NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3450

PRELIMINARY INVESTIGATION OF PROPERTIES OF HIGH-TEMPERATURE BRAZED JOINTS PROCESSED IN VACUUM OR IN MOLTEN SALT

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SUMMARY

An investigation was conducted to determine the shear strengths of high-temperature-alloy brazed joints. The variables investigated were the method of brazing (molten salt bath or vacuum furnace), nickel addition to the brazing alloy (AMS-4775), brazing temperature, holding time at temperature, and a protective coating on the braze area for salt-bath specimens. These variables were investigated simultaneously according to planned factorial experiments; the data were analyzed for the significance of the variance attributable to each variable or interaction.

The experimental results indicate that both methods of brazing are capable of producing good joints having shear strengths of the order of 63,000 and 48,000 psi for vacuum and salt bath, respectively. Data indicate that strengths obtained were greater than that reported for joints processed in dry hydrogen. In the molten-salt-bath process, the shear strength of a braze increases as the brazing temperature is increased, and the use of a protective coating increases the strength and decreases the variability of the results. In the vacuum process, temperature and time at temperature are the important variables, the best average strength occurring at 2075° F with a 15-minute holding period. The addition of nickel to the brazing alloy, within the range studied in these experiments, had no significant effect on the strength of the brazed joint processed in vacuum but was slightly beneficial in the salt-bath process.

INTRODUCTION

Brazing is a common fabrication method in the production of many items used at ordinary temperatures. Some of the advantages of brazing are: Complex assemblies can be made from formed components with a resultant saving in materials and machining costs, assemblies can be made from two or more different alloys to meet specific design requirements, and thin sections that can not be feasibly machined can be joined to heavier sections without sacrificing strength.

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These same features also make fabrication by brazing desirable for assemblies for high-temperature service. If brazed joints are able to withstand operating stresses at the high temperatures, brazing will be a practical method for fabricating assemblies for high-temperature service. The brazing alloy for high-temperature applications must be selected for its high-temperature properties and must be processed at some point above the use temperature. Both the braze material and the parent metal may contain constituents subject to oxidation at the brazing temperature. Therefore, the joint must be protected during the brazing. This protection may be obtained by brazing in dry hydrogen, vacuum, or molten salt.

The adaptation of brazing to the high-temperature field has been limited and little data have been published. Brazed joints of high-temperature alloys using AMS-4775 (Nicrobraz) have been successfully processed in dry hydrogen; reported room-temperature shear strengths for this process were of the order of 42,000 psi (ref. 1). No data have been reported for brazing in vacuum, and the little data available for salt brazing are limited to low-temperature applications (ref. 2). Experience at the NACA Lewis laboratory indicates that high-temperature alloys can be successfully salt-brazed with AMS-4775. In the preliminary work it was noted that the parent metal was damaged by erosion and diffusion of boron during the brazing cycle, but the addition of nickel seemed to reduce these effects.

The object of the present investigation was to evaluate the effects of temperature and holding time for both molten-salt and vacuum brazing. Also, the effect of nickel additions and a protective coating for salt-bath brazing were studied. Statistical methods were used to analyze the data. Microstructures present in the joint area were studied by conventional metallographic procedures. Limited stress-rupture data at 1300° F were obtained.

MATERIALS AND APPARATUS

Materials

The alloy combinations used for the different processes are given in table I(a), and their chemical compositions are given in table I(b). Most of the data reported herein concern the brazing of AMS-5537 sheet (L-605) to AMS-5765A (S-816 bar stock). AMS-4775 (Nicrobraz) alloy was used for brazing all joints. The AMS-4775 brazing alloy contained 4.8 percent boron and was used both plain and modified with pure nickel. The braze is described as a nickel-base alloy having a solidus point of 1850° F and a flow point near 1950° F. It forms a solid solution with stainless steel alloys. During brazing, the base metal dissolves into the Nicrobraz and forms a new phase with higher melting point and viscosity (ref. 1).

Reference 3 describes the reaction between the brazing material and the base metal as diffusion of the boron into the base material and suggests that the use of excess brazing alloy be avoided to minimize diffusion through thin sections and erosion of the base metal. In processing, the brazing alloy must be heated to a temperature sufficiently above its melting point to develop enough fluidity to flow between mating parts; but if the temperature is too high, the joint area is severely penetrated and eroded by the braze alloy.

Designs of specimens used to test the shear strengths of brazed joints are shown in figure 1. Specimens of designs A, B, and C fractured in the base metals instead of shearing through the joint. Although such an outcome did not give values for the joint strength, it did indicate that brazed joints of high-temperature materials could be obtained by processing in molten salt or vacuum. Specimens of design D yielded quantitative data upon which the statistical analyses were based. Specimens of design E were used to determine the stress-rupture life of brazed joints at 1300° F.

Some of the joints brazed in the molten salt bath were protected by a coating to minimize the loss of the braze alloy. The coating consisted of 100 parts of graphite, 10 parts of enamelers' clay, 1 part of ammonium alginate, and water. At various times, the coating has been used as a paste, a thick slurry for dipping, and a thin slurry for spray application.

Apparatus

Vacuum. - Most of the vacuum brazing was conducted in the resistance-heated furnace shown in figure 2. The furnace chamber consists of an alundum cylinder wound with a tungsten resistance wire. The outer steel jacket is water-cooled, and the top plate makes a vacuum seal against the O-ring.

The vacuum is produced in the system through the use of a conventional vacuum system consisting of a roughing pump coupled to a vapor diffusion pump using a silicone fluid. The vacuum obtainable in this system ranges between 2 and 150 microns (2.0×10^{-3} to 1.5×10^{-1} mm Hg) depending upon the outgassing of the material being processed. The average vacuum obtained for the work in this investigation was of the order of 3 to 5 microns as measured by a Pirani gage.

The temperature in the furnace was measured by the use of a platinum-rhodium (type QR) thermocouple and an electronic recording-controlling potentiometer. The maximum capacity of the furnace was four test pieces per cycle.

Salt bath. - The induction-heated salt-bath furnace consisted of an Inconel pot approximately $4\frac{3}{8}$ inches in inside diameter and 7 inches high with a 1/4-inch wall, which was heated in a nine-turn $6\frac{1}{2}$-inch-inside-diameter water-cooled inductor. The power supply for the coil was a 200-kilowatt 3000-cycle-per-second motor generator unit operated at about 5 percent of rated capacity. The salt pot and heating coil are shown in figure 3. A commercial heat-treating salt prescribed for use in the range 1900° to 2450° F was used. This salt was essentially dehydrated barium chloride. Temperature was measured by a protected chromel-alumel thermocouple immersed in the molten salt.

PROCEDURE

The brazing techniques used in this investigation require that the mating parts of the assembly maintain clearances and alinement and be free of grease, dirt, and oxides. Therefore, the parts were ground to proper tolerances (to result in a press fit) and chemically cleaned or electromachined in an acid solution to yield the desired surfaces. No effort was made to determine the effect of surface-cleaning methods on the brazing process.

In order to obtain the desired braze surface area, the sheet material of the specimens was inserted into the slotted bar-stock bases for a controlled distance as measured by the positioning jig shown in figure 4.

Preparation and Application of Braze

The braze material consisted of standard AMS-4775 powder suspended in acrylic resin, with additions of pure nickel powder in some cases. The acrylic resin is used to "glue" the braze powder to the area desired and to serve as a temporary binder during handling and transporting of specimens prior to heating. It may be thinned with acetone or toluene to the desired consistency for application and burns off at 800° F without leaving a residue.

Pure nickel powder was mixed with the AMS-4775 alloy powder to give brazing materials containing either 5 or 10 percent of added nickel by dry weight. The brazing materials were mixed with the thinned acrylic binder to form a viscous slurry which was applied in the desired amount to the assembled joint.

Vacuum brazing process. - The prepared specimens were placed in the inner heating chamber of the furnace, and the furnace head was placed in the vacuum chamber. After the vacuum had been applied and the pressure had reached the desired level of 3 to 5 microns, the power was turned on. The furnace specimens were brought to the required temperature in approximately 55 minutes; then the recording-controlling potentiometer took over to maintain the holding temperature. Approximately 45 minutes was required for cooling from the brazing temperature to 500° F, so that the furnace could be opened and the specimens removed. The complete time cycle depended upon the length of the holding period at peak temperature.

Salt-bath process. - The barium chloride salt was heated by conduction from the Inconel pot. The specimens were placed on a stainless steel rack and immersed in the liquid for varying periods of time after the molten salt had reached the desired temperature. The power input was controlled to give temperature recovery of the bath in the desired time. The total time cycle is very short, compared with that used in vacuum or hydrogen brazing, primarily because of the rapid recovery and cooling rates possible.

Protective coating in salt-bath process. - In the course of the work using the molten salt bath for brazing, a coating was developed to protect the applied braze material from erosion by the molten salt. Specimens used in the first experiment were not coated, but those for all subsequent salt-bath processes were coated. The protective coating was mixed dry, then tumbled with water in a ball mill to form a slurry. The protective coating was applied by dipping the assembly into the slurry after the brazing material had set. The water was removed by drying in an oven heated to a temperature of approximately 180° F. In some cases this was followed by a resin burn-off in a furnace at 800° F. Then, care had to be exercised in the handling of the specimens, since the coating and braze material could be rubbed off very easily.

Brazing Variables Studied

As the investigation progressed, the procedures had to be modified in order to obtain data amenable to statistical treatment. To simplify the presentation of results, the investigation has been divided into six studies or phases as follows:

(1) The initial phase of this investigation was conducted to determine the possibility of brazing a number of different alloy combinations in vacuum and to develop a suitable specimen for shear-strength determination. Specimen types A and B (fig. 1) were used.

(2) The second phase was a study of the effect of brazing temperature, time at temperature, and nickel additions to the AMS-4775 on the shear strengths of brazed joints processed in a molten salt bath. Twenty-seven specimens of design C were processed, one specimen for each change in variable. The brazing temperatures used were 1950°, 2050°, or 2150° F; the brazing times were 2, 6, or 10 minutes; and

nickel additions were 10, 30, or 50 percent. Since the specimens frequently fractured outside the braze area, the results of this phase yielded only qualitative shear data, and a third phase had to be conducted to obtain quantitative shear-strength data.

(3) In the third phase, the brazing was again conducted in a molten salt bath. Specimens used were of design D, in which the thickness of the sheet was greater and the depth to which it was inserted in the base was less than the corresponding dimensions of design C. This phase was conducted to determine the effect of brazing temperature, nickel additions to the AMS-4775 braze, and the use of a protective coating during brazing on the shear strength of the brazed joints. The holding time was kept constant at 4 minutes, and new limits were set on the temperature and nickel additions in accordance with experience gained from the second phase. Eighteen specimens were processed, one specimen for each change in variable. The brazing temperatures were 2000°, 2075°, or 2150° F; nickel additions were zero, 5, or 10 percent; and specimens were brazed either with or without protection. The data from this phase were analyzed by the statistical method (analysis of variance), which is explained in the appendix.

(4) The fourth phase compared the shear strengths of joints produced by vacuum brazing with those of joints produced by molten-salt-bath brazing. Nine specimens of design D were used. The brazing temperatures and nickel additions were the same as in phase (3). Protection was unnecessary and not used. The holding time at the brazing temperature was set at half an hour, because preliminary runs in vacuum had shown that this time would produce adequate braze strengths. The results from this phase were compared by statistical procedures with results obtained in phase (3).

(5) The purpose of phase (5) was to determine the optimum conditions for vacuum brazing. Variables investigated were temperature in 75° increments from 1850° to 2150° F, holding time of zero, 15 or 30 minutes at temperature, and zero, 5-, or 10-percent additions of nickel. This investigation required 45 specimens with one specimen for each change in variable. Statistical procedures were used to evaluate the data.

(6) In phase (6) an attempt was made to determine the stress-rupture life at 1300° F of slurry-protected specimens brazed in a salt bath under the conditions used in phase (3). Specimen design E of figure 1 was used in this determination.

RESULTS

The effect of certain variables upon the shear strengths of brazed joints has been determined by planned factorial experiments that can be analyzed by statistical methods. This analysis provides a mathematical measure of the degree of certainty that can be attached to those trends observed by simple inspection of the experimental data and also helps to define those actions and interactions of the variables studied that might be overlooked by a less rigorous analysis. The statistical treatment does not change the interpretation of the original data, but it evaluates the degree of certainty. Results of the statistical analysis are given in the appendix.

Individual Phases

The shear-strength data are reported in tables II and III. The average shear-strength values shown in these tables were obtained by averaging all the values associated with a given variable.

Phase (1). - The results of the first phase (table II) show that the braze area was too large to permit failure due to shear. Large variations are observed in the tensile strength of the L-605 sheet.

Phase (2). - The shear strengths obtained in the second phase are listed in table III(a). The fact that six of the nine specimens processed in salt at 2150° F did not fail in shear precluded the use of statistics to evaluate the effect of the variables efficiently. However, the following trends were noted:

(a) Shear strengths increased from an average value of 18,385 psi to greater than 24,531 psi as the brazing temperature was increased from 1950° to 2150° F.

(b) The effect of time at temperature could not be determined for the range used. The indications were that only sufficient time to melt the braze alloy and permit some diffusion to occur would be required to produce adequate shear strengths.

(c) Shear strengths were usually least with 50 percent added nickel.

Phase (3). - The effectiveness of a protective coating, of added nickel, and of brazing temperatures can be noted in table III(b). The protective coating improved the average shear strength by about 6000 psi and decreased the variability of results. Average strengths for protected and unprotected joints were 48,430 and 42,680 psi, respectively; the range of strengths was from 42,900 to 54,900 psi for protected joints and from 33,000 to 50,900 psi for unprotected joints.

The effect of brazing temperature followed the pattern established in the second phase, in that the average shear strength increased with temperature from 41,950 psi at 2000° F to 49,700 psi at 2150° F, a gain of approximately 18 percent.

As indicated by the statistical analysis (see appendix), the nickel additions improve the shear strength to a limited extent in salt-bath brazing. The greatest average strength, which occurred in the brazed joints having 10 percent nickel, was approximately 3000 psi greater than those of specimens containing zero or 5 percent added nickel. Shear strengths of the order of 50,000 psi should be realized by molten-salt brazing with proper techniques.

Although there was no known difference in the brazing technique between phases (2) and (3), the shear strengths reported in table III(b) are considerably higher than those reported in table III(a). However, it is recognized that the specimens used in these two phases were not identical and resulted in somewhat different loading conditions at the junction between the braze and parent metals.

Phase (4). - The results of the comparison of salt-bath brazing with vacuum brazing are given in table III(c). The average strengths were 59,560 psi for vacuum and 48,430 psi for salt brazing. This experiment indicated that average shear strengths approaching 60,000 psi could be realized from vacuum processing.

Phase (5). - The results of tests to determine optimum vacuum brazing are shown in table III(d). Under all the test conditions, there was a definite increase in the average shear strength as the temperature increased to 2075° F. There is no indication that higher temperatures would be of any advantage for the conditions investigated.

The time at temperature is of particular importance when the brazing temperature is near the flow point of the braze alloy. Thus, large increases in average shear strength for brazing at 1850° F can be obtained by increasing the brazing time to 30 minutes. This effect of time gradually disappears as the brazing temperature is increased; in fact, at the highest temperatures long times may be detrimental. In general, it appears that the highest shear strengths, of the order of 65,000 to 70,000 psi, are associated with brazing at 2075° F for 15 minutes.

Within the range of the variables investigated, there was no effect of nickel addition.

Phase (6). - The time to rupture at 1300° F under stresses of 15,000 and 25,000 psi are given in table IV. Unfortunately, only three out of the ten specimens failed in the shear area. However, the data indicate that the higher brazing temperatures result in considerably improved rupture life. The 300-hour shear stress for 2150° F brazing appears to be at least 15,000 psi.

Microstructure of Brazed Joints

During brazing some erosion and penetration of the parent metal occurred on each specimen regardless of the medium used (vacuum or salt). A typical brazed specimen is shown in figure 5. The braze alloy eroded approximately 0.004 inch off the face of the AMS-5537 base metal and penetrated an additional 0.002 inch.

Figure 6 shows typical brazed joints between AMS-5765A and AMS-5537. These joints were well made with only occasional voids occurring in the joint area. The microstructure of the braze within the body of the joint is of the solid-solution type.

DISCUSSION OF RESULTS

Within the scope of this investigation, vacuum brazing produced better shear strengths than salt-bath brazing. Thus, shear strengths of the order of 63,000 psi are obtainable with vacuum, and of the order of 48,000 psi with molten salt. With regard to the effect of temperature, the shear strengths in salt brazing were greatest at the highest temperature investigated (2150° F). In vacuum, the shear strength also increases with increasing temperature to a maximum value at 2075° F and then may decrease slightly.

There was no effect of holding time (between 2 and 10 min) at temperature in salt brazing. However, it may be hypothesized that a successful braze can be made in salt if the holding time is only sufficient to cause flow of the braze alloy. In contrast, in vacuum brazing there was a pronounced improvement in shear strength at the low brazing temperatures as the holding time increased.

There was no effect of nickel for the range of additions investigated in vacuum brazing and only a slight beneficial effect in salt brazing. This latter improvement is not considered large enough to be of practical interest. However, it is felt that the general effects of nickel (or other element) additions should be further considered, since experience has indicated that less erosion and penetration of the parent metal occurs in the presence of nickel additions.

The erratic values of the sheet tensile strength reported in table II indicate that parent metals may be damaged by the braze alloy.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the high-temperature braze material AMS-4775 processed in vacuum or molten salt:

1. The vacuum and molten-salt-bath processes were capable of producing brazed joints with shear strengths of the order of 63,000 and 48,000 psi, respectively, under proper conditions. These values are higher than the 42,000-psi shear strength reported in the literature for hydrogen-atmosphere brazing.

2. For salt-bath brazing, the average shear strength of joints increases approximately 18 percent with an increase in the temperature of brazing from 2000° to 2150° F.

3. For vacuum-brazed joints, the strengths were found to be a function of temperature and time at temperature. The strongest joints (strengths of the order of 63,000 psi) were produced by brazing at 2075° F for 15 minutes.

4. The addition of nickel to the AMS-4775 alloys produced only a slight improvement in the shear strength of salt-brazed specimens and had no effect on the shear strength of vacuum-brazed specimens.

5. The protective coating increases the average shear strength of joints processed in molten salt by about 14 percent and decreases the variability of the shear-strength values.

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APPENDIX - STATISTICAL ANALYSIS OF EFFECTS OF TEMPERATURE, TIME AT TEMPERATURE, AND NICKEL ADDITIONS ON SHEAR STRENGTH OF BRAZED JOINTS

The effect of certain variables upon the shear strengths of brazed joints has been determined in this investigation by planned factorial experiments that can be analyzed by statistical methods. The factorial experiment will detect the effects of varying a specific independent variable while other independent variables are also varied over their full range. Interdependence or interaction between independent variables may also be shown. The factorial experiment is much more efficient than the usual classical experiment in which all independent variables except one are held constant.

Within the body of this report, conclusions were drawn from the results by a critical examination of the tabular data; in this appendix, three sets of data are analyzed with the use of statistics to establish confidence limits for these conclusions and to check for significant interactions between the independent variables.

Procedure

The data that are reanalyzed herein are related to (1) the effect of nickel additions to the braze, of brazing temperature, and of a protective coating on the shear strength of joints brazed in salt (table III(b)); (2) a comparison of the shear strengths of salt- and vacuum-brazed joints (table III(c)); and (3) the effect of nickel additions to the braze, of brazing temperature, and of time at temperature on the shear strength of joints brazed in vacuum (table III(d)). For convenience of calculation and presentation of results, these data are retabulated in tables V, VI, and VII, respectively. In order to simplify the mathematics, the data were coded; the code formula is given in brackets below the table of actual shear strengths obtained. A description of the methods of statistical analysis that were used may be found in reference 4.

Each of the tables is divided into three parts. Part (a) tabulates the experimental data. Part (b) is the analysis of variance. The first column lists the variables, combinations of variables or interactions, total variance of the system, and the residual experimental variance; the second column gives the degrees of freedom associated with the item in the first column. The third and fourth columns (coded experimental data) give the variance (sum of squares) and mean squares for each item. The data in the columns under the heading "Pooled data" have the same meaning as those in columns three and four, respectively, and are used when pooling of the data is necessary, because the variance of some of the items is so small as to be considered nonexistent. The F-test-ratio column, which gives the variance ratio (Fisher's F test), was derived by dividing the mean square for an item by the mean square of the residual variance. The last three columns are used to record the values of the F-test ratio that must be equalled or exceeded for a factor to be considered significant at the level indicated.

Part (c) of the table lists the mean shear strength and the standard deviation of the mean for each level of any variable. These items are of interest because they indicate the over-all effect of a variable more readily than an examination of the experimental values. In addition, the data can be used in tests to determine the significance of difference between means, variances, or populations according to accepted statistical procedures.

Results

The results of the study of the effects of a temperature of 2000°, 2075°, or 2150° F, zero, 5, or 10 percent added nickel, and protection against erosion on the shear strength of joints processed in a molten-salt bath (phase (3)) listed in table III(b) and V are as follows:

(1) Temperature influences the shear strength of brazed joints and has a level of significance which falls between 0.01 and 0.001. As the temperature increases from 2000° to 2150° F, the mean shear strength of the brazed joints increases from 41,950 to 49,700 psi, with a standard deviation of the mean strength of ±690 psi.

(2) The effect of added nickel is significant at the 0.05 level, and the best shear strength was obtained at 10 percent added nickel. No significant difference could be determined between the shear strengths of brazed joints having 5 percent added nickel from those having no added nickel. The average shear strength increased from 44,280 psi for brazed joints having no added nickel to 47,650 psi for brazed joints having 10 percent added nickel, each with a standard deviation of the mean strength of ±690 psi.

(3) Protection, with a level of significance between 0.01 and 0.001, also has an effect upon shear strength. Protection increases the mean strength of salt-bath brazed joints from 42,680 psi for the unprotected assemblies to 48,430 psi for the protected assemblies, each with a standard deviation of the mean strength of ±565 psi.

(4) In this study, interactions between protection and the percent added nickel and between the temperature and the percent added nickel

were indicated at the 0.05 level of significance, and an interaction between protection and temperature was indicated at the 0.01 level of significance. However, the effects of the various interactions upon the value of the shear strength of the brazed joints could not be determined with any degree of certainty, because data were not obtained to show the magnitude of these effects.

The statistical evaluation of phase (4)(table VI), in which the effects of brazing method, percent added nickel, and temperature on the shear strength of brazed joints were studied, shows that the method of brazing is highly significant (higher than the 0.001 level). A comparison of the mean shear strengths obtained for each method shows that vacuum brazing produces stronger shear joints than salt-bath brazing, their respective mean values being 59,560 and 48,430 psi, respectively, each with a standard deviation of the mean of ±1100 psi.

The results of statistical evaluation of the effects of a temperature of 2000°, 2075°, or 2150° F, time of zero, 15, or 30 minutes at temperature, and zero, 5, or 10 percent added nickel on the shear strength of joints processed in vacuum listed in table VII show that time and temperature are significant at the 0.05 level, and that the percent added nickel is not a significant variable in this range. The comparison-of-means table shows that best shear strengths are obtained with a holding time of 15 minutes at a brazing temperature of 2075° F.

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TABLE I. - ALLOY COMBINATIONS, PROCESSES, AND CHEMICAL ANALYSES OF ALLOYS USED TO PRODUCE BRAZED JOINTS WITH AMS-4775 ALLOY

(a) Alloy combinations and processes used to produce brazed joints with AMS-4775 alloy

Alloy combinations				Process	
Alloy	AMS number	Alloy	AMS number	Vacuum	Salt
L-605	5537	S-816	5765A	x	x
L-605	5537	HS-21	5385	x	x
L-605	5537	Inconel	5540D		x
L-605	5537	Inconel X	5542D		x
Inconel	5540D	HS-21	5385		x
Inconel X	5542D	HS-21	5385		x
16-25-6	5725A	N-155	5532B		x

(b) Compositions of parent metals used in brazed joints

Alloy	AMS number	Composition, percent										
		C	Cr	Ni	Co	Mo	W	Fe	Cb	Ti	Al	Other
L-605	5537	0.10	19.5	10.0	51.3	----	14.5	2.5	----	---	---	B 0.04
S-816	5765A	.40	20.0	20.0	43.7	4.0	4.0	2.8	3.75	---	---	-----------
HS-21	5385	.30	26.5	3.0	62.0	5.25	----	1.5	----	---	---	-----------
16-25-6	5725A	.09	16.0	25.0	----	6.25	----	50.5	----	---	---	N 0.15
N-155	5532B	.13	21.0	20.0	20.0	3.0	2.2	30.0	1.0	---	---	N 0.13
Inconel	5540D	.05	14.5	77.5	----	----	----	6.5	----	---	---	Cu 0.20
Inconel X	5542D	.05	15.0	72.5	----	----	----	7.0	1.0	2.5	0.7	Cu 0.05
Nicrobraz[a]	(a)	----	15.0	71.5	----	----	----	4.5	----	---	---	Si 4.0 B 4.8
Nicrobraz[b]	4775	----	13-20	65-75	Fe + Si + C = 10 max				----	---	---	B 2.75-4.75

[a]Chemical analysis performed at NACA Lewis laboratory.

[b]Chemical analysis taken from ref. 2.

TABLE II. - STRENGTH OF NICROBRAZED JOINTS FOR MISCELLANEOUS METAL COMBINATIONS PROCESSED IN VACUUM. PHASE (1)

Type of specimen (fig. 1)	Nickel added, percent	Materials		Shear strength of brazed joint, psi	Tensile strength of parent metal, psi	Location of failure
A	0	AMS-5725 16-25-6	AMS-5532B N-155	> 21,400	114,000	N-155
B	10	AMS-5537 [a]L-605	AMS-5532B N-155	> 7,400	157,000	L-605
				> 5,100	110,000	L-605
			AMS-5385 HS-21	> 12,600	139,000	L-605
			AMS-5765A S-816	> 21,600	125,500	L-605
				16,100	> 74,600	Braze
	20	AMS-5537 L-605	AMS-5765A S-816	> 11,400	134,200	L-605
				> 9,400	111,100	L-605

[a]L-605 used as 0.030-in. sheet.

TABLE III. - SHEAR STRENGTHS OF BRAZED JOINTS BETWEEN AMS-5537 SHEET AND AMS-5765A BAR STOCK

(a) Phase (2). Effect of brazing temperature, time at temperature, and nickel addition. Molten-salt process; specimen C

Temperature, °F	Time, min	Shear strength, psi			
		Nickel added, percent			Average for temperature
		10	30	50	
1950	2 6 10	21,060 21,670 20,100	16,000 18,570 17,870	13,390 15,910 20,900	18,385
2050	2 6 10	23,120 24,500 26,100	25,880 24,750 24,450	22,490 20,870 19,390	23,505
2150	2 6 10	22,370 [a] >26,660 [a] >27,390	[a] >29,860 [a] >26,010 [a] >24,220	23,060 18,920 [a] >22,290	>24,531

[a] Specimens failed by tension failure in sheet; thus shear strength of brazed joint is greater than this stress applied at time of sheet fracture.

TABLE III. - Continued. SHEAR STRENGTHS OF BRAZED JOINTS BETWEEN AMS-5537 SHEET AND AMS-5765A BAR STOCK

(b) Phase (3). Effect of protective coating, brazing temperature, and nickel addition. Molten-salt process; time at temperature, 4 minutes; specimen D

Protective coating	Nickel added, percent	Shear strength, psi				
		Temperature, °F			Average without and with coating	Average for nickel added
		2000	2075	2150		
Without	0	37,900	41,700	50,100		44,280
	5	33,000	35,600	49,100	42,680	44,730
	10	38,000	47,800	50,900		
With	0	48,600	42,900	44,500		
	5	47,300	48,500	54,900	48,430	47,650
	10	46,900	53,600	48,700		
Average shear strength for temperature, psi		41,950	45,020	49,700		

CP-3

TABLE III. - Continued. SHEAR STRENGTHS OF BRAZED JOINTS BETWEEN AMS-5537 SHEET AND AMS-5765A BAR STOCK

(c) Phase (4). Effect of brazing process, temperature, and nickel addition. Time at temperature, 30 minutes in vacuum, 4 minutes in salt; specimen D

Brazing process	Nickel added, percent	Shear strength, psi			
		Temperature, °F			Average for process
		2000	2075	2150	
Salt (with protection)	0	48,600	42,900	44,500	48,430
	5	47,300	48,500	54,900	
	10	46,900	53,600	48,700	
Vacuum	0	57,900	56,400	57,000	59,560
	5	62,200	63,600	54,300	
	10	61,900	58,000	64,700	

TABLE III. - Concluded. SHEAR STRENGTHS OF BRAZED JOINTS BETWEEN

AMS-5537 SHEET AND AMS-5765A BAR STOCK

(d) Phase (5). Effect of brazing temperature, time at temperature, and nickel addition. Vacuum process; specimen D

<table>
<tr><th rowspan="3">Temperature, °F</th><th rowspan="3">Time, min</th><th colspan="6">Shear strength, psi</th></tr>
<tr><th colspan="3">Nickel added, percent</th><th colspan="2" rowspan="2">Average for temperature</th><th rowspan="2">Recalculated for above 2000° F</th></tr>
<tr><th>0</th><th>5</th><th>10</th></tr>
<tr><td rowspan="3">1850</td><td>0</td><td>3,000</td><td>1,300</td><td>200</td><td colspan="2" rowspan="3">17,070</td><td rowspan="3"></td></tr>
<tr><td>15</td><td>8,100</td><td>12,900</td><td>10,100</td></tr>
<tr><td>30</td><td>33,600</td><td>27,300</td><td>57,100</td></tr>
<tr><td rowspan="3">1925</td><td>0</td><td>24,300</td><td>56,300</td><td>11,800</td><td colspan="2" rowspan="3">45,100</td><td rowspan="3"></td></tr>
<tr><td>15</td><td>36,000</td><td>34,600</td><td>56,800</td></tr>
<tr><td>30</td><td>55,800</td><td>64,500</td><td>65,800</td></tr>
<tr><td rowspan="3">2000</td><td>0</td><td>46,500</td><td>54,000</td><td>50,500</td><td colspan="2" rowspan="3">57,490</td><td rowspan="3">57,490</td></tr>
<tr><td>15</td><td>67,800</td><td>60,500</td><td>56,100</td></tr>
<tr><td>30</td><td>57,900</td><td>62,200</td><td>61,900</td></tr>
<tr><td rowspan="3">2075</td><td>0</td><td>62,100</td><td>59,000</td><td>64,700</td><td colspan="2" rowspan="3">63,060</td><td rowspan="3">63,060</td></tr>
<tr><td>15</td><td>70,000</td><td>68,200</td><td>65,500</td></tr>
<tr><td>30</td><td>56,400</td><td>63,600</td><td>58,000</td></tr>
<tr><td rowspan="3">2150</td><td>0</td><td>60,100</td><td>63,900</td><td>61,800</td><td colspan="2" rowspan="3">61,290</td><td rowspan="3">61,290</td></tr>
<tr><td>15</td><td>57,800</td><td>70,800</td><td>61,200</td></tr>
<tr><td>30</td><td>57,000</td><td>54,300</td><td>64,700</td></tr>
<tr><td colspan="2" rowspan="3">Average shear strength for nickel added</td><td rowspan="3">46,430</td><td rowspan="3">50,230</td><td rowspan="3">49,750</td><td colspan="3">Average for time</td></tr>
<tr><td>0</td><td>15</td><td>30</td></tr>
<tr><td>41,300</td><td>49,090</td><td>56,010</td></tr>
<tr><td colspan="2">Recalculated for above 2000° F</td><td>59,510</td><td>61,830</td><td>60,490</td><td>58,070</td><td>64,210</td><td>59,560</td></tr>
</table>

TABLE IV. - STRESS-RUPTURE LIFE AT 1300° F OF SALT-BRAZED SPECIMENS. PHASE (6); SPECIMEN E

Shear stress on braze, psi	Brazing temperature, °F	Nickel added, percent	Stress-rupture life, hr
15,000	2000	0	21.6
		5	33.1
		10	93.8
	2075	0	[a]>152.9
		10	[a]>258.8
	2150	0	[a]>350.9
		5	[a]>215.8
		10	[a]>399.7
25,000	2150	5	[a]>0.6
		10	[a]> .8

[a]Broke in pin area.

TABLE V. - STATISTICAL TREATMENT OF DATA OF TABLE III(b)

(a) Experimental data

Protective coating	Nickel added, percent	Shear strength, psi		
		Temperature, °F		
		2000	2075	2150
Without	0	37,900	41,700	50,100
	5	33,000	35,600	49,100
	10	38,000	47,800	50,900
With	0	48,600	42,900	44,500
	5	47,300	48,500	54,900
	10	46,900	53,600	48,700

[Data code, $\frac{x - 30,000}{100}$]

(b) Analysis of variance

Factor	Degrees of freedom	Raw data		F-test ratio	Significant limit of F for P of		
		Sum of squares	Mean square		0.05	0.01	0.001
Protection	1	14,906	14,906	[a]51.9	7.7	21.2	74.1
Nickel addition	2	4,008	2,004	7.0	6.9	18.0	61.3
Temperature	2	18,280	9,140	[a]31.9	6.9	18.0	61.3
Protection and nickel addition	2	6,510	3,255	11.3	6.9	18.0	61.3
Protection and temperature	2	10,914	5,457	[a]19.0	6.9	18.0	61.3
Nickel addition and temperature	4	8,936	2,234	7.8	6.4	18.0	53.4
Experimental error	4	1,146	287				
Total	17	64,700					

[a]Significant at 0.01 level.

(c) Comparison of shear-strength means

Protection	Mean, psi	Standard deviation of mean, psi	Nickel added, percent	Mean, psi	Standard deviation of mean, psi	Temperature, °F	Mean, psi	Standard deviation of mean, psi
Without	42,680	±565	0	44,280	±690	2000	41,950	±690
With	48,430		5	44,730		2075	45,020	
			10	47,650		2150	49,700	

TABLE VI. - STATISTICAL TREATMENT OF DATA OF TABLE III(c)

(a) Experimental data

Brazing process	Nickel added, percent	Shear strength, psi		
		Temperature, °F		
		2000	2075	2150
Salt (with protection)	0	48,600	42,900	44,500
	5	47,300	48,500	54,900
	10	46,900	53,600	48,700
Vacuum	0	57,900	56,400	57,000
	5	62,200	63,600	54,300
	10	61,900	58,000	64,700

$$\left[\text{Data code, } \frac{x - 40{,}000}{100}\right]$$

(b) Analysis of variance

Factor	Degrees of freedom	Raw data		Pooled data		F-test ratio	Significant limit of F for P of		
		Sum of squares	Mean square	Sum of squares	Mean square		0.05	0.01	0.001
Process	1	55,667	55,667	55,667	55,667	[a]51.0	4.6	8.9	17.1
Nickel addition	2	7,020	3,510	7,020	3,510	3.2	3.7	6.5	11.8
Temperature	2	28	14						
Process and nickel addition	2	393	196						
Process and temperature	2	1,067	534						
Nickel addition and temperature	4	2,124	531						
Experimental error	4	11,660	2,915	15,272 (for 14 d.f.)	1,091				
Total	17	77,959							

[a]Significant at 0.001 level.

(c) Comparison of shear-strength means

Brazing process	Mean, psi	Standard deviation of mean, psi	Nickel added, percent	Mean, psi	Standard deviation of mean, psi	Temperature, °F	Mean, psi	Standard deviation of mean, psi
Salt (with protection)	48,430	±1100	0	51,220	±810	2000	54,130	±810
Vacuum	59,560		5	55,130		2075	53,830	
			10	55,630		2150	54,020	

TABLE VII. - STATISTICAL TREATMENT OF DATA OF TABLE III(d) ABOVE 2000° F

(a) Experimental data

Temperature, °F	Time, min	Shear strength, psi		
		Nickel added, percent		
		0	5	10
2000	0	46,500	54,000	50,500
	15	67,800	60,500	56,100
	30	57,900	62,200	61,900
2075	0	62,100	59,000	64,700
	15	70,000	68,200	65,500
	30	56,400	63,600	58,000
2150	0	60,100	63,900	61,800
	15	57,800	70,800	61,200
	30	57,000	54,300	64,700

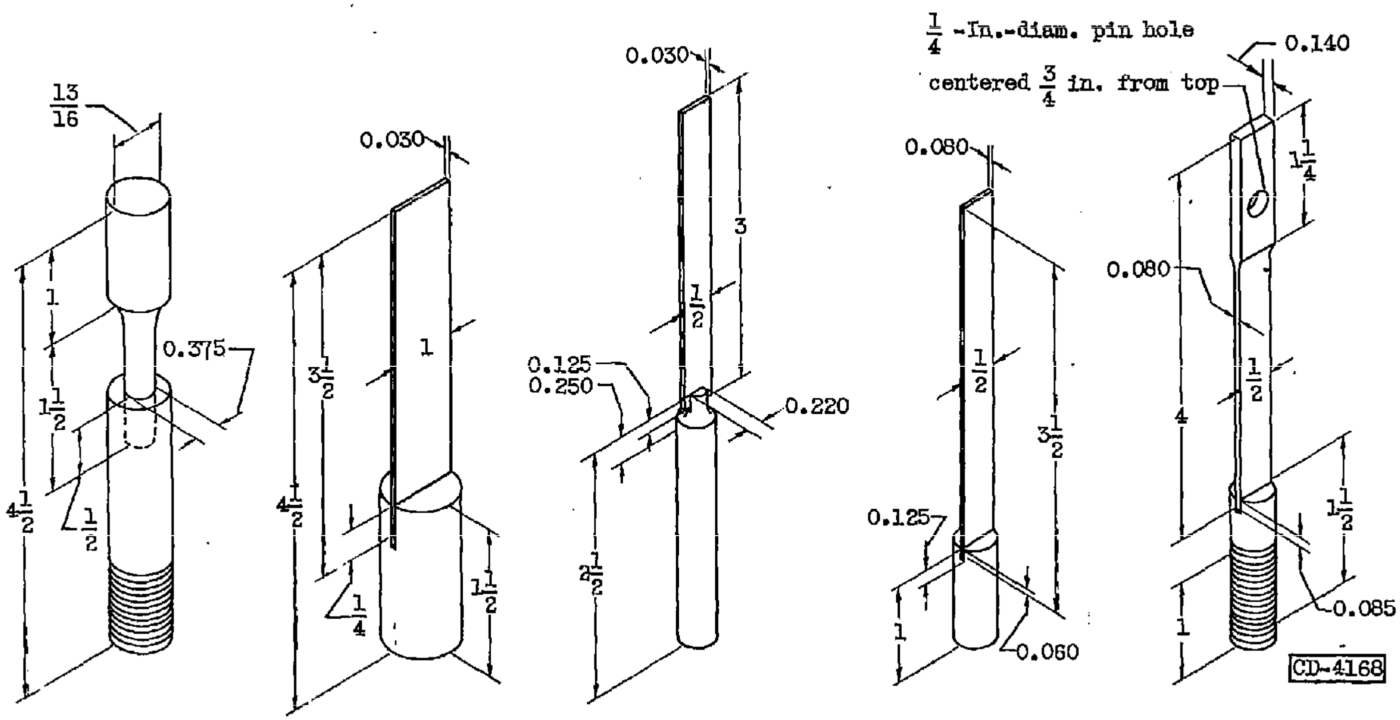
$$\left[\text{Data code, } \frac{x - 40{,}000}{100}\right]$$

(b) Analysis of variance

Factor	Degrees of freedom	Experimental data		Pooled data		F-test ratio	Significant limit of F for P of		
		Sum of squares	Mean square	Sum of squares	Mean square		0.05	0.01	0.001
Nickel addition	2	2,447	1224						
Time	2	18,494	9247	18,494	9247	5.2	3.7	6.5	11.8
Temperature	2	14,565	7282	14,565	7282	4.1	3.7	6.5	11.8
Nickel addition and time	4	7,205	1801	7,205	1801	1.0	3.1	5.0	8.6
Nickel addition and temperature	4	2,806	715						
Time and temperature	4	19,579	4895	19,579	4895	2.8	3.1	5.0	8.6
Experimental error	8	19,649	2456	24,902 (for 14 d.f.)	1779				
Total	26	84,745							

(c) Comparison of shear-strength means

Nickel added, percent	Mean, psi	Standard deviation of mean, psi	Time, min	Mean, psi	Standard deviation of mean, psi	Tempera-ture, °F	Mean, psi	Standard deviation of mean, psi
0	59,510	±1410	0	58,070	±1410	2000	57,490	±1410
5	61,830		15	64,210		2075	63,060	
10	60,490		30	59,560		2150	61,290	



Design type:	A	B	C	D	E
Shear area:	0.589 sq in.	0.500 sq in.	0.055 sq in.	0.060 sq in.	0.085 sq in.

Figure 1. - Specimens of designs used in brazing experiments. (All dimensions are in inches.)

Figure 2. - Vacuum furnace and automatic control. Extra furnace head at left.

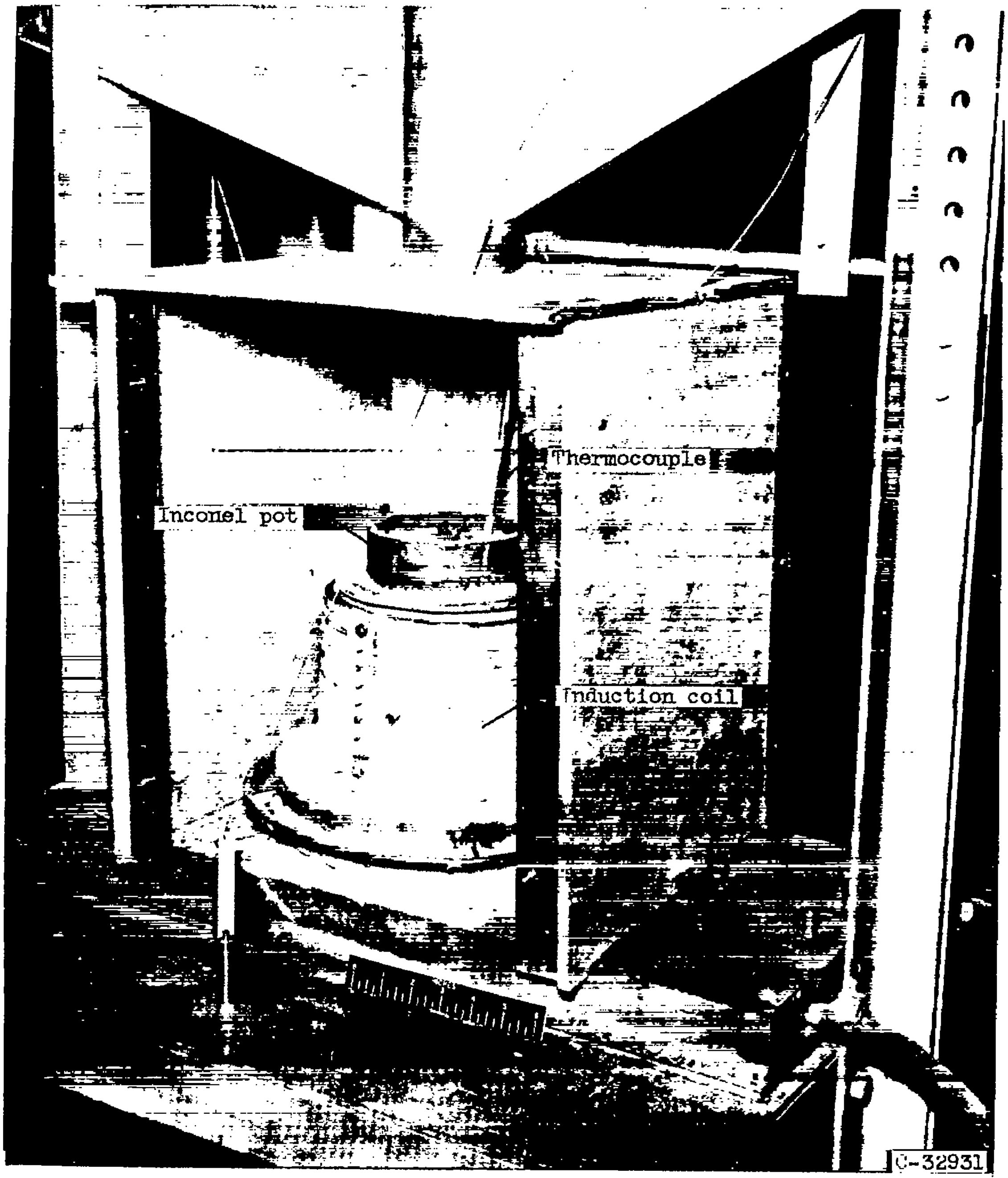


Figure 3. - Induction-heated salt bath.

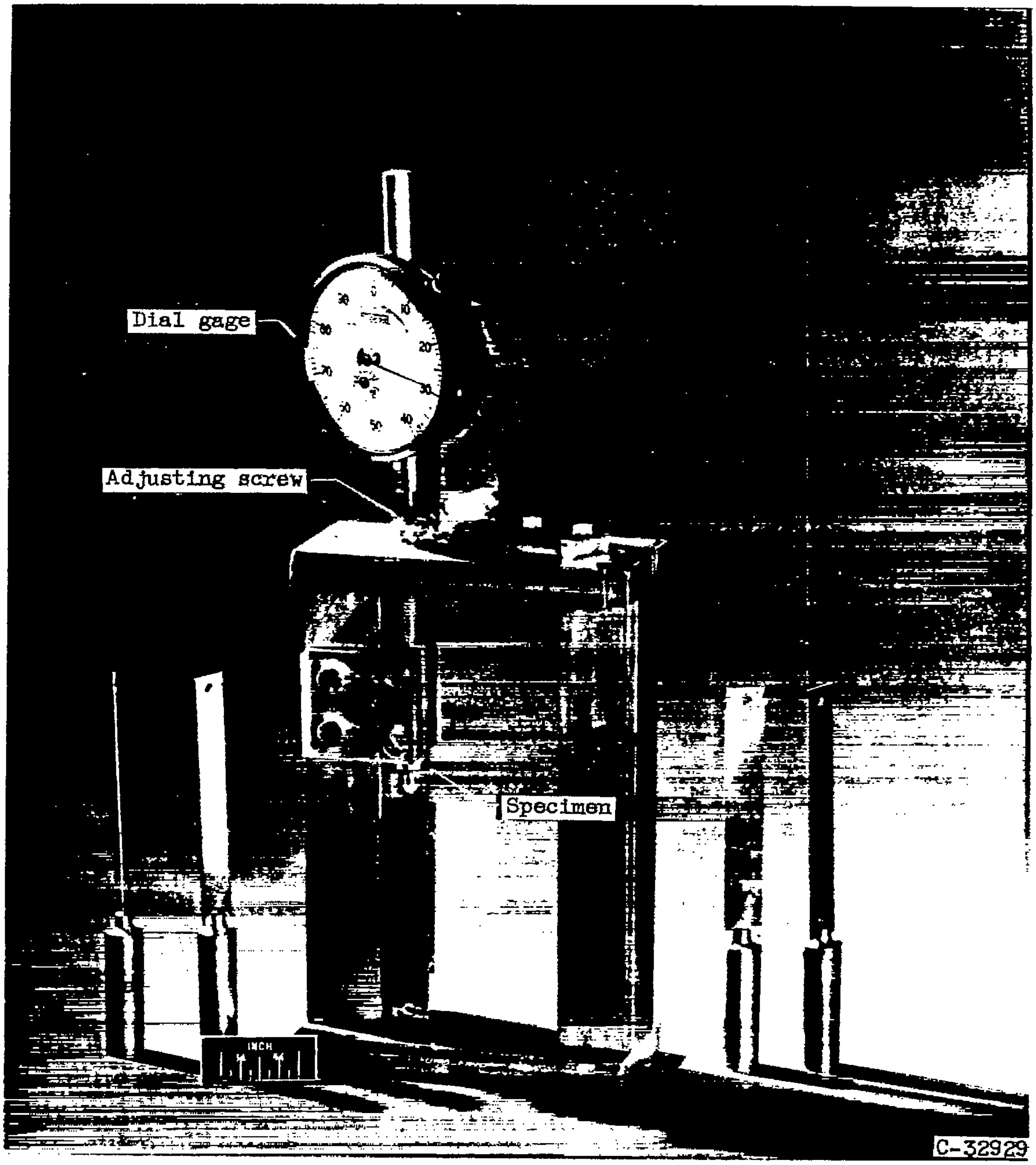
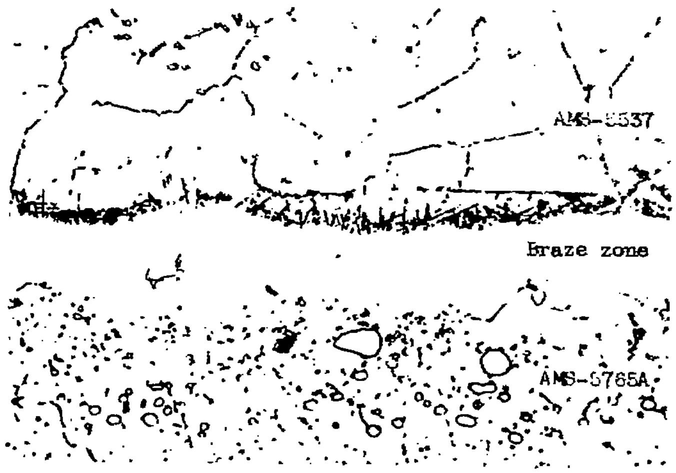


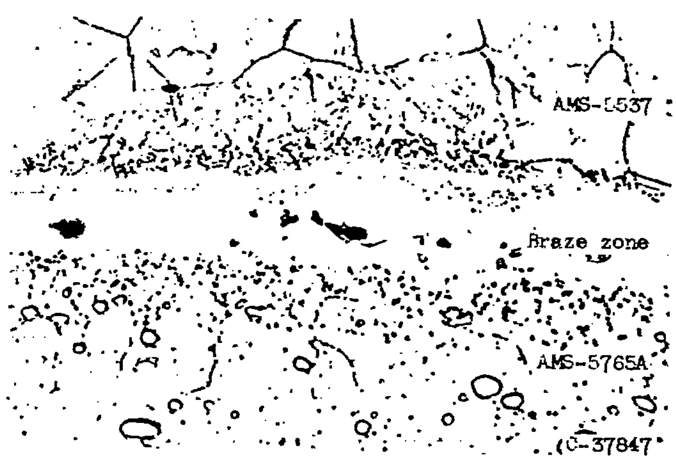
Figure 4. - Positioning jig and shear-test specimens.

Figure 5. - Typical erosion-penetration zone of braze material on AMS-5537. Murakami's etching solution. X50.



(a) No nickel.

(b) 5 percent nickel.



(c) 10 percent nickel.

Figure 6. - Typical joints formed by braze material between AMS-5537 and AMS-5765A (processed in molten salt). Immersion in Murakami's etching solution. X750.