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SUMMARY

An investigation was conducted to determine the effects of two nickel base brazing alloys, applicable brazing variables (temperature cycling and nickel plating), and heat treatment on the 1200° F stress-rupture properties of sheet L-605, A-286, and Inconel 700 specimens. The braze was applied to yield a 1-mil coating on both sides of the specimens. Nickel plating was employed on A-286 and Inconel 700 specimens to promote wetting of the base metal by the braze alloys.

The stress-rupture strengths of two of the sheet materials (A-286 and Inconel 700) were decreased by the brazing temperature and nickel plating. Excessive quantities (sumps) of the brazing alloys studied were detrimental to the base metal structures. The damage incurred in sheet material by the braze alloy or the brazing temperature is a function of the original condition of the sheet material. Braze NiCrSiB improves the stress-rupture strength of L-605 and Inconel 700 sheet materials by the diffusion of boron from the braze alloy into the parent metal. NiCrSiB decreases the stress-rupture strength of A-286. Braze NiCrSi appears to strengthen L-605, but the strengthening results from the temperature cycle required for brazing. NiCrSi appears to add mechanical strength and prohibits the deleterious effects of nickel plating on Inconel 700 sheet material. NiCrSi is less harmful to A-286 than NiCrSiB.

INTRODUCTION

Conventional brazing is used to bond many items used at ordinary temperatures, but the need for brazed joints that would withstand temperatures in the range of 1200° to 2000° F has brought about the development of new brazing alloys. Some of the most successful brazing materials developed for use up to 2000° F have been nickel alloys. The development of these alloys was needed to permit fabrication of objects to be used at high temperatures that could not be produced by forging, casting, or machining. Examples are: air-cooled turbine blades fabricated from formed, thin sheets brazed together to produce intricate air passageways (fig. 1); heat exchangers for nuclear reactors consisting of thin-walled stainless steel tubes brazed to headers; assemblies of extremely thin sections brazed to heavy ones; composite structures; and lightweight assemblies for high-temperature service in supersonic aircraft and space vehicles.

To produce a liquid phase in many high-temperature-service braze alloys it is often necessary to heat the joints or entire parts to temperatures in the range from 2000° to 2300° F. This high processing temperature not only may solution treat or otherwise alter the structure of the alloy being brazed but may also cause the brazing alloy (filler metal) to adversely affect the mechanical properties of the metals being joined. Additional detrimental effects may arise from solutioning of the base metal by the brazing alloy, excessive diffusion or penetration into the base metal by the braze alloy, or grain growth of the base metal that may result from the heating required for brazing.

A past investigation at the Lewis Research Center (ref. 1) has shown that the tensile strengths of braze-coated A-286 (tested at 1200° F) were reduced 6000 to 28,000 psi when AMS-4775, a braze containing boron, was used. In addition, ductility of the specimens, as measured by elongation, which was originally as much as 3 percent, was reduced to 0 in every case. Room-temperature tensile strengths and ductility of L-605 (AMS-5537) were also reduced by AMS-4775. Here the tensile strength reductions ranged from 19,000 to 30,000 psi. Ductilities originally as high as 48 percent were reduced to as low as 10 percent. Further data are given in reference 1, which show that ultimate strengths and ductilities, as measured by elongation, of Inconel X (AMS-5542A) and N-155 (AMS-5532B) are reduced when the metals are coated with boron-bearing, nickel-base braze.

Since the earlier work conducted in this laboratory utilized tensile tests, which are short-time tests, to evaluate braze damage, it was felt that further studies of braze damage should be made utilizing stress-rupture tests (longer time tests). A stress-rupture test temperature of 1200° F was selected for these studies because it has been considered a typical temperature for a component of interest - cooled turbine blades. Therefore, this investigation was undertaken to determine whether the stress-rupture properties of several high-temperature alloys in sheet form were damaged by different brazing alloys or by the heating cycles required to perform brazing operations. Furthermore, it was intended to determine if damage could be prevented or corrected by some heat treating procedures prior to or following the brazing operation.

Three sheet materials were selected as being representative of some of the basically different types of alloys useful at high temperatures. These were: L-605 (AMS-5537), a cobalt-base alloy; Inconel 700, a nickel-base alloy; and A-286 (AMS-5525), an austenitic stainless steel. L-605 is strengthened principally by solution treatment, and Inconel 700 and A-286 are precipitation strengthened.

Solution heat treatments and/or aging treatments were used on the alloys where it was thought that they might bring the alloy into a more optimum condition prior to brazing or might prevent or correct damage caused by brazing.

Two nickel-base brazing compounds were used in the evaluation. These were AMS-4775, a boron-bearing alloy, and a boron-free, silicon-bearing alloy. Specimens of each sheet material were thinly braze coated (2 mils before fusion) and tested in stress-rupture machines at a test temperature of 1200° F. A separate group of L-605 specimens was also given a thick coat (15 mils before fusion) of boron bearing braze before being tested at 1200° F to determine the effect of a thick layer of braze on the stress-rupture life of L-605.

Specimens were tested in the as-received and braze-coated conditions and also following each of the various steps required for completion of the brazing process. In addition, specimens were tested following each step of certain heat treatments and/or aging treatments recommended by the manufacturers to put the materials in optimum condition or to correct for overheating done when brazing.

This report presents the results of these investigations on the effects of brazes, brazing variables, and heat treatments on the 1200° F stress-rupture lives and ductilities of L-605, A-286, and Inconel 700 alloys.

MATERIALS, APPARATUS, AND PROCEDURE

Sheet Metal and Brazing Alloys

The chemical compositions of the sheet metals and the brazing alloys used in this investigation are given in table I. Some of the significant facts concerning the alloy sheet materials selected for study follow:

L-605 (AMS-5537) was selected as being representative of some high-strength cobalt-base sheet alloys. It has an ultimate tensile strength greater than 74,000 psi at 1200° F and an average 100-hour stress-rupture strength of 45,000 psi at the same temperature (ref. 2). Optimum properties are produced in the sheet material by solution heat treatment at 2200° to 2275° F, and no significant improvement in rupture life is achieved by aging at lower temperatures (ref. 2). The material was received in the form of a hot-rolled, solution-heat-treated sheet of 0.020 inch nominal thickness. L-605 is not difficult to braze, for it is readily wetted by the brazing alloys used.

A-286 (AMS-5525) is a stainless steel strengthened with a nickel titanium and aluminum intermetallic compound, which forms coherently with the austenitic matrix. At 1200° F A-286 has an ultimate tensile strength of more than 100,000 psi and a 100-hour stress-rupture strength of approximately 63,000 psi (ref. 3), and is useful for service up to 1300° F (ref. 4). The titanium and aluminum alloying elements form surface oxides that interfere with the wetting of the base metal by brazing alloys. These oxide formations cannot be prevented in the vacuums that were maintained in brazing (i.e., 2 to 5 μ). Even in an atmosphere of hydrogen with a dewpoint of -100° F and at temperatures up to 2300° F, it is almost impossible to reduce even a minute scale and permit brazing. Therefore, electrolytic nickel plating of the base metal was used to facilitate brazing. It was found that a minimum thickness of 0.0002 inch of nickel was sufficient to permit brazing. The A-286 was received as hot-rolled solution-treated sheet nominally 0.020 inch thick.

Inconel 700 is a high-strength nickel-base alloy strengthened by precipitation of a titanium and aluminum phase. It has an ultimate tensile strength greater than 145,000 psi at 1200° F and a 100-hour stress-rupture strength of approximately 100,000 psi at this temperature, as reported in reference 5. The behavior of Inconel 700 during brazing is similar to that of A-286 because of its titanium and aluminum content (i.e., forms surface oxide layers), and, therefore, electrolytic nickel plating was again used to make brazing possible. The material was received as a cold-rolled annealed sheet nominally 0.030 inch thick.

All sheet materials were within the commercial thickness tolerances of ±0.0015 inch of the nominal thicknesses used in this investigation.

The two braze alloys used with the three sheet materials were nickel based, one containing boron that, for convenience, will be referred to hereinafter as NiCrSiB and the other, boron free, designated as NiCrSi. The NiCrSiB braze has a solidus of 1760° F and a flow point of 1950° F (ref. 6). During brazing, the NiCrSiB combines with the base metal and forms a new material with a higher melting point (ref. 7); it also tends to penetrate the base metal since the boron from the braze diffuses into the base metal. NiCrSi is an eutectic-type, silicon-bearing brazing alloy; it is less reactive with high-temperature alloys and therefore tends to penetrate the base metal to a less degree than NiCrSiB.

Stress-Rupture Specimens

The stress-rupture specimen developed for these tests is shown in figure 2 together with the loading adapter. The specimen, having a 1- by 1/2-inch test section, had to be reinforced in the grip area by welding strips on each face to prevent failure through the pin holes. The actual appearance of specimens can be noted in figure 3, which shows a series of specimens in the following conditions: as-received, nickel plated, braze coated, and failed after stress-rupture testing.

Fabrication of specimens. - Stress-rupture specimens were machined from 1- by 6-inch blanks that had been sheared from sheet stock. The blanks were sheared so that the tensile axes of the specimens were parallel to the final rolling direction. Following machining, the reinforcing plates were heliarc welded on the ends of the specimens.

Plating of specimens. - A-286 and Inconel 700 contain titanium and aluminum and could not be brazed directly as previously explained. During the early phases of this investigation, it was determined that a minimum thickness of 0.0002-inch nickel plate was needed to permit the brazing alloys to wet the surface. Therefore, initial specimens were sent to an electroplater to be nickel plated to a thickness of from 0.0002 to 0.0004 inch. Micrometer examinations of two lots of these specimens made before and after plating showed that the thicknesses of the plates were within specifications. In the case of specimens plated following the initial two lots, it was assumed that the plate thickness would also be within the specifications.

Since the sheet metal thickness varied within the acceptable tolerances of ±1.5 mils, and the pilot plating lots had 0.2- to 0.4-mil-thick electroplated nickel, the thicknesses of the remainder of the plated specimens were determined prior to testing. This procedure was adopted because it was expedient. Also, it was felt that the cause of any great variation in the thickness of the finished product could be determined by metallographic techniques after testing.

Braze coating of specimens. - The brazing materials, NiCrSiB (AMS-4775) and NiCrSi, were received in powder form. To facilitate holding the desired amount of braze alloy in contact with the base metal prior to and during heating, the powder was suspended in an acrylic resin (Rhom and Haas acryloid B-72, 40 percent solids). The acrylic resin was diluted with acetone to the desired consistency. The suspension was so compounded that, after application to the stress-rupture specimens by dipping or brushing, a dried layer of braze-resin suspension 0.002 inch thick would yield a 0.001-inch layer of braze alloy after temperature cycling. The braze coating was applied to cover the specimen from 3/4 radius to 3/4 radius as shown in figure 3. The acrylic resin was completely volatilized at a temperature of 800° F and left no residue.

A brazing cycle of 2075°±10° F for 15 minutes was chosen for processing the specimens. This cycle was shown to produce optimum shear strengths in brazed joints (ref. 8).

The specimens were placed into the resistance-heated vacuum furnace shown in figure 4. 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 an O-ring. The vacuum system consists of a mechanical roughing pump coupled to a vapor diffusion pump using DC-702 silicone fluid. The vacuum obtainable in this system ranged 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 2 to 5 microns as measured by a Pirani gage. The temperature in the furnace was maintained by use of a platinum platinum - 13 percent rhodium (QR) thermocouple and an electronic recording-controlling potentiometer.

After a vacuum had been effected, the specimens were brought to the 2075° F temperature as rapidly as possible (approx. 45 min). This temperature was held for 15 minutes at which time the power was cut off and the specimens allowed to cool in vacuum until a temperature of 300° F or lower was reached (about 80 min). Then the vacuum was broken, and the specimens were removed from the furnace. During the heating, outgassing occurred at approximately 400° F and continued until a temperature of 900° F was reached; at 900° F a vacuum level of 2 to 5 microns was obtained and was maintained throughout the remainder of the process.

Braze-temperature-cycle. - To effect a braze joint, the braze assembly must be subjected to a thermal cycle that causes the braze alloy to liquefy and allows sufficient time to permit the molten material to flow throughout the joint.

The temperature and time at temperature (2075° F for 15 min) were of such magnitude that the properties of the parent metal could be affected. To determine the magnitude of the effect of this thermal cycle, groups of specimens of each alloy were subjected to the thermal treatment in proper sequence to permit evaluation of the variable; that is, the thermal cycle was imposed on materials in the following conditions: as-received, plated, heat-treated, and heat-treated and plated, as the cases required. The groups of specimens that contain the term braze-temperature-cycled in their designation refer to specimens that have been subjected to the previously mentioned thermal cycle without the presence of a braze.

Heat treatment of specimens. - In addition to running stress-rupture tests on braze-coated specimens of the three sheet materials in the as-received condition, tests were made on the materials following the heat-treatments indicated below:

(1) L-605

Solution treated at 2250° F for 1/2 hour prior to brazing: Since microscopic examination of the as-received material revealed precipitates, it was felt that it was not received in the fully solution-treated condition. Hence, this heat treatment was used to attempt to obtain the best possible properties in the sheet material (ref. 2). The specimens were placed in the vacuum resistance furnace shown in figure 4 and brought to 2250° F as rapidly as possible (approx. 90 min). This temperature was held for 30 minutes at which time the power was cut off and the specimens allowed to cool in vacuum until a temperature of 300° F or lower was reached (about 100 min). The vacuum was then broken and the specimens removed.

(2) A-286

(a) Solution treated at 1800° F for 1 hour, aged at 1325° F for 16 hours after brazing: This treatment is a corrective treatment recommended by the manufacturer for the damage caused by heating the A-286 to 2075° F during brazing. The solution treatment was carried out in a vacuum induction furnace equipped for helium quenching (fig. 5). The specimens were in an Inconel susceptor within the induction coil of the furnace. They were brought to the solution-treating temperature of 1800° F in approximately 20 minutes and held for 1 hour. The power was then cut off, helium was admitted to increase the cooling rate, and the specimens cooled to 300° F or lower in approximately 50 minutes after which they were removed from the furnace. The specimens were then placed in a tube furnace and aged in a flowing argon atmosphere at 1325° F for 16 hours after which they were air cooled.

(b) Aged at 1325° F for 16 hours after brazing: This treatment was also recommended by the manufacturer as a corrective treatment to restore the properties of A-286 after the 2075° F brazing process in which the metal was heated much higher than the normal heat-treatment temperature for the material (1800° F). The specimens were placed in a tube furnace in a flowing argon atmosphere and aged for 16 hours at 1325° F after which they were removed from the furnace and air cooled.

(3) Inconel 700

(a) Solution treated at 2275° F for 1 hour before brazing, aged at 1600° F for 16 hours after brazing: This heat treatment, recommended by the manufacturer to produce optimum properties in Inconel 700, consists of solution treating at 2275° F for 1 hour, furnace cooling to 2150° F, air cooling to room temperature, and aging at 1600° F for 16 hours. Normally the entire treatment would be given following brazing; however, since brazed specimens sagged in the furnace during the heating to 2275° F (fig. 6), it was necessary to heat to 2275° F prior to brazing at 2075° F and then carry out the aging at 1600° F following the brazing. The specimens were placed in an Inconel susceptor within the coil of the vacuum induction furnace (fig. 5). They were brought to the solution-treatment temperature of 2275° F in approximately 25 minutes and held at this temperature for 1 hour. The power was then cut off, and the specimens were allowed to cool in vacuum to 2150° F to simulate furnace cooling conditions (about 1 min required). Then helium was admitted to increase the cooling rate, and the specimens were cooled to 300° F or lower in approximately 1 hour. After braze coating, the specimens were aged in a tube furnace in flowing argon for 16 hours at 1600° F and air cooled.

(b) Solution treat at 2150° F for 1 hour, age at 1600° F for 16 hours after braze coating: This is a low-temperature heat treatment recommended by the manufacturer to bring out desirable properties in Inconel 700 where the higher temperature treatment described previously cannot be used. The solution treatment was carried out in the vacuum induction furnace equipped for helium cooling (fig. 5). The specimens were placed in an Inconel susceptor within the coils of the induction furnace. They were brought to the solution temperature of 2150° F in approximately 25 minutes and held at this temperature for 1 hour. The power was cut off, helium was admitted to increase the cooling rate, and the specimens were cooled to 300° F or lower in approximately 1 hour. The specimens were then aged in a tube furnace in flowing argon for 16 hours at 1600° F and air cooled.

Stress-Rupture Tests

Specimens were tested in lever-loading stress-rupture machines having a load-to-weight ratio of 10 to 1. Measurements between specimen shoulders were made to the nearest 0.01 inch before and after stress-rupture testing for the purpose of calculating elongations. The width and thickness of the test sections were measured to the nearest 0.0001 inch with micrometer calipers. Cross-sectional area calculations for determining stresses were based on total thickness and width, which include nickel plate and braze coating whenever present.

After loading, specimens were heated to the test temperature of 1200°±3° F in conventional Kanthal wound tube furnaces incorporated into the stress-rupture machines. Temperature was controlled by the use of controlling-recording fast-acting potentiometers.

Stress-rupture tests were made on the three sheet materials in the as-received and braze-coated conditions as well as on specimens following the various operations that they would be put through prior to, during, or following brazing such as nickel plating, heat treating, and heating to the brazing temperatures for the time required for the brazing process. Table II shows the 11 conditions for L-605, the 15 conditions for A-286, and the 15 conditions for Inconel 700 specimens tested in stress rupture.

Ductility Determinations

The method for determining the elongation of specimens consisted of measuring the distance between the reinforcing strips before and after testing. The differences obtained in the length were assumed to accrue from the elongation of the constant cross section of the 1-inch gage length. This method was necessary because scribing lines or punching gage marks at the extremities of the gage length caused failure to occur through the gage marks.

Some error in elongation may be introduced by deformations occurring outside the gage length; however, it was believed that this elongation would be negligible. After checking the specimens, all deformation appeared to occur within the 1-inch gage length.

RESULTS AND DISCUSSION

Curves of stress plotted against the logarithm of time to rupture for each alloy and condition are shown in figures 7 to 9. The stress-rupture data along with percent elongations determined for each specimen are given in tables III, IV, and V.

L-605

Stress-rupture strengths of as-received and processed as-received materials. - The results comparing the 1200° F stress-rupture life of as-received L-605 (group L) with the lives of the alloy heated for the time and temperature used for brazing (braze-temperature-cycled, group LC) and in the NiCrSiB (group LB) and NiCrSi (group G6) coated conditions are shown in figure 7(a). The curve for L-605 in the as-received condition (group L) shows a 100-hour life at 45,000 psi, which is in agreement with data given for wrought L-605 by the manufacturer in reference 2. It may be observed that braze-temperature-cycling alone (group LC) (heating the material to 2075° F for 15 min in a vacuum) significantly increased the stress-rupture strength over that of the as-received material (group L). The stress to produce a 100-hour life was 56,200 psi for the first group against 45,000 psi for the latter group. This improvement in properties was unexpected for two reasons: First, the alloy is reported to be a solid solution strengthening type (refs. 2 and 4), with its maximum stress-rupture properties developed solely by a solution treatment at 2200° to 2275° F (aging is not deemed beneficial); second, no obvious differences were noted in the microstructures of the as-received (shop annealed) condition (group L) and the braze-temperature-cycled condition (group LC), as can be noted by comparing the photomicrographs of figures 10(a) and (b). However, a change in hardness was found to exist between the two conditions. The braze-temperature-cycled specimens were approximately 2.2 R_{15-N} points harder than the as-received specimens - R_{15-N} 73.6 against 71.4.

This increase in hardness may have resulted from two causes. First, the braze-cycling temperature may have produced a high-temperature aging phenomenon at the coherency level of precipitation, which would not be detectable by metallographic means. Secondly, the braze-cycling temperature may have resolutioned minuscule amounts of the precipitate existing in the as-received material and thus hardened the braze-temperature-cycled material by solution hardening.

Coating with NiCrSiB produced a tremendous improvement in stress-rupture properties over those of the as-received material. The stress to produce a 100-hour life was approximately 74,000 psi for the NiCrSiB coated specimens (group LB) compared to approximately 45,000 psi for the as-received specimens (group L). This increase in stress-rupture strength may have been obtained from two interrelated but separate phenomena. Part of the increase in stress-rupture strength may have been associated with the strengthening obtained from braze-temperature-cycling discussed earlier, and the rest of the increase in strength is attributed to the change in base alloy as a result of the diffusion of boron from the braze alloy.

Chemical analysis for boron in as-received and NiCrSiB coated L-605 showed that the boron content of the brazed specimen was raised from 0.007 to 0.043 percent. (Analysis on the braze-coated specimen was performed after all traces of the braze coating had been removed by grinding.) The strengthening effect of boron in cobalt-base alloys is known. For example, S-816 containing 0.06 percent boron exhibits a twofold increase in 1600° F stress-rupture life over the boron-free alloy (ref. 9). Thus, the increase of 0.036 percent boron resulting from diffusion from the NiCrSiB accounts for the additional improvement obtained in the NiCrSiB coated specimens.

The NiCrSi coated material (group G6) showed an improvement in properties over the as-received sheet (group L). Stress for 100-hour life extrapolates to 52,500 psi against 45,000 psi, respectively. A more valid comparison of the effect of the braze on the life of the base metal can be obtained by comparing the brazed group (G6) to the braze-temperature-cycled group (LC). In this comparison the effect of the temperature cycle is removed as a variable, and the effect of the braze can be determined. The curves in figure 7(a) show that the braze apparently decreased the stress-rupture life of L-605. A comparison of stresses to produce 100-hour life shows that the brazed group (G6) stress extrapolates to 52,500 psi and the braze-temperature-cycled group (LC) stress is 56,200 psi.

Metallographic comparison of the brazed specimens (G6) and the braze-temperature-cycled specimens (LC) indicated no appreciable difference between the two groups except the presence of the braze (see figs. 10(b) and (d)).

Comparison of the stress-rupture properties between the NiCrSiB coated group (LB) and the NiCrSi coated group (G6) shows the former to be appreciably better. Stresses to produce 100-hour lives were 74,000 psi against extrapolated 52,500 psi, respectively.

<u>Effect of solution treatment</u>. - Figure 7(b) shows the results of solution treatment of L-605 at 2250° F for 30 minutes prior to brazing. It may be observed that solution treatment alone improved the strength of the material for lives less than 12 hours and decreased the strength for longer lives relative to that of the sheet in the as-received condition (group K against group L). Heating to 2075° F for 15 minutes in vacuum (braze-temperature-cycling) following solution treatment gave a slight improvement in stress-rupture life when compared with the solution-treated material (group MH against group K). A further slight improvement was brought about by the NiCrSiB coating, although this improvement was not nearly as much as the improvement that occurred in the as-received

NiCrSiB coated material (group MB against group LB). In fact, none of the stress-rupture curves for the solution-treated series even closely approach the curve for the as-received braze-temperature-cycled material superimposed on figure 7(b).

Solution treatment of the as-received material at 2250° F caused the precipitate to go into solution, but no difference in hardness could be detected between the solution-treated group (K) and the as-received group (L). Braze-temperature-cycling of the solution-treated specimens probably caused formation of precipitates at the coherency level and increased the hardness to the same level as obtained in the as-received braze-temperature-cycled specimens.

From the foregoing, it should be expected that the solution-treated braze-temperature-cycled material (group MH) should have a stress-rupture life similar to that of the as-received braze-temperature-cycled material (group LC). However, this was not the case, for the solution-treated braze-temperature-cycled specimens (group MH) were markedly inferior to the as-received braze-temperature-cycled material (group LC). This deviation from the expected can be accounted for by the differences in grain size between the two conditions of material. Comparison of photomicrographs of all specimens of the as-received series (fig. 11) with those of all specimens of the solution-treated series (fig. 12) indicates the magnitude of the grain growth encountered during solution treatment. The presence of these massive grains in the solution-treated specimens decreased the stress-rupture life of the material.

NiCrSiB strengthened the solution-treated L-605, as can be noted by comparing the NiCrSiB coated data (group MB) with the solution-treated braze-temperature-cycled group (MH) in figure 7(b); however, the strengthening in this instance was not as great as that obtained in the as-received series. Addition of the braze to the solution-treated L-605 emphasizes the strengthening ability of NiCrSiB when applied to L-605, for it overcomes some of the deleterious effect of excessive grain size produced during solution treatment.

Effect of NiCrSiB applied in a localized area. - Figure 7(c) presents stress-rupture properties obtained from L-605 sheet on which braze was applied in a localized area. (Braze was applied on one side only in a 1/4-in.-long band 0.015 in. thick as contrasted to braze coating the full gage length with 0.002 in. thick braze on both sides for the other specimens.) The brazing temperature in this series was 2150° F to duplicate that used in the earlier work (ref. 1). It may be seen that heating the sheet material to 2150° F for 5 or 15 minutes (groups J2 and J3) improved the stress-rupture properties over the as-received condition. This improvement was less than that obtained by braze-temperature-cycling at 2075° F for 15 minutes (group LC) for specimens with higher stresses and shorter lives. For specimens loaded to lower stresses and having lives beyond 1000 hours, results for both series were essentially equivalent.

Comparative photomicrographs of specimens braze-temperature-cycled at these two temperatures are given in figures 10(b) and 13. Even though the specimen in figure 13 had been stress-rupture tested 3.8 hours, no significant metallographic differences were noted.

The brazed specimens (groups J5 and J4) had a great deal of scatter in their stress-rupture lives and showed no improvement in life over the as-received 2075° F braze-temperature-cycled specimens (group LB). The scatter and lack of improvement in stress-rupture life may be attributed to the presence of an excess or a "sump" of braze alloy. This sump is generally undesirable because it enhances erosion and excessive diffusion of reactive elements into the parent metal. Metallographic study of the brazed areas revealed no erosion of the specimens; however, evidence of excessive diffusion was present in all specimens. In some instances, complete penetration of the base metal occurred as evidenced by the presence of eutectiferrous structure on the side opposite the application of the braze (figs. 14(a) and (b)). These figures may be compared with figure 15, which presents a view of L-605 with NiCrSiB coatings of 0.001 inch. Here the L-605 structure is not affected throughout the entire cross section as in figures 14(a) and (b). When complete penetration by the braze alloy was obtained, stress-rupture life was low; but when the penetration was not complete, the stress-rupture life began to approach that of the conventionally brazed specimens.

Ductilities. - L-605 is a relatively ductile high-temperature alloy and follows the pattern of all ductile alloys in that high stresses with accompanying short life produce the greatest elongations for each set of conditions tested.

The data in table III indicate that the as-received material (group L) was the least ductile, and any thermal processing used in this study improved the ductility. The very significant increase in ductility obtained by solution treatment (group K) of the L-605 over that obtained in the as-received material (group L) may be associated with the complete annealing. In these specimens, a decrease in strength accompanied the increase in ductility; however, the improvement in ductility obtained from the braze-temperature-cycling at 2075° F (group LC) or 2150° F (groups J2 and J3) was anomalous in that significant increases in strength were also obtained. The mechanism by which increases in both ductility and strength occur simultaneously is not known, and the determination of the mechanism is beyond the scope of this report.

When as-received L-605 was considered as the base line, brazing did not adversely affect the ductility. The NiCrSiB coated specimens (group LB) exhibited approximately the same ductility as the as-received braze-temperature-cycled specimens (group LC), while the NiCrSi braze-coated specimens (group G6) showed superior ductility.

The ductility obtained in specimens having a 1/4-inch band (groups J4 and J5) resulted primarily from the elongation of the unbrazed section of the gage length of the specimens. Very little elongation occurred in the brazed area, and the failures, which always occurred in the brazed area, were of the brittle type. This indicates that excessive amounts of NiCrSiB embrittle the alloy.

A-286

Stress-rupture strength of as-received and processed as-received materials. - Figure 8(a) shows the comparison of the 1200° F stress-rupture life of as-received A-286 with the stress-rupture lives of A-286 sheet specimens that have been subjected to the various operations used in brazing. It may be noted immediately that all of the treatments applied to the as-received material reduced the stress-rupture life of the A-286 sheet. The curve for the as-received A-286 sheet (group A) shows a 100-hour stress-rupture strength of about 58,000 psi, which is in fair agreement with the 62,000 psi stress shown for a 100-hour stress-rupture life at 1200° F in reference 4. Actually the data point for 62,000 psi fell very close to 100 hours, but the best curve of all points obtained fell slightly below this value. Braze-temperature-cycling A-286 sheet at 2075° F for 15 minutes (group AC) appreciably reduced the 1200° F stress-rupture life of the alloy.

The decrease in the properties brought about by the heating is not surprising. A-286 is normally solution treated at 1800° F and aged at 1325° F for precipitation strengthening. Heating to 2075° F causes a loss of all advantage of any precipitation strengthening that may have been present in the as-received material. It also would tend to destroy any strengthening effect produced by the rolling process (cold work). This strengthening would not be completely destroyed by the shop annealing at the temperature of about 1650° F normally used. A comparison of figures 16(a) and (c) also indicates that grain growth occurred during the braze-temperature-cycling. This growth is great enough to yield a sheet material with as few as 2 grains in thickness in some areas, which could conceivably result in a reduction in stress-rupture life.

The nickel plated specimens (group AP) showed approximately the same reduction in stress-rupture life as the braze-temperature-cycled ones (group AC) (fig. 8(a)). This reduction in life was unexpected because it was felt that a plate thickness of 0.2 to 0.4 mil would not appreciably affect the load-carrying capacity of the specimens if the total cross section of the composite were assumed to be A-286.

However, the thickness of the plate varied considerably from the desired thickness and produced a "geometry effect" on the specimens, as explained in the appendix. A correction for the effect of plate thickness on stress-rupture life showed that the presence of the nickel plate was not actually harmful to the A-286.

Braze-temperature-cycling of the plated specimens (group AH) reduced the stress-rupture lives below those of the as-received braze-temperature-cycled A-286 specimens (group AC) (fig. 8(a)). The magnitude of reduction was roughly equivalent to the sum of the reductions in life resulting from the braze-temperature-cycling and nickel plating.

Neither NiCrSiB coating (group AB) nor NiCrSi coating (group ZCB) improved stress-rupture lives over that of the nickel-plated braze-temperature-cycled material (group AH) (fig. 8(a)). In fact, at the higher stresses and shorter lives (under 100 hr) the braze-coated specimens (groups AB and ZCB) showed a shorter stress-rupture life than the nickel plated braze-temperature-cycled ones (group AH). NiCrSiB coating apparently damaged the specimens to a greater extent than NiCrSi brazing (fig. 8(a)).

The causes for the deterioration of the stress-rupture strength of A-286 resulting from the addition of the braze alloys, NiCrSiB or NiCrSi, were not determinable. Study of the microstructures of the braze-coated specimens revealed that the braze alloys diffused into the nickel plate in all instances, and that occasionally the braze alloy penetrated the nickel plate completely (figs. 17(c) and (d)). However, the amount of diffusion of the braze alloy, the dispersion of the precipitates, and the condition of the braze surfaces at the braze-air interfaces did not appear to account fully for the large loss of stress-rupture strength obtained with these specimens.

Effect of heat treatment on braze-coated A-286. - A-286, a precipitation strengthened stainless steel, is normally heat treated at temperatures below the 2075° F temperature required for brazing. In order to overcome the deleterious effects on the stress-rupture life of A-286 caused by the brazing temperature and the presence of the braze coating, a series of specimens was subjected to a complete heat treatment consisting of a solution treatment at 1800° F for 1 hour followed by an aging treatment at 1325° F for 16 hours (normal heat treatment for A-286). The heat treatment proved to be ineffective as shown by the data plotted in figure 8(b).

Aging the processed A-286 at 1325° F for 16 hours without prior solution treatment appeared to be ineffective also as can be seen by the data plotted in figure 8(c). The reason for the lack of response to heat treatment of the processed A-286 is not definitely known; however, it may be associated with the excessive grain growth encountered during the 2075° F braze-temperature-cycle. The determination of the cause or causes of lack of response to heat treatment would have required research beyond the scope of this investigation.

Ductilities. - Ductilities, as indicated by the elongation measurements of the A-286 stress-rupture specimens, were not impaired by the brazes or the processes necessary to perform the brazing operations; in fact, in some cases elongations were improved. Heat treatment (solution treatment plus aging or aging alone) improved ductilities of the processed A-286 as shown in table IV. Percent elongations of the A-286 specimens ranged from 93 percent for the highly stressed, short-lived specimens to 0 percent for the low stressed, long-lived specimens.

Inconel 700

Stress-rupture strength of as-received and processed as-received materials. - The results of the stress-rupture tests on Inconel 700 specimens are summarized in figure 9. In figure 9(a), which compares the stress-rupture life of as-received Inconel 700 sheet with that which has undergone the various processes necessary for brazing, it can be seen that the 100-hour stress-rupture strength of as-received Inconel 700 was at about 80,000 psi. This is somewhat higher than the 72,000 psi for annealed sheet reported in reference 10. All operations necessary to brazing reduced the stress-rupture life as compared with the life of the as-received sheet material.

The heating required for brazing (15 min at 2075° F in vacuum) decreased the stress-rupture life of Inconel 700 significantly relative to that of the as-received sheet (fig. 9(a); group IC against group I, table V). Since Inconel 700 is a precipitation hardening (strengthening) alloy, a decrease in stress-rupture life might be expected from this treatment if solutioning of coherent precipitates would occur during the braze cycle. This premise was strengthened by the fact that the microstructures of the as-received and braze-temperature-cycled specimens were almost identical as to grain size, precipitation, and grain-boundary materials (figs. 18(a) against 18(b) and 19(a) against 19(b)).

Nickel plating actually damaged the Inconel 700 sheet, in contrast to the geometry effect it produced on A-286. The damage was made apparent when the geometry effect of the nickel plate was taken into consideration (see appendix), and the corrected stress-rupture lives of the plated specimens fell below those of the as-received material (group IP against group I, table V).

Contrary to the results obtained with A-286, the decrease in stress-rupture life brought about by braze-temperature-cycling nickel plated specimens (fig. 9(a), group IH against group I) was not as great as the sum of the decreases caused by each process separately (fig. 9(a), groups IC and IP against group I). Hence, it may be assumed that braze-temperature-cycling strengthened the composite (i.e., nickel plated Inconel 700). This strengthening effect was investigated, and it was concluded that plating possibly reduced the life of Inconel 700 through hydrogen embrittlement and the 2075° F temperature annealed out the damaging effect of the plating. In addition, the braze-temperature-cycle may have caused sufficient diffusion of chromium, cobalt, and molybdenum from the sheet into the nickel to strengthen the plate.

The NiCrSiB coated specimens showed stress-rupture strengths superior to those of the as-received specimens. The increase in strength was attributed to the strengthening of the Inconel 700 by boron diffusion from the braze alloy and possibly from a "case hardening effect" of the thin envelope of braze coating.

NiCrSi coating apparently improved the stress-rupture strength of Inconel 700. The magnitude of strengthening could not be quantitatively determined because the majority of failures occurred in the grip area after appreciable life at stresses of 80,000 and 90,000 psi (fig. 9(a) and table V). The strengthening of the Inconel 700 in this case was primarily attributed to a mechanical strengthening of the nickel plated coating by the envelope of braze.

A study of the photomicrographs of figure 18 shows that appreciable penetration of the nickel plate and base metal occurred when NiCrSiB was employed, but considerably less penetration was obtained when NiCrSi braze was used. The magnitude of diffusion can be readily seen by comparing the unaltered thicknesses of the base metal in figures 18(d) to (f).

<u>Effects of heat treatment on the stress-rupture life of NiCrSiB coated Inconel 700 specimens</u>. - The effects of a 2275° F solution treatment for 1 hour prior to braze processing followed by a 16-hour age at 1600° F after processing are presented in figure 9(b) and table V (groups G, GP, GH, and GB). This heat treatment impaired the properties of the Inconel 700 for all conditions present during the processing. Addition of the NiCrSiB coating improved the strength of the heat-treated material in that it caused the stress-rupture properties to be somewhat better than those of the as-received unprocessed material (group GB

against group I, table V).

The effects of a 1-hour solution treatment at 2150° F plus a 16-hour age at 1600° F following the braze processing are presented in figure 9(c) and table V (groups H, HC, HP, HH, and HB). This heat treatment improved the stress-rupture properties of the Inconel 700 sheet as compared to the as-received properties. Greatest improvement was obtained for specimens that were NiCrSiB coated.

The effects of the heat treatments on as-received Inconel 700 sheet are directly compared in figure 20. It is readily apparent that the 2150° F solution treatment plus a 1600° F age was beneficial and the 2275° F solution treatment plus a 1600° F age was detrimental. The latter treatment, which is recommended to produce optimum properties in Inconel 700 bar stock, causes excessive grain growth in the sheet material and thus decreases its properties. The 2150° F solution treatment did not appreciably affect the as-received grain size and yielded the best stress-rupture life.

The effects of the heat treatments on NiCrSiB coated specimens are directly compared in figure 21. In this comparison, it appears that both heat treatments improved the life and that the best life was obtained from the 2150° F solution treatment. By superimposing figure 20 on figure 21, it becomes apparent that the stress-rupture life of the as-received 2150° F solution-treated specimens falls on the same curve as the NiCrSiB coated 2150° F solution-treated specimens. This suggests that the NiCrSiB coating does not affect the stress-rupture life of Inconel 700 when it is heat treated to its optimum condition; however, if the processing variables impair the life of Inconel 700, the NiCrSiB does overcome the adverse effects of the processing variables.

From the limited data obtained on the effects of NiCrSi coating, it may be surmised that an analogous behavior exists; however, additional work would have to be done to substantiate it.

Ductilities. - Ductilities, as indicated by the elongation measurements of the Inconel 700 stress-rupture specimens, are shown in table V. The elongations for Inconel 700 were generally much less than those for L-605 and A-286 and varied from a maximum of 38 percent for highly stressed specimens with zero lives to a minimum of 0 percent for lower stressed specimens with long stress-rupture lives. The effect of the brazing process and the braze coating on the ductility of Inconel 700 could not be definitely determined because the elongations determined for the processed specimens fell in the same range as those obtained in the as-received material. Heat treatments, especially the 2275° F solution treatment, may have enhanced ductility; however, again the majority of the elongation data points fell within the range obtained on the as-received specimens. A point-by-point analysis of elongation data was inconclusive; however, it appears that neither of the brazes, NiCrSiB or NiCrSi, adversely affected the ductility of the Inconel 700 sheet used in this investigation.

GENERAL CONCLUSIONS

1. Some materials, when brazed, are severely damaged simply by the thermal

treatments alone. The damage that a brazing cycle or brazing may do to a material is often related to the initial condition of the material. If it is in a fully solution-treated condition and then subsequently brazed at a temperature lower than the solution-treatment temperature, damage due to thermal effect would probably not occur during brazing.

2. Materials brazed with NiCrSiB or NiCrSi can be either improved or damaged by the brazes depending on the metallurgical structure resulting from the brazing process.

3. Large quantities (sumps) of the brazes are to be avoided if possible because of their damaging effects upon base metal structure.

4. When plating is required to enable brazing to be done, embrittlement of the resulting structure may occur, perhaps as a result of hydrogen pickup. This can be alleviated, at least in part, by thermal treatment during or following brazing.

SPECIFIC RESULTS

The results are presented of an investigation to determine the effects of two brazing alloys (NiCrSiB and NiCrSi), applicable brazing variables (temperature cycling and nickel plating), and heat treatment on the 1200° F stress-rupture properties of sheet L-605, A-286, and Inconel 700 specimens.

NiCrSiB

1. A 1-mil coating of braze alloy improves stress-rupture properties of L-605. The improvement results from the strengthening of the L-605 by boron, which diffuses from the NiCrSiB during thermal processing.

2. The braze alloy apparently damaged A-286. The damage to stress-rupture life of A-286 could not be mitigated by heat treatments tried in this investigation.

3. When Inconel 700 was heat treated to produce optimum stress-rupture strength, the braze alloy had no effect; however, strengthening of Inconel 700 was obtained when it was not at its optimum strength. This strengthening of the Inconel was attributed to boron diffusion from the braze alloy during thermal processing.

NiCrSi

1. L-605 appears to be strengthened by the braze alloy; however, the strengthening actually results from the thermal processing.

2. The braze alloy apparently damaged the stress-rupture strength of A-286. The damage was less severe than that produced by the NiCrSiB. Post-braze heat treatments used did not appear to be beneficial.

3. The braze alloy appears to add mechanical strength to the nickel plate on Inconel 700 and apparently alleviates the deleterious effect produced by electrolytic nickel plating.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 3, 1963

APPENDIX - EFFECT OF NICKEL PLATING ON STRESS-RUPTURE LIFE OF A-286 AND INCONEL 700

Since the titanium and aluminum strengthening agents in A-286 and Inconel 700 formed oxides that interfered with the wetting of the base metal by the braze alloys during the brazing process, it was decided to nickel plate these metals prior to brazing. It was determined by experiment that a minimum of 0.0002 inch of nickel plate was necessary to permit the brazing alloys to wet the base metal surfaces. Therefore, initial specimens were sent to a commercial electroplater to have nickel plates applied to a thickness of 0.0002 to 0.0004 inch. Micrometer measurements made before and after plating indicated that the plate thickness met the specifications. Later, when the bulk of specimens were sent out for plating, it was assumed that the plate thickness would again be close to the specified limits.

As stress-rupture testing progressed, a running series of plots of stress against log time showed that the plated specimens had inferior lives to those of the unplated specimens. At this time the test cross section was computed on the total thickness - base metal plus plate. Later, metallographic examination of tested specimens revealed that nickel plate thickness of the electroplated specimens varied from 0.0002 to as much as 0.003 inch. Where nickel plate was as thick as 0.003 inch, the stress-rupture specimens had approximately 23 percent of the nominal cross-sectional area of the test section made of nickel metal. Since the nickel is not as strong as the base metal and the applied loads were based on the total cross-sectional area of the plated specimens, it would be expected that, where nickel plates were as thick as these, the stress-rupture lives of the materials reported would be low relative to what they would be with thinner plating or no plating. It was also found during subsequent metallographic examination that the plating was not uniform, particularly in those cases where the nickel plates were thicker. Figure 22 shows an example of such a case. At the edges the plating was thicker than in the centers of the cross section. Furthermore there were buildups at the corners, which is normal in electroplating. Several steps were taken to determine the true effects of electroplated nickel on the stress-rupture lives of the specimens. A series of A-286 specimens was electroplated with different thicknesses of nickel, and rupture lives of the specimens were determined. Calculations for loading were based on the total cross section of the specimens, that is, on the base metal area plus the nickel plated area. The data obtained from these specimens were combined in table VI with data obtained from similar specimens (AP-1 to AP-6) used in this investigation to permit construction of a three-dimensional plot (fig. 23) that shows the general effect of nickel plate thickness on the stress-rupture life of A-286 at 1200° F. Figure 23 indicates that, as the plating thickness decreases, the stress-rupture lives of the plated A-286 specimens approach the lives of the as-received, unplated specimens.

Another of the steps used to determine the true effects of nickel plating on stress-rupture life was applied to both A-286 and Inconel 700. In this method, it was assumed that the base metal was carrying all of the load applied during stress-rupture testing and that the plate was carrying none. Figure 24 presents the results of these calculations. In the case of the A-286, the stress-rupture lives come back up to the lives of the as-received (unplated) material, which indicated that the plating produced a geometry effect. In the case of the Inconel 700, the recalculated values fell below the values of the as-received material, which suggests that the plating had an adverse effect on the stress-rupture life of Inconel 700 beyond that caused by the geometry effect of the plate alone.

Sample calculations are as follows (obtain data from table VII, specimen AP-1):

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} = \frac{I}{\text{Area}} = \frac{I}{B(F - E)} = \frac{I}{(B)(G)} = \frac{I}{H} = \frac{712 \text{ lb}}{0.0104 \text{ sq in.}} = 68,462 \text{ psi}$$

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TABLE I. - CHEMICAL COMPOSITIONS, PERCENT BY WEIGHT

Alloy	Analysis	C	Mn	Si	P	S	Cr	Ni	Mo	Fe	Co	Ti	Al	W	B	V	Cu
L-605 (AMS-5537)	Typical	0.05/0.15	1.00/2.00	1.00 max	0.040 max	0.030 max	19.00/21.00	9.00/11.00		3.00 max	Bal			14.00/16.00			
A-286 (AMS-5525)	Typical	0.08 max	1.00/2.00	0.40/1.00	0.040 max	0.030 max	13.50/16.00	24.00/27.00	1.00/1.50	Bal		1.75/2.25	0.35 max			0.10/0.50	
Inconel 700	Typical	0.16 max	2.00 max	1.00 max		0.015 max	13.00/17.00	Bal	1.00/4.50	4.00 max	24.00/34.00	1.75/2.75	2.50/3.50				0.50 max
	Vendors	0.15	0.08	0.34		0.007	15.47	47.09	3.03	0.73	27.96	2.22	2.88				0.02
NiCrSiB braze (AMS-4775)	Typical	0.65		4.50			15.00	72.00		4.00					3.50		
NiCrSi braze	Typical	0.14		10.00			19.50	70.00		1.00							

TABLE II. - CONDITIONS UNDER WHICH MATERIALS WERE STRESS-RUPTURE TESTED

Group	Condition of specimens	Details of heat treatment or braze-temperature-cycle			Brazing cycles or treatments			Details of aging treatment			Reasons for special heat treatments or variations applied to specimens, if any
		Furnace conditions in vacuum, °F	Time, min	Type of cooling	Furnace conditions, °F	Time, min	Type of cooling	Conditions in argon, °F	Time, hr	Type of cooling	
					L-605						
1	As-received										
2	Braze-temperature-cycled	2075	15	Furnace cooled	----	--	---	----	--	----	
3	NiCrSiB coated	----	--	---	2075	15	Furnace cooled	----	--	----	
4	NiCrSi coated	----	--	---	2075	15	Furnace cooled	----	--	----	
5	Braze-temperature-cycled	2150	5	Furnace cooled	----	--	---	----	--	----	To determine effect of braze-temperature-cycling at 2150° F for 5 or 15 minutes (ref. 1)
6	Braze-temperature-cycled	2150	15	Furnace cooled	----	--	---	----	--	----	Same as above
7	NiCrSiB coated	----	--	---	2150	5	Furnace cooled	----	--	----	To determine effect of large amounts of braze applied in a localized area when processed at 2150° F for 5 or 15 minutes (ref. 1)
8	NiCrSiB coated	----	--	---	2150	15	Furnace cooled	----	--	----	Same as above
9	Solution treated	2250	30	Furnace cooled	----	--	---	----	--	----	To put as-received material into condition of full heat treatment recommended by manufacturer
10	Solution treated and braze-temperature-cycled	[a]2250 [b]2075	30 15	Furnace cooled Furnace cooled	---- ----	-- --	--- ---	---- ----	-- --	---- ----	
11	Solution treated and NiCrSiB coated	2250	30	Furnace cooled	2075	15	Furnace cooled	----	--	----	
					As-received series, A-286						
1	As-received										
2	Braze-temperature-cycled	2075	15	Furnace cooled	----	--	---	----	--	----	
3	Nickel plated	----	--	---	----	--	---	----	--	----	
4	Nickel plated, braze-temperature-cycled	2075	15	Furnace cooled	----	--	---	----	--	----	
5	Nickel plated, NiCrSiB coated	----	--	---	2075	15	Furnace cooled	----	--	----	
6	Nickel plated, NiCrSi coated	----	--	---	2075	15	Furnace cooled	----	--	----	
					Solution-treated and aged series, A-286						
1	Solution treated and aged	1800	60	Helium quenched	----	--	---	1325	16	Air cooled	Corrective treatment for overheating done during brazing; recommended by manufacturer
2	Braze-temperature-cycled, solution treated and aged				2075	15	Furnace cooled				
3	Nickel plated, solution treated and aged				----	--	---				
4	Nickel plated, braze-temperature-cycled, solution treated and aged				2075	15	Furnace cooled				
5	Nickel plated, NiCrSiB coated, solution treated and aged				2075	15	Furnace cooled				
					Aged series, A-286						
1	Aged	----	--	---	----	--	---	1325	16	Air cooled	Corrective heat treatment for overheating done during brazing; recommended by manufacturer
2	Nickel plated, braze-temperature-cycled, aged	----	--	---	2075 in vacuum	15	Furnace cooled				
3	Nickel plated, NiCrSiB coated, aged	----	--	---	2075 in vacuum	15	Furnace cooled				
4	Nickel plated, NiCrSi braze coated, aged	----	--	---	2075 in vacuum	15	Furnace cooled				

[a]Solution-treating details.
[b]Braze-temperature-cycle details.

TABLE II. - Concluded. CONDITIONS UNDER WHICH MATERIALS WERE STRESS-RUPTURE TESTED

Group	Condition of specimens	Details of braze-temperature-cycle or brazing			Details of solution treatment			Details of aging treatment			Reasons for special heat treatments or variations applied to specimens, if any
		Furnace conditions in vacuum, $^{\circ}F$	Time, min	Type of cooling	Heat-treat conditions in vacuum, $^{\circ}F$	Time, min	Type of cooling	Conditions in argon, $^{\circ}F$	Time, hr	Type of cooling	
					As-received series, Inconel 700						
1	As-received	----	--	---	----	--	----	----	--	----	
2	Braze-temperature-cycled	2075	15	Furnace cooled	----	--	----	----	--	----	
3	Nickel plated	----	--	---	----	--	----	----	--	----	
4	Nickel plated and braze-temperature-cycled	2075	15	Furnace cooled	----	--	----	----	--	----	
5	Nickel plated and NiCrSiB coated	2075	15	Furnace cooled	----	--	----	----	--	----	
6	Nickel plated and NiCrSi coated	2075	15	Furnace cooled	----	--	----	----	--	----	
					Solution treated at 2275° F series, Inconel 700						
1	Solution treated and aged	----	--	---	2275	60	Furnace cooled to 2150° F, helium quenched to room temperature	1600	16	Air cooled	High-temperature treatment for Inconel 700 to give optimum properties.
2	Solution treated, nickel plated, and aged	----	--	---							
3	Solution treated, nickel plated, braze-temperature-cycled, and aged	2075	15	Furnace cooled							
4	Solution treated, nickel plated, NiCrSiB coated, and aged	2075	15	Furnace cooled							
					Solution treated at 2150° F series, Inconel 700						
1	Solution treated and aged	----	--	---	2150	60	Helium quenched	1600	4	Air cooled	Low-temperature heat treatment recommended by manufacturer.
2	Braze-temperature-cycled, solution treated and aged	2075	15	Furnace cooled							
3	Nickel plated, solution treated and aged	----	--	---							
4	Nickel plated, braze-temperature-cycled, solution treated and aged	2075	15	Furnace cooled							
5	Nickel plated, NiCrSiB coated, solution treated and aged	2075	15	Furnace cooled							

TABLE III. - EFFECTS OF BRAZING VARIABLES AND HEAT TREATMENTS ON 1200° F STRESS-RUPTURE LIFE AND DUCTILITY OF 0.020-INCH-THICK L-605 SHEET SPECIMENS

Series	Condition	Specimen number	Stress, psi	Life, hr	Elongation, percent	Remarks
As-received	As-received	L-1	65×10^3	1.0	30	
		L-6	60	1.3	30	
		L-7	55	5.1	23	
		L-5	50	35.8	8	
		L-2	50	20.1	14	
		L-8	45	79.5	7	
		L-3	40	6.7	--	Failed in gage mark
		L-4	40	317.4	5	
		L-9	40	348.5	7	
		L-10	40	484.4	5	
	As-received, braze-temperature-cycled at 2075° F for 15 minutes	LC-7	70×10^3	13.5	35	
		LC-5	65	25.6	36	
		LC-8	65	29.5	26	
		LC-2	60	29.4	29	
		LC-4	60	61.2	24	
		LC-9	60	78.3	23	
		LC-3	55	32.7	36	
		LC-1	50	209.7	19	
		LC-6	50	236.2	--	Initial gage length not recorded
		LC-10	40	1763.7	17	
		LC-11	40	1560.5	17	
	As-received, NiCrSiB coated at 2075° F for 15 minutes	LB-7	80×10^3	22.2	35	
		LB-8	75	119.3	28	
		LB-9	70	176.7	25	
		LB-6	65	542.2	26	
		LB-2	60	298.4	18	Failed outside test area
		LB-3	55	897.0	12	Failed outside test area
		LB-5	55	683.0	--	Overheated to 1500° F at 520 hours
		LB-1	50	1422.8	11	Failed outside test area
		LB-4	50	>2160	8	Test discontinued
	As-received, NiCrSi coated at 2075° F for 15 minutes	G6-1	80×10^3	1.4	109	Prestressed at 37,600 psi for 24.7 hours
		G6-2	75	5.2	77	
		G6-3	70	9.5	60	
		G6-4	65	16.25	54	
		G6-5	60	37.85	38	
		G6-6	55	74.1	32	
Solution treated	Solution treated at 2250° F for 1/2 hour before processing	K-1	75×10^3	0	159	Failed on loading
		K-4	60	5.1	88	
		K-5	55	9.6	71	
		K-2	50	17.0	60	
		K-3	45	32.85	39	
	Solution treated, braze-temperature-cycled at 2075° F for 15 minutes	MH-1	70×10^3	3.5	89	
		MH-2	65	4.5	83	
		MH-3	60	9.2	68	
		MH-4	55	17.1	56	
	Solution treated, NiCrSiB coated at 2075° F for 15 minutes	MB-1	80×10^3	0	74	Failed on loading
		MB-2	75	0	62	Failed on loading
		MB-3	70	5.05	53	
		MB-4	65	10.0	42	
1/4-Inch band of braze	Braze-temperature-cycled at 2150° F for 5 minutes	J2-1	70×10^3	6.6	53	
		J2-2	60	17.95	32	
		J2-0	50	220.5	25	
		J2-3	40	1328.9	16	
	Braze-temperature-cycled at 2150° F for 15 minutes	J3-1	70×10^3	3.8	56	
		J3-2	60	24.55	30	
		J3-0	50	200.9	17.5	
		J3-3	40	1174.1	16	
	NiCrSiB coated, 0.25- by 0.015-inch ribbon of braze on one side only, 2150° F for 5 minutes	J5-1	70×10^3	0	35	Failed on loading
		J5-2	60	0	17	Failed on loading
		J5-3	50	132.6	27	
		J5-4	40	>1850	22	Test discontinued
	NiCrSiB coated, 0.25- by 0.015-inch ribbon of braze on one side only, 2150° F for 15 minutes	J4-1	70×10^3	0	41	Failed on loading
		J4-0	60	47.7	38	
		J4-2	50	1.1	40	
		J4-3	40	>1706	16	Test discontinued

TABLE IV. - EFFECTS OF BRAZING VARIABLES AND HEAT TREATMENTS ON 1200° F STRESS-RUPTURE LIFE AND DUCTILITY OF 0.022-INCH-THICK A-286 SHEET SPECIMENS

Series	Condition	Specimen number	Stress, psi	Life, hr	Elongation, percent	Remarks
As-received	As-received	A-9	75×10^3	0.27	48	
		A-8	70	.7	42	
		A-2	65	12.3	22	
		A-4	62	97.5	14	
		A-1	60	142.8	17	
		A-3	55	295.8	9	
		A-7	55	337.7	7	
		A-6	50.4	788.8	2	
		A-5	50	807.45	5	
	As-received, braze-temperature-cycled at 2075° F for 15 minutes	AC-1	65×10^3	0.15	49	
		AC-2	60	4.0	29	
		AC-3	55	39.1	25	
		AC-4	50	253.2	12	
		AC-5	45	407.45	13	
		AC-6	40	>1967	0	Test discontinued
	As-received, nickel plated	AP-1	60×10^3	5.8	22	
		AP-4	60	4.3	29	Test time questionable
		AP-2	55	111.4	9	
		AP-5	55	111.3	21	
		AP-3	50	278.2	27	
		AP-6	45	1657.3	3	
		AP-7	40	>1676	0	Test discontinued
	As-received, nickel plated, braze-temperature-cycled at 2075° F for 15 minutes	AH-1	60×10^3	0.25	37	
		AH-2	55	.05	79	
		AH-4	55	.9	42	
		AH-3	50	24.3	21	
		AH-5	45	101.35	10	
		AH-6	40	2262.1	1	
	As-received, nickel plated, NiCrSiB coated at 2075° F for 15 minutes	AB-1	60×10^3	0	71	Failed on loading
		AB-2	55	0	77	Failed on loading
		AB-4	50	.1	75	
		AB-8	50	0	57	Failed on loading
		AB-9	47	4.2	35	
		AB-5	45	1259.2	24	
		AB-3	40	>1105	13	Test discontinued
	As-received, nickel plated, NiCrSi coated at 2075° F for 15 minutes	ZCB-3	55×10^3	0.1	51	
		ZCB-4	50	9.1	21	
		ZCB-2	45	230.9	18	
		ZCB-1	35	>3933	1	Test discontinued
Solution treated, aged	As-heat-treated: solution treated at 1800° F for 1 hour, aged at 1325° F for 16 hours	B-1	70×10^3	1.65	50	
		B-2	65	5.55	43	
		B-3	60	16.9	38	
		B-4	55	107.6	19	
	Braze-temperature-cycled at 2075° F for 15 minutes, heat treated	BC-1	70×10^3	0	80	Failed on loading
		BC-2	65	.1	85	
		BC-3	60	3.9	57	
	Nickel plated, heat treated	BP-1	65×10^3	0.25	50	
		BP-2	60	.8	54	
		BP-3	55	3.9	39	
		BP-4	50	30.55	14	
	Nickel plated, braze-temperature-cycled at 2075° F for 15 minutes, heat treated	BH-1	60×10^3	0.03	36	
		BH-2	55	5.5	22	
		BH-3	50	3.5	31	
		BH-4	45	32.9	20	
	Nickel plated, NiCrSiB coated at 2075° F for 15 minutes, heat treated	BB-1	55×10^3	1.0	57	
		BB-2	50	9.1	50	
		BB-3	45	74.4	43	
		BB-4	40	669.5	21	
Aged	As-received aged: Aged at 1325° F for 16 hours after processing	C-1	65×10^3	6.3	39	
		C-2	60	18.5	60	
		C-3	55	173.7	23	
		C-4	50	420.1	13	
	Nickel plated, braze-temperature-cycled at 2075° F for 15 minutes, aged	CH-1	65×10^3	0	93	Failed on loading
		CH-2	60	.4	57	
		CH-3	55	15.8	38	
		CH-4	50	24.0	38	
	Nickel plated, NiCrSiB coated at 2075° F for 15 minutes, aged	CB-1	65×10^3	0	46	Failed on loading
		CB-2	60	.45	44	
		CB-3	55	.08	55	
		CB-4	50	6.8	51	
		CB-6	45	780.3	10	
		CB-5	40	316.0	22	Temperature rose to 1450° F sometime after 262 hours
	Nickel plated, NiCrSi coated at 2075° F for 15 minutes, aged	XCB-2	60×10^3	0	60	Failed on loading, specimen had an excessive amount of braze
		XCB-3	55	0	33	Failed on loading
		XCB-4	50	0	57	Failed on loading
		XCB-6	45	504.1	4	
		XCB-5	40	1480.2	4	
		XCB-1	30	>2565	1	Test discontinued

TABLE V. - EFFECTS OF BRAZING VARIABLES AND HEAT TREATMENTS ON 1200° F STRESS-RUPTURE LIFE AND DUCTILITY OF 0.0293-INCH-THICK INCONEL 700 SHEET SPECIMENS

Series	Condition	Specimen number	Stress, psi	Life, hr	Elongation, percent	Remarks
As-received	As-received	I-1	120×10^3	0.	38	Failed on loading
		I-10	100	.15	16	
		I-11	95	.6	12	
		I-6	90	17.8	10	
		I-3	85	35.2	4	
		I-2	80	140.9	2	
		I-4	80	52.2	1	Failed through loading pin
		I-5	80	100.7	7	
		I-7	78	97.1	0	
		I-8	75	14.75	2	Flaw in sheet
		I-9	75	29.3	2	Flaw in sheet
	As-received, braze-temperature-cycled at 2075° F for 15 minutes	IC-1	85×10^3	23.2	0	
		IC-6	80	10.9	1	
		IC-3	75	24.4	2	
		IC-5	72	573.8	1	
		IC-2	70	505.2	0	
		IC-4	65	2.5	--	Flaw in sheet
	As-received, nickel plated	IP-2	85×10^3	4.3	5	
		IP-1	80	6.65	7	
		IP-6	75	4.4	6	
		IP-3	70	12.6	2	
		IP-7	70	66.95	2	
		IP-4	65	>1343	0	Test discontinued
		IP-5	60	>1322	0	Test discontinued
	As-received, nickel plated, braze-temperature-cycled at 2075° F for 15 minutes	IH-3	80×10^3	10.0	3	
		IH-2	75	1.6	2	
		IH-6	75	41.6	1	Temperature was at 990° F for 23 of the 41.6 hours
		IH-6a	75	14.1	1	
		IH-1	70	5.2	3	
		IH-7	70	30.5	2	
		IH-4	65	198.6	0	
		IH-5	60	357.5	2	
	As-received, nickel plated, NiCrSiB coated at 2075° F for 15 minutes	IB-10	100×10^3	47.75	8	
		IB-11	95	3.5	--	Failed through loading pin
		IB-12	90	149.9	7	
		IB-7	85	490.3	9	
		IB-3	80	38.1	2	Failed outside of brazed area
		IB-4	80	255.2	10	
		IB-8	80	52.5	2	Failed through loading pin
		IB-13	80	28.45	--	Failed through loading pin
		IB-2	75	139.9	4	Failed outside of brazed area
		IB-9	75	>1057	1	Test discontinued
		IB-1	70	360.4	0	Failed outside of brazed area
		IB-5	70	909.5	0	Failed at grip
		IB-6	65	>1511	0	Test discontinued
	As-received, nickel plated, NiCrSi coated at 2075° F for 15 minutes	IG-1	100×10^3	1.3	6	
		IG-2	90	21.45	--	Failed in grip
		IG-3	90	7.1	--	Failed through loading pin
		IG-4	90	15.5	6	
		IG-6	90	31.0	--	Failed in grip
		IG-7	90	27.2	--	Failed in grip
		IG-8	80	55.3	--	Failed in grip
		IG-9	80	66.8	--	Failed through loading pin
		IG-14	80	53.6	--	Failed through loading pin
		IG-15	80	126.9	--	Temperature went up to 1400° F
		IG-16	80	191.1	--	Failed through loading pin
		IG-17	80	295.5	--	Failed through loading pin

TABLE V. - Concluded. EFFECTS OF BRAZING VARIABLES AND HEAT TREATMENTS ON 1200° F STRESS-RUPTURE LIFE AND DUCTILITY OF 0.0293-INCH-THICK INCONEL 700 SHEET SPECIMENS

Series	Condition	Specimen number	Stress, psi	Life, hr	Elongation, percent	Remarks
Heat treated, 2250° F	As-heat treated: solution treated at 2275° F for 1 hour, furnace cooled to 2150° F, He quench to RT, before processing; aged 16 hours at 1600° F after processing	G-1	100×10^3	0	22	Failed on loading
		G-2	90	.03	9	
		G-3	80	.22	5	
		G-5	75	.15	6	
		G-4	70	>2060	0	Test discontinued
	Solution treated, nickel plated, aged	GP-1	100×10^3	0	34	Failed on loading
		GP-2	90	0	12	Failed on loading
		GP-3	80	14.1	7	
		GP-4	70	283.8	4	
	Solution treated, nickel plated, braze-temperature-cycled, aged	GH-1	100×10^3	0.01	36	
		GH-2	90	.03	21	
		GH-3	80	10.2	7	
		GH-4	70	49.0	2	
	Solution treated, nickel plated, NiCrSiB coated at 2075° F for 15 minutes, aged	GB-1	100×10^3	0	17	Failed on loading
		GB-2	90	31.9	15	
		GB-3	80	1002.1	10	
		GB-4	70	175.9	21	Temperature controller failed, temperature went too high
Heat treated, 2175° F	As-heat treated: solution treated at 2150° F for 1 hour, aged at 1600° F for 16 hours after processing	H-7	110×10^3	7.35	12	
		H-4	100	41.8	6	
		H-1	90	413.8	4	
		H-2	85	712.1	2	Failed at grip
		H-3	80	>1038	2	Test discontinued
	Braze-temperature-cycled at 2075° F for 15 minutes, heat treated	HC-1	85×10^3	832.3	5	
		HC-2	80	642.5	6	
		HC-3	75	1660.4	2	Failed through loading pin
		HC-4	70	>3331	0	Test discontinued
	Nickel plated, heat treated	HP-1	110×10^3	0.15	19	
		HP-2	100	11.0	13	
		HP-3	90	128.5	4	
		HP-4	80	348.4	3	
	Nickel plated, braze-temperature-cycled at 2075° F for 15 minutes, heat treated	HH-4	100×10^3	13.8	12	
		HH-3	90	71.0	6	
		HH-1	85	205.5	6	
		HH-2	80	503.2	6	
	Nickel plated, NiCrSiB coated at 2075° F for 15 minutes, heat treated	HB-1	120×10^3	0	7	Failed on loading
		HB-2	110	0	7	Failed on loading
		HB-4	100	0	6	Failed on loading
		HB-5	95	183.25	8	
		HB-3	90	630.9	3	
		HB-6	90	296.0	11	
		HB-7	85	1118.2	6	
		HB-8	80	>1199	3	Test discontinued

TABLE VI. - 1200° F STRESS-RUPTURE LIVES OF A-286 SHEET SPECIMENS

WITH VARYING THICKNESSES OF ELECTROLYTIC NICKEL PLATING

Plating thickness, mils	Specimen number	Stress, psi	Life, hr	Elongation, percent	Remarks
1.3	AP-17	70×10^3	0.008	69	Study of effect of plating thickness on stress-rupture life
.45	AP-16	70	.12	64	
.25	AP-15	70	.13	66	
2.5	AP-1	60×10^3	5.8	22	
2.4	AP-4	60	4.3	29	
.2	AP-8	60	88.6	11	
3.0	AP-2	55×10^3	111.4	9	
1.0	AP-5	55	111.3	21	
1.0	AP-14	55	84.1	19	
.5	AP-13	55	161.7	12	
.2	AP-12	55	264.4	1	
1.7	AP-3	50×10^3	278.2	27	
.2	AP-10	50	541.6	5	
0.9	AP-6	45×10^3	1657.3	3	

TABLE VII. - STRESS-RUPTURE DATA ON NICKEL PLATED A-286 RECALCULATED ON BASIS THAT A-286 SHEET MATERIAL CARRIED APPLIED LOAD DURING TESTING AT 1200° F

[Sample calculations: $\text{Stress} = \frac{\text{Load}}{\text{Area}} = \frac{I}{\text{Area}} = \frac{I}{B(F - E)} = \frac{I}{(B)(G)} = \frac{I}{H} = \frac{712 \text{ lb}}{0.0104 \text{ sq in.}} = 68{,}462 \text{ psi.}$]

A	B	C	D	E	F	G	H	I	J	K
Specimen number	Thickness of A-286, in.	Thickness of plated A-286, in.	Thickness of plating, $\Delta T = C - B$, in.	Thickness of plating on edges = $2 \times \Delta T$, in.	Measured width of plated A-286, in.	Corrected width of A-286, F - E, in.	Corrected cross-section area of A-286 under test, B × G, sq in.	Applied load, lb	Corrected stress, I/H, psi	Actual life of specimen, hr
AP-1	0.0220	0.0247	0.0027	0.0054	0.4802	0.4748	0.0104	712	68,462	5.85
AP-2	0.0220	0.0247	0.0027	0.0054	0.4823	0.4769	0.0105	655	62,381	111.4
AP-3	0.0220	0.0231	0.0011	0.0022	0.4758	0.4736	0.0105	549	52,286	278.2
AP-5	0.0220	0.0241	0.0021	0.0042	0.4773	0.4731	0.0104	633	60,865	111.3
AP-6	0.0220	0.0240	0.0020	0.0040	0.4909	0.4869	0.0107	530	49,533	1657.0

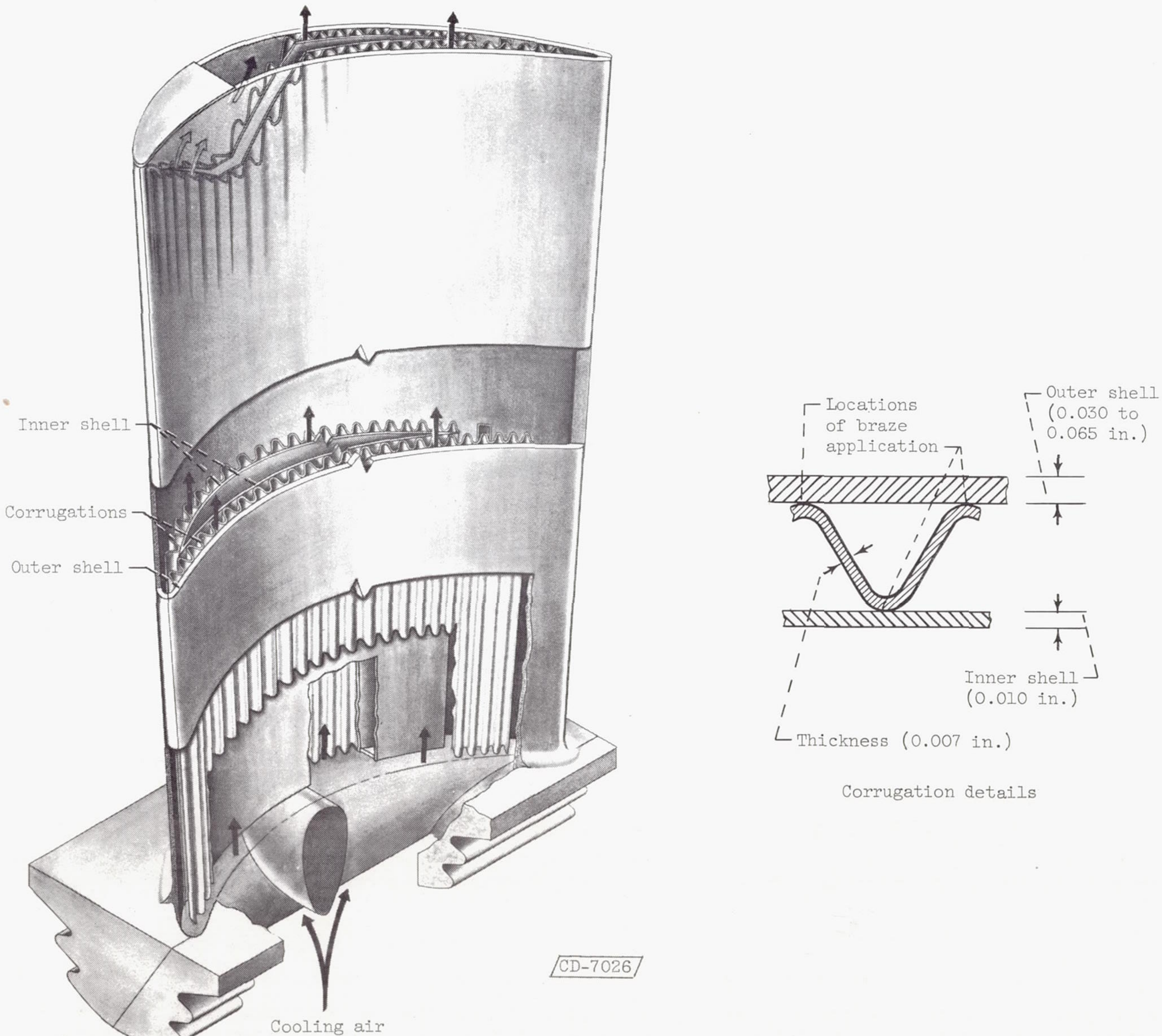
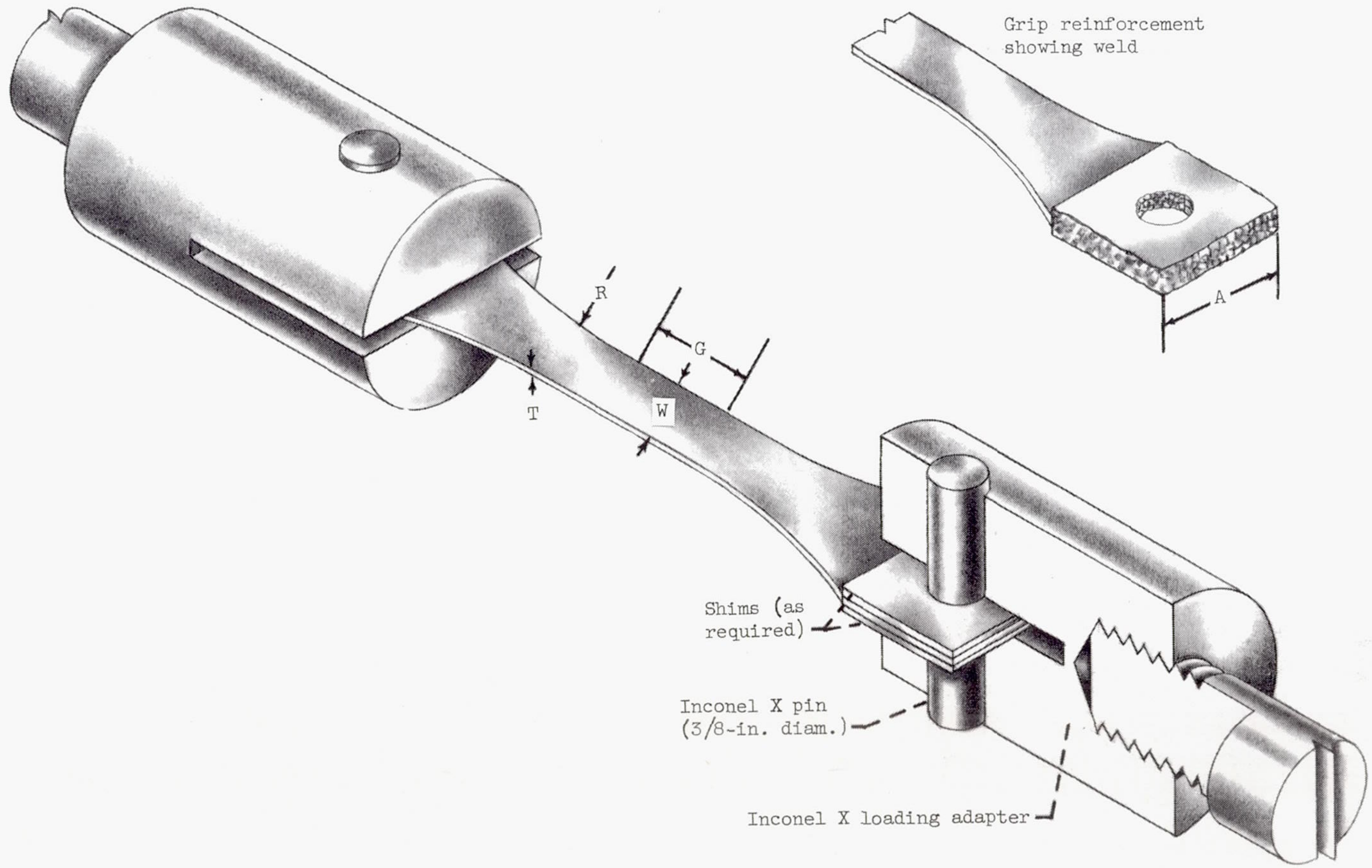


Figure 1. - Isometric view of air-cooled turbine blade requiring assembly by brazing.

Edges of test section parallel to ±0.002 inch

Alloy	T	A	R	W	G
L-605	0.021	1.00	5.00±0.01	0.500±0.002	1.000±0.001
A-286	.022	1.00	5.00±0.01	.500±0.002	1.000±0.001
Inconel 700	.030	1.00	5.00±0.01	.500±0.002	1.000±0.001



CD-7656

Figure 2. - Isometric view of stress-rupture specimen and loading adapter. (Dimensions in inches.)

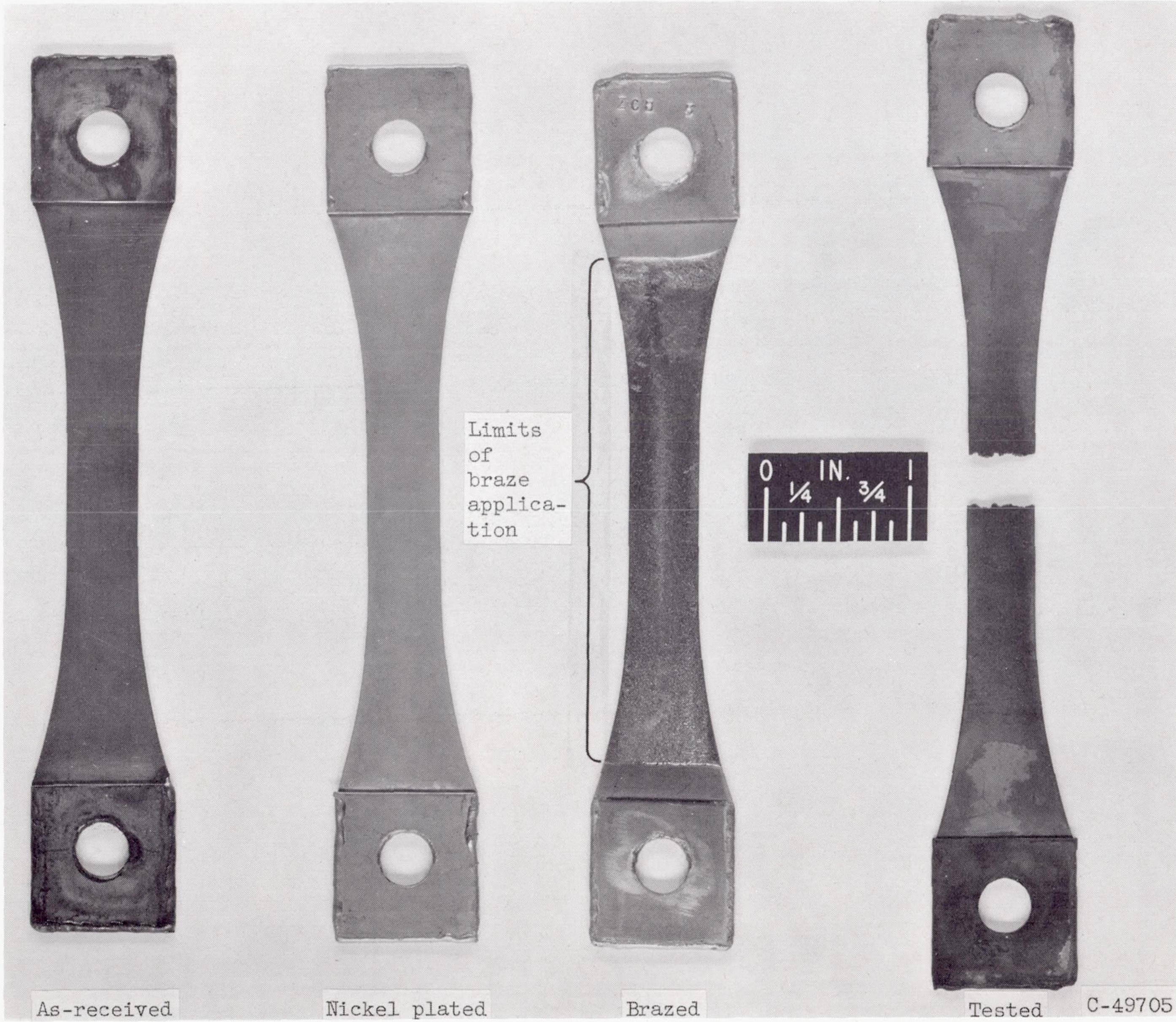


Figure 3. - Typical stress-rupture specimens.

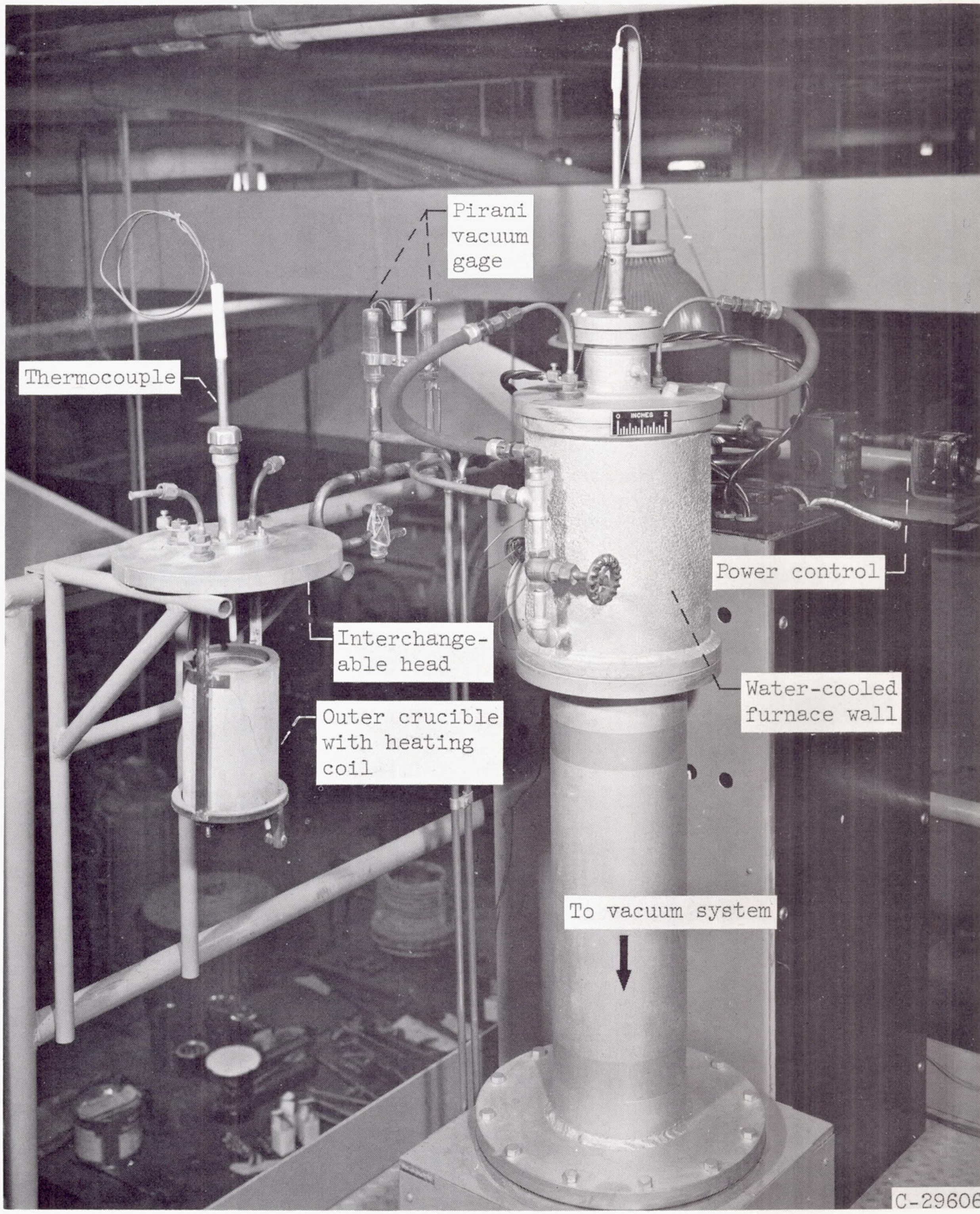


Figure 4. - Automatically controlled vacuum furnace. Extra furnace head at left.

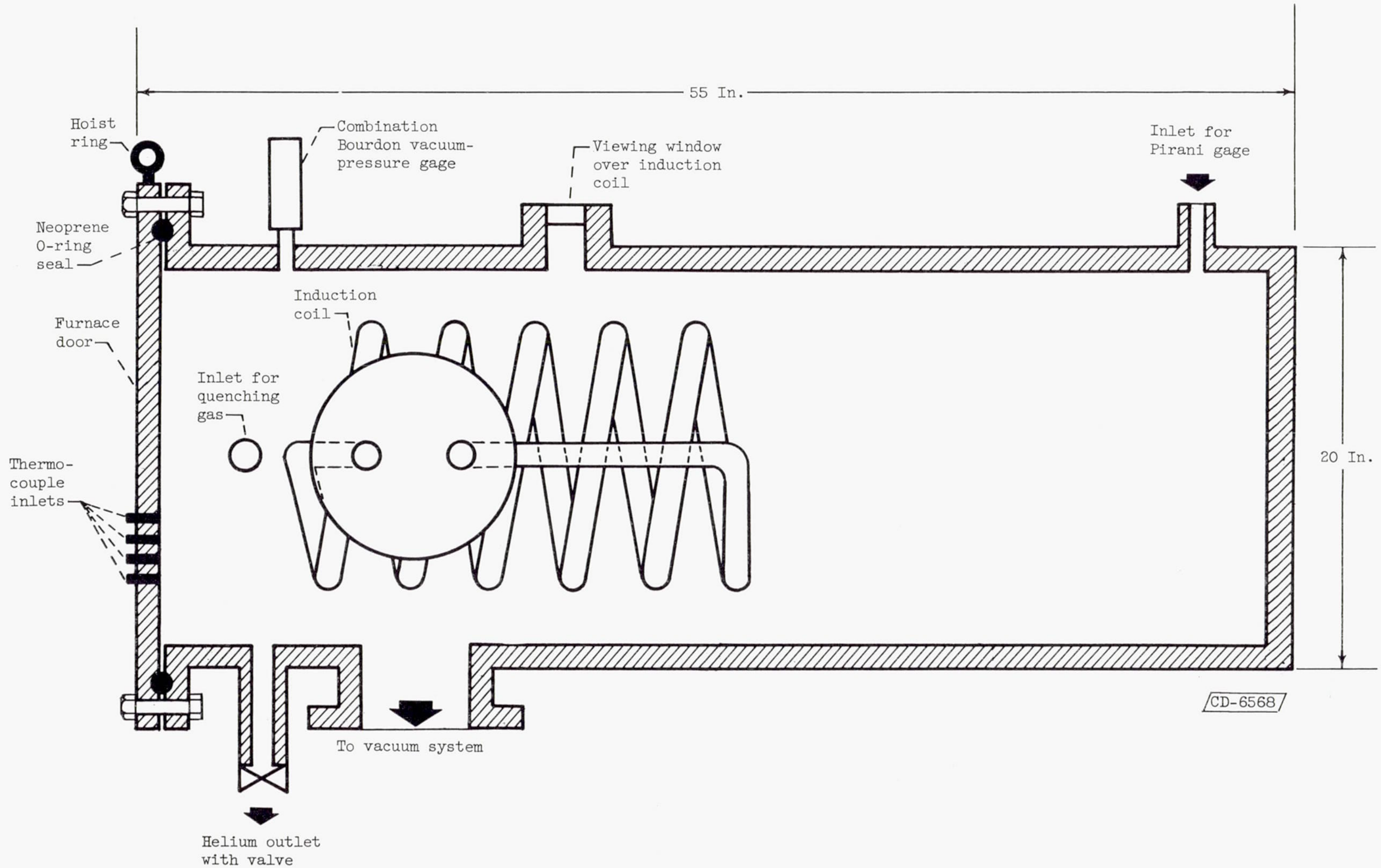


Figure 5. - Schematic diagram of vacuum induction furnace equipped for helium quenching.

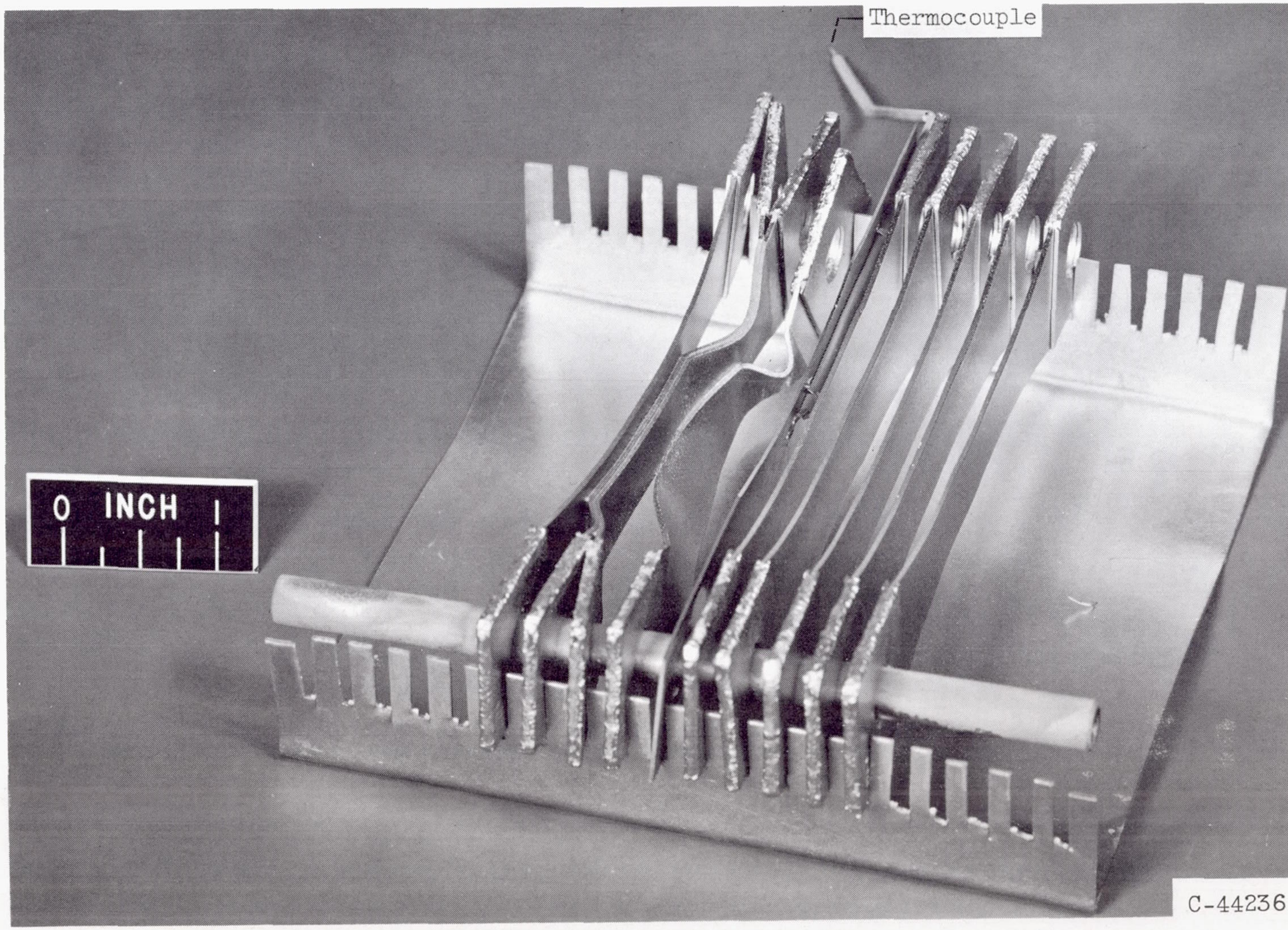
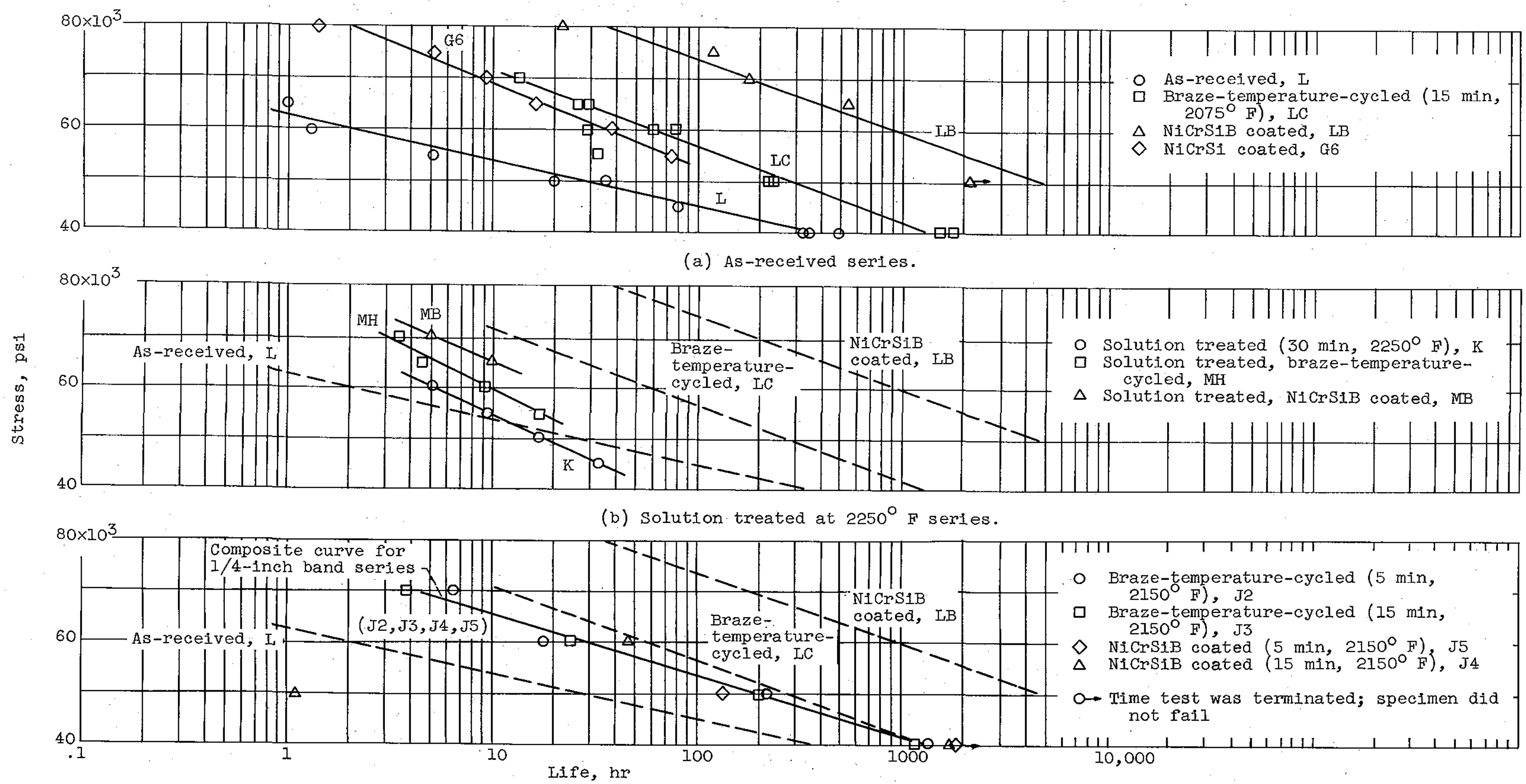


Figure 6. - Sagging of Inconel 700 stress-rupture specimens heat treated at 2275° F following application of NiCrSiB. (Specimens to right of thermocouple are not braze coated.)



(c) Braze applied in 0.25- by 0.0015-inch band, processed at 2150° F.

Figure 7. - Effect of brazing variables and heat treatment on 1200° F stress-rupture life of 0.020-inch-thick L-605 sheet material. (Data given in table III.)

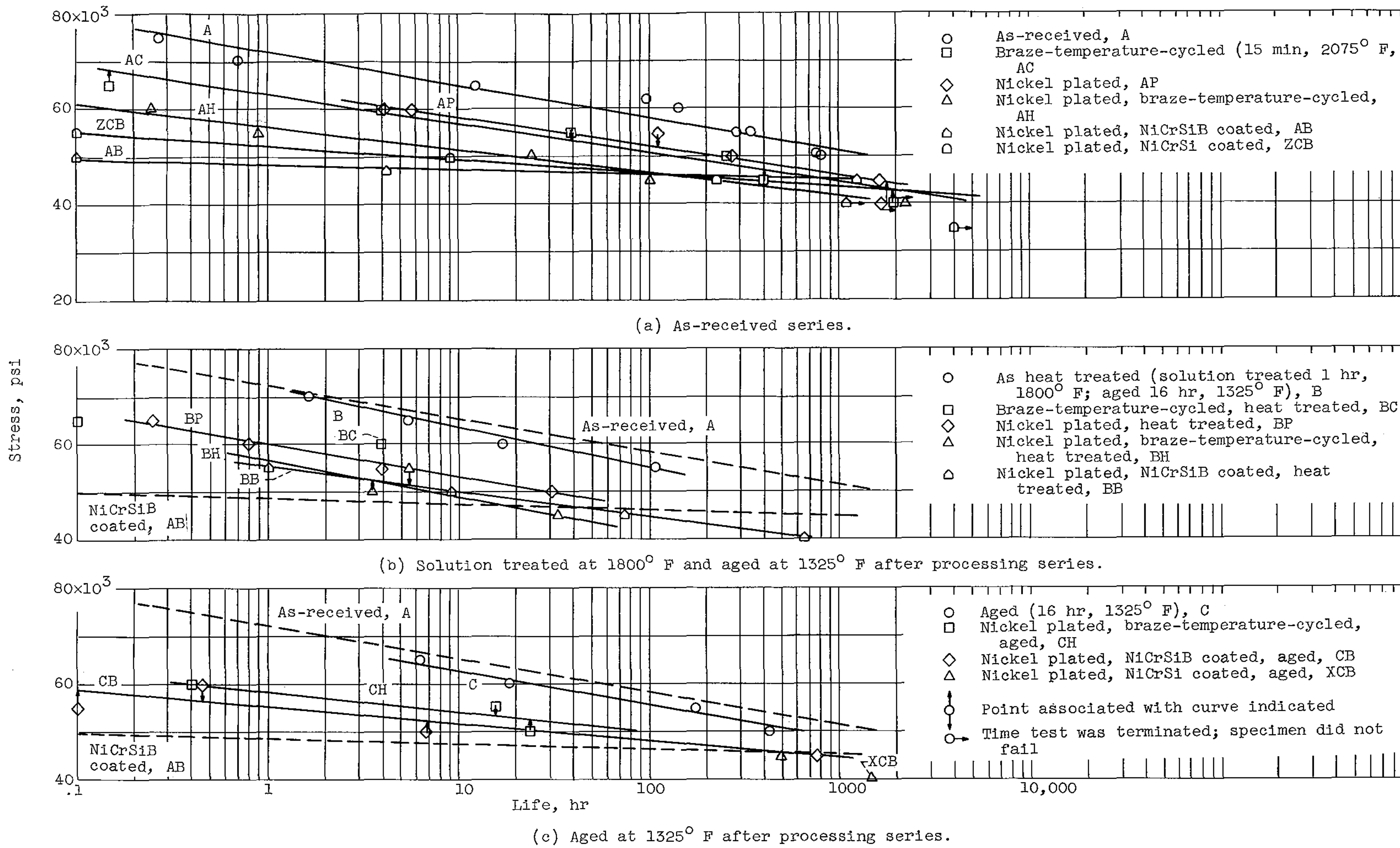
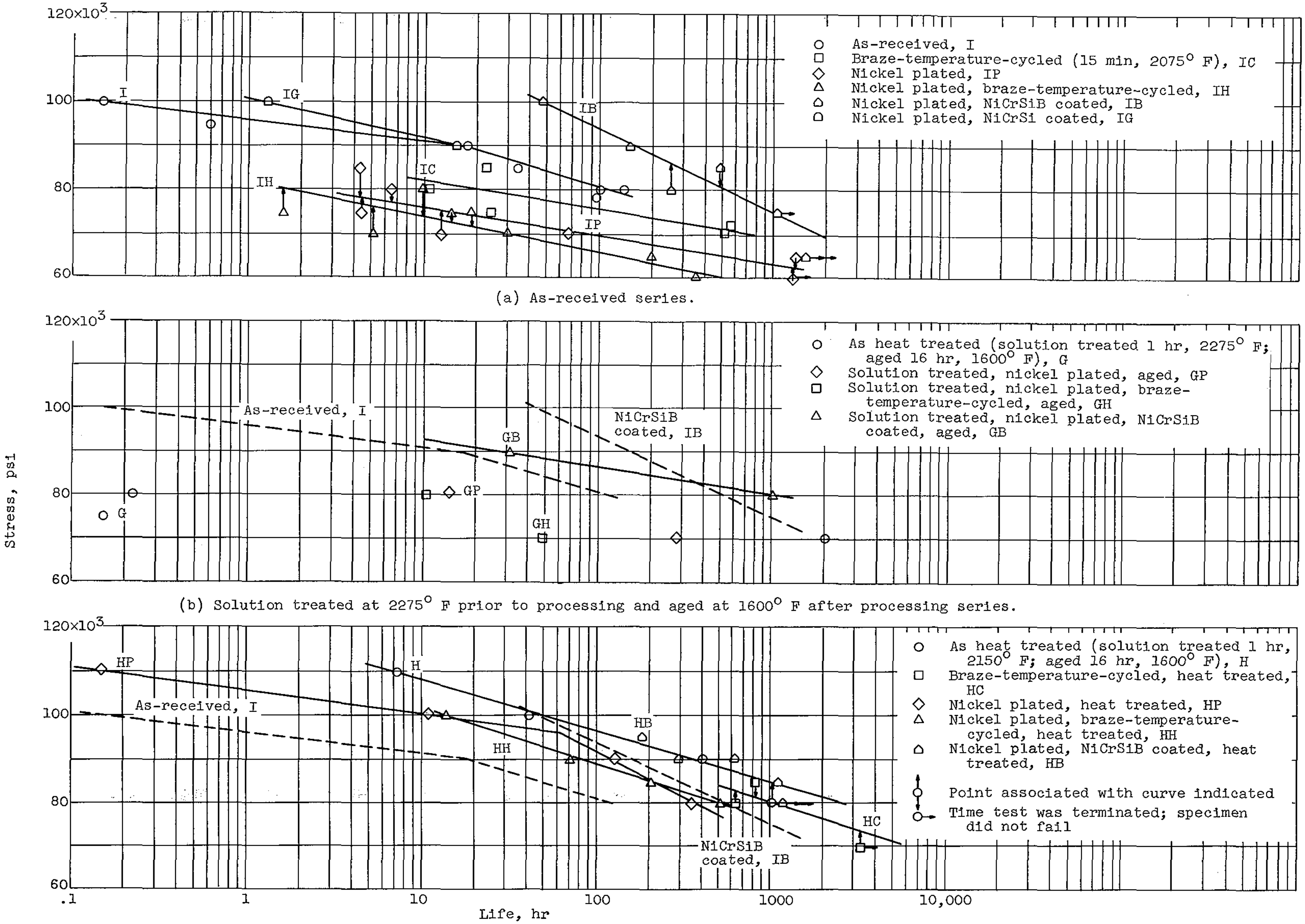


Figure 8. - Effect of brazing variables and heat treatment on 1200° F stress-rupture life of 0.020-inch-thick A-286 sheet material. (Data given in table IV.)

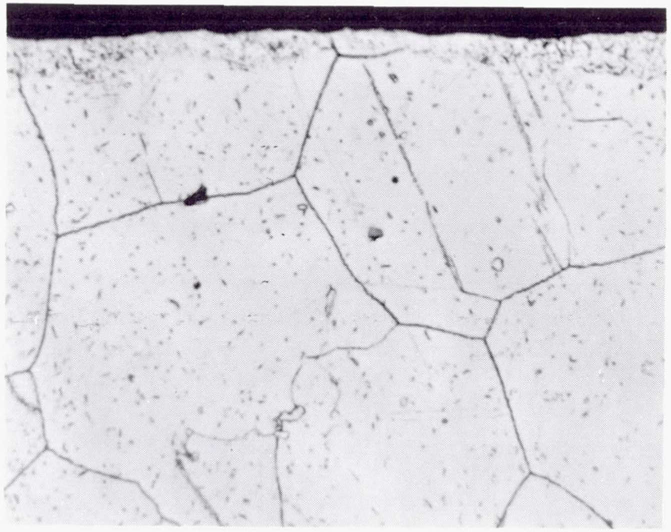


(a) As-received series.

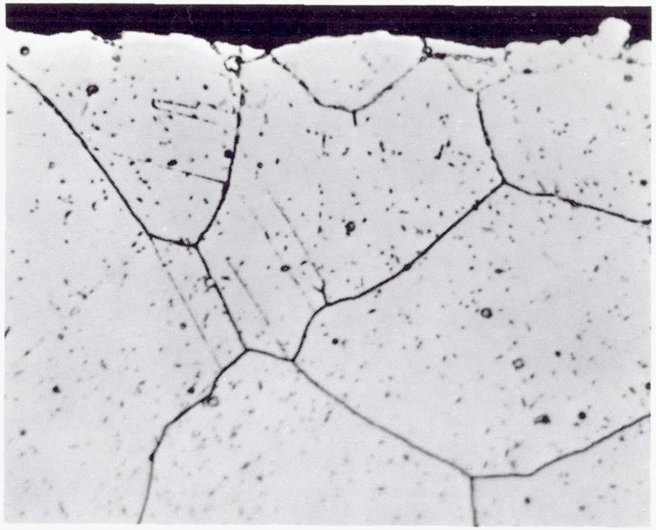
(b) Solution treated at 2275° F prior to processing and aged at 1600° F after processing series.

(c) Solution treated at 2150° F and aged at 1600° F after processing series.

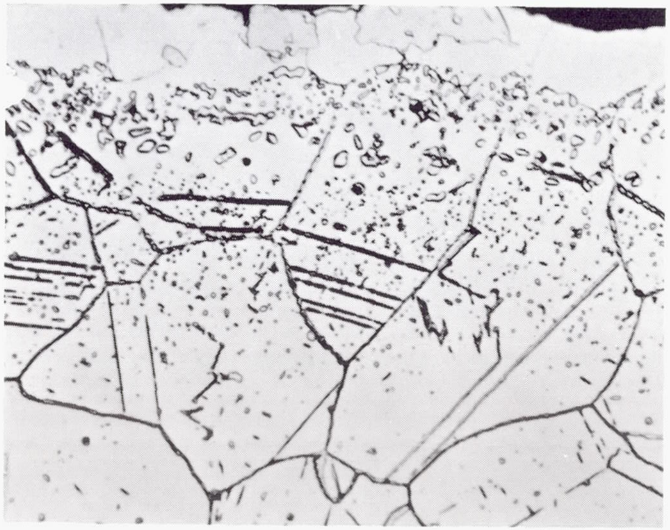
Figure 9. - Effect of brazing variables and heat treatment on 1200° F stress-rupture life of 0.030-inch-thick Inconel 700 sheet material. (Data given in table V.)



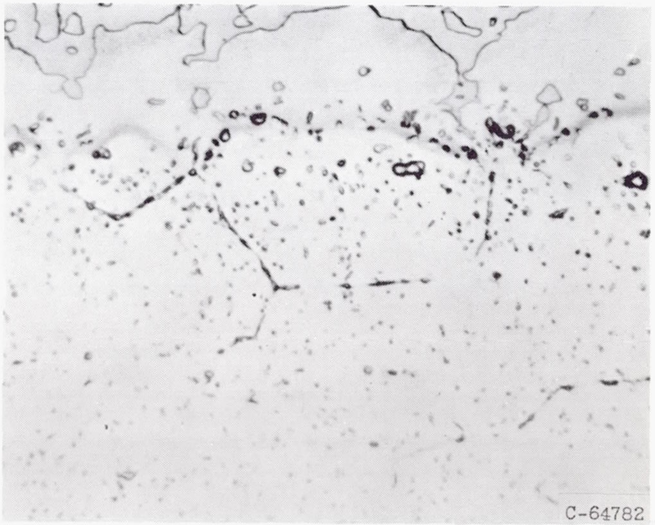
(a) As-received.



(b) Braze-temperature-cycled at 2075° F for 15 minutes.

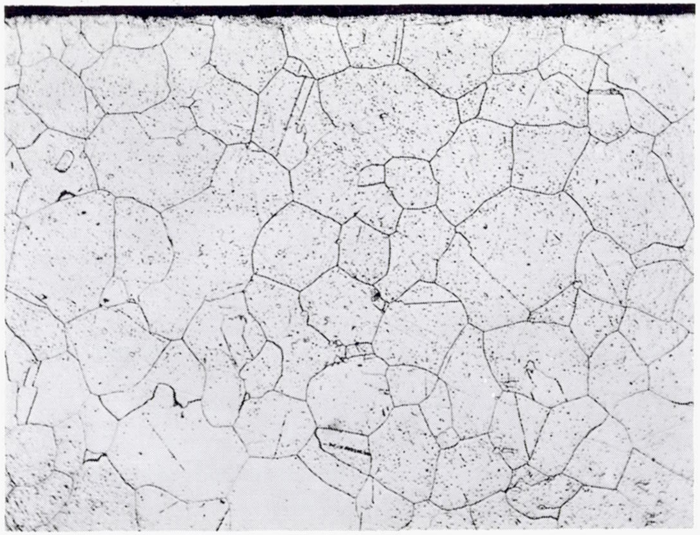


(c) NiCrSiB coated at 2075° F for 15 minutes.

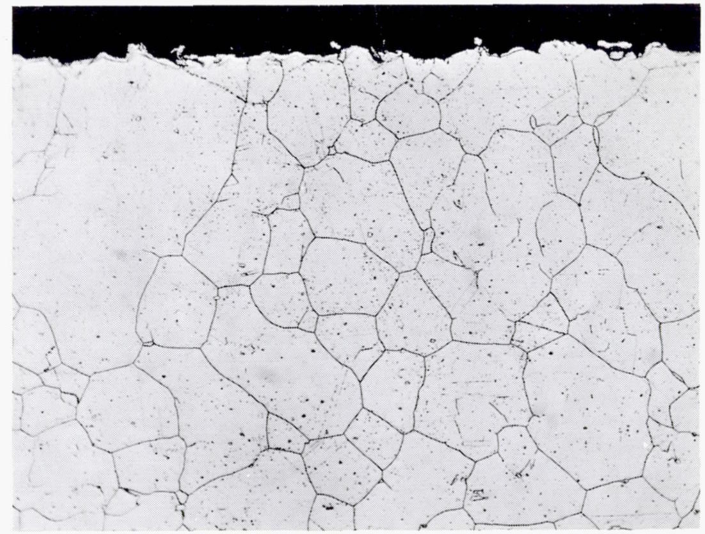


(d) NiCrSi coated at 2075° F for 15 minutes.

Figure 10. - Microstructures of L-605 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 70 parts saturated boric acid solution, 30 parts 5 percent sulfuric acid solution. ×900.



(a) As-received.

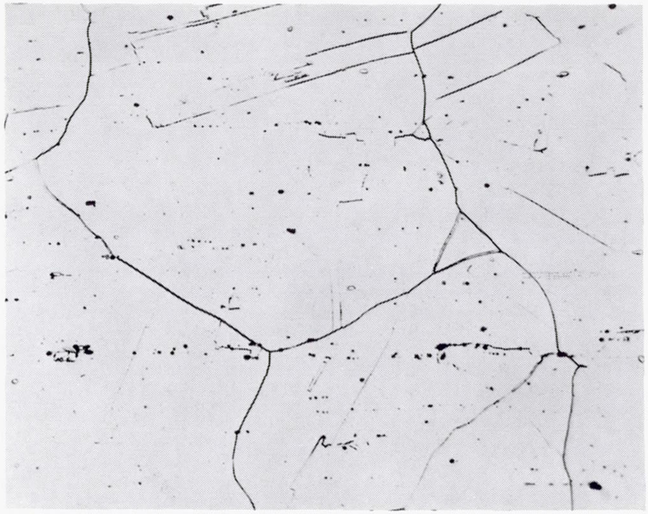


(b) Braze-temperature-cycled at 2075° F for 15 minutes.

(c) NiCrSiB coated at 2075° F for 15 minutes.

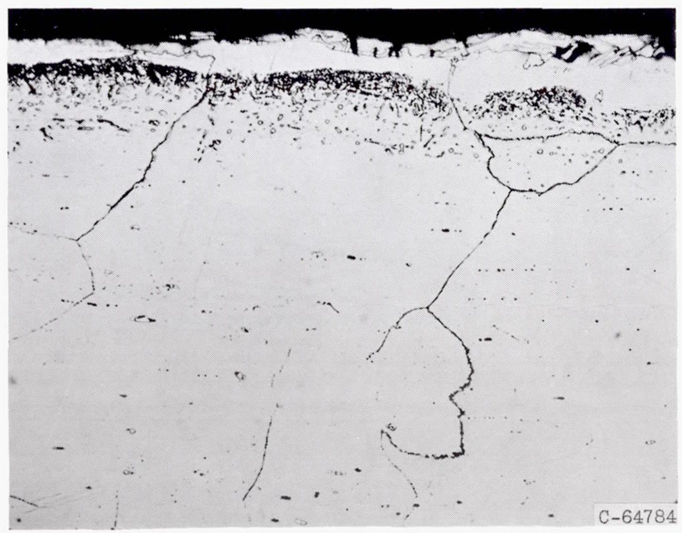
(d) NiCrSi coated at 2075° F for 15 minutes.

Figure 11. - Microstructures of L-605 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 70 parts saturated boric acid in water, 30 parts 5 percent sulfuric acid solution. ×250.



(a) Solution treated; operated 32.8 hours. Etched in glycerine - aqua regia.

(b) Solution treated and braze-temperature-cycled (2075° F) for 15 minutes; operated 3.5 hours. Etched in glycerine - aqua regia.



(c) Solution treated and NiCrSiB coated at 2075° F for 15 minutes.

Figure 12. - Microstructures of L-605 stress-rupture specimens. Solution treated at 2250° F for 30 minutes. Electrolytically etched in aqua regia in glycerine or solution of 70 parts saturated boric acid solution, 30 parts 5 percent sulfuric acid solution. ×250.

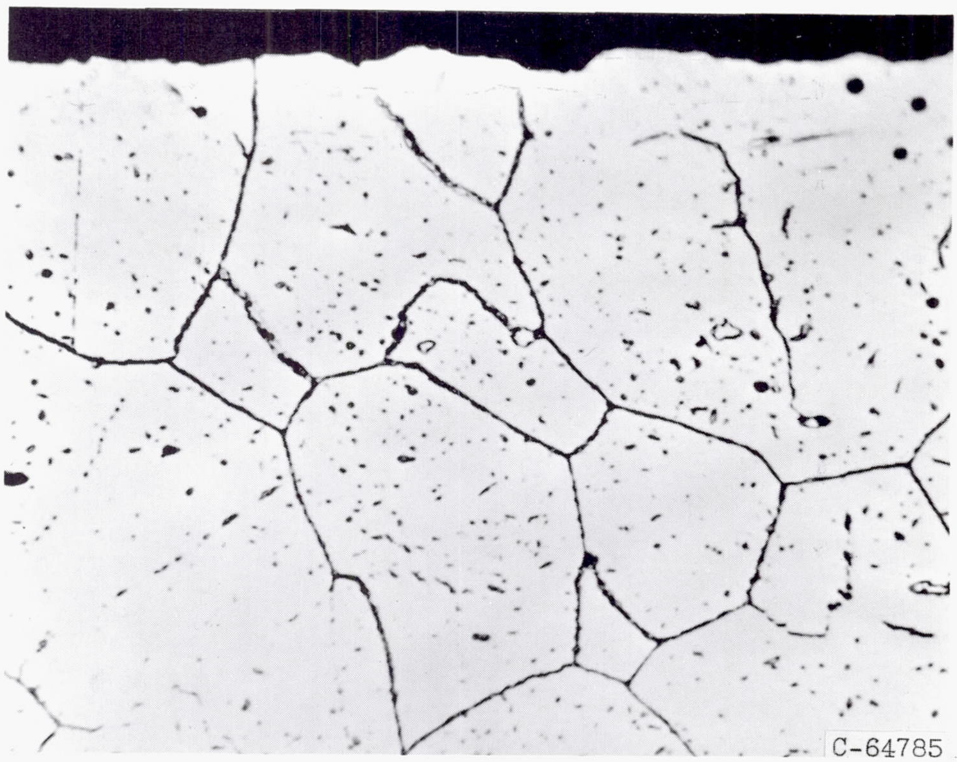
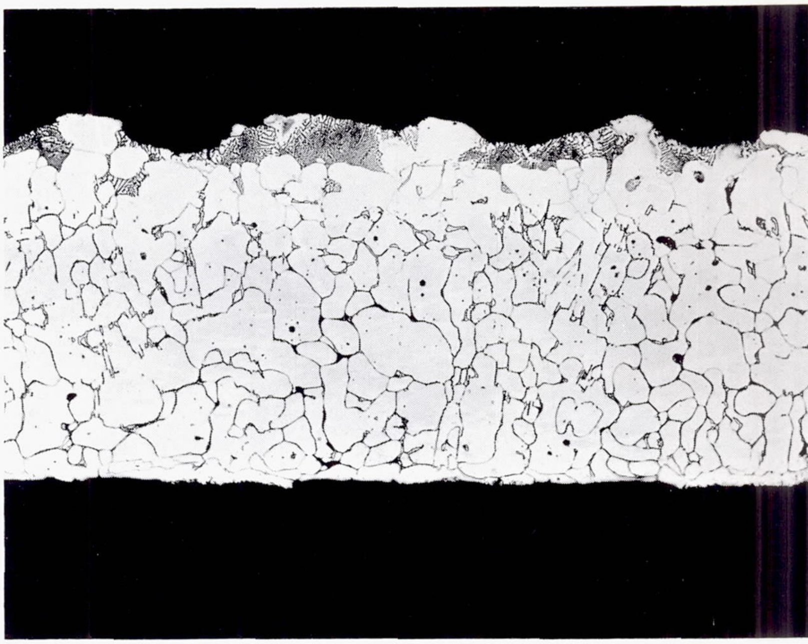
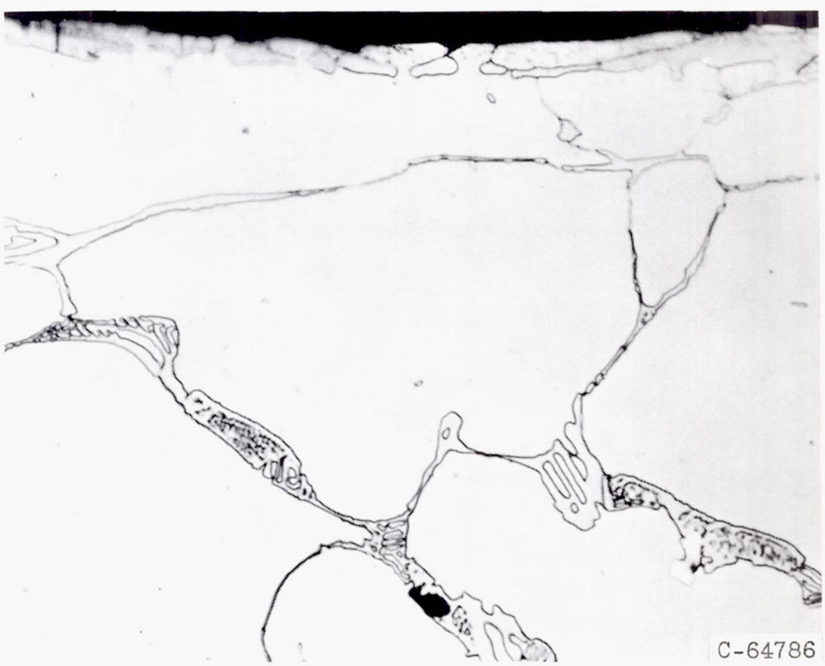


Figure 13. - Microstructure of L-605 stress-rupture specimen braze-temperature-cycled at 2150° F for 15 minutes; operated 3.8 hours. Electrolytically etched in solution of 70 parts saturated boric acid solution and 30 parts 5 percent sulfuric acid solution. ×900.



(a) General microstructure. ×100.



(b) Braze penetration through to side opposite braze application. ×900.

Figure 14. - Microstructures of L-605 coated with 0.25- by 0.015-inch strip of NiCrSiB on one side. Brazing conditions: 2150° F, 15 minutes, vacuum. Electrolytically etched in a solution of 70 parts saturated boric acid in water, 30 parts 5 percent sulfuric acid solution.

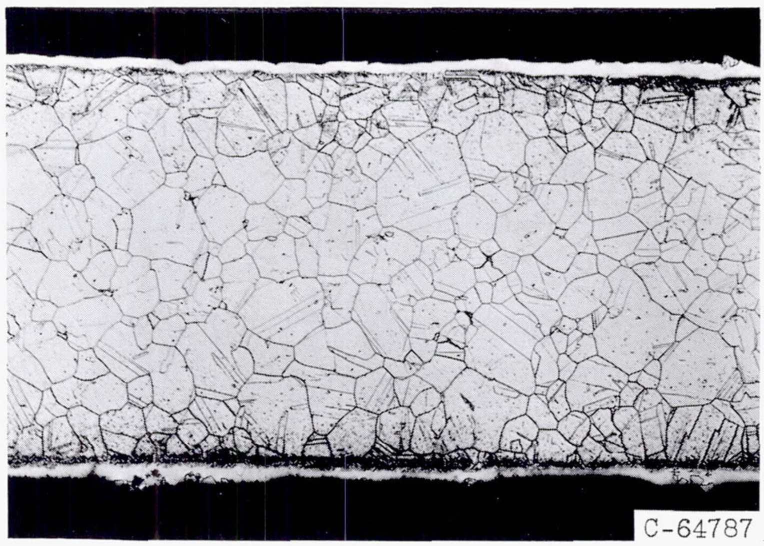
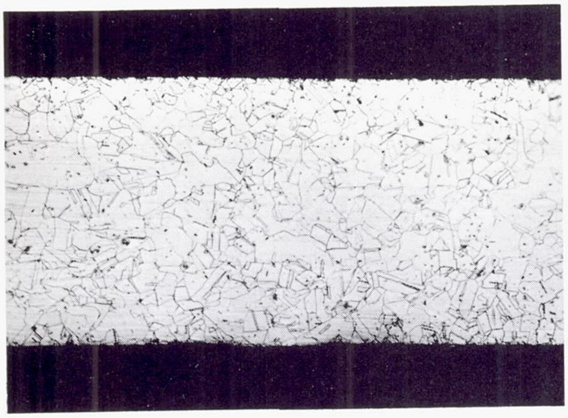
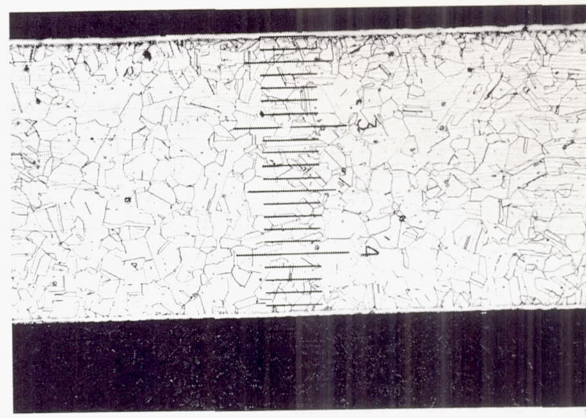


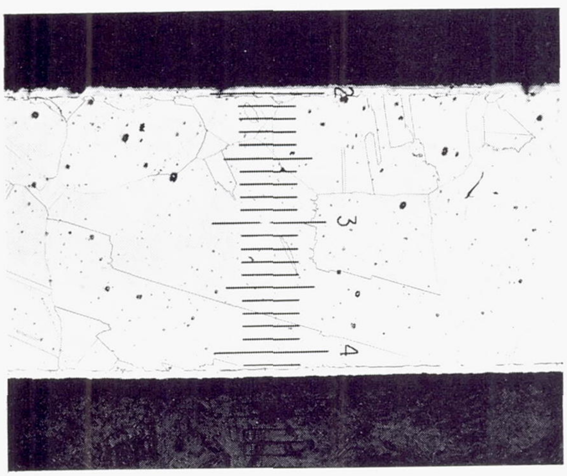
Figure 15. - Microstructure of L-605 NiCrSiB coated with 0.001-inch layer of braze alloy. Brazing conditions: 2075° F, 15 minutes, vacuum. Electrolytically etched in a solution of 50 percent distilled water, 40 percent hydrochloric acid, and 10 percent nitric acid. ×100.



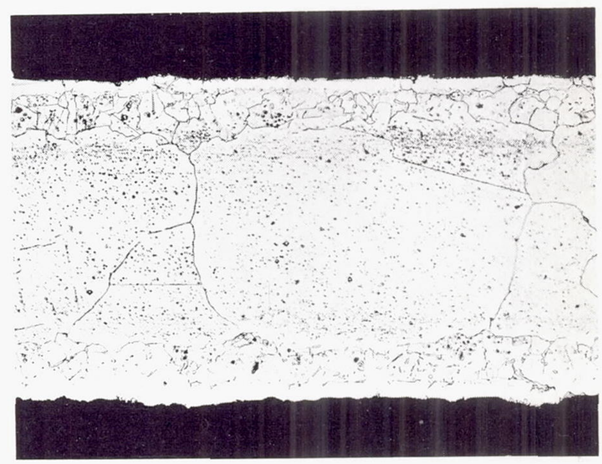
(a) As-received.



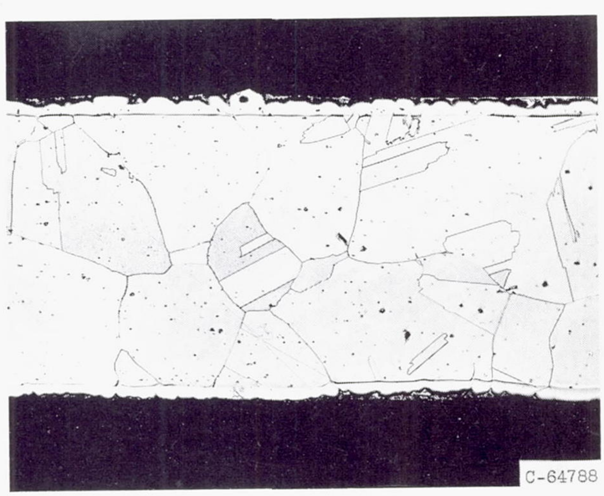
(b) Nickel plated.



(c) Nickel plated and braze-temperature-cycled at 2075° F for 15 minutes.

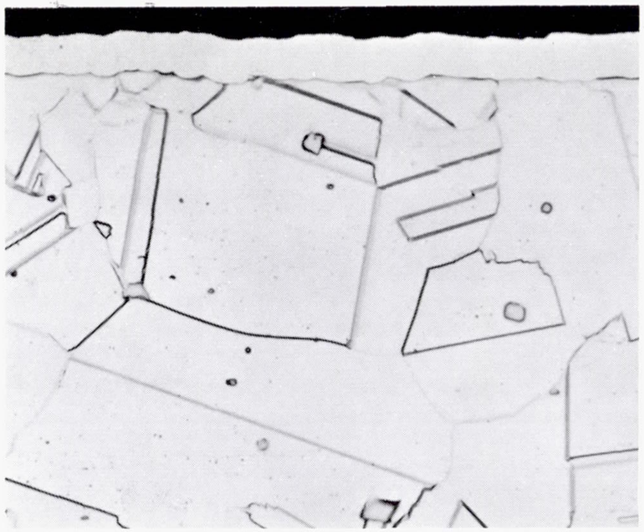


(d) Nickel plated and NiCrSiB coated at 2075° F for 15 minutes.

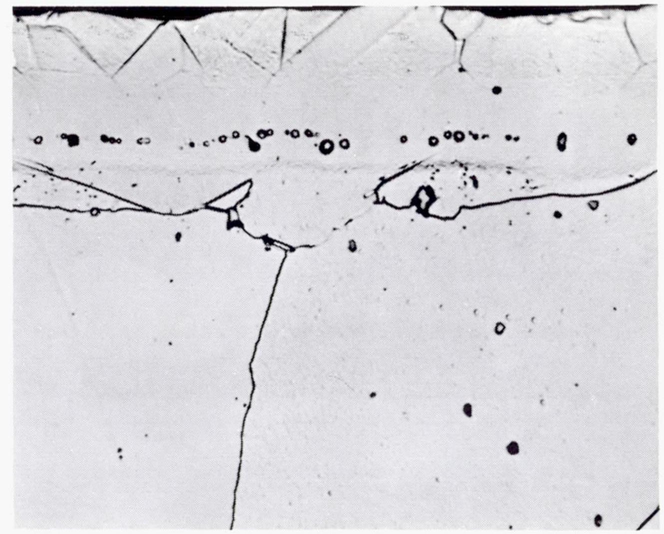


(e) Nickel plated and NiCrSi coated at 2075° F for 15 minutes.

Figure 16. - Microstructures of A-286 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 50 percent distilled water, 40 percent hydrochloric acid, and 10 percent nitric acid. ×100.



(a) Nickel plated.



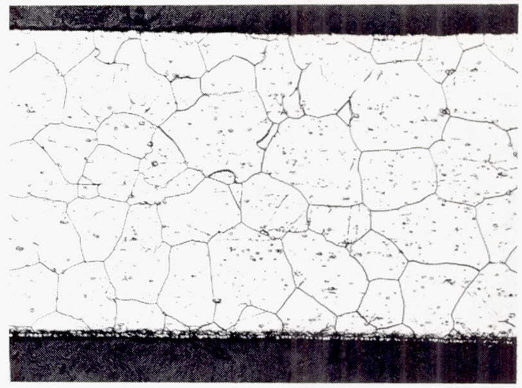
(b) Nickel plated and braze-temperature-cycled at 2075° F for 15 minutes.

(c) Nickel plated and NiCrSiB coated at 2075° F for 15 minutes.

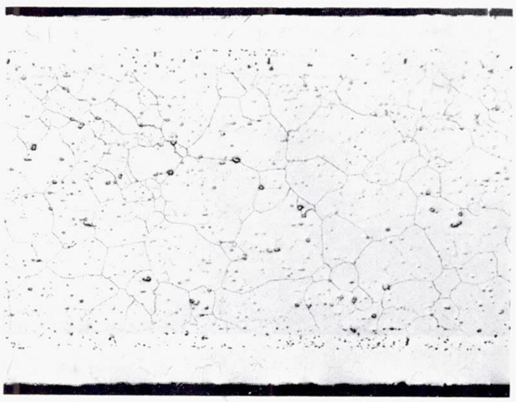
(d) Nickel plated and NiCrSi coated at 2075° F for 15 minutes.

Figure 17. - Microstructures of A-286 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 50 percent distilled water, 40 percent hydrochloric acid, and 10 percent nitric acid. ×900.

(a) As-received.

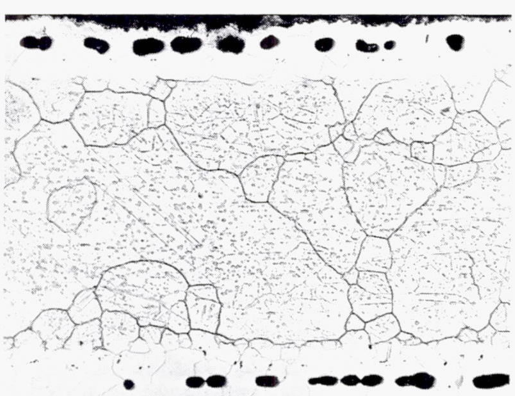


(b) Braze-temperature-cycled at 2075° F for 15 minutes.

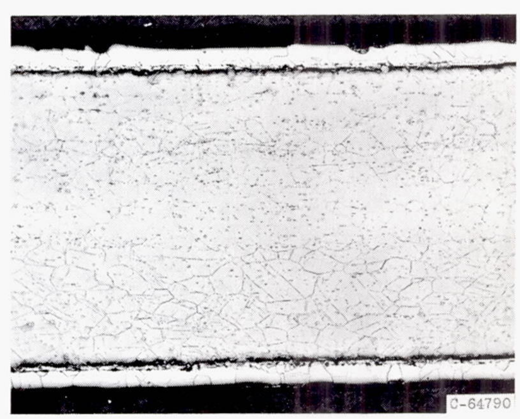


(c) Nickel plated.

(d) Nickel plated and braze-temperature-cycled at 2075° F for 15 minutes.

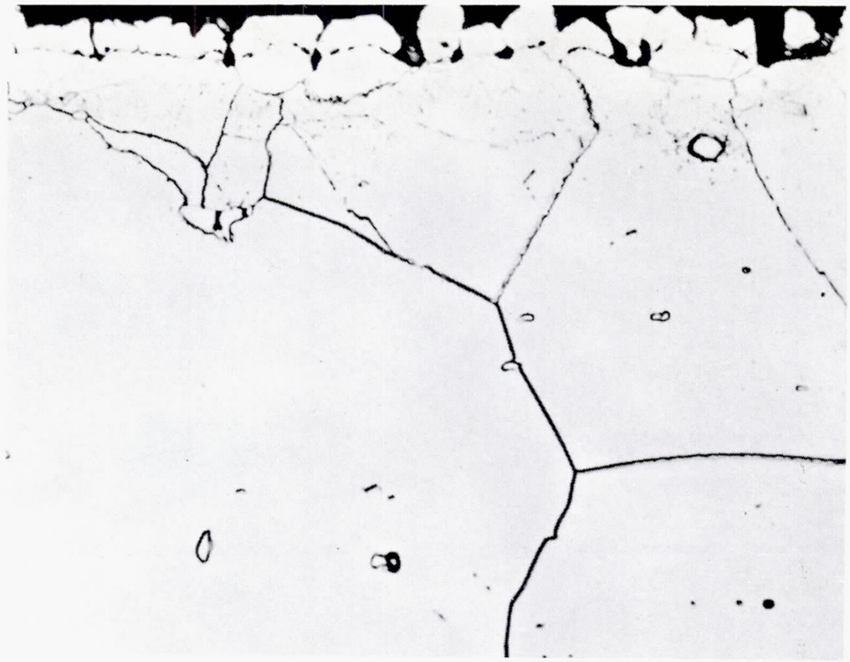


(e) Nickel plated NiCrSiB coated at 2075° F for 15 minutes.



(f) Nickel plated and NiCrSi coated at 2075° F for 15 minutes. Etched in 92 parts hydrochloric acid, 5 parts sulfuric acid, 3 parts nitric acid.

Figure 18. - Microstructures of Inconel 700 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 50 percent distilled water, 40 percent hydrochloric acid, and 10 percent nitric acid unless otherwise noted. X100. Photographs reduced 39 percent.



(a) As-received.

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(b) Braze-temperature-cycled at 2075° F for 15 minutes.

Figure 19. - Microstructures of Inconel 700 stress-rupture specimens prior to testing. Electrolytically etched in a solution of 20 parts glycerine, 20 parts water, 10 parts nitric acid, 5 parts hydrofluoric acid. ×900. Photographs reduced 23 percent.

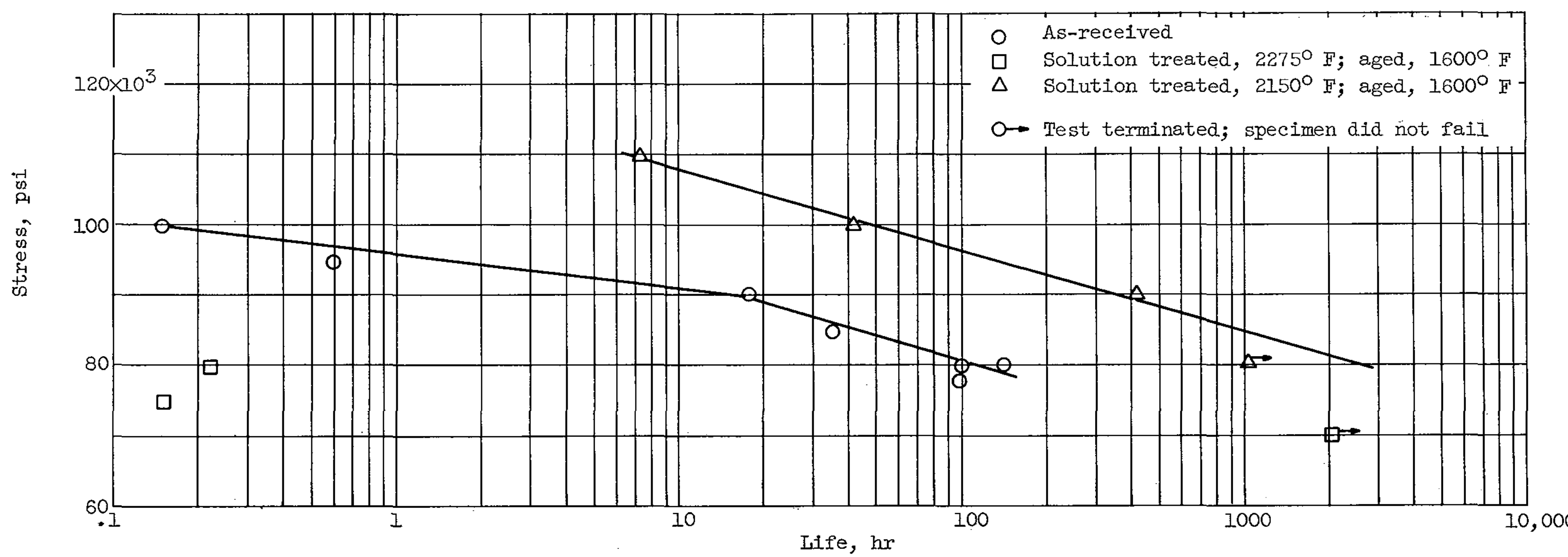

Figure 20. - Comparison of stress-rupture life of Inconel 700 sheet in as-received and solution-treated condition.

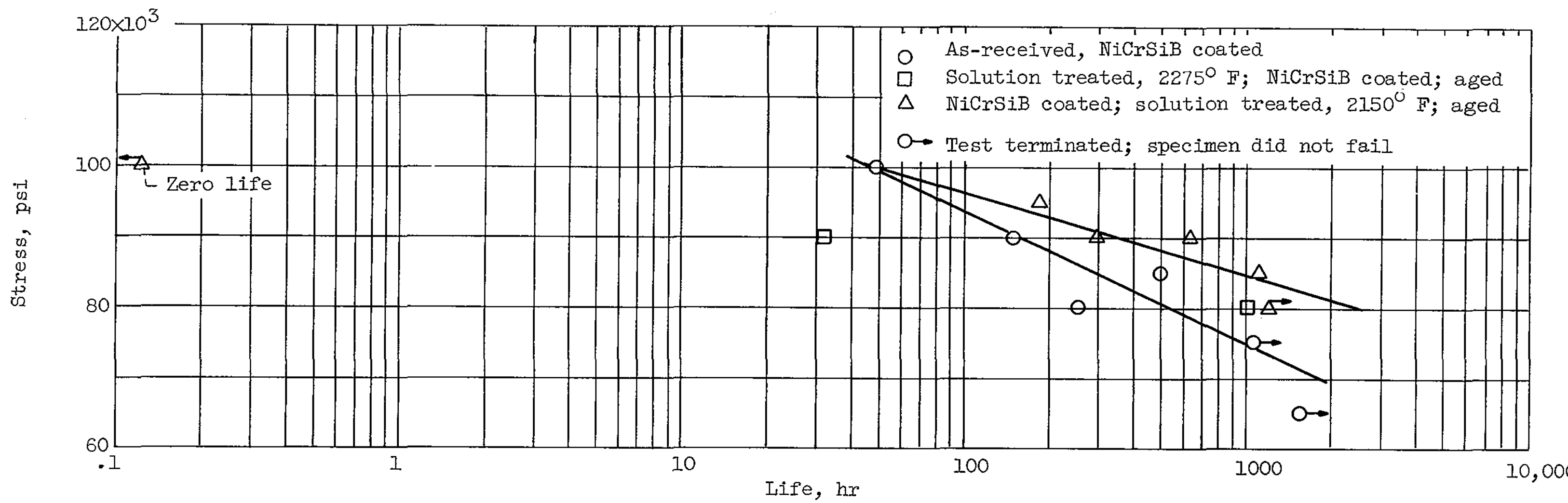

Figure 21. - Comparison of stress-rupture lives of NiCrSiB coated Inconel 700 in as-received and solution-treated condition.

Figure 22. - Variation of nickel plating thickness with distance from edge. Electrolytically etched in a solution of 50 percent distilled water, 40 percent hydrochloric acid, and 10 percent nitric acid. X110. Photograph reduced 16 percent.

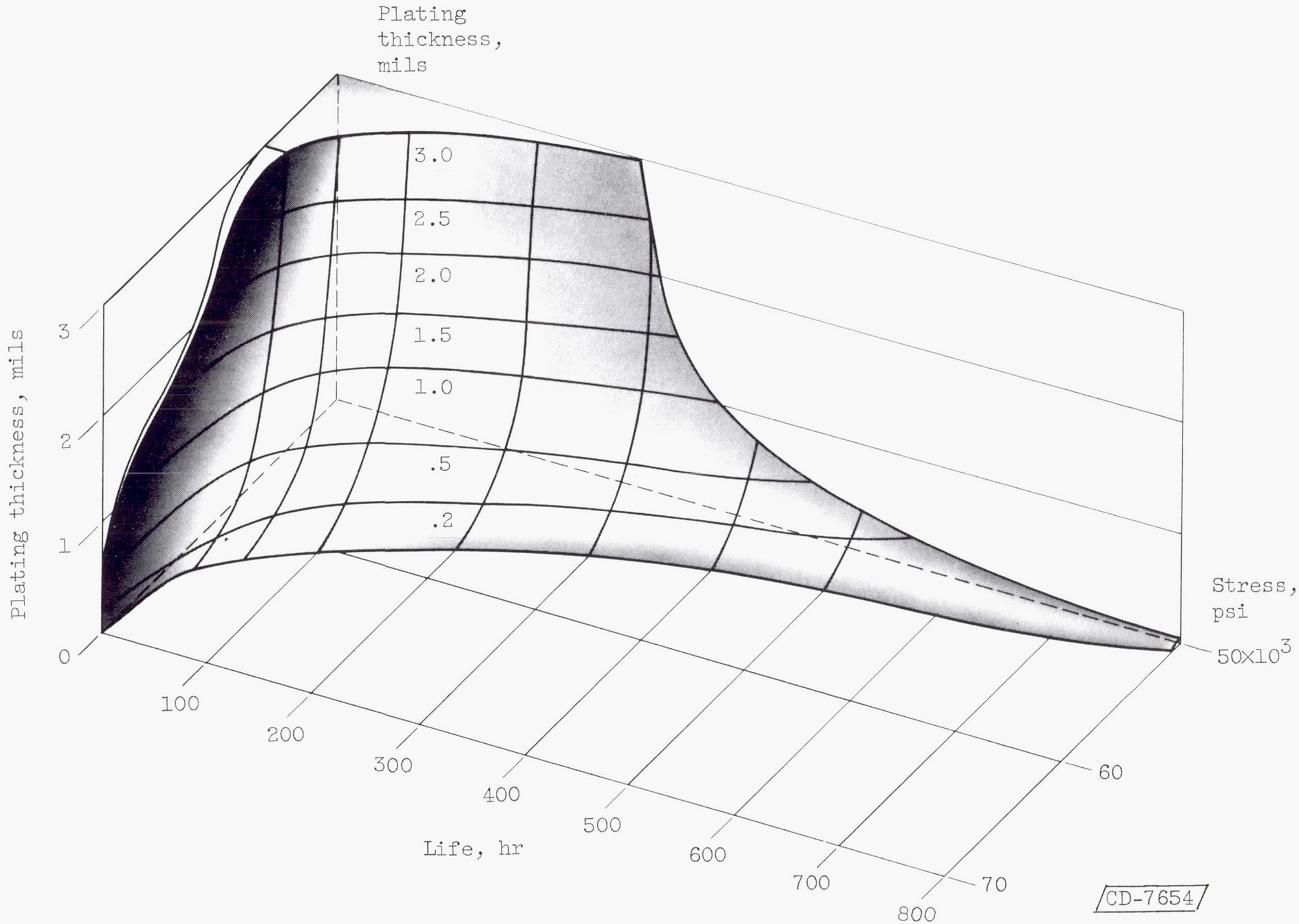

Figure 23. - Effect of nickel plating thickness on stress and life of A-286 tested in stress-rupture at 1200° F.

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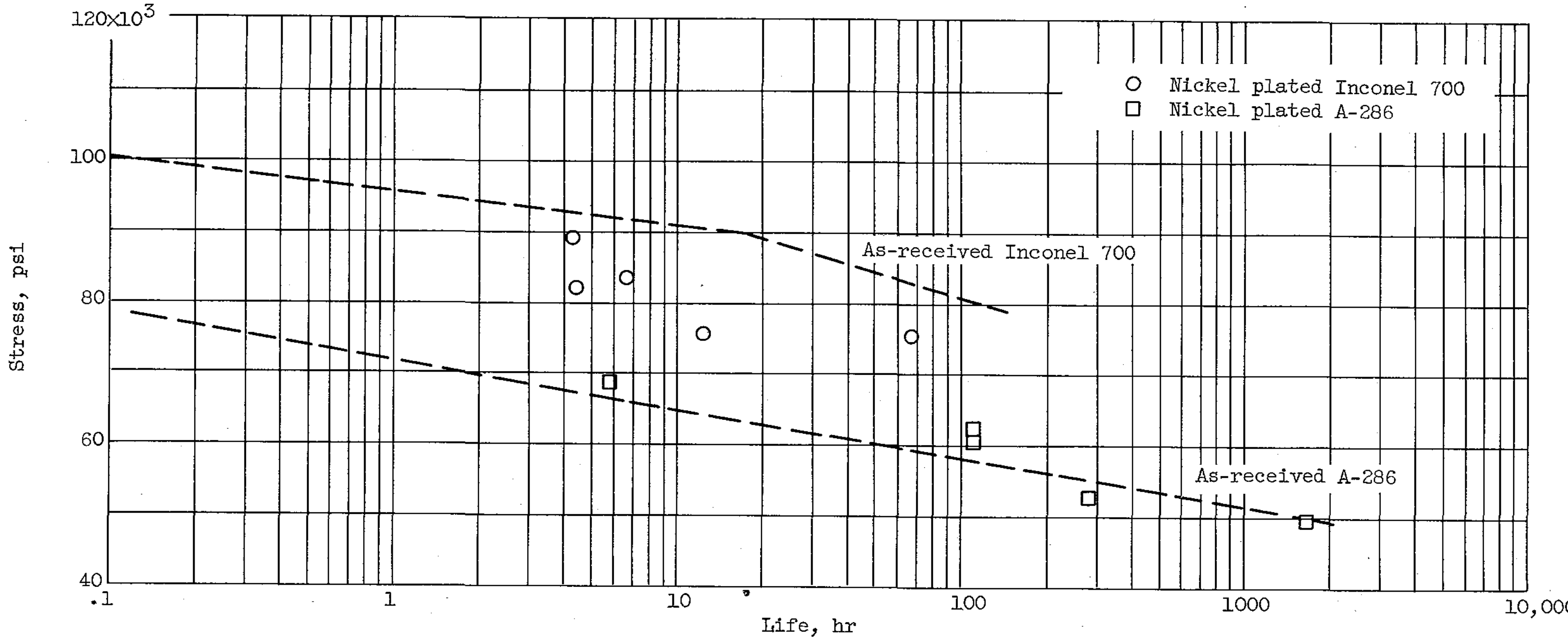

Figure 24. - Comparison of 1200° F stress-rupture life of as-received and plated specimens, assuming that base metal only was carrying stress imposed on plated specimens.