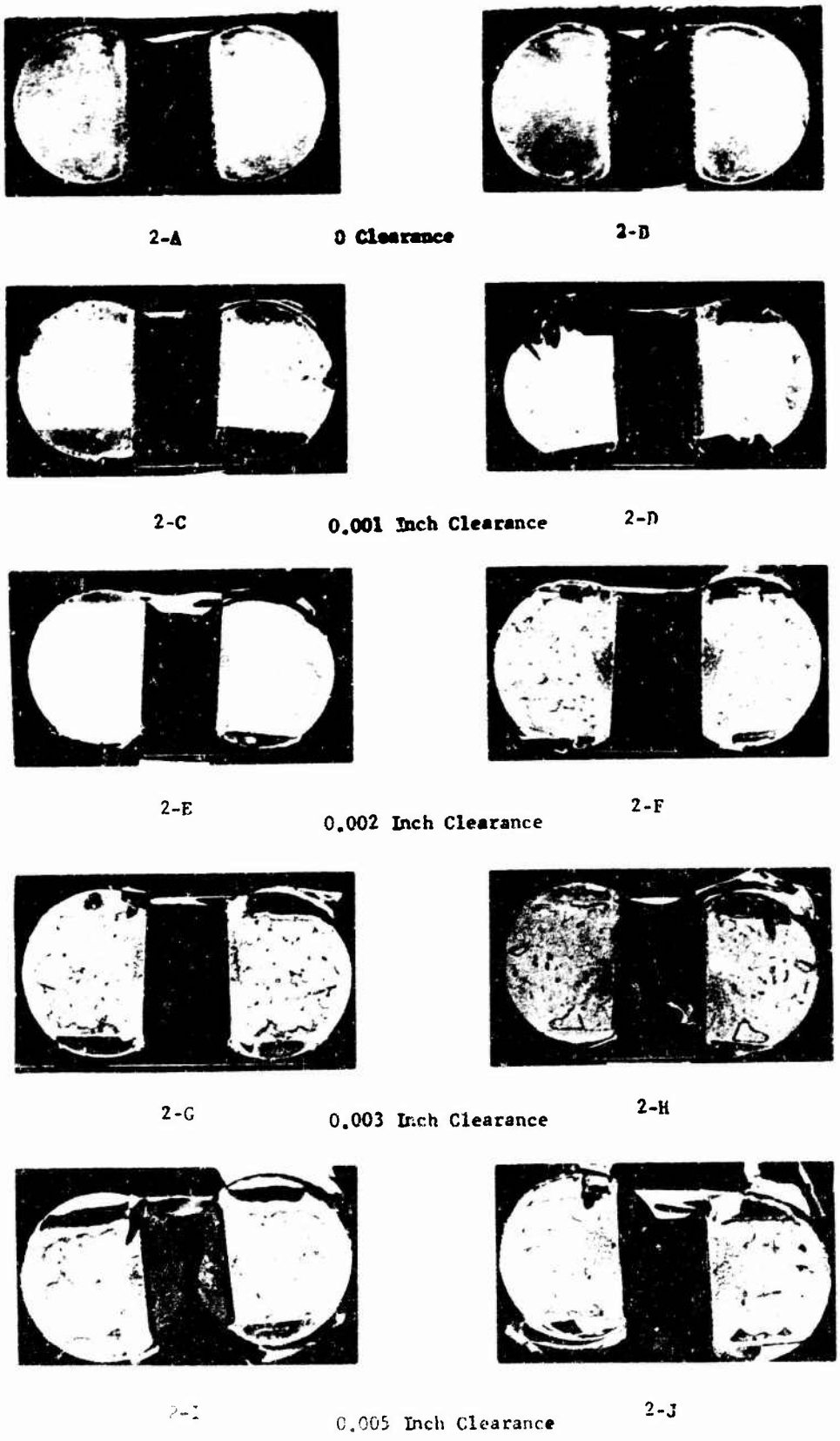
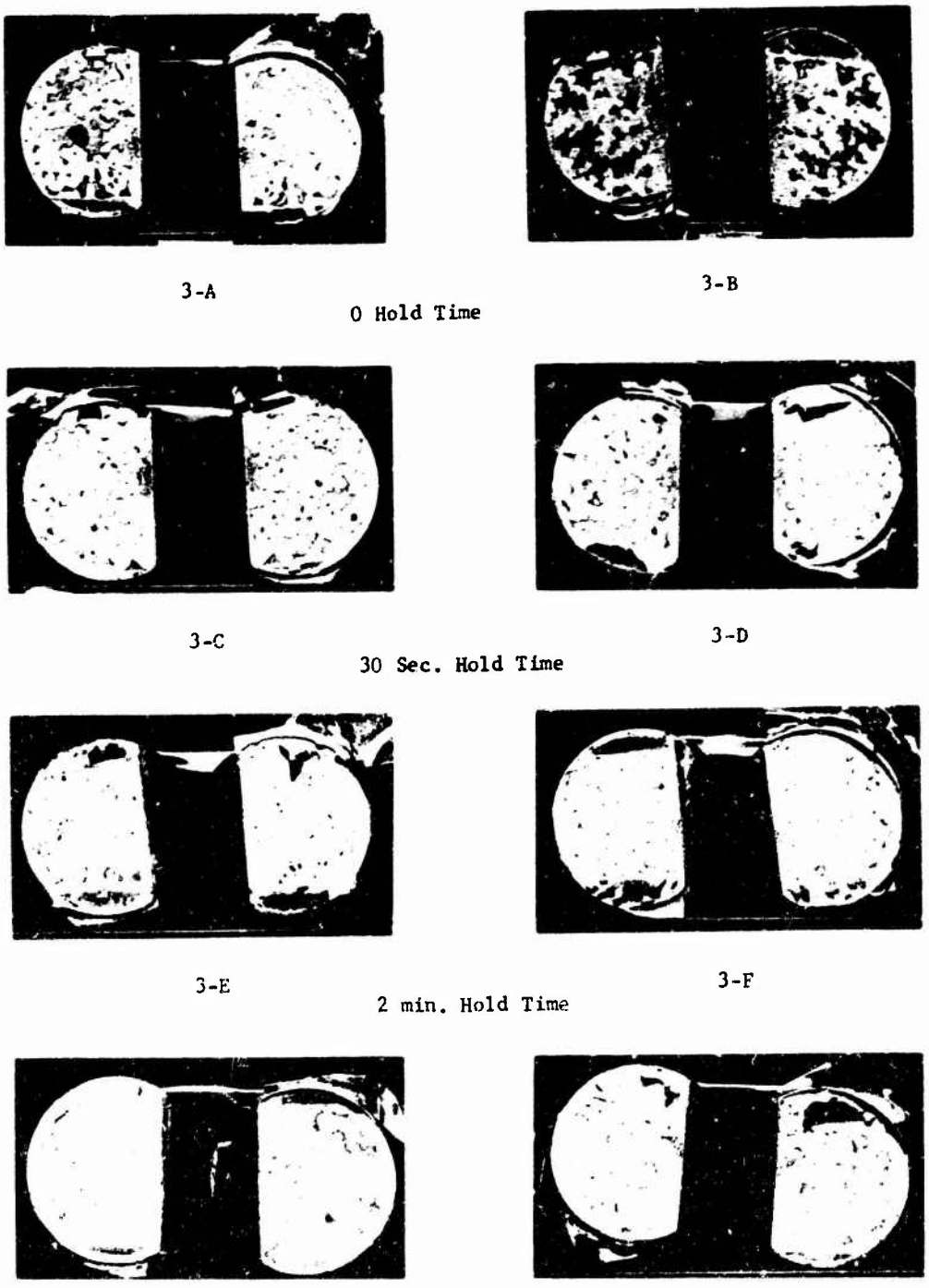


Figure 10. Results of Experiment 2 - Variations in Joint Clearance



3-A 3-B

0 Hold Time

3-C 3-D

30 Sec. Hold Time

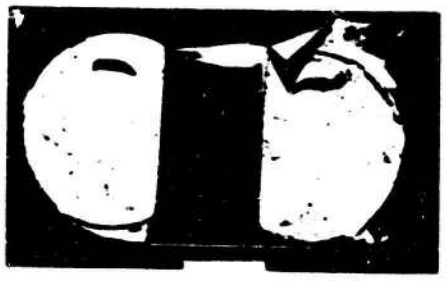
3-E 3-F

2 min. Hold Time

3-G 3-H

5 Min. Hold Time

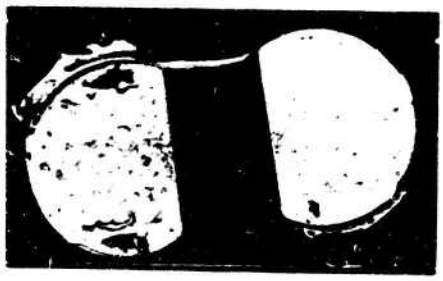
Figure 11. Results of Experiment 3 - Variations in Hold Time

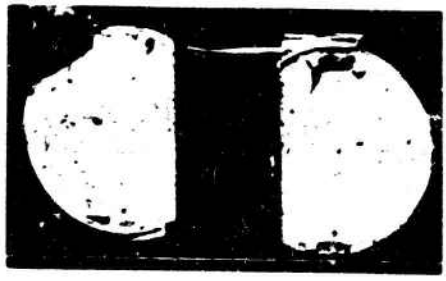


4-A

4-B

Filler Wire Introduced at 1200°F.

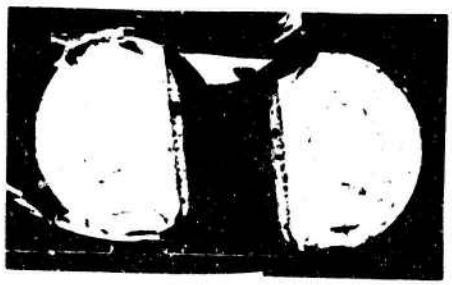


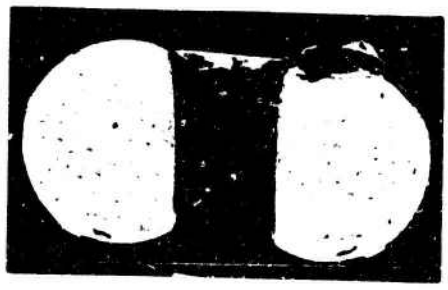


4-C

4-D

Filler Wire Introduced at 1300°F.





4-E

4-F

Filler Wire Introduced at 1400°F.

Figure 12. Results of Experiment 4 - Variations in Temperature at which Filler Wire is Introduced

Experiment 5 - Effect of Capillary Flow Against Gravitional Force

Figure 13 shows specimens in which the direction of filler metal flow was opposed to gravitational force. Clearances were 0.001, 0.002, 0.003 and 0.005 inch, respectively. These specimens are directly comparable to those shown in Figure 10, except for the direction of filler metal flow. Somewhat more filler metal was used in some instances for flow opposed to gravity, but this is not considered a significant variation since all specimens had more than adequate amounts of filler metal, according to volume calculations.

It may be seen by comparison of the various Figures that flow opposed to gravity does not produce great improvement with respect to defect formation. However, at the lesser clearances, (0.001 and 0.002 inch) the specimens in which filler flow was opposed to gravity do appear to be better with respect to the large defects formed along the outside of the flow path. For this reason it is probably desirable to employ flow opposed to gravity where it is feasible; however, it is obviously not a panacea for the problem of defects in brazed joints.

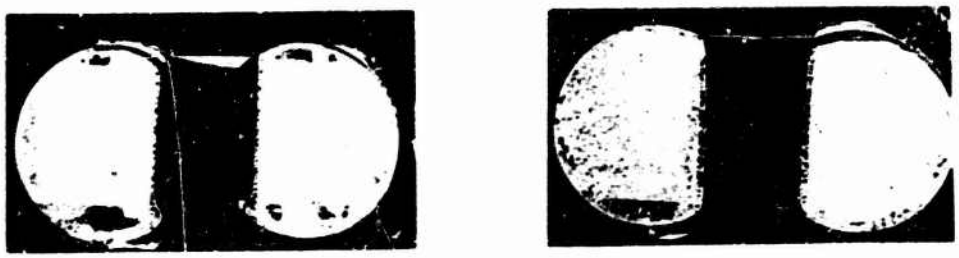
Experiment 6 - Effect of Variation in Flow Path Width

Figure 14 shows the results of experimentation with flow path width. The specimens are shown in order of decreasing path width. The reasoning behind this experimentation was that if it could be shown that paths of restricted width produce less defects, then joints of larger area could perhaps be divided into many small paths by the inclusion of wire spacers or some other type of preform. However, as may be seen from the specimens, restriction of flow path width produced little or no benefits. Even the 0.06 inch wide paths have major defects directly through the center of the path.

Experiment 7 - Effect of Preplaced Foil Filler Metal

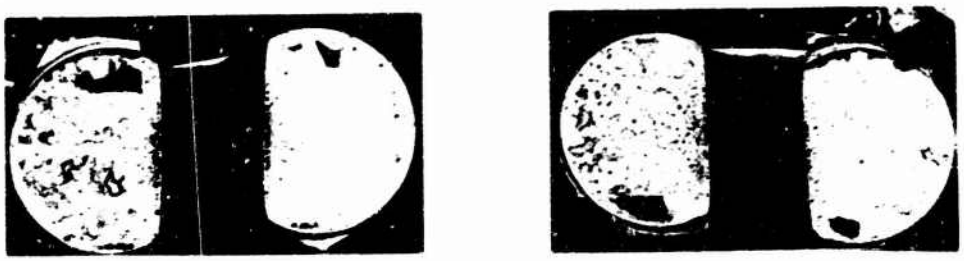
Figure 15 shows the results of experimentation with foil filler metals. Specimens 7-A and 7-B are the specimens which were made with 0.003-inch filler metal and no clearance spacer. It should be realized that in these specimens, after the filler metal melts, the spring-loaded brazing fixture automatically closes the gap to zero or near zero clearance.

While it may not be obvious in the photographs, the broken specimens appear to be unbonded throughout a large area in the center, even though they also appear to be satisfactorily wetted in that area. It is not clear at this time why or how this happens, and further study will be required to determine with certainty what mechanisms are at work in this situation.



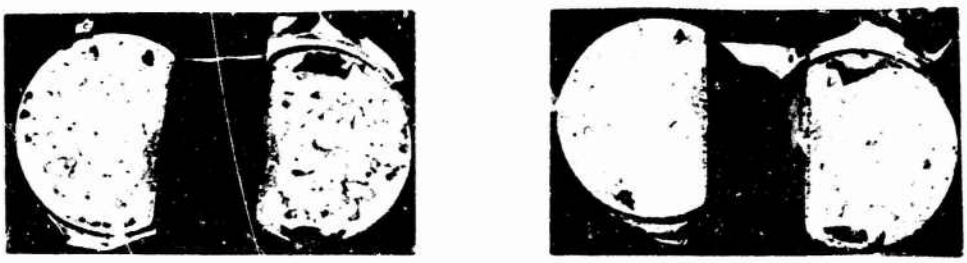
5-A 5-B

0.001 Inch Clearance



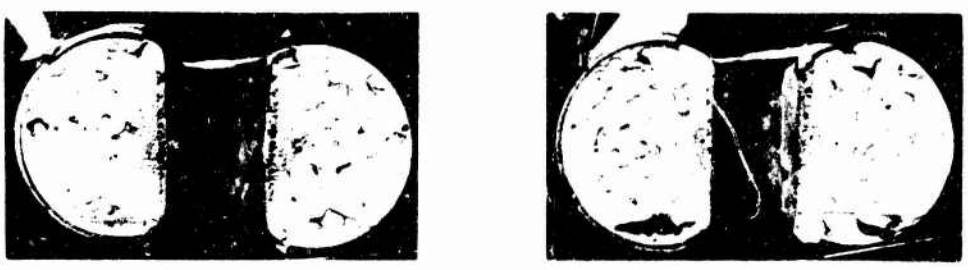
5-C 5-D

0.002 Inch Clearance



5-E 5-F

0.003 Inch Clearance



5-G 5-H

0.005 Inch Clearance

Figure 13. Results of Experiment 5 - Effects of Flow Opposed to Gravity

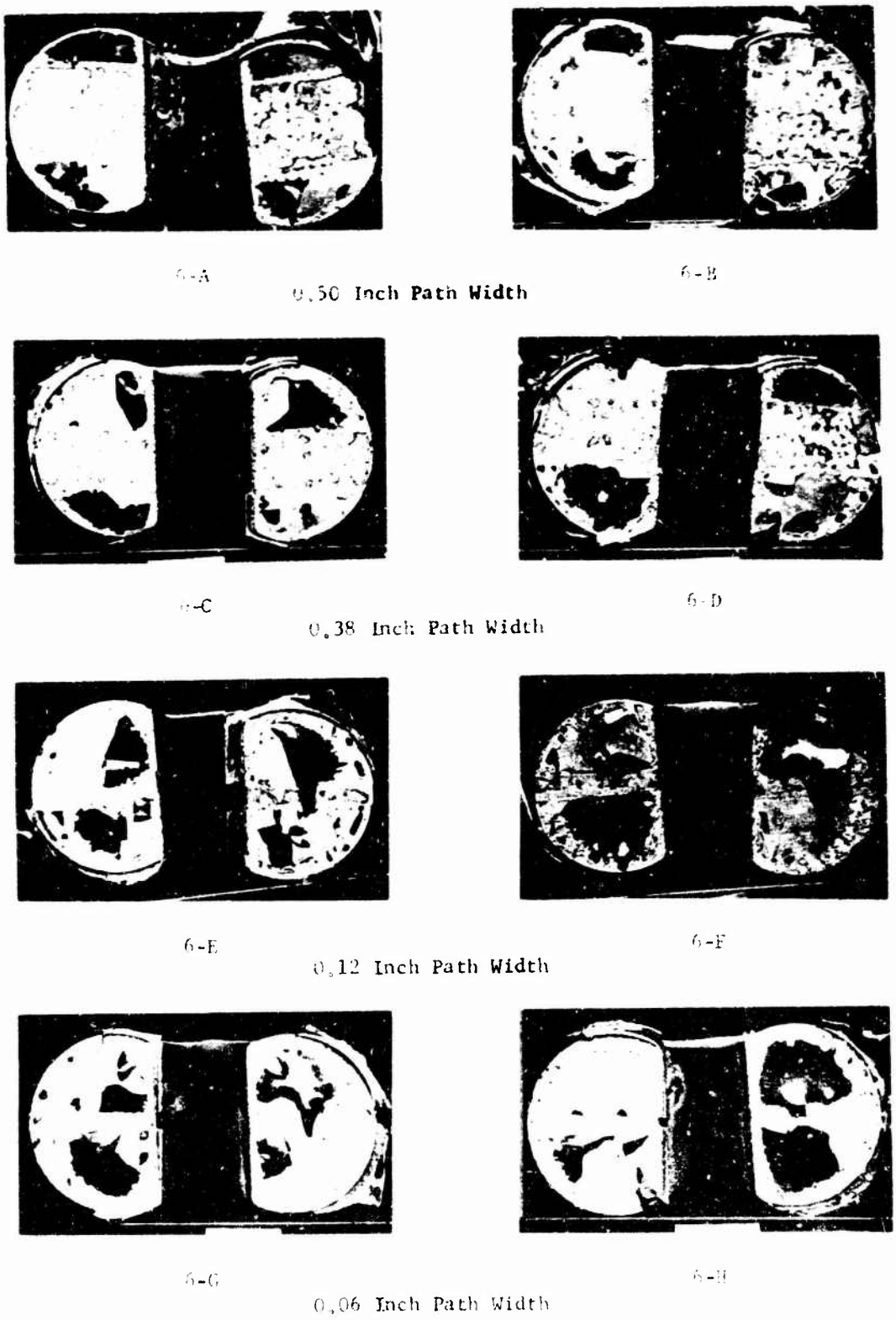
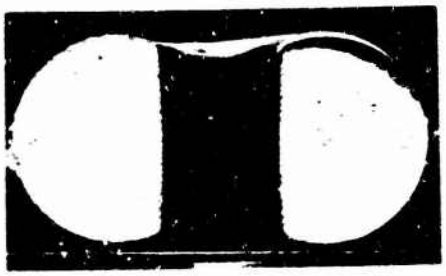


Figure 14. Results of Experiment 6 - Effect of Variation in Flow Path Width

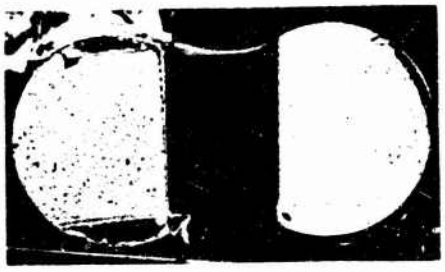


7-A

7-B

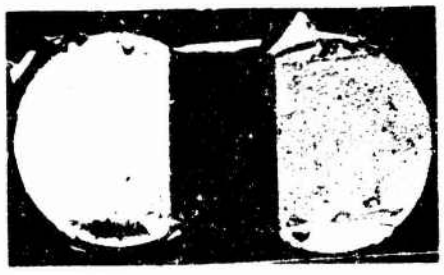
0 Clearance

7-C

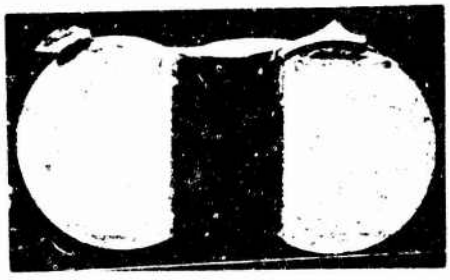


7-D

0.003 Inch Clearance



7-E



7-F

0.002 Inch Clearance

Figure 15. Results of Experiment 7 - Effect of Foil Filler Metal

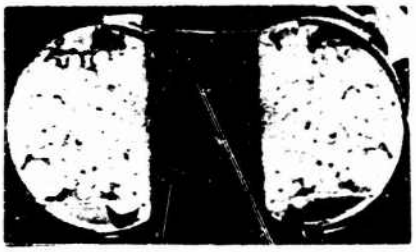
Specimens 7-C and 7-D, 7-E and 7-F are specimens that were brazed with 0.003-inch foil filler metal and 0.003-inch and 0.002-inch steel clearance spacers, respectively. The general appearance of the fractured interfaces is about the same and it may be seen that, in general, the distribution, size, and regularity of the defects is considerably better than is generally observed in specimens made with filler wire.

Experiment 8 - Effect of Brazing in Argon Atmospheres

In Figure 16, the fracture surfaces of the specimens brazed in argon are shown. Specimens 8-A and 8-B are the specimens which were brazed with filler wire and flux in argon. These may be compared directly with specimens 2-G and 2-H of Figure 10, which were brazed under the same conditions except in air. It may be seen that there is little, if any, improvement. This observation tends to negate the theory expressed by Bredzs that defects are caused by oxygen diffusion through the flux and filler metal, with resultant formation of carbon monoxide bubbles at the steel interface. It also renders the dissolved hydrogen rationale unlikely.

Specimen 8-C is the specimen that was brazed in argon using filler wire, no flux, and a 0.003-inch clearance. This specimen was so poor in external appearance that only one specimen was made. The filler metal did not penetrate all the way through the joint and a large amount of it balled up in the "V" groove. However, when the specimen was broken, it was observed that the filler metal film which formed the brazed joint contained far less defects than any other specimen made in this study. While silver brazing in argon may not be a practical technique in most instances because of wetting difficulties, the specimen does strongly suggest that much of the difficulty encountered with defects is related to the flux-filler metal displacement mechanism.

Specimens 8-D through 8-G are the specimens brazed in argon with flux and 0.003-inch foil filler metal. No clearance spacer was used for specimens 8-D and 8-E, and the results obtained were very similar to those obtained in an air atmosphere where other conditions were the same (see Figure 15); i.e., a large portion in the center of the specimen was wetted but not bonded. The perimeters of the brazing interface were bonded but contained many small defects. Specimens 8-F and 8-G are the specimens made with foil filler and a 0.002-inch clearance spacer. Similar specimens were made in air (see Figure 15) and the results obtained in argon do not differ appreciably. However, as was previously observed, specimens made with foil fillers appear to be generally of better quality than those made by capillary flow of melted wires.



8-A 8-B

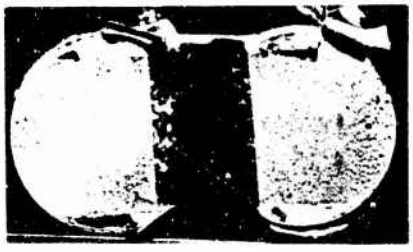
Filler Wire, Flux

8-C

Filler Wire, No Flux

8-D 8-E

Foil Filler, Flux, 0 Clearance



8-F 8-G

Foil Filler, Flux, 0.002 Inch Clearance

Figure 16. Results of Experiment 8 - Effect of Argon Atmospheres

CONCLUSIONS

It was found that all joints made with flux contained large numbers of defects. The use of foil filler metals was the most helpful option in overcoming this problem in that it produced small, regularly shaped defects whereas capillary flows produced very erratic joint quality, defect size, and defect distribution. Nearly defect-free capillary flows could be achieved in argon atmospheres without fluxes.

A listing of the observations follows.

1. With AWS BAg-1 filler wire, brazing results vary considerably, depending upon the composition of steel being brazed. Sulphurized steels produce less desirable capillary flow characteristics.

2. The joint clearances generally recommended for brazing steels with BAg-1 (0.002 to 0.005 inch) are also the best with respect to minimizing defect formation.

3. Increasing time at brazing temperature has no beneficial effect with respect to defect formation in steels brazed with BAg-1 wire.

4. Introducing wire filler metal at brazing temperatures substantially above the melting point of the filler metal seems to reduce defect size and number, but further work should be done to verify this conclusion.

5. Filler metal capillary flow opposed to gravity is marginally helpful in reducing defects.

6. Reduced flow path widths are not helpful in reducing defects.

7. The use of filler metals in foil form is very helpful in producing regularly distributed defects of small and uniform size.

8. Argon atmospheres are not significantly helpful in reducing defects when flux is used. However, brazing in argon without flux, while not completely practicable, produced nearly defect-free capillary flow in the one specimen for which it was tried.

9. The evaluation of brazed joints by observation of the filling of the capillary gap opposite the point of entry of the filler metal is inadequate as a means of judging brazement quality.

10. The vast majority, if not all, BAg-1 brazed joints in steel probably contain many defects, especially where filling of the joint is dependent upon capillarity.

It was concluded from these observations that the major cause of defects in the brazed joints was the irregular flow modes produced by the mechanism of flux displacement by filler metal. It is believed that these irregular flow modes are characteristic of the process at its current state of development, and that only revision of the basic system will correct the problems encountered.

RECOMMENDATIONS

It is recommended that foil filler metal be used in brazing steel, with BAg-1 filler metal, where feasible. This does not eliminate defects, but makes them individually smaller and more regular in character.

Where filler wires must be used, flow against gravity is to be preferred.

FUTURE WORK

Further work should be done on the flow of BAg-1 alloy in steel capillary gaps in the absence of flux. Reducing atmospheres should be examined, in addition to inert atmospheres. Experimentation in this vein should be enlightening with respect to the role of flux in defect formation.

The mode of displacement of flux from joints should also be studied in greater detail, with perhaps particular attention being given to determination of whether or not one liquid may be displaced from a capillary gap by another without the entrapment of the first liquid and, if so, what the controlling parameters for this condition are. As of the writing of this report, it appears that this flux-filler metal interaction is responsible for the erratic and irregular flow modes encountered and that the displacement of the flux in an erratic mode is responsible for the formation of the defects.

In addition, it does not appear that brazing defects are necessarily the result of incorrect or inadequate procedure, at least not as presently defined. The causes of defects in brazing steel with BAg-1 and flux appear, on the contrary, to be inherent in and characteristic of the brazing process as it is presently constituted. It is believed that correction of the problem, if possible, will only come about through modification of the basic process. This may entail the compounding of new and better fluxes or other major changes to the brazing system.