NASA TECHNICAL NOTE

NASA TN D-5918

c. 1

NASA TN D-5918

SOLID-STATE WELDING OF TD-NICKEL BAR

by Thomas J. Moore and Kenneth H. Holko

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1970

1. Report No. NASA TN D-5918	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SOLID-STATE WELDING OF TD-NICKEL BAR		5. Report Date July 1970
		6. Performing Organization Code
7. Author(s) Thomas J. Moore and Kenneth H. Holko		8. Performing Organization Report No. E-5651
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 129-03
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Solid-state butt and lap joint welds were made in 1/2-inch (12.7-mm) diameter TD-nickel bar in a hot isostatic press at 2000° F (1093° C) and 20 ksi (138 MN/m^2) for 2 hours. Various interlayer materials were used in the butt joints. Best butt joint efficiency (percent of parent material strength) at 2000° F (1093° C) was obtained with a 0.004 inch (0.10 mm) cobalt-alloy interlayer: stress-rupture joint efficiency was 15 percent for 100-hour life and tensile joint efficiency was 100 percent. Thus, stress-rupture testing was found to be a more severe criterion. In short-time shear tests of lap joints (without interlayers) parent material shear strength was matched in 2000° F (1093° C) tests.

17. Key Words *(Suggested by Author(s))* Welding TD-nickel		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 39	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

SOLID-STATE WELDING OF TD-NICKEL BAR

by Thomas J. Moore and Kenneth H. Holko

Lewis Research Center

SUMMARY

Solid-state welds were made in 1/2-inch (12.7-mm) diameter thoriated-nickel (TD-Ni) bar both in butt joints (with and without interlayers) and in lap joints. Minimum disruption of the parent material microstructure was anticipated with a nonfusion welding process. Welding was accomplished by using hot isostatic pressure (HIP) with peak temperature and pressure parameters of 2000° F (1093° C) and 20.0 ksi (138 MN/m^2) in helium for 2 hours. Short-time tensile and shear joint efficiencies (defined as percent of parent material strength) were determined at room temperature and at 2000° F (1093° C). Stress-rupture tests were run at 2000° F (1093° C) on butt joints. Metallographic techniques also were used in the evaluation.

Stress-rupture testing of butt joint weldments at 2000° F (1093° C) was a more severe criterion of performance than 2000° F (1093° C) tensile tests. The strongest butt joint tested in stress-rupture had a 0.004-inch (0.10-mm) cobalt-alloy interlayer. And this joint had only 15 percent joint efficiency for 100-hour life. In 2000° F (1093° C) tensile tests, butt joints with cobalt-alloy and Hastelloy X interlayers had up to 100 percent and 87 percent joint efficiency, respectively. These represented the best results of the 15 interlayer materials evaluated. Without interlayers, joint efficiency in the 2000° F (1093° C) tensile tests was about 55 percent. All weldments tested at 2000° F (1093° C) in tensile and stress-rupture tests failed at the weld with a characteristic square-edge appearance and less than 1 percent elongation. Butt joints with cobalt-alloy interlayers, Hastelloy X interlayers, or with no interlayers at all were stronger than the parent material when tested at room temperature.

Parent material strength was matched in room temperature and in 2000° F (1093° C) short-time shear tests of lap joints. For these specimens, the joint was in the plane of the axis of the bar.

INTRODUCTION

Higher operating temperatures in advanced jet engines have increased the demand for high-temperature materials. One of the most promising materials in the 1900° to 2200° F (1038° to 1204° C) temperature range is thoriated-nickel (TD-Ni). This material is strengthened with a fine dispersion of thoria (~2 vol. %) in a pure nickel matrix.

TD-Ni has good ductility and therefore good fabricability. Joining by fusion welding processes, however, is not suitable because melting destroys the thoria dispersion and strengthening effects produced by thermomechanical processing. Solid-state welding processes would appear to offer great promise because welds can be made without melting the parent material. (A discussion of the solid-state welding mechanism is presented in appendix A.)

The objective of this study was to weld TD-Ni by using a solid-state welding process which produced only microdeformation. A hot isostatic pressure (HIP) process was selected to produce the welds. (This process has been called gas pressure bonding, but HIP welding is used throughout this report and is suggested as a more proper term in appendix B.)

TD-Ni in bar form was selected as the parent material for several reasons. In bar form, TD-Ni is considerably stronger than sheet material (ref. 1). The bar has a wrought microstructure that is stable to about 2400° F (1316° C), and application of solid-state welding techniques to TD-Ni bar has not been extensively investigated. In cursory studies of solid-state butt welds in TD-Ni bar, Metcalfe (ref. 2) reported 30 percent joint efficiency in 2000° F (1093° C) tensile tests.

$$\text{Joint efficiency} = \frac{\text{Weld strength}}{\text{Parent material strength}} \times 100$$

In this study, HIP welds were made in 1/2-inch (12.7-mm) diameter TD-Ni bar in a square butt configuration with and without interlayers. Several interlayer materials were evaluated. Weldments were evaluated on the basis of tensile tests at room temperature and at 2000° F (1093° C). Stress-rupture tests were also run at 2000° F (1093° C). In addition, exploratory studies were made on lap joints. Lap joints (without interlayers) were tested in short-time shear tests at room temperature and at 2000° F (1093° C). Joint quality and structural stability of both types of joints were evaluated using metallographic techniques.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

Commercial 1/2-inch (12.7-mm) diameter TD-Ni bar (purchased from E. I. duPont deNemours and Co.) was used to make both butt and lap joints. This material was in the wrought condition, and it contained elongated pencil-shaped grains parallel to the axis of the bar. The structure was very stable; it could not be recrystallized by heat treatment at 2500° F (1371° C) for 100 hours. Tensile and shear strengths of the 1/2-inch (12.7-mm) diameter bar at room temperature and at 2000° F (1093° C) are shown in table I. Note that at 2000° F (1093° C) the shear strength is only one-seventh of the ultimate tensile strength, which indicates the directionality of the properties of the bar material.

Sheet materials of the following commercially pure metals were used as interlayers in butt joints: 0.001-inch (25-μm) Cb; 0.0003-inch (7.5-μm) Ta; 0.001-inch (25-μm) Mo; 0.001-inch (25-μm) W; 0.005-inch (0.13-mm) V; and 0.00025-inch (6-μm) Ti. For one joint, 0.020-inch (0.51-mm) TD-Ni sheet was used. A NASA-developed cobalt-base alloy (ref. 3) was used in two thicknesses. Hastelloy X,[1] a Ni-base alloy, was also used in two thicknesses. Chemical analyses of the cobalt alloy and Hastelloy X sheet materials were as follows:

Alloy	Composition, wt%											
	C	Mn	Si	Cr	Ni	Co	Mo	W	Fe	Ti	Zr	Re
Hastelloy X (0.018 in., 0.46 mm)	0.06	0.84	0.68	21.74	Bal	0.80	8.66	0.14	17.71	---	---	---
NASA cobalt-base alloy (nominal except for carbon)	[a]0.34 [b]0.15	----	----	2.8	---	Bal	----	25.0	-----	0.9	0.4	2.0

[a]0.013-in. (0.33-mm) material.
[b]0.004-in. (0.10-mm) material.

[1]Tradename of Stellite Division, Cabot Corp.

The criteria for selecting these and other materials that were applied to the faying (mating) surfaces of the TD-Ni bar were as follows:

Interlayer material	Primary basis for selection
W, Mo, Cb, Ta	Good strength at 2000° F (1093° C) for the interlayer
Ti, Cr, V, Pd, Fe	Increase in diffusion across the weld interfaces to promote grain growth and eliminate the original weld interface; also selected to avoid ordered phase formation
ThO_2	Extra thoria to compensate for possible losses
TD-Ni sheet	Relatively good strength at 2000° F (1093° C) for the interlayer
Hastelloy X	Strong Ni-base alloy in sheet form: Good tensile strength to 2000° F (1093° C) Good stress-rupture strength to 1800° F (982° C)
Cobalt-base alloy	Strongest[a] cobalt-base alloy available in sheet form: At 2000° F (1093° C) ultimate tensile strength $\approx$25 ksi (172 MN/m^2) At 2000° F (1093° C) stress for rupture in 100 hours $\approx$10 ksi (69 MN/m^2)

[a]Strength given here is for tests of as-cast material (ref. 3). This material may be somewhat weaker in sheet form.

These interlayer materials were selected with the assumption that strong metallic bonds could be achieved and that the weld interfaces would not be planes of weakness. It was recognized that some interlayer materials would have poor oxidation resistance and considerable differences in coefficient of thermal expansion in comparison to TD-Ni bar. Differential diffusion rates across weld interfaces during a 100-hour 2000° F (1093° C) heat treatment were expected to produce varying degrees of Kirkendall voids. But the extent and pattern of void formation could not be predicted.

Commercially pure nickel (Ni 200) bar, 1/2 inch (12.7 mm) in diameter, was used in several runs as a substitute for TD-Ni parent material in diffusion studies.

Apparatus

The HIP welding runs were made in a cold-wall autoclave of the type shown in figure 1. The autoclave used in this study can be operated at helium pressures to 30.0 ksi (207 MN/m^2) at temperatures to 3000° F (1649° C). Equipment of this type has been used for the compaction of ceramics, cermets, and metals, as well as for the HIP welding of structural members (ref. 4). The construction of the molybdenum-wound resistance heater assembly within the water-cooled jacket (fig. 1) is shown in detail in figure 2. Microquartz is packed between the two stainless-steel cylinders in the heater assembly. The test specimens were surrounded with bubble alumina, and all open areas were packed with bubble alumina to minimize the quantity of helium gas required. Platinum - 6-weight-percent-rhenium/platinum - 30-percent-rhenium thermocouples were used to monitor the temperature in this program. An inverted molybdenum shell placed over the open upright molybdenum shell, and molybdenum baffles, effectively minimized thermal gradients in the furnace (fig. 2). The inverted shell and baffles also served to prevent overheating of the autoclave cover.

Welding Procedure

General procedure. - A schematic sketch presented in figure 3 shows the setup for HIP butt welding two specimens 1/2 inch (12.7 mm) in diameter by $1\frac{1}{2}$ inch (38.1 mm) long to produce a 3-inch (76.2-mm) long weldment. AISI Type 304 stainless steel wire was wrapped around the TD-Ni specimens to minimize offset at the weld joint in the slightly oversize Type 304 cans. After the TD-Ni specimens were placed in the can, the lid with the evacuation tube was gas tungsten-arc welded to the can in an argon-filled welding chamber. An electron beam welding machine was used for evacuation and tube closure. Prior to making the electron beam closure weld, the can was heated to 600° F (316° C) and held at 2×10^{-5} torr (2.7×10^{-3} N/m^2) for 1/2 hour in the electron beam welding chamber.

After a helium leak test, the sealed cans were placed in the cold-wall autoclave (as shown in fig. 2) and exposed to the HIP-welding cycle shown in figure 4. Time for the entire run was about 12 hours, during which the peak temperature and pressure of 2000° F (1093° C) and 20 ksi (138 MN/m^2) helium were maintained for 2 hours. Typical appearance of the cans after exposure to the HIP-welding cycle is shown in figure 5. The TD-Ni specimens inside the can were welded to each other and to the can. Note that the imprint of the wire that was wrapped around the TD-Ni specimens shows through the can. Also note that the evacuation tube was flattened.

Surface finish for butt joints. - Several faying surface preparation procedures were used in a cursory study of surface effects on microstructure and properties of HIP welds. The flow diagram in figure 6 shows that both as-ground, 16 rms (40.7×10^{-6} cm rms), and as-lapped, 4 rms (10.1×10^{-6} cm rms), surface finishes were used. The TD-Ni specimens were ultrasonically cleaned in freon, then in a detergent, followed by a distilled water rinse. And the stainless-steel cans were cleaned with a light acid etch, and rinsed in distilled water. In further faying surface preparation (see fig. 6), some groups of TD-Ni specimens were treated in one of the following ways:

(1) Pickle - Immerse specimens in a 125° F (52° C) solution (300 ml HNO_3, 50 ml HF, 1000 ml H_2O) for 10 minutes. Rinse in distilled water.

(2) Chemically polish - Immerse specimens in a 170° F (77° C) solution (42.5 ml H_3PO_4, 42.5 ml CH_3CO_2H, 15 ml HNO_3, 3 ml H_2SO_4, 15 ml H_2O) for 10 minutes. Rinse in a solution of 5 percent ammonium hydroxide in distilled water.

(3) Electropolish - Polish specimen in a 30-ml HNO_3, 70-ml CH_3OH solution at room temperature for $2\frac{1}{2}$ minutes at $7\frac{1}{2}$ volts.

Interlayers for butt joints. - For some other butt joints, a metal interlayer in the form of thin sheet material was cleaned in acetone and placed between as-ground faying surfaces. For still other butt joints, as-ground faying surfaces were clad with various pure metals by using vapor plating or electron beam evaporation techniques. Thoria powder was used as an interlayer for one butt joint with as-ground faying surfaces.

The balance of the procedures outlined in figure 6 was followed after the TD-Ni welding specimens were placed in the can.

Lap joints. - In addition to the butt joints, some work was done in the HIP welding of lap joints using similar procedures, except that the lap joint had as-milled 32-rms (81.3×10^{-6}-cm-rms) faying surfaces. The design of the lap joint that was subsequently tested in shear is shown in figure 7.

Testing Procedure

Tensile and stress-rupture testing were conducted on the welded specimens in the as-welded and in the heat-treated conditions. Heat treatment involved exposure at 2000° F (1093° C) for 100 hours in argon. Some specimens were heat treated while inside (and still welded to) the stainless-steel can. Others were heat treated after the can had been removed by machining. Tensile tests were conducted using a button-head specimen, 2 inches long (50.8 mm) with a 0.160-inch (4.06-mm) diameter by 1-inch (25.4-mm) gage length. The 3-inch (76.2-mm) long stress-rupture specimens had threaded ends and a 0.250-inch (6.3-mm) diameter by 1-inch (25.4-mm) gage length. Design of the lap joint specimen was previously shown in figure 7. The lap joint was designed to be tested in shear upon the application of a tensile load. Although pure shear was not achieved, there was only slight joint rotation because of the low shear strength and low shear ductility of the TD-Ni bar. All these test specimens were machined from the central portion of the 1/2-inch (12.7-mm) diameter TD-Ni bar with the joints at mid-length. Unwelded parent material specimens were machined to obtain comparative test data.

Tensile tests were run in air and in vacuum (5×10^{-5} torr, 6.6×10^{-3} N/m^2). Vacuum testing was used primarily to prevent oxidation of reactive- and refractory-metal interlayers. One tensile test was run in argon in order to prevent oxidation of a tungsten-interlayer. The short-time tensile and shear specimens, tested at 2000° F (1093° C), were held at temperature for 5 minutes prior to the application of load. For all tensile and shear tests, a crosshead speed of 0.05 inch (1.3 mm) per minute was maintained. Stress-rupture testing was conducted at 2000° F (1093° C) in helium for two reasons. First of all, the helium atmosphere eliminated possible stress-oxidation effects for joints with interlayers. Secondly, fracture path and location can more readily be studied if the fracture surfaces are not oxidized.

RESULTS AND DISCUSSION

Effect of Surface Finish on Butt Joints

Microstructure. - The microstructures of HIP butt welds in the TD-Ni bar with the various surface finishes studied are shown in figure 8. No unwelded regions were found during examination of unetched specimens at up to ×500 magnification. Thus, these HIP welds were judged to be sound. Varying amounts of recrystallization can be observed in figure 8. Two factors are believed to influence the extent of recrystallization that occurs during HIP welding: (1) surface flatness, and (2) amount of residual cold work produced in surface preparation. Thus, joints with ground surfaces had the most recrystallization (fig. 8(a)). Microhardness in the recrystallized region of this joint was 238 DPH compared to 254 DPH in the wrought structure. Lapped surfaces produced a fine-grained recrystallization zone (fig. 8(b)). And lapped-plus-chemically-polished surfaces gave only localized areas of recrystallization (fig. 8(c)). Once formed, these microstructures appear to be extremely stable, as evaluated by light microscopy. Heat treatment at 2000° F (1093° C) for 100 hours showed no apparent effect.

However, electron microscopy (fig. 9(a)) and electron microprobe X-ray raster micrograph examination (fig. 9(b)) of the joint with as-ground surfaces shows thoria depletion in the recrystallized region. Some recrystallized grains appeared to have a normal dispersion; others appeared to be thoria-free (fig. 9(a)). These changes in thoria distribution were confirmed by electron microprobe line scan and spectral scan. It would appear, therefore, that recrystallization promotes thoria movement resulting in areas of depletion and agglomeration. As-welded joints showed lesser thoria depletion and agglomeration than heat-treated joints.

Loss of the uniform thoria dispersion and loss of the original texture are believed to weaken the TD-Ni material, especially at elevated temperatures. In addition, since elevated-temperature fracture occurs by an intergranular mechanism (ref. 5), reduced tensile strength would be expected for tests normal to the butt welds.

Properties. - The results of mechanical tests of HIP weldments with various surface finishes studied are shown in table II. In the room-temperature tensile test of a specimen with ground surfaces, failure took place in the parent material away from the joint. This showed that at room temperature the HIP weld is stronger than the parent material. This confirms reports from the literature (refs. 2 and 6) that solid-state welds in TD-Ni are strong at room temperature. Tensile testing at 2000° F (1093° C) gave quite a different story. Joint efficiency varied from 40 to 54 percent using comparative parent material strength data from table I. All weldments failed at the joint with a square-edge fracture. For all 2000° F (1093° C) tensile fractures, there was no measurable percent elongation or reduction of area. The fracture path for the as-ground specimen (no. 1, table II(b)) tested in air at 2000° F (1093° C) occurred partly through the recrystallized grain boundaries and partly at the junction between recrystallized and wrought parent material (fig. 10). A large portion of the fracture took place along the original weld interface.

One of the 2000° F (1093° C) tensile tests (no. 4, table II(b)) was run in vacuum and in three cases the HIP weldments were heat treated prior to tensile testing. But these variations had little effect on 2000° F (1093° C) tensile strength.

One 2000° F (1093° C) stress-rupture test (in helium) of a specimen with ground surfaces gave very poor stress-rupture strength. Joint failure occurred in 0.2 hour at a stress of 3 ksi (21 MN/m^2). In comparison, unwelded parent material can sustain a stress of 11 ksi (76 MN/m^2) for 100 hours at 2000° F (1093° C) (ref. 7).

Discussion. - Various faying surface finishes on TD-Ni bar were found to produce varying degrees of recrystallization at HIP butt welded joints. This recrystallization was accompanied by loss of the thoria dispersion, and, in no case, was it possible to retain the original microstructure at the joint. At room temperature, the HIP weld was stronger than the parent material. But, at 2000° F (1093° C), the HIP weld was weak in both tensile and stress-rupture tests.

Effects of Interlayers on Butt Joints

Microstructure. - The microstructures of the two most promising butt joints containing interlayers are shown in figure 11 in the heat-treated condition. In the as-welded condition, no voids were observed. However, during the 100-hour 2000° F (1093° C) heat treatment, Kirkendall voids developed sporadically in the TD-Ni bar near the cobalt-alloy interleaf (see fig. 11(a)). For the joint with the Hastelloy X interlayer, a few Kirkendall voids formed just inside the interlayer. Small voids of this type are shown in figure 11(b). Microprobe and hardness data, shown in figure 11, indicate the extent of diffusion that has taken place across the weld interfaces.

In the cobalt-alloy - TD-Ni joint (fig. 11(a)), nickel has diffused into the cobalt-alloy from the TD-Ni faster than the interlayer elements have diffused into the TD-Ni. This results in porosity formation in the TD-Ni. Apparently the stable, elongated TD-Ni bar grain boundaries offer high diffusion rate paths during heat treatment. Similar cobalt-alloy - Ni 200 joints did not exhibit porosity after the same heat treatment. For both the cobalt-alloy - TD-Ni and the cobalt-alloy - Ni 200 joints, the interlayer elements were restrained from taking advantage of the grain boundary diffusion if they were tied up as carbides and other compounds.

A small amount (0.3 to 0.5 wt.%) of Th was present in the cobalt-alloy interleaf. That was indicated by using the spectral scan technique on a cobalt-alloy - Ni 200 weldment and comparing it to the cobalt-alloy - TD-Ni weldment. Also, ThO_2 depletion has occurred 50 to 100 micrometers into the TD-Ni from the weld interface (fig. 11(a)). The Th-depleted region will not be as strong as the parent material.

Heat treatment moves the hardness gradient well inside the interlayer and away from the weld interface, as seen in figure 11(a). This movement of the hardness gradient by virtue of diffusion increases joint strength, as described by Kharchenko (ref. 8).

In the Hastelloy X - TD-Ni joint (fig. 11(b)), the interlayer elements diffuse into the TD-Ni slightly faster than Ni diffuses into the interlayer. The molybdenum in the Hastelloy X interlayer formed carbides and a compound that was rich in Si. It is believed that the formation of these compounds prevented Mo diffusion out of the interleaf rather than a decreased diffusion rate of Mo.

A joint in a TD-Ni bar with a 0.001-inch (25-μm) Mo interlayer is shown in figure 12(a), along with microprobe analysis and hardness determinations. A similar HIP weld with Ni 200 parent material and a Mo interlayer is presented in figure 12(b) in order to illustrate relative diffusion effects in the different base materials. Kirkendall voids are evident in the TD-Ni base material (fig. 12(a)) because Ni has diffused into the Mo interlayer faster than the Mo diffused into the TD-Ni. However, most of the Mo has diffused out of the original interlayer, producing an alloy of about 97.5 percent Ni and 2.5 percent Mo. The Mo diffusion into the parent material is believed to have taken place primarily along the TD-Ni grain boundaries. So, by comparing the Mo - TD-Ni joint (fig. 12(a)) to the Hastelloy X - TD-Ni joint (fig. 11(b)), it is verified that Mo compound formation, and not the relatively large size of the Mo atom, is the reason for the immobility of the Mo in the Hastelloy X - TD-Ni joint. In addition, radically different diffusion effects are also noted in microprobe analysis and hardness of the Mo-interlayer joint in TD-Ni compared to that found for a Mo-interlayer joint in Ni 200 parent material. For the Mo - Ni 200 joint, the Mo was essentially unable to move into the Ni 200 because only a minimum number of grain boundaries are available as diffusion paths (fig. 12(b)). On the other hand, nearly all the Mo diffused along the many grain boundaries of the TD-Ni (fig. 12(a)).

The decrease in the hardness gradient (fig. 12(a)) and the diffusion of the Mo into TD-Ni was accompanied by a strengthening effect at 2000° F (1093° C), as will be shown.

Properties. - The results of room-temperature tensile tests on HIP-welded butt joints with several interlayers are shown in table III. The joints with cobalt-alloy and Hastelloy X interlayers were stronger than the parent material since fracture took place away from the joints. Elongation was 20 to 26 percent for the cobalt-alloy and Hastelloy X joints. Brittle fracture took place at the joint with the 0.001-inch (25-μm) W interlayer; joint efficiency was 85 percent.

Table IV shows the 2000° F (1093° C) tensile test results for joints with interlayers between ground faying surfaces. Note that square-edge fracture at the joint with <1 percent elongation was characteristic of all tests. All the weldments listed in table IV were free of voids, as determined by light microscopy in the as-welded condition. Other interlayers tried that produced unsound joints (not listed in table IV) were 0.001-inch (25-μm) Cb and 0.005-inch (0.12-mm) V joints which cracked during HIP welding and an electron-beam-evaporated Cr joint which had entrapped oxides at the weld line.

After postwelding heat treatment (2000° F (1093° C) for 100 hr), Kirkendall voids, in varying degrees, were found in all joints listed in table IV except for the ThO_2-coated joints (specimens 24, 31, 32, and 36).

A graphic presentation showing tensile strength data for the stronger joints with interlayers and the base material is shown in figure 13. Heat treatment produced a strengthening effect for joints with cobalt-alloy, Hastelloy X, and Mo interlayers even though some Kirkendall voids were inherently produced. The exception for this strengthening effect was one specimen with a 0.004-inch (0.10-mm) cobalt-alloy interlayer. This specimen (specimen 11 from table IV), which was heat treated after first removing the can, had lower strength than the as-welded specimen (specimen 10). Other specimens (12 and 13) with the 0.004-inch (0.10-mm) cobalt-alloy interlayer that were heat treated in the Type 304 can were much stronger than the as-welded specimen (specimen 10) whether subsequent tensile testing was conducted in air (94 percent joint efficiency) or in vacuum (99 percent joint efficiency).

Examination of the strength data (table IV) for tests of joints with 0.018-inch (0.46-mm) Hastelloy X interlayers indicated that test atmosphere had a pronounced effect on 2000° F (1093° C) tensile strength (fig. 13). Specimen 15, heat treated with the can removed and tested in air, gave 62 percent joint efficiency; specimen 16, tested in vacuum, gave 87 percent joint efficiency. Similar effects can be noted for joints with the 0.002-inch (51-μm) Hastelloy X interlayer. These data, therefore, suggest that a stress-oxidation effect may reduce 2000° F (1093° C) tensile strength of joints with Hastelloy X interlayers.

For joints with a 0.001-inch (25-μm) Mo interlayer, heat treatment in the can increased joint efficiency to 61 percent compared to 48 percent as-welded.

Figure 14 shows the mode of fracture for 2000° F (1093° C) tensile tests of butt joints with cobalt-alloy, Hastelloy X, and Mo interlayers. For the cobalt-alloy (fig. 14(a)) and Hastelloy X (fig. 14(b)) joint, fracture took place at the interfaces between the interlayer and the parent material. Fracture for the joint with the Mo interlayer took place partly through the interlayer and partly at the interlayer - parent material interface. Actually, the composition of the Mo interlayer after the 2000° F (1093° C) for 100-hour heat treatment was about 97.5-percent Ni - 2.5-percent Mo (fig. 12(a)).

Stress-rupture tests were conducted at 2000° F (1093° C) in helium on the joints with cobalt-alloy and Hastelloy X interlayers that were highly efficient in 2000° F (1093° C) tensile tests. These stress-rupture data are shown in table V. All weldments were heat treated prior to stress-rupture testing (table V).

From the stress-rupture plot of these data shown as figure 15, it is evident that the weld joints are much weaker than the parent material. For instance, the stress for rupture in 100 hours is about 11 ksi (75.8 MN/m^2) for the parent material (ref. 7) and 1.7 ksi (11.7 MN/m^2) for the strongest joints (0.004-in. (0.10-mm) cobalt-alloy interlayers). This is only 15 percent joint efficiency, where stress-rupture joint efficiency is defined as the ratio of weld joint to parent material strength for 100-hour life at 2000° F (1093° C). All the weldments exhibited a characteristic square-edge fracture at the joint with less than 1 percent elongation.

In regard to the mode of stress-rupture fracture, the joints with cobalt-alloy interlayers failed at the cobalt-alloy - parent material interface. In no case did failure occur within the interlayer material. Loss of the uniform ThO_2 dispersion and loss of texture are probable factors in weakening the TD-Ni bar very near the weld interface. Shear stress produced by differential thermal expansion is also believed to contribute to a weakening effect at the weld interface. Data published by Freche, et al. (ref. 3) indicate that the cobalt-alloy interlayer at 2000° F (1093° C) can support a stress of 10 ksi (689 MN/m^2) for about 100 hours in the as-cast condition. If the cobalt alloy in sheet form has similar strength, it would nearly match the TD-Ni bar in stress-rupture strength. The weak link, however, is the weld interface.

With the Hastelloy X interlayer, the weld interface was also a plane of weakness (fig. 14(b)). But since the Hastelloy X material is weak in stress-rupture above about 1800° F (982° C), fracture in the 2000° F (1093° C) stress-rupture tests took place partly at the weld interface and partly through the Hastelloy X interlayer material.

Discussion. - HIP butt welded joints in TD-Ni bar with cobalt-alloy and Hastelloy X interlayers were stronger than the parent metal at room temperature. Use of these interlayers also produced butt joints with up to 100 percent joint efficiency in 2000° F (1093° C) tensile tests. Unfortunately, the 2000° F (1093° C) stress-rupture strength of all joints with interlayers was poor. Therefore, it was shown that stress-rupture testing is a much more severe criterion than 2000° F (1093° C) tensile testing. Room-temperature tensile tests are of little or no value in evaluating the suitability of weldments for long-term elevated-temperature service.

Lap Joints

Microstructure. - Figure 16 shows the structure obtained in the lap joints. This photomicrograph was taken at mid-length of the joint, as indicated by the sketch. Except for the small unwelded region, the joint is difficult to find because it is oriented parallel to the long pencil-shaped grains. Heat treatment at 2000° F (1093° C) for 100 hours did not change the appearance of the microstructures at ×500 magnification.

Shear tests. - Short-time shear test data are shown in table VI for duplicate tests of weldments at room temperature and at 2000° F (1093° C). A summary of the shear test data is shown in figure 17 with comparative data for the parent material taken from table I. At room temperature, joint efficiency was 96 percent, and at 2000° F (1093° C) the joint efficiency was 94 percent. Note that the parent material is relatively weak in shear. At 2000° F (1093° C), the tensile strength is 23.1 ksi (159 MN/m^2) compared to a shear strength of 3.3 ksi (22.8 MN/m^2) (table I). As noted in table VI, one weldment failed at the joint and one failed in the parent material away from the joint at both room temperature and at 2000° F (1093° C).

These studies have shown that the shear strength of lap joints is about equivalent to that of the parent material both at room temperature and at 2000° F (1093° C).

CONCLUDING REMARKS

The results of this solid-state welding study have indicated that an interruption in the microstructure of TD-Ni bar at a butt weld produces a weakening effect. Butt joints in which the long pencil-shaped grain pattern is distributed are about half as strong as the parent material in 2000° F (1093° C) tensile tests. Interlayers can be used to increase 2000° F (1093° C) tensile strength. But stress-rupture properties of joints with interlayers are very poor. Foreign materials of any kind may be undesirable where the stress-rupture strength of solid-state welded or brazed joints is important. Thus, we believe that welded butt joints that match the strength of TD-Ni bar at elevated temperatures probably cannot be made unless the original bar microstructure is somehow preserved or restored at the joint. The usage of TD-Ni material may not be seriously impaired by the fact that butt joints are weak because (1) butt joints are not used extensively in industrial applications, (2) it may be possible to increase the material thickness at the joint, and (3) the joint may be located at a low-stress region of the structure.

It is suggested that high-temperature weakening effects near the weld line in butt joints with and without interlayers include loss of the original TD-Ni texture, loss of the thoria dispersion, and the presence of a large percentage of grain boundary area normal to the testing direction. Shear stresses that are developed because of differential thermal expansion of interlayers could also contribute to a weakening effect at the butt joints.

Based on the fact that in short-time shear tests lap joints are about as strong as the parent material, lap joints show considerable promise. Similar lap joints tested in stress-rupture must be run in order to confirm the desirability of using lap joints. Scarf joints may merit study also because a scarf butt joint would offer more joint area than a square butt joint. The scarf butt joint would also be at some angle to the applied axial load rather than normal to the load.

SUMMARY OF RESULTS

Solid-state welds were made in 1/2-inch (12.7-mm) diameter thoriated-nickel (TD-Ni) bar in both butt joints (with and without interlayers) and lap joints. Welding was accomplished in a 12-hour cycle using the hot isostatic pressure (HIP) welding process with peak parameters of 2000° F (1093° C) and 20.0 ksi (138 MN/m^2) helium for 2 hours. Tensile and shear joint efficiencies (defined as percent of parent material strength) were determined at room temperature and at 2000° F (1093° C). Stress-rupture tests were run at 2000° F (1093° C) on butt joints. Metallographic techniques also were used in the evaluation. The results are as follows:

1. For the joint with interlayers, stress-rupture tests at 2000° F (1093° C) were a much more severe criterion of joint strength than 2000° F (1093° C) tensile tests. The strongest joints in stress-rupture (with the 0.004-in. (0.10-mm) cobalt-alloy interlayer) for 100-hour life and 15 percent joint efficiency.

2. Short-time shear tests of lap joints which have the joint in the plane of the axis of the TD-Ni bar indicate that the HIP welds are about as strong as the parent material at room temperature and at 2000° F (1093° C).

3. All 2000° F (1093° C) tensile and stress-rupture specimens obtained from butt joint weldments failed with a characteristic square-edge appearance and less than 1 percent elongation.

4. In 2000° F (1093° C) tensile tests, butt joints with cobalt-alloy and Hastelloy X interlayers had up to 100 and 87 percent joint efficiency, respectively. This represented the best results of the 15 interlayer materials evaluated. Without interlayers, maximum joint efficiency was about 55 percent.

5. Diffusion effects produced by post-welding heat treatment (2000° F (1093° C) for 100 hr) tended to increase 2000° F (1093° C) tensile strength for joints with cobalt-alloy, Hastelloy X, and Mo interlayers.

6. Butt joints with cobalt-alloy or Hastelloy X interlayers, or with no interlayer, have greater room-temperature strength than the parent material.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 1, 1970,
129-03.

APPENDIX A

SOLID-STATE WELDING MECHANISM

In solid-state welding, the metallic bond can be achieved by bringing two clean surfaces into intimate contact (refs. 9 to 13). Nikiforov (ref. 14) points out that, in diffusion welding, deformation caused by creep plays the leading part in making contact over the greater part of the weld interface. Thus, although diffusion across the weld interface may improve joint strength, it is secondary to joint formation.

In any solid-state welding process, however, it is likely that there will be at least some diffusion across the weld interface. Taylor's studies (ref. 15) with low-energy electron diffraction of the epitaxy of copper films on tungsten showed that the copper penetrated the tungsten to a depth of about five atomic layers.

In the HIP welding process used in this program, solid-state welding occurs when the combination of heat and external helium pressure cause the evacuated stainless-steel cans to collapse and pressurize TD-Ni parts. The component of force normal to the faying surfaces promotes the intimate contact that is necessary to achieve welding. During the 2-hour hold time at high temperature and pressure, creep produced by diffusion mechanisms on either side of the weld interface is believed to play the major role in achieving the necessary contact over the entire faying surfaces. The pressure on the parts to be welded is equal in all directions. Thus, there is no macrodeformation of the TD-Ni bar. A side effect that occurs during the HIP welding process is that the stainless-steel can is welded to the TD-Ni bar.

APPENDIX B

TERMINOLOGY

The hot isostatic pressure (HIP) welding process used in this study to butt-weld bar stock has been referred to as gas pressure bonding by its Battelle inventors (ref. 4). "Bonding" processes in American Welding Society (AWS) terminology refer to the adhesive bonding of metals (Ch. 46, Welding Handbook (ref. 16)) and not to joining processes that involve development of the metallic bond between members. Since AWS has defined a process entitled "pressure gas welding" that involves heating with a gas flame (ref. 17), it could cause confusion if the HIP welding process were called gas pressure welding. Therefore, HIP welding is believed to be a more suitable term.

REFERENCES

1. Rice, L. P.: Metallurgy and Properties of Thoria-Strengthened Nickel. DMIC Memo 210, Battelle Memorial Inst., Oct. 1, 1965.
2. Metcalfe, A. G.: Diffusion Bonding of Dispersion Strengthened Nickel Alloys. Oxide Dispersion Strengthening. George S. Ansell, Thomas D. Cooper and Fritz V. Lenel, eds., Gordon and Breach Science Publ., 1968, pp. 783-812.
3. Freche, John C.; Ashbrook, Richard L.; and Sandrock, Gary D.: Further Investigation of High-Temperature Cobalt-Tungsten Alloys for Aerospace Applications. Cobalt, Sept. 1964, pp. 125-127.
4. Paprocki, S. J.; Hodge, E. S.; and Gripshover, P. J.: Gas-Pressure Bonding. DMIC Rep. 159, Battelle Memorial Inst., Sept. 25, 1961.
5. Doble, G. S.; Leonard, L.; and Ebert, L. J.: The Effect of Deformation on Dispersion Hardened Alloys. Case Western Reserve Univ. (NASA CR-92510), Nov. 1967.
6. Yount, R. E.: Joining Techniques for Thoria Dispersion Strengthened Materials. Advanced Techniques for Materials Investigation and Fabrication. Vol. 14 of SAMPE Proceedings. Western Periodicals Co., 1968, paper II-2B-1.
7. Anon.: High Temperature, High Strength Nickel-Base Alloys. Second ed., International Nickel Co., Inc., June 1968.
8. Kharchenko, G. K.: Problems in the Diffusion Welding of Dissimilar Metals (Review of Published Works). Automatic Welding, vol. 22, no. 4, Apr. 1969, pp. 31-35.
9. Lancaster, J. F.: The Metallurgy of Welding, Brazing and Soldering. American Elsevier Publ. Co., 1965.
10. Benzovskii, M. V.; and Oleinikov, A. A.: X Ray Microprobe Investigation of Diffusion Welds Between Some Dissimilar Metals. Welding Prod., vol. 14, no. 5, 1967, pp. 26-30.
11. King, W. H.; and Owczarski, W. A.: Diffusion Welding of Commercially Pure Titanium. Welding J. Res. Suppl., vol. 46, no. 7, July 1967, pp. 289-s to 298-s.
12. Shorshorov, M. Kh.; et al.: The Problem of the Quantitative Estimation of Pressure Welding Conditions. Welding Prod., vol. 14, no. 7, 1967, pp. 24-31.
13. Kazakov, N. F.: Diffusion Welding in a Vacuum. Rep. FTD-MT-24-419-68, Foreign Technology Division, Air Force Systems Command, Aug. 13, 1969. (Available from DDC as AD-698097.)

14. Nikiforov, G. D.; et al.: The Mechanism of Joint Formation in Welding and Brazing. Welding Prod., vol. 14, no. 12, 1967, pp. 6-12.

15. Taylor, Norman J.: A LEED Study of the Epitaxial Growth of Copper on the (110) Surface of Tungsten. Surface Sci., vol. 4, no. 2, Mar.-Apr. 1966, pp. 161-194.

16. Phillips, Arthur L., ed.: Welding Handbook. Sect. 3. Fifth ed., American Welding Society, 1965.

17. Anon.: Terms and Definitions. Standard AWS A3.0-69, American Welding Society.

TABLE I. - TENSILE AND SHEAR PROPERTIES OF 1/2-INCH (12.7-mm)

DIAMETER TD-NICKEL BAR

(a) Tensile data[a]

[Test atmosphere, air.]

Heat treatment	Test temperature		Yield strength		Ultimate tensile strength		Percent elongation	Percent reduction in area
	°F	°C	ksi	MN/m^2	ksi	MN/m^2		
2000° F (1093° C) for 2 hr	RT	RT	85.1	586	95.3	656	22	82
None	2000	1093	----	---	22.9	158	[b]4	[b]5
2000° F (1093° C) for 2 hr	2000	1093	----	---	23.3	161	[b]4	[b]5

(b) Shear data

[No heat treatment; test atmosphere, air.]

Test temperature		Shear strength[c]	
°F	°C	ksi	MN/m^2
RT	RT	56.0	386
2000	1093	3.3	23

[a]Room-temperature properties represent the average of five tests of butt welds where failure took place in the TD-Ni bar parent material (specimen 1 from table II, and specimens 2, 3, 4, and 5 from table III).

RT = Room temperature.

[b]Data taken from ref. 1.

[c]Test specimen:

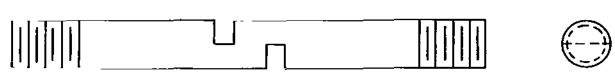


TABLE II. - TENSILE AND STRESS-RUPTURE DATA FOR HIP BUTT WELDMENTS WITH VARIOUS SURFACE FINISHES

(a) Room-temperature tensile test

Specimen	Surface preparation	Ultimate tensile strength		Percent elongation	Percent reduction in area	Fracture location
		ksi	MN/m^2			
1	As ground	95.0	655	18	63	Parent material

(b) 2000° F (1093° C) Tensile tests

Specimen	Surface preparation	Postwelding heat treatment	Test atmosphere	Ultimate tensile strength[a]		Joint[b] efficiency, percent
				ksi	MN/m^2	
1	Ground	None	Air	12.1	83	52
2	Lapped	2000° F (1093° C) for 100 hr[c]	Air	11.1	76	48
3	Lapped and electropolished	2000° F (1093° C) for 100 hr[c]	Air	9.3	64	40
4	Ground and pickled	None	Vacuum	10.3	71	45
5	Lapped and chemically polished	2000° F (1093° C) for 100 hr[c]	Air	12.5	86	54

(c) 2000° F (1093° C) Stress-rupture test

Specimen	Surface preparation	Postwelding heat treatment	Test atmosphere	Stress		Life, hr[a]
				ksi	MN/m^2	
1	Ground	Outgassed at 2200° F (1204° C) for 1/2 hr in vacuum (with can removed)	Helium	3	21	0.2

[a]Square-edge fracture at the joint with <1 percent elongation.

[b]Joint efficiency = $\frac{\text{Weld joint strength}}{\text{Parent material strength}} \times 100$.

[c]Heat treated in the can in an argon atmosphere.

TABLE III. - ROOM-TEMPERATURE TENSILE DATA FOR HIP BUTT WELDMENTS WITH INTERLAYERS

[Welds made with as-ground surfaces. No postwelding heat treatment.]

Specimen	Interlayer	Yield strength		Ultimate tensile strength		Percent elongation	Percent reduction in area	Fracture location
		ksi	MN/m^2	ksi	MN/m^2			
1	0.001 in. (25 μm) tungsten	----	---	81.4	560	0	0	At joint
2	0.013 in. (0.33 mm) cobalt alloy	80.8	556	94.9	654	26	81	Parent material
3	0.018 in. (0.46 mm) Hastelloy X	85.7	590	95.1	655	20	81	↓
4	0.004 in. (0.10 mm) cobalt-alloy	90.6	625	95.7	660	21	82	↓
5	0.002 in. (51 μm) Hastelloy X	83.2	574	95.9	660	24	81	↓

TABLE IV. - 2000° F (1093° C) TENSILE DATA FOR HIP BUTT WELDMENTS WITH INTERLAYERS

Specimen	Interlayer	Postweld heat treatment[a]	Test atmosphere	Ultimate tensile strength[b]		Joint efficiency,[c] percent
				ksi	MN/m^2	
6	0.013 in. (0.33 mm) cobalt alloy	None	Air	13.0	90	56
7		HT1	Air	14.6	101	63
8		HT2	Vacuum	23.8	164	100
9		HT2	Vacuum	17.0	117	74
10	0.004 in. (0.10 mm) cobalt alloy	None	Air	15.3	105	66
11		HT1	Air	14.4	99	62
12		HT2	Vacuum	22.8	157	99
13		HT2	Air	21.8	150	94
14	0.018 in. (0.46 mm) Hastelloy X	None	Air	13.2	91	57
15		HT1	Air	14.4	99	62
16		HT1	Vacuum	20.1	139	87
17		HT2	Vacuum	20.1	139	87
18		HT2	Vacuum	19.0	131	82
19	0.002 in. (51 μm) Hastelloy X	None	Air	13.7	94	59
20		HT1	Air	14.7	101	64
21		HT1	Vacuum	18.6	128	80
22		HT2	Air	14.1	97	61
23		HT2	Vacuum	19.1	132	83
24	0.020 in. (0.51 mm) TD-Ni sheet	None	Vacuum	10.6	73	46
25	0.001 in. (25 μm) molybdenum	None	Vacuum	11.2	77	48
26	0.001 in. (25 μm) molybdenum	HT2	Vacuum	14.2	98	61
27	0.001 in. (25 μm) tungsten	None	Argon	10.2	70	44
28	0.001 in. (25 μm) tungsten	HT2	Vacuum	6.4	44	28
29	0.00025 in. (6 μm) titanium	HT2	↓	12.9	89	56
30	0.0003 in. (7.5 μm) tantalum	None	↓	10.7	74	46
31	Titanium vapor plate	HT2	↓	10.2	70	44
32	Palladium vapor plate	↓	↓	11.8	81	51
33	Molybdenum electron beam (EB) evaporated	↓	↓	7.3	50	32
34	Tungsten EB evaporated	↓	↓	10.4	72	45
35	Iron EB evaporated	↓	↓	6.4	44	28
36	ThO_2 sintered on faying surfaces	↓	Air	12.6	87	54

[a]HT1: Can removed, then heat treated at 2000° F (1093° C) for 100 hr in argon.
HT2: Heat treated in the can at 2000° F (1093° C) for 100 hr in argon.

[b]All square-edge fractures at the joints with <1 percent elongation.

[c]Joint efficiency = $\frac{\text{Weld joint strength}}{\text{Parent material strength}} \times 100$.

TABLE V. - 2000° F (1093° C) STRESS-RUPTURE DATA FOR

HIP BUTT WELDMENTS WITH INTERLAYERS

[Stress-rupture atmosphere, helium.]

Interlayer	Specimen	Postwelding heat treatment[a]	Stress		Life,[b] hr
			ksi	MN/m^2	
0.013-in. (0.33-mm) cobalt alloy	1	HT1	6	41	0.1
	2	HT1	2	14	1.0
	3	HT1	1.5	10	4.0
0.004-in. (0.10-mm) cobalt alloy	4	HT3 + HT1	2.5	17	25.6
	5	HT1	3	21	2.2
	6	HT1	2	14	41
	7	HT1	1.5	10	191
0.018-in. (0.46-mm) Hastelloy X	8	HT1 + HT3	3	21	1.0
	9	HT1	2	14	10
0.002-in. (51-μm) Hastelloy X	10	HT1	3.5	24	2.4
	11	HT1 + HT3	3	21	.2
	12	---------	2	14	3.8

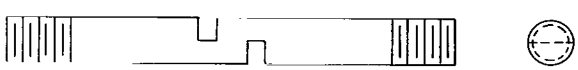
[a]HT1: Can removed. Then specimen heat treated at 2000° F (1093° C) for 100 hr in argon.
HT3: Outgassed at 2200° F (1204° C) for 1/2 hr in vacuum with can removed.
[b]All square-edge fractures at joints, with <1 percent elongation.

TABLE VI. - SHORT-TIME SHEAR TEST DATA[a] FOR HIP LAP

WELDMENTS (WELDED PARENT MATERIAL)

Specimen	Test temperature		Shear strength		Joint efficiency,[b] percent	Fracture location
	$^\circ$F	$^\circ$C	ksi	MN/m^2		
1	RT	RT	53.8	371	96	At joint
2	RT	RT	54.1	373	97	Parent material
3	2000	1093	3.2	22	97	Parent material at joint
4	2000	1093	3.0	21	91	Parent material at joint

[a]Test specimen:



[b]Joint efficiency = $\dfrac{\text{Strength of weld joint}}{\text{Strength of parent material}}$

RT = Room temperature.

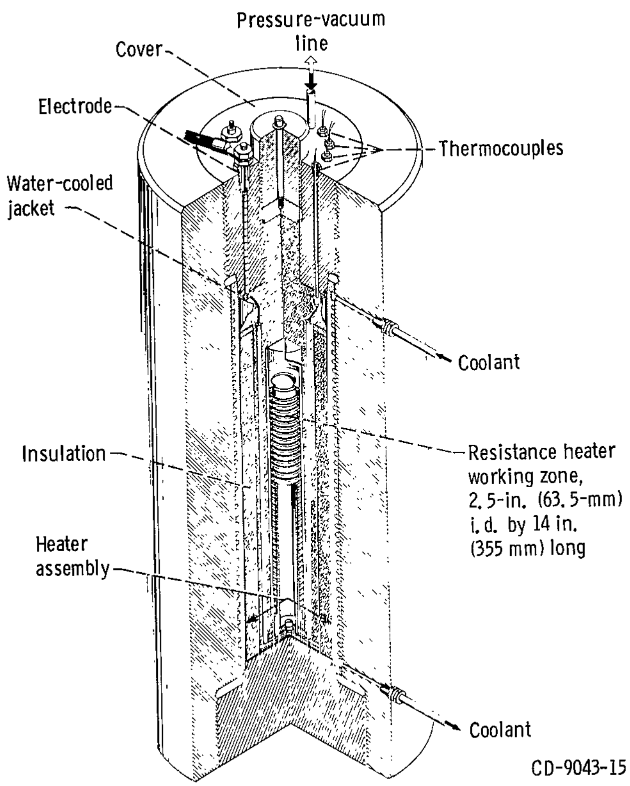


Figure 1. - Cold-wall autoclave used for hot-isostatic-pressure welding.

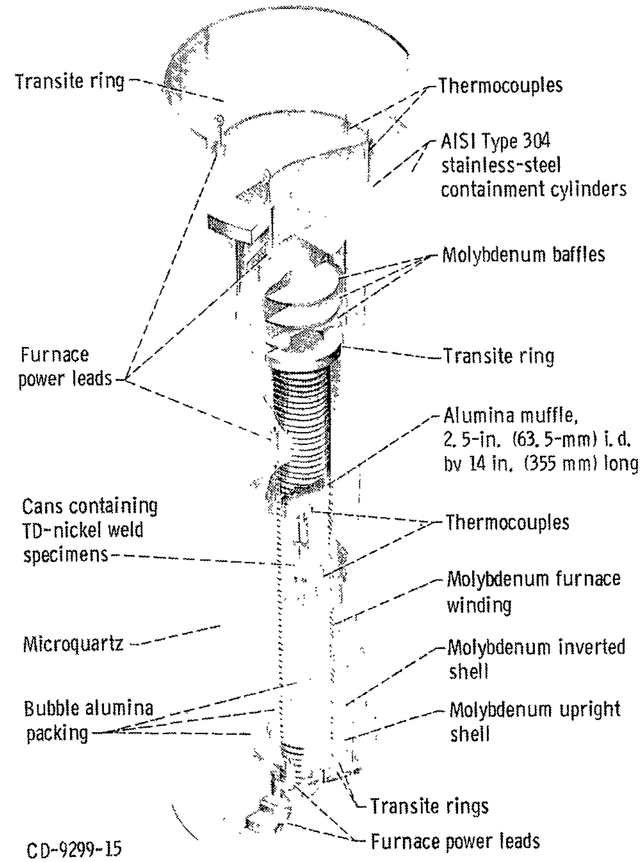


Figure 2. - Heater assembly with specimen location.

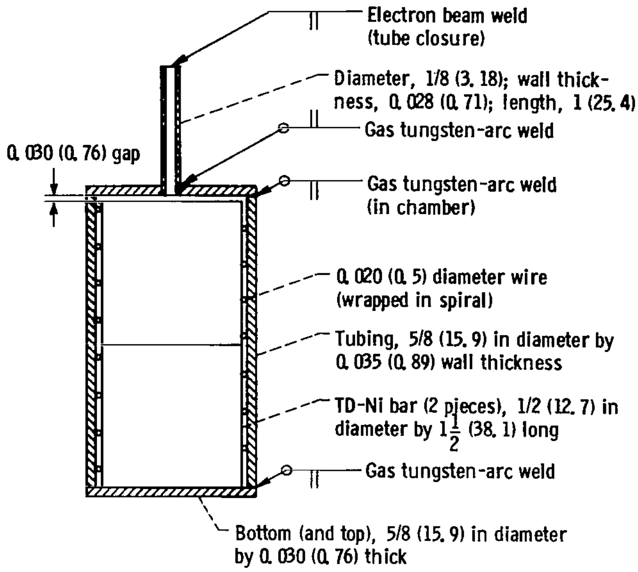


Figure 3. - Schematic of 1/2-inch (12.7-mm) diameter TD-nickel bar specimens in AISI Type 304 stainless-steel cans. Specimens are wrapped with Type 304 stainless-steel wire to minimize misalinement of the specimens at the butt joint. (Dimensions are in inches (mm).)

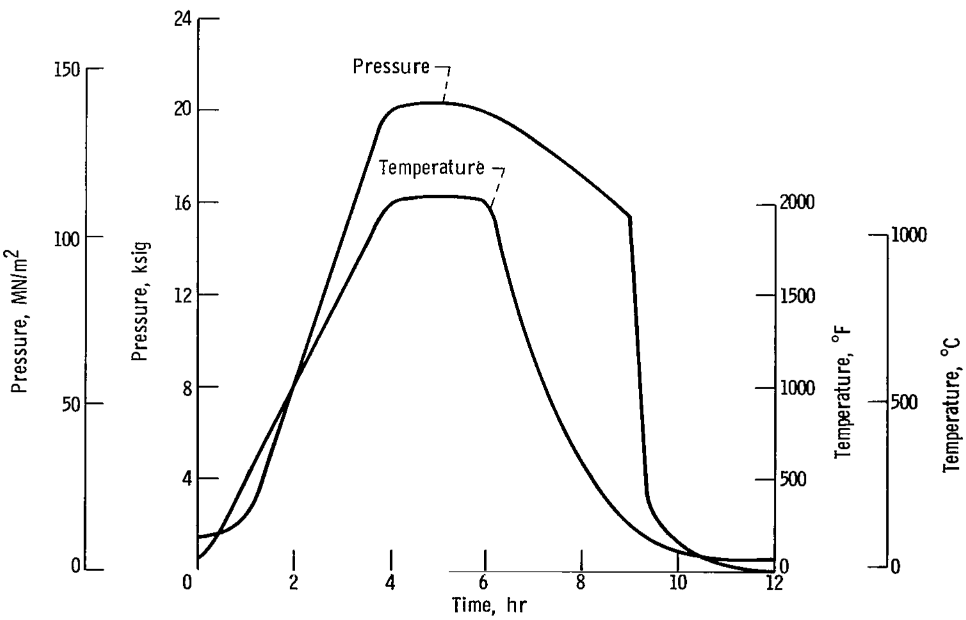


Figure 4. - Typical pressure and temperature profiles for hot-isostatic-pressure (HIP welding run.

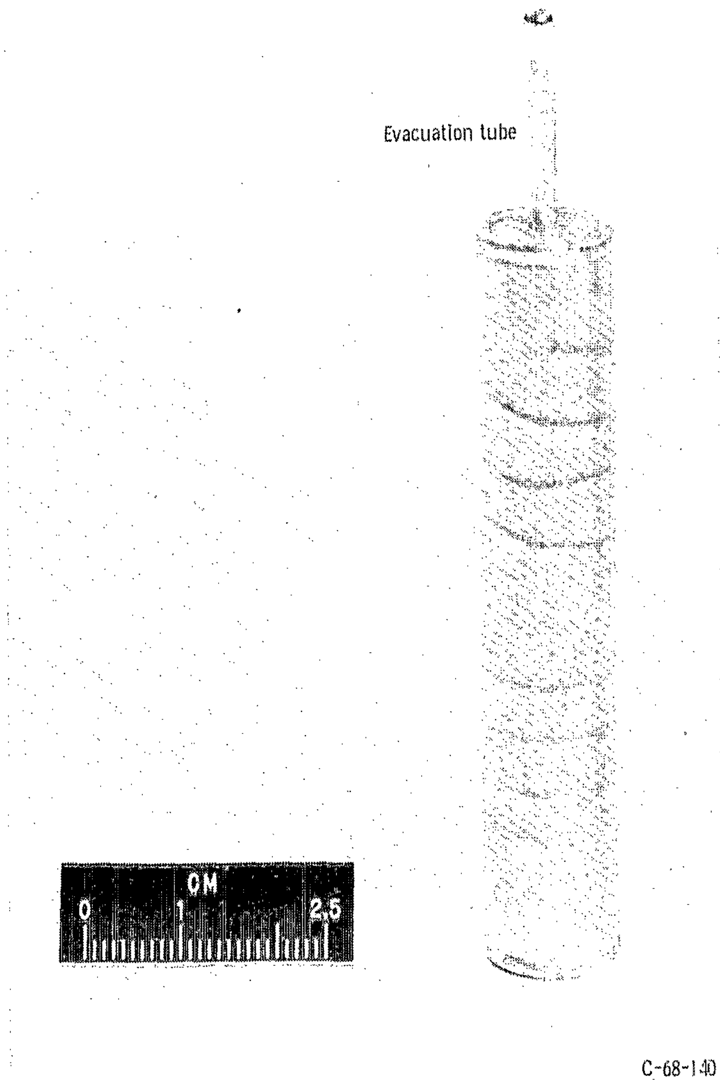


Figure 5. - AISI Type 304 stainless-steel can containing TD-nickel weldments after exposure to hot-isostatic-pressure (HIP) welding cycle. (The imprint of the wire on the can and the flattening of the evacuation tube attest to the fact that HIP welding of the specimens was achieved.)

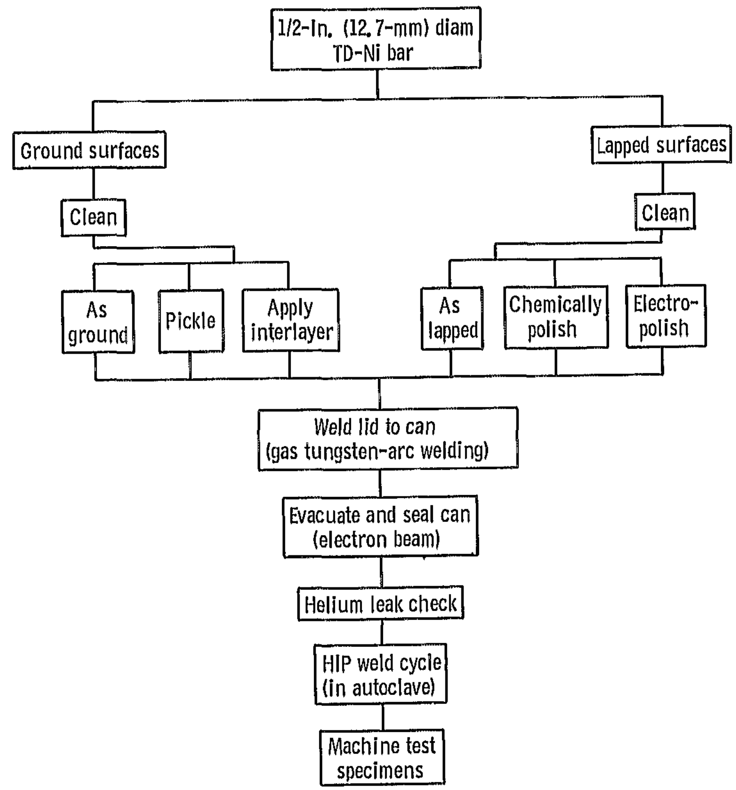
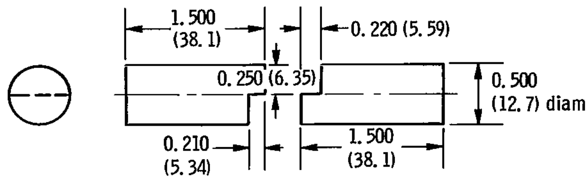
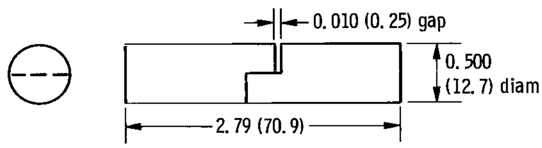


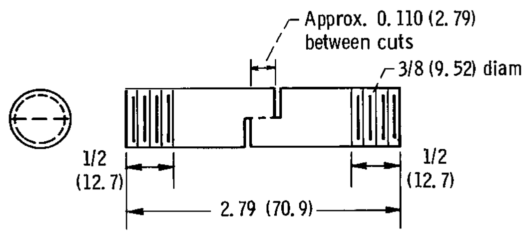
Figure 6. - Flow diagram for hot-isostatic-pressure (HIP) welding TD-nickel bar.



(a) Mating pieces for lap joints.

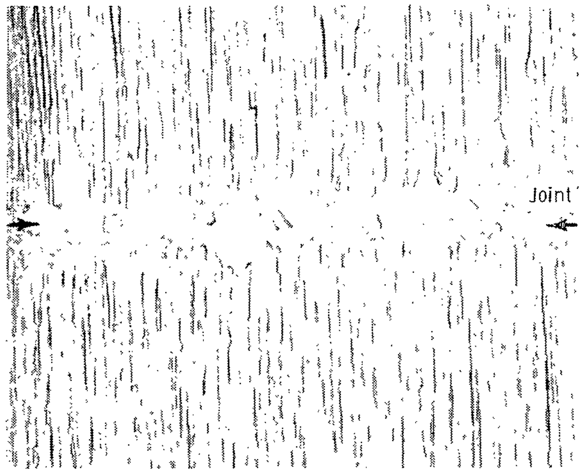


(b) Setup for hot-isostatic-pressure welding.

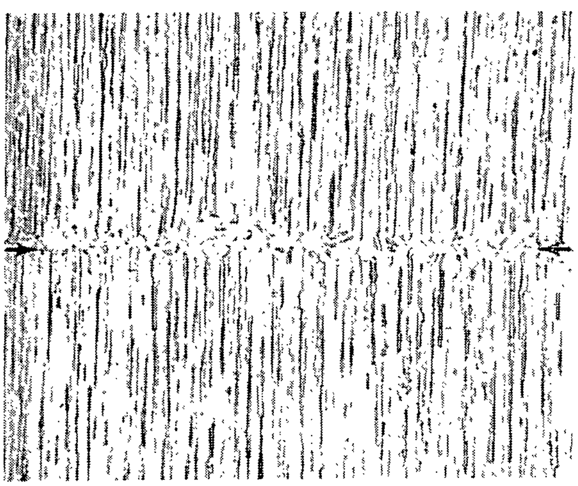


(c) Machined for shear test of lap joint. Area in shear = 0.110 x 0.375 = 0.041 sq in. (26.6 sq mm).

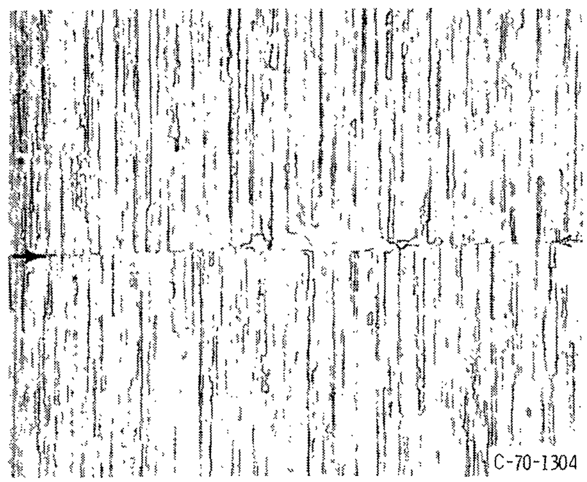
Figure 7. - Design of lap joint shear test specimen. (Dimensions are in inches (mm).)



(a) Ground surfaces, heat treated for 100 hours at 2000° F (1093° C). Etched; X500.

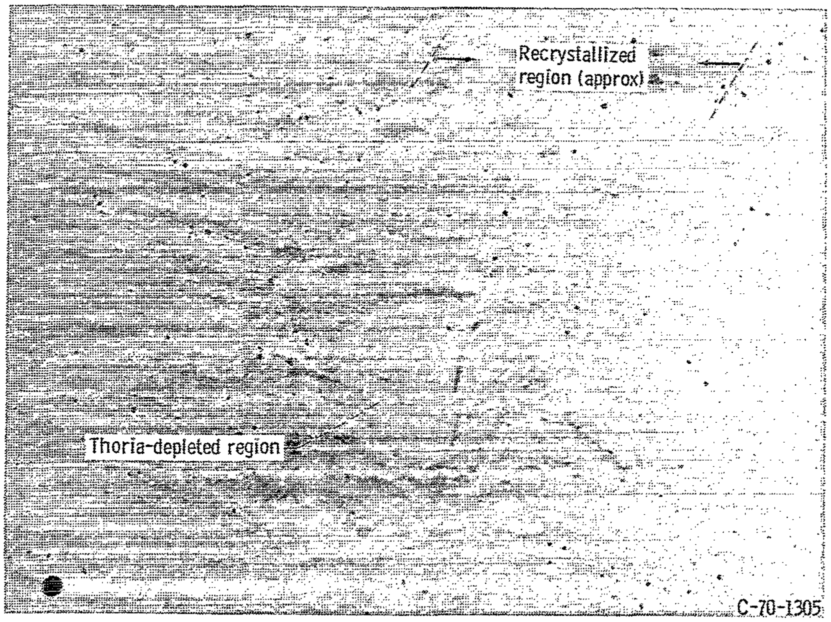


(b) Lapped surfaces, as-welded. Etched; X500.

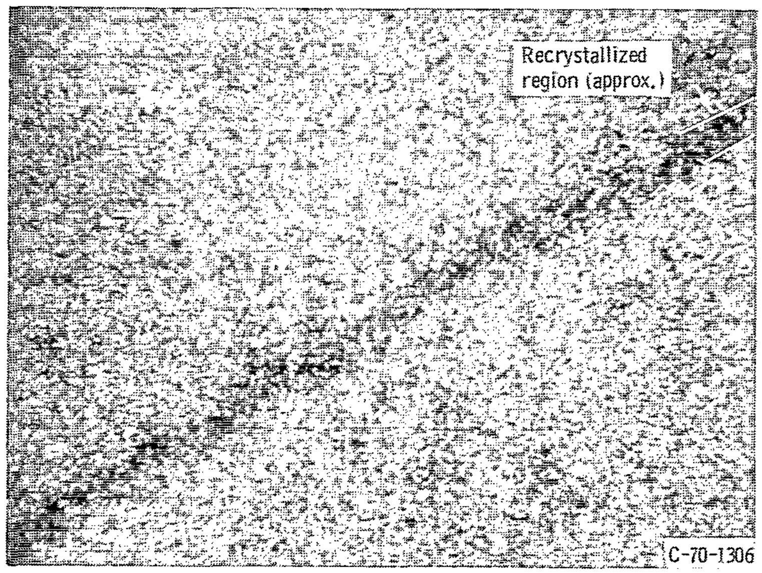


(c) Lapped plus chemically polished surfaces, as-welded. Etched; X500.

Figure 8. - Effect of surface finish on microstructure of hot-isostatic-pressure weldments in 1/2-inch (12.7-mm) diameter TD-nickel bar. Etchant: 92 milliliters HCl, 3 milliliters HNO_3, 5 milliliters H_2SO_4 (swab).



(a) Electron photomicrograph of replica taken from recrystallized region of HIP butt weld in TD-nickel bar with wrought parent material structure on either side. Regions of thoria depletion and normal distribution as compared to parent material, are shown. Etched; X9500.



(b) Electron microprobe X-ray raster micrograph of thorium at recrystallized region shown in figures 8(a) and 9(a). Low resultant thorium concentration shown is due to presence of thoria-depleted and normal distribution regions. Unetched; x2000.

Figure 9. - Regions of thoria depletion and normal distribution in recrystallized region of heat-treated TD-nickel bar hot-isostatic-pressure (HIP butt weld shown in figure 8(a). Etchant. electrolytic using 2 volts and solution of 30 milliliters H_2O, 30 milliliters H_2SO_4, and 40 milliliters H_3PO_4.

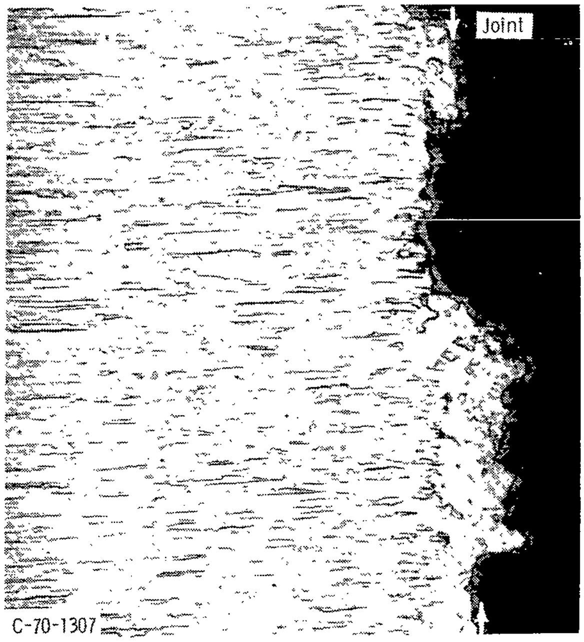
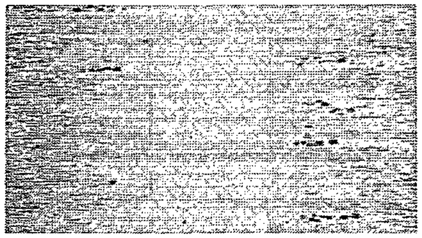
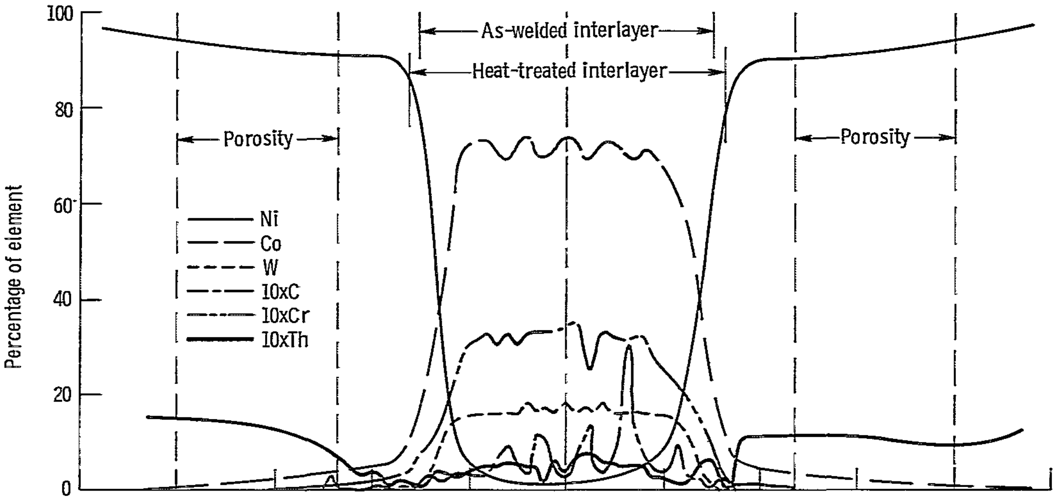


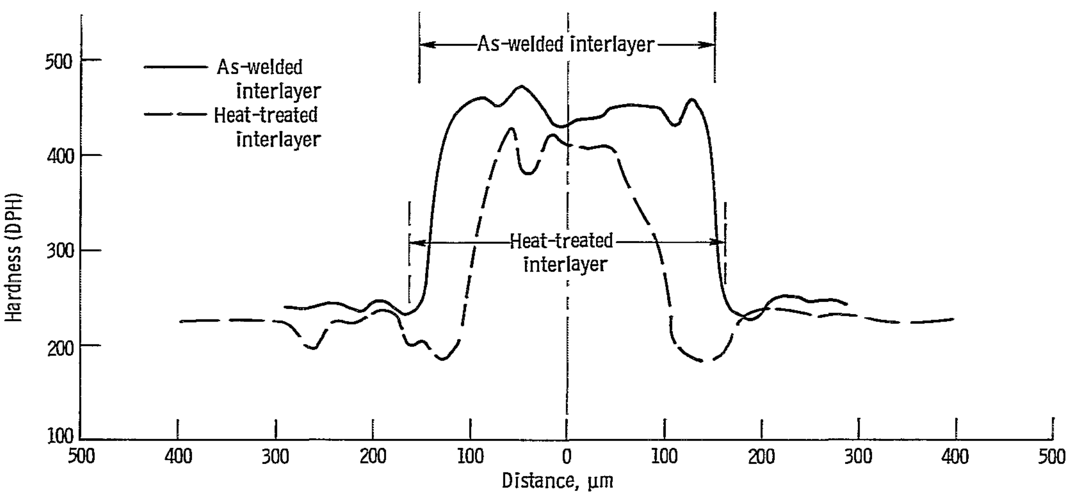
Figure 10. - Fracture of hot-isostatic-pressure butt weldment (as-ground surfaces) in 2000° F (1093° C) tensile test (specimen 1, table III). Etchant: 92 milliliters HCl, 3 milliliters HNO_3, 5 milliliters H_2SO_4 (swab). X500.



(a-1) Structure in heat-treated condition. ×100.



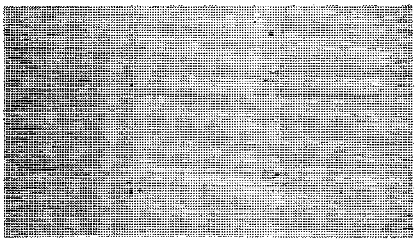
(a-2) Chemistry in heat-treated condition.



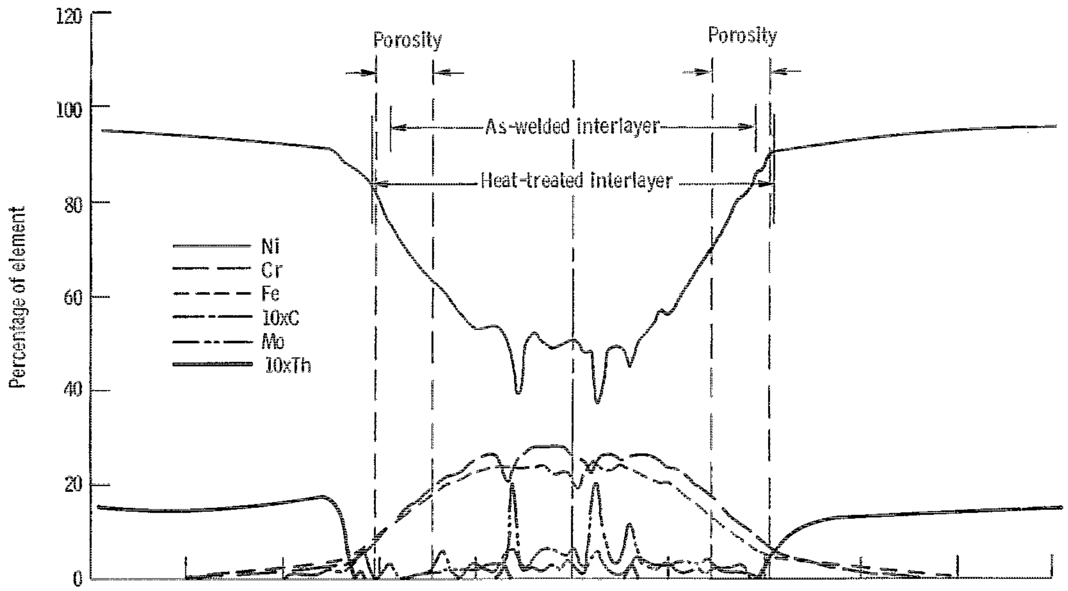
(a-3) Hardness in as-welded and heat-treated conditions.

(a) 0.013-inch (0.33-mm) cobalt-alloy interlayer.

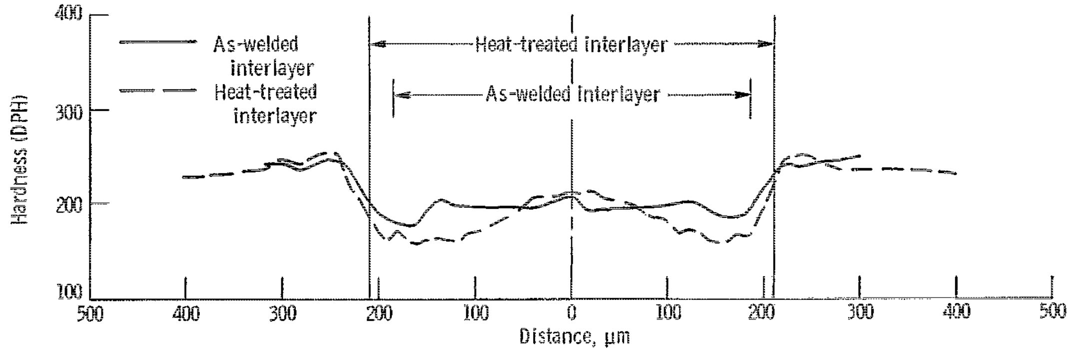
Figure 11. - Microstructure, microprobe chemistry traverses, and microhardness traverses of hot-isostatic-pressure (HIP) welds in 1/2-inch (12.7-mm) TD-nickel bar with cobalt alloy and Hastelloy X interlayers. Etchant, 92 milliliters HCl, 3 milliliters HNO_3, 5 milliliters H_2SO_4 (swab).



(b-1) Structure in heat-treated condition. Etched, x100.



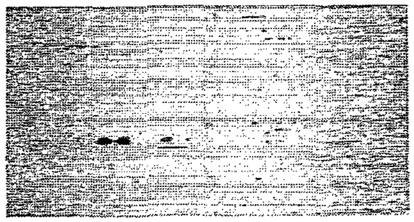
(b-2) Chemistry in heat-treated condition.



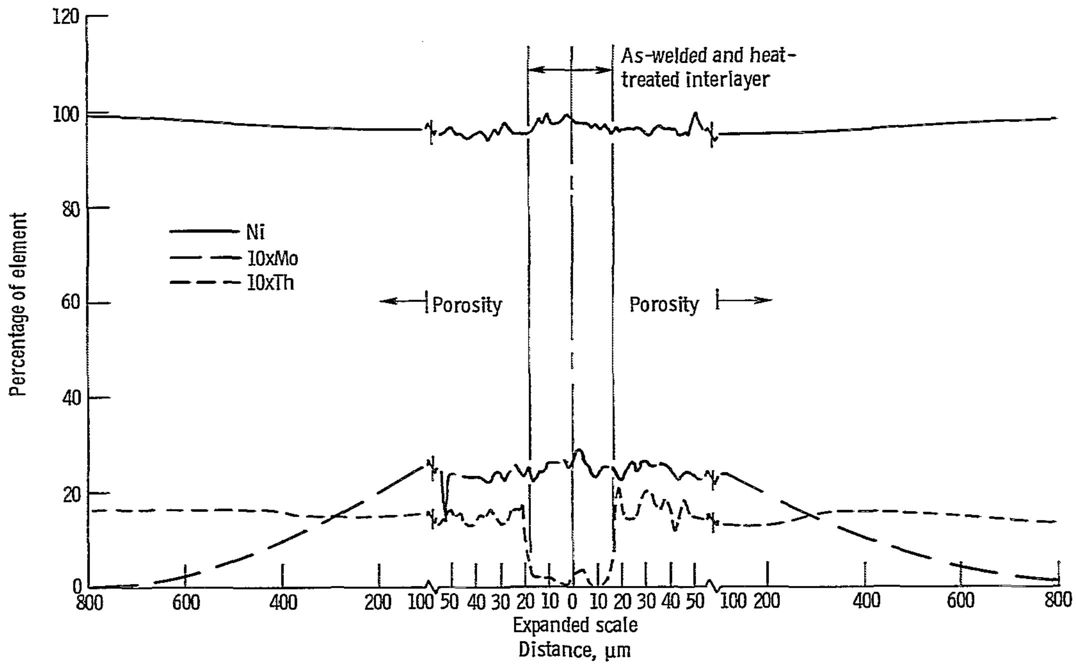
(b-3) Hardness in as-welded and heat-treated conditions.

(b) 0.018-Inch (0.43-mm) Hastelloy X interlayer.

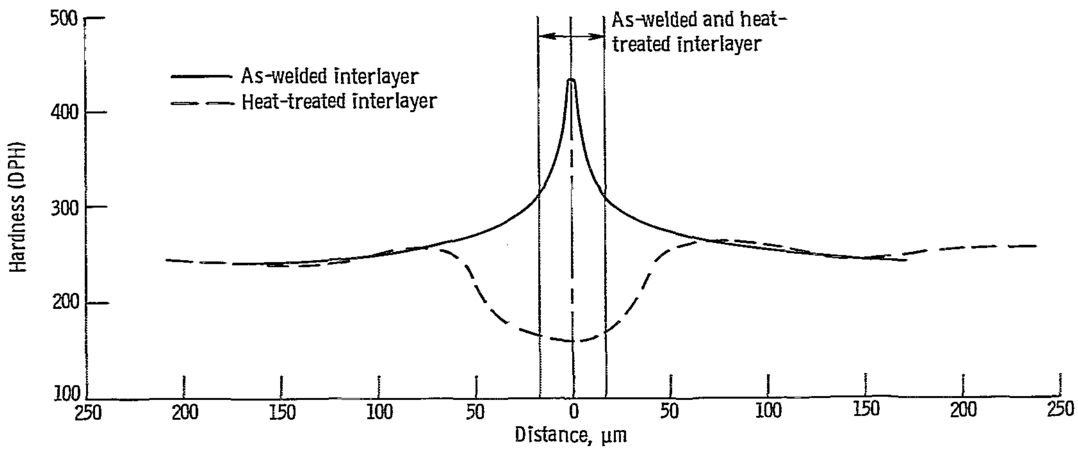
Figure 11. - Concluded.



(a-1) Structure in heat-treated condition. Etched; x100.



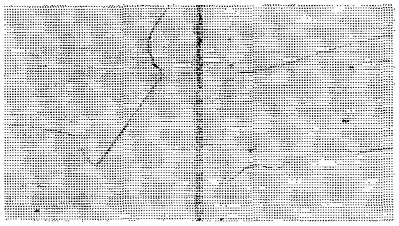
(a-2) Chemistry in heat-treated conditions.



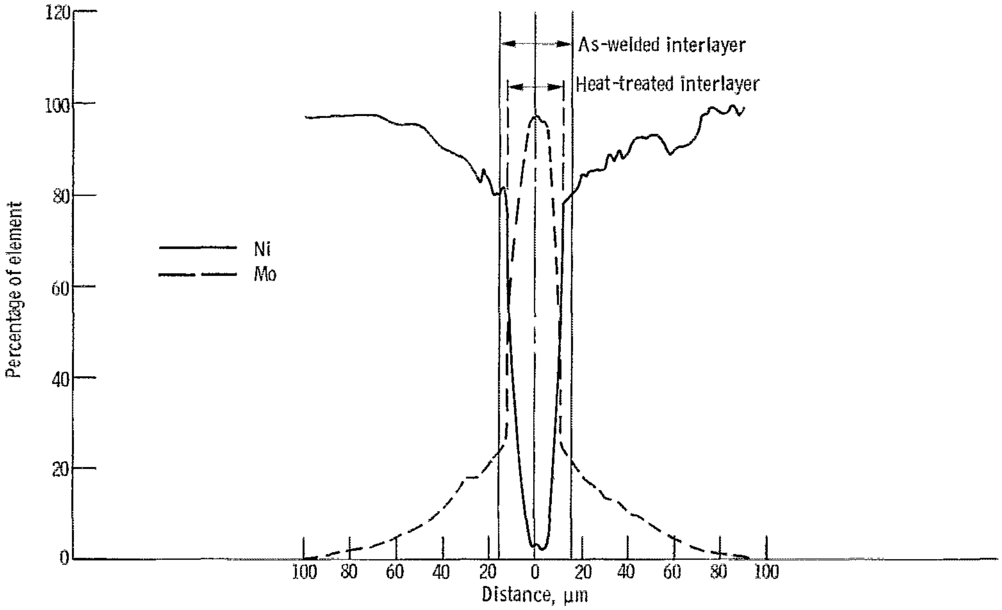
(a-3) Hardness in as-welded and heat-treated conditions.

(a) 0.001-inch (25-µm) molybdenum interlayer and TD-Ni parent material. Etchant, 92 milliliters HCl, 3 milliliters HNO_3, 5 milliliters H_2SO_4 (swab).

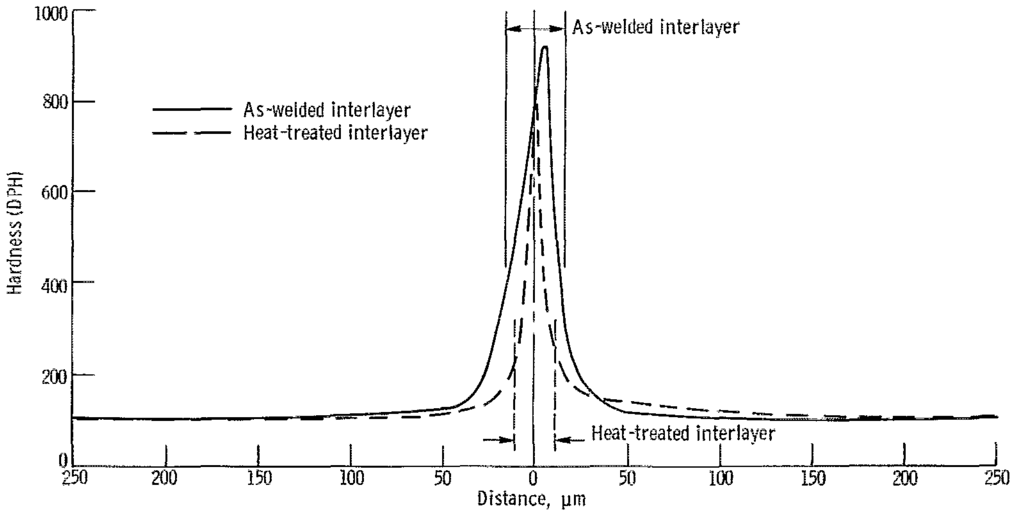
Figure 12. - Microstructure, microprobe chemistry traverses, and microhardness traverses of hot-isostatic-pressure (HIP) butt welds in 1/2-inch (12.7-mm) TD-nickel and nickel 200 bars with 0.001-inch (25-µm) molybdenum interlayers.



(b-1) Structure in heat-treated condition.
Etched; x100.



(b-2) Chemistry in heat-treated condition (no thorium).



(b-3) Hardness in as-welded and heat-treated conditions.

(b) 0.001-inch (25-µm) molybdenum interlayer and nickel 200 parent material. Etchant: swab in 92 milliliters HCl, 3 milliliters HNO_3, and 5 milliliters H_2SO_4; then swab in Murakami's reagent.

Figure 12. - Concluded.

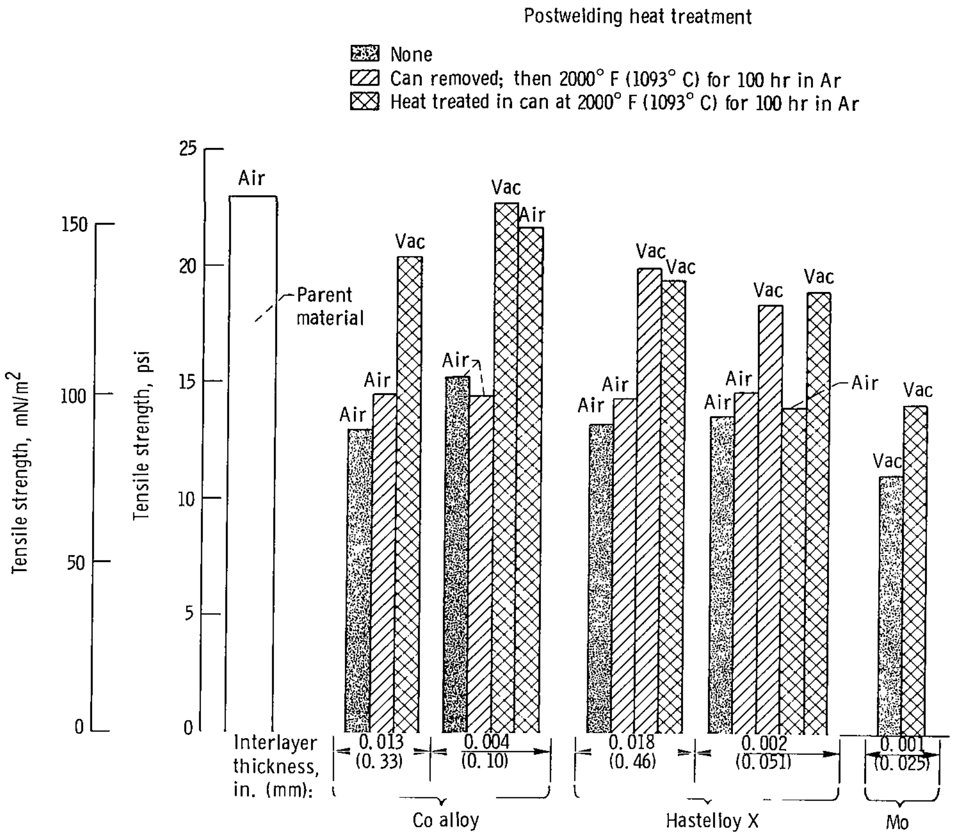
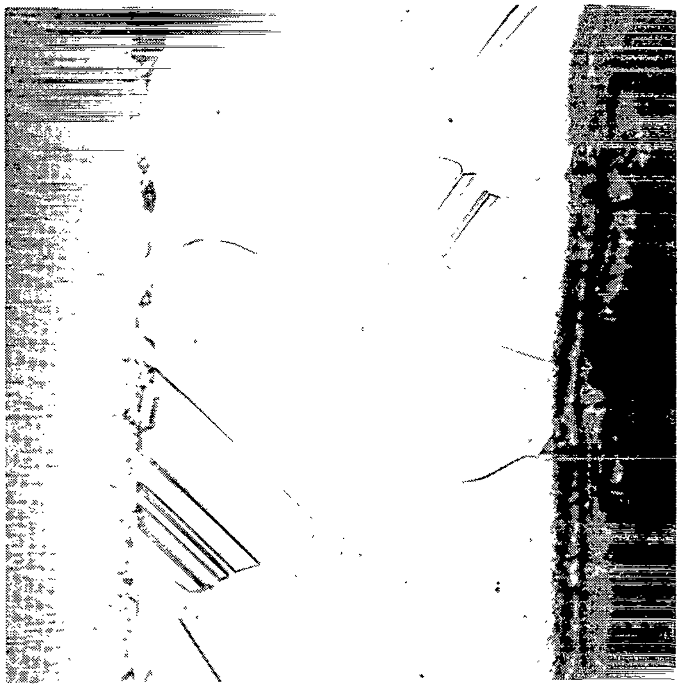
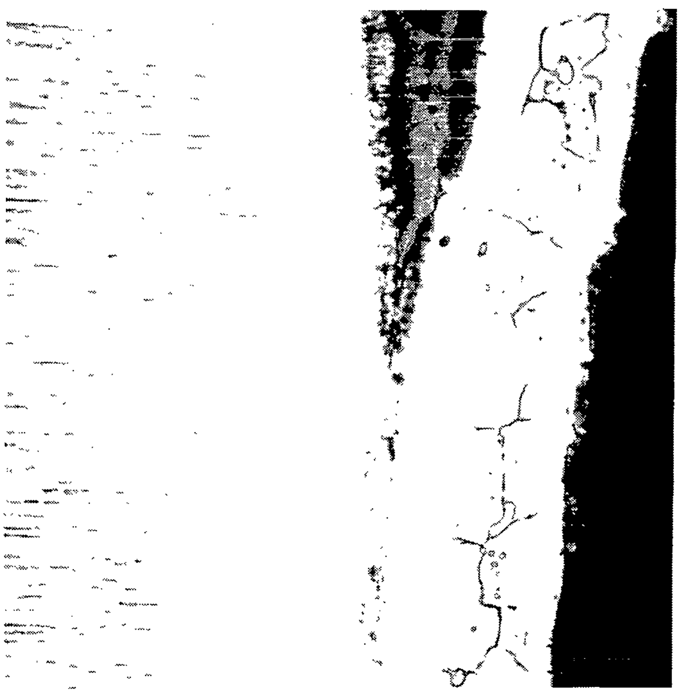


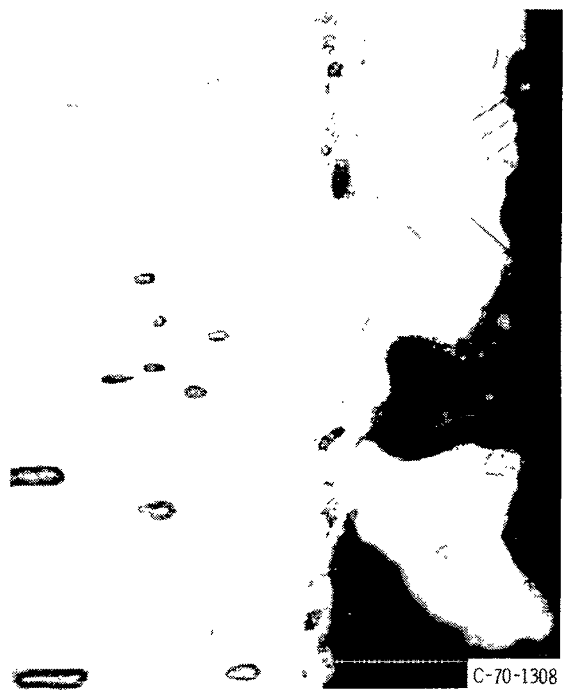
Figure 13. - Ultimate tensile strengths, at 2000° F (1093° C), of 1/2-inch (12.7-mm) diameter TD-Ni bar parent material and hot-isostatic-pressure (HIP) butt weldments with cobalt-alloy, Hastelloy X, and molybdenum interlayers. Testing was done both in air and in vacuum.



(a) Interlayer, 0.004 inch (0.10 mm) of cobalt alloy (specimen 11, table IV). Etched; X500.



(b) Interlayer, 0.002 (51 μm) of Hastelloy X (specimen 19, table IV). Etched; X500.



(c) Interlayer, 0.001 inch (25 μm) of molybdenum (specimen 26, table IV). Etched; X500.

Figure 14. - Fractures in 2000° F (1093° C) tensile tests of hot-isostatic-pressure butt welds with various interlayers. Etchants: (a) and (b)-swab with 92 milliliters HCl, 3 milliliters HNO_3, and 5 milliliters H_2SO_4, then electrolytically etch with 1 part H_2SO_4, 2 parts oxalic acid saturated solute; (c) swab with 92 milliliters HCl, 3 milliliters HNO_3, and 5 milliliters H_2SO_4.

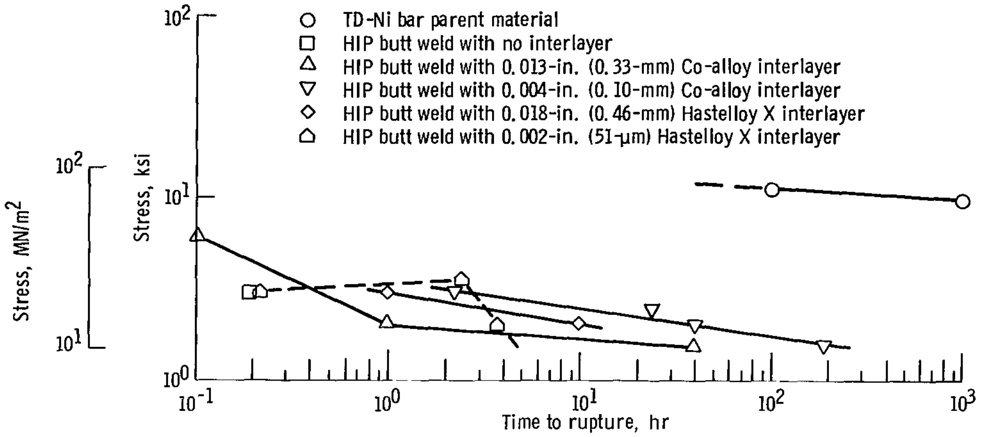


Figure 15. - Stress as function of time to rupture at 2000° F (1093° C) for hot-isostatic-pressure (HIP) butt weldments in 1/2-inch (12.7-mm) diameter TD-nickel bar with and without various interlayers.

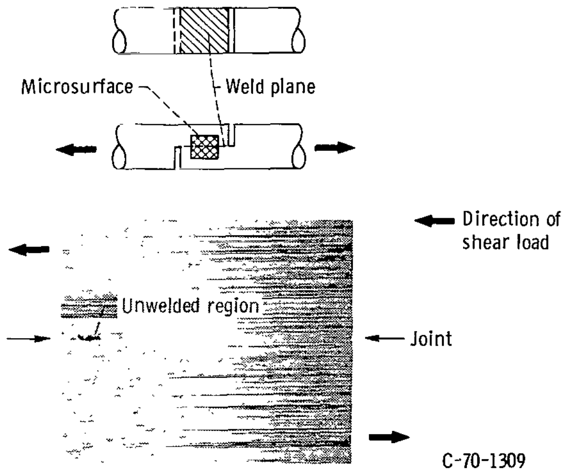


Figure 16. - Hot-isostatic-pressure-welded lap joint in 1/2-inch (12.7-mm) diameter TD-nickel bar. Original faying surfaces were milled and joint was heat treated at 2000° F (1093° C) for 100 hours after welding. Etchant: 92 milliliters HCl, 3 milliliters HNO_3, 5 milliliters H_2SO_4 (swab). X500.

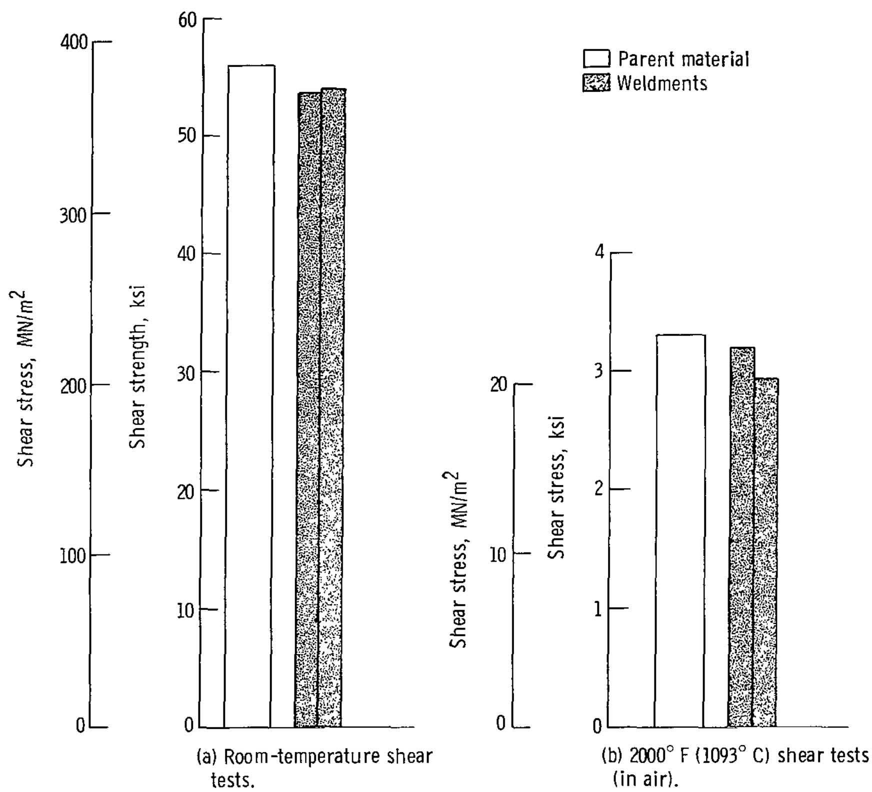


Figure 17. - Shear test results at room temperature and 2000° F (1093° C) of hot-isostatic-pressure-welded lap joints in 1/2-inch (12.7-mm) diameter TD-nickel bar in the as-welded condition. Parent material specimens were shear tested using the same specimen design for purposes of comparison.

NASA-Langley, 1970 —— 15 E-5651

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546