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Relationships Among Brazing Defects and Brazing Conditions

Variations in eight brazing parameters are examined for their effects on quality of steel joints brazed with silver base filler metals

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ABSTRACT. The purpose of this work was to examine and define the causes of defects in steel joints brazed with silver base filler metals, 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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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 assemblies contain defects that frequently arouse doubt as to the quality of brazed products.

In some assemblies that have requirements for a high percentage of bonded area (for example, 85%), defects occur in sufficient degree to cause rejection. 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 certain 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 (Ref. 1) under an Army contract. He was able, for example, to demonstrate that in brazing steel with silver base filler metals, 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-filler metal 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 backfilling of shrinkage decrements. This met with some degree of success but was not a practical solution for most real brazing situations.

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 prior to that reported here, a number of torch 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 kW, high frequency, induction heating unit of the electronic tube type.

Steel for the specimens was obtained in the form of 1 in. 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 1.

Table 1 — Nominal Composition of Steels, wt %

	SAE 1021	SAE 1117	SAE 4340	AISI 416
C	0.18-0.23	0.14-0.20	0.38-0.40	0.15 max
Mn	0.10-0.90	1.00-1.30	0.60-0.80	1.25 max
P	0.040 max	0.040 max	0.035 max	—
S	0.050 max	0.08-0.13	0.040 max	0.15 min
Si	—	—	0.20-0.35	1.00 max
Ni	—	—	1.65-2.00	—
Cr	—	—	0.70-0.90	12.0-14.0
Mo	—	—	0.20-0.30	—

Filler metal for all experiments was AWS grade BAg-1. This was employed as 0.003 in. (0.076 mm) thick foil or 0.031 in. (0.787 mm) diam wire. The nominal composition of this material is 45%Ag, 15%Cu, 16%Zn and 24%Cd.

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 that manufacture them.

Methods and Procedures

Induction heating was selected 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 in-

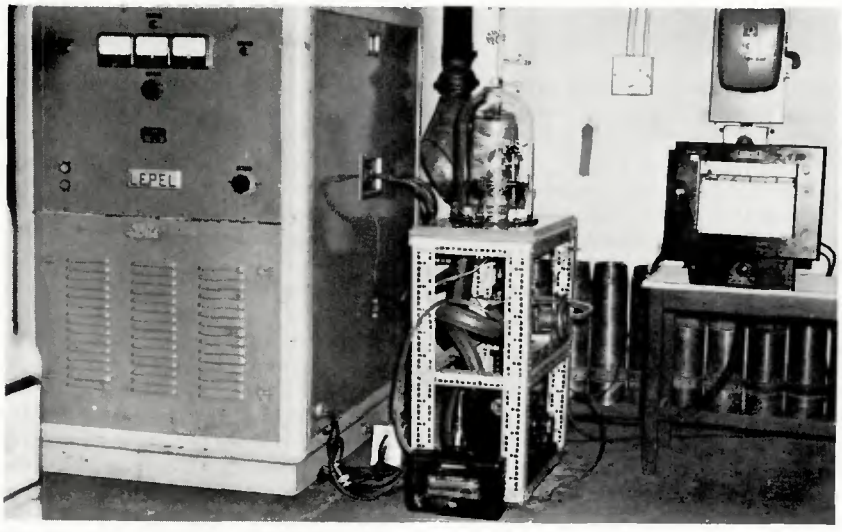

Fig. 1 — Overall view of brazing setup

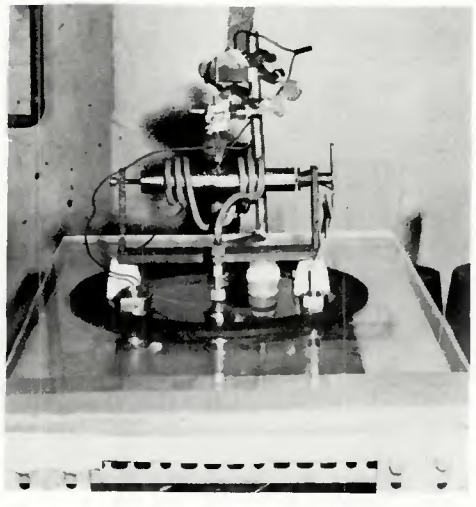

Fig. 2 — Detailed view of immediate brazing arrangement

side 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 Fig. 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 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 1 in. diam 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 1 in. 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 the bar stock by facing off the two ends in a lathe, milling the bevel, and then drilling the necessary

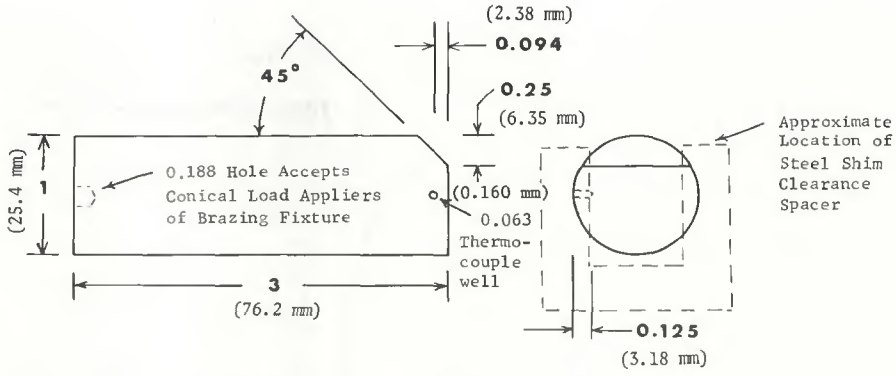

Fig. 3 — Scale drawing of specimen half used in brazing experiments

holes. The surfaces to be brazed were then ground to a 3 microinch (76.2 μm) 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 in detail below.

Exp. 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 in. (0.051 mm). The filler metal was a 2 in. (50.8 mm) length of 0.031 in. (0.787 mm) diam BAg-1 wire, which provided a filler metal volume about 25 percent in excess of the joint volume. A commercial good quality, silver-brazing 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 (205 C). 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 Fig. 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 (224 C). 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

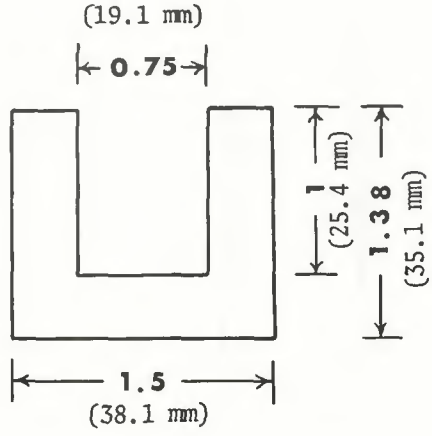

Fig. 4 — Configuration and dimensions of sheet steel shims used to maintain joint clearances

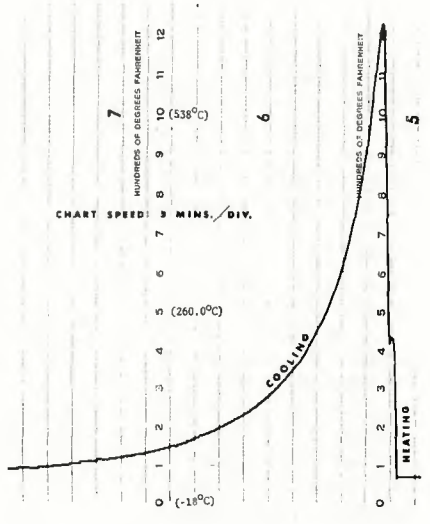

Fig. 5 — Time-temperature record of typical brazing cycle

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

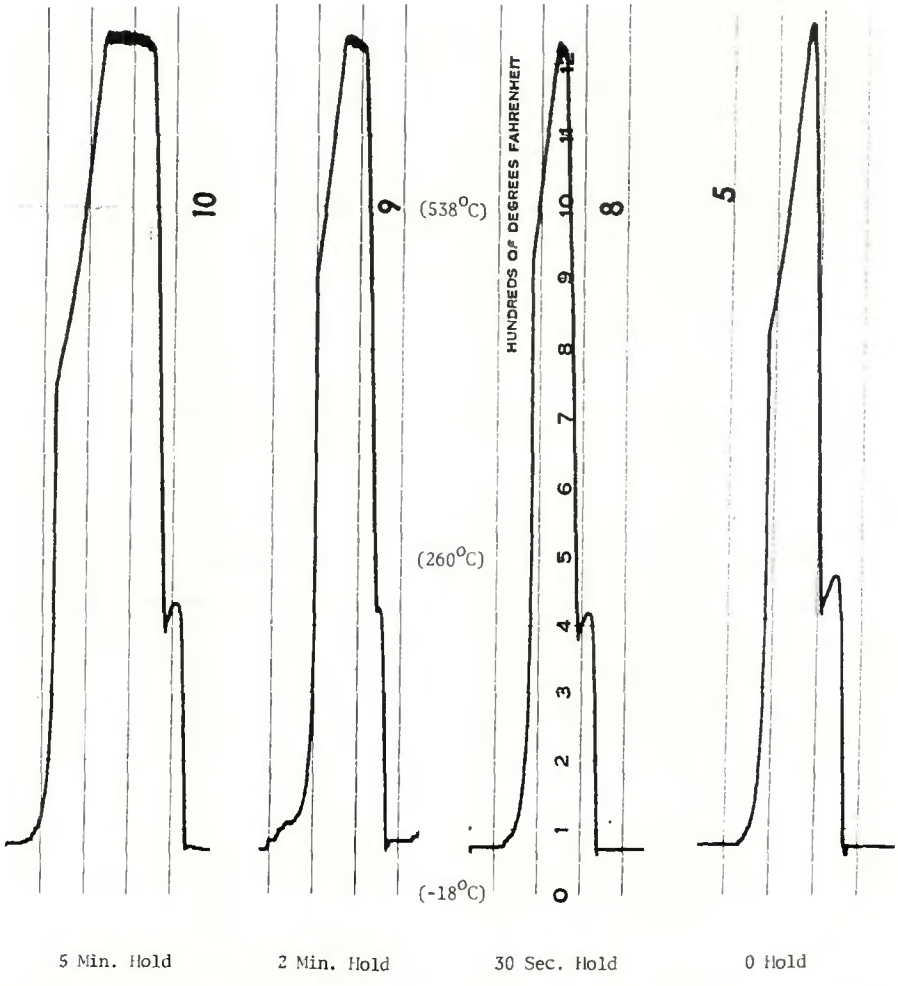

Fig. 6 — Thermal records of specimens held at 1250 F for various lengths of time after filler metal melts

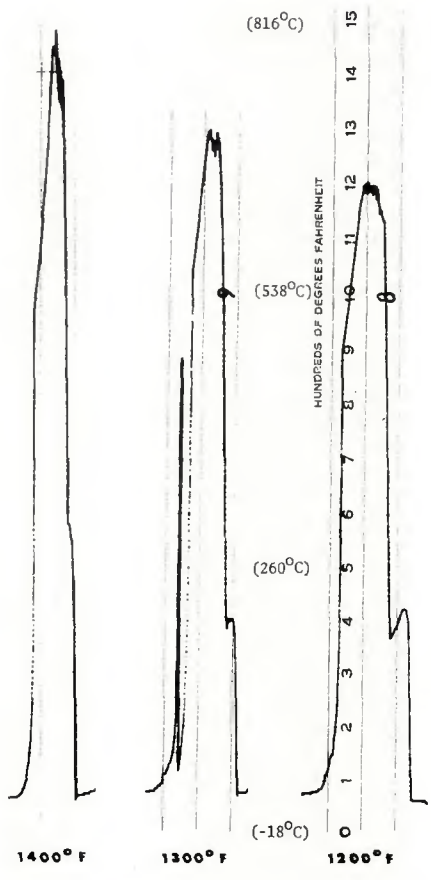

Fig. 7 — Thermal records of specimens brazed at various temperatures

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.

Exp. 2 — Variations in Joint Clearance

Procedures for Experiment 2 were the same as those used in Experiment 1 except that the major variable was joint clearance. Grade 4340 steel 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 in. (0.025, 0.051, 0.076, and 0.127 mm). One inch (25.4 mm) of 0.031 in. (0.787 mm) diam filler wire was used for the 0 and 0.001 in. clearances, and 2 in. (50.8 mm), 3 in. (76.2 mm) and 5 in. (127.0 mm) of 0.031 in. diam filler wire used, respectively, for the 0.002, 0.003 and 0.005 in. clearances.

Exp. 3 — 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 in. and the power to the induction coil was left on for various lengths of time after the filler metal melted. A 3 in. length of filler metal was used for these specimens. The controlling instrument was set to maintain a temperature of 1250 F (678 C) 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 F (371 C) and 1000 F (539 C). This is necessary because otherwise the flux freezes the thermocouple in its well. The specimens cool off in accordance with the curve shown in Fig. 5.

Exp. 4 — Effect of Temperature at which Filler Metal Is Introduced

In this experiment, grade 4340 steel and a 0.003 in. clearance were again used. The remote filler wire release was used, and a 3 in. length of filler wire was released when the specimen reached a preselected temperature. The temperatures were 1200 F (649 C), 1300 F (704 C), and 1400 F (762 C). 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 (649 C) specimen temperature the filler wire would not melt, and above 1400 F (762 C) the flux deteriorated so rapidly as to preclude brazing. In fact, even at 1400 F (762 C), 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 1. Figure 7 shows typical thermal experience records of specimens in this group.

Exp. 5 — Effect of Capillary Flow against Gravitational Force

In this experiment, grade 4340 steel was used at clearances of 0.001 in., 0.002 in., 0.003 in., and 0.005 in. 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 in. clearance; a 5 in. length was used at that clearance. All specimens were held for one minute at brazing temperatures (1250 F) (678 C) after the filler metal completely melted.

Exp. 6 — 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 in. (12.7 mm), 3/8 in. (9.52 mm), 1/8 in. (3.18 mm), and 1/16 in. (1.59 mm). Clearance was 0.002 in. The filler metal was preplaced in the tube guide, and all specimens were held at 1250 F (678 C) 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.

Exp. 7 — Effect of Preplaced Foil

In this experiment, 0.003 in. 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 in. steel shim clearance spacer, and with a 0.002 in. steel spacer. With the "no clearance" and 0.002 in. 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) (664 to 672 C) after the filler metal melted.

Exp. 8 — 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, (400 μm), 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 $\times$ 10^{-1} torr (300 to 400 microns Hg). As techniques improved in later experiments, pumpdown levels of about 1 $\times$ 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 was opened and adjusted so as to produce a flowing atmosphere at that pressure.

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, 0.003 in. clearance and 3 in. 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 in. clearance, 3 in. of filler metal and no flux, also allowing one minute after the filler metal melted.

Two specimens were made with flux, using 0.003 in. thick foil, BAg-1 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 in. foil filler metal, and a 0.002 in. steel shim spacer, also allowing one minute at the brazing temperature after the filler metal melted.

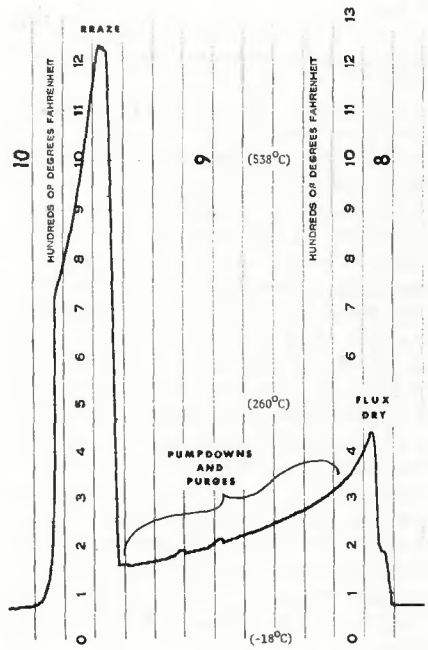

Fig. 8 — Time-temperature record for specimen brazed in argon in bell jar

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 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

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 introduced in the approximate center of the "V" groove, so it is obvious that the path 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.

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 in.) 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 in. clearance specimens show the general tendency to produce smaller, but more frequent, defects at smaller clearances. Generally, the 0.003 in. clearances produced about the best results and, accordingly, this clearance was used in most of the succeeding experiments.

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 Fig. 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, of such joints are similarly defective.

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) (762 C) is obviously better in quality than specimens 4-A and 4-B (filler introduced at 1200 F) (649 C). Its mate, Specimen 4-E, except for the large defect in the center, also shows smaller and more regularly shaped defects.

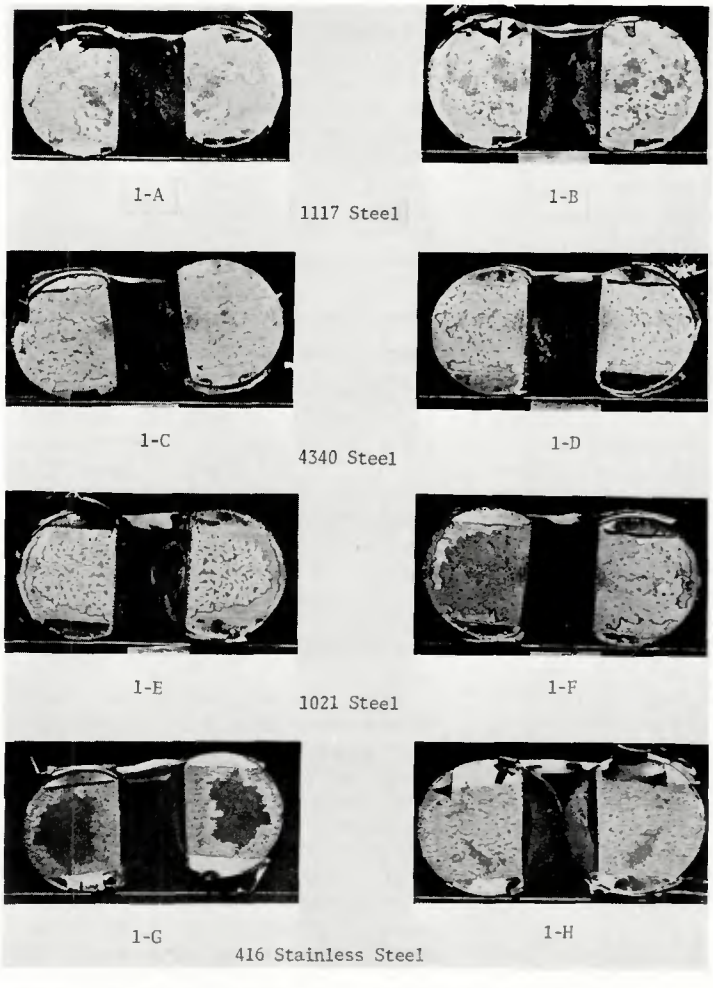

Fig. 9 — Results of Experiment 1 — variations in composition of steel

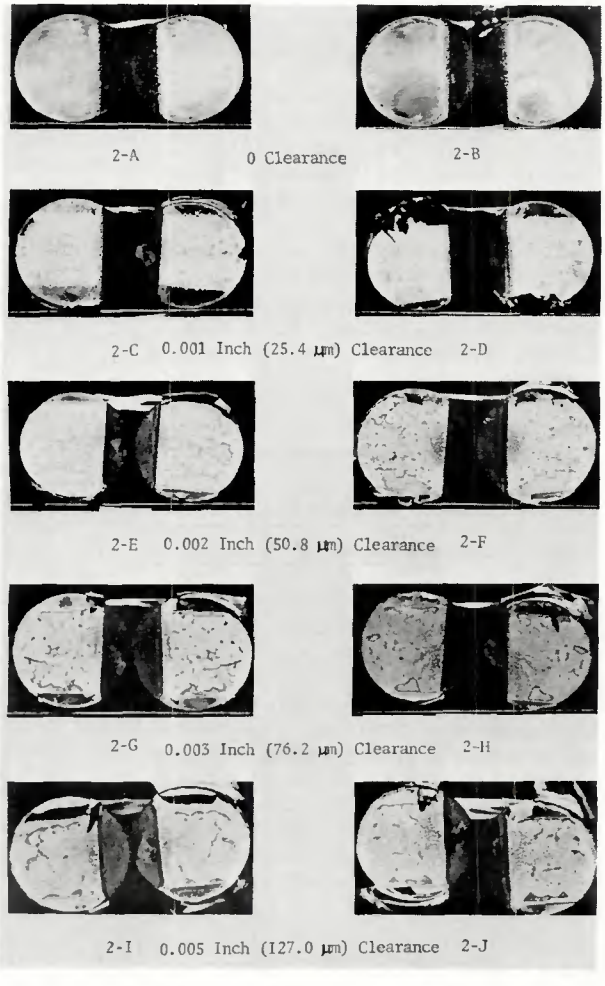

Fig. 10 — Results of Experiment 2 — variations in joint clearance

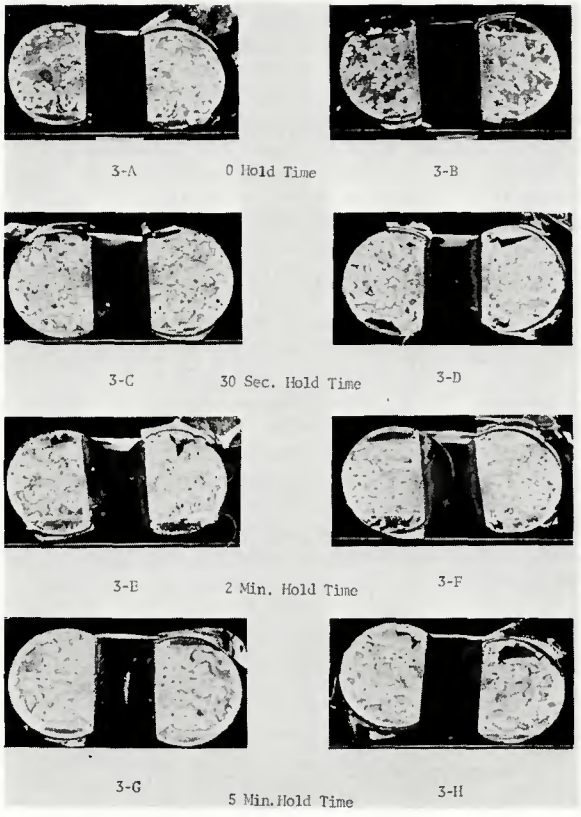

Fig. 11 — Results of Experiment 3 — variations in hold time

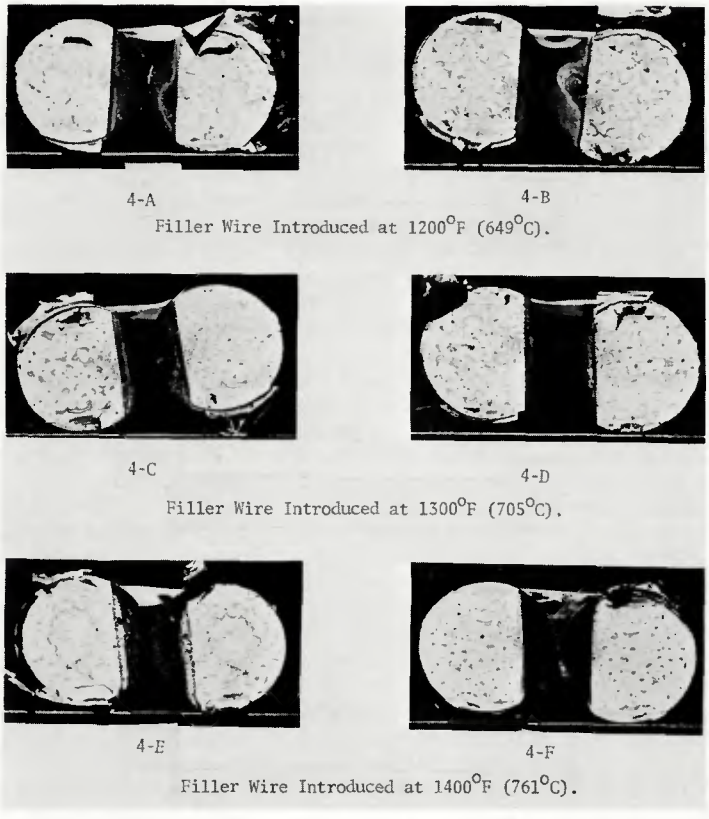

Fig. 12 — Results of Experiment 4 — variations in temperature at which filler wire is introduced

Effect of Capillary Flow Against Gravitational Force

Figure 13 shows specimens of Experiment 5 in which the direction of filler metal flow was opposed to gravitational force. Clearances were 0.001, 0.002, 0.003 and 0.005 in., respectively. These specimens are directly comparable to those shown in Fig. 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 in.) 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.

Effect of Variation in Flow Path Width

Figure 14 shows the results of Experiment 6 in varying 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 in. (1.52 mm) wide paths have major defects directly through the center of the path.

Effect of Preplaced Foil Filler Metal

Figure 15 shows the results of Experiment 7 with foil filler metals. Specimens 7-A and 7-B are the specimens which were made with 0.003 in. 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.

Specimens 7-C and 7-D, 7-E and 7-F were brazed with 0.003 in. foil filler metal and 0.003 in. and 0.002 in. 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.

Effect of Brazing in Argon Atmospheres

In Fig. 16, the fracture surfaces of the specimens brazed in argon (Experiment 8) 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 Fig. 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 in. 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 in. 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 Fig. 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 in. clearance spacer. Similar specimens were made in air (see Fig. 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.

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 in.) 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.

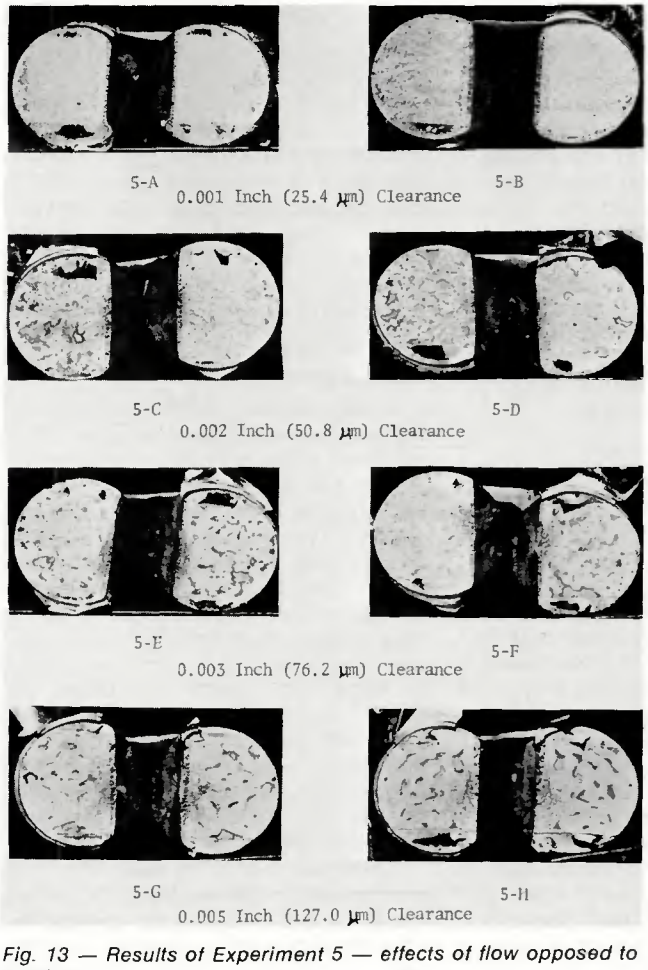

Fig. 13 — Results of Experiment 5 — effects of flow opposed to gravity

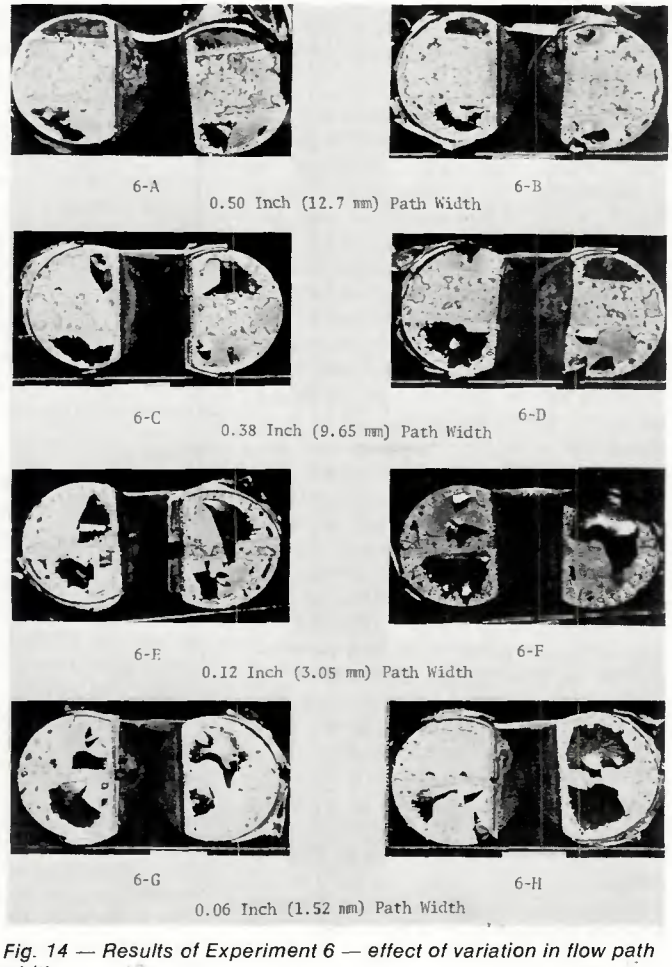

Fig. 14 — Results of Experiment 6 — effect of variation in flow path width

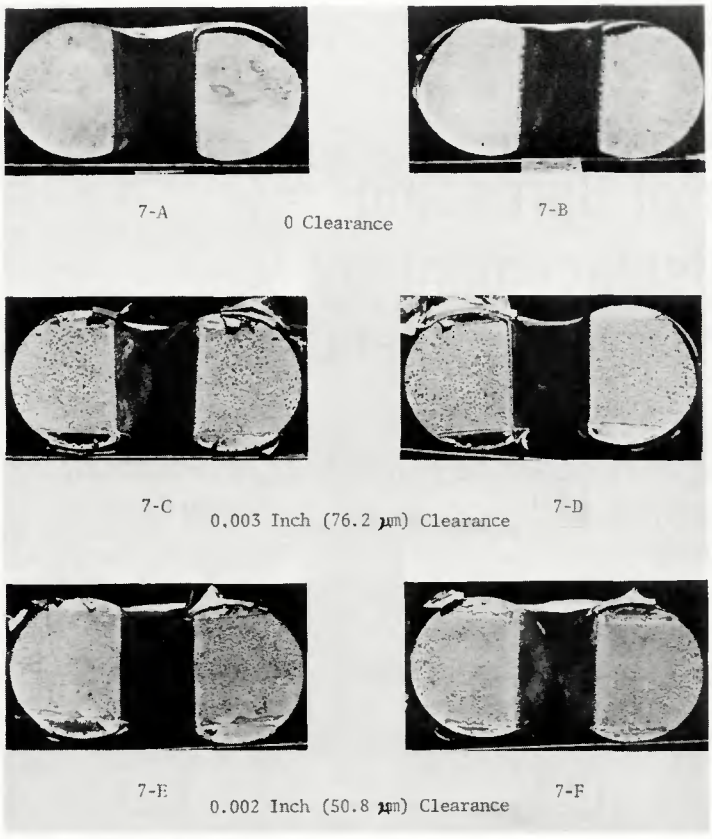

Fig. 15 — Results of Experiment 7 — effect of foil filler metal

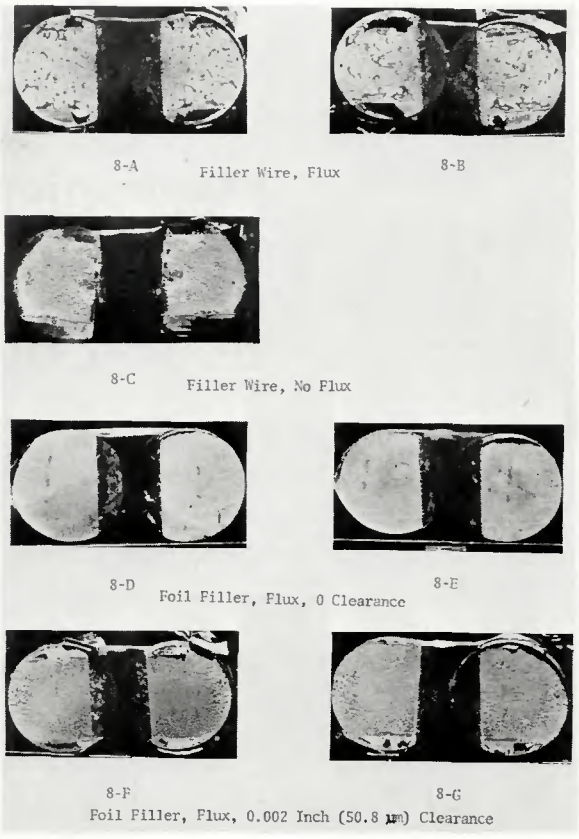

Fig. 16 — Results of Experiment 8 — effect of argon atmospheres

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.

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Discussions

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